AN EVALUATION OF POTENTIAL GEOTHERMAL RESERVOIRS IN CENTRAL AND WESTERN NEW YORK STATE

Final Report

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ABSTRACT

Computer processed geophysical well logs from central and western New York State were analysed to evaluate the potential of subsurface formations as a source for low-temperature geothermal water. The analysis indicated that porous sandstone sections at the top of the Ordovician Theresa Formation and at the base of the Cambrian Potsdam Formation have the required depth, porosity, and permeability to act as a source for geothermal fluids over a relatively large area in the central part of the state. The fluid potential plus an advantageous geothermal gradient and the results of the test well drilled in the city of Auburn in Cayuga County suggest that low temperature geothermal energy may be a viable alternative to other more conventional forms of energy that are not indigenous to New York State.

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SUMMARY

Information from oil and gas wells drilled in central and western New York State was obtained to determine those formations capable of producing low-temperature geothermal water. Sources of information included driller's logs, well completion reports, production reports and geophysical well logs. When the initial survey indicated that only the lower Ordovician-Cambrian Theresa and Potsdam Sandstones had the potential for producing large volumes of water at temperatures greater than 50 degrees Celsius, these formations were mapped in detail and analysed for porosity zone thickness. Computer processed geophysical well logs were used for this analysis. All suitable logs from wells in the area which penetrated the Theresa-Potsdam section were obtained from the New York State Department of Environmental Conservation. The logs were checked by a log analyst and then digitized on a continuous mode digitizer for computer analysis. Because the logs were old and recorded on a variety of scales, they were first standardized to uniform lithology response. The standard logs were then used to compute lithology corrected formation porosities that had well-to-well regional validity. Syacuse University computers and processing programs were used for all data evaluation. The results were compiled into maps and cross sections displaying the elevation of the porous intervals, thickness of the interval containing the porosity, and thickness of the porous zones. The maps, when combined with temperature measurements made at SUNY Buffalo, strongly indicate that Central New York contains water filled porous sections where good flows of warm water at geothermal temperatures are anticipated. The study suggests that low-temperature geothermal energy can be a viable energy source in Central New York State.

AREA OF INVESTIGATION

The proposed area of investigation is that part of western New York State lying west of 75 degrees West Longitude and south of the southern shoreline of Lake Ontario. It is the area designated by Hodge, Hilfiker, Morgan and Swanberg (1979) as having potential for low-temperature geothermal energy resources derived from groundwater.

Counties included in the study area are:

Niagara	Wayne
Erie	Yates
Chautauqua	Schuyler
Cattaraugus	Chemung
Orleans	Tioga
Genesee	Tompkins
Wyoming	Cayuga
Allegany	Seneca
Monroe	Oswego
Livingston	Onondaga
Ontario	Broome

With parts of:

Chenango
Madison
Oneida
Lewis
Otsego
Delaware

GEOLOGIC BACKGROUND

With the exception of surficial glacial deposits, all of the sedimentary rocks of western New York are of Paleozoic age. Silurian and Upper Ordovician rocks crop out in eastward-trending belts across western New York, and Silurian strata also are exposed in a narrow southward-trending belt in south-central New York. Middle and Lower Ordovician and Cambrian strata are exposed around the flanks of the Adirondack uplift. Devonian outcrops cover the southern portion of central New York. The sedimentary section ranges in thickness from a feather-edge near the borders of the Precambrian outcrop area of the Adirondack uplift to more than 13,000 ft in Steuben County in the southwestern part of the state. Devonian, Silurian, and Upper Ordovician strata are predominantly clastic, but some carbonate rock and evaporites are present in the Lower Devonian and Silurian sections. Middle and Lower Ordovician and Cambrian rocks are predominantly carbonate but include minor amounts of sandstone and shale.

Regional dip of the surface formations in western New York is southward at about 50 ft/mi. In the subsurface, particularly on the older beds, the rate of dip increases because of convergence of the section northward, but nowhere except near faults or other local structural features does the dip exceed a few degrees. Large-scale block faulting is present around the flanks of the Adirondack uplift, and minor faulting is associated with anticlinal features in southern New York.

With the exception of certain Lower Ordovician and Cambrian sandstones, porosity and permeability of reservoirs in the Appalachian basin are generally low in comparison with porosity and permeability of reservoirs in many other geologic provinces. Porosity of rocks in the Appalachian basin commonly is less than 10 percent and permeability generally is on the order of a few millidarcys. Natural fracturing greatly increases both porosity and permeability.

Formation pressures found during drilling appear to be normal (expected hydrostatic pressure) or subnormal, except for abnormally high pressures reported from a few gas wells in the old Trenton fields in northern New York.

CAMBRIAN AND LOWER ORDOVICIAN

The Cambrian section in New York consists of rocks of Early and Late Cambrian ages, lying unconformably on an eroded basement complex of granitic and metamorphic rocks. The formations which make up the Cambrian and basal

Ordovician section in western New York are, in ascending order, the Potsdam Sandstone and the Theresa, Little Falls, and Beekmantown Dolomites. The Upper Cambrian Lower Ordovician is separated from the overlying Lower Ordovician Tribes Hill Limestone by a major unconformity.

The Cambrian and Lower Ordovician sedimentary rocks in western New York are predominately carbonate with a high clastic content. Where fossiliferous, their faunas suggest nearshore or shallow shelf environments. The dolomite is thinly bedded and commonly interbedded with clean sandstone and light-colored shale and siltstone. All of the Cambrian strata are truncated northward and pinch out against the south flank of the Canadian Shield. Regionally they thicken basinward toward the south and southwest. The dip of the deeper rocks is homoclinal, interrupted only by local south-plunging noses, synclines, and faults.

The Potsdam sandstone is the basal sedimentary unit recognized in western New York state. The Potsdam generally is considered to be of Late Cambrian age. The formation crops out on the flanks of the Adirondack uplift. The type locality is near the village of Potsdam, St. Lawrence County, New York. Drill cuttings have been described as very fine- to medium-grained sandstone, light brown to gray, both quartzose and dolomitic, and in places calcareous. Large frosted quartz grains, muscovite, and orthoclase feldspars interbedded with thin layers of light-gray, very finely crystalline, porous, slightly vugular, sandy dolomite are present.

The basal part of the Potsdam is extremely porous and permeable. This zone has been commercially productive of natural gas in the Memphis area (1897) of Onondaga County, and 12 miles west of Buffalo in the Point Abino field (1916) of Welland County, Ontario. The same zone also has yielded salt water where tested in Cattaraugus, Wyoming, Seneca, Cayuga and Livingston Counties, New York.

The Potsdam Sandstone strikes generally east-west and regionally dips southward at an average rate of 100 ft/mi (about 19 m/km). It ranges in depth from 3,000 ft (915 m) in the vicinity of Buffalo, New York to 13,000 ft (3,962 m) in southern Steuben County, near the Pennsylvania state line. In Oswego County, at the eastern end of Lake Ontario, the Potsdam is 1,500-2,000 ft deep. The Theresa overlies the Potsdam and is of Late Cambrian age. It crops out on the flanks of the Adirondack uplift. The formation was described originally from its exposure at Theresa, New York. The distribution of the Theresa is general throughout the western part of the state. In the subsurface, a maximum thickness of 1,486 ft (453 m) was found in the New York Natural Gas Corp. No. 1 Robert Olin well in southern Steuben County. The subsurface Theresa Dolomite has an average thickness of 700 ft.

In the subsurface the Theresa consists primarily of porous, sandy dolomite which grades into a distinct sandstone facies at its upper limits. The dolomite is buff, tan, gray, and brown; finely to medium crystalline; and contains finely disseminated subangular grains of quartz, pyrite, and biotite, and in places oolites and chert. Where the sand predominates in the samples, the cement is either calcareous or dolomitic. The clastic section at the top of the Theresa Dolomite is a white, clean sandstone with fine, subrounded grains, shows of gas and/or salt water are common. This section ranges from zero to 250 ft in thickness, depending on the degree of truncation, and appears to be developed best in the west-central part of the state.

The Little Falls dolomite directly overlies the Theresa and its distribution in the subsurface is restricted generally to the southern half of western New York. A maximum thickness of 950 ft (290 m) is found in the New York State Natural Gas Corp. No. 1 Kesselring well in Chemung County.

In the subsurface the Little Falls consists primarily of buff to light-gray to brown, finely to medium crystalline dolomite containing much very fine to coarse quartz sand and, in places, thin bedded siltstone. The overall section is commonly pyritic, cherty, and oolitic. Lithologically, it appears to be fairly uniform throughout the study area.

The Lower Ordovician Beekmantown Dolomite is the youngest of the Cambrian-Lower Ordovician formation preserved in the deeper parts of Central New York State. It appears to be transitional with the underlying Little Falls Dolomite and is made up of dark, very finely crystalline, silty and sandy dolomite commonly interbedded with medium- to dark-gray to black pyritic shale. At the top of the Cambrian-Lower Ordovician sequence is the Knox Unconformity. This stratigraphic break is widespread in the Appalachian basin and eastern United States. During this hiatus, the Cambrian strata were truncated in New York, Michigan, Ohio, Kentucky, Tennessee, Virginia, and other states, and in Ontario.

The Tribes Hill unconformably overlies the Cambrian/Lower Ordovician section. A basal zone of gray-green siltstone and shale containing glauconite is everywhere present at the base of the Tribes Hill. This zone is easily recognized both in drill cuttings and on radioactivity logs. Subsurface distribution is general throughout the western part of the state. There is onlap of the strata on the north beyond the updip limits of the truncated Upper Cambrian Potsdam Sandstone. In the subsurface the Tribes Hill consists primarily of light-gray to tan to buff, very finely crystalline, sublithographic, argillaceous, fossiliferous, pyritic limestone interbedded with light-gray-green dolomitic siltstone, thin stringers of green waxy shale, and clean, white, fine-grained calcareous sandstone. Basinward, to the south, the limestone grades into dolomite with interbeds of light-green pyritic shale, light-gray to white, fine-grained sandstone, tan dolomitic siltstone, and a few stringers of black pyritic shale.

In Central New York, the Theresa and the Potsdam sands are locally composed of clean sandstones exhibiting good porosity. These zones are generally water bearing and will form the main reservoirs for potential geothermal waters.

MIDDLE AND UPPER ORDOVICIAN

Sedimentary formations of Middle and Upper Ordovician age outcrop in the northern part of the area and dip southward into the Appalachian basin. Thickness ranges from zero around the Adirondack uplift to more than 3,700 ft (1,128 m) in southern Steuben County near the Pennsylvania border. Dip is southward at less than 100 ft/mi. The Ordovician rocks can be divided into two lithologic units - an upper clastic unit consisting of shale, siltstone, and fine-grained sandstone and very minor amounts of carbonate rock and a lower unit which is predominantly carbonate but has a few thin calcareous shale and dolomite sandstone beds.

The Ordovician-Cambrian boundary is within the lower pre-Knox carbonate unit and is difficult to recognize in the subsurface. The lithologic units transgress time zones, generally becoming younger northward and westward. The Ordovician-Silurian boundary is an angular unconformity in the eastern part of the area and a disconformity in the western part of New York. In places where Silurian sandstone beds lie on Upper Ordovician sandstone the contact is obscure.

The Middle Ordovician Trenton Limestone and the Upper Ordovician Queenston sand and shale sequence have both produced gas in the northern part of the state, however, their porosities and permeabilities have invariably proven too low for them to be considered as potential sources for geothermal waters.

The Middle Ordovician

The Black River Limestone unconformably overlaps older rocks from south to north. The Black River Formation consists of dark-gray to brown cherty limestone and various amounts of shale. It is slightly sandy in places. The thickness is varied, because of erosional relief on the depositional surface. Transitionally overlying the Black River is the Trenton Limestone which consists of light-to dark-gray limestone beds and alternate thin, gray, calcareous shale beds. The limestone ranges from coarsely crystalline and very fossiliferous to dense and argillaceous.

The Black River displays very little intergranular porosity but locally appears to be highly fractured. This fracture porosity may contribute to the flow of geothermal waters. Unfortunately, there is not sufficient well information to map the fractured areas effectively; however, these areas are undoubtedly related to tectonic activity that could be interpreted from reflection seismic profiles. Similarly, there is known fracture porosity and some intergranular porosity in the overlying Trenton Formation. Unless this porosity is locally enhanced by faulting, it is not likely to be a source for geothermal waters.

Above the Trenton Limestone is the Utica Shale. At the type locality the Utica Shale is black, carbonaceous, fissile, pyritic, and slightly calcareous, and is characterized by an abundance of graptolite fossils. In the subsurface, the color ranges from gray to brown or black. Siltstone and mica are present in places, particularly in the western counties.

Upper Ordovician.

The Lorraine Shale, which overlies and is transitional with the underlying Utica Shale, ranges in thickness from 500 to 800 feet. It is present in the subsurface in most of western New York and crops out in the northern parts of the area. The Lorraine grades upward from dark-gray, carbonaceous, slightly calcareous, pyritic shale at the base to very fine-grained, very fossiliferous sandstone, shale, and siltstone interbedded with dark-gray, silty, micaceous shale at the top. The

Lorraine Shale is transitional with the overlying Oswego Sandstone where it is present, and the boundary commonly is difficult to recognize.

The Oswego Sandstone is regarded as the sandstone facies of the Queenston Shale. It is present in most of western New York and crops out in the northern part of the area. Thickness ranges from zero in the west, where the Oswego section is silty shale, to about 900 ft in Chemung County. It is a monotonous sequence of fine- to very fine-grained sandstone, shale, and siltstone. The sandstone is quartzose, slightly calcareous, tightly cemented with silica cement, and argillaceous in part. The Oswego Sandstone is overlain by sandstone, siltstone, and shale of the Queenston Shale, and the only distinction is a color change. In the easternmost counties of western New York, the Oswego Sandstone is absent because of pre-Silurian erosion, and in eastern Madison County the Oswego is overlain unconformably by the Silurian Oneida Conglomerate.

The Queenston Shale is a thick sequence of red, brown, gray, and green shale, siltstone, and fine- to medium-grained sandstone. In the eastern and central parts of western New York the Queenston is predominantly siltstone and sandstone; westward it grades into a slightly calcareous, brown to green, gray, and red silty shale. In general the clastic material becomes finer from east to west. The Queenston Shale is about 800-900 feet thick in most of western New York and crops out in the northern part of the area. With the exception of the Black River, the upper Ordovician sediments display very low porosity and permeability and will not contribute geothermal water unless the well directly intersects a fault zone.

SILURIAN

In central New York State the Silurian consists of numerous lithologic units characterized by erosion, nondeposition and differences in depositional environments. The basal unit is the Medina series of sandstones, siltstones and shales. The Whirlpool or "White Medina" Sandstone is the basal member of the Medina Series, and is an almost pure, white quartzose sandstone. It extends from western to central New York, where it pinches out by onlap.

The Cabot Head Shale overlies the Whirlpool Sandstone in western New York, but disappears eastward by facies change and pinchout.

The Grimsby or "Red Medina" Sandstone overlies the Cabot Head Shale in western

New York. It is approximately 100 ft thick in west-central New York and consists of red, silty shale; red siltstone; and pink to red, fine-grained sandstone. In central New York where the Whirlpool sandstone is not present, the contact between the base of the Grimsby Sandstone and the top of the underlying Ordovician Queenston Shale is difficult to recognize from well data because of the sandstone development of the Queenston in that area. The youngest Medina formation is the Thorold Sandstone, which overlies the Grimsby Sandstone. It is light gray, fine grained, silty, shaly, and locally dolomitic and hematitic. The Thorold Sandstone is identified easily in well cuttings and is a good marker because it is the first sandstone found below the Lockport. The overlying Clinton group consists of basal shale members, locally named Bear Creek and Sodus Shales averaging a total of 100 ft in the project area. They in turn are overlain by the Reynales Limestone. The Reynales is a true limestone in central New York State but becomes dolomitic in the west. The upper Clinton, the overlying Rochester Shale is approximately 100 ft thick and is gray to dark gray, dolomitic, and silty. It becomes more dolomitic toward the top and appears to be gradational with the overlying Lockport dolomite strata.

Immediately overlying the Clinton is the Lockport Group. The Lockport is dark-gray, finely crystalline, argillaceous dolomite containing some interbedded shale. The Lockport is dolomite in the western area, but becomes more calcareous in east-central New York and grades into limestone. Above the Lockport is the Salina group of interbedded evaporites, carbonates and shales. The generally recognized lower member, the Vernon shale is composed of red and green shales and siltstones with minor dolomitic stringers. West of Seneca Lake several salt beds occur in the middle Vernon attaining a maximum thickness of 75 feet.

The Syracuse Formation comprises the middle Salina. It has been called the Syracuse Salt although it contains numerous interbeds of shale, dolomite and anhydrite along with the salts that may total as much as 800 feet in the southcentral portion of the area. The Bertie Formation consisting of a rather thin sequence of dolomites and shales is the uppermost Salina member in the general project area. Silurian formations outcrop in an east-west band across central New York at the approximate latitude of Syracuse. Dip of the formations is generally south at 75 ft/mi.

The Medina Sandstones are the main gas producing horizons in western New York State. They appear to be gas saturated wherever porosity permits gas entry. Very little water is produced along with the natural gas. Considerable water flows have been obtained locally from the Salina Formation; however these appear to be confined to those areas where the Syracuse salt members have been removed by solution permitting collapse of the overlying formations with subsequent fracture porosity.

DEVONIAN

In the eastern portion of the area, the Lower Devonian consists of the Helderberg Group of transgressive limestones topped by the Oriskany sandstone where present. The thickness of the Lower Devonian Series, including the Oriskany Sandstone, ranges from a featheredge in southwestern New York to possibly 800 ft in the southeastern part of the state. The Oriskany Sandstone is quartzose sandstone that ranges in thickness from a wedge edge to 70 ft or more in the south-central part of New York. The Middle Devonian Series is composed of the Tully Limestone at the top, the Onondaga Limestone at the base, and an intervening shale section. The Onondaga Limestone comprises some 85 to 95 feet of coarse to fine grained limestone that is often cherty at the base. The overlying Hamilton Shale Group consists of calcareous shales and silts with minor limestones. The sequence is capped by the Tully Limestone which is a distinctive log marker. Regional dip is generally southward; the rate increases from about 60 ft/mi in western New York to about 160 ft/mi in south-central New York. The Upper Devonian Series consist of interbedded shales, siltstones, and sandstones. They form the bedrock of the southern half of the project area. Porous zones in the Devonian are locally restricted and are not expected to be a source for geothermal waters.

HYDRODYNAMICS

Gravity-induced cross-formational flow is an important form of groundwater movement. It allows infiltrating meteoric waters to reach great depths, the topographic relief to generate differences in the fluids potential energy, and subsurface drainage basins to form in relation to watersheds on the land surface. The distribution patterns of hydraulic potentials, pressures, and mass movements in these flow systems are basically different from those due to other sources of energy such as compaction, heat or osmosis, or from those that are confined to pervious strata by relatively impermeable boundaries. Consequently, the traffic patterns and accumulations of dissolved, colloidal, and suspended material such as ionic constitutents, trace metals, hydrocarbons, and other matter are also controlled by particular criteria when moving in gravity-induced cross-formational flow systems.

Geologically mature basins are hydraulically continuous environments in which the relief of the water table, commonly a subdued replica of the land surface, generates interdependent systems of groundwater flow with patterns modified by permeability differences. In these systems, meteoric waters infiltrate and move downward in upland recharge areas, migrate laterally under regions of medium elevations, and are discharged in topographic depressions. Where flow systems meet or part, relatively stagnant zones develop and flow directions change abruptly. Deep groundwater fluid systems are in thermal equilibrium with heat flow thru the rock matrix and are the source for low temperature geothermal energy.

In most basins, the best information on the subsurface formations and their hydrologic characteristics is obtained from cores, tests and geophysical well logs derived from wells that have been drilled for oil and natural gas. Of these, only the geophysical well logs are capable of presenting a detailed three-dimensional picture of formation characteristics. Cores are expensive to take and are virtually non-existent in New York State. Standard drilling practice in the area does not require drill stem tests for formation evaluation and shut-in gas pressure tests pertain only to gas bearing zones. Most wells are logged throughout their depth and the recorded physical parameters can be converted to computer processable information and analyzed to present a vertical picture of the lithologic formations and their interstitial porosities. Although the geophysical measurements in New York State wells do not permit direct permeability measurements, there is normally a close relationship between porosities and permeabilities so that if lithology and porosity are known, a good estimate of hydraulic permeability can be made. Consequently a detailed analysis of the well logs combined with geologic knowledge of the subsurface formations can provide the necessary parameters for a three-dimensional model of regional ground water movements in central New York State.

The hydrodynamic systems of New York State largely reflect topography, however, the porosity and permeability of the upper sections (Upper Ordovician, Silurian and Devonian) are so very low that hydraulic response is in terms of geologic time. Consequently, potential patterns in the deep lower Ordovician-Cambrian geothermal reservoirs will vary smoothly, displaying only a very subdued relation to surface topography. In fact, there may still be areas of higher than normal hydrodynamic potentials as unresolved relics of suprapressures developed during ice age glacial loadings.

Unfortunately, there are no available reservoir pressures for the pre-Knox formations in the southern part of the state. Some estimates can be obtained from gas pressures in the northern part of the area. These suggest that fluid pressures are largely equivalent to the pressures developed by a fresh water column whose head is at or near the topographic surface. One would expect relic pressures to be more prominent in the southern and central parts of the state where the thicker section prevents rapid return to normal pressures.

Standard pressures in pounds per square inch can be estimated by multiplying the depth in feet to the geothermal reservoir by 0.435. The actual height to which the geothermal fluid will rise in the borehole is a function of the solids dissolved in the fluid which add to the density of the fluid. Anticipated solids (mainly NaCl) in the fluids suitable for geothermal use range from 200 thousand to 300 thousand parts per million (0.495 to 0.521 psi per foot). Elevation of the fluid in the borehole will then be:

Elevation of Geothermal Reservoir + reservoir psi / (0.49 to 0.521)
(as appropriate)

The area of drainage within an individual reservoir for a geothermal well is a function of fracture and intergranular permeability. These parameters have never been tested in the main area of interest. Produceability and drainage need to be determined from the evaluation of sustained pump tests from individual reservoirs.

WELL LOGGING

INTRODUCTION

It has become general practice, when a hole has been drilled, or at intervals during the drilling, to run an electrical survey and/or a radioactivity survey for the purpose of obtaining quickly a complete record of the formations penetrated. This recording is of immediate value for the geological correlation of the strata, and also for the detection and evaluation of possibly productive horizons. The information derived from the electrical and/or radioactivity logs, may at the same time be supplemented by side-wall samples of the formations taken from the wall of the hole, or by still other types of investigations which can be performed in drill holes.

"Well Logging" denotes any operation, wherein some characteristic data of the formations penetrated by a borehole are recorded in terms of depth. This record is called a log. The log of a well, for example, may simply be a chart on which abridged descriptions of cores are written opposite the depths from which the cores were taken. A log may also be a graphic plot with respect to depth of various characteristics of these cores, such as porosity, permeability, residual oil...etc....

Electrical logging is one of the important branches of well logging. Essentially, it is the recording of the resistivities (or their reciprocals, the conductivities) of the subsurface formations, and the Spontaneous Potentials generated in the boreholes. Electrical logging was presented to the oil industry more than 25 years ago and has been accepted as one of the most efficient tools in the search for and the production of oil and gas.

Other significant varieties of well logs measure the natural radioactivity of the formations (Gamma Ray Logging), and the secondary effects due to the bombardment of the formations by neutrons (Neutron Logging). Radioactivity logging is more recent, and has also proved extremely valuable.

Quite recently, a new type of well log has been introduced which provides a record of the sound-velocity across the formations (Sonic Logging).

With electrical, radioactivity, and sonic logging, the corresponding parameters are measured in situ by means of appropriate down-hole instruments, called "sondes", and are continuously recorded at the surface.

In electrical and sonic logging, the measurements are performed in the uncased portions of the borehole only. With radioactivity logging, the measurements can also be recorded in cased hole.

The general information provided by the logs is essentially the following:

- Differentiation between shales, other rocks, their individual beds, and their well-to-well correlation. These data make possible the delineation of structural features and the determination of the thickness and lateral extension of potential reservoirs.
- In most cases, qualitative descrimination between oil- or gas-bearing and water-bearing beds, as well as location of oil-water contacts. In favorable cases, quantitative evaluation of porosity and water saturation.

The logs accordingly are of great assistance for an accurate selection of the intervals to be tested for production, and for the computation of reserves. They also help in the estimation of well productivity.

Resistivity methods can be divided into two main groups, according to whether the measurements involve large or small volumes of material. Measuring devices of the first group are adapted to the investigation of comparatively large volumes of material around the borehole, from about 10 to 100 cubic feet or more. The corresponding logs are used for the definition of formations, for correlations, and for qualitative and quantitative analyses of reservoirs in terms of fluid saturation and porosity.

This group includes the Induction Log and the devices using electrodes (conventional devices and Laterolog).

Induction Logging makes use of currents induced in the formations surrounding the sonde which is lowered into the borehole. By proper design and placement of the coils mounted on the sonde, the response is confined to a horizontal slice of formation of limited thickness. The effects of the mud column and of adjacent beds are minimized or even rendered negligible in many cases.

With the present equipment, the Induction Log works best in soft or moderately consolidated formations drilled with fresh muds, and it is generally more reliable than the conventional electrical log even in hard formations. The combination of Induction Log, Short Normal and SP Log is now being used more and more extensively in fresh mud, instead of the conventional logs. Also, the induction method can be used to log wells drilled with oil-base mud, or with no liquid at all in the hole. Wells drilled in New York State commonly are air or cable tool drilled and are logged with an empty bore hole.

Conventional devices (normals and laterals) use electrodes from which electric currents flow into formations and between which the resulting potentials are measured. The borehole must contain conducting liquids which allow currents to flow; (e.g. water-base muds). The path of the current used for the measurement is submitted to no other restriction than the location of the electrodes between which the current flows. The measurements, accordingly, are affected not only by the presence of the bed located at the level of the device, but also by the mud column and, if the thickness of the bed is not great, by the formations above and below it. The relative effect of the mud column and of the adjacent formations depends upon: a) the physical configuration of the electrode system, b) the geometry and the respective resistivities of the media involved in the measurements. The conventional devices therefore are not suitable for a correct investigation of thin beds, where the resistivity contrasts between different beds or between the formations and the mud are great.

The Laterolog also uses electrodes, but the surveying current is constrained to flow into the formations within a horizontal disk of limited vertical thickness It is, therefore, well adopted to the investigation of thin beds. The Laterolog has completely replaced conventional devices in hard formations drilled with very salty muds.

The devices of the second group are designed so that a very small volume of material (a few cubic inches) behind and close to the wall of the hole is investigated, and also, the effect of the mud column on the measurement is practically eliminated. The delineation of the beds with these devices is accordingly much more accurate and more detailed than with the devices of the first group - even those devices using focusing systems.

With the Microlaterolog, a focusing system is involved so that the effect of the mud cake is minimized or even eliminated when the mud cakes are thin enough. Under these conditions the measurements give values close or equal to the resistivity of the formations flushed by mud filtrate behind the wall of the hole: this provides an approach toward the determination of the formation factor and hence of porosity.

Radiation logs are of two very general types: those which measure the natural radioactivity of formations (Gamma Ray Log) and those which indicate radiation reflected from or induced in the formations as a consequence of bombarding the formations with neutrons emitted from a source contained in the sonde. The type of radiation which is detected in neutron logging is also gamma radiation. The origins and energies of the gamma rays are different in the two cases.

There are a few elements existing in nature which spontaneously emit gamma rays: those belonging to the radioactive families of uranium and thorium, and also the radioactive isotope of potassium (K40). It is these gamma rays which are detected in the Gamma Ray Log.

The Gamma Ray Log is used principally for bed definition, determination of interfaces, and correlation. in particular, in open holes drilled with high salinity mud - whereas the SP curve lacks resolution, the Gamma Ray Log will locate shales and shaly formations.

Gamma Ray Logs may be recorded in both open and cased holes filled with any fluid whatsoever including air.

The neutron logging method consists of placing a source of fast neutrons and a suitable radiation detector close together in a sonde and lowering them into the borehole. The method makes use of a detector sensitive to the capture gamma rays.

When the hydrogen concentration of material surrounding a neutron source is large, the neutrons are slowed down and captured within a short distance from the source. On the contrary, if the hydrogen concentration is small, the neutrons travel relatively far from the source before being captured.

The hydrogen concentrations in water and in oil are not sufficiently different to cause noticeable differences in the counting rates. Therefore, for oil-bearing or water-bearing formations, the counting rate is essentially responsive to porosity.

DEFINITIONS OF POROSITY, SATURATION AND PERMEABILITY

Porosity

is the fraction of the total volume of a sample which is occupied by pores, or voids. A dense, uniform substance such as a piece of glass, would have zero porosity: a sponge on the other hand, has a high porosity.

Effective porosity is that in which the pores or voids are interconnected so that fluids can pass through the sample. Total or bulk porosity of a sample includes not only pores which are connected, but also those which are sealed off by cementing material.

Porosities of subsurface formations can vary widely. Dense limestones and anhydrites may show practically zero porosity; well-consolidated sandstones show about 10 to 15 percent porosity; and unconsolidated sands show up to 30% or more porosity. Shales and clays may contain over 40% liquid by volume, but they are so fine-grained that they are practically impervious to the flow of fluids. For all practical purposes, their voids are not interconnected, and their porosity is not effective.

Porosities may be classified also according to the physical arrangement of the material which surrounds the pores. Thus, in a clean sand, the pores exist between the grains. Such porosity is called "intergranular", and is inherent in sand formations since the time they were deposited. Vugular and secondary porosities are caused by the action of formation waters on materials after deposition.

Saturation

Saturation of a formation is the fraction of its effective pore volume which is occupied by the fluid considered. In electrical logging practice, it is customary to consider the formation water as the saturating liquid because it conducts the electric currents.

Water saturation, then, is the fraction of pore volume which contains formation waters. If nothing but water exists in its pores, a formation has a water saturation of 100 percent - the volume of water equals the pore volume.

Permeability

Permeability is a measure of the ease with which a formation permits fluids to flow through it. For a given sample of rock and for any homogeneous fluid, the permeability will be a constant provided the fluid does not interact with the rock itself.

In order to be permeable at all, a rock must have some interconnected pores, capillaries or fractures: that is, it must have some effective porosity. There exists some rough relationship between the values of porosity and permeability. Greater permeability, in general, corresponds to greater porosity, but this is far from being an absolute rule.

Some sands can have large effective porosities, but the grains are so small that the paths available for the movement of fluid through the sands are quite restricted and tortuous; thus, their permeabilities may be very low.

Other formations, such as limestone, may be composed of a dense rock broken by a few small fissures of great extent, which are penetrated by the borehole. The porosity of such a formation would surely be very low, but the permeability of a fissure can be enormous. In fact, it has been shown that a 0.05 inch fissure will have a permeability equivalent to about 550 feet of sand of 1000 millidarcies permeability. Therefore, fissured limestones may have very low porosities, together with exceedingly high permeabilities.

Effective permeability refers to the permeability of a formation to one fluid when another fluid, immiscible with the first, is also present. It not only depends upon the rock itself, but also upon the relative amounts of the two (or more) different fluids present in the pores.

Permeabilities of porous reservoirs can be estimated from drill stem tests, cores, production tests and the electric logs which measure the amount of mud filtrate entering the formation. Unfortunately, there are no Drill Stem Tests or cores of the potential geothermal reservoirs, and the type of drilling most commonly employed precludes the use of standard electric logs. Permeability estimates must await additional drilling and testing. It is suggested that the petroleum and natural gas operators be approached to test for geothermal fluid flow in new venture wells.

Pump tests of deep wells in the Buffalo area where there is little intergranular porosity and permeability have largely reflected water flow from fracture porosity. Preliminary tests of the geothermal well in Auburn suggest fluid contribution from both fracture and intergranular permeability. The actual permeability measurements will require sustained pump tests. However, it is anticipated that the optimum geothermal fluid production will be obtained from fractures, either natural or artificially induced, within reservoirs containing a high degree of intergranular porosity and permeability, the intergranular porosity providing the volume of water necessary for sustained geothermal energy production and the fractures providing the avenues of access to the borehole.

Fluids in geothermal reservoirs are essentially single phase brines. Reservoirs containing even a small percentage of gas are generally not suitable for geothermal production. Consequently there are very few real tests of produceability from potential geothermal reservoirs, because the vast majority of test wells in the state were drilled solely in search of petroleum and natural gas.

LOG NOMENCLATURE

Gamma Logs

- Gamma Ray
- Gamma-Gamma
- Scintillometer

Neutron Logs

- Compensated Neutron
- Porosity
- Neutron Porosity
- Sidewall Neutron Porosity

Density Logs

- Formation Density
- Formation Density Compensated
- Borehole Compensated Density

Electric Logs

- Spontaneous Potential (SP)
- Guard
- Resistivity
- Shallow Induction
- Medium Induction
- Deep Induction
- Dual Induction
- Induction Spherically Focused
- Laterlog
- Laterlog 8
- Dual Laterlog
- Dual Induction Laterlog
- Microlaterlog
- Proximity
- Continuous Dipmeter
- High Resolution Dipmeter
- Short Normal
- 16 inch Normal
- 64 inch Normal
- 18 foot 8 inch Lateral
- Conductivity

Sonic Logs

- Sonic
- Borehole Compensated Sonic
- Velocity

Caliper Logs

Temperature Logs

Other Logs

- Sibilation
- 3-D Velocity
- Liquid Isotope Injection
- Radiocative Tracer
- 3-D Bond
- Cement Bond
- Salinometer
- Casing Collar Locater
- Fracture Identification Log

PROPERTIES OF LOGS COMMONLY RUN IN NEW YORK STATE IN ORDER OF THEIR USE AND FREQUENCY

The Gamma Ray Log

Description and Calibration.

The gamma ray is the most common and probably the most useful log from New York State wells. It is a measurement of the natural radioactivity of the formations. The log is therefore useful in detecting and evaluating deposits of radioactive minerals such as potash or uranium ore.

In sedimentary formations, the gamma ray log normally reflects the shale content of the formations. This is because the radioactive elements tend to concentrate in clays and shales. Clean formations usually have a very low level of radioactivity, unless radioactive contaminants such as volcanic ash or granite wash are present or when the formation waters contain dissolved potassium salts.

The Gamma Ray Log can be recorded in cased wells, which makes it useful as a substitute for self or spontaneous potential (SP) in cased holes where the SP is unavailable or in open holes where the SP is unsatisfactory. In both cases, it is useful for the location of the non-shaly beds and for correlation.

The Gamma Ray Log response, after correction for borehole, casing, etc., is proportional to the weight concentration of the radioactive material in the formation. Two formations having the same amount of radioactive material per unit volume but having different densities will show, on the gamma ray log, different radioactivity levels with the less dense formations appearing to be more radioactive.

The number of gamma rays reaching the counter fluctuates even when the sonde is stationary in the hole; the phenomenon is statistical in nature. The fluctuations are more noticeable for lower count rates. However, the number of gamma rays counted per second over a sufficiently long period of time will be practically constant. The period of time required to obtain a good average value is appreciable, usually a few seconds.

In order to average out the statistical variations, condenser-resistor smoothing circuits are used in the measuring circuits. Various "time constants" may be selected according to the radioactivity level measured.

The smoothing circuits introduce a lag in the recording, and, in order to avoid excessive curve distortion, the recording speed is chosen so that the counter will not travel more than about one foot during the time constant. For a time constant of 2 seconds, the logging speed is 1800 ft/hr.

Gamma Ray Logs are now usually calibrated in American Petroleum Institute (API) units. The radioactivities observed in sedimentary formations range from a few API units in anhydrite or salt, to 200 or more in shales.

Prior to the API calibration procedure, Gamma Ray Logs were scaled in micrograms of radium equivalent per ton of formation.

The API calibration is based on the use of a permanent calibration facility to establish standard units for nuclear logs.

The gamma ray deflection is a function not only of the radioactivity and density of the formations, but also of hole conditions (hole diameter, mud weight, casing...) since the materials interposed between the counter and the formations absorb gamma rays. The corrections can be important in large holes and in cased holes.

Applications Of The Gamma Ray Log.

- The Gamma Ray Log is particularly useful for defining shale beds when the SP curve is rounded in very resistive formations, or flat, or when the SP curve cannot be recorded (non-conductive muds - empty holes - cased holes).
- The Gamma Ray Log reflects the proportion of shale and, in some regions, can be used quantitatively as an indicator of shale content.
- The Gamma Ray Log is used for the detection and evaluation of radioactive minerals, such as potash or uranium ore. The gamma ray may also be used to detect and to evaluate uranium deposits, but in this case there is no simple proportionality between gamma-ray deflections and the "richness" of the deposits.

- The Gamma Ray Log can also be used for the delineation of nonradioactive minerals including coal beds.
- The Gamma Ray Log is used for correlations in cased holes. The simultaneous recording of the gamma ray and of a casing collar locator makes it possible to position perforating guns very accurately. As compared with the corresponding open-hole log, the deflections on the cased-hole log are somewhat attenuated due to absorption of the gamma rays in the steel casing and cement.
- The Gamma Ray Log is sometimes used in connection with radioactive tracer operations.

Gamma Ray Log Response Standards Computed at Syracuse University.

The Gamma Ray Log is the most common correlation and lithological log run in New York State. There have been many service companies performing the logging operations and there have been changes in calibration within as well as between companies. Log responses thus display considerable variation in amplitude and cannot be used directly for lithologic identification in a well-to-well comparison. Fortunately the Gamma Ray Log is a direct record of the radioactivity within formations and can be considered as constant for identical rocks. Thus where formations are known to have uniform levels of radioactivity, the logs can be adjusted to a uniform response to these formations. Gamma Ray Logs can be standardized to a uniform amplitude response to formations known to have a uniform level of radioactivity for enhanced well to well correlations and lithologic determinations.

Modern Gamma Ray logs are recorded to uniform scales and uniform responses to test conditions. Many are now recorded digitally and are amenable to between well standardization. However, the older logs are not uniform and can only be transformed to a uniform lithologic response when corrections are applied by computer to digital log values. Each log must be examined on an individual basis, and average response to clean formations must be determined for the entire area. Then correction parameters must be measured and then applied via computer programs to produce standard logs that show a unifrom response over a region. The standard logs can then be used in a comprehensive program to compute the amount of shale percent in the section.

Standardization measurements were made on all Gamma Ray curves used in this project. The values were entered into computer programs that computed and displayed standard gamma curves for use in correlation and for entry into programs that computed lithology corrected porosities. Computer programs used in this project were written at Syracuse University.

Once Gamma Ray logs are corrected to a standard response to known zones of clean shale and clean limestone, the shale fraction can be computed:

$$\text{Shale Fraction} = (1.0 \times ((G-G_{sh})/(G_{cl} - G_{sh})))^{1.1}$$

where:

cl = clean limestone formation

sh = pure shale

G = Gamma reading

The exponential (1.1) was experimentally determined for maturely compacted shales in New York State. Because shaliness directly relates to effective porosity, porosity calculations must be corrected for any contained shale.

Neutron Logs

Description.

Neutron Logs or neutron derivative, porosity logs are normally run with the Gamma Ray Logs in New York State.

Neutrons are electrically neutral particles, each having a mass almost identical to the mass of a hydrogen atom.

High-energy neutrons are continuously emitted from a radioactive source which is mounted in the sonde. These neutrons collide with nuclei of the formation materials in what may be thought of as elastic type collisions. With each collision a neutron loses some of its energy. The amount of energy lost per collison depends on the relative mass of the nucleus with which the neutron collides. The greatest energy loss occurs when the neutron strikes a nucleus of practically equal mass. Collisions with heavy nuclei do not slow the neutron down very much. Thus, the slowing-down of neutrons depends largely on the amount of hydrogen in the formation. Within a few microseconds the neutrons have been slowed down by successive collisions to thermal velocities, corresponding to energies of around .025 electron volts. They then diffuse randomly, without losing any more energy, until they are captured by the nuclei of atoms such as chlorine, hydrogen, silicon, etc. The capturing nucleus becomes intensely excited and emits a high-energy gamma ray of capture. Depending on the type of

Neutron Logging tool, either these capture gamma rays or neutrons themselves are counted by a detector in the sonde.

When the hydrogen concentration of the material surrounding the neutron source is large, most of the neutrons are slowed down and captured within a short distance of the source. On the other hand, if the hydrogen concentration is small, the neutrons travel farther from the source before being captured. The counting rate at the detector varies according to the hydrogen concentration.

The natural gamma rays and those emitted by the source generally have much lower energies than the capture gamma rays. Hence, it is possible, by proper design and shielding of the detector, to eliminate the natural gamma rays and those coming up directly from the source, and to reduce the effect of these scattered by the formations to a very small amount.

Neutron logs are used principally for delineation of porous formations and determination of their porosity. They respond primarily to the amount of hydrogen present in the formation. Thus, in clean formations whose pores are filled with water or oil, the Neutron Log reflects the amount of liquid-filled porosity.

Gas zones can often be identified by comparing the Neutron Log with another porosity log or a core analysis. A combination of the Neutron Log with one or two other porosity logs yields even more accurate porosity values and lithology identification, including evaluation of shale content.

The concentration of hydrogen in gas is practically always much less than in oil or water; so for equal porosity values, a formation which contains gas will give a higher counting rate than a formation free of gas.

In a shaly formation, the volume fraction occupied by shale does not contribute to the effective porosity, because shale is practically impervious. On the other hand, shale contains a great amount of hydrogen because of the water which is either occluded in its pores or combined chemically in its molecules. The interstitial shale accordingly contributes to the hydrogen content of the formation; and for equal effective porosities, the number of counts per second will be less for a shaly formation than for a clean formation.

Besides the hydrogen content of the formation, the Neutron Log may be also affected by the chemical composition of the minerals which constitute the rock, and by the borehole conditions such as diameter, nature of borehole fluid and presence of casing.

If the borehole conditions are about the same throughout the section surveyed, the intervals with a lower counting rate will correspond to higher porosity and/or to greater shale content. The deflections of the log which correspond to variations of porosity can be differentiated, to a great extent, from those corresponding to variations of shale content, by means of the gamma ray curve and/or the SP curve. In particular, these curves usually indicate pure shale beds without ambiguity.

Empirical approaches make possible the derivation of fairly reliable porosity values from the Neutron Logs in many cases, at least in open holes and in essentially clean formations. Appreciable errors, however, may occur even in clean formations, because of the influence on the Neutron Log readings of the borehole conditions. Test results indicate that the influence of hole diameter variations is important and should be taken into account in the interpretation of the logs. The presence of casing and cement has an appreciable effect, which depends on the positions of the casing and of the sonde in the borehole. It is very difficult to correct for this effect, since the exact geometry of casing and cement is rarely known. The variations of mud density can be neglected, but increasing mud salinity increases the counting rate, all other conditions being the same. This effect, nevertheless, is not important except when the salinity becomes very high.

In the case of empty holes and with the type of logging instrument used at present, the interpretation of the Neutron Logs becomes difficult for hole diameters greater than 6". Some improvement can be obtained by increasing the spacing between the emittor and the detector.

The position of the logging instrument with respect to the wall of the hole is a critical factor and sidewall neutron tools use a device to hold the sonde against the borehole wall.

The Neutron Log is a useful tool for the delineation of formations and for correlation, in wells filled with water-base mud, or oil-base mud or in empty holes - in open holes or in cased holes. The Neutron Log and Gamma Ray Log provide a qualitative record of shales, tight formations and porous sections in cased wells, which is valuable in particular, for workover jobs or for the surveying of old wells.

Determination of porosity by means of the Neutron Log is probably one of its most important applications. For equal porosity values, a gas-containing reservoir will show a higher counting rate than an oil- and/or water-bearing formation, provided the gas in the volume of formation penetrated by the neutrons has not been flushed by mud filtrate. The Neutron Log therefore can be used under favorable conditions for the distinction between oil and gas.

Neutron Log Scales and Syracuse University Standards.

Early Neutron Logs were scaled in counts per second according to each logging company's instruments and logging rates. Scales varied over a considerable range, and only recently has a standard A.P.I. scale been used . However even the standard scale logs show considerable variation due to hole parameters and operator idiosyncrasies. Fortunately, Neutron scales are linear and the logs can be standardized to a uniform response to clean formations. Again it was necessary for Syracuse University personnel to examine neutron logs and determine the average response to clean formations, pick the connections for each log, then use the computer to generate standardized neutron logs for correlations and for use in computing lithologic neutron porosity logs.

Neutron Porosity Logs and Syracuse University Computer Computations.

The Neutron tool responds largely to the concentration of hydrogen ions in the formations and borehole. If corrections are made for borehole fluids, then the response is proportional to the water or oil that is contained in the rock pores. Thus formation porosity can be computed from the Neutron Log, providing compensations are made for borehole effects and rock type. Because of this porosity response, logging companies began computing formation porosity and displaying it as an additional curve along with the neutron response. These porosity curves were a linear dependent form of the Neutron and thus were only correct under specific borehole, lithology and formation fluid conditions. Later, specific neutron porosity tools were developed such as the Side Wall Neutron Porosity Log which applies a neutron tool to the borehole wall by means of a spring loaded skid. With these logs, the neutron response was no longer displayed and the logs report porosity only. Such porosities are borehole corrected and are more accurate than older versions but still are only correct for specific lithologies and non-gas reservoirs.

Where both neutron and dependent porosity curves were displayed, only the neutron was digitized because it is more efficient to compute the porosity curve. However all, porosity-only curves were digitized. Curves where a direct neutron response was available were recorded and standardized.

Although the neutron porosity parameters are complex, they can be reduced in practice to functions that are derived empirically from actual porosity measurements. Logging company computations usually consider porosity to be a logarithmic function of the neutron response. However, detailed comparisons of log and core porosities has shown that the most accurate porosities are a linear function of the natural log of the Neutron values. The Syracuse Algorithm uses the log of the Neutron response, applies a rock matrix adjustment, and corrects for shale:

$$\phi ls = (-(m * \ln N) + k) * 100$$
$$\phi ss = \phi ls - 2.5$$
$$\phi dol = \phi ls + 3.0$$
$$\phi = (\phi) ss, dol \text{ or } ls * sh \text{ fraction}$$

where:

N = neutron log response

ϕ = porosity

ls = limestone

sh = shale (fraction from Gamma Ray Log)

ss = sandstone

dol = dolomite

m and k are constants which have been empirically determined to be 33.04615 and 43.39889 respectively in western New York State.

Lithology corrected porosities were computed from standard neutron logs using this formula as appplied by computer programs written at Syracuse University.

Formation Density Logs.

Next to the Gamma-Neutron Logs, the Formation Density Logs are the most popular and useful logs run in New york State boreholes.

A radioactive source, applied to the hole wall in a shielded sidewall skid, emits medium-energy gamma rays into the formations. These gamma rays may be thought of as high-velocity particles which collide with the electrons in the formation. At each collision a gamma ray loses some, but not all, of its energy to the electron, and then continues with diminished energy. This type of interaction is known as Compton scattering. The source and detector are so designed that the tool response is predominantly due to this phenomenon. The scattered gamma rays reaching the detector, at a fixed distance from the source, are counted as an indication of formation density.

The number of Compton-scattering collisions is related directly to the number of electrons in the formation. Consequently, the response of the Density tool is determined essentially by the electron density of the formation. Electron density is related to the true bulk density, Db, in gms/cc, which in turn depends on the density of the rock matrix material, the formation porosity, and the density of the fluids filling the pores.

A correction is needed when the contact between the skid and the formations is not perfect, due to mud cake or roughness of the borehole walls. Two such measurements are used in borehole compensated log calculations and the distance between the face of the skid and the extremity of the centering arm is recorded as a caliper log, from which it is possible to assess the quality of contact between the skid and the formation.

The FDC tool may not follow the same track up the side of the hole on subsequent overlap and/or repeat - runs. If the formations are quite heterogeneous, having, for instance, more vugs and/or fissures on one side of the hole wall than on the other, the two runs may disagree slightly. Disagreement between runs is infrequently encountered, however, because the heavy skid tends to ride the downhill side of the hole, which seldom is vertical.

If residual hydrocarbons exist in the region investigated by the FDC, their presence may affect the Density Log readings. The effect of oil may not be noticeable, since the average fluid density of both oil and filtrate may be close to unity. But if there is appreciable residual gas saturation, its effect will be lower than Da (apparent Db value), resulting in a superfluously large computed porosity.

Interpretation of the Density Log may be affected by the presence of shale or clay in the formations. Although the properties of shales may vary with the formation and the locality, a typical density for shale beds and laminar shale streaks is of the order of 2.2 to 2.65. Shale densities tend to be smaller at shallow depths where the compacting forces are not as great. Dispersed clay or shale disseminated in the pore spaces may have a somewhat smaller density than the interbedded shales.

Formation Density Logs are effective in uncased, air filled boreholes and are popular in the gas exploration areas of central New York State. Where lithology is known, formation density can be related to porosity. However, the accuracy of the porosity computations are dependent on knowledge of the density of both the rock framework and the pore filling fluids. Density logs generally display the corrected density curve, the applied correction curve and possibly a density derived porosity curve. Because the corrections have been incorporated into the density values and porosity is a direct transformation, only the density curve has been digitized.

If Density porosity and Neutron porosity are displayed on the same log, the differences can be interpreted directly to indicate the presence of natural gas. This is an immediate advantage to the versatility of digitized logs that can be displayed to any format and in any combination; because most logging companies have tended to present these important curves on different logs and to different scales. The natural gas determination is based on the density calculated porosity which considers the rock pores to be filled with a fluid; consequently porosity is overestimated. Conversely neutron porosity is based on contained hydrogen and gas filled porosity is underestimated. Where both logs are available and lithology is known, the errors can be corrected and an accurate porosity can be obtained. Density values used for this project are the raw bulk density values displayed on the original log and digitized at Syracuse. New York State lacks the rock sample derived density necessary to determine parameters for computing standard density curves.

Syracuse uses standard density porosity calculations with a correction for shale content:

$$Dma = ((1-Sh\ fraction) * Dcf) + (Sh\ fraction * Dsh)$$

$$\phi = (Dma-Db)/(Dma-Df)$$

where:

D = density

cf = clean formation

ϕ = porosity

ma = rock matrix

f = pore fluid

b = measured bulk density

Matrix is corrected for shale fraction.

Caliper Logs

Caliper logs utilize expanding arms to make a record of borehole diameter. Because variations in borehole size and roughness can have a major effect on the calculation of formation parameters from well logs, caliper curves have been digitized for this project at Syracuse University for all the wells for which they were available.

Temperature Surveys

Temperatures encountered in drill holes are dependent not only on the natural geothermal gradient, but also on the circulation of the mud or other borehole fluid. In a strongly circulated well the mud is thoroughly mixed and its temperature tends to become uniform. When the drill pipe is removed and the well is allowed to stand, the mud in the hole at each depth gradually comes to the temperature of the formation around it. The mud temperature at each level changes at a rate which depends on the heat conductivity of the surrounding formations and on the volume of mud, which itself is a direct function of the hole diameter. Almost all temperature surveys in mud filled holes are made during the transition period, before thermal equilibrium has been reached. In air drilled holes where the borehole is dry, thermal equilibrium is attained considerably faster than with conventional mud. Where the borehole is filled with formation fluid, the pre equilibrium temperature relates to the water reservoir temperature.

At the present time, temperature measurements in gas and oil wells are primarily used for:

- o Locating gas-producing horizons.
- o Locating the depth of lost circulation
- o Locating the height of the cement behind the casing, and the possible zones of channeling.
- o Correlation with the electrical log for depth control in perforation operations.
- o Estimating Potential gas production.
- o Computing formation temperature and geothermal gradients.

The survey is made by lowering the instrument into the hole slowly in order that the thermometer may have time to come to the temperature of the surrounding mud. Surveying speeds up to about 5,000 feet per hour may be used. Measurements are made while going down in order to eliminate the perturbing effect of the presence of the cable. If another run must be made in the hole, it is necessary to wait from 6 to 12 hours so that the stable temperature conditions will have been re-established.

During the process of gas production the temperature in the borehole is strongly affected by cooling due to the expansion of the gas. The drop of temperature opposite a gas-producing zone may attain 20 degrees F or more. Under these conditions and using special thermometers with high sensitivity and short time, constant temperature surveys show the points of entry of gas into the hole with great precision. In favorable cases, it is even possible to derive from the temperature log an approximate estimate of the amount of gas produced by each separate horizon. Temperature surveys in open air filled boreholes are very effective in indicating gas zones even in very tight and fractured reservoirs.

Where stabilized temperatures are available at two or more points in the bore hole, the temperature log can be used to compute geothermal gradients and heat flow. All recorded temperature curves were digitized for project wells and desplayed in correlation playbacks.

Formation Resistivity and Electric Logs

Electricity can pass through earth formations because of the mineralized (formation) water they contain. Perfectly dry rocks are very rarely encountered in drilling, therefore, subsurface formations have finite, measurable resistivities because of the water which is contained in their pores or adsorbed on their interstitial clay. In the case of clean formations, the laws of electrolytic conduction apply to currents passing through them. The resistivity of earth formations may change appreciably with the resistivity of the water in the pores as well as with the rock type and in the case of formations containing hydrocarbons, with water saturation.

Clays and shales which are porous yet practically impervious formations are often very uniform throughout their mass. They are impregnated with capillary water of constant and generally high salinity; consequently their resistivity is comparatively low and practically constant over wide intervals.

Compact and impervious rocks, such as gypsum, anhydrite, rock salt, dense calcareous formations, or certain kinds of coal, are highly resistive because of their very small interstitial water content.

The resistivities of porous and permeable formations such as sands vary over a wide range, depending on the fluid content; they can be low if the formations are salt-water bearing, or very high if the formations contain large amounts of oil and gas and very little water.

The presence of non-conducting oil or gas in pores along with formation water will obviously affect the resistivity of a formation, which then becomes a function of the relative amounts of hydrocarbons and water it contains. A wide variety of electric logs have been run in New York State although the usual need for a conductive fluid in the borehole has prevented their general application. Only the induction electric logs can be run in air filled boreholes and have been proven effective, however they have been utilized only in local areas.

Conventional Resistivity Logs.

In conventional resistivity logs, currents are passed through the formation via certain electrodes, and voltages are measured between certain others. These measured voltages provide the resistivity determinations. So that there will be a current path between electrodes and formation, the sonde must be run in holes containing electrically conductive mud or water.

In a homogeneous isotropic formation of infinite extent, the equipotential surfaces surrounding a single current-emitting electrode are spheres. The voltage between a second electrode situated on one of these spheres and one at infinity is proportional to the resistivity of the homogeneous formation, and the galvanometer deflection corresponding to such voltage can be scaled in resistivity units.

Two electrical circuits are utilized, the current circuit and the measuring circuit. One or more electrodes of the measuring circuit are placed in the electromagnetic field set up by the current circuit and the electrical potential is measured. The placing of the two circuits determines the type of electric log.

The Normal Device. In the Normal arrangement, single electrodes of the current and the potential circuits are placed on the sonde with the other electrodes at some distance that is considered infinitely removed from the sonde. The distance between the sonde electrodes determines the radius of measurement of the device and is included in the log nomenclature.

The Lateral Device. In the Lateral arrangement, three electrodes are on the sonde and only one is electrically far removed. This provides a greater depth of investigation with less averaging in proportion to its spacing, than is provided by the normals.

The Conventional Survey. The conventional electric log survey consists of a 16 inch Normal, a 64 inch Normal and an 18 foot 8 inch Lateral. Under ideal conditions which require conductive fluid or mud in the borehole, the flushed zone surrounding the borehole, the invaded zone and the undisturbed formation can all be evaluated. The presence of oil or gas and some estimate of permeability can be determined. A few conventional resistivity logs have been run in western New York.

Focusing-Electrode Logs. The responses of conventional electric logs can be greatly affected by the borehole and adjacent formations. These influences are minimized by tools that utilize focusing currents to control the path of the measure current. The focusing currents are supplied by special electrodes on the sonde. These tools include the Laterologs and Spherically Focused Logs. Because they utilize electrodes, they are limited to boreholes that contain conducting fluids. Only a very few logs of these types have been run in New York State.

Microresistivity Logs. Microresistivity devices are used to measure resistivity of the flushed zone and to delineate permeable beds by detecting the presence of mud cake.

With the Microlog tool, two short-spacing devices with different depths of investigation provide resistivitiy measurements of a very small volume of formation immediately adjoining the borehole. Thus they readily detect the presence of any mud cake, indicating invaded (hence permeable) formations. They also incorporate two-arm calipers which show the size and condition of the borehole.

The Proximity tool is similar in principle to the Microlaterolog. The electrodes are mounted on a somewhat wider pad which is applied to the wall of the borehole; the system is automatically focused by monitoring electrodes. A few Micrologs have been run in western New York State, however the results generally have been poor; and they have not been digitized.

Induction Logs. Induction Logging, measures the conductivity of formations by means of induced alternating currents. Since this is an induction method, insulated coils rather than electrodes are used to energize the formatrions, and the borehole can contain any fluid: water-base mud, oil-base mud, gas or air. However, the hole must be encased.

Practical Induction sondes include a system of several coaxial transmitter and receiver coils. High-frequency alternating current of constant intensity is sent through the transmitter coil. The alternating magnetic field thus created induces secondary currents in the formations. These currents flow in circular ground-loop paths coaxial with the transmitter coil. These ground-loop currents, in turn, create magnetic fields which induce signals in the receiver coil. The receiver signals are essentially proportional to the conductivity of the formations. Any signal produced by direct coupling of transmitter and receiver coils is balanced out by the measuring circuits.

The Induction Log operates to advantage when the borehole fluid is an insulator - even air or gas. But the tool will also work very well when the borehole contains conductive mud, provided that the mud is not too salty, the formations not too resistive, and the borehole diameter is known.

Induction Logs Digitized at Syracuse University. Induction Logs have been successfully used in New York State wells and are common in local areas. They make a good correlation tool although there is not sufficient information on actual formation conductivities for any form of standardization. All good Induction Log curves from project wells have been digitized and displayed for visual formation analysis.

Spontaneous-Potential Logs. The Spontaneous-Potential, Self-Potential (or SP) curve is a recording versus depth of the difference between the potential of a movable electrode in the borehole and the fixed potential of a surface electrode.

The SP is useful in holes filled with fresh muds to:

- Detect the permeable beds.
- Locate their boundaries and to permit correlation of such beds.
- Determine values of formation water resistivity.
- Give qualitative indication of bed shaliness.

Opposite the shales, the readings of the SP curve are usually fairly constant and tend to follow a straight line on the log, called the shale base line. Opposite the permeable formations, the SP curve shows excursions from the shale base line; in thick enough beds, they often tend to reach an essentially constant deflection defining a sand line. The deflection may be either to the left (negative) or to the right (positive), depending mostly on the relative salinities of the formation water and of the mud filtrate.

The SP cannot be recorded in holes filled with non-conductive muds because such muds do not provide electrical connection between SP electrode and formation. Furthermore, if the resistivities of the mud filtrate and formation water are about equal, the SP deflections will be small and the curve will be rather featureless.

Spontaneous Potential Logs Digitized at Syracuse University. Because the Spontaneous Potential Log requires not only a borehole filled with a conducting fluid, but also a resistivity difference between the borehole fluid and the formation fluid, only a very few have been run in Central New York State. Also, most of the ones that have been run are of little value because the boreholes are usually empty or filled with formation fluid. Spontaneous Potential curves have been evaluated and digitized whenever satisfactory results could be obtained.

Sonic Logs

The Sonic Log is a recording versus depth of the time, delta, required for a compressional sound wave to traverse one foot of formation. Known as the interval transit time, delta is the reciporcal of the velocity of the compressional delta sound wave. The interval transit time for a given formation depends upon its lithology and porosity. Its dependence upon porosity, when the lithology is known, makes the Sonic very useful as a porosity log. Integrated Sonic transit times are helpful in interpreting siesmic records.

Variations of velocity in different types of rock produce a Sonic curve with some correlatable character. In addition to this, the very good vertical definition of the Sonic Log and the reduced hole effect on the BHC tool make this log excellent for correlation use. It is very helpful in some cases where other logs give poor results. Moreover, some types of formations, evaporites in particular, can be identified from their delta values:

- The relationship between delta t and porosity is somewhat complex, but good values can be found for formations containing intergranular porosity.
- With the Borehole Compensated (two reciever) system the quality of the measurement is very good with accurate calibration, no borehole effect, and excellent vertical definition.
- The Sonic Log is useful for correlation. in many cases where other logs give poor results; some lithologies are identified by the magnitude of the reading.
- The Sonic Log can be used in combination with other porosity logs to evaluate shaly sands, determine formation lithology, and determine the amount of secondary porosity.
- The integrated travel time is useful in seismic interpretation.

Sonic logs require a fluid filled borehole and are only occasionally run in Central New York State. Their sparseness prevents their use as a correlation log but the interval and total travel times are necessary for seismic formation identification. Sonic curves that have been recorded in a satisfactory manner have been digitized.

Sonic Porosity Computed at Syracuse University.

Sonic Porosity is calculated according to standard formulae with a correction for shale fraction:

d(t)ma = (1-sh fraction) * d(t)cf + sh fraction * d(t)sh

∅ = (d(t) - d(t)ma)/(d(t)f - d(t)ma)

Where:

d(t) = delta (t), sonic time in milleseconds per foot.
sh = shale
cf = clean formation
ma = rock matrix
∅ = porosity
f = pore fluid
t = time

Formation travel times are for clean well indurated Paleozoic formations and shale times are averaged from known clean shale zones in the area.

POROSITY DISPLAY FOR NEW YORK STATE LOGS

Where both the Neutron and Density Logs are available, and the log responses are consistent and responding well to lithology, the calculated neutron and density porosity curves will show the same porosity in clean tight formations. They will also show approximately the same porosity under good borehole conditions where the formations contain only water filled intergranular porosity.

The computed density and neutron porosities will diverge where natural gas is present in the formations and where fracture porosity is present. Under ideal conditions, the best estimate porosity is the root mean square value of the neutron and density porosity. Sonic porosity although affected by by fractures, behaves more like the neutron than it does like the density; and it is often possible to average neutron and sonic porosities. However, computed porosities for each type of curve depend on the drilling fluid, borehole shape and size, formation mineralogy, and contained fluids.

New York State well logs were recorded by a variety of logging operators over a considerable period of time using tools with differing responses. Neutron log responses to lithology were standardized; then neutron porosities that appear reasonable for tight dense formations were computed. However, the Neutron Logs give a low porosity reading when natural gas is present, a very common occurrence in the reservoirs of New York State. Consequently, there were very few real checks on the formation parameters used in the neutron porosity calculations. Density Logs measure porosities that are too high in gas filled zones yet the computed density should equal that of the neutron porosity in tight formations. Calculations of porosity from the Density Log assume that the original curve displays an accurate presentation of formation density, and such does not appear always to be the case. Most subsurface rocks contain varying amounts of minerals other than carbonates and quartz sands so that the Limestones, Dolostones, or Sandstones that constitute the common reservoir rocks exhibit a range of densities. Consequently, determination of the true density of the specific formations in any one area requires measurements on cores, which are very scarce in New York State. Densities as recorded have had to be accepted for porosity computations.

Also, the density tool is a sidewall device and is sensitive to borehole conditions and fractures; so that erroneous values can be recorded. Similarly the sonic porosity calculations are very sensitive to borehole conditions. Although very few Sonic Logs have been recorded in New York State, the majority do appear to give reasonable results.

Because of divergence among the computed porosities, the automatic computation of a composite porosity curve was not utilized on a regional basis. The problem stems from divergences in the original density values as recorded on a very wide variety of instruments. There are no core derived densities from the area to set up standardized density parameters for the computation of standard density porosities. There is thus a variable bias in the computed porosities. Instead, the Lower Ordovician-Cambrian sand reservoir section of each well was interpreted on an individual basis, taking into account borehole conditions as indicated by the caliper log and divergence between the computed porosity curves in zones that are known to be reasonably tight. This approach did require considrable input by an experienced log analyst, but the results were consistant, and porosities were comparable among wells.

Because both gas and water production are readily obtained from reservoirs with approximately 10% or greater porosity, porous sections are considered to include all measured portions of the reservoir that display intergranular porosity of more than 9 to 10 percent. Fracture porosity that appears as a porous zone has been included in the porosity estimations.

MAPS

Maps in this report include:

- Structure Trenton Formation.
- Structure First Lower Ordovician-Cambrian Sandstone.
- Structure Contours Precambrian Basement.
- Isopach Lower Ordovician-Cambrian Sandstone to Precambrian.
- Net Feet Effective Porosity Lower Ordovician-Cambrian Sandstone.
- Temperature at Top of Theresa Formation. (Hodge and Fromm, SUNY Buffalo)
- Temperature at Top of Theresa Formation - Disequilibrium Area
- Temperature at Top of the Theresa Formation - Bottom Hole Temperature Corrected

STRUCTURE TRENTON FORMATION

The top of the Trenton Formation is an easily recognizable break from the thick Utica Shale Formation into a massive limestone. It is readily picked from samples and all geophysical logs and is the best and most consistent marker formation in the area. The configuration of the Trenton map serves as a model for all maps of deeper formations. The Trenton map was constructed using information from the deep wells that were digitized and interpreted for this project plus other Trenton Formation picks retrieved from the New York State Tops and Production File. These include wells that did not penetrate more than a short distance into the Trenton Formation. The map indicates that the formation dips to the southeast at a rate that increases gradually to the south. Minor tectonic features are in evidence in the northern portion of the map in the areas of best control.

Trenton and Potsdam tests are infrequent in the southern part of the area, and contours are likely to be too smooth. Unfortunately, here, the shallow and better tested horizons are affected by Appalachian structures that are discordent with the deep configuration; so that they cannot be used to indicate relief on lower horizons. The Trenton Formation and the underlying Black River Formation are carbonates containing only a few silty layers. These formations do not exhibit sufficient intergranular porosity for geothermal water reservoirs; however, the section often displays fracture porosity and indeed has produced gas from fractures in the northern part of the state.


NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
1982
J.E. ROBINSON SYRACUSE UNIVERSITY
5 0 5Mi
5 0 5Km
C.I. 250'
STRUCTURE TRENTON FORMATION
DATUM SEA LEVEL
LAKE ONTARIO
LAKE ERIE
-500
0
-1000
-1000
-1500
-2000
-2000
-2500
-2500
-3000
-3000
-3000
-3500
-3500
-3500
-4000
-4000
-4000
-4500
-4500
-4500
-5000
-5000
-5000
-5500
-5500
-6000
-6000
-6500
-6500
-7000
-7000
-7500
-7500
-8000
-8000
-8500

41-42

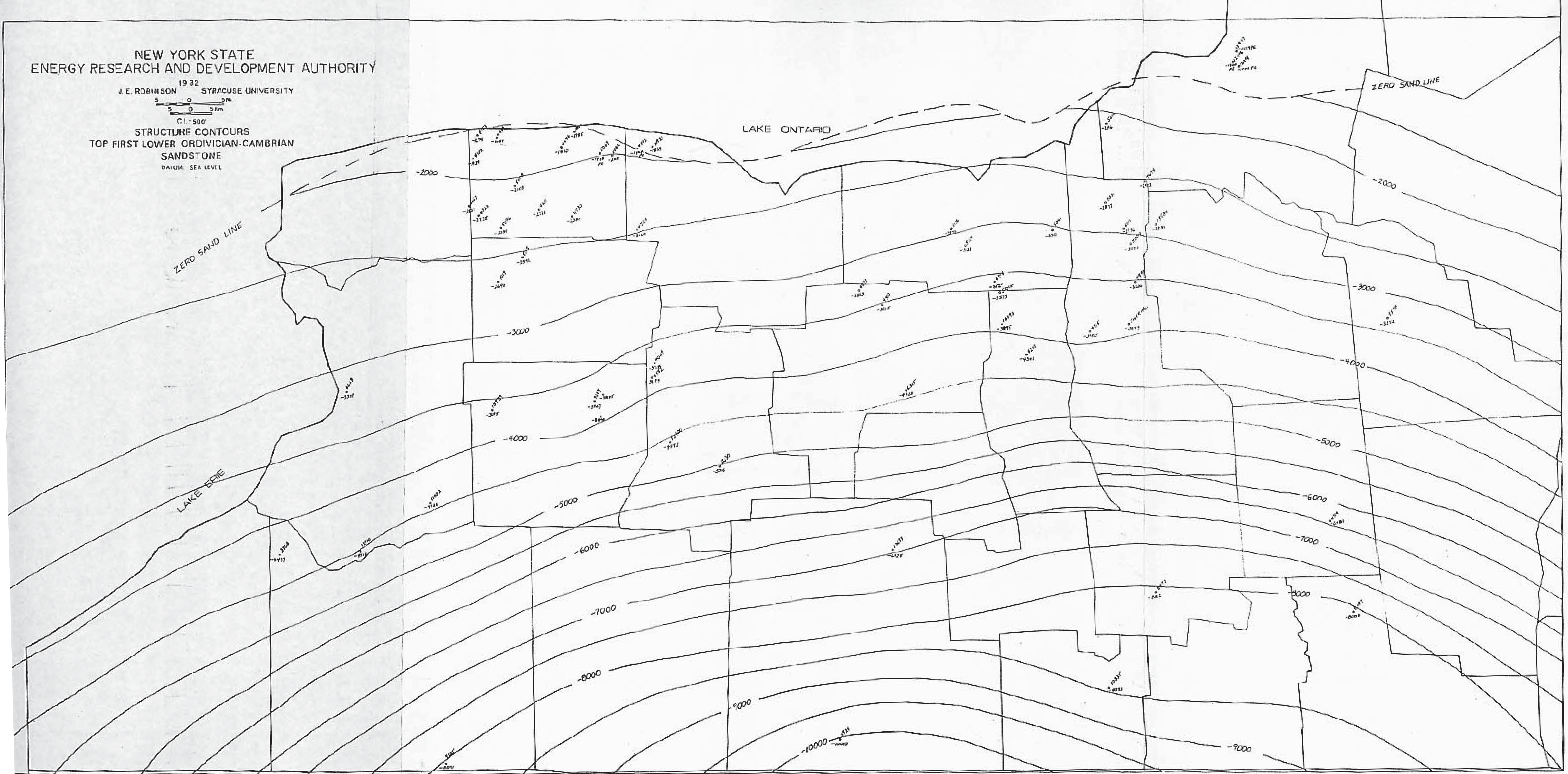
The fracture zones, in the vicinity of tectonic warping or faulting, may be of sufficient lateral and vertical extent to provide large water flows. The Trenton reaches sufficient depth in the southern portion of the project area so that contained waters would have attained geothermal resource temperatures. Unfortunately, the Gamma Ray and the Neutron Log, which are the most common geophysical logs used in New York State, are not good indicators of fractures and fracture porosity. Density and Sonic Logs do show fractures but were not commonly used in the older wells. Consequently, it is not possible to map the fractured zones from the well evidence. Accurate delineation of zones of fracture porosity requires the geological interpretation of other information such as seismic profiles or other remotely sensed geophysical data.

STRUCTURE FIRST LOWER ORDOVICIAN-CAMBRIAN SANDSTONE

This map displays the elevation of the top of the first porous Ordovician-Cambrian Sandstone having geothermal reservoir quality.

The Cambrian-Ordovician sandstone generally consists of a section of clean sometimes porous Potsdam Sandstone that directly overlies the Precambrian basement and grades upward into a Theresa sand member that is continuous with the Potsdam in the northern part of the area but may be separate in the south. The Potsdam section may also include some older Precambrian sandstones which have been reported as porous in some of the old drilling reports. This lower sand varies in thickness from 0 to over a hundred feet, and it is truncated by erosion approximately along the southern shore of Lake Ontario. Local variations in thickness and in porosity of the Potsdam sandstones were controlled by paleotopography of the Precambrian surface. The cleaner more porous sands generally are found in the topographic lows where the shallow Cambrian sea permitted the thickest accumulations.

The next important porous sand occurs in the Lower Ordovician Theresa Formation. This sandstone is also locally clean and porous and appears to be permeable. However, it is more variable than the Potsdam sand and in places ranges from a relatively clean dolostone to a dolomite-cemented sandstone. The Theresa generally becomes more dolomitic and thus tighter in the eastern and southeastern parts of the project area. Also, the section thickens to the south, and the sand portion is generally confined to the upper approximately 100 feet with carbonates making up the lower section separating the Theresa Sandstone from the Potsdam Sandstone.


NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
1982
J.E. ROBINSON SYRACUSE UNIVERSITY
C.I.-500'
STRUCTURE CONTOURS
TOP FIRST LOWER ORDIVICIAN-CAMBRIAN
SANDSTONE
DATUM: SEA LEVEL
LAKE ONTARIO
ZERO SAND LINE
ZERO SAND LINE
LAKE ERIE
-2000
-2000
-3000
-3000
-4000
-4000
-5000
-5000
-6000
-6000
-7000
-7000
-8000
-8000
-9000
-9000
-10000

The entire Cambrian-Lower Ordovician section thins and is truncated by erosion to the north. However, both the Theresa and the Potsdam Sandstone tend to maintain their identity until they coalesce into what is essentially a single sandstone unit in the central part of the project area. It is this area that appears to have the optimum thickness of water laden sandstone suitable for geothermal use. The contour map displays the elevation of the top of the Theresa sandstone.

STRUCTURE CONTOURS PRECAMBRIAN BASEMENT

This map displays the elevation of the Precambrian surface which dips to the south reaching a depth of more than 12,000 feet below sea level near the Pennsylvania border in the central part of the state. Although well control is reasonably dense immediately south of Lake Ontario where the section is thin and the Precambrian is shallow, control is very sparse in the southern part of the state. In the areas where control is scarce, the configuration of the Trenton map has been used to infer regional topography on the Precambrian in order to make a more realistic map. Except for local areas, where the surface is composed of thin Precambrian sandstones, this map displays the maximum known depths for sedimentary rocks with potential intergranular porosity. The Potsdam Sandstone directly overlies the basement. Only fracture porosity is anticipated within the basement itself.

ISOPACH LOWER ORDOVICIAN-CAMBRIAN SANDSTONE TO PRECAMBRIAN

This sequence, which is topped by the Theresa sandstone and terminated at the base of the Potsdam Sandstone, thickens from its zero edge at the southern shore of Lake Ontario to over 1500 feet at the Pennsylvania border. Although it is generally topped and bottomed in sandstone, much of the intervening section consists of carbonates, siltstones and carbonate cemented sandstones. The sandstone section itself ranges from 0 to approximately 400 feet of which less than 100 feet is usually considered to be of reservoir quality. This entire section is erosionally truncated northward in a structurally updip direction, and consequently, is a stratigraphic trap for natural gas. There is evidence that a gas-water contact exists at approximately the -4000 foot elevation level. The area to the north of the -4000 foot contour on the top sand structure map can be expected to contain at least some natural gas. Fortunately, this does not affect potential geothermal resources; because in the gas area, the temperatures are generally too low for geothermal use. However, the presence of gas suggests that hydrocarbons have migrated northward throughout the entire section, and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1982
J.E. ROBINSON SYRACUSE UNIVERSITY
5 0 5 Mi
5 0 5 Km
C.I. 250'
STRUCTURE TRENTON FORMATION
DATUM SEA LEVEL
LAKE ONTARIO
LAKE ERIE
-500
0
-1000
-2000
-2500
-3000
-3500
-4000
-4500
-5000
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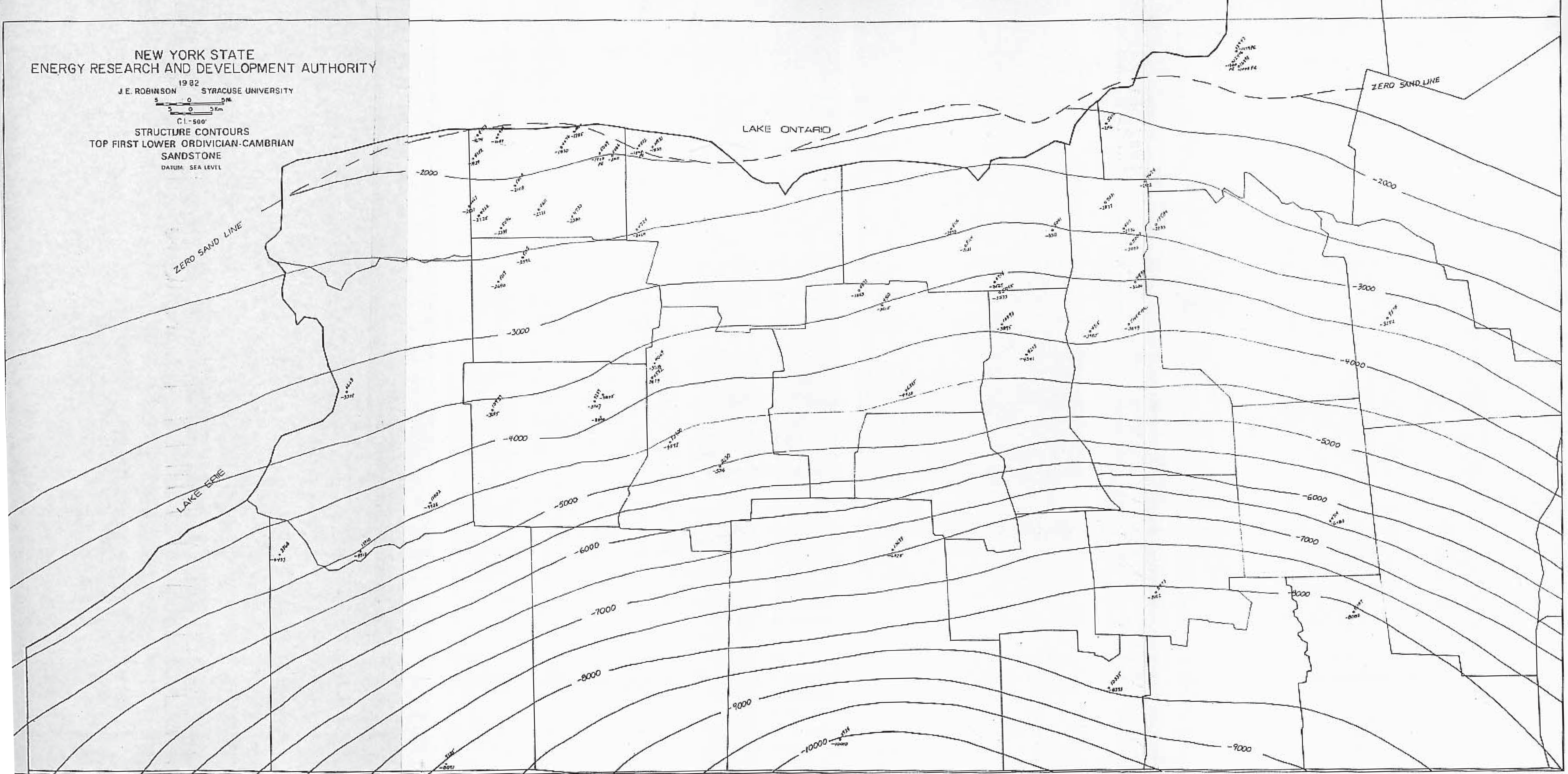
-7500
-8000
-8500



NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
1982
J.E. ROBINSON
SYRACUSE UNIVERSITY
C.I.-500'
STRUCTURE CONTOURS
TOP FIRST LOWER ORDIVICIAN-CAMBRIAN
SANDSTONE
DATUM SEA LEVEL
LAKE ONTARIO
ZERO SAND LINE
ZERO SAND LINE
LAKE ERIE
-2000
-2000
-3000
-3000
-4000
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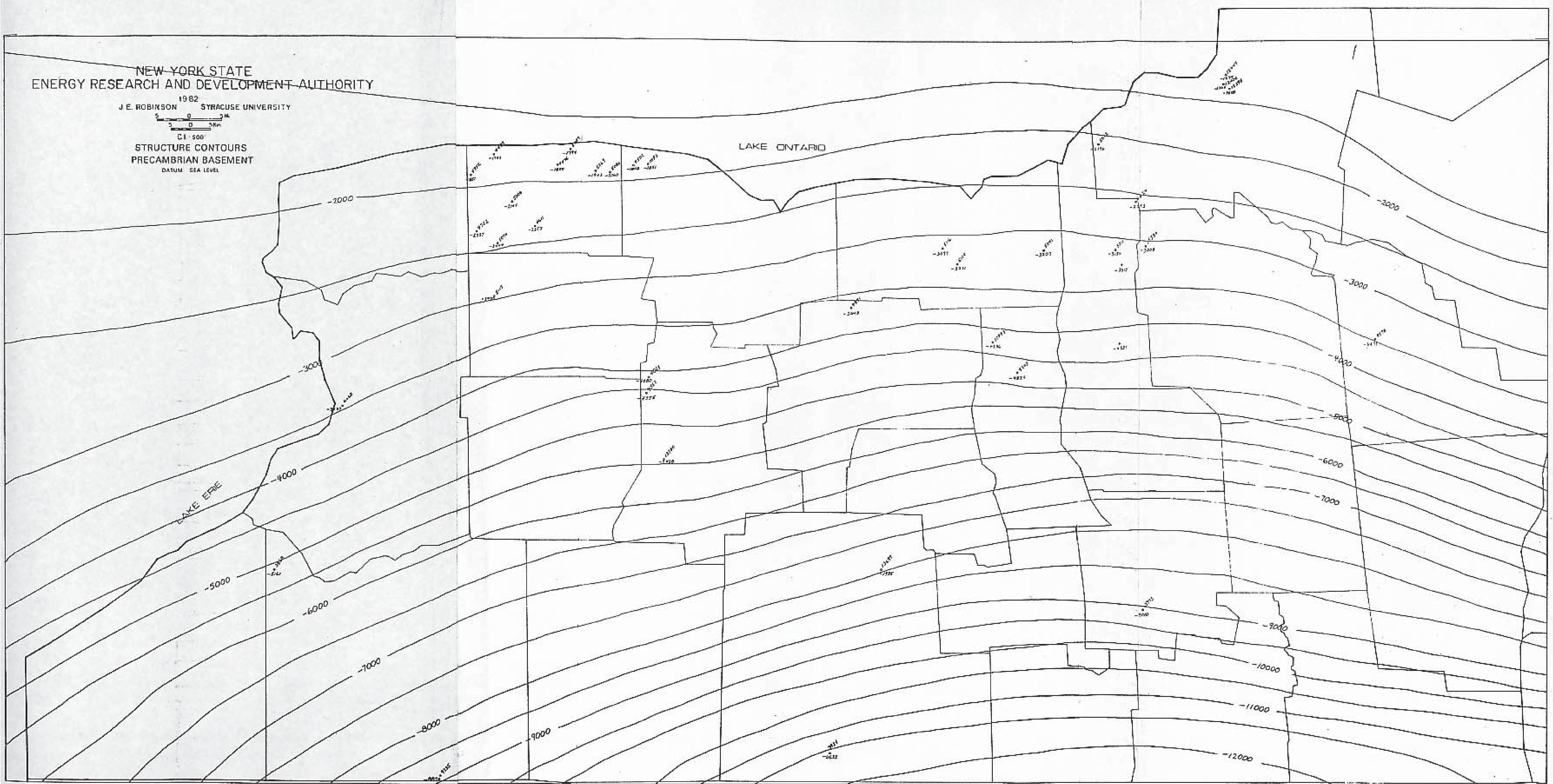
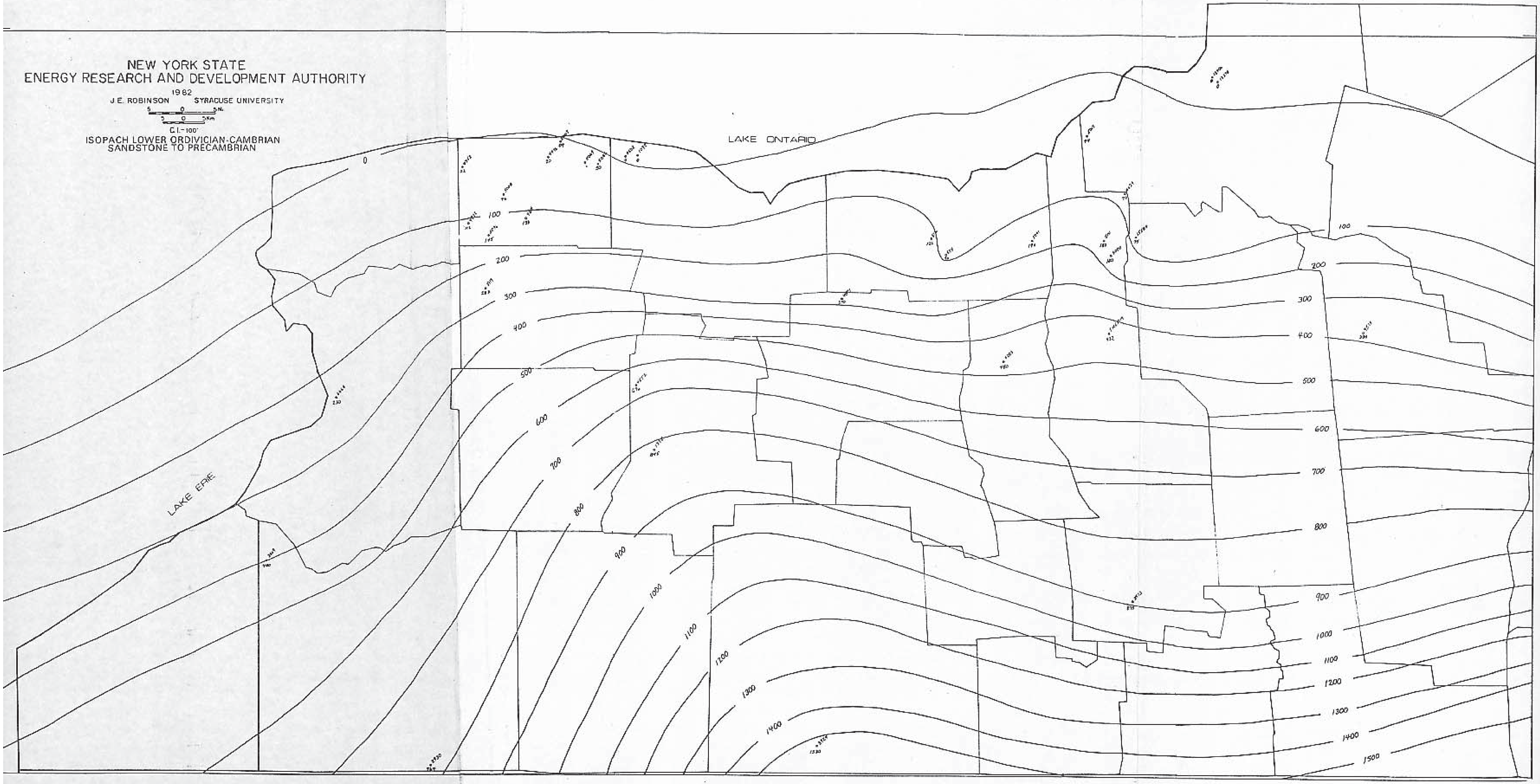
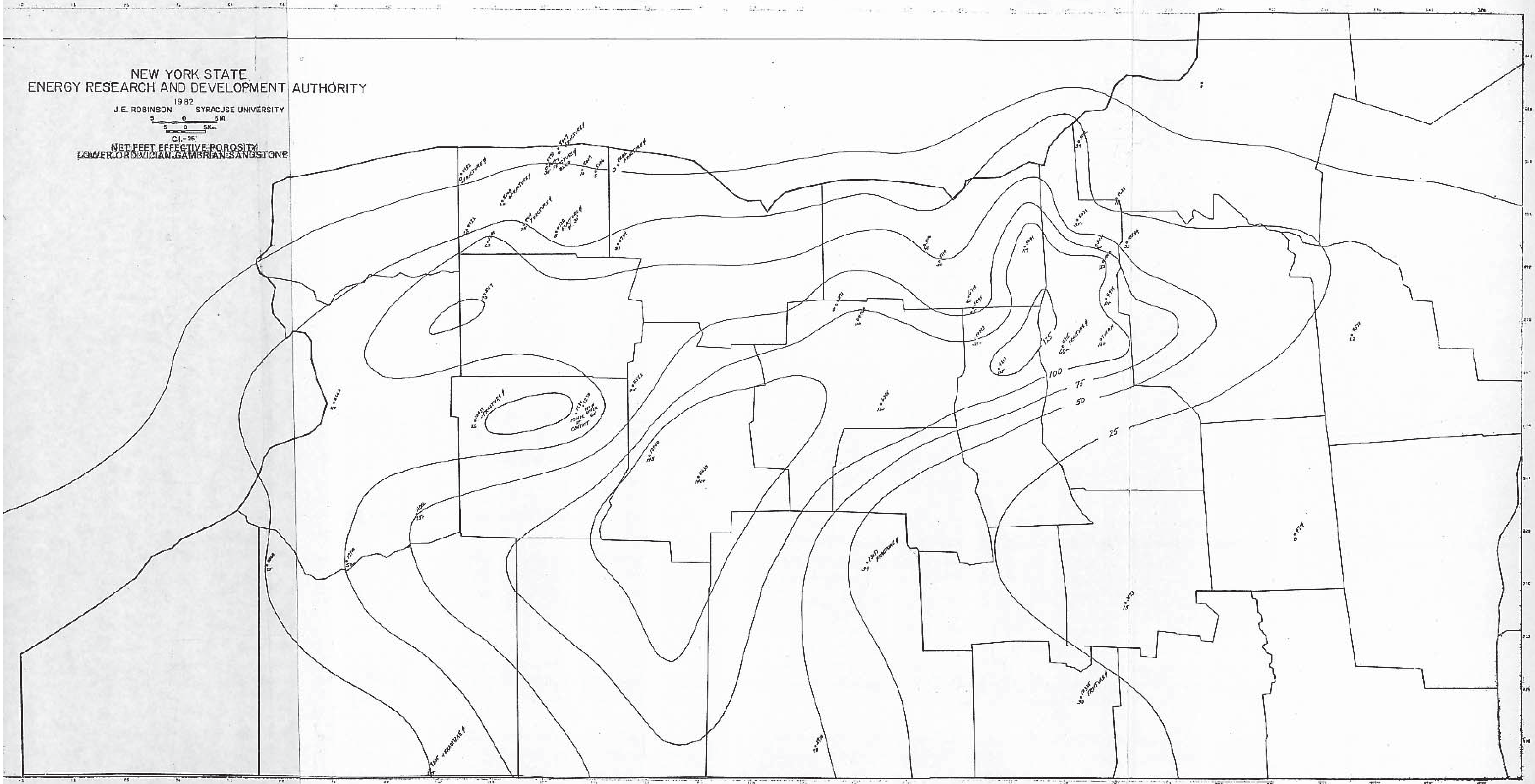
-9000
-9000
-10000


NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
1982
J.E. ROBINSON
SYRACUSE UNIVERSITY
5 0 5 Mi
5 0 5 Km
C.I. 500'
STRUCTURE CONTOURS
PRECAMBRIAN BASEMENT
DATUM SEA LEVEL
LAKE ONTARIO
LAKE ERIE
-2000
-3000
-4000
-5000
-6000
-7000
-8000
-9000
-10000
-11000
-12000


NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
1982
J.E. ROBINSON SYRACUSE UNIVERSITY
C.I.-100'
ISOPACH LOWER ORDIVICIAN-CAMBRIAN SANDSTONE TO PRECAMBRIAN
LAKE ONTARIO
LAKE ERIE
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500


NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
1982
J.E. ROBINSON
SYRACUSE UNIVERSITY
5 0 5 MI.
5 0 5 Km.
C.I.-25'
NET FEET EFFECTIVE POROSITY
LOWER ORDOVICIAN CAMBRIAN SANDSTONE
125
100
75
50
25

consequently, any test drilled into the lower Ordovician-Cambrian could encounter natural gas in isolated structural or stratigraphic reservoirs. Drilling operators should be prepared to deal with this possibility.

NET FEET EFFECTIVE POROSITY LOWER ORDOVICIAN-CAMBRIAN SANDSTONE

The thicknesses of the porous sand reservoirs have been interpreted from the porosity curves generated by computer from the digitized well logs. In general the map reflects the sum total of the footage in the lower Ordovician-Cambrian section that displays porosities greater than 10%. Porosity computations have been based on formation parameters as determined from the suite of very good logs that were run in the Auburn geothermal well.

Porosity thickness displayed in the isopach is the sum total of porous sections within the Theresa Potsdam interval. The porous intervals usually consist of a few feet of good porosity interspersed with zones of poor porosity. The individual porous zones are not normally continuous but do interconnect to provide flow paths for regional fluid movement. Total porous thickness is thus a statistical measure of regional variation in interconnecting porosity. The local position and frequency of the porous zones are best shown by the cross sections on which the actual well logs are displayed.

Unfortunately many of the logs in the older wells were run with a variety of tools with different and undocumented formation responses. Also, mineralogy of the formations varies considerably over the area. Because of the variations in response, computed porosities were subject to interpretation and estimates of porous zones considered not only the computed porosity of the zone but also those zones above and, where possible, below the actual reservoir. In general, Neutron porosities are considered best because of the computed standard response to clean formations, but they are still subject to errors due to fluids in the borehole, fracturing and caving in the borehole, instrument drift, and the presence of natural gas.

The Density Log can give accurate porosities but it is also affected by borehole conditions. In addition, porosities must be estimated according to the displayed formation densities which often show considerable variance and probable error. Porosity thickness is therefore an interpreted best estimate, and the values assigned are relative. However, they do appear to reflect reservoir quality when compared to measured values from the Auburn well.

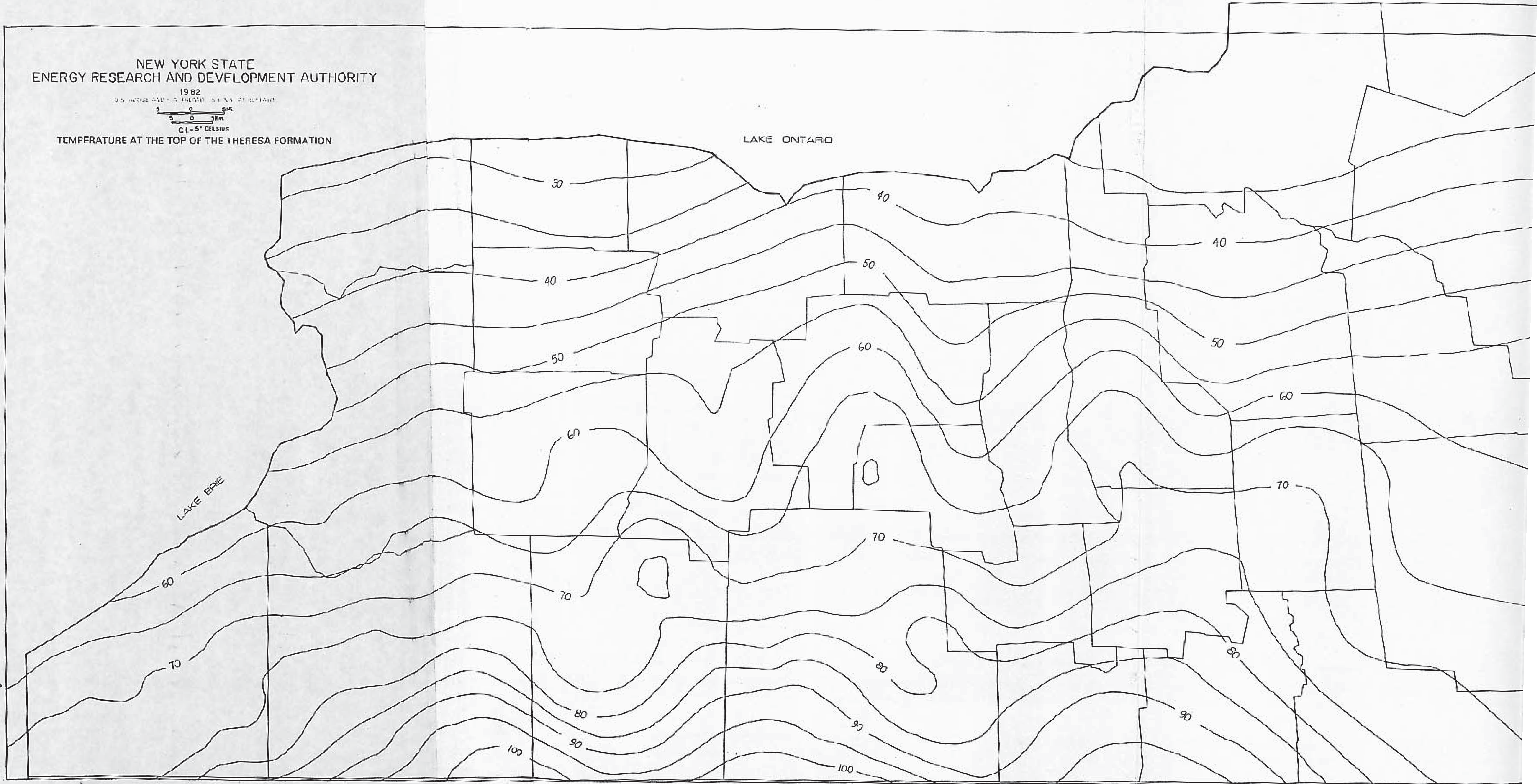
TEMPERATURE AT THE TOP OF THE THERESA FORMATION

There are three maps in this sequence. All were produced by Dr. Dennis Hodge and Kurt Fromm of SUNY Buffalo as part of the joint geothermal project. The maps indicate the expected temperature at the top of the Theresa Formation which is the top of the uppermost geothermal reservoir. The large map, (Fig. vi) which displays the effect of corrected bottomhole temperatures is drawn on the same scale as the geologic maps and can be used with them.

The first small map (fig. vii) indicates the temperature at the top of the Theresa Formation based on revised bottom hole temperatures. The dashed line contours are in an area where bottom hole temperatures in the wells had not reached equilibrium at the time of testing. The second small map (fig. viii) indicates the expected temperature at the top of the Theresa with corrections applied to the bottom hole temperatures. These are the present best estimates of the expected fluid reservoir temperatures at the top of the Theresa.

The higher temperature area to the south of the 50 degree Celsius line has geothermal potential wherever it coincides with a reasonable thickness of porous Ordovician-Cambrian sandstones. These maps (Figs. vi, vii, viii) can be used in conjunction with the structure maps, isopachs and cross sections to evaluate local areas. Only in the more southern parts of the state does the added depth to the geothermal reservoirs at the base of the Potsdam make a significant addition to the displayed temperature. The lower reservoir may be up to 12 degrees Celsius warmer near the Pennsylvania border where the total Theresa-Potsdam thickness approaches 1500 feet.

Immediately to the north of the 50 degree Celsius contour, there may be slightly (one or two degrees Celsius) higher temperatures in the deeper part of the porous section. However, geothermal exploration is not recommended. The geophysical logs indicate that the porous sections are often saturated with natural gas rather than water. Thus the 50 degree Celsius contour approximates the demarcation line between the gas-filled and the water-filled reservoirs.


NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
1982
C.I. = 5° CELSIUS
TEMPERATURE AT THE TOP OF THE THERESA FORMATION
LAKE ONTARIO
LAKE ERIE
30
40
40
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90
100
100

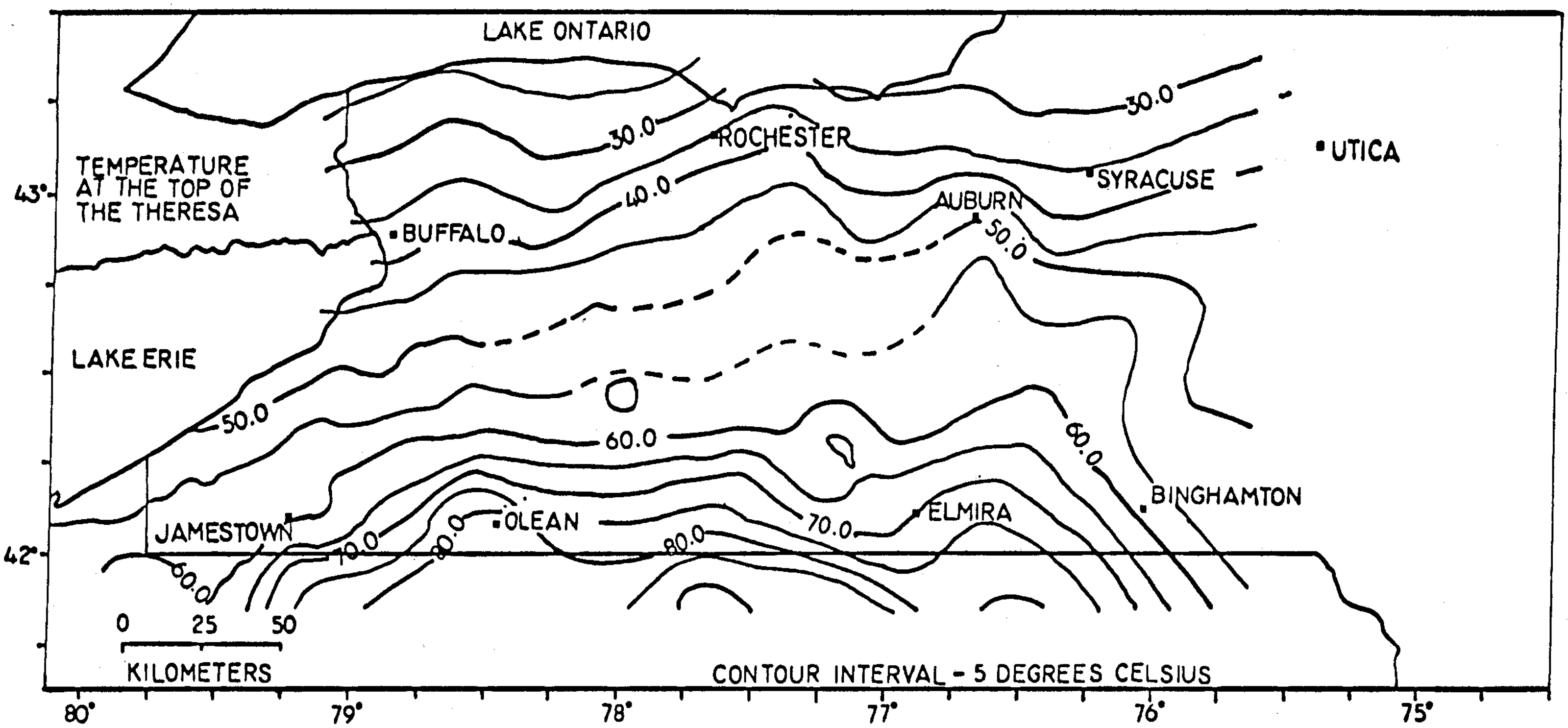

Fig. vii Temperature at Top of the Theresa Formation - Disequilibrium Area

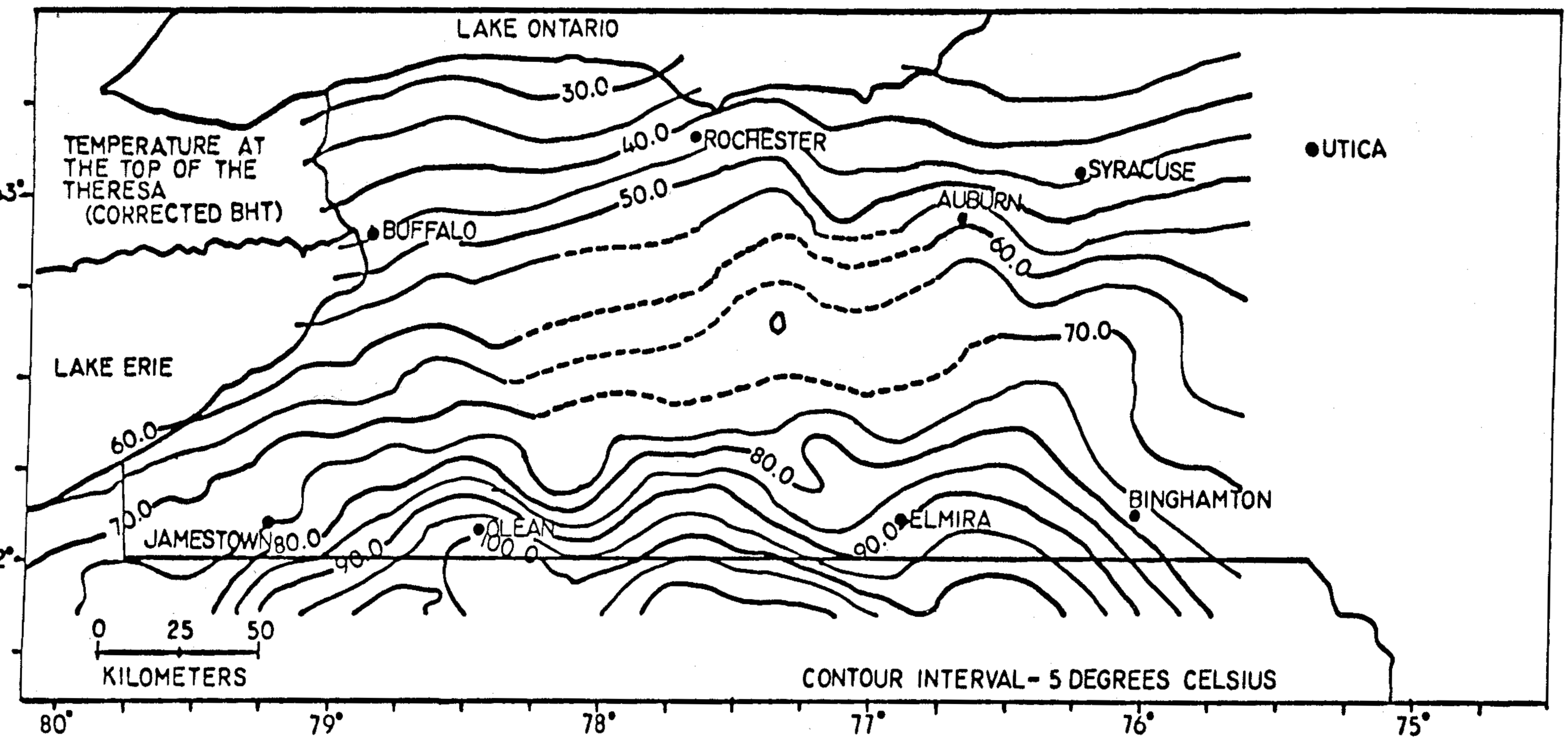

Fig. viii Temperature at Top of the Theresa Formation - Bottom Hole Temperature Corrected

CROSS SECTIONS

Three cross sections trending approximately north/south, east/west and north-east/south-west have been constructed to display the variations in the stratigraphic section below the Trenton Formation. The Gamma Ray log is displayed on the left for correlation, and the best computed porosity is displayed on the right. All cross sections intersect the Auburn geothermal well which displays Neutron, Density and Sonic porosities as well as the Gamma Ray Log displayed as representing shale content. Porous zones are readily recognizable by leftward swings of the porosity log. Sharp leftward peaks are commonly caused by fractures or hole cavings, and porosity evaluation is tempered by interpretation of the Caliper Logs. However, the cross sections do give a good indication of those zones that are considered to be potential geothermal reservoirs.

The main porous zones occur at the top of the Theresa sandstone and in the underlying Potsdam sandstone. However, the most acceptable porous zones and their position vary so that individual porous zone maps are not practical. At any location, the Theresa and the basement map indicate elevations of the top and the base of the zone that may contain porosity. The porous thickness map gives total expected porosity footage and the nearest cross section can be used to locate the position of the porous layers within the section.

All porous intervals in the Theresa Potsdam section where the temperature is higher than 50 degrees Celsius have potential for low temperature geothermal fluid recovery.

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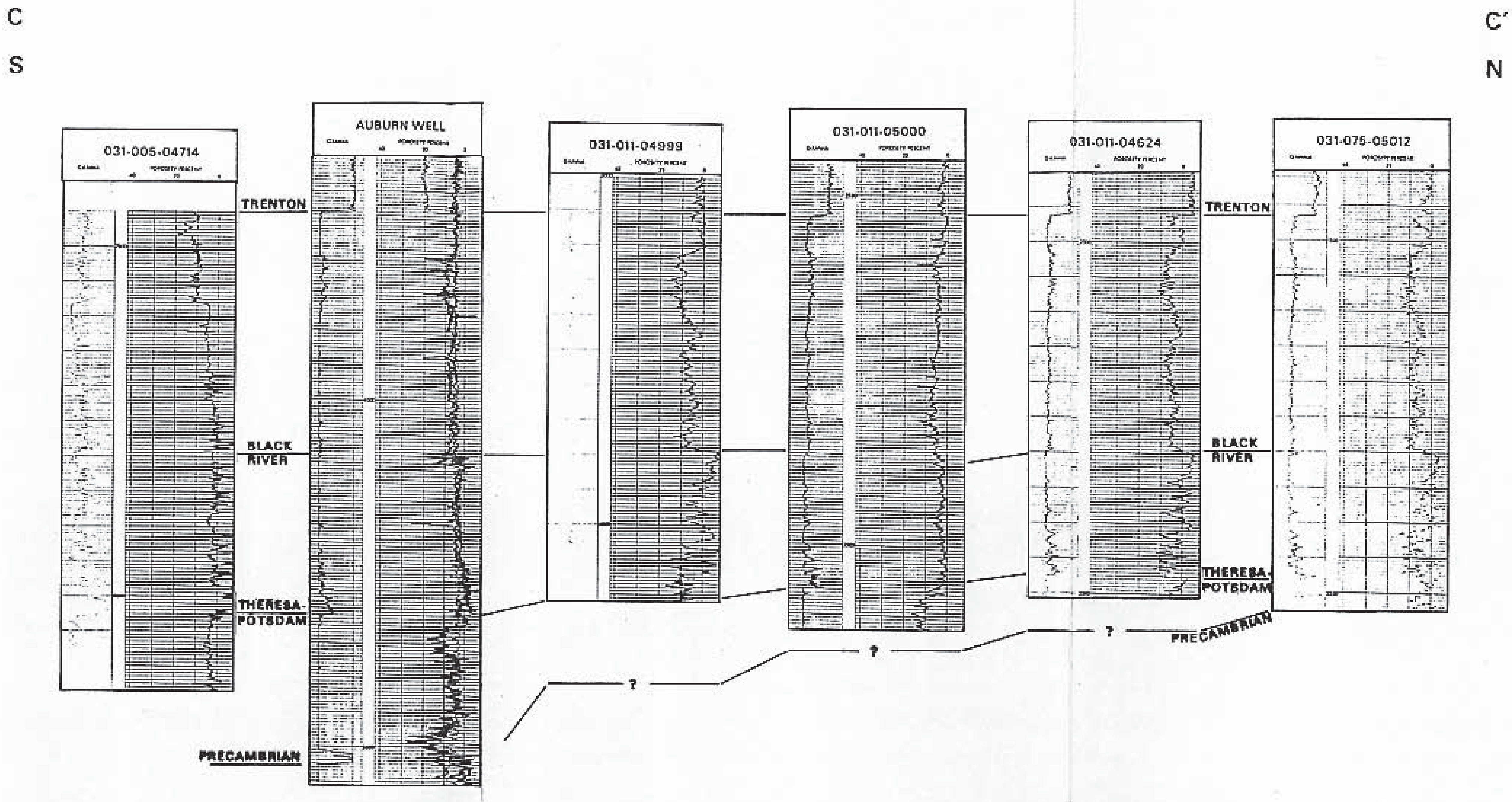

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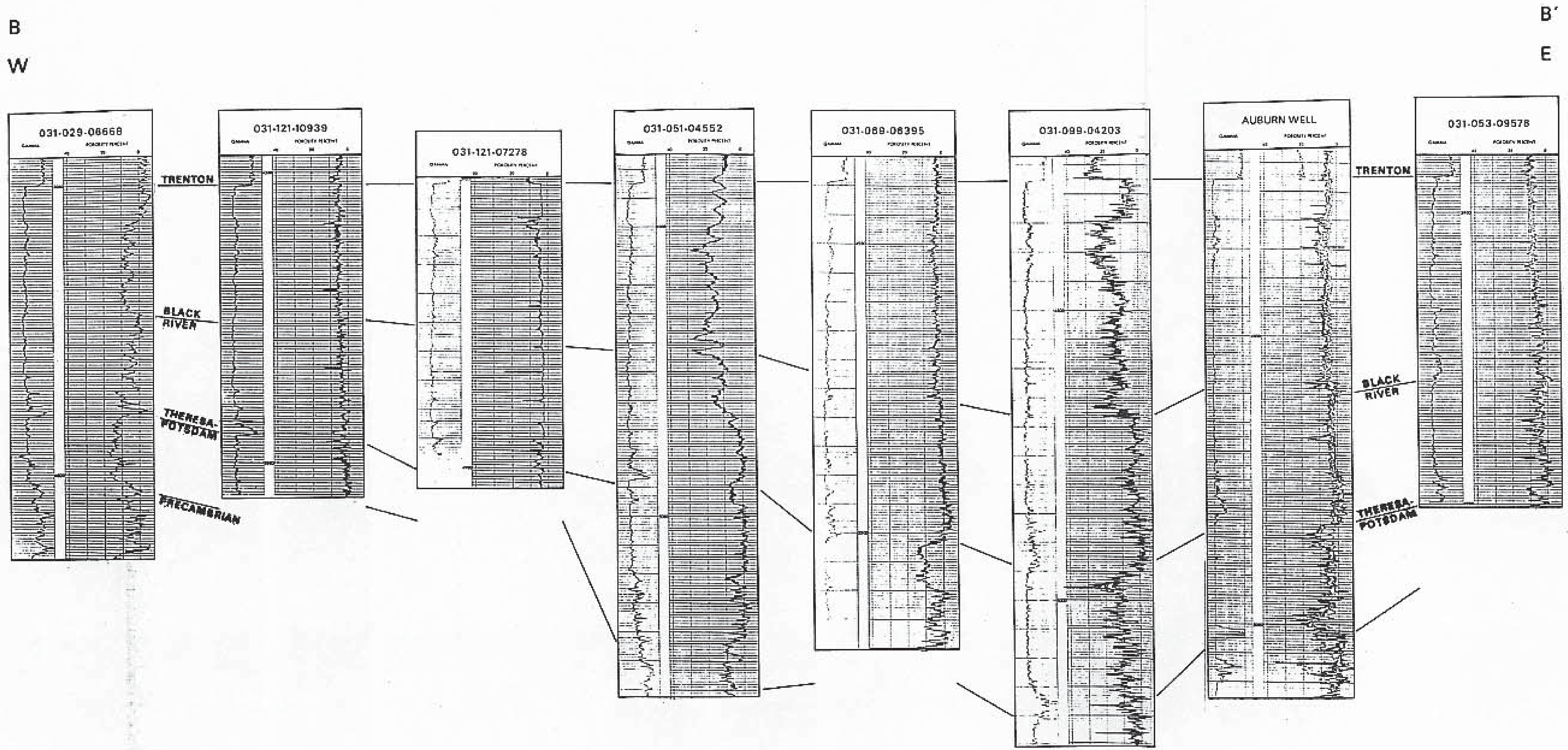
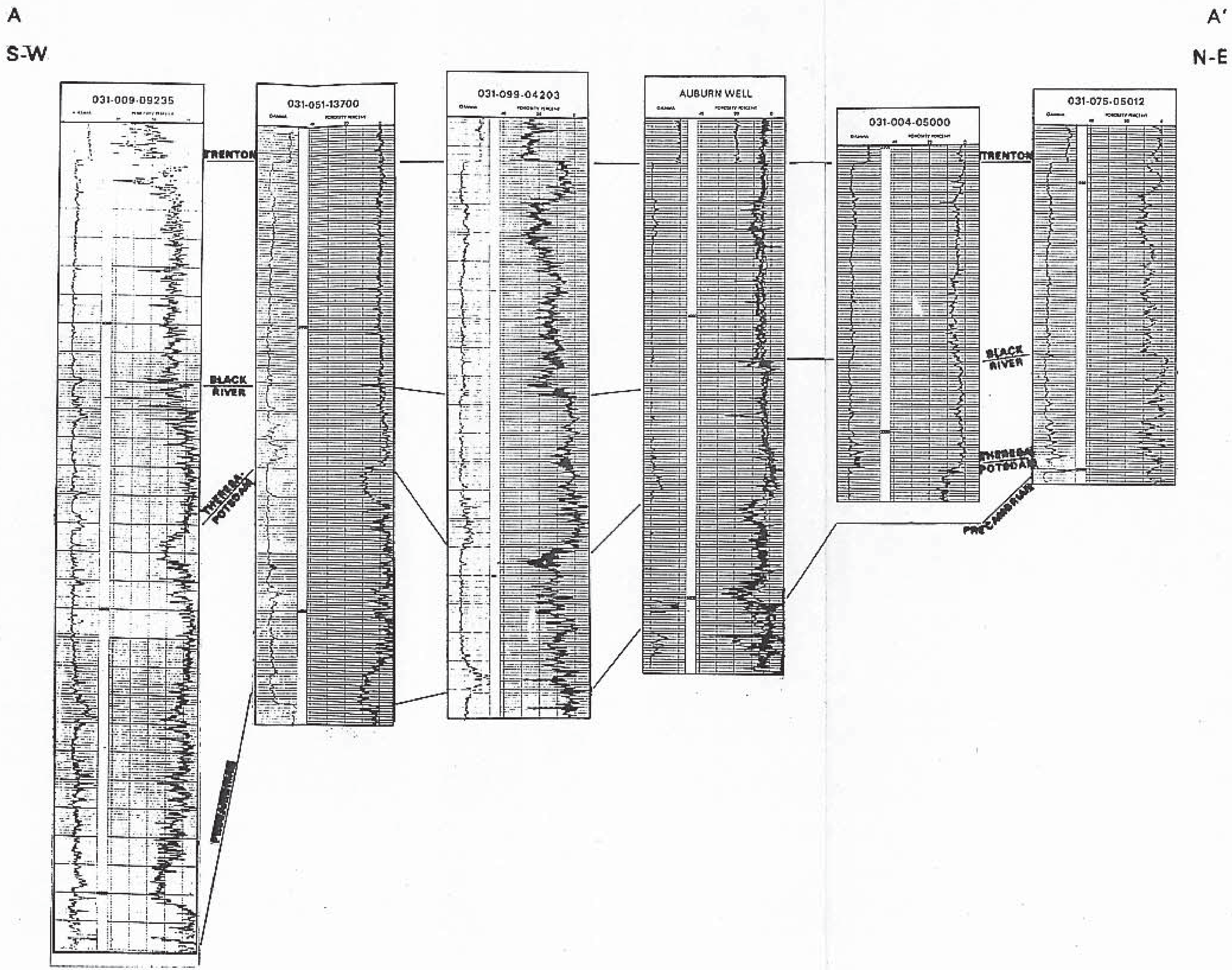
1982



NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
J.E. ROBINSON
SYRACUSE UNIVERSITY
1982



CONCLUSION

Central New York State appears to possess all the necessary geologic requirements for the development of low temperature geothermal energy. Potential reservoirs appear to have sufficient thickness, lateral extent and porosity and are at a depth sufficient to be considered as sources for low temperature geothermal waters. The prime reservoir candidates are the Theresa and Potsdam Sandstones in the Lower Ordovician-Cambrian section lying below the Knox Unconformity. These sandstones have porous zones that are estimated to be of reservoir quality at least 100 feet thick in the central part of the project area. In this area the northward attrition of the deep section has caused the main reservoir sandstones to coalesce into what is practically a single unit of relatively clean generally porous quartzose sandstone. In addition to the intergranular porosity, the reservoirs are often fractured, and the fractures enhance both porosity and permeability acting as natural conductors to transmit the water from the intergranular pores to the borehole. The porous sand isopach displays those areas that are most prospective for geothermal reservoirs on the basis of intergranular porosity; however, even marginal areas could be good producers where there is sufficient fracture porosity. Also minor adjustments in formation parameters which cannot be accurately determined from present subsurface information, could alter the position of the contours on the map. It is estimated that all areas south of the 50 degree Celsius geothermal barrier and within the 50 foot porosity thickness contour are suitable for the development of low temperature geothermal fluids.

Should zones of greater than average tectonic faulting or folding be interpreted from other geologic measurements, then these would likely be zones of enhanced porosity due to increased fracturing. The coincidence of intense fracturing with thick intergranular porous reservoirs would provide an ideal situation for geothermal prospecting.

The stratigraphic section of New York State above the Knox Unconformity is not considered prospective for geothermal fluid except for zones of intense fracturing associated with tectonic activity. Even in these cases, it is expected that the fractures would communicate with the deeper intergranular porosity reservoirs. With the exception of the fracture zones, the upper formations are relatively tight; and often appear to contain natural gas. The geophysical logs also indicate that the Theresa-Potsdam reservoirs are often gas saturated north of the 50 degrees Celsius temperature line; so caution should be exercised when drilling close to the minimum geothermal temperature area.

The geothermal potential for local areas can be estimated by considering the elevation map of the top of the Theresa Porosity , the thickness of the porous intervals and the elevation of the basement. Temperatures are estimated from the Top Theresa Temperature map, and locations of the porous intervals are determined from the cross sections. Topographic maps are used to determine drilling depths.

Finally, this report was based on the analysis of geophysical well logs that indicate the porosity of subsurface formations. Logs that indicate permeability are not run in New York State, and there are no cores or production tests to measure permeability directly. Porosity normally is related linearly to permeability; and on the Auburn well, preliminary estimates appear promising. However, Actual liquid flow rates for local geothermal reservoirs must await drilling and testing.

ERDA Report 83-4

State of New York Mario M. Cuomo, Governor

New York State Energy Research and Development Authority
James L. Larocca, Chairman Irvin L. White, President