LBL-8669
~~GREMP-2~~
UC-66a

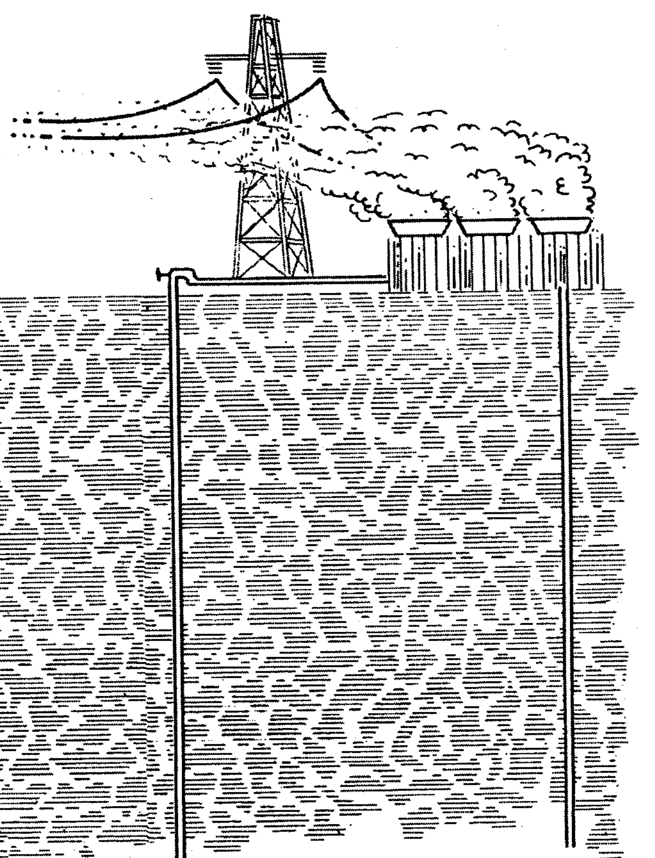
Summary of Reservoir Engineering Data: Wairakei Geothermal Field, New Zealand

J. W. Pritchett, L. F. Rice and S. K. Garg

Systems, Science and Software
La Jolla, California

JANUARY 1979

Geothermal Reservoir Engineering Management Program



Lawrence Berkeley Laboratory
University of California, Berkeley

Prepared for U.S. Department of Energy under Contract W-7405-ENG-48

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price Code: A03

SUMMARY OF RESERVOIR ENGINEERING DATA: WAIRAKEI GEOTHERMAL FIELD, NEW ZEALAND

J. W. Pritchett, L. F. Rice and S. K. Garg
Systems, Science and Software
La Jolla, California 92038

ABSTRACT

This is an abbreviated summary of the final project report[1] on an extensive collection of fundamental field information concerning the history of the Wairakei geothermal field in New Zealand. The purpose of the effort was to accumulate any and all pertinent data so that various theoretical reservoir simulation studies may be carried out in the future in a meaningful way. Categories of data considered include electrical resistivity measurements, magnetic force surveys, surface heat flow data and a catalog of surface manifestations of geothermal activity, geological and stratigraphic information, residual gravity anomaly surveys, laboratory measurements of formation properties, seismic velocity data, measurements of fluid chemical composition, monthly well-by-well mass and heat production histories for 1953 through 1976, reservoir pressure and temperature data, and measurements of subsidence and horizontal ground deformation. The information is presented in three forms. A review of all the data is contained in the final project report.[1] The present report summarizes that information. In addition, a magnetic tape suitable for use on a computer has been prepared. The magnetic tape contains a bank of information for each well in the field, on a well-by-well basis. For each well, the tape contains the completion date, the surface altitude, the bottomhole depth, the geographic location, the slotted and perforated interval locations, the bottomhole diameter, locations of known casing breaks, the geologic drilling log, fault intersections, shut-in pressure measurements, and month-by-month production totals of both mass and heat for each month from January 1953 through December 1976.

INTRODUCTION

This summary report presents a brief discussion of the results of a six-month effort to acquire and summarize data pertaining to the character, performance and response to production of the Wairakei geothermal field in New Zealand. The complete report[1] consists of two volumes containing approximately 850 pages. The purpose of the work was to assemble a data base which would be of use in reservoir engineering studies, particularly large-scale numerical simulations of the mass and heat flow and associated phenomena over the lifetime of the field. The Wairakei geothermal system is of particular interest since it was the first (and until 1973 the only) liquid-dominated geothermal reservoir to be exploited for electrical power. Drilling began at Wairakei in 1950 and ceased in 1968; mass production rates reached a peak in the mid-1960's and have been slowly declining since. Thus, a substantial production history for a liquid-dominated geothermal system has been accumulated which is unique in the world.

The data collection process was accomplished in four phases. First, a search was made for all relevant data available concerning Wairakei in the United States. This information generally fell into two categories: published journal papers and reports, and a substantial collection of raw data accumulated by James Mercer of the U. S. Geological Survey in 1972, which he kindly contributed to the present effort. Once this data was gathered and assessed, one of the present authors (Pritchett) made a two-week visit to New Zealand in November 1977. It was during this visit that the bulk of the information was gathered. Pritchett was given free access to the Wairakei files and was provided ample help by the New Zealanders, both at the Ministry of Works (MOW) and the Department of Scientific and Industrial Research (DSIR) headquarters in Wellington and at Wairakei itself. The data was then organized in final form for the comprehensive final report.[1] Finally, the present summary report was prepared.

In line with the basic purpose of the work, only data relevant to the reservoir mechanics were considered. Thus, for example, little discussion of such matters as the power plant design, the economics of the system, plant management and the like is included. Emphasis was placed upon information which is not generally available in the U. S. For example, the geology of the Wairakei area is very intricate and forms a fascinating subject in itself. Grindley[2] has already written a 130 page book on the subject, and hence the section on geologic structure in the report is largely a précis of his work and that of Healy.[3] Similarly, the pressure-drawdown data for the field have been discussed by Bolton;[4] therefore, the discussion of pressures follows Bolton very closely, but includes data for the interval 1969-1976 which Bolton, obviously did not treat.

From the standpoint of the reservoir engineer, the data bank available concerning Wairakei is somewhat frustrating. On the one hand, enormous amounts of information are available concerning geological structure, production rates, discharge enthalpy, pressure trends, and many other subjects. On the other, certain measurements which are of great importance in reservoir engineering either were not made at all, or were made in such a way that the results are ambiguous or misleading. The two most important parameters which fall into this category are the permeabilities of the various formations and the early temperature distribution in the field.

As regards permeabilities, the classical procedure in the petroleum industry for determining effective formation permeability is the wellhead test. For several reasons (not the least of which is the fact that a rapid-response pressure gauge capable of withstanding the geothermal environment was not then available), such tests were never performed in the early days at Wairakei. Now that the technology for making pressure-transient tests is available, the long history of production has resulted in the creation of a two-phase (water/steam) system in the area of principal production which renders the interpretation of such a test very difficult and uncertain. Lacking well-test information, core samples from Wairakei have been tested in the laboratory. These laboratory results indicate, however, matrix permeabilities for the principal producing aquifer which are several orders of magnitude smaller than the minimum required to sustain reservoir production at the observed rate. The Wairakei field is located in an intensely faulted and seismically active region; clearly, most of the effective reservoir permeability consists of "fracture permeability" as opposed to "matrix permeability".

The situation is somewhat different concerning the early temperature distribution in the field. The procedure was to shut a well in for a period of time and then to make temperature measurements at various levels within the well, thereby constructing a temperature/depth profile for the well. A substantial amount of information of this sort is available. There are, however, at least two serious difficulties with this approach. First, it often turns out that the shut-in time was insufficient to permit thermal equilibration between the rock outside the well and the fluid inside. An even more serious difficulty is that the Wairakei temperature/depth measurements were made inside cased wells. Due to the formation of convective cells in the fluid within the well, under such circumstances the vertical temperature distribution within the well may never equilibrate with that of the rock outside, irrespective of the duration of the shut-in interval. Therefore, although a maximum temperature found within a well at a particular time may indeed reflect the rock temperature at that particular depth, the remainder of the temperature-depth profile should be regarded with considerable suspicion. A preferable procedure for determining the temperature-depth profile would have been to make measurements during drilling, allowing for temperature equilibration at different depths during the drilling of the well prior to making the temperature measurement. It should be assumed that the pre-production temperature distribution in the field is simply not well known.

Lest the reader become discouraged, it should be reiterated that in other respects the data available from Wairakei are excellent and quite complete. Wairakei is almost certainly the best-documented geothermal field in the world (with the possible exception of Lardarello), at least in the public domain. As can be seen from the main report, the available information on geological structure, reservoir pressure, well-by-well production histories and other quantities is complete enough that the principal unknowns (permeability and initial temperature) can likely be estimated or at least bracketed by good engineering judgement with the help of numerical simulation studies.

At this point, it is worthwhile to discuss the way in which the data are presented. Generally speaking, measured quantities are given in the same system of units as that in which they are obtained. Thus, for example, pressures are usually expressed in pounds per square inch. Mass of fluid produced is given in pounds, and enthalpies are provided in BTU/pound relative to liquid-saturated conditions at 0°C. Temperatures, however, are given in degrees Celcius. Depths are measured in feet, usually with respect to sea level; for example, the notation "RL-900" refers to a depth of 900 feet below mean sea level (and roughly 2,500 feet below the surface at Wairakei's altitude). Geographic locations (i.e., locations of wells and the like) were provided in as many as three different coordinate systems, but by far the bulk of the data was in feet, with respect to the 1949 Maketu datum; this system was adopted throughout for this report.

The report[1] actually consists of three parts. The first of these is the lengthy written document, Volume I. In addition, substantial amounts of data are contained on a magnetic computer tape, and computer programs have been written which permit interrogation of this tape. For the benefit of those who lack ready access to a large computer, all the data on the tape are also reproduced (in a form more amenable to human consumption) in Appendix D, which forms the rather bulky Volume II of the report. It is hoped, however, that the presentation of the data in computer readable format will facilitate the use and manipulation of these data for input to numerical reservoir simulation computer programs.

Not all the data acquired during the course of this project are to be found on the magnetic tape. Generally speaking, the data on the tape have been restricted to information which (a) readily lends itself to digital representation, and (b) is too cumbersome for efficient presentation in a written report. The data on the tape are organized on a well-by-well basis. That is, for a particular well, all relevant data are presented in a particular data block on the tape. The tape thus consists of a linear series of such data blocks, one for each well in the field. For each well, the data on the tape consists of the following:

1. The coordinates of the wellhead in feet with respect to the 1949 Maketu datum, and the altitude of the wellhead (in feet) above sea level.

2. The depth of the bottom of the well (in feet, with respect to sea level); also, if the well was deviation drilled, the depth at which deviation began and the 1949 Maketu coordinates of the well bottom.

3. The month and year during which the well was completed.

4. The depth (in feet with respect to sea level) at which major geologic formation interfaces were encountered during drilling.

5. The depth (feet, RL) of the top and bottom of the major slotted interval in the well.

6. Numbers, diameters and top and bottom altitudes of gun-perforation intervals.

7. The diameter of the well bottomhole (inches).

8. Depths (in feet, with respect to sea level) where fissures or faults were encountered during drilling.

9. Depths (feet, RL) where casing breaks were detected.

10. For each month from January 1953 to December 1976 (inclusive), the total mass of fluid (in pounds) and the total heat (BTU) produced during the month. The mean discharge enthalpy may be computed by dividing the heat production by the mass production.

11. Pressure measurements, as applicable.

12. Occasional general comments concerning unusual events or characteristics of the well.

In the written portion of the report, the sources and general implications of the data on the magnetic tape are discussed at some length. Also discussed are data of other kinds which did not readily lend themselves to digital representation. The complete report consists of fourteen chapters plus four appendices. Chapter II contains a general description of the history of the development and exploitation of the Wairakei field. In Chapter III, the results of electrical resistivity and magnetic surveys are presented. The former indicates, in an approximate manner, the thermal boundary of the field; the latter suggests, among other things, that the source of hot fluid lies to the west of the present production area, and that natural groundwater flow is generally from west to east. Chapter IV discusses the natural geothermal surface manifestations in the Wairakei area and the changes in these phenomena that have occurred over the years. In Chapter V the geological structure of the Wairakei field is described, based principally on borehole evidence. This chapter amounts to a summary of the previous work of Healy[3] and Grindley,[2] supplemented by more recent data relevant to the nearby Tauhara field and certain later boreholes. Chapter VI consists basically of data concerning laboratory measurements of rock density, porosity and permeability, and also contains comments relevant to the bulk effective permeability of the reservoir. In Chapter VII, seismic data are presented. Briefly, seismic surveys intended to map geologic layering have been relatively unsuccessful due to absorption in the unconsolidated surface layer, but seismic velocity measurements in the various strata, when compared to laboratory measurements, strongly suggest an extensive fracture structure. Chapter VII presents data relevant to the chemical composition of the fluids discharged from the Wairakei bores. These data indicate that, for practical reservoir engineering purposes, the fluid may be regarded as pure H_2O. In Chapter IX, temperature distributions within the field and trends in temperature with time are described. As discussed above, however, serious uncertainties exist concerning the temperature data. Chapter X describes trends in the drilling program, the spatial and temporal distribution of the production of mass and heat, and changes with time of such quantities as mean discharge enthalpy. Also discussed are uncontrollable-discharge "accidents" that have occurred, and the various sources of mass and heat production data which are contained on the magnetic tape. Chapter XI summarizes the numerous pressure measurements made at Wairakei. It is shown that the pressure trends within the field are consistent with two-phase behavior, and that the rate of pressure drop has been declining in recent years in spite of sustained production rates. Pressure evidence to define the hydrodynamic boundaries of the field is described and correlated with temperature data. It is also demonstrated that the Wairakei field communicates strongly with the Tauhara field to the southeast. In Chapter XII, gravity survey data are discussed. It is shown that changes in gravity anomaly measurements indicate an increasing rate of natural recharge over the years. In Chapter XIII, the ground motion that has accompanied fluid production at Wairakei is described. Both vertical motions (subsidence) and horizontal deformations have been measured. In Chapter XIV, the data on the magnetic tape are discussed in detail; Appendices A, B and C show various examples of output available from the magnetic tape, examples of computer programs suitable for interrogating the tape, and user-instructions for the tape. Finally, Appendix D (presented as Volume II of the report) contains, in condensed form, the detailed data available on the tape.

The sections which follow in this document before you are only summaries of the information contained in the chapters discussed above.

DEVELOPMENT OF THE WAIRAKEI GEOTHERMAL FIELD

Between Mt. Ruapehu (an active volcano) in the center of New Zealand's North Island and White Island in the Bay of Plenty some 150 miles to the northeast, lies a 20 mile wide belt in which numerous surface manifestations of geothermal activity are to be found. Within this region (see Fig. 1) which is believed to be associated with the Tonga-Samoa submarine volcanic ridge,[2] geysers, hot springs, steam vents, large regions of steaming ground, and evidence of hydrothermally-altered rocks are common.

Most of the electrical generating capacity of the North Island consists of a series of hydroelectric power stations along the Waikato River, which has its origins at Lake Taupo near the south end of the thermal belt and discharges to the sea near Auckland to the north. In 1950, a joint effort was made by the Ministry of Works (MOW) and the Department of Scientific and Industrial Research (DSIR) to assess the geothermal potential of the thermal belt generally, and in particular, the vicinity of Wairakei just to the north of Lake Taupo. The principal surface manifestations of thermal activity at Wairakei are the Karapiti area

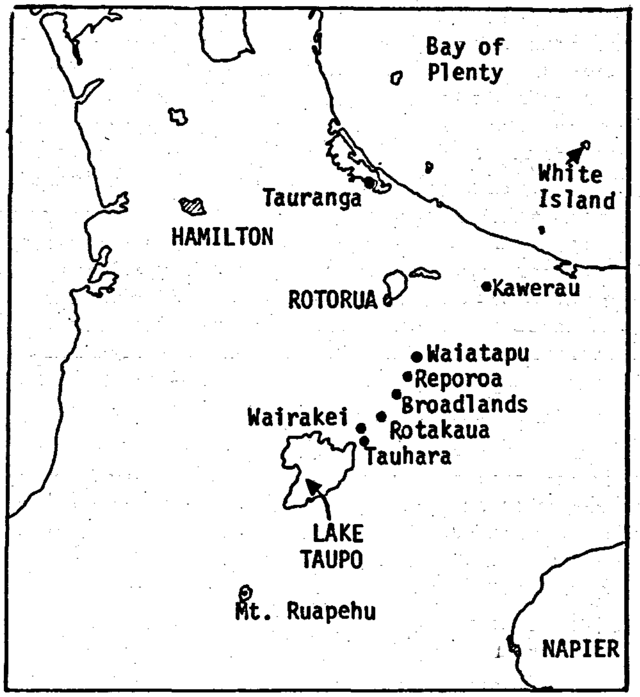


Figure 1. Thermal areas, hot springs and volcanoes of the thermal belt, North Island, New Zealand.

in the south, Geyser Valley to the north, and the Waiora Valley to the west. The conclusions of the study,[6] generally speaking, were that some potential definitely existed for power production using shallow drilling alone, and that much more might exist if deep wells were drilled.

In 1955, a decision was made to construct a power plant capable of producing 69 megawatts of electrical power and, as a by-product, to provide heavy water for the British Atomic Energy Authority. The heavy water scheme was soon abandoned, but by 1957 the first stage (59 MW) of the power plant was under construction. In 1953, a program of deep drilling was begun that soon demonstrated the existence of a much larger resource than had been estimated based upon the earlier relatively shallow bores.

Drilling activity at Wairakei ceased in 1968; since then, mass production rates have been declining at about 4 percent per year. Bore field pressures have dropped over 350 psi over the years, and temperatures have likewise dropped. Various modifications have, however, improved the thermal efficiency of the system such that the electrical generating capacity has been maintained.

Wairakei has been producing electrical power since the mid-1960's at an average of about 140 MW. It is now regarded in New Zealand as an operating facility which is slowly being depleted but which will doubtless continue to produce power for many years to come, and no fundamental changes are contemplated.

ELECTRICAL AND MAGNETIC MEASUREMENTS

The results of surface resistivity surveys are generally interpreted as being indicative of the presence or absence of hot water at depth. That is, as temperature increases, the electrical conductivity of electolytes also increases. Low resistivities tend to occur in regions surrounding a geothermal anomaly. As a general practice, the "boundary" of a geothermal reservoir is considered to correspond to resistivities in the range of 10-20 ohm-meters. The reservoir itself, in its central region, may have resistivities less than 5 ohm-meters, while the surrounding relatively cold rock is often characterized by resistivities as high as 100 ohm-meters or more.

A resistivity survey was carried out in the Wairakei area in 1963-1964; Fig. 2 shows the resistivity contours resulting from that survey. These contours definitely indicate two large low resistivity regions, at Wairakei and at Tauhara, with a relatively narrow neck connecting them. Even more compelling evidence for such a connection is provided by the pressure data discussed elsewhere in the report.[1]

A vertical magnetic force survey was reported by Cullington.[7] Modriniak and Studt[8] drew attention to the contrast between the low intensities in the vicinity of the Waiora Valley at the western end of the bore field and the high intensities in the vicinity of Geyser Valley. They believe that this general increase in magnetic intensity from west to east across the bore field indicates that the source of hot fluid is to the west, and that the general flow is from west to east. They drew this conclusion by noting that hydrothermally altered ignimbrite is much less polarized than relatively unaltered ignimbrite.

NATURAL HEAT FLOW AT THE SURFACE

Prior to its development as a geothermal power system, Wairakei and its immediate neighborhood were popular tourist attractions, in large measure due to the various geysers, hot pools and similar phenomena in the vicinity.[9] The most prominent of these features were the geysers in Geyser Valley (just north of the main bore field), the thermal pools of the Waiora Valley (just to the west), the Karapiti area to the south of the bore field, including the Karapiti Blowhole fomarole, and the geysers at Spa Sights in the Tauhara area.

During the years of production at Wairakei, much of this natural activity has subsided. Activity in Geyser Valley began to decrease preceptibly as early as 1954, and the attraction was closed in 1972. The Waiora Valley, on the other hand, has retained most of its activity. The Karapiti Blowhole has ceased to discharge, as have the geysers at Spa Sights. As a general rule, throughout the area, surface manifestations such as geysers and hot springs have declined, whereas "steaming ground" has become more extensive.

Numerous natural heat flow assessments of Wairakei have been carried out.[5,10-16] Estimates for the total heat flow vary, but Grindley[17] indicates that the total natural flow has increased

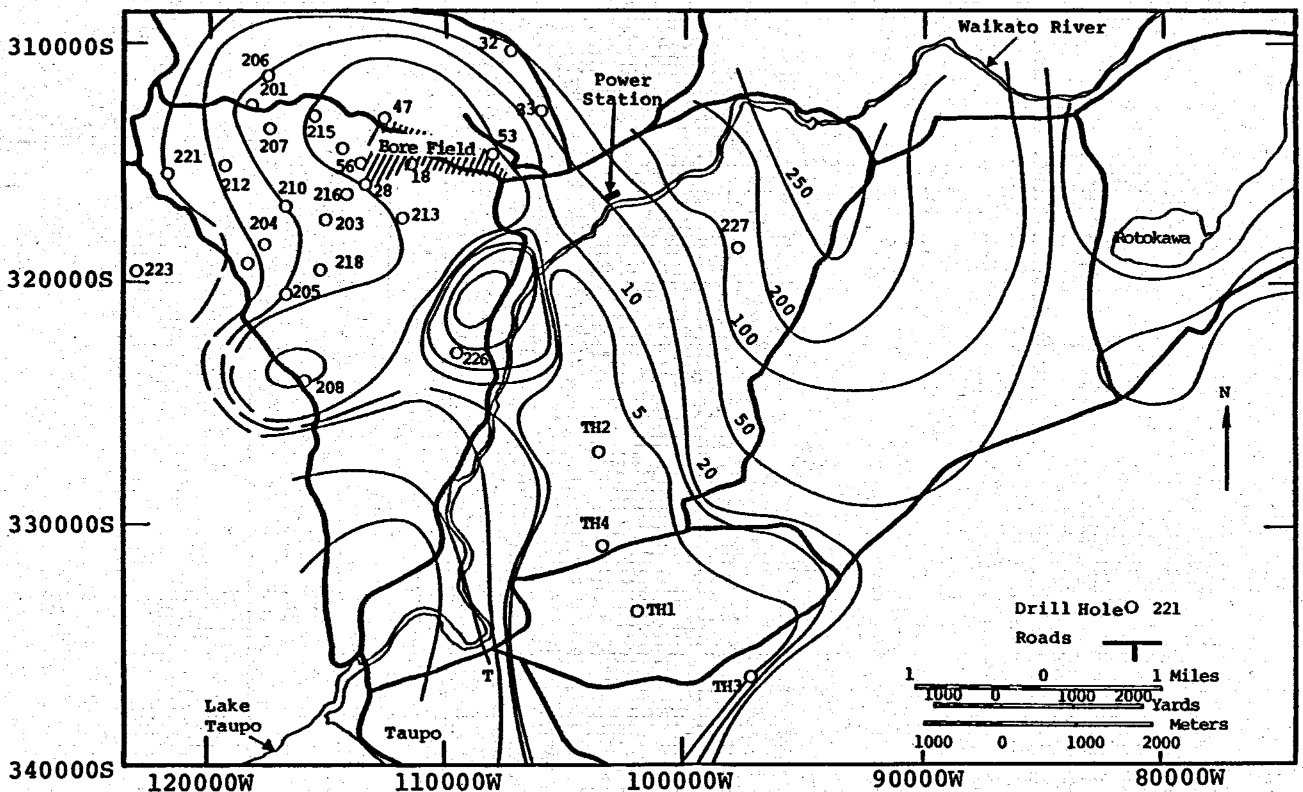


Figure 2. Resistivity contours values in ohm-meters.

from about 450 to about 750 megawatts over the life of the field. Substantial amounts of shallow temperature data have been collected. Figure 3 shows temperature contours at a depth of 1 meter over the Wairakei field in 1966. Dawson and Fisher[18] showed that, at this depth, diurnal variations in air temperature do not penetrate. The regions of high heat flow are seen to be at Geyser Valley, Waiora Valley and Karapiti, as well as at other isolated locations. The overall heat flow pattern changed only slightly between 1958 and 1966.

GEOLOGICAL STRUCTURE

The Wairakei geothermal field includes the area of Geyser Valley, the Waiora hot springs, and the Karapiti fumarole area. The field lies to the west of the Waikato River and to the north of Lake Taupo. The Tauhara geothermal region lies to the south-southeast of the Wairakei geothermal area and is associated with low lying acid volcanoes. In the Tauhara field, the stratigraphic sequence forms a shallow basin, which is thickest near bore TH1 and thins to the north, west and south. The eastern edge of the basin extends beneath Mt. Tauhara. Pressure evidence clearly shows that Tauhara is part of the same aquifer system as the Wairakei field. Therefore, any analysis of Wairakei necessitates examination of the Tauhara region as well. Hence, the stratigraphy of the combined area is discussed here.

The geology of the Wairakei geothermal area has been described in general by Grange[19] and in greater detail by Grindley[2] and Healy.[3] The geology of Tauhara has also been discussed by Grindley, et al.[20] It is not the intent of the present authors to reiterate the extensive geologic analyses already concluded. Rather, a discussion of the geologic structure necessary for reservoir engineering studies of the hydrothermal area has been undertaken.

With the continuing development of the Wairakei field since the early 1950's and with the commencement of subsurface exploration at Tauhara in 1964, a stratigraphic picture of the entire hydrothermal region has been evolving, primarily through examination of the outcrops in the region and, more importantly, through the data obtained from drilling logs. The well summaries presented in Volume II of the report[1] give the geologic formations penetrated by each bore. This information was obtained through examination of the drilling logs presented by Grindley.[2] His information was supplemented by the examination of well logs for recent bores not included in his report. Indeed, those addtional bores have provided important information about the subsurface structure.

Figure 4 shows a general topographic map of the entire Wairakei/Tauhara region. The portion of the map within the small rectangle has been enlarged in Fig. 5 to give a more detailed picture of the main production area. These two maps identify the locations of all bores and major surface features in the region. In the next several paragraphs, the characteristics and general distributions of the principal members of the stratigraphic sequence will be discussed in detail. Figure 6 shows a cross-section running approximately E-W across the main bore field. The full report contains many such cross-sections to give a better geologic picture of the entire region. In the following subsections, each major

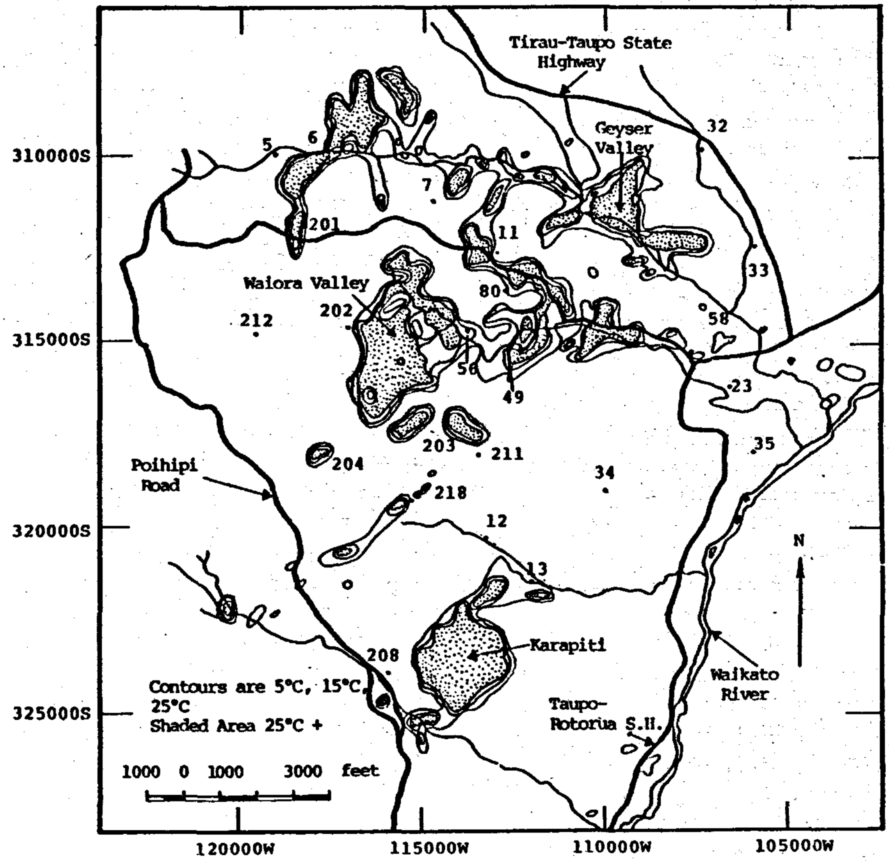


Figure 3. Temperature elevation above mean air temperature at 1 meter depth - 1966.

formation is briefly described, proceeding from deep to shallow. For more details, see the full report.[1]

Ohakuri Group

This group is composed of pumice breccias and pumiceous sediments. In the Wairakei area, the name is applied to the pumiceous pyroclastics and sediments underlying the Wairakei Ignimbrites in the region of bores 219 and 121. In bore 219, the Ohakuri Group was encountered from RL-1633 to the bottom of the hole at RL-2304. In bore 121, which was drilled in 1968, the formation was encountered at RL-3885. From that point to the bottom of the hole at RL-5940, it alternates with layers of andesite. Evidence from bore 121 suggests that the Ohakuri Group is virtually impermeable.[22]

Wairakei Ignimbrites

The Wairakei Ignimbrites have been encountered in 54 wells at Wairakei and Tauhara. The Wairakei Ignimbrite is a dense quartz-bearing formation with, according to Healy,[3] also abundant plagioclase with minor hypersthene and biotite. The ignimbrite layer lies approximately 2000 feet below the surface in the main production area and is at least 1700 feet thick in bore 48. To the northwest, in bore 219, the formation has thinned to about 800 feet and to the west in bore 121 the formation is approximately 3400 feet thick.

Waiora Formation

The Waiora Formation lies above the Wairakei Ignimbrites. It consists of pyroclastic rocks, tuffaceous sandstones, silty sandstones, grey siltstone, ignimbrites and interbedded sediments. In the main production region, the Waiora lies about 600-700 feet below the present land surface and is approximately 1500 feet thick. In the southeast and eastern regions where the ignimbrites dip steeply, the Waiora is up to 3000 feet thick. The formation has been encountered in all but a few holes at Wairakei and Tauhara. This formation is the primary aquifer which supports the production from the region. It is, in general, sandwiched between the ignimbrites below and the Huka Falls formation above. These serve essentially as aquitards. From drill logs, the formation is known to be thicker to the west in the Te Mihi Basin, where bore 207 was drilled into at least 2000 feet of the formation without encountering the underlying ignimbrites. Similarly, to the east in the Taupo-Reporoa Basin holes 60 and 37 encountered about 2500 feet of Waiora without finding the ignimbrites.

Waiora Valley Andesite

Lying interbedded with the Waiora, a little above the ignimbrite, is the Andesite Formation. It is dense and has been hydrothermally altered. The formation has been encountered in 31 wells in the region. It appears closely associated with the Waiora, Wairakei and Upper Waiora Faults, and according to Grindley[2] appears to have been

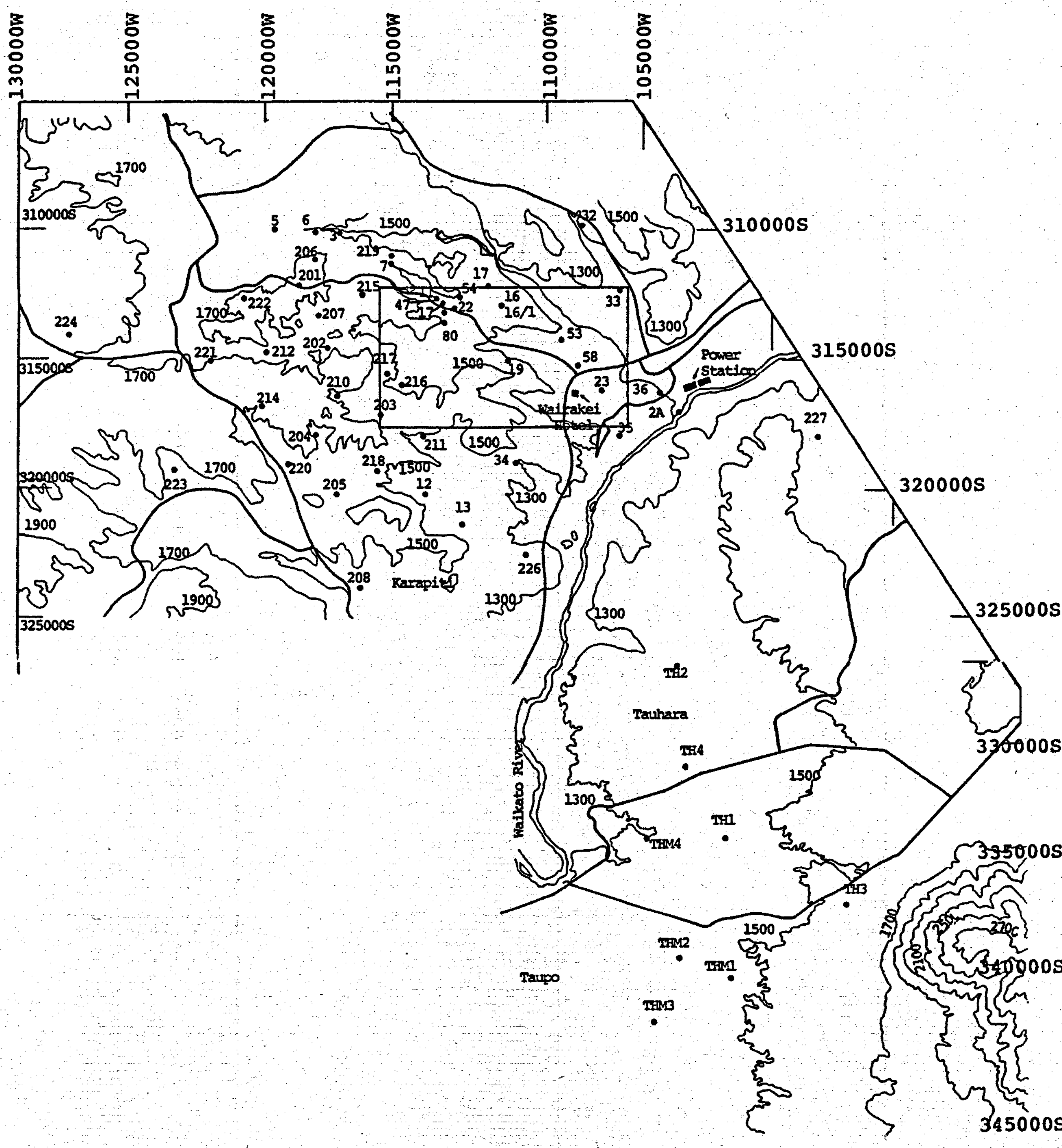


Figure 4. Topography of Wairakei/Tauhara region showing peripheral bores (rectangular) outline denotes region shown in Fig. 5).

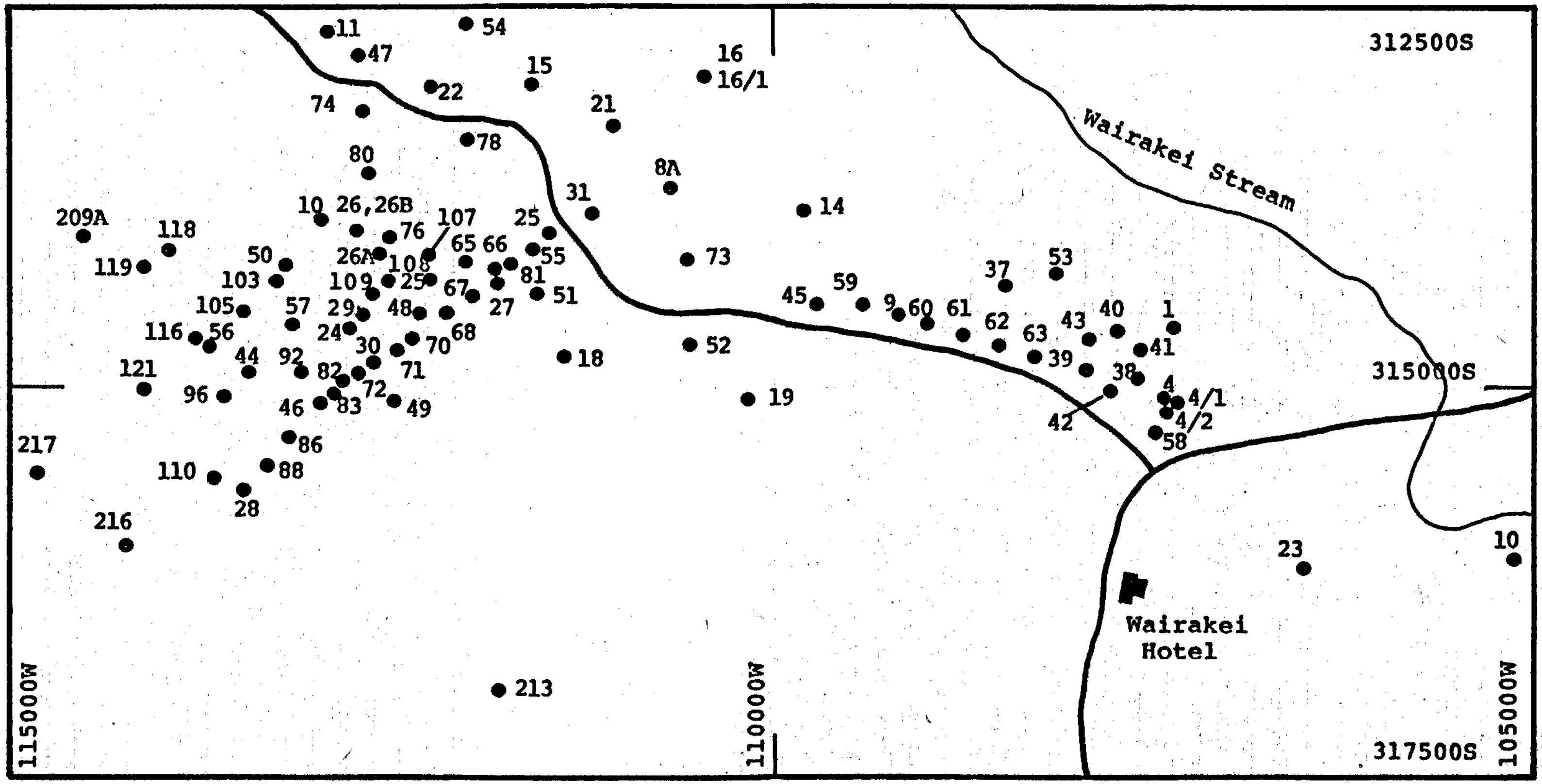


Figure 5. Bore locations in main bore field.

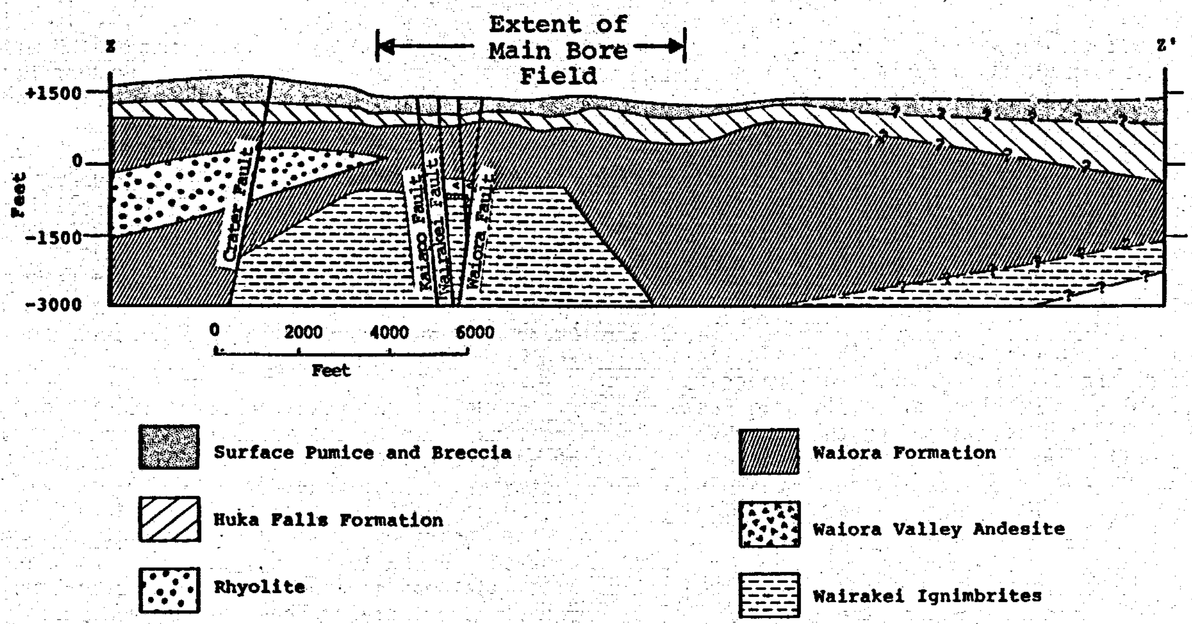


Figure 6. Section ZZ'.[21]

extruded along fissures at fault intersections. Away from these intersections, it appears to thin rapidly.

Haparangi Rhyolite

This name denotes the subsurface rhyolites which are encountered in drillholes in the southwestern region of the production area and also in bore 219 in the north. The formation has been encountered in 27 bores. The rhyolite encountered at Wairakei includes pumiceous, perlitic, speruli-tic and banded lithoidal rhyolites, and varies from about 1600 feet thick at bore 208, to 1520 feet in 205, to 1460 feet in 210, to 230 feet in 213 and to 200 feet in bore 28. The thinning of the formation from south to north is consistent with the postulate that the flow occurred from the south.

Huka Falls Formation

This name applies to the grey siltstones, mudstones, and sandstones between the top of the Waiora formation and the base of the Wairakei breccia. This formation has been encountered in all boreholes at Wairakei with the exception of 208 and 223. It is believed to have originated as an ancient lake-bed. In general, it ranges from less than 200 feet in the southwest and northwest to between 200 and 300 feet in the western part of the production area.

Wairakei Breccia

This formation was apparently laid down as ash-flow deposits and conformably overlies the Huka Falls formation. It has been drilled in nearly all of the bores in the area, however, it is absent east of bore 4. The maximum thickness encountered in the drilling was about 550 feet in holes 5 and 6.

Recent Pumice Cover

This name applies to the pumice alluvium, wind-blown ash and lapilli and ash showers which have been deposited over the Wairakei breccia. They are found in all bores at Wairakei and are in general fairly thin layers (less than 100 feet). The pumice cover is of no real significance to this report or the stratigraphy of the region.

There are three major structures which are identifiable in the area; the Wairakei Block, the Taupo-Reporoa Basin and the Te Mihi Basin. According to Grindley,[2] the Wairakei Block is an elliptic structure extending in the north-northeasterly direction. He believes that the high gravity and magnetic values recorded at the southern end of the region may be due to the thick intrusions of rhyolite which lie in that region. The northern end of the block are characterized by lower magnetic values. Grindley believes that the ignimbrites bounded by faults may indicate there has been an uplift in the basement rock. This area of presumed uplift actually corresponds to the large concentration of deep hydrothermal activity. Indeed, over the main production region, the surface of the ignimbrites lies at about RL-700 whereas away from the main bore field the surface of the ignimbrites is deeper; as much as 1300 feet deeper to the east.

To the east of the Wairakei Block is the Taupo-Reporoa Basin which trends again in a north-northeasterly direction between the Kaingaroa Plateau and the Paeroa and Wairakei Blocks. The greywacke basement in this region is postulated by Modriniak and Studt[8] to be about RL-8500, approximately 4000 feet lower than in the Wairakei Block. Drillholes in the eastern part of the field have provided evidence of sloping into the basin. As Grindley[2] comments, the total displacement of the ignimbrites is at least 750 feet along the fault.

The Kaiapo Graben and the Te Mihi Basin lie to the west of the Wairakei Block. The Graben is bounded by faults. The block tilts slightly eastward by about 10° and is bounded on the east by the Kaiapo Fault. The Te Mihi Basin lies as a northeasterly extension of the Graben. According to Grindley[2] it does not appear to have been fault produced.

Faults are dominant features throughout the entire Wairakei region. However, the Tauhara region is less strongly fault-dominated. Essentially all faults have a northeasterly orientation. It should be noted that the production from the region is believed to be strongly influenced by faults - indeed, as evidenced by laboratory work, the rock formations tend to have low matrix permeability. Hence, the flow through the system is believed to be primarily through the faults and associated fractures. As Grindley[2] comments, drilling of successful wells at Wairakei depends upon the intersection of the borehole with a fault -- thereby providing the necessary increased permeability. Many wells were in fact drilled in an attempt to intersect major faults. The full report[1] gives a more complete discussion of the faulting of the region.

ROCK PROPERTIES

The rock properties of principal interest for reservoir engineering studies are the porosity, permeability, density, thermal conductivity and heat capacity of the various layers. If bulk deformation effects (i.e., subsidence) are of interest, the thermoelastic properties of the rock are also required. The available laboratory data concerning these properties makes it clear, however, that the behavior of the reservoir cannot be explained in terms of the properties of the rock samples alone. That is, measured porosities are higher and permeabilities are much lower than one would expect based upon the performance of the reservoir.

Clearly, much of the effective permeability of the reservoir as a whole arises from the fracture network known to be present within the system. Since these fractures do not penetrate the entire body of the reservoir and consequently do not intersect all pores, the effective porosity (or fluid volume) for the reservoir as a whole is doubtless smaller than the actual pore volume fraction measured in individual rock samples. Likewise, the presence of such a fracture network would tend to explain the discrepancy between laboratory and in situ values for seismic velocities. Thus, for example, theoretical analyses of the reservoir response at Wairakei have used effective permeabilities of the order of 100 millidarcies and porosities of about 20 percent for the Waiora aquifer and have obtained fairly good history matches.[21,23] Grindley[2] has pointed out that the effective permeability for a well penetrating the Waiora formation appears to be dependent upon the number and size of fissures it intersects as much as upon any other parameter. This observation certainly suggests that the bulk of the Waiora permeability is "fracture permeability" as opposed to "matrix permeability". Thus, the data to be presented in this section should be used with caution.

Banwell[21] reports mean saturated and dry densities of 16 core samples taken from some of the early bores as 1.86 and 1.55 grams/cm^3, respectively. These cores were taken from holes drilled to depths of between 1500 and 2000 feet, but the locations of the cores themselves were not reported. Presumably, they represent the Huka Falls mudstones and/or the Waiora aquifer, most probably the latter. These measurements imply a porosity of 31 percent and a grain density of 2.25 grams/cm^3 for the region.

More recently, Hendrickson[21] presented the results of an exhaustive suite of thermomechanical tests upon five core samples taken from various layers in the Wairakei field; one from the surface layer, one from the Huka formation, two from the Waiora, and one from the deep Ignimbrites. Hendrickson noted that the effective porosity of a rock sample may be determined if the dry and saturated densities are known, but that the true porosity may be higher if some of the pore-space is unconnected. He, therefore, pulverized some of the sample material to obtain a direct measure of grain density and hence total porosity. For the surface pumice, Huka Falls and Waiora formations, the porosities were in range 38 percent - 49 percent. For the ignimbrite sample, porosity was about 18 percent. Permeability measurements were also conducted on the Huka Falls and Waiora samples, which yielded matrix permeabilities less than 0.1 millidarcy. In addition, Hendrickson reports measurements of thermal and elastic properties for the rock samples.[1,21]

SEISMIC MEASUREMENTS

Seismic velocity data at Wairakei are rather sparse. Penetration is handicapped by poor shooting conditions in the shallower loosely compacted pumice beds. The ignimbrites show a substantial variation in seismic velocity[8] reflecting the variation in degree of welding. Poorly welded ignimbrites cannot be distinguished seismically from alluvium or non-welded tuffs. Available velocity data,[8] when compared with laboratory measurements of seismic velocities performed by Hendrickson[21] show the laboratory values for P wave velocities to be higher than the in situ values; this difference is indicative of the presence of extensively fractured formations at Wairakei.

COMPOSITION OF THE GEOTHERMAL FLUIDS

Compared to many other geothermal fields elsewhere in the world, the water withdrawn from Wairakei is remarkably pure. Most of the information presented by Pritchett, et al.[1] is derived from the work of Wilson,[25] Ellis,[26] and Glover.[27] The total dissolved solids loading is about 4 × 10^{-3} by mass, consisting of primarily sodium and potassium chlorides with a smaller amount of silica and a few trace minerals. This mass loading is about one-eighth that of seawater. The incondensible gas molar traction in the steam component of the discharge (separated at one atmosphere) is about 6.4 × 10^{-4}. About 90 percent of this gas is CO_2 with the bulk of the remainder being H_2S. For reservoir engineering purposes, therefore, the Wairakei fluids may be adequately treated as pure H_2O.

TEMPERATURE MEASUREMENTS

Grange[19] presented a description of the thermal activity in New Zealand as part of a general geological survey. However, it was not until the 1950's when the development of Wairakei commenced that a somewhat regular observation of temperature in boreholes was undertaken. As Banwell[24] comments, the temperature measured in boreholes cannot always be considered as an accurate reflection of the true ground temperature. This is because of convective currents which may be occurring in the borehole and because of the lack of equilibration time between drilling operations which cool the formation and some of the temperature runs which were made. However, once drilling operations have ceased, a longer standing or equilibration time is possible so that the temperature run made in the hole may yield a somewhat reliable maximum temperature in the hole.

Banwell[24] believes that bore 9, near the center of the field, could be regarded as typical of a bore in the main production region. Temperature runs made prior to 1955 appear to show that the ground temperature was above the boiling point for hydrostatic pressure at depth. Grange believes that there was initially a supply of super-heated steam in the reservoir, however, he comments that it appeared to be limited.

In 1958, temperatures measured in 25 boreholes from 1500 feet to 4000 feet deep were used to map a series of horizontal temperature profiles extending from sea level to 1640 feet below sea level. These maps are presented in the report.[1] According to Banwell these isotherms show a complex convective pattern in the western area of the field. There are cold recharge channels at several different levels with hot recharge occurring primarily at the surface of the ignimbrite formation with movement from a hot water source in the west.

As Grindley[2] comments, many fluctuations occur in the data due to geothermograph errors. The authors wish to reiterate that all reported temperature information should be used with great caution. Inasmuch as the data were recorded in cased holes, it is difficult to accurately determine the relation between the measured values and the true ground temperatures. However, the authors would feel remiss if they did not record the data available to them.

Bolton[28] points out that, over the years, temperature in the upper layers of the Waiora formation have declined, whereas at sufficiently great depth temperatures have remained essentially unchanged over the production history. In Fig. 7, average maximum temperatures in the shallow regime for wells in the production area at the beginning of 1963, 1964, 1965, 1966, 1967 and 1969 are plotted as functions of the mean bore field pressure referred to a horizon 900 feet below sea level at the same times. These data were taken from Bolton.[28] As can be seen, the data can be fitted with a straight line with slope approximately equal to 11 psi/°C. Figure 8 shows the slope of the phase line as a function of temperature. That is, if P_s is the vapor pressure of water at a temperature T_s, then the quantity plotted in Fig. 8 is dP_s/dT_s in pounds per square inch per degree Centigrade. Note that dP_s/dT_s is equal to 11 psi/°C, which turns out to be about the maximum temperature in the reservoir. In other words, the temperature decline in the upper layer noted by Bolton may be explained as a consequence of water flashing to steam in the upper part of the reservoir, and the fact that deep temperatures have not changed is because at greater depth the fluid has not flashed, but is still all-liquid. Thus, it is not necessary to hypothesize cold-water recharge to explain the temperature drop.

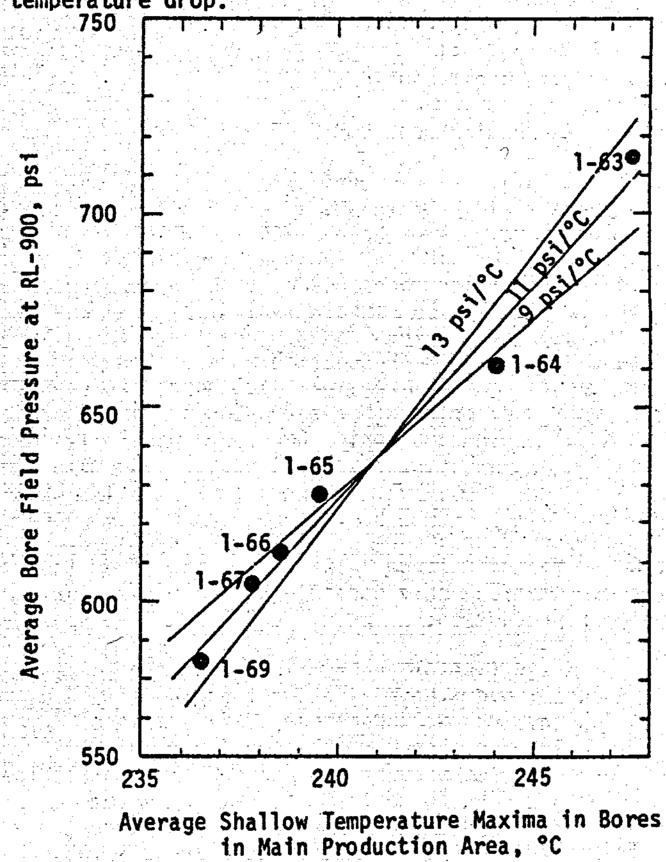


Figure 7. Average bore field pressure at RL-900 versus average maximum bore temperatures; temporal trend.

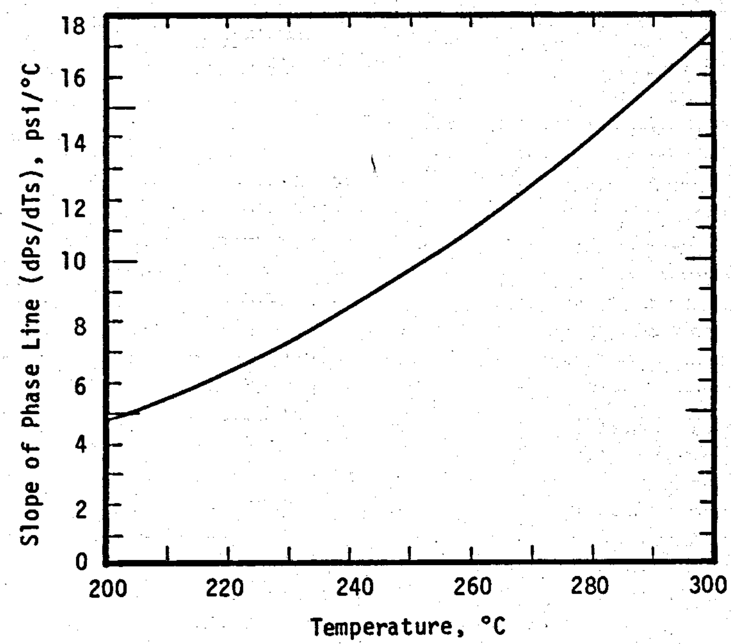


Figure 8. Slope of phase line versus temperature.

General trends in temperatures such as discussed above are probably meaningful. As Bolton[4,29] has pointed out, temperature maxima observed in wells after a long shut-in interval are probably representative of formation temperatures at the depth of the observed maxima. The detailed structure of the temperature profiles are much more questionable owing to the convective heat transfer within the shut-in wells as discussed previously. Data of this sort should be used with great caution.

MASS AND HEAT PRODUCTION

A total of 141 bores exist in the Wairakei/Tauhara field. Of these, 12 are shallow pressure-temperature monitor holes (26P and M1-M7 at Wairakei; THM1-THM4 at Tauhara) from which no fluid production takes place. Four deep bores are located in the Tauhara field (TH1-TH4) and little production has taken place there for reasons discussed in the section on pressure measurements. Of the remaining 125 bores, 26 consist of the "200 series" (bores 201-208, 209A, 210-224, 226-227). The 200 series bores are generally located to the north, south and west of the main bore field and were considered investigative bores when drilled, even though many of them are potentially good producers of high enthalpy fluid. Owing to their large relative distance from the power station, only bore 216 has been used for power production.

Sixty-five of the remaining 99 bores have produced, over their lifetime (herein defined as 1 January 1953 - 31 December 1976) a mass of fluid in excess of 5×10^9 pounds per well. These 65 bores account for about 95 percent of the total fluid produced from the entire system (Wairakei plus Tauhara plus 200 series bores). Thirty-four bores have produced over 30×10^9 pounds each, accounting for 73 percent of the total production, and seventeen bores have produced over 50×10^9 pounds each. These seventeen bores account for 45 percent of the fluid production for the system as a whole. To date, the most productive bore at Wairakei (in a mass sense) has been bore 30 (total production 81.213×10^9 pounds) followed closely by bore 27 (80.650×10^7 pounds).

Total mass production for the Wairakei/Tauhara system as of 31 December 1976 was 2329×10^9 pounds; the mean enthalpy of the discharged fluid was 481.64 BTU/pound. The total mass and energy production for each well are summarized in tabular form in Table 10.1 of Pritchett, et al.[1]

Drilling activity ceased at Wairakei in December 1968, with the completion of non-productive bore 121, which is also by far the deepest well in the area (7400 feet). The early bores were all fairly shallow and relatively unproductive. The most productive wells tend to be drilled to depths between 500 and 1000 feet below sea level. Under the main bore field, this level corresponds to the base of the Waiora formation, the andesite extrusion, and the top of the ignimbrite layer. Occasionally, a well drilled deeper into the ignimbrites will strike a fissure and prove productive, but generally speaking the vicinity of the Waiora/Ignimbrite contact has proven to be the best level for production. Accordingly, a large fraction of the bores were completed at this level. Based on the performance of the first six deep bores, three of which intercepted fissures, most production wells were deliberately sited in such a way as to intercept faults at the most productive horizon.[2]

Although the entire Wairakei/Tauhara field has now been extensively drilled, over 96 percent of the fluid production has come from the "main bore field"; a relatively small area of about one-half square miles centered about one and one-half miles WNW of the power station and extending approximately from 107,000W to 114,000W and from

312,500S to 316,500S with respect to the 1949 Maketu datum.

The production rate from the field as a whole has changed substantially over the years. Figure 9 shows that the rate of discharge increased to a peak in early 1964. Thereafter, with the decline and termination of drilling activity, the field pressure drop has resulted in a decline in total production of about four percent per year. The "partial shut-down" of early 1968 discussed elsewhere in the report can be clearly seen in the plot.

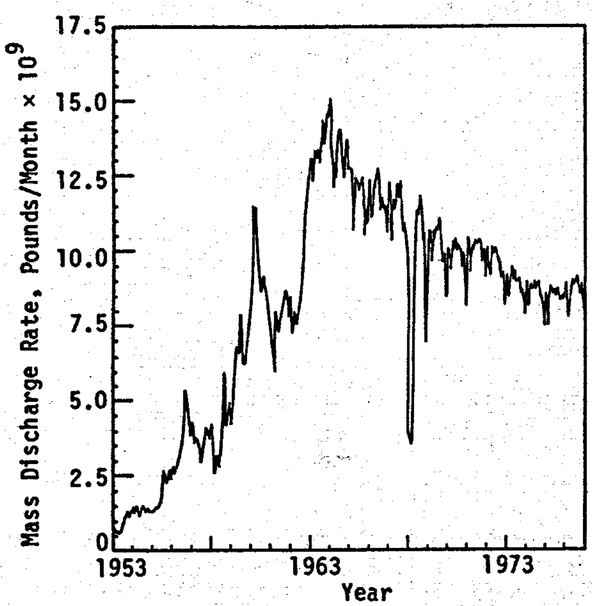


Figure 9. Mass discharge rate (all bores) as a function of time.

In Fig. 10, the trend of the average output enthalpy for all wells is displayed as a function of time. The raw data has considerable scatter, particularly during the early years when mass production rates were low. Note, however, the peak in early 1968 corresponding to the partial shut-down. This peak occurs because high enthalpy wells were preferentially maintained on production during this interval. The smoothed curve indicates a gradual increase in mean discharge enthalpy up to about 1965 followed by an equally gradual decrease. One interpretation of this trend is as follows. At early times, the steam (as opposed to liquid water) mass fraction entering the bores increased with time owing to the gradual increase in reservoir volume occupied by steam and the envelopment of the bores by a steam/water mixture. Later, however, steam and water continued to enter the bores but the drop in general reservoir pressure and temperature was accompanied by a drop in the specific enthalpy of both steam and water, resulting in a decline in mean enthalpy with time.

The overall variation of total enthalpy with time is not great; the same cannot be said, however, for the variation from bore to bore in lifetime average enthalpy. As mentioned earlier, the average discharge enthalpy for all fluid withdrawal from the system is 481.64 BTU per pound. The 200 series bores appear to be preferentially located in regions of relatively high steam quality; for those bores alone, located to the northwest, west and southwest of the main bore field, the mean lifetime discharge enthalpy is 629.20 BTU per pound. It is unfortunate that the distance to the power plant precluded more production from this area.

During the course of the drilling program at Wairakei, three mishaps occurred resulting in uncontrolled discharges from wells. Bore 201, located about a mile west-northwest of the main bore field, struck a fissure at RL+501 feet resulting in a loss of circulation and hence a loss of pressure during drilling in May 1958. The resulting flow was able to penetrate into permeable surface breccias and erupt from the surface along the line of the fault a short distance from the drilling rig. The flow shut itself off in short order and little discharge occurred.

In April 1960, an eruption of water and steam on a hillside began near bore 50 within the main bore field. For some time, it was believed that bore 50 was responsible for the discharge, but in fact the eruption was caused by a casing break at about 600 foot depth in bore 26 which had been producing fluid normally since 1954. The casing break permitted fluid to escape upward due to flaws in the cementing around the hole into the permeable layers above, and then to the surface. This activity persisted for several months, generating a mudslide which buried the bore 26 wellhead. Bore 26A was successfully deviation-drilled into the hole below the break, relieving pressure and bringing the discharge to a stop in November 1960. Bore 26 was then cemented up. The total mass and heat discharge rates were estimated as 1.7×10^8 pounds per month and 1.6×10^{11} BTU per month, respectively, for April 1960 through November 1960, yielding an average discharge enthalpy of 941 BTU/pound and a total uncontrolled discharge of 1.36×10^9 pounds.

By far the most spectacular and significant eruption to take place at Wairakei was that of bore 204, often called the "Rogue Bore". Thompson[30] has summarized the history of bore 204 which is sited approximately one mile southwest of the main bore field near the Wairakei fault. Drilling began in February 1969. After considerable trouble with circulation losses which probably resulted in a poorly cemented upper casing, in early May the drill-bit penetrated a cavity at a depth of 1224 feet and dropped five feet. The hole came under pressure and a violent eruption of dry steam, mud and rocks commenced. Within a few days, a crater 50 feet in diameter and 100 feet deep had been created, with the discharge emerging from the stub of the casing at the bottom. The eruption of steam continued for several months.

In October, the discharge abruptly became substantially wetter, and in a few days filled the cavity with water. Within a short time, the phenomenology had changed completely to periodic geysering within the water-filled crater, pronounced ground vibrations and occasional overflow

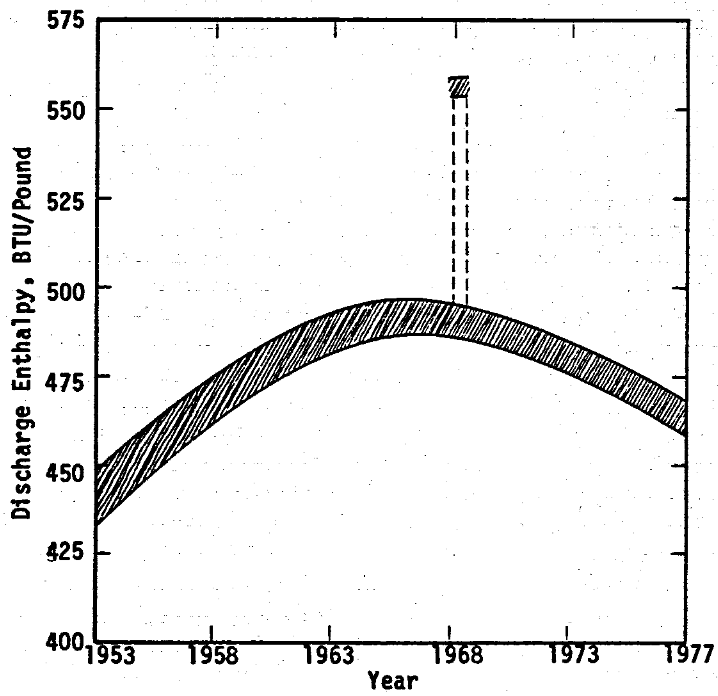


Figure 10. Trend in total field discharge enthalpy (all bores).

of the water in the crater. This general state of affairs persisted for many years with varying intensity until 1973 when between August and November activity slowly declined, water levels dropped in the crater and the whole system cooled down. By early 1974, the crater was entirely dry and activity had utterly ceased. From 1968 until late 1973, the "Rogue Bore" became a popular tourist attraction owing to the ground vibration and visual spectacle produced by the discharge.

Once again, no direct measures of enthalpy or discharge rates are available for bore 204. Estimates of the discharge enthalpy and flow rates for the period of uncontrolled discharge have been based on values discussed by Thompson[30] and Banwell[31] and on the discharge enthalpy of other wells in the area. The total discharge is estimated at 8.1×10^9 pounds with a mean discharge enthalpy of 500 BTU/pound.

Aside from the estimates for uncontrolled discharge listed above, the well-by-well monthly mass and heat production data stored on the magnetic tape were taken directly from data banks maintained by the Ministry of Works in New Zealand. This data was obtained in three different forms. Monthly mass and heat production totals for each well were at one time kept on a data file manipulated by programs written for an IBM model 650 computer. The punched card decks containing this data have long since been lost and the IBM 650 itself now resides as an inert exhibit at the Museum of Transport and Technology in Auckland. Microfilm copies of output listings of the monthly totals from January 1953 through December 1962 were, however, retained and were the source of data for the present compilation up to that date. Production prior to 1953 was very slight: total field production for 1952 was approximately one-third that for 1953 (which was itself very small) and in earlier years even less.

From January 1963 through December 1966, hand written logs were maintained, once again, of monthly total mass and heat production for each well. Finally, starting in January 1967, a new computerized system was implemented which recorded, among other things, weekly mass and heat production figures for each well. A magnetic tape containing this information was kindly supplied by R. S. Bolton of the Ministry of Works for this study. Thus, a complete record of monthly mass and heat production figures for each well from January 1953 through December 1976 was compiled.

PRESSURE MEASUREMENTS

Extensive measurements of pressures have been carried out in the main Wairakei bore field as well as in surrounding holes over the years. Bolton[4,28] provides an excellent summary of the bore field pressure data and that for some of the peripheral bores, particularly as they relate to the discharge history, for the interval 1953 through 1968. Bolton[28] also presents substantial detail concerning the pressure response to the partial shut-down of early 1968. Grant[33,34] discusses pressure response in the Tauhara field and performed an analysis suggesting substantial hydraulic connection between Wairakei and Tauhara. In this section, this work is summarized and extended as necessary to include the most recent available pressure data. Substantial amounts of pressure data are also included in the bore-by-bore data summaries contained on the magnetic tape. For a more detailed treatment, see Pritchett, et al.[1]

Borehole pressures at Wairakei were generally determined in one of two ways. In the early days, no direct measurements of pressure were made. Frequently, however, temperature profiles were measured in shut-in wells. The applicability of this data as concerns true formation temperatures is somewhat questionable (as discussed elsewhere) but, if the water level in the well is known, it is possible to calculate a density profile from the temperature profile in the well. Then, by assuming hydrostatic equilibrium, the pressure-depth curve within the bore may be determined.

Beginning about 1959, an Amerada Bourdon-tube type pressure gauge was acquired and by 1962 most pressure profiles in the bores were obtained by direct measurement. Bolton[29] estimates the accuracy of the earlier indirect determinations as ± 20 psi and of the direct measurements as ± 10 psi.

A summary of the pressure-depth profiles determined by either method for the entire history of the Wairakei field would be exceedingly cumbersome. The raw data and charts upon which such a summary need necessarily be based are contained in files occupying approximately fifteen linear feet of book shelf space at the Ministry of Works laboratory facility near the Wairakei site. Instead, Bolton and others have found it expedient to consider pressure data from each hole, at a particular time, referred to certain discrete imaginary horizontal planes within the reservoir. The two most popular choices are the RL-500 and RL-900 levels (500 feet and 900 feet below sea level, respectively). Since within the shut-in bores the pressure distribution is essentially hydrostatic, a single datum such as at one or another of these levels can then approximate the entire pressure profile at a particular point in time.

On the magnetic tape which is an essential part of the report, numerous such values of pressure at both RL-500 and RL-900 have been recorded as a function of time. Many wells have data at both levels. The RL-500 data extends from 1955 to 1976; RL-900 data is available only for the interval 1959 to 1967, plus some data for 1968.

As Bolton[4] and others have pointed out, the pressure response of the main bore field to fluid withdrawal has been remarkably uniform across the entire area, suggesting a high degree of horizontal communication and thus a high permeability for the Waiora aquifer. The pressure data for RL-500 for all data on the tape is given in Fig. 11 and for RL-900 in Fig. 12 as a function of time. Note the similarity in the two sets of data. This same information is presented somewhat differently in Fig. 13, which illustrates the pressure drop as a function of total cumulative discharge. It can be seen that there is little difference between the RL-500 and RL-900 data, except for a shift in scale due to the greater hydrostatic head at RL-900. Actually, there is a slight areal dependence of pressure. Bolton[4] indicates that pressures are somewhat lower in the eastern portion of the bore field than elsewhere, but that the difference between the two areas is not large in comparison with the overall drawdown. A general pressure increase exists from east to west across the field. This tends to confirm the conclusions drawn from magnetic evidence that the general flow in the system prior to production was from west to east.

Three distinct regions in the pressure history of the bore field can be discerned (see Figs. 11 and 12). Pritchett, et al.,[21] using a numerical two-phase two-dimensional vertical section reservoir simulation has attempted to explain the behavior as follows. During the early years (prior to 1958 or so), boiling begins below the Huka mudstones and a steam cap forms near the top of the Waiora aquifer - this process maintains nearly-constant pressures at early times at the deeper production horizons. Later (1959-1963), the two-phase region begins to invade the production horizon, and pressures drop rapidly due to fluid mobility inhibition owing to the relative permeability effect. Still later (post 1965) the entire Waiora aquifer below the main production area begins to boil; the drawdown curve begins to flatten since vaporization around the wells provides pressure support for the system as a whole. Also, as discussed elsewhere, gravity measurements suggest a substantial increase in recharge rate in this latter period, which would provide additional pressure support. At present, pressures in the aquifer are declining only very slowly even though fluid withdrawal rates remain quite high. Figure 13 also supports this general overall hypothesis. As time goes on, the slope of the drawdown-discharge curve decreases, due both to increasing recharge and to a gradual increase in overall fluid compressibility as more and more liquid water in the formation flashes to steam.

The relevance of Fig. 13 to the character of the reservoir response (i.e., single-phase versus two-phase flow) may be shown in the following way. Let us tentatively assume that the pore space in the reservoir is filled entirely with compressed liquid water at an average temperature of 250°C. We will take the average thickness of the Waiora aquifer as 1300 feet, and assume that the effective "area" of the reservoir is 15 km^2, as estimated by Grindley.[2] We further assume that the porosity is 35 percent, and that (according to gravity change evidence) the recharge rate was about one-half the production rate in the early years (pre-1964). It may be shown that the average drawdown versus withdrawal curve will be given approximately by:

$$\frac{dP}{dM_p} = -B\left(\frac{\dot{M}_p - \dot{M}_R}{\dot{M}_p}\right) / (\phi HA)$$

where

P = pressure

M_p = cumulative mass produced

$\dot{M}_p$ = production rate

$\dot{M}_R$ = recharge rate

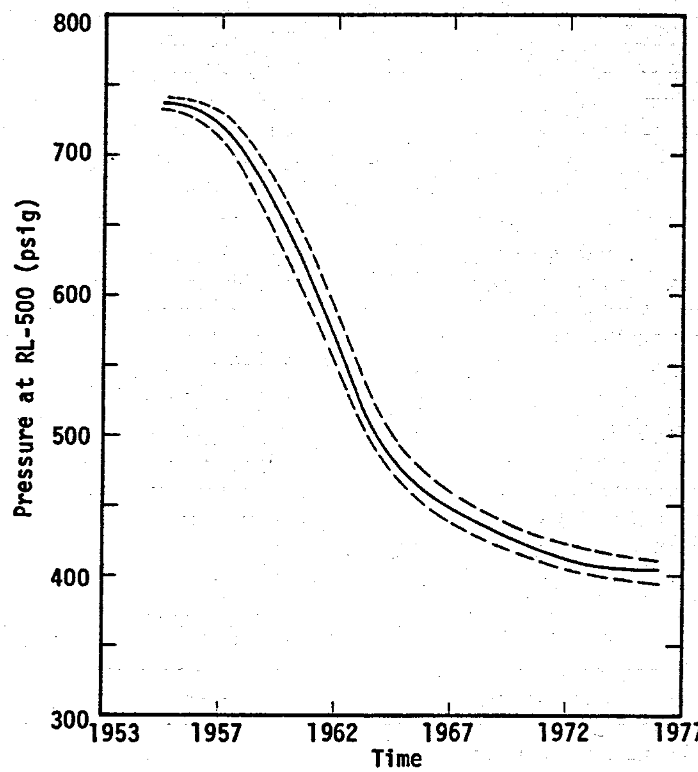


Figure 11. Pressure measurements at RL-500 as a function of time for bores following the trend of the main bore field.

ϕ = porosity

H = aquifer thickness

A = reservoir area

B = $(\partial P/\partial \rho)_{T=const}$; available from steam tables.

Using the values listed above and assuming that, for compressed liquid water at 250°C, B = 8.93×10^5 m^2/sec^2, we obtain

$$\frac{dP}{dM_p} \approx -14{,}000 \text{ psi}/10^{12} \text{ pound}.$$

Figure 13 indicates a much smaller value; about -300 psi/10^{12} pound at early times, and even smaller later. That is, the actual response of the reservoir is much more compressible than it would be were it single phase, by a factor of order 50. This appears to be conclusive evidence for two-phase (water/steam) flow throughout the Wairakei history.

In early 1968, a temporary surplus occurred in the New Zealand electrical power grid due to the commissioning of new equipment at the Marsden hydroelectric station. Advantage was taken of this circumstance to perform a "partial shut-down" of the Wairakei geothermal plant which began on December 21, 1967 and lasted 104 days; that is, to perform a "shut-in test" on a grand scale.[32] Although electrical output was reduced by about half, the total mass production rate was cut by a factor of three by retaining on-line only bores of unusually high enthalpy production. The response of the bore field to this perturbation was dramatic. Within a few weeks, pressures throughout the field began noticeably to increase - although the data is somewhat scattered, the pressure rise averaged about 11 psi by the end of the shut-down. Once the shut-down was over, pressures quickly dropped again to their pre-shut-down values. Bolton[29] and others (the authors included) feel that any adequate theoretical model of the transient behavior of the Wairakei field should be capable of reproducing the pressure-transient effects of the partial shut-down.

Bolton[4] presents a summary of the pressure data for other bores surrounding the main bore field in an attempt to establish the locations of hydrological boundaries for the field. For the subsequent discussion, reference should be made to Fig. 14, which shows (among other things) the spatial relationships among the various peripheral wells, the main bore field, and the "resistivity boundary" of the Wairakei/Tauhara field. For the purpose of this figure, the resistivity boundary

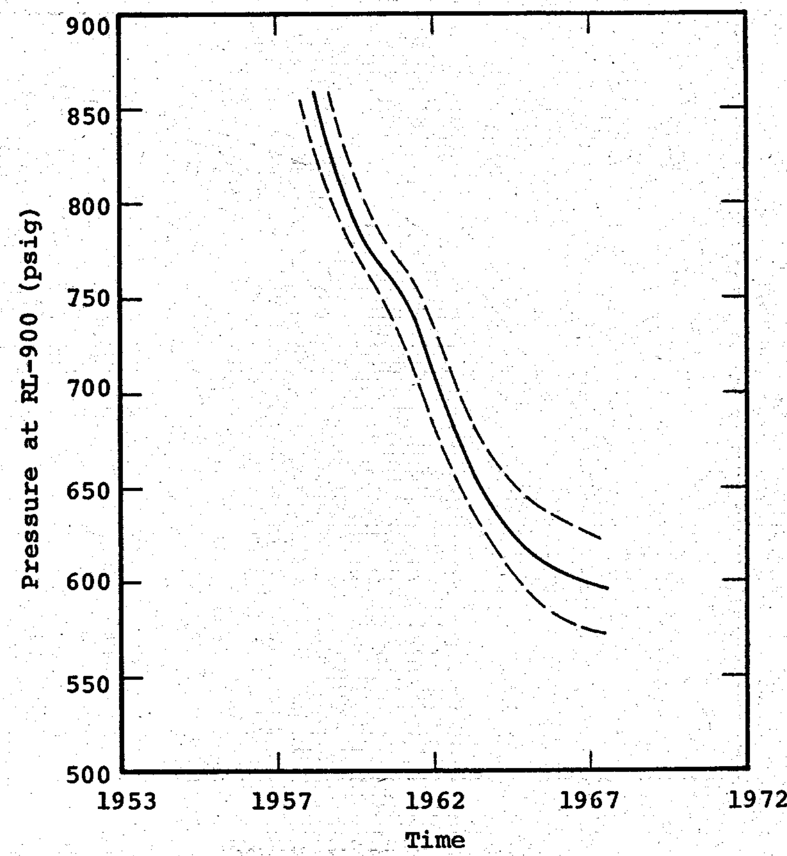


Figure 12. Pressure measurements at RL-900 as a function of time for bores following the trend of the main bore field.

is taken as the region between the 10 and 20 ohm-meter contours.

Bore 36 is located to the southeast of the main bore field near the power station between the 10 and 20 ohm-meter resistivity contours. It produces fluid of only moderate temperature and has consequently never been used for power generation. Prior to 1959, pressures in bore 36 followed those in the main bore field. Thereafter, however, when the main bore field pressure began to drop rapidly, the rate of pressure decline in bore 36 remained much the same as before. The disparity in pressures between the bore field and bore 36 has been increasing ever since.

Bore 33, located to the northeast of the main bore field just outside the resistivity boundary appears to have little if any connection to the field.

Bores 219, 206 and 222 represent the northern limit of drilling and lie to the northwest of the bore field. All are high-temperature bores with maximum temperatures exceeding 250°C. Pressure histories for all three bores follow the trends of the main bore field. Thus, the northwest boundary of the field has not been established by drilling.

Bore 224 is the westernmost hole drilled at Wairakei, and is cold (T_{max} = 82°C). It is well beyond the 20 ohm-meter contour as well. Pressures in bore 224 are, however, influenced to some extent by fluid production from the bore field.

Bore 223 is located west-southwest of the bore field, well beyond the resistivity boundary. It is also a cold well but, somewhat surprisingly, the pressures in bore 223 follow the main bore field very closely. Bolton[4] speculates that the bore is fault-connected to the main bore field, and that the low temperatures are due to a local down-flow of cold water which meets an up-flow of hot water from below at a depth below the bottom of the hole; the mixed fluid then flows toward the bore field through the fault system at a deep level.

Bores 221, 212, 214, 210, 220 and 205 are located somewhat closer to the bore field along the resistivity boundary, between bore 223 and the main bore field. Temperatures in bores 214 and 220 are somewhat lower than the main field; the other four wells are quite hot ($\geq$ 250°C). None of the six have been produced extensively; pressures in all six follow the main bore field very closely.

Bore 208 (to the south-southwest of the bore field) and bore 226 (due south) are both

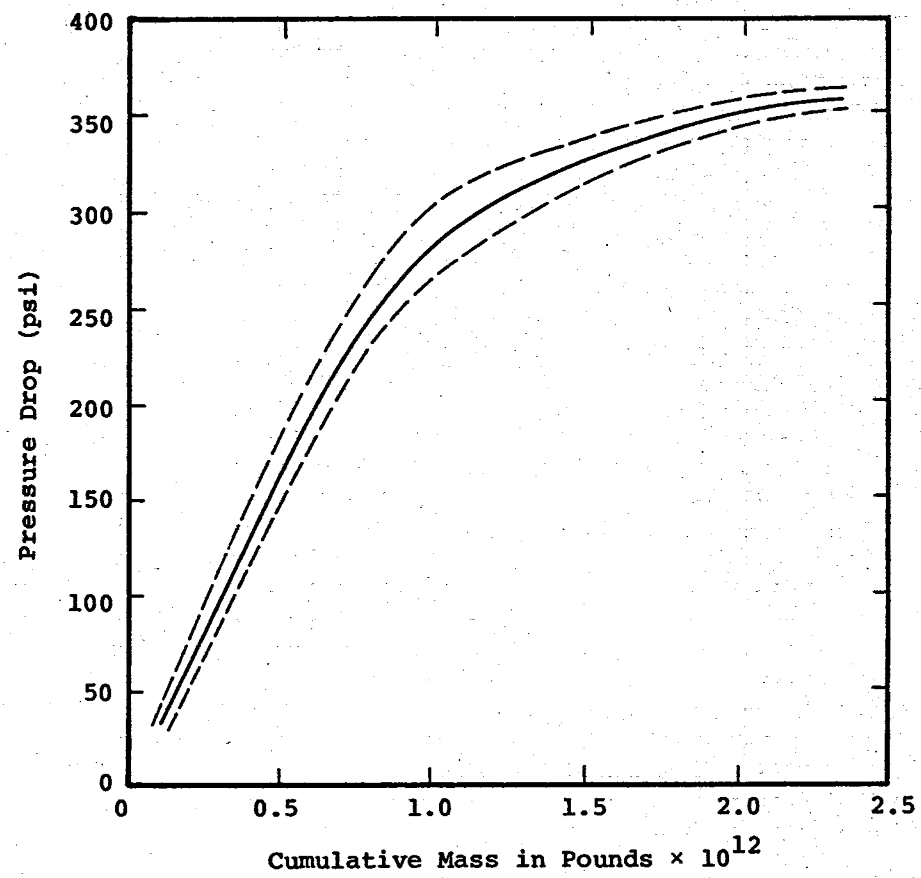
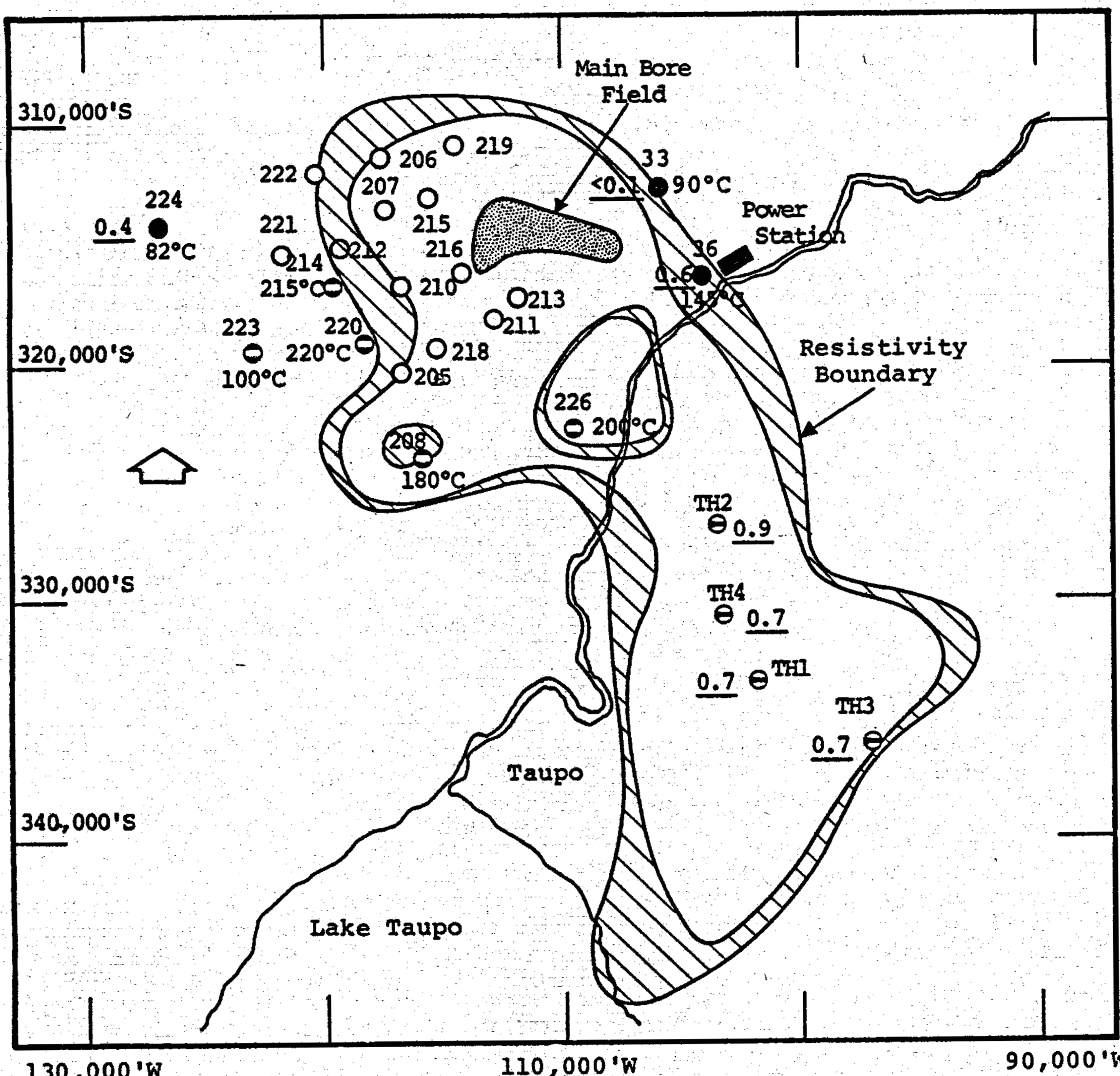


Figure 13. Main bore field pressure drop as a function of cumulative produced fluid mass. Plot includes RL-500 and RL-900 data.

somewhat cooler than the major production bores, and neither has been produced for power. Both lie within "islands" of higher resistivity within the general resistivity low. Pressures in both holes follow main bore field trends. Thus, as in the case to the north, the southern boundary of the field has not been established by drillhole pressure evidence.

The bores in the Tauhara field were drilled late in the history of the Wairakei development program - the first (TH1 - originally designated bore 225) was completed in June 1964. It had originally been thought that the Tauhara field was a separate resource, but it soon became apparent that the drawdown from Wairakei was influencing Tauhara. It was, therefore, feared that power production from Tauhara would cause premature depletion of Wairakei. Consequently, only eight holes were drilled at Tauhara of which four were shallow monitor bores. Total fluid production from Tauhara has been about 5.9×10^9 pounds, of which 95 percent was from bore TH1; Tauhara production as a whole amounts to about 0.25 percent of the total for the system.

Since production had been taking place at Wairakei for more than a decade before the completion of bore TH1, no direct measures of early pressures are available for the Tauhara bores. Grant[33] has estimated the initial gauge pressures in the four deep Tauhara bores at various levels as if the bores were located at the center of the main Wairakei bore field with the same wellhead heights. He concluded that substantial pressure reductions had taken place at Tauhara prior to the time the bores were drilled. The greatest pressure reduction is believed to have taken place in bore TH2; approximately 240 psi at the time of completion in May 1966. At this same time, the pressure drop in the main bore field was about 270-280 psi. Drawdowns in the other three bores are less, owing to their greater distance from the main production area. There can be little doubt that the two reservoirs are connected, probably by a thin neck between bores 226 and TH2. Indeed, the pressure drop at Tauhara has caused some concern in the nearby town of Taupo, where surface manifestations such as increases in regions of steaming ground have been noted in recent years. It seems clear that, in modeling the behavior of the Wairakei field, it is essential to consider Wairakei and Tauhara as two parts of a single, larger geothermal field.



25 ○	Location and numbers of bores with maximum temperature > 225°C and with pressure histories matching main bore field.
36 0.6 ● 145°C	Bore with maximum temperature < 225°C (i.e., 145°C) and with total pressure drop only a fraction (i.e., 0.6) of that of the main bore field as of mid-1968.
223 ⊖ 100°C	Bore with low maximum temperature whose pressure history follows main bore field.
TH2 0.9 ⊖	Bore with maximum temperature > 225°C with less pressure drop than main bore field.

Figure 14. Pressure and temperature distribution surrounding the main bore field.

GRAVITY MEASUREMENTS

Gravity surveys of the Wairakei/Tauhara vicinity were carried out in 1950[35] and in 1961, 1967, 1968, 1971 and 1974.[36,37] Hunt[38] indicates that the changes between successive gravity surveys must be due principally to vertical motion of the ground surface (subsidence) and to net mass changes in the field.

Hunt[37] noted that even though comparable quantities of water were withdrawn from the field in the intervals 1961-1967 and 1967-1974, the gravity changes in the earlier interval (corrected for subsidence effects) were substantially greater than the later changes. He, therefore, concluded that the rate of recharge increased between the earlier and later intervals. Using data from Benchmark A97, located near the eastern edge of the bore field and adjacent to the region of maximum subsidence, Hunt then qualitatively estimated the cumulative mass balance as a function of time for Wairakei, as shown in Fig. 15.

SUBSIDENCE AND SURFACE DEFORMATION

Ground subsidence at Wairakei was first measured in 1956 when benchmark levels were compared with those established in 1950.[39] A subsidence network was then established, first on the steam main supports and then outward in the field. Periodic measurements have indicated that the area affected by subsidence exceeds 11.5 square miles.[40] It is noteworthy that the area of maximum subsidence lies outside the main production region. Maximum subsidence at Wairakei is of the order of 15 feet; this has been accompanied by horizontal movements of the order of 1.5 feet.[41]

A benchmark (A93) situated about 3 miles northeast of Wairakei has been arbitrarily chosen as datum for precise leveling. Indications are that any subsidence that may be occurring at this point is likely to be small. Local subsidence in the bore field is measured relative to benchmark TH7 located in the power house. The power house is not completely outside the zone of subsidence; it is, however, believed to be sufficiently so for local subsidence checks.

A horizontal control network was set up in 1966 and repeated in 1968, 1969, 1972 and 1973. The last horizontal survey was done in 1977.[42]

Periodic surveys of benchmarks have indicated that the area affected by subsidence (> 10 mm/year) exceeds 11.5 square miles (Fig. 16). Within this area are two zones each of about 0.4 square miles which have subsided comparatively rapidly. The zone at Karapiti - an area of natural thermal activity about 2 miles south of the production field - was the most rapidly subsiding part of the survey network until about 1963, when the subsidence rate decreased to the same rate as for the surrounding ground surface.[40]

Around 1960 the subsidence rate of benchmark A97 began to increase and over the next several years the zone of rapid subsidence immediately north of the eastern production field (Fig. 16) was delineated. Subsidence at BM A97 is shown in Fig. 17. This region of subsidence is of substantial economic interest as both the steam mains and waste water canals from the production field cross this area. Benchmarks in this region, as noted elsewhere, are surveyed annually.

The last comprehensive survey of benchmarks was conducted in 1971. The subsidence history at several selected benchmarks is presented in the report.[1] Figure 18 shows the average subsidence rate in the Wairakei production field (relative to benchmark TH7 in the power house) for the period 1964-1974.

The horizontal movement vectors at Wairakei for the period 1966-1974 show that vector movement is towards the center of subsidence. Annual horizontal movement between 1968 and 1977 was between 4.3 inches/year at a radius of 800 feet from the center of subsidence decreasing to about 0.6 inches/year at 2500 feet radius.

DATA COMPILED ONTO MAGNETIC TAPE

A primary product of the project is a magnetic tape which contains a summary of well-by-well information for the bores at Wairakei and Tauhara. This compilation of data includes information such as locations, completion dates, geologic horizons

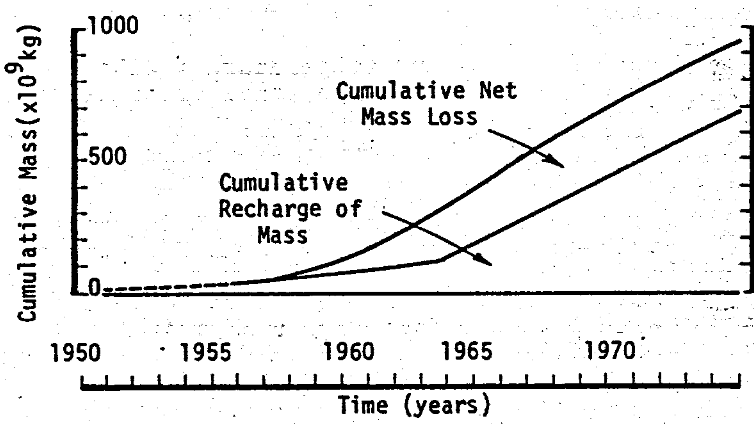


Figure 15. Cumulative recharge and cumulative net mass loss, estimated from corrected gravity differences at benchmark A97, Wairakei Geothermal Field.[37]

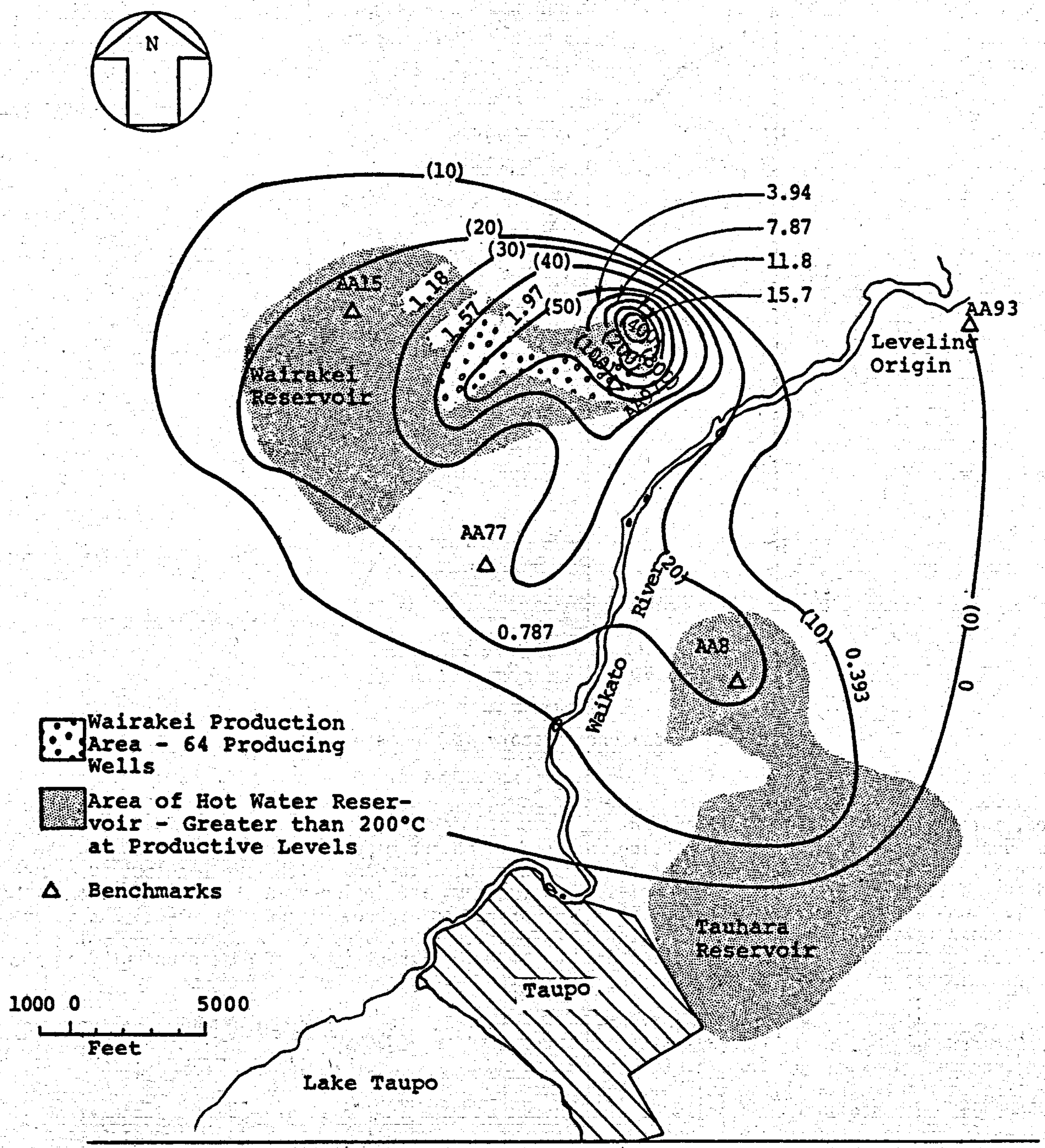


Figure 16. Average land subsidence rates, 1956-1971. Contours of equal subsidence in inches per year. Values in parenthesis are millimeters per year.

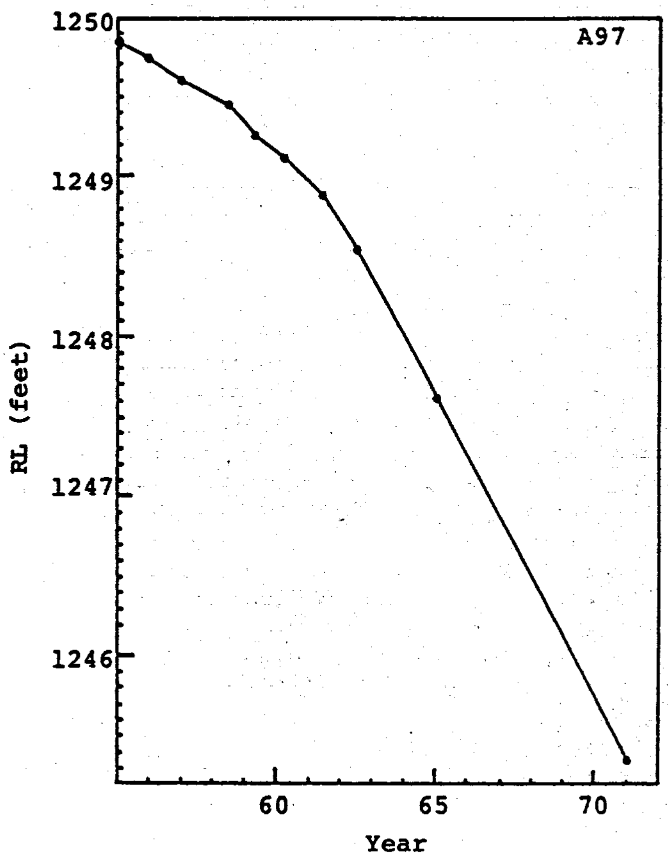


Figure 17. Subsidence history at benchmark A97.

penetrated, intervals open to flow, perforated intervals, depths where major faults and casing breaks were detected, general comments about the well, and the mass and heat production histories. Additionally, some pressure data is recorded at different reduced levels (i.e., elevations with respect to sea level) which give an indication of the pressure response of the field to discharge.

This body of data has been accumulated from various sources. Much of the well information other than the mass, heat and pressure histories has been garnered from well drilling charts. The geologic horizons encountered in the wells have been obtained from examination of well logs and information contained in Grindley.[2]

The mass and heat production histories for each well have been constructed from several sources. Data from January 1953 to December 1962 were from microfilm copies of the output of an old IBM 650 computer program. This data was all keypunched onto IBM cards for incorporation into the final tape. Data from January 1963 to December 1966 were all originally presented in tabular form. Again this data was keypunched and incorporated into the data base. Data from January 1967 to December 1976 were available on an IBM tape which was converted to be compatible with the Systems, Science and Software Univac 1108 system. This data required some editing before it was added to the final tape. The sources of the pressure data have been discussed elsewhere in the report and will not be repeated here.

Two computer programs are used to access the data on the magnetic tape. Copies of programs LIST and EDIT, together with sample output from each program, are included in the report. Program LIST prints out a copy of the data exactly as it appears on the magnetic tape. Program EDIT provides three different types of edited output from the tape. They are:

1. The summary of information for each well in a list of wells, where the list consists of data input to EDIT.

2. The total of the mass and heat production for a specified list(s) of wells, where each list consists of data input to EDIT.

3. The total of the mass and heat production for all wells in a specified region(s) of the field, where the regions are defined as rectangles bounded by grid lines with respect to the 1949 Maketu Datum.

A complete description of the information on the magnetic tape and a discussion of programs LIST and EDIT are contained in Pritchett, *et al.*[1]

ACKNOWLEDGMENTS

This data compilation could not have been carried out without the interest and cooperation of a number of people. In the United States, the

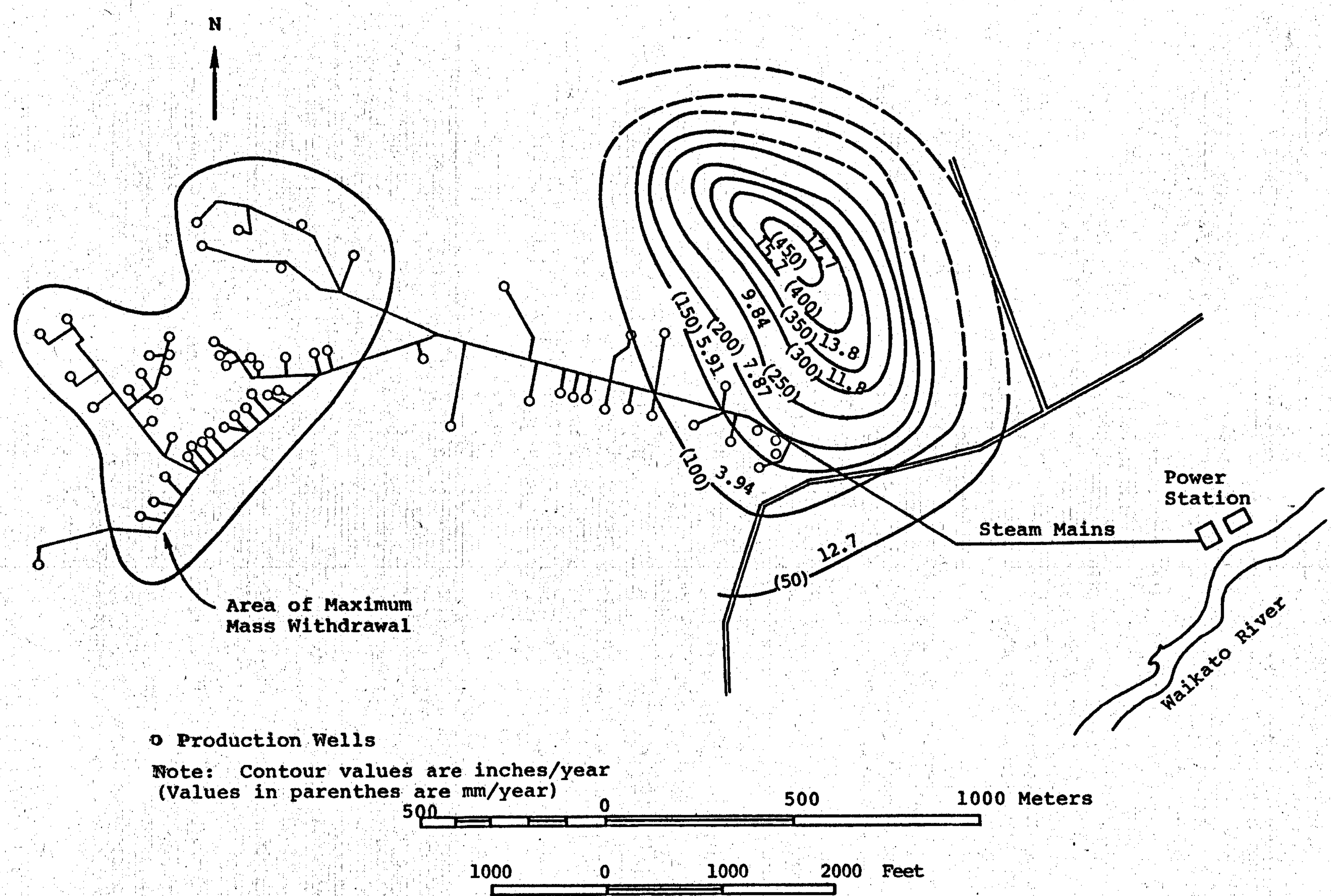


Figure 18. Subsidence rate in Wairakei production field 1964-1974.[41]

authors wish to thank Jim Mercer of the U. S. Geological Survey for sharing with us the voluminous collection of data which he compiled several years ago. The authors also wish to thank Jack Howard and Werner Schwarz of Lawrence Berkeley Laboratory which funded this project through the Division of Geothermal Energy of the U. S. Department of Energy. In New Zealand, the cordial hospitality and willingness to spend valuable time helping with this work on the part of many people at both DSIR (Department of Scientific and Industrial Research) and MOW (Ministry of Works) were somewhat overwhelming to Pritchett during his data-gathering expedition there. Particular thanks are extended to Frank Studt, George Grindley, Pat Browne and Trevor Hunt of DSIR and Dick Bolton, Ian Innes, Basil Stilwell and Paul Bixley of MOW. Above all, the extended technical interchange (and week-long chauffeur-service) provided by Ian Donaldson of DSIR is gratefully acknowledged.

REFERENCES

1. Pritchett, J. W., L. F. Rice and S. K. Garg, "Reservoir Engineering Data: Wairakei Geothermal Field, New Zealand," Systems, Science and Software Report, SSS-R-78-3591, March 1978.

2. Grindley, G. W., "The Geology, Structure and Exploitation of the Wairakei Geothermal Field, Taupo, New Zealand," DSIR Bulletin n.s. 75, 1965.

3. Healy, J., "Geology of the Wairakei Geothermal Field," Proceedings Eighth Commonwealth Mining and Metallurgical Congress, Australia and New Zealand, New Zealand Section, 1965.

4. Bolton, R. S., "The Behavior of the Wairakei Geothermal Field During Exploitation," Proceedings U.N. Symposium on the Development and Utilization of Geothermal Resources, Pisa, Geothermics, Special Issue 2, pp. 1426-1449, 1970.

5. Dawson, G. B. and D. J. Dickinson, "Heat Flow Studies in Thermal Areas of the North Island of New Zealand," Proceedings U.N. Symposium on the Development and Utilization of Geothermal Resources, Pisa, Geothermics, Special Issue 2, pp. 466-474, 1970.

6. DSIR -- No author listed, "Results of Geothermal Investigations -- Wairakei-Taupo Area," Department of Scientific and Industrial Research Report dated September, 1951.

7. Cullington, A. L., "The Geothermal Field in New Zealand at Epoch 1950.5," DSIR Memorandum 2, 1954.

8. Modriniak, N. and F. E. Studt, "Geological Structure and Volcanism in the Taupo-Tarawera District," N.Z.J. Geol. Geophys., 2, pp. 654-684, 1959.

9. Banwell, C. J., E. R. Cooper, G. E. K. Thompson and K. J. McCree, Physics of the New Zealand Thermal Area, DSIR Bulletin 123, 1957.

10. Ellis, A. J. and S. H. Wilson, "The Heat from the Wairakei-Taupo Thermal Region Calculated from the Chloride Output," N.Z.J. Sci. Tech., B36, pp. 622-631, 1955.

11. Grange, L. I. (Compiler), Geothermal Steam for Power in New Zealand, DSIR Bulletin 117, 1955.

12. Healy, J., "Preliminary Account of Hydrothermal Conditions at Wairakei, New Zealand," Proceedings Eighth Pac. Sci. Cong., pp. 214-217, 1956.

13. Gregg, D. R., "Natural Heat Flow from the Thermal Areas of the Taupo Sheet District," N.Z.J. Geol. Geophys., 1, pp. 65-75, 1958.

14. Benseman, R. F., "Estimating the Total Heat Output of Natural Thermal Regions," J. Geophys. Res., 64, pp. 1057-1062, 1959.

15. Thompson, G. E. K., C. J. Banwell, G. B. Dawson and D. J. Dickinson, "Prospecting of Hydrothermal Areas by Surface Thermal Surveys," Proceedings U.N. Conference on New Sources of Energy, Paper 35/G/54, 1961.

16. Fisher, R. G., "Geothermal Heat Flow at Wairakei During 1958, N.Z.J. Geol. Geophys., 7, pp. 172-184, 1964.

17. Grindley, G. W., "Wairakei, Tauhara Geothermal Fields," Part D, Sections 3.20 and 3.21, Minerals of New Zealand, NZGS Report 38, 1974.

18. Dawson, G. B. and R. G. Fisher, "Duirnal and Seasonal Ground Temperature Variations at Wairakei," N.Z.J. Geol. Geophys., 7, pp. 144-154, 1964.

19. Grange, L. I., The Geology of the Rotorua-Taupo Subdivision, Rotorua and Kaimanawa Divisions, DSIR Bulletin 37, 1937.

20. Grindley, G. W., D. W. Rishworth and W. A. Watters, "Geology of the Tauhara Geothermal Field, Lake Taupo," DSIR Geological Survey Geothermal Report No. 4, 1966.

21. Pritchett, J. W., S. K. Garg, D. H. Brownell, Jr., L. F. Rice, M. H. Rice, T. D. Riney and R. R. Hendrickson, "Geohydrological Environmental Effects of Geothermal Power Production -- Phase IIA," Systems, Science and Software, Report SSS-R-77-2998, 1976.

22. Grindley, G. W., Private Communication to J. W. Pritchett, 1977.

23. Mercer, J. W., G. F. Pinder and I. G. Donaldson, "A Galerkin Finite-Element Analysis of the Hydrothermal System at Wairakei, New Zealand," J. Geophys. Res., 80, pp. 2608-2621, 1975.

24. Banwell, C. J., "Physical Investigations," in Geothermal Steam for Power in New Zealand (L. I. Grange, Compiler), DSIR Bulletin 117, 1955.

25. Wilson, S. H., "Chemical Investigations," in Geothermal Steam for Power in New Zealand (L. I Grange, Compiler), DSIR Bulletin 117, 1955.

26. Ellis, A. J., "Quantitative Interpretation of Chemical Characteristics of Hydrothermal Systems," Proceedings U.N. Symposium on the Development and Utilization of Geothermal Resources, Pisa, Geothermics, Special Issue 2, pp. 516-528, 1970.

27. Glover, R. B., "Interpretation of Gas Compositions from the Wairakei Field over 10 Years," Proceedings U.N. Symposium on the Development and Utilization of Geothermal Resources, Pisa, Geothermics, Special Issue 2, pp. 1355-1366, 1970.

28. Bolton, R. S., "Management of a Geothermal Field," in Geothermal Energy (Earth Sciences, 12), UNESCO, 1973.

29. Bolton, R. S., Private Communication to J. W. Pritchett, 1977.

30. Thompson, G. E. K., "Birth and Death of 'The Rogue'; A History of Drillhole 204, Wairakei," DSIR Geophysics Div. Report No. 117, 1976.

31. Banwell, C. J., "Data from Prospecting Bore No. 204, Wairakei," DSIR Geothermal Circular C.J.B. 29, 1960.

32. Bolton, R. S., "Wairakei Geothermal Power Project: Report on the Partial Shut Down of the Field, 21 December 1967 to 2 April 1968," MOW Report 92/14/20/2, 1969.

33. Grant, M. A., "Pressure Response: TH1, TH2, TH3, TH4," DSIR Appl. Maths. Div. Internal Memorandum dated 13 September 1977.

34. Grant, M. A., "Two-Phase Linear Geothermal Pressure Transients - A Comparison with Single-Phase Transients," Soc. of Petroleum Engineers Paper SPE 6972, 1977.

35. Robertson, E. I., "Gravity Survey of the Wairakei-Taupo Area," DSIR Geophysics Div., unpublished report, 1951.

36. Hunt, T. M., "Gravity Changes at Wairakei Geothermal Field, New Zealand," Geol. Soc. of America Bulletin 81, pp. 529-536, 1970.

37. Hunt, T. M., "Recharge of Water in Wairakei Geothermal Field Determined from Repeat Gravity Measurements," N.Z.J. Geol. Geophys., 20, pp. 303-317, 1977.

38. Hunt, T. M., "Repeat Gravity Measurements at Wairakei, 1961-1974," DSIR Geophysics Div. Report No. 111, 1975.

39. Hatton, J. W., "Ground Subsidence of a Geothermal Field During Exploitation," Proceedings U.N. Symposium on the Development and Utilization of Geothermal Resources, Pisa, Geothermics, Special Issue 2, pp. 1294-1296, 1970.

40. Bixley, P. F., "Land Subsidence in the Wairakei Geothermal Field," manuscript to be published, dated September 1977.

41. Stilwell, W. B., W. K. Hall and J. Tawhai, "Ground Movement in New Zealand Geothermal Fields," Proceedings Second U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, pp. 1427-1434, 1975.

42. Rogan, J. F., "Survey Report -- Wairakei Geothermal Area - Deformation Studies: 1977 Resurvey of the Steam Mains Control Networks," unpublished manuscript, 1977.