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15 GEOTHERMAL WATERS

By

G. W. GRINDLEY[1] and G. J. WILLIAMS[2]

Geothermal waters and metallogenesis

Whether or not geothermal steam be regarded as a "mineral" in the true sense, this Chapter is included as a tribute to those scientists and engineers of the Department of Scientific and Industrial Research and of the Ministry of Works who have brought a unique geothermal-steam electric-generating project to fruition. Of particular interest in this geological Volume, however, are the accompanying scientific investigations which have contributed to an understanding of near-surface hydrothermal metasomatic processes, wherein magmatic and meteoric waters meet. There is an obvious genetic link between these processes and those which resulted in the highly profitable Tertiary volcanic gold-silver mineralization of the Hauraki goldfields—a link that could provide, for years to come, a series of fascinating studies.

GEOTHERMAL WATERS AS A SOURCE OF POWER[3]

Introduction

Geothermal energy may be defined as the heat contained in the rocks and interstitial water of the earth's crust due to the geothermal gradient—together with the natural heat flow per unit area, these factors are critical. A mean value for the geothermal gradient in continental areas is generally taken as 30°C/km (1°C/110 ft). This value may be lower in some sedimentary basins that have been, or are being depressed relatively rapidly—and may be higher in mountainous regions that have been or are being elevated relatively rapidly. Magma may be formed and injected upward by strain release during tectonic movements at depths of 50-60 km; or at shallower depths—where the geothermal gradient is inevitably steeper. The geothermal gradient may be further steepened by upward injection of magma into the crustal rocks and cause fusion of these rocks at depths ranging from 10 to 25 km—this may result if the geothermal gradient is steepened sufficiently. Volcanism, plutonism and steep geothermal gradients are therefore intimately associated.

Due to varying geothermal gradients within different parts of the earth's surface, the heat flow varies from place to place. The mean heat flow is commonly taken as 1.1×10^{-6} cal/cm^2 (Bullard 1963). The heat flow at the surface also depends on the efficiency of heat transfer from depth, and also on the heat-transfer mechanism. Convective heat-transfer by upward movement of hot water, vapour or magma is efficient and gives a greater heat flow at the surface than purely conductive heat transfer, where little mass movement of the heat-carrying medium takes place. This is most easily appreciated in active volcanic areas, where heat flow is considerably augmented by eruption of lava and ash and by vigorous hot-spring and fumarolic activity. Both convective and conductive heat-transfer normally operate in conjunction, but for large heat flows convective mechanism must dominate. In 1958, the heat flow at Wairakei was approximately 5.5×10^{-4} cal/cm^2 or 500 times the accepted mean for the earth (Fisher, 1964). It is unlikely that this heat flow was concentrated from an area 500 times as large at a depth of 8 km, where the maximum temperature of 265°C would be attained under a normal geothermal gradient (Healy 1964). It seems inescapable that a large heat source and an efficient convective transfer of heat to the surface are required in large hydrothermal fields, especially if they have been active for a very long time.

It is apparent that exploitation of geothermal energy depends on rapid transfer of heat to the surface in a convenient form for conversion to power. The most rapid heat-transfer mechanism available is molten rock or magma—which may be erupted at temperatures as high as 1,100°C and in voluminous quantities. Although experimental drilling has been carried out at Kilauea lava lake on the island of Hawaii on the extraction of heat from newly-formed lava, a successful method of heat extraction has yet to be devised. Kilauea lava lake, which was filled by an eruption in 1959, was estimated to contain about 2×10^9 kWh of potentially recoverable energy—sufficient to operate a 100,000 kW plant for 10 to 20 years (Rawson, Bennett, 1961)—a significant resource. Geothermal development to date has depended on the extraction of heat carried in the more conventional form of steam or hot water or a mixture of both. Consequently, it is necessary in geothermal investigation to consider not only the heat flow but also the presence of water or steam in the rocks. Efficient extraction of geothermal energy, therefore, requires:

Rocks at high temperature
Permeable sub-surface aquifers or fissured zones that yield large quantities of steam or hot water when drilled

Hydrothermal fields

Geothermal development has as yet been confined exclusively to the hydrothermal fields, of which the most obvious surface indications are hot springs, fumaroles, geysers and steaming ground. Hydrothermal fields can be broadly classified into

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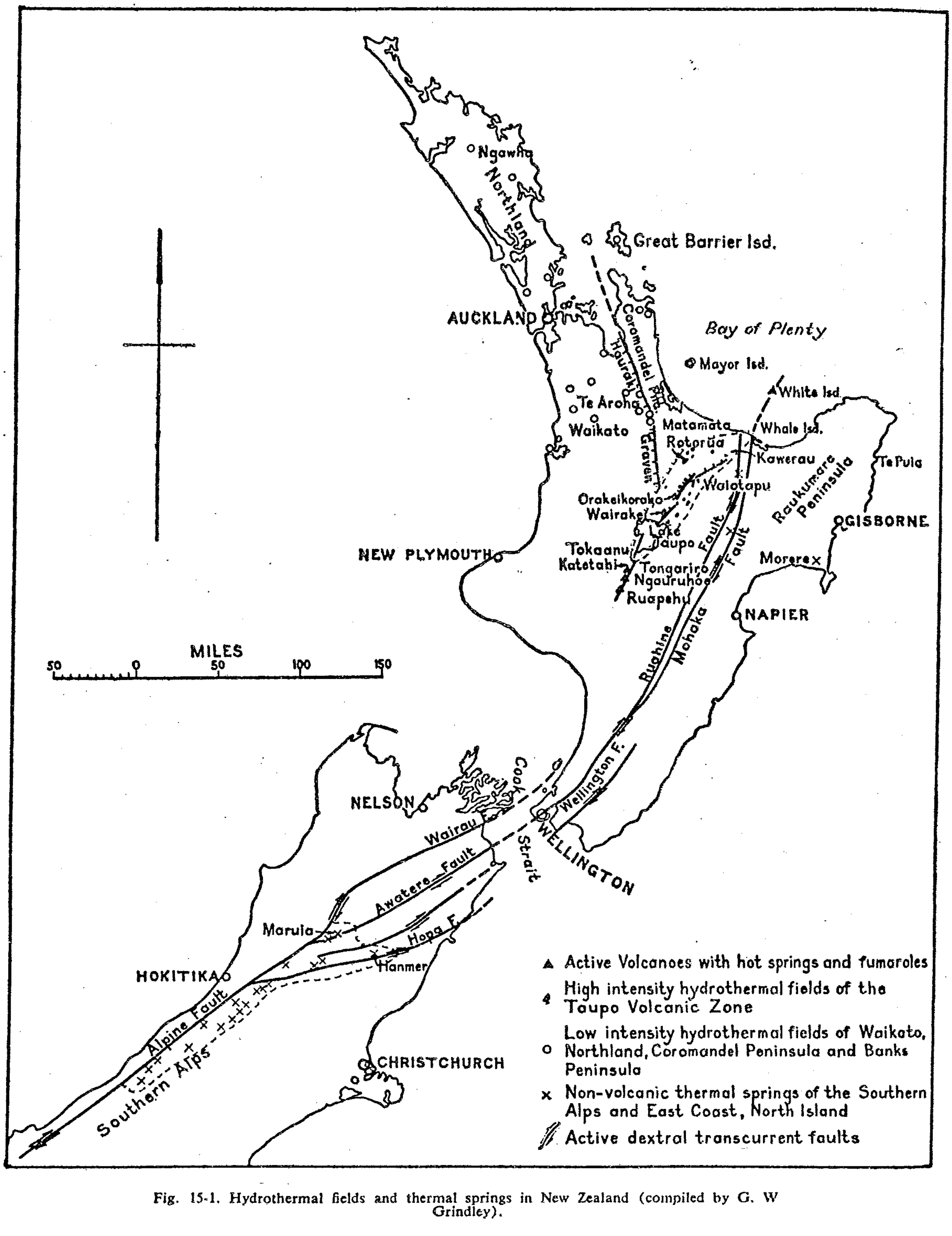

Fig. 15-1. Hydrothermal fields and thermal springs in New Zealand (compiled by G. W Grindley).

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five groups on the grounds of their relation to the heat source and the nature of the heat-transfer mechanism. The distribution of four of these broad groups in New Zealand is shown in Fig. 15-1: they are briefly described below.

Direct volcanic exhalations

Fumaroles and hot springs are commonly found in the craters or on the flanks of active volcanoes. Such springs are thought to be heated directly by magmatic steam exhaled directly from the magma chamber at the volcano roots. The springs are generally strongly acidic and the steam has a relatively high gas content (3 to 5 per cent). Variable quantities of sulphur dioxide, hydrogen and hydrochloric acid may be present in the gases as well as carbon dioxide and hydrogen sulphide. Heat flows vary but are generally larger than in acid springs associated with alkaline chloride fields. For example, the heat flow from the crater lake on Mt. Ruapehu is about 55,000 kcal/s, and this may be trebled during periods of increased activity (Mr R. R. Dibble, pers. comm). Ketetahi springs on the north flank of Tongariro, and White Island (Plate XXXIV) in the Bay of Plenty are other New Zealand examples (Hamilton, Baumgart *et al.*, 1959). Because of relative inaccessibility and proximity to potential eruptive centres, these springs and fumaroles heated directly by magmatic steam are of little interest for geothermal development.

Low intensity fields in decadent volcanic districts

Hot springs are found around the margins of many quiescent and extinct volcanoes and in extinct or decadent volcanic districts where the geothermal gradient is still substantially higher than normal following volcanism. Such springs are thought to derive their heat supply by downward penetration of meteoric water to comparatively shallow masses of hot volcanic and sedimentary rocks. Around an extinct volcano, a convection system may be set up with hot water rising axially and spreading laterally near the surface, and meteoric water descending around the margins. Since the volume of hot rock accessible to the descending water is not great and cools rapidly close to the surface, such hydrothermal fields may not rise notably in temperature with depth. Because of the low intensity of activity and the absence of a direct magmatic contribution, the waters are not highly mineralised, and all the dissolved constituents can be explained by leaching of the country rocks during passage of the heated water to the surface. New Zealand examples include the numerous, medium to low temperature, moderately to weakly mineralised springs of Waikato, Coromandel Peninsula, Hauraki Graben, Northland and outlying islands which are associated with late Tertiary and early Quaternary basaltic, andesitic and rhyolitic volcanism. Similar thermal springs are found around the flanks of the Lyttelton early Quaternary basalt volcano on Banks Peninsula in Canterbury. The Ngawha field in Northland (Fleming, 1945) is associated with late Quaternary basaltic volcanoes and lava flows and small rhyolitic and andesitic cones, and is the only one of these fields that has been considered seriously for geothermal power development. The hot springs at Ngawha emerge where there are several thousand feet of impermeable Cretaceous marine sediments. The maximum temperature is 83°C, the heat flow is about 8,000 kcal/s, and geothermal prospects depend entirely on the discovery of a suitable aquifer by drilling. Maximum temperatures in the low intensity fields may be insufficient for power generation where temperatures greater than 200°C are normally required. However, other uses for low pressure steam in the drying of timber, salt making, the heating of greenhouses and for central heating, seem to be worth investigation.

High intensity fields in active volcanic districts

The most extensive hydrothermal fields with a high heat flow are in active volcanic districts and are fed from relatively deep-seated plutonic sources—probably cooling batholiths or zones of granitization. Some geologists believe that large magma bodies are formed within the crust by large-scale crustal foundering and melting along narrow, tectonically-controlled zones of high heat flow. Crustal melting on an important scale may have taken place in many acidic volcanic provinces where large volumes of ignimbrite, pumice, pyroclastics and rhyolite lava have been erupted (Healy, 1962). The capacity of the individual heat sources in such areas may be extremely large, and where permeable near-surface formations allow deep penetration of meteoric waters, large convection systems may be set up, allowing effective transfer of heat to near-surface aquifers. Maximum temperatures in such systems are commonly high (200 to 300°C), the volumes of hot rock and interstitial water may be large and the surface heat flows considerable. Several such hydrothermal fields are known in the Taupo Volcanic Zone between Lake Taupo and the Bay of Plenty (Figs. 15-1, 15-2). These hydrothermal fields, fed by convective heat transfer from large semi-permanent acidic magmas, provide attractive potential geothermal power opportunities. Of this general type are the Wairakei, Waiotapu, Rotorua and Kawerau fields, all of which have been exploited for geothermal energy. The major assets of such fields are the great heat capacity of the source and the relatively high permeability of the pumiceous volcanics deposited in the large volcano-tectonic basins so typical of this active tectonic and volcanic zone.

High temperature steam fields from active plutonic sources

A few hydrothermal fields that have been exploited produce dry steam instead of a steam-water mixture. The chief example is the well-known Italian field of Larderello, but the Geysers in California is also a dry-steam field: dry steam has been located in the southern part of the Wairakei field. White (1961) suggested that the differences between the dry steam fields and the more common hot-water fields are due principally to the relation between heat supply and the supply of meteoric water. If the entry of meteoric water deep into the system is restricted by rocks of low permeability, the heat supply may be great enough to vapourise the small amount of interstitial water to dry steam. At Larderello, permeable formations containing dry steam are overlain by thick impermeable shales which effectively restrict the entry of meteoric water into the aquifer. At the Geysers in California, dry steam is tapped in a steep-dipping transcurrent fault-zone traversing otherwise impermeable rocks (McNitt, 1961). At Wairakei, the lowering of hydrostatic level produced by exploitation has produced local pockets of accumulated dry steam: in the south of the field, a large output of dry steam was tapped in a subsurface fault fissure. Whether this steam was produced by drying out of the aquifer or from a steam trap at greater depth has yet to be determined. The dry steam fields, therefore, differ from the more common hot-water fields, only in that the dominant method of heat transfer is by ascending steam rather than hot water. Isotopic studies (Craig, Boata and White, 1956) indicated that the dry steam is dominantly vapourised meteoric water and not of direct magmatic origin; Marinelli (1963) produced good evidence favouring a deep-seated acid magmatic intrusion as the heat source at Larderello.

Non-volcanic hydrothermal fields

Although there is a world-wide association of hydrothermal activity and volcanism, this is by no means universal. No volcanic rocks are known at the Californian Geysers or Larderello, where the heat source is believed to be a deep-seated intrusive body, and in certain zones of active tectonic uplift, hotter rocks have been brought closer to the surface and the geothermal gradient steepened without associated volcanism. In New Zealand, the hot springs of the Southern Alps appear to be a result of recent rapid uplift of the Alps along the line of the Alpine Fault. This uplift has been estimated at between 6 and 9 miles in late Pliocene and Quaternary times (Mason, 1962), amounting to approximately 1 ft of uplift in 150 years. Since the Alpine rocks are relatively impermeable and conductive, heat transfer to the surface is slow, and it is not surprising that a steep geothermal gradient has resulted. This is shown by the numerous small hot springs in many of the river valleys scattered through the mountains. Temperatures range from 40 to 85°C and discharges are generally between one and ten litres per second. All the springs are associated with faults, some with major transcurrent faults such as the Hope and Awatere Faults, and others with minor crush-zones. They are believed to originate by downward percolation of meteoric water to the hot rocks at shallow depth with subsequent uprise along fault zones to the surface. The springs are only weakly mineralized and close to surface waters in composition (Morgan, 1908).

Somewhat similar hot springs are found in the North Island Axial Ranges to the east of the Central Volcanic Region. These springs—Tarawera, Waiohau and Waiau—are related to active transcurrent faults traversing Mesozoic greywackes and are of low temperature and weakly mineralised. Further north-east in Raukumara Peninsula, Te Puia and Morere Springs discharge from sandy sediments associated with diapiric anticlines of incompetent early Tertiary bentonites and Cretaceous shales. These are low temperature (50 to 55°C) springs with a high mineral content; the relatively high content of calcium chloride and sodium iodide is typical of mildly thermal, connate waters or meteoric waters rising from considerable depths through thick marine sediments. Neither the Alpine or East Coast springs can be considered as potential geothermal resources, though they may be useful for recreational and therapeutic purposes.

Geothermal fields

Three hydrothermal fields—Wairakei, Waiotapu and Kawerau—have been exploited to varying degrees as sources of geothermal energy; the investigation of two others, Orakei Korako and Ngawha, in under way. The Taupo and Rotorua fields have been drilled for hot water for use in swimming baths, central heating, timber drying and greenhouses. Apart from Ngawha in Northland all the above fields lie within the Taupo Volcanic Zone (Figs. 15-1 and 15-2).

Wairakei

Investigations on the Wairakei field (Plate XXXV) have been going on for 15 years and a power station of 192 MW capacity[4] is now operating Extension to 250 MW or 280 MW is possible within the next few years. Both high (200 p.s.i.) and intermediate (80 p.s.i.) pressure steam are used in back-pressure and steam-condensing turbine-generator units. Numerous publications have appeared over the years describing the physical, geological, chemical and engineering aspects of the investigation—Grange *et al.* (1955), Banwell (1963, 1964), Healy (1956, 1964), Studt (1957, 1958), Steiner (1953), Ellis and Wilson (1960), Grindley (1957, 1961, 1963) and Smith (1958). Important references appeared in a series of 28 papers contributed to the United Nations Conference on New Sources of Energy (e.g. McNitt, 1961).

The hydrothermal field is underlain by an acid volcanic sequence consisting of Recent pumice cover, Wairakei Breccia, Huka Falls Formation, Haparangi Rhyolite, Waiora Formation, Waiora Valley Andesite, Wairakei Ignimbrites and Ohakuri Group (Grindley, 1956). The stratified volcanic sequence is draped over a basement horst and thickens both eastwards and westwards into adjoining

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[4] Plant factor 70-90%; load factor 80-90%; peak output about 175MW.

volcano-tectonic depressions. The bulk of the steam production is obtained from a thick aquifer of pumice breccias (Waiora Formation) between 1,300 and 2,500 ft thick, capped by lacustrine shales of the Huka Falls Formation. The Ohakuri Group (lying below the ignimbrites) constitutes a lower aquifer which has been little exploited by drill-holes. Hydrothermal water up to 265°C in the Waiora aquifer is fed through linear fissures in the underlying ignimbrites, principally at the crest of a small structural dome. These fissures are believed to be related to active north-east striking, predominantly normal faults, with a small dextral transcurrent component. Major zones of heat liberation have been localised by intersection of secondary north-westerly cross-faults. Fossil, hydrothermal mud-flow conglomerates intercalated in the mid-Pleistocene Huka Falls Formation suggest that hydrothermal activity at Wairakei is at least 0.5 million years old. As mentioned earlier, siting of successful drill-holes involves a search for permeable zones at high temperature. Since sub-surface fault zones have proved excellent producing zones, most production holes have been sited to intersect them.

Waiotapu

An investigation of the Waiotapu field was undertaken between 1956 and 1958, seven wells being drilled[5].

This field is underlain by an acid volcanic sequence consisting of the following units in downward succession:

Earthquake Flat Formation
Maungakakaramea Dacite
Huka Group (lake beds)
Rangitaiki Ignimbrites
Huka Group (pumice breccias)
Waiotapu Ignimbrites
Paeroa Ignimbrites
Ngakoro Andesite
Ohakuri Group
Haparangi Rhyolite

The general sequence is similar to that at Wairakei, except that the Huka lake beds are thin at the surface and the underlying aquifer is thinner and not as effectively capped. Consequently temperatures and pressures are lower, and the Huka aquifer at Waiotapu is unsuitable for steam production (except at very low pressures). Deeper drilling undertaken to find a lower aquifer was only partly successful. A succession of ignimbrite sheets of rather low permeability was drilled in the three deep holes, but despite record temperatures (275 to 295°C), outputs from the thin aquifers encountered were disappointing. Further, the bicarbonate content of the water caused the wells to be blocked up with calcite within a few months. No deep fissured zones were encountered, and it was felt that utilisation may depend on finding them. The hydrothermal field lies at the northern end of the upper Quaternary Taupo-Reporoa Basin; better results may yet be achieved by drilling towards the southern end of the field where the aquifers are expected to be thicker, and where a group of intersecting dextral-normal and sinistral-normal faults may mark one of the major fissured zones feeding the hydrothermal field.

> According to Grindley (1963): "Nothing so far discovered at Waiotapu has contradicted the theory, developed by the writer at Wairakei (Grindley, 1957), that the hot water in the thermal areas is fed from directly below along a relatively few, near-vertical, active fault zones. The essential factor in continuing hydrothermal activity is the continuity of active faulting. If the faults cease to move, the fault zones eventually become blocked by mineral deposition, pressures build up in the near-surface strata, and hydrothermal explosions result. This appears to have happened over much of the Waiotapu field and accounts for the lack of success, compared with Wairakei, in tapping feed zones along faults".

Kawerau

The Tasman forest-product mills at Kawerau use geothermal steam to supplement conventional steam boilers fired by mill wastes and coal. Both intermediate (100 p.s.i.) and high (200 p.s.i.) pressure steam are used in two steam generators and a turbo-electric generator. Ten wells have been drilled in the field. Four of them feed the generating sets at the mill, and were deepened from 2,000 to 3,000 ft in 1960 after the original wells had practically ceased producing as a result of cold-water incursion and calcite deposition. The best well has an output superior to most of those at Wairakei—with a maximum temperature of 285°C (Dench, 1962).

The Kawerau hydrothermal field is underlain by an acid volcanic sequence consisting of the following units:

Recent alluvium
Haparangi Rhyolite
Huka sandstones and breccias
Andesite and Ignimbrite

The general sequence is thus similar to that at Wairakei and Waiotapu. The steam production originally came from the Huka aquifer above 2,000 ft in depth, but since deepening, production has come from fissured zones in the underlying andesite. Production is variable depending on the thickness and permeability of the andesite. The andesite 'aquifer' appears to be sealed by mudstones and the future of the field may depend on the effectiveness of this mudstone cap-rock in preventing eventual cold-water incursion into the lower producing zones. Present discharge from the field is approximately twice the natural heat flow prior to drilling (20,000 kcal/s), but little fall in output has so far been noted.

Effects of exploitation

Only in the geothermal field of Wairakei has exploitation gone on long enough for the results to become obvious. It had previously been assumed that the natural heat flow would provide a reasonable yardstick for estimating the safe rate of extraction, geothermal resources being estimated on this basis (Grange, *et al.*, 1955). A total minimum potential of 200 MW was estimated for the Taupo Volcanic Zone. Over the past few years, it has become apparent that the natural heat flow can be exceeded—by how much and for how long is

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[5] Waiotapu geothermal field: *Dept. Sci. Ind. Res. Bul. 155.*

not yet known. At present, the 1951-52 natural heat flow at Wairakei (102,500 kcal/s) is being exceeded by a factor of about six. In 1958 when the natural heat flow from the field was re-assessed, practically no change was noted even though discharge from the field through bores was 160,000 kcal/s (Fisher, 1964). Since 1958, bore discharge has increased to almost 600,000 kcals/s and the natural heat flow has certainly not diminished appreciably although no further precise measurements are available. The major effect of exploitation has been a reduction in water discharge at the surface accompanied by an increase in steam escape. A similar trend is apparent in the shallower drill-holes and is brought about by lowering of the hydrostatic level, boiling of water in the pores of the rocks and in fissures, and replacement by steam. The total fall in aquifer pressure at sea-level datum was approximately 200 p.s.i. from 1954 to 1964, corresponding to a fall in actual water level of approximately 570 ft (at a water density of 50 lb/cu. ft.). The fall in aquifer pressures extends beyond the vicinity of the production area, and is apparent throughout the whole hydrothermal field, even in those parts little exploited by drill-holes.

The fall in aquifer pressure reduces the pressure drive in drillholes and leads to loss in output and eventually to degradation from the high-pressure (200 p.s.i.) class to intermediate-pressure (80 p.s.i.). This first takes place in the shallower holes with low bottom-hole pressures, and in low-permeability holes where draw-down of aquifer pressures during discharge is substantial (up to 450 p.s.i.). In high-permeability holes, especially those drawing on substantial fissures near the well-bottom, the effects of fall in aquifer pressure are least critical—such wells have the longest productive life. These results demonstrate the importance of accurate hole siting so as to intersect the fault-determined fissure zones at deep levels in the aquifer where pressures and temperatures are high.

The natural effect of the fall in aquifer pressures is the formation of steam at progressively lower levels in the aquifer. This is unavoidable and indeed necessary for the extraction of heat from the aquifer. Because minerals tend to become concentrated in the water phase, steam separation on a large-scale encourages mineral deposition and thus reduces permeability. When steam separation takes place within the solid casing (as in the early stages of exploitation), the deposits of calcite and silica can be reamed out and the well reconditioned without permanent loss in output. If, on the other hand, mineral deposition takes place in the aquifer below the casing, steady and irreparable deterioration in output may result. Mineral deposition is suspected to be a prime cause (the others are loss in temperature and working head) governing the life of geothermal wells. At Waiotapu, mineral deposition has led to the temporary abandonment of geothermal investigations and at Wairakei, although this is not nearly so serious a problem, it may contribute to the steady deterioration of output observed in most wells that have been operating more than a year or two. At present, the drilling of at least five new wells per year is required to keep the steam supply at a level sufficient for the power needs of the station.

Recharge of the aquifer appears to be slow, for considerably more water is being extracted than is being replaced naturally. In fact, the pressure drop is expressed by a linear rather than by an exponential curve when plotted against time with constant discharge. The pressure fall is directly proportional to the cumulative mass discharge above a base figure comparable with the original discharge. The linear pressure fall may be more apparent than real due to the short time the field has been producing at peak capacity, but certainly bears out the observation that the overall permeability of the aquifer is low. This low permeability is partly due to compaction of the soft pumice breccias, but it may mainly be due to cementation by hydrothermal minerals. Except on the margins of the field, the slow rate of recharge allows time for recharge water to become heated to aquifer temperatures before being extracted in drill-holes. In 1964, temperatures in the lower part of the aquifer (below sea-level) had not fallen more than 10°C since exploitation began. Such falls in temperature as have been observed appear to be due to the falling enthalpy of the formation water following separation of steam. In the higher, more permeable parts of the aquifer, temperatures have risen due to the presence of separated steam. This steam being under pressure below the confining mudstones, tends to exclude the influx of colder formation water from outside the hydrothermal field. The large difference in viscosity between hot water (0.1 centipoise) and cold water (1.0 centipoise) favours more rapid movement of hot water and preferential recharge of the aquifer by less viscous, hotter water from below. Aquifer pressures are therefore still high in the surrounding region, except in restricted regions where replacement water is being drawn down along faults or through exceptionally permeable formations.

Production trends

Present indications are that much of the replacement water is hot and is being fed from below the Wairakei Ignimbrites along fault planes; further exploitation should aim at increasing this flow. Deeper drilling into the fault fissures and into the underlying (Ohakuri) aquifer has, therefore, been recommended (Grindley, 1965). Deeper drilling is also considered desirable to investigate the origin of a large output of dry steam, that was tapped by an exploratory hole in the south of the field. This discharge which was tapped unexpectedly in a sub-surface fault fissure, amounts to over 500 Klb/hr and is at present discharging "wild". The theory has been advanced that a dry steam trap may exist in depth in this area, possibly below the Wairakei Ignimbrites, and when the "wild" hole is tamed, deeper drilling on the fissure zone should follow.

The final design of the Wairakei power station depends on the trends in availability of the high-pressure and intermediate-pressure steam and the waste hot water separated at the well-heads. In the original plan (Smith, 1958) it was proposed to flash the hot water in flash tanks to produce low-pressure steam (0.5 lbs/in^2) to feed the final stage condensing turbines. This plan has not yet eventuated because of uncertainty in respect of the supply of hot water. If the supply appears to be adequate for the life of the station, the station capacity could be boosted to 250 or 280 MW by utilization of the hot water. An alternative use for the hot water would be as replacement water for artificial injection into the aquifer to maintain formation pressures. If, on the other hand, the field gradually changes to a steam field, as current trends in enthalpy seem to suggest, production may still be boosted beyond the present 175 MW by transmission of readily available extra-intermediate-pressure steam to the power house.

At present, there is no certain method for estimating the ultimate capacity or the best extraction rates from the Wairakei geothermal field. Experience over 40 years at Larderello has shown similar production trends. Hydrostatic levels have fallen drastically (by several hundred metres), shallow wells have gone out of production and deeper drilling has proved necessary to maintain output (Chierici, 1961). At Larderello, however, cold-water incursion has proved to be a lesser problem than at Wairakei, principally because of the effectiveness of the thick capping shale in restricting the inflow of meteoric water into the aquifer. The temperature of the steam has, in fact, risen by 40°C and become superheated due to its long passage through fissures in low-conductivity, hot rocks to reach the drill-holes. Even so, a production ceiling has been reached at Larderello at present drilling depths, above which it has been found impracticable to increase output. This ceiling is the equivalent of 350 MW of generated power.

Future trends at Wairakei are likely to be comparable—continually falling aquifer pressures, gradually rising enthalpy, deterioration in the production of shallow and marginal wells, and an increasing need towards production from greater depth. Problems of field management will arise for the Wairakei geothermal field is a unique experiment. With intelligent and careful planning of future exploratory and production drilling it does not seem unreasonable to hope that present production rates can be maintained or even exceeded. The pioneering work at Wairakei will undoubtedly assist in the exploitation of other hydrothermal fields in the Taupo Volcanic Zone; as knowledge increases, the results of this pioneering work should lead to more accurate evaluation of geothermal resources in the years to come.

CHEMICAL CONSTITUENTS OF GEOTHERMAL WATERS[6]

Wairakei

According to Wilson (1959) the steam at Wairakei is accompanied by six times its mass of hot water which is mainly a 0.3 per cent solution of NaCl. Significant lithium contents amounting to 12 p.p.m. were found during the earlier investigations—owing to the low atomic weight of Li this element is much more important in the water than calcium—on a mole concentration—and nearly as important as potassium. "It was calculated that the value of the lithium in the water rejected, was about the same as that of the electric power that could be generated from the steam".

Both high and low pressure bores exist, the former probably coming from fissures in the ignimbrite, and the latter from hot water in permeable volcanics: respectively the well-head pressures are 200 and 70 p.s.i.

Gas

Wilson noted that of the gaseous constituents from the condensers, the mixture of hydrogen and methane is roughly equivalent in calorific value to town gas. The daily output of a major gas works may be, say, 3 million c.ft. per day, whereas Wilson gave the combined yearly output of these gases from Wairakei at 11.3 million c.ft. He added that "The output of methane is about equal to the yearly output from the oil wells at New Plymouth.

[6] Abstracted by G. J. Williams from Wilson (1959).

TABLE 15-1.
CONSTITUENTS OF WATERS FROM GEOTHERMAL BORES, WAIRAKEI[7]

	High pressure bores (p.p.m.)	Int. pressure bores (p.p.m.)	Annual amounts produced[8]	Assumed value	Annual value
NaCl	3,064	3,128	113,000 tons	£5/ton	£565,000
KCl	378	291	11,700 tons	£30/ton	£351,000
Na_2SO_4	55	50	2,000 tons	—	—
NaF	17	16	620 tons	—	—
$CaCO_3$	34	50	1,300 tons	—	—
LiCl	83	77	6,720,000 lbs	8s 0d/lb	£2,340,000
RbCl	4.1	3.4	328,000 lbs	3s 6d/lb	£137,000
CsCl	2.8	2.8	230,000 lbs	(as pollucite)	£334,000
H_3BO_3	146	158	5,400 lbs	£20/ton (borax)	£166,000
SiO_2	395	344	14,200 tons	—	—
As_2O_3	5.5	5.7	537,000 lbs	£85/ton	£10,800

[7] Wilson (1959).

[8] At possible full development of the order of 280,000 kW.

Water

The constituents of the bore waters at the final stage of construction of the power units are set out in Table 15-1. Wilson pointed out that the amount of boric acid is about the same as that recovered at Larderello[9] in Italy, but that it could be recovered economically only if it were found desirable to concentrate the Wairakei water for the recovery of other constituents, "It would be less uneconomic to recover boric acid from the ash of Waikato coals (which are relatively high in boric acid content)". Wilson thought that if it would seem to be economic to win lithium from the water[10] it might also be possible to extract the sodium and potassium chlorides together with the rubidium and caesium salts. He added that mixed K-Rb-Cs carbonates have some use in glass manufacture.

Chloride water in other thermal areas[11]

Wilson noted that the most important thermal areas contain underground chloride water, the main exceptions being Ketetahi and Tikitere. Data for the various areas are set out in Table 15-2 from which Wilson noted that only Tokaanu, Waiotapu and Taupo Spa have concentrations of chloride comparable with those at Wairakei—only at Tokaanu is the chloride content higher than at Wairakei.

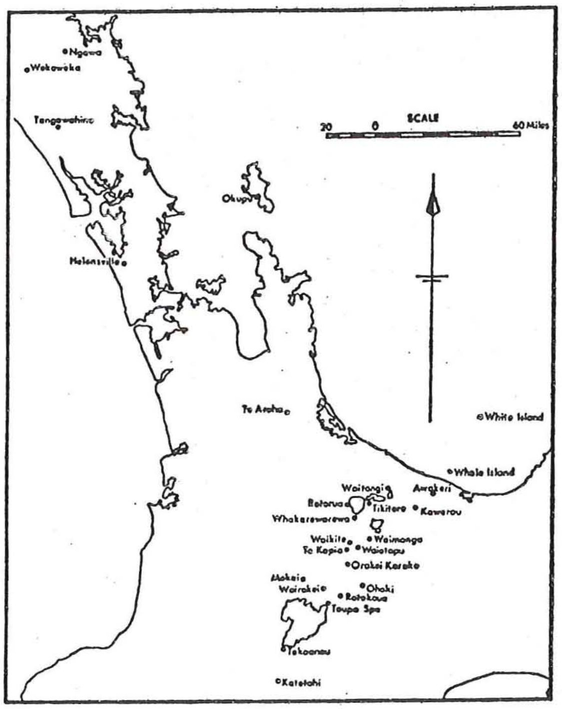

Fig. 15-2. Hot springs in northern areas (Wilson, 1959).

TABLE 15-2.

CONTENTS OF SODIUM CHLORIDE, POTASSIUM CHLORIDE AND LITHIUM IN WATERS OF THERMAL AREAS OF THE NORTH ISLAND[12]

	NaCl %	KCl %	Li p.p.m.	Mole ratio Na/Li
Tokaanu	0.462	0.032	24.0	23
Waiotapu				
Champagne Pool	0.291	0.030	8.0	43
Bore No. 6	0.218	0.030	6.6	39
Wairakei				
Champagne Cauldron	0.271	0.019	11	29
H.P. bores	0.314	0.038	13.5	27.5
Taupo Spa	0.257	0.013	11.5	27
Kawerau				
Bore	0.173	0.015	7.25	28
Onepu Spring	0.107	0.009	2.9	44
Ohaki	0.226	0.015	9.5	28
Waimangu	0.155	0.015	4.0	46
Rotokaua	0.128	0.009	3.8	37
Rotorua				
Whakarewarewa	0.119	0.012	3.4	38
Rotorua town				
Rachel Spring	0.137	0.006	2.35	69
Bore	0.145	0.006	3.0	57
Kuirau	0.081	0.005	2.5	39
Kuirau bore	0.088	0.008	2.4	43
Orakei Korako	0.085	0.006	3.9	28
Waitangi	0.077	0.004	1.7	47
Waikite	0.046	0.006	1.9	29
NORTHLAND				
Tangowahine	1.17	0.050	10.5	132
Wekaweka	0.64	0.009	5.7	133
Okupu (Great Barrier Island)	0.65	0.055	50	15.5
Helensville	0.152	0.004	2.3	80
Ngawha	0.175	0.011	5	42

[12] Wilson (1959).

NEAR-SURFACE HYDROTHERMAL METASOMATISM

Wairakei

Stratigraphic succession

Steiner (1953) studied hydrothermal alteration in the rocks penetrated by the geothermal-steam bores at Wairakei. He found that hydrothermal alteration had significantly altered the flat-lying tuffaceous and arenaceous rocks, but that it has not appreciably altered inter-bedded argillaceous rocks.

TABLE 15-3.

STRATIGRAPHIC SEQUENCE REVEALED BY DRILL HOLES SHOWN IN FIG. 15-3, WAIRAKEI[13]

	Thickness in ft	
	Western holes	Eastern holes
Recent cover	0-240	0-240
Upper Wairakei lapilli tuff	115-231	absent
Chalazoiditic vitric tuff	0- 4	absent
Lower Wairakei lapilli tuff	81-280	absent
Altered chalazoiditic vitric tuff	3- 30	absent
Diatomaceous mud- and silt-stones	absent	200-240
Huka Formation	197-729+	

[13] Steiner, 1953.

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[9] Which was, of course, originally exploited for its boric acid content rather than for power.

[10] He pointed out that the concentration of Li is 130 times greater than that in sea water; Rb—15 times; Cs—11,000 times; F—10 times; B—6 times; I—30 times; and As—1,100 times.

[11] For White Island see Wilson, *in* Hamilton and Baumgart (1959).

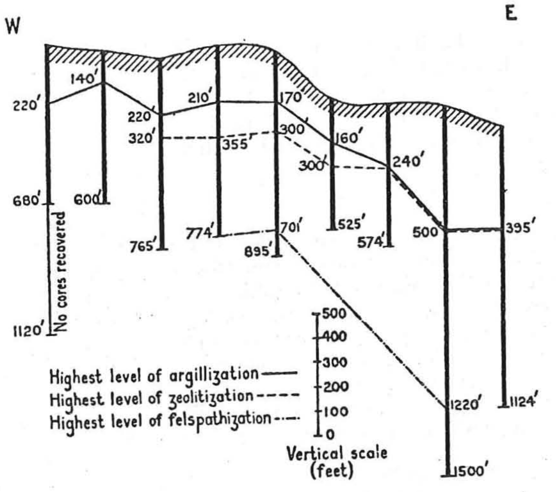

Fig. 15-3. Hydrothermal metasomatic zonation along line of geothermal steam bores, Wairakei (Steiner, 1963).

The line of bores shown in Fig. 15-3 went to a maximum depth of 1,500 ft within which depth the stratigraphic succession shown in Table 15-3 was found. In more detail the material penetrated is as follows:

A Recent cover of clay with pumiceous and rhyolitic sands.

The Upper and Lower Wairakei lapilli tuffs have the composition of plagioclase rhyolite; the phenocrysts in decreasing order of abundance are andesine plagioclase, quartz, hypersthene, and hornblende. Magnetite and rare apatite are accessory minerals. The ground-mass consists of glass shards and pumiceous streaks and lapillae; there are elliptical bodies up to 1 cm in diameter of rhyolitic glass fragments (chalazoide).

The chalazoiditic vitric tuff, and its altered counterpart lower in the series are embedded in a matrix consisting of the same material.

The diatomaceous mudstones consist of clay with some detrital oligoclase, quartz and volcanic glass.

The Huka Formation consists of sedimentary beds including claystones, mudstones and siltstone embedded in vitric tuffs and pumiceous sandstone. Their dominant contituent is montmorillonite-like material; there is also some carbonaceous material.

Steiner recognized in downward succession the following hydrothermal metasomatic zoning (as shown in Fig. 15-3):

Sulphuric acid leaching
Argillization
Zeolitization
Felsphatization

These zones are shown in chemical form in Table 15-4.

Zone of sulphuric acid leaching

Secondary minerals characteristic of this zone are kaolinite (Chapter 20), alunite (Chapter 14) and opal: of the primary constituents only quartz phenocrysts survive. A few grains of leucoxene represent primary titanomagnetite. At 32 ft alunite appeared and persisted to 50 ft scattered through the rock. Some pyrite was detected at this depth, but below 80 ft montmorillonite-like clay and pyrite are characteristic constituents. At 90 ft the appearance of siderite witnessed a profound change in the character of the hydrothermal alteration manifested mineralogically by the absence of kaolinite, opal and alunite. It is evident that kaolinite, opal and alunite are superficial. It was suggested that the sulphuric acid solutions form by the oxidation of H_2S vapours by oxygen entrained in descending meteoric water.

TABLE 15-4.

COMPARISON OF ALTERED AND UNALTERED ROCKS, WAIRAKEI[14]

	A	B	C	D	E
SiO_2	73.86	72.05	69.20	75.93	73.47
Al_2O_3	13.53	15.46	14.40	12.84	14.56
Fe_2O_3	1.35	0.48	0.58	0.34	1.75
FeO	1.53	1.47	2.19	1.07	0.66
TiO_2	0.37	0.34	0.51	0.21	0.29
MgO	1.28	0.84	0.58	0.22	0.24
CaO	2.22	2.93	1.00	1.45	1.36
Na_2O	1.61	1.87	0.93	4.00	4.31
K_2O	3.13	2.74	10.16	3.65	2.99
P_2O_5	0.09	0.15	0.08	0.02	0.09
MnO	0.16	0.06	0.10	0.05	0.09
BaO	0.04	0.10	0.07	0.13	0.11
ZrO_2	—	0.01	—	0.04	0.01
FeS_2	0.78	1.32	0.15	0.01	0.02
Cl	—	0.05	0.01	tr.	—
$H_2O + 105°C$	4.06	6.30	0.97	0.35	1.18
$H_2O — 105°C$	2.76	4.48	0.14	0.04	0.44

A—Argillized zone: Wairakei lapilli tuff at 230 ft
B—Zeolitized zone: tuffaceous sandstone with ptilolite at 419 ft
C—Felspathized zone: tuffaceous sandstone with adularia at 701 ft
D—Fresh obsidian from Whakapoungakau Mountain, east side Lake Taupo (Grange, 1937)
E—Fresh ignimbrite, Waihaha (Grange, 1937).

Zone of argillization

The dominant form of alteration within this zone is the conversion of glass and pumiceous threads into clay minerals of the montmorillonite group—with superimposed alterations represented by zeolitization and felspathization. At high levels the argillization is accompanied by the introduction of pyrite, occurring in cubical crystals with octagonal faces in contrast with the pyrite which appears in the Huka Formation with pyritohedral faces. Plagioclase remains unaffected by argillization—except locally by the formation of calcite. The ferromagnesian minerals are reduced to clay in some drill holes, and in others are unaltered.

Zone of zeolitization

Ptilolite is the characteristic zeolite: it fills pores in the pumice. Heulandite was only occasionally identified[15]. "The fact that plagioclase remains unaltered in rocks containing ptilolite points to alkaline solutions, which, apart from being rich in soda and lime, contain an excess of silica".

Zone of felspathization

This zone is characterized by the presence of secondary adularia, which was identified in several bores, commonly containing some sericite. "The

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[14] Stiener (1953).

[15] See also notes on zeolites in Chapter 14.

replacement of adularia is generally associated with the development of titanomorphite, minute granules of which are scattered throughout the rock and rarely enclose remnants of titaniferous magnetite. Secondary quartz is another common hydrothermal mineral accompanying the formation of adularia. Prehnite, probably of hydrothermal origin, has been identified in one of the cores . . . . containing adularia and titanomorphite; the vertical range is less than 23 ft". Ptilolite is not present in the cores containing adularia, it presumably being destroyed during the replacement of soda and lime by potash.

Waiotapu

Later, Steiner (1963) studied hydrothermal metasomation in the Waiotapu geothermal field, where the exploration bores were sunk to greater depths than those at Wairakei—the deepest bottomed at 3,282 ft. Steiner was thus able to study deeper zones and discuss the relation between sodic and potassic metasomatism.

Stratigraphy

"A sequence of ignimbrite sheets with interbedded sedimentary rocks is a characteristic feature of the explored vertical range . . . . volcanic rocks of relatively low permeability make up in average 70 per cent of the total thickness penetrated by three deep holes . . . . and thus predominate over sedimentary permeable, water-bearing rocks. This may be contrasted with the great thickness—about 1,700 ft—of permeable sedimentary and pyroclastic rocks overlying the ignimbrite sheets at Wairakei". All rocks with the exception of the Maungaongaonga dacite are rhyolitic, and the sedimentary material contains mainly rhyolitic material.

Hydrothermal minerals

In this region, Steiner noted that the primary minerals behaved as follows under hydrothermal influences:

> Quartz alone is resistant to attack
>
> Pyroxene and hornblende are always completely altered, even if plagioclase remains unaltered
>
> Partly altered biotite sometimes occurs alongside fresh plagioclase
>
> Plagioclase is thus less susceptible to alteration than pyroxene, hornblende and biotite
>
> Magnetite is the most susceptible of all the primary minerals
>
> Acid volcanic glass is readily altered—its susceptibility being comparable with that of pyroxene and hornblende

Susceptibility to alteration in decreasing order is therefore: magnetite, pyroxene and hornblende, biotite, plagioclase, and quartz. The sub-surface zonation of hydrothermal metasomatism is discussed below.

Epigene sulphuric acid alteration

Near the surface glassy siltstones, sandstones and a dacite are generally unaffected by hydrothermal alteration except for the formation of pyrite, although in three holes, sulphuric acid alteration was found to be characterized by the formation of alunite for a depth of not more than 100 ft. The alunite replaces felspar, and together with opal, fills interstices; carbonates are absent. Thus, as at Wairakei, alunite and opal result from an epigene process rather than from ascending hydrothermal solutions.

Hypogene alteration

Steiner recognized both potassium silicate alteration and albitization associated with the formation of calcite and occasionally wairakite. The former alterations are characterized by hydromica and potassic felspar, replacing primary soda-lime plagioclase. On the other hand conversion of primary soda-lime plagioclase into albite is commonly associated with the crystallization of calcite—occasionally with the formation of wairakite.

Origin of alteration pattern

In the cores of several holes, an association of potassium silicate alteration with steeply-dipping pyritized veins was discovered. Steiner presumed that alkaline solutions rose along pre-existing fissures to bring about potassic metasomation:

> "Since vein filling tends to seal off fissures, it is evident that hydrothermal solutions which brought about the potassic alteration must have arrived before the vein-filling fluids. In fact, petrographic evidence indicates that the fissures at Waiotapu are filled mainly with pyrite and quartz, and are thus largely sealed off as channelways for ascending hydrothermal solutions".

Steiner concerned himself with the relationship between potassium and sodium metasomatic influences. He seemed to regard the former, associated as it is with pyritized veins, as having been formed from ascending solutions along the fissure: "This seems to be the logical explanation of the occurrence at shallow depth of the potassic alteration, requiring a comparatively high temperature . . . .".

Albitization was occasionally noted overlapping potassic metasomatism. Steiner was inclined to the view that albitization was brought about independently and mostly at a later stage than the potassic alteration. He associated the former with a gaseous phase consisting mainly of CO_2 and H_2S rising from depths greater than those explored by the bores—these gases heated the pores of the rocks and becoming dissolved in ground-water, he believed the combination now to be attacking the rocks to bring about albitization of the soda-lime plagioclase. "The presence of CO_2 is reflected in the formation of calcite which is an abundant hydrothermal mineral in the albitized zones at Waiotapu".

Metal-bearing near-surface hydrothermal metasomatism

Ngawha

There has been some argument as to whether the cinnabar at Ngawha is still forming, but at least there can be no argument that it formed at the surface.

It is noted in Chapter 13 that Henderson (1944) believed cinnabar to be currently forming from

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thermal waters at Ngawha. He stated that "Some waters also contain arsenic, mercury and gold in small amount, and sinter containing mercury edges some of the hot pools, which are still probably depositing cinnabar". Fleming (1945) examined several separate thermal exudations in this area and noted that:

The waters have a higher boron content than any others in New Zealand (1,400 p.p.m.)
They are consistently high in chloride
Carbonate is present even in the most acid water analysed and much more abundantly in most alkaline waters
The ammonia content is relatively high
Sodium greatly exceeds potassium in all analyses
The silica content is relatively low
The calcium content is relatively high

He considered that alkaline conditions were more prevalent at an earlier stage in the history of Ngawha, as indicated by the widespread occurrence of sinterized deposits and the deposition of cinnabar. He noted that two springs rich in sulphates are still active in this area. Fleming quoted overseas references to the effect that cinnabar forms only from hot alkaline waters, and came to the conclusion that the present acid conditions at Ngawha are a later development, though he thought it possible that the acid waters now play a part in reducing the sulphide to native mercury: "certainly no mercury could be contained in solution in any of the Ngawha waters analysed"—a statement which is contradictory to that of Henderson who believed that cinnabar is being deposited at the present time.

Metallic constituents of thermal waters in Rotorua-Taupo area

In Chapter 8 (p.125) it is noted that certain geyser waters of the Wairakei and Taupo areas (Bell, 1907) contain metallic constituents such as antimony, gold and silver, and that a mineralized rock containing an appreciable amount of gold and silver had been formed in a branch of the Tarawera River. It is therefore desirable that the additional chemical work necessary to recognize any metallic constituents in the waters obtained from geothermal steam bores should be undertaken[17].

Hauraki goldfield

It is very clear that the gold-silver mineralization of the Hauraki goldfield is derived from the Tertiary volcanic rocks of the Coromandel Peninsula. The propylitization in the First Period andesites is explained chemically in Table 8-5 (Finlayson, 1910) in which it will be noted that an increase of potash is characteristic. Adularia occurs in the Waihi veins (see footnote, p.95, in which it is explained that this mineral was vernacularly known as valencianite).

There appears to be no chemical data relating to the late Tertiary gold-silver sinterous mineralization in the Third Period (rhyolitic) rocks: this mineralization must have been very shallow indeed; if not at the surface itself. A chemical study of the alteration of these rhyolitic rocks, combined with a study of the metallic constituents of the water from the geothermal steam bores might well produce information of considerable metallogenetic interest.

The results obtained from the Niland geothermal bore sunk to a depth of 5,232 ft close to the Salton Sea in California are fascinating. The alkali metal components of the water from this bore are greatly in excess of those from Wairakei (Table 15-2)—but the bore was much deeper. A line of Quaternary pumiceous rhyolite and obsidian domes was mapped near this geothermal area. "The well tops a very hot brine which has an unusually high potassium content, and perhaps the highest lithium and heavy-metal content known for natural waters. During a production test, the material deposited in discharge pipes was astonishingly rich in silver, copper and other scarce elements normally associated with ore deposits. Considerable evidence favours the geologically fascinating possibility that this brine is a present example of an 'active' ore solution of the type that may have formed many of the world's economic concentrations of ore metal in the geological past"—note by D. E. White of U.S. Geol. Survey, E. T. Anderson of Imperial Geothermal Inc., and D. K. Grubbs of Univ. [illegible]

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