Programme Geothermal Workshop 27 October (Thursday)
Totara Room, Park Heritage Rotorua

8:30 Opening Remarks. Stuart F Simmons

8:35 John Lund (Oregon Institute of Technology): Worldwide perspectives on direct utilisation of geothermal energy KEYNOTE SPEAKER

9:10 Deborah A Bowyer (MRP): Results of recent drilling at Rotokawa

9:30 Karl Spinks, Luis Urzua, Bill Cumming, & Deborah Bowyer (MRP): The geology and geothermal exploration of Mangakino

9:50 David Wilson & Luis Urzua (MRP): Putauaki Exploration Update

10:10-10:40 morning tea

10:40 Phil White (SKM): Latest developments in subsidence at Wairakei-Tauhara

11:00 Chris Bromley, Jessica Hole and Steve Currie (IGNS): Taupo subsidence reassessment with the help Boltzmann functions, INSAR and GPS data

11:20 Roger Young and Stephen White (IRL): A new method for the prediction of reservoir subsidence

11:40 Malcolm Grant (MAGAK): Spatial Correlation of well performance

12:00-1:00 Lunch

1:00 Warwick Prebble and Manfred Hochstein (University of Auckland): Building the Tokaanu powerhouse on top of a high temperature geothermal system

1:20 Sadiq Zarrouk, Mike O' Sullivan and Adrian Coucher (University of Auckland): Numerical modelling of production from the Poihipi dry steam zone, Wairakei geothermal system

1:40 Warwick Kissling (IRL): The spatial distribution of the geothermal fields of the TVZ

2:00 Ed Mroczek, Duncan Graham and Lew Bacon (IGNS): Removal of arsenic from geothermal fluids by electrocoagulation

2:20 Chris Matthews and Graeme Beardsmore (Monash University): Precision water bore temperature logging as a tool for geothermal energy exploration

2:40 Yasuhiro Fujimitsu, Toshiharu Kido, Jun Nishijima and Sachio Ehara (Kyushu University): Estimation of heat discharge rates from Unzen geothermal area, Japan, by using the heat balance technique.

3:00 Ian Bogie and Jim Lawless (SKM): Basinal analysis of the TVZ as a guide to the prospectivity of its geothermal fields

3:20 Kevin Brown and Doone Wyborn (GEOKEM: Geochemistry of the Habanero hot fractured rock system.

Posters

Pri Utami, Patrick Browne, Stuart Simmons & Suroto (University of Auckland): Hydrothermal Alteration Mineralogy of the Lahendong Geothermal System, North Sulawesi, Indonesia: a Progress Report

Agnes Reyes (GNS): Low-enthalpy springs of the Waikato region

J.Graaf, C.J.N Wilson, S.F. Simmons & P.R.L. Browne (University of Auckland): Hydrothermal System of Raoul Island:Past and Present

WORLD-WIDE DIRECT-USES OF GEOTHERMAL ENERGY 2005

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An updated summary of the world-wide direct utilization of geothermal energy is presented based of material gathered in country update papers for the World Geothermal Congress 2005 (WGC2005), held in Turkey. Data are presented from 72 countries with a total installed capacity of 28,268 MWt (an increase of 87% over data from WGC2000) and an annual energy use of 273,372 TJ or 75,943 GWh (an increase of 43% compared to data from WGC2000). The largest use is from geothermal heat pumps, which has increase 276% over the past five years, with over 1.3 million units installed world-wide. Space heating, district heating, greenhouse heating, fish farming, agriculture crop drying, industrial processing, and cooling and snow melting are discussed along with examples. New trends in the direct-use development are combined heat and power plants which are gaining popularity in Europe using resources as low as 100^{o}C. The annual energy savings amounts to an equivalent 129 million barrels (19.2 million tonnes) of fuel oil, 17 million tonnes of carbon and 62 million tonnes of CO_2. With the recent increases in fuel oil and natural gas prices, the use of geothermal energy for direct utilization will certainly increase in the future.

RESULTS OF RECENT DRILLING AT ROTOKAWA

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Due to increasing pressure in a shallow hydrothermal reinjection aquifer, MRP decided to drill three new deep reinjection wells between October 2004 and February 2005. The wells were drilled from a newly constructed pad, approximately 1.25km to the west-southwest of the Rotokawa Power Station, with the aim of penetrating the western edge of the Rotokawa reservoir, as defined by geophysics.

RK16 was drilled vertically to 3076m and penetrated the top of the Rotokawa Andesite at 870m, several hundred metres shallower than previous wells. Epidote was first noted in drill cuttings at 1550m. Completion tests showed RK16 to have poor permeability (~1 darcy-metre) spread over wide intervals and the capacity to accept 200-300 t/h, up to half of the reinjection fluid from the Rotokawa Power Station. After heating for 23 days the well showed a maximum temperature of 306°C at 1675m. The injectivity of RK16 was retested in February 2005 following three weeks of cold water injection. Permeability had increased (to ~3 darcy-metres) with the well now having a capacity of ~600 t/h, making it a good injector. Brine at 145°C has been injected into the well at 470 t/h since May 2005.

RK17 was deviated to the east-southeast to a total depth of 1951m MD (1901m TVD). While the top of the Rotokawa Andesite was penetrated at a similar depth to RK16, Waikora Formation sediments and Ohakuri Group tuffs which normally overlie the andesite were encountered from 1394-1565m (TVD). Epidote was first noted in drill cuttings at 1510m (TVD). Completion tests showed RK17 to have excellent permeability (5-7 darcy-metres) with an upper permeable zone at 1101-1120m (TVD) and a lower zone with 5-10 times the permeability at 1602-1671m (TVD). The well showed a maximum temperature of 318°C after heating for two weeks, and 330°C after being on bleed for several months. A vertical discharge test on April 1st showed an estimated production capacity of 22 MW.

RK18 was deviated to the south-southwest to a total depth of 2607m MD (2448m TVD). While penetrating a similar lithological sequence to RK16, the first epidote encountered was deeper at 1748m (TVD). Completion tests showed RK18 to have poor permeability (~0.8 darcy-metres) with a maximum temperature of 291°C after heating for six days, and 310°C after being shut for several months.

A fault has been proposed to account for the shallow depth of the top of the Rotokawa Andesite in RK16, RK17, and RK18. This fault is proposed as a major zone of permeability along the western boundary of the Rotokawa geothermal system, bringing >300°C fluid to 1000m below the surface, and is therefore a potential target for future production drilling at Rotokawa.

THE GEOLOGY AND GEOTHERMAL EXPLORATION OF MANGAKINO

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The recent exploration of the Mangakino geothermal field was based on: 1) new MT-TDEM data which identify a low-resistivity layer consistent with an areally extensive hydrothermal clay cap; 2) the known shallow resource encountered in Crown exploration well MA-1, drilled in 1986 with a maximum temperature of 185°C; and 3) discharge geothermometry of MA-1 and widely spaced surface features that indicate a 250°C resource. Exploration well MA-2 targeted an apex in the generally flay-lying clay cap, and was drilled to a depth of 3192m through massive ignimbrite. High-temperature fluids (250°C) but very poor permeability (injectivity <1 tonne/hour-bar) were encountered at total depth. MA-3 and MA-2A targeted potential structural targets in a re-interpreted fault-hosted reservoir model. MA-3 encountered insufficient temperature (150°C) and the only permeable zones were cool inflows. MA-2A was impermeable. MA-4 targets an intense resistivity anomaly close to MA-1, and well-completion data is yet to be obtained.

The geology encountered in the four new wells is consistent with that expected in a deep caldera complex. Basement was not encountered, indicating there is at least 3200m of caldera infill, composed largely of welded ignimbrite. At least 8 massive welded ignimbrite units greater than 100m thick were encountered, with a maximum thickness of 600m and all units exhibiting very little lithologic variation. Minor thin polylithologic volcaniclastic horizons likely reflect the basal lithic-rich zones of ignimbrites and re-sedimented pyroclastics accumulated between ignimbrite eruptions. The 340 ka Whakamaru Ignimbrite ponded in the Mangakino caldera to a maximum thickness of 300m, overlying thick (200-400m) ‘Ohakuri formation’ volcaniclastics and lacustrine sediments, which reflect deposition after the last phase of Mangakino caldera collapse.

Drill cuttings from the Mangakino wells showed a smectite-illite transition zone between 500-800m. MA-2 was the only well deep enough to encounter epidote, occurring in trace amounts below ~2200m. Lithologically the wells are very similar, with the exception of MA-3 which encountered two weakly-altered rhyolite intrusives at 1170-1425m and 1825-1860m. These intrusives are considered as feeder-dikes to the nearby rhyolite dome field and are associated with cold water inflows that ultimately led to the abandonment of MA-3.

PUTAUAKI EXPLORATION UPDATE

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The Kawerau geothermal field is located on the north east boundary of the Taupo volcanic zone. Early resistivity measurements in 1969 and 1970 suggested a field area of about 10km^2 although the surface activity is mostly concentrated in a 2km^2 area. Later soundings to greater depth identified an anomaly to the east with the Kawerau geothermal field now enclosing an area of between 19 km^2 and 35km^2. This new larger area to the east situated largely on Putauaki Trust land was the target of exploration drilling by Mighty River Power (MRP).

MRP began exploring the eastern extension of the Kawerau geothermal field by running Magnetotelluric (MT) and Time Domain Electro-Magnetic (TDEM) surveys. The MT-TDEM surveys and existing well data have been used to identify the extent of the productive reservoir. This productive reservoir extent in turn is used to guide the drilling program. Production wells are targeted within the productive reservoir and reinjection wells are targeted further away, on the margins but within the geothermal reservoir. The results from the drilling program are then used to evaluate the original interpretation of the geophysics and adjust it as necessary.

Most of the existing at Kawerau production is from the volcanics or weathered top of the greywacke. Historically the greywacke itself has not been considered as a reservoir rock. A key aspect of the MRP development plan for Kawerau is to use the basement greywacke as the reservoir rock deriving production from the fracture network that was predicted in the hot basement. This has required drilling deeper than any existing well at Kawerau. Testing during drilling has been used to evaluate wells so that they can be completed early if sufficient permeability has been found or drilled on until the fracture network is encountered.

Six wells have been drilled by MRP to date. The well drilling has confirmed the interpretation of the geophysical surveys and has proven the greywacke as a reservoir rock. Both production and reinjection areas have been identified. MRP is confident in production from the greywacke and therefore the drilling of up to two more confirmation wells to verify the permeability structure of the greywacke is planned.

Latest Developments in Subsidence at Wairakei-Tauhara

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Subsidence was first detected at Wairakei geothermal field by repeat leveling surveys of benchmarks during output tests prior to commissioning of the power plant in 1958. Minor subsidence now affects virtually the entire field, while a deep (>15 m) subsidence bowl has formed to the north of the Wairakei borefield. Subsidence rates within this bowl accelerated to a maximum of almost 500 mm/year in the 1970's, but have gradually declined to a maximum of 87 mm/year (relative to the survey origin) now. Outside the subsidence bowl, rates have increased in recent years over most of the Wairakei field, particularly in the Te Mihi-Poihipi area. A second subsidence bowl, or possibly an extension to the Wairakei bowl, has appeared west of Poihipi Road and north of Karapiti in the most recent (2004) survey, with a maximum subsidence rate of 52 mm/year.

Subsidence was first observed at Tauhara in the 1960's, but it was not until 1999 that two separate subsidence bowls were distinguished, after benchmarks installed in 1997 were resurveyed. The 2001 survey revealed yet another subsidence bowl in the Crown Road area on the outskirts of Taupo. The 2004 survey data now indicates that a fourth subsidence bowl has appeared at Tauhara, south of Centennial Drive between Owen Delany Park and Rakaunui Road. 2001-2004 subsidence rates in the Tauhara bowls range from 51 to 88 mm/year.

Subsidence of geothermal origin is superimposed on tectonic movements, which affect some parts of the field more than others. The survey origin is known to be subsiding, while the 2004 survey points to a broad tectonic tilting away from Lake Taupo that was not apparent in previous surveys. This has partly to completely cancelled out the geothermal subsidence in southern Tauhara, though the subsidence bowls and the differential movements around them remain.

The recent changes in the behaviour of subsidence due to geothermal extraction, including the appearance of new subsidence bowls, is consistent with previous predictions by SKM.

Taupo-Wairakei subsidence reassessment with the help of InSAR, GPS monitoring and the Boltzmann function

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The significance of observed changes in subsidence rates in specific parts of the Wairakei-Tauhara geothermal field at Taupo has been reassessed by considering new (2004/5) field-wide leveling by Energy Surveys, satellite-based ground deformation images since 1996 from differential radar interferometry (InSAR), and continuous GPS monitoring since 2002 at the GEONET permanent geodetic site at Taupo airport. The observed GPS-derived vertical level and horizontal changes are variable in time over periods of several months to years (between about -10 and +20 mm/yr). Because such changes are occurring outside the geothermal system they are presumed to be of tectonic or deep magmatic origin. Despite limitations caused by vegetation growth, some 3-year differential InSAR images reveal patches of coherent deformation, particularly in urban areas, that match the leveling results. A recent Envisat InSAR image reveals consistent anomalies over larger areas which include parts of the main subsidence bowls. Significant geographic differences in deformation rates, plus and minus, can be seen across the Taupo region, both inside and outside the geothermal field. These new methods provide an effective means of constraining and interpolating contours from traditional leveling surveys and distinguishing between subsidence rate changes that are of natural tectonic origin from induced origin.

Despite a significant amount of historical leveling data for calibration purposes, predictive modeling of the subsidence anomalies at Wairakei and Tauhara has proven to be difficult and controversial, largely because of the large number of unknown subsurface parameters that affect pressure changes, the rate and amplitude of the compaction process, and the resulting subsidence anomalies. To help overcome this difficulty, a simple analytical model using Boltzmann functions to fit the observed historical changes in subsidence rates at specific sites, has been devised. These functions provide an alternative, and in some aspects superior, means of extrapolating subsidence behavior into the future, under a status-quo scenario. The principal assumptions inherent in a function fit of this type are that the maximum amount of potential compaction within anomalously compressible formations is physically limited, and that the process of compaction can be approximated by a diffusion equation with two time constants. These relate to the date of the midpoint (or inflexion in the rate curve) and a diffusion coefficient which affects the spread of the curve. The diffusion coefficient is probably controlled by the permeability and resulting rate of pressure change migration through the formation, but also by the exponential decay factor that governs the slow plastic response of compacting clays to pressure drop. Fitting Boltzmann functions to observed rates at the centre of the Wairakei anomaly (benchmark p128) results in maximum predicted additional accumulated subsidence to 2050 (under status-quo pressure conditions) of 0.5m (ie. 3% of the existing total of 15m). At the Crown Road anomaly in Taupo there is greater uncertainty because of the limited duration of the subsidence event but the best function fit predicts an extra 0.33m by 2020 at the centre (RM59), relative to an accumulated total subsidence of 0.46m between 1980 and 2005.

A New Method for the Prediction of Reservoir Subsidence

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Subsidence may be defined as the slow sinking of the land surface. While it may occur naturally subsidence may also be caused by the extraction of fluids from groundwater or geothermal reservoirs. The reduction in pore pressure can lead to compaction of reservoir rocks and the subsidence of overlying rock. In some cases, such as at Wairakei, subsidence may be several meters at the ground surface.

A key tool in mitigating subsidence is the reinjection of produced fluids to reduce pressure decline, particularly if this can be targeted to provide pressure support in the weak porous sediments most likely to be responsible for most subsidence.

A number of approaches, each with strengths and weaknesses, are available to predict subsidence and to investigate the effects of different production/reinjection scenarios on surface deformation. In this talk we will develop the theory of an extension to the compacting disk model of reservoir subsidence due to Geertsma. Normal Geertsma theory is extended to arbitary shaped disks and combined with a reservoir simulation model. This permits a simple dynamic description of the surface subsidence caused by fluid withdrawal from the reservoir.

Spatial correlation of well performance

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Defining the area of a geothermal field by drilling raises the question of how densely need the wells be drilled? Given a successful well, how large an area around it can be regarded as productive? This is similar to the proving of a mineral deposit, except that permeability in a geothermal field is typically very random, compared to relatively smooth variation of an ore deposit. Well performance depends primarily on two factors, temperature and permeability. Temperature varies relatively smoothly, but permeability can be highly heterogeneous.

Standard geostatistical methods were applied to well success at Kawerau. All wells greater than 500m depth were used, which raises the further problem of comparing 1960s wells drilled to 600m to recent wells finding permeability at 2km. This problem was ignored. Semivariograms were constructed for two statistics: steam flow at 7 bar gauge, and well success. Well success was defined as 1 if the well was commercial, 0 if it was not.

Well success is correlated over short distances, 200m or less, whereas well flow is correlated up to 500m. This latter reflects the effect of temperature – a high well flow requires high temperature, which in turn implies high temperatures within several hundred metres, improving the likely steam flow within that distance. By contrast well success, which primarily reflects permeability, is correlated over shorter distances – the chance of a new well being highly permeable is better within 200m of a highly permeable well, presumably because of the possibility of intersecting the same structure. Beyond 200m there is no relation. Permeability is random over distances greater than 200m.

For the purposes of field proving, the 500m radius of influence of well flow is the appropriate criterion.

Construction of the Tokaanu Hydro-power Scheme during 1966/69 over the southern sector of the Tokaanu Geothermal System

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The Tongariro Power Development, a major hydroelectric scheme, was started in the early 1960’s. A key feature was the construction of the Tokaanu Power Station which, together with the 6 km long, water-supplying Tokaanu Tunnel, had to be erected and dug within the southern sector of the high temperature Tokaanu geothermal reservoir. When foundation drilling for tunnel and powerhouse began, the actual extent of the geothermal field was poorly known.

By the middle of 1966 work in the tunnel had reached sections with intense thermal rock alteration which were associated with elevated temperatures at tunnel level (up to 42 deg C). Simultaneous foundation studies at the power station site and over the tailrace canal encountered boiling temperatures in volcanic sediments at the bottom level of the planned canal which, in turn, caused short-lived geysering discharges of boiling water in several shallow investigation holes. Continuous temperature monitoring and detailed geological mapping in the tunnel showed that completion of the tunnel in a safe manner was feasible. The high ground temperatures beneath the tailrace and close to the power house led to a re-design of the canal adopting rather shallow and wide sections over the hot ground areas. Dredging of ponds to the revised bottom level and a sequence of pumping tests, using also monitoring of temperature and chemistry of pond and infiltrating waters, showed that dredging of the whole canal section was feasible. That work could finally be started in late 1969.

The geological and temperature section of the tunnel project are presented in this paper together with a geological and temperature section of the ’hot’ tailrace canal segment. The geological and temperature logs of the 130 m deep hole G 168 located within the hot tailrace stretch (and attaining a maximum temperature of 175 deg C at the bottom) is also shown. An analysis of the pumping tests of ponds which had filled up with diluted thermal water is presented. The results clearly show that a hydrothermal eruption did not occur during the pumping tests of the ponds, thus dispelling rumours of such an inferred event which have been circulating in the NZ geological and engineering fraternities since completion of the Tokaanu power house project.

The Distribution of the Geothermal Fields in the Taupo Volcanic Zone, New Zealand.

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The Taupo Volcanic Zone (TVZ) is a 150 km x 30 km region of intense volcanic and geothermal activity in the North Island of New Zealand. The 23 individual geothermal fields in the TVZ are distributed about the margins of this region, with approximately 75% of the total heat output of 4200 MW coming from the eastern geothermal fields. Numerical modelling of the entire TVZ hydrological system using a 'super-critical' version of TOUGH2 has been carried out. This shows that the geothermal fields form around the boundary of a high permeability 'TVZ envelope', which is defined by the Taupo Fault Belt and the known recent volcanic calderas. A heat sweep mechanism is identified, where descending cool surface waters are heated at a depth of about 8 km, and are then swept laterally to the lower permeability boundary of the TVZ envelope, where they ascend in discrete plumes to the surface to form the geothermal fields. The locations of these plumes can be identified with most of the major geothermal fields in the TVZ (Tokaanu, Lake Taupo, Wairakei and Tauhara, Rotokawa, Ohaaki, Waiotapu and Waikite, Tikitere, Rotoiti and Rotoma, Rotorua, Mokai). In addition, the model predicts two bands of convective upflow across the TVZ, both of which correspond roughly to the known geothermal features of Ngatamariki and Orakeikorako in the south, and Lakes Rotomahana and Tarawera in the north. The model correctly predicts the absence of geothermal fields in the central region of the TVZ, and the circulation time and magmatic water content of the geothermal fluids derived from the model are consistent with values inferred from isotope chemistry.

THE REMOVAL OF ARSENIC FROM GEOTHERMAL FLUIDS BY ELECTROCOAGULATION

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Electro-coagulation (EC) treatment appeared, at the outset of the investigation, to offer a simpler and more cost-effective method of removing arsenic from separated geothermal water (SGW) than the traditional treatment methods of coagulation and flocculation. It is an electrochemical process that uses direct current to remove a wide range of contaminants. There are many benefits of this technology but primarily EC drastically reduces the use of chemicals and hence reduces operational costs. It generates less sludge compared to other technologies and the effluents are more likely to be suitable for discharge to surface waters. This method has the potential to allow efficient downstream utilization of heat in low enthalpy fluids through cascaded direct use applications and provide a more cost effective disposal option than reinjection.

The laboratory electrolytic cell consisted of a 1 L reactor with a 1.5 L reservoir for settling the floc. Wairakei fluid (pH 8.3, SiO_2 533 mg/L, As 4 mg/L) was circulated through the apparatus past electrodes (Al or Fe, 80 cm^2 geometric surfaced area, separation ~ 5 mm) connected to a power supply through which the current and voltage could be varied independently (typically ~1.5 A, 5-10V). Samples were taken at known time intervals for analysis. Thirty experiments were completed and the main findings were that:

1. EC quickly removes silica from geothermal fluids to less than amorphous silica saturation. Typically for cooled aged fluid the silica was reduced to <100 mg/L in ~6 minutes using Al electrodes and ~8 minutes with Fe electrodes.

2. The time to reduce the concentration of silica in hot fresh fluid at 81^oC (i.e. little or no silica polymer or colloid) increased to 14 and 28 minutes for Al and Fe electrodes respectively.

3. Dosing cooled aged brine to pH <5 caused a significant increase in the silica precipitation rate, down to 2 minutes using Al electrodes and 4 minutes with Fe electrodes.

4. The removal of As was inefficient using Al electrodes; in fluid aged 1-3 days it took between 20 and 26 minutes to remove half of the As (down to 1.5-2 mg/L) while in fluid aged for 3 weeks the As reduced to 0.5 mg/L over a similar time period. Dosing fluid which had been aged for only a few days with hydrogen peroxide increased the removal rate to < 0.5 mg/L in 16 minutes.

6. The removal of As with Fe electrodes was significantly faster than with Al and occurred co-currently with the precipitation of the silica; viz. to < 0.5 mg/L in 8 minutes.

Initial costs estimates for consumables were for power $0.05 per tonne and electrodes $0.01 per tonne. By comparison chemical costs alone for the conventional chemical treatment process were estimated in 2001 to be $0.25 per tonne.

This work was funded by FRST under Contract C05X0201.

Precision water bore temperature logging as a tool for geothermal energy exploration

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The geothermal energy industry in Australia is in its infancy. Lacking historic volcanic activity, applications to date have been restricted to low enthalpy direct uses and very small scale electricity generation. Recent exploration and development activity in South Australia, however, has highlighted opportunities for large-scale electricity generation from deep, high enthalpy resources. The main obstacle to large-scale development is the remote location of known resources with respect to the national electricity grid. This provides a strong economic incentive to locate high enthalpy resources closer to the transmission system.

Southeast South Australia is considered prospective because it has some of the youngest volcanic features in Australia. The area is extensively covered by regional geophysical data, but gravity and magnetic data are poorly suited to explore for geothermal energy targets in the region. The “Obswells” network of groundwater monitoring holes, however, provides a distribution of shallow boreholes across the Western Otway Basin region, many of which pass through the Dilwyn Formation, a sandstone aquifer of relatively consistent local lithological composition. In this study, we measured thermal gradients within the Dilwyn Formation sections of the Obswells bores, and used the data as proxies for heat flow, to identify variation across the region.

Thermal gradient in the Dilwyn Formation varies by a factor of two across the 14 bores accessed in this study (Figure 1), implying a similar variation in heat flow. Where water bores coincide with petroleum exploration wells, the deeper data from estimated bottom hole temperatures confirm the heat flow estimates obtained from the shallow boreholes. Thermal data from the Obswells bores have been instrumental in targeting future drilling programs in southeast South Australia to confirm the existence of geothermal resources.

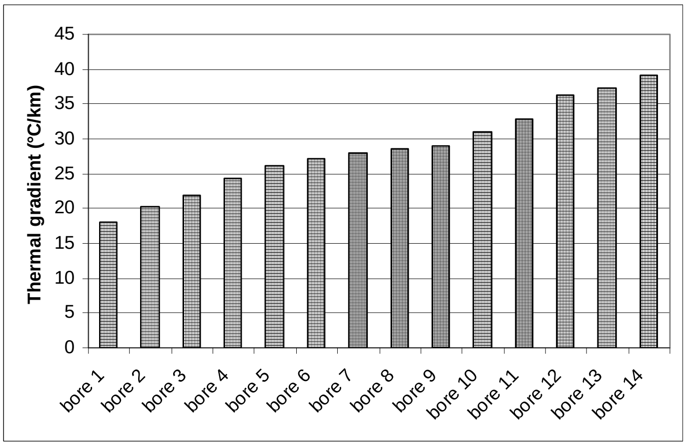

Figure 1. Spread of thermal gradient values in the Dilwyn Formation within the Obswells network

ESTIMATION OF HEAT DISCHARGE RATES FROM UNZEN GEOTHERMAL AREA, JAPAN, BY USING HEAT BALANCE TECHNIQUE

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The heat discharge rates of 6 geothermal units (Kyu-Hachiman-Jigoku, Seishichi-Jigoku, Hachiman-Jigoku, Oito-Jigoku, Daikyokan-Jigoku and Ko-Jigoku) in Unzen geothermal area, Nagasaki Prefecture, Western Kyushu, were estimated by the heat balance technique (Sekioka, 1983) using the thermal images taken from the disaster-prevention helicopter of Nagasaki Prefecture on 9 September 2004. And in order to comprehend the temporal change of micrometeorological conditions and the coefficient of geothermal flux (L), which is essential for the heat balance technique, we manufactured an automated continual measurement system and measured micrometeorological data at the Kyu-Hachiman-Jigoku geothermal unit from 17:20 on 8 September to 15:50 on 10 September, 2004 with a 10-minute interval. The values of L, which is calculated from the obtained data, showed a turbulent change in a wide range and a high negative correlation with the atmospheric humidity.

The values of the coefficient of geothermal flux, which were interpolated from the 31-point moving average of the values of L by the measurement system, were used for the heat discharge estimation. The amount of heat discharge from the 6 geothermal units is about 40 MW. This value is about 5 times greater, and the heat discharge of each geothermal unit is about 2 to 20 times greater than those estimated by Yuhara et al. (1981) by using the data obtained in 1978. One of the reasons is that the value of L adopted by Yuhara et al. (1981) was smaller than the values we used for the heat discharge estimation. Another reason may be the effect of the latest eruption of Unzen Volcano. It is inferred that there is one of three magma chambers of Unzen Volcano beneath Unzen geothermal area, and it is conceivable that the activity of the 1990-95 eruption of the volcano increased the heat discharge rates of Unzen geothermal area.

References:

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Basinal Analysis of the Taupo Volcanic Zone as a Guide to the Prospectivity of its Geothermal Fields

by

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Basinal analysis is widely used as an oil exploration tool, partly because cap rocks have predictable distributions in sedimentary basins. Geothermal fields also require cap rocks. Not to trap and maintain pressures in reservoirs as in oilfields, but to prevent the influx of cold waters that may restrict hot waters to too great a depth to exploit; or in exploited fields, to prevent the excessive influx of cold water upon draw down to cool them and contribute to well scaling. For geothermal systems in basins that contain cap rock sediments, basinal analysis may likewise offer a predictive tool to evaluate the prospectivity of geothermal resources, by consideration of the possible distribution of cap rocks.

Basinal geothermal systems with low salinities are thermo-artesian, thus without a cap deep hot waters have the potential to ascend to the surface over their upflows, limiting the development of overlying groundwater aquifers, unless the upflow is under a local topographic high within the basin such as a rhyolite dome complex. Deep, low salinity geothermal waters in basins have low calcium concentrations, which even where there are overlying groundwaters, limit the scope for anhydrite and calcite deposition by the mixing of reservoir waters and the waters of groundwater aquifers that have absorbed geothermal gases. Silica deposition can occur on the side of a geothermal reservoir by mixing as a consequence of the non-linearity of silica solubility with temperature and by relatively higher silica concentrations in groundwater aquifers in which the silica concentration is not controlled by quartz. Shallow silica deposition will be stronger above the centre of the upflow in systems without overlying rhyolite domes, due to boiling and adiabatic cooling. Such sealing will be inconstant, since it will be subject to brittle fracture upon tectonism. So unless the basin has low rainfall and thus limited groundwater aquifers, geothermal reservoirs will be in direct hydrological connection with significant, shallow ground water aquifers if there is only mineral-deposition capping. Hence, to maintain an effective cap over low salinity basinal systems and thus increase their economic viability requires that shallow low permeability lithologies are present to act as cap rocks. In the non-marine basins that are likely to host exploitable geothermal fields, this requirement can be met by thick, fine grained lacustrine siltstones. Their distribution in basins is dependent upon the location and persistence of lakes, and the rate of sedimentation, which is dependent upon the nature of the basin.

In the case of the segmented rift of the TVZ, basins have formed in its central and northern segments and their contiguous accommodation zones. These basins have formed due to an interaction of rifting and the formation of calderas - which are favoured to form in large accommodation zones. Outside of the large accommodation zones the greatest subsidence is along the rift axis, but is likely to have received its greatest sediment load from the east where isostatic uplift of the rift margin has occurred. Therefore lacustrine sediments are likely to be thickest east of the rift axis consistent with their thickening in this direction at Wairakei. In the case of calderas, the persistence of intra-caldera lakes is dependent upon the interaction of the pre-caldera topography, ongoing tectonism and their consequent drainages. Calderas that form outside of major regional drainage networks can have persistent lakes, but if the caldera is within a major drainage there will eventually be an outlet breach and restriction of the lake's persistence. The blocking of major drainages by the uplifted area east of the rift means that calderas on the eastern part of the rift may have both more persistent lakes and high rates of sedimentation.

If thick, fine grained, shallow, lacustrine sediments are a necessary requirement for geothermal systems in the TVZ to be prospective, such systems should preferentially be located to the east of the rift axis; the large accommodation zones are filled by current lakes and systems in them are not currently exploitable. However, since the TVZ does not have a solely sedimentary filling, local variations in basin filling due to volcanic activity complicates this pattern, this includes: young impermeable ignimbrite as a cap rock (eg Mokai), the presence of rhyolite domes as islands in lakes preventing complete formation of a cap (eg cold water inflow and well scaling at Ohaaki), explosive activity removing part of the cap (eg cold water inflow on the western side of Kawerau) or the overlap with an earlier volcanic arc complicating the drainage pattern (eg the persistence of Lake Rotorua). Therefore, basinal analysis can be a general, but not a specific guide, to the prospectivity of geothermal fields in the TVZ.

Hydrothermal Alteration Mineralogy of the Lahendong Geothermal System, North Sulawesi, Indonesia: a Progress Report

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Lahendong is a hot-water dominated geothermal system located in the north arm of Sulawesi Island, in Quaternary volcanic terrain about 750 m above sea level. Cores and cuttings from 9 of the 18 wells drilled in the system were re-examined to determine its subsurface geology and to construct the hydrothermal history of the field. There are two styles of alteration in the subsurface, namely replacement of the primary minerals and secondary minerals in fractures and cavities. The hydrothermal fluid-rock interactions at depths have produced clays, calcite, anhydrite, pyrite, iron oxide, quartz, actinolite, adularia, albite, epidote, prehnite, pumpellyite, and wairakite. Most of the subsurface rocks have undergone a pervasive alteration, producing a sequence of secondary minerals. The hydrothermal mineral parageneses in 59 cores were studied to characterise the changes in physical and chemical conditions that have taken place in the geothermal system.

In most of the studied wells, there are 5 stages of vein & cavity mineralization although a stage in one well might not correspond to the same stage in other wells. Stage 1, usually characterised by the extensive chlorite, but sometimes with hematite and pyrite, represents the earliest surviving record of the early geothermal system, when the reservoir fluid was liquid.

Stages 2 and 3 are marked by calcite and quartz, respectively, formed when the fluid boiled and cooled. Albite, adularia, prehnite, epidote, and actinolite appeared during the stage 4, and marked the hottest regime ($\geq 250\ ^{o}C$) in the system. The complex deposition textures in the stage 4 veins probably reflect the complex pattern of fluid flow at this stage. Sporadic occurrences of anhydrite, some with calcite and pyrite, may be due to the incursions of steam condensates into the hotter part of the system.

The last stage (stage 5) possibly reflects the present-day conditions, and in some parts of the system this interpretation is supported by the present day temperatures measured in the deep part (1000 – 2500 m) of the system, i.e. 250 – >350 ^{o}C. In the marginal wells (LHD-3 and 7) the absence of high-temperature indicator minerals in veins assigned to this stage and the occurrence of hematite in veins together with late calcite and late quartz are consistent with the lower temperature now measured there.

Low-Enthalpy Springs of the Waikato Region

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Nearly 40 low-enthalpy hot spring systems, outside the Taupo Volcanic Zone, have been reported in the Waikato Region from the mid-19th century to the early 1980's although only about 34 are still extant. Most of the springs occur along or in the middle of rivers and streams e.g.,Waihou, Waitoa, Manawaru, Waingaro, Maire, etc and therefore are often admixed with river water. Two are intertidal e.g., Hot Water Beach in Coromandel and Te Puia in Kawhia. About 16 areas have boreholes supplying swimming pool complexes (e.g., Miranda) and sometimes for domestic purposes (Crystal Springs, Waitoa). Because of their location along waterways most springs emerge from Recent alluvial sediments or Pleistocene siltstone, sandstone and gravel terraces. These overlie Mesozoic greywacke, ignimbrite flows or Miocene andesite.

Spring discharge temperatures range from 22-65^{o}C and shallow boreholes drilled adjacent to springs discharge 70-85^{o}C waters. Most springs discharge HCO_3 and HCO_3-Cl waters with very low SO_4 contents. Chloride concentrations range from 11 to 580 mg/kg with Te Puia and Hot Water Beach Cl concentrations of 1200 to 11000 mg/kg affected by seawater contamination. HCO_3 ranges from 13 to 6700 mg/kg. Silica temperatures indicate subsurface temperatures ranging from 40^{o}C in Manawaru to 160^{o}C in Waitoa.

The HCO_3/Cl ratio generally increases from west to east in the Waikato, with some of the highest values found in springs located along the eastern fault margin of the Hauraki graben with ratios mostly at >10. These are the springs with the highest silica temperatures at 120^{o} to 160^{o}C. Most of the high HCO_3 waters are oversaturated with respect to calcite, witherite, various smectite species, dolomite and siderite. Precipitates in these springs consist of mostly of calcite, monohydrocalcite and rarely, some aragonite. The high silica temperatures in springs along the eastern fault margin of the Hauraki graben is supported by calculated saturation indices (log Q/K) that indicate equilibration to albite, zeolites and smectite at 80^{o}C to 170^{o}C.

HYDROTHERMAL SYSTEM OF RAOUL ISLAND: PAST AND PRESENT

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Raoul Island is located ~1155km northeast of Auckland, and is an active caldera volcano with an area of approximately 30km^2. It has had witnessed eruptions in 1814, 1870 and 1964 and records a Holocene history of explosive eruptions. The central geothermal system represents one of only two rare sub-aerial manifestations of hydrothermal activity of the Kermadec arc.

Hydrothermal activity within Raoul caldera occupies the Green Lake eruption site of 1964. Geothermal manifestations are concentrated along the western side of the lake, with further activity located inland along Fumarole Ridge. Activity includes bubbling within the lake and several vigorous hot springs of near-neutral pH, concentrated on the silicified ridge jutting into Bubbling Bay, where sinter and geyserite are common. The dominant thermal feature is warm and steaming ground. Much of the ground in the near vicinity of the lake shore is moist and has temperatures exceeding 90 °C at 10cm depths. The general area appears to be largely affected by steam-heating of the pyroclastic host rocks, with no evidence for acid sulfate fluids.

Altered rocks found in the 1964 and 1870 hydrothermal eruption breccias revealed mineralogy with implications for the hydrothermal system at depth. Intensely altered samples display propylitic alteration assemblages comprising secondary quartz, epidote, chlorite, pyrite, actinolite, albite, adularia, titanite and late stage calcite alteration. Secondary quartz crystals have both liquid rich and gas rich fluid inclusions, with at least two samples showing the presence of halite daughter minerals, hence, reflecting strongly saline hydrothermal waters at depth of likely magmatic origin.

Although the 1964 eruption was initially interpreted as phreatic in nature, the discovery of possible juvenile magmatic material in the 1964 breccia suggests that the hydrothermal explosions may have a magmatic trigger. This interpretation is reinforced by earlier observations of fresh pumice rising to the surface at Denham Bay in 1964.

Overall, the hydrothermal system appears as though it may be transient at best, waxing and waning according to new influxes of hydrothermal fluids from depth, or disruption by magmatic inputs. The modern hydrothermal system appears to be dying based on declining temperatures and diminishing surface activity. The ‘normal’ state of the caldera may be to not have a hydrothermal system, contrasting with the apparent long-lived steady state of submarine hydrothermal systems along the Kermadec arc.