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The Role of Advanced Geophysical Monitoring in Improved Resource Expansion and Make-up Drilling Strategy

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ABSTRACT

Geophysical monitoring tools such as micro-gravity, micro-seismicity and ground deformation provide geothermal reservoir modellers and resource managers with improved information on reservoir behaviour, especially when fields are under development. As-a-consequence, better production and reinjection strategies can be tested, and future operational scenarios can be fine-tuned to improve utilisation sustainability. Advanced and novel monitoring methods also help improve forecasts of near-surface environmental effects and monitor the results of mitigation efforts undertaken through adaptive reservoir management. This paper reviews current knowledge gained from such methods and discusses the potential for using this knowledge to help develop better strategies for resource expansion and make-up drilling strategy.

Recent advances in research into continuous monitoring techniques using geophysical methods include the use of: micro-gravity, seismic-tomography, ground-deformation, repeat resistivity and various forms of remote-sensing. Knowledge has also been gained from reviewing the decades of monitoring of physical changes that have occurred in conventional geothermal projects around the world. To make full use of this information, and to accurately simulate geophysical property changes resulting from reservoir fluid and heat transport, advanced reservoir modelling benefits from coupled thermal, hydraulic, mechanical, and chemical (THMC) processes. Consequently, rock properties used in reservoir simulation, such as permeability and porosity, are variables rather than constants over the lifetime of a reservoir.

The benefits of this improved understanding of reservoir processes is an improvement in conceptual models of geothermal resources and therefore better projections of their sustainable energy extraction capacity and recharge parameters. This knowledge is also applied to exploration and expansion strategies to provide better drilling targets and improved production-reinjection strategies for well-established, but aging, geothermal developments.

1. INTRODUCTION

Geophysical monitoring techniques applied to producing geothermal fields are becoming significantly more advanced and sophisticated. The results have helped improve simulation models of the behavior of geothermal reservoirs when fluids are extracted and/or injected. The physical changes to fluid and rock properties, that are induced by fluid pressure, temperature and flowrate changes, can, in principle, be detected remotely using methods such as micro-seismic (MEQ) velocity tomography, MEQ amplitude attenuation, gravity change, resistivity and magnetic field changes, remote sensing of surface heat-loss and ground deformation mapping. By making better use of these geophysical tools, our understanding of the dynamic response of reservoirs to various levels of energy extraction, and various production/injection strategies, will improve. We can apply this knowledge to exploration, expansion and make-up drilling strategies as well. The overall objective is to reduce the cost of drilling required to expand or sustain energy extraction, and thereby to improve the overall economics of future geothermal development.

Conventional geophysical exploration methods for geothermal resources have generally concentrated on : a) resistivity to delineate reservoir structure (typically consisting of heat source, fluid up-flow, clay cap and fluid outflows), b) gravity to help map subsurface contrasts in rock density (caused by differences in lithology, hydrothermal alteration products, silicification or dissolution of minerals over geological timescales), c) magnetics to map subsurface contrasts in magnetization (lithology or hydrothermal alteration), and d) active seismic surveys to map subsurface velocity structure, or to detect reflecting horizons. These are static surveys, a snapshot in time, and, unless repeated with suitable precision, do not provide information on the dynamic behavior of reservoir fluids and host formations under various potential extraction scenarios. This dynamic behavior strongly depends on lithologic permeability and interconnected fracture networks.

Permeability is the most important unknown when initially setting up simulation models of a reservoir, in-order-to predict long term performance and to provide economic justification of resource capacity for installing power plants or other forms of energy extraction. Unfortunately, reservoir permeability is not a parameter that can be measured directly using these exploration geophysics methods. Inferences can be drawn by integrating exploration models from different disciplines (e.g. geophysics, geology and geochemistry) to develop a conceptual hydrological model, but, in the end, deep exploration drilling into the reservoir itself is usually required before development options and investment levels can be considered. This is an expensive step. Many promising-looking new geothermal projects have failed because of poor permeability encountered by the exploration wells. The consequences are increased risk factor for investors and increased profit expectations from those projects that are successful, in-order-to compensate for the other failures. Any improvement in the initial conceptual models of reservoir permeability distribution, and development over time, would therefore be very well received.

The key geothermal conceptual model parameters that are usually poorly known in advance, but are necessary to make robust reservoir models and long-term performance predictions, are listed below:

- Fracture zone or fault locations: controlling influence of fracture distribution on permeability (K) and fluid flow
- Effective porosity: fluid storage and potential recharge
- Reservoir compartments: inter-connections and long-term sustainability
- Upflow locations: prime hot recharge: depths, temperature and chemistry
- Downflow locations: usually adverse cooling but beneficial pressure recharge effects
- Permeability & temperature gradients with depth : deep drilling prognoses
- Injectivity stimulation prognosis, to reduce the need for future make-up wells
- Permeability ‘boundaries’ beyond the extent of drilled wells

Conceptual model improvements that are anticipated to arise from better integrated geophysical observations (both static and monitoring surveys) are listed below:

- Reservoir top: lower-strength (yielding) and lower-resistivity smectite clays
- Reservoir base: MEQ – reveals brittle-ductile transition: low permeability, high temperature
- Reservoir thickness: deep injection cooling may cause change from ductile to brittle, increased deep MEQ & permeability
- Upflow locations: resistivity & MEQ, Vp, Vp/Vs, Qp, Qs

  [Note Q=inverse of seismic amplitude attenuation, p=primary or longitudinal wave, s=secondary or shear wave)
- Geomechanical properties: elastic and plastic deformation from thermal & pressure change
- Saturation state (boiling or condensation): precise gravity detects fluid density changes in fractures and matrix
- Reservoir barriers, fluid compartments, permeable conduits, & fracture anisotropy, using MEQ and MT resistivity

2. PRODUCING GEOTHERMAL FIELDS REVIEWED

Examples selected for this review of integrated geophysical interpretation come mainly from New Zealand, the Philippines, Indonesia, and Kenya. Table 1 provides a listing of some key parameters from producing geothermal reservoirs in these countries. These data are obtained from literature and approximated or extrapolated where needed. Together, these examples represent approximately 30% of the global installed capacity. The purpose of this list is to illustrate the similarities, but also the differences, in the respective geophysical responses of a wide range of producing geothermal fields, each with its own unique development management plan in terms of net mass extraction, production targets and reinjection strategies.

An obvious observation from these examples is that many fields exhibit induced seismicity, although two exceptions are Ohaaki and Ngawha in New Zealand. In the case of Ngawha, the explanation may be that the natural state of stress is low (i.e. the field is located outside the tectonically active region, with negligible natural seismicity), and the net mass loss and pressure drop has also been very low (i.e. a relatively small binary plant operation with full infield reinjection). In the case of Ohaaki (located within the tectonically active Taupo Volcanic Zone), the explanation is not so clear. Possibly the natural stress state is locally sub-critical (deformation may be locally accommodated through ductile or creep processes) and the pressure and temperature transients from production have been insufficient to trigger induced seismicity. Reinjection is partial (~70%) and mostly outfield to minimize the cooling effects of reinjection returns. Note also that Ohaaki is the only New Zealand field where well productivity has not been sufficient to sustain the initial installed turbine capacity (current running capacity has been reduced by 50%). Deep hot fluid recharge is limited, and this may be related to poor recharge permeability indicated by the local absence of natural or induced seismicity.

Most other producing fields exhibit ongoing induced seismicity. Typically, events cluster in time and space, and are associated with both production and reinjection sectors and the flow channels linking them (i.e. triggered by both positive and negative pressure changes and injection cooling, as well as the redistributed stress transients from shear failure linked to fluid flow through fracture networks). Maximum magnitudes are typically in the range of 2 to 4 (i.e. felt, but not damaging, earthquakes). The depth range is typically 3 to 5 km, with one example (Wairakei) reaching depths of 7 km. The maximum depth is inferred to indicate a transition to ductile deformation, and probable supercritical temperatures (>400 °C). The permeability is assumed to be constrained because of the absence of brittle failure. This information is often used to establish the bottom boundary in reservoir simulation models. Hence it is an important parameter for estimating sustainable reservoir capacity.

Table 1. Operational and geophysical parameters from selected geothermal fields (approximations extrapolated from literature). (*b)= binary plant; MEQ=micro-earthquakes (typical number/month above a threshold magnitude, maximum magnitude, and maximum hypocenter depth or range of depths); accumulated maximum subsidence in meters and maximum rate in mm/year (+ve maximum uplift rate); accumulated micro-gravity change (+ve or -ve) in mgal; accumulated net mass loss of fluid in Mtonnes (production-injection); and accumulated maximum pressure drop (or +ve increase) in main production horizons and at various stages in development history.

Geothermal Field	MWe	Operate yrs	MEQ /month	MEQ max mag.	MEQ max depth km	Subsidence max;mm/yr	uGravity mgal	Massloss Mt net	Pressure drop MPa
MacBan	400	35	~75	2.9	3 - 5	-1 33	-0.7	750	4.5 5.5
Tiwi	200	38	~80	2.9	4	-3	-0.4 +0.4	900	5.5 6.2(+1.5)
Palinpinon	200	34	~400	2	3 - 5	-0.3 10	-0.5 +0.5	270	6
Wairakei	370	59	~20	3.2	3 - 7	-15 500	-0.5 +0.3	2500	2 2.5 (+.3)
Ohaaki	60	28	0	NA	NA	-7 350	-0.3	200	2.5 3.5 (+1)
Rotokawa	175	20	~100	4.1	3 - 5	+/-0.2 47 (+7)	+0.3	50	4
Mokai (*b)	115	17	~50	3.3	3	+/-0.2 28 (+7)	-.25,+.15	1	1.5 3.5
Ngawha (*b)	25	19	0	NA	NA	-0.04 3	NA	0.2	0.2
Olkaria	670	36	~200	2.5	3.5 - 6.5	NA	-0.2 +0.1	200	1.2
Salak	375	23	~80	3.6	4.5	-0.3 20	-0.3	500	6.8
Darajat	260	23	~10	3.4	3.5 - 5	-0.2 10	-0.15	200	1.6

Another observation from Table 1 is that ground deformation in producing geothermal fields (subsidence or uplift) is common, but the rates and accumulated magnitudes vary significantly between fields. Although the driving mechanism is usually reservoir pressure decline, and propagation of this change to shallower aquifers, the subsidence rate is not closely related to the amount of pressure change. This is because the variable that has greatest influence on subsidence rates is rock compressibility (especially plastic yielding of smectite clay). Other causes of elastic ground deformation are cooling contraction or pressurized inflation from injected fluids (especially if relatively shallow, e.g. Rotokawa and Mokai). Micro-gravity changes are also common and typically fall within the range of -0.7 to +0.5 mgals. The causes are density changes from saturation changes in 2-phase zones (i.e. from boiling or cooler water inflow). The amplitude of the change appears to be greater for boiling liquid-dominated reservoirs with larger net mass-loss, and smaller for vapor-dominated reservoirs (e.g. Darajat, Olkaria). Reinjection strategy and induced downflows of groundwater both have a strong influence. Effective aquifer porosity is an important parameter that affects the amplitude of gravity change. Maintaining a balance of saturation state in 2-phase zones is a key objective for long term operational sustainability. However, some successful projects have been associated with large gravity decline (e.g. MacBan), implying that boiling processes in 2-phase zones can be an important component of sustainable energy extraction.

3. MICRO-SEISMICITY

Locating permeable fracture zones or faults that are seismically active is an important objective for geothermal exploration. Imaging of seismic properties can provide information on the physical properties of rocks and fluids within and adjacent to geothermal reservoirs. Micro-seismic (MEQ) monitoring has long been used, particularly for environmental reasons, at numerous geothermal fields around the world. Summary results from some examples are listed above in Table 1. Initially, hypocenter distribution maps were also used as preliminary indicators of fault-related permeability, especially in resources that are associated with regions of anomalous tectonic or volcanic stress (e.g. above young intrusions, or within extensional basins). Early on it was recognized, however, that not all geothermal resources host natural seismicity, so the passive MEQ monitoring method went out of favor as an exploration method. Subsequently, however, with better-quality 3-component digital data, the ability to invert such data to produce seismic velocity (Vp, Vs, Vp/Vs,), and amplitude attenuation (Qp, Qs) tomography, as well as indications of stress direction, and fracture anisotropy (from fault-plane solutions or moment tensors) has rejuvenated interest (e.g. Bannister et al, 2015, Tezel et al, 2016). Seismic reflection imaging using MEQ as a source has also been proposed (Asanuma et al, 2011). Fang et al (2018) describe a modelling procedure for linking induced seismicity to changes in reservoir permeability by adopting a simple shear dilation – permeability enhancement relationship. Complications (not yet modelled) include the probable occurrence of clay gouge causing partial permeability decrease on faults, also long-term shear slip and aseismic deformation induced by thermal contraction as cooler fluids pass through the fractures.

In liquid-dominated reservoirs, Vp typically increases with depth and is inversely proportional to compressibility, while Vp/Vs is mostly influenced by Vp variations. At deeper levels, temperature has a significant influence on both parameters, and shear waves are attenuated in magmatic melt. Water- and steam-filled pore spaces affect P and S wave transmission differently, so in 2-phase reservoirs, Vp/Vs ratios decrease from liquid to vapor-saturated conditions. S-waves are more strongly affected by anisotropy than P-waves, and shear-wave splitting analysis of the S-waves can reveal the orientation and location of anisotropic permeability along fracture zones.

Sherburn et al (2015) give an overview of the induced and natural seismicity that occurs within and adjacent to many of the operating geothermal fields in New Zealand. Some fields are aseismic (Ohaaki and Ngawha, Table 1). Conversely. seismic tomography and hypocenter distribution from numerous events recorded during many years of MEQ monitoring data at Rotokawa, Ngatamariki and Wairakei fields have been used to draw conclusions regarding the permeability structure of these fields (Sewell et al, 2017, Sepulveda et al., 2016).

Bromley and Majer (2012) addressed the risks and rewards of geothermal induced seismicity, arguing for a balanced view of the risk of damage to surface infrastructure from larger induced events, versus the long-term benefits to a sustainable operation of the continuous generation of MEQ-generated interconnected fractures, which enhances and expands reservoir permeability. Understanding of the triggering mechanisms (cause and effect) has been the subject of much research effort for many years, but the key mechanisms summarized in Bromley and Majer (2012) remain: a) increased pore pressure that decreases normal stress on existing fracture surfaces, allowing critically stressed faults to slip; b) redistribution of thermal stress induced by injection of cooler water into hot rock; and c) redistribution of volumetric contraction stress induced by pressure decline. Hence any pressure transient, small or large, and any change in temperature from injection flow-rate changes, has the potential to become an initial seismic trigger. The natural state condition in the reservoir of numerous critically-stressed fractures, oriented across a wide range of angles with respect to the variable stress transients, allows for the stimulation of persistent 'clusters' or 'swarms' of earthquakes. The timing of the first triggered seismic event, in terms of correlations with operational changes in well flowrate, is sometimes quite obvious, but diffusion effects of both pressure and temperature changes can create significant delays in terms of cause and effect. Sepulveda et al (2016) observes that deep (> 4km) and shallow (~2 km) seismicity at Wairakei occur together in coincident time-clusters, implying that self-triggering acting across large volumes of rock is a significant mechanism, and that, in most cases, stress redistribution following one event will triggers others, rather than a specific production- or injection-induced pressure/temperature transient.

Simiyu (2000) provides a good example from Olkaria, Kenya, of the application of micro-seismic monitoring data and interpreted seismic velocity structure to characterizing a large geothermal reservoir with multiple upflows. Stress along the floor of the Kenyan rift zone is released by MEQ activity in geothermal areas, while larger earthquakes occur along the rift boundary faults. Within the Greater Olkaria region (central rift), cross-sections of hypocenters show localized clustering and several up-doming regions of ductile rock (correlated with high-temperature at depth). The brittle-ductile transition in these regions starts from about 3.8 km depth and the anomalies are inferred to be related to magmatic (intrusive) heat sources at about 6 km depth beneath the known Olkaria reservoirs. Anisotropy in the stress and heat source orientation is inferred from Poisson's ratio distribution versus azimuth and depth. Low Vp/Vs anomalies in several production zones are interpreted to be due to exploitation-induced phase changes caused by : pressure drop and boiling, high steam saturation, high crack density, high CO_2 gas or very high temperature (or some combination of these). The resulting conceptual model is strengthened by integration with other geophysical data (aero-magnetics and resistivity).

Numerous reservoir studies using geophysical monitoring techniques have been published for The Geysers field in California. An example by Tezel et al (2016) discusses the use of seismic tomography images as a monitoring tool through time (4D). Lin and Wu (2018) present a comprehensive study of seismic velocity structure at The Geysers which confirms that Vp is mainly influenced by rock composition, while Vp/Vs anomalies are correlated with fluid content: low values map the extent of the geothermal reservoir. A change in the mix of focal mechanisms (more reverse type relative to the common normal and strike-slip types) between 2008 and 2012 was tentatively linked to a period of deep injection stimulation in Northwest Geysers, causing local cooling and volumetric contraction.

3.1 Coupling MEQ and MT

In principle, both seismic data and magneto-telluric (MT) tensor resistivity data contain embedded information on anisotropy and so the coupled inversion of good quality MT and MEQ data should produce a more robust 3D model of subsurface fracture zones to assist with modelling reservoir structure and help target exploration or delineation wells. In practice, however, the interpretation process is complicated by the variety of rock and fluid properties that can influence seismic and electro-magnetic wave propagation. An example is the presence of clay along faults (gouge) which forms an electrical conductor but a cross-flow fluid barrier, and may facilitate aseismic slip. Another issue is that of resolution. Joint 3D inversions of seismic and MT data at the typical 1 km block scale do not usually provide sufficient target confidence for drilling into a potential fracture zone at the required scale (10 m to 100 m). However, further work on this joint inversion objective should prove fruitful as datasets improve.

At deeper levels, the joint interpretation of MT inversions and MEQ tomography at the 1 km block scale has already proven fruitful in several instances. An example is the interpretation of data from the Taupo Volcanic Zone, New Zealand, including magmatic (partial melt) heat sources at about 8 km depth (or deeper) connected through seismically active zones (fault structures) which provide conduits for hot fluid upflow into known geothermal reservoirs (Heise et al, 2016, Bannister et al, 2015, Bertrand et al, 2015).

4. MICRO-GRAVITY CHANGE

Gravity changes over time provide constraints for calibrating numerical reservoir models, by showing the effects of fluid density changes from saturation changes (boiling or condensation). Nordquist et al (2010) demonstrated this by reporting on the results of eight repeat precision gravity surveys over the Awibenkok (Salak) geothermal field in Indonesia between 1994 and 2008. These resulted from net mass depletion (brine and condensate are injected, but some vapor is lost through the cooling towers), along with the effects of fluid recharge from re-injection, plus natural inflow from aquifers outside the production zone. The gravity change data revealed a region of mass recharge coming from an external aquifer in the northeast sector and/or from local downflows of shallow groundwater. Such sources of cooling recharge fluids threatened the long-term viability of steam production wells, particularly those in the northeast of Salak, and so long-term production strategy was adjusted accordingly. A similar interpretation of gravity change data at MakBan (Bulalo) geothermal field in the Philippines (Nordquist et al, 2004) was used to modify the simulation model (permeability and inflow structure) to better represent saturation changes (hence density changes) in 2-phase zones. A similar issue with external recharge of cooling fluids from shallow or peripheral aquifers combining with reinjectate returns was investigated and an improved reservoir simulator helped with long-term production/injection strategy and optimal selection of make-up well sites.

An example of the interpretation of gravity changes associated with the Tauhara sector of the Wairakei-Tauhara geothermal system in New Zealand is documented in Hunt and Graham (2009). They attributed large gravity decreases between 1972 and 1985 to expansion of steam zones (mass loss) resulting from liquid pressure drawdown caused by fluid extraction at Wairakei, some 5 km away. From 1985 to 2009 the gravity increased by up to +0.4 mgals across a 1km radius zone centered on an unused deep exploration borehole (TH4). It has been inferred that this gravity increase was caused by a local downflow of cooler groundwater into the base of an intermediate-depth steam zone, possibly through a casing break in the well, and ponding in a depression across the top surface of a mudstone aquiclude (Lower Huka Falls Formation). The groundwater level was unaffected, implying strong lateral recharge at the source of the downflow.

Figure 1 illustrates the shape of a dipolar gravity anomaly that formed during the early years of development of a 57 MWe binary power-plant where there was negligible net mass-loss but production and injection sectors were separated by about 2 km, so local gravity anomalies formed in response to production-induced boiling (mass loss) and reinjection-induced 2-phase saturation (mass gain).

Note that modelling of the gravity change data in isolation can be problematic in terms of the interpreted depth of aquifers experiencing saturation change (a consequence of imperfect data and the non-uniqueness of model fit). However, when combined with constraints from other information sources (e.g. core porosity, borehole pressure and temperature data), the integrated models are more robust. The benefits of the improvements to the integrated model are that predictions of future reservoir performance also improve and development strategy (including expansion options) can be progressed with improved chances of success.

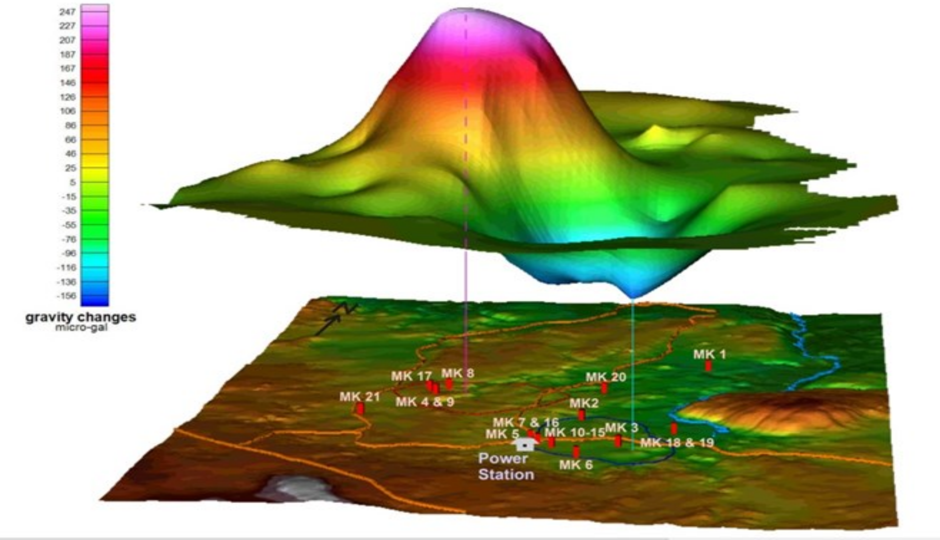

Figure 1: Example of gravity change observed over the first four years of a ~57 MWe binary development with negligible net mass change but a displacement of mass from production to injection sectors (right to left above) resulting in 2-phase expansion (boiling) and re-saturation, respectively, causing these gravity changes. (Image courtesy of S. Soengkono).

5. RESISTIVITY CHANGE

Resistivity signatures of conventional high temperature convecting geothermal systems are known to be dependent on a combination of rock and fluid properties. These include: rock porosity, fluid salinity, temperature, clay content and clay type. The parameters that are arguably most important for resource delineation purposes are: connected porosity, fluid temperature and salinity. However, the dominant parameter affecting measured resistivity is often smectite clay content which typically forms a doming, low-permeability cap at <200 ºC across the top part of the convecting system. Consequently, the lowest resistivity layers (i.e. the smectite clay) are typically insensitive to subsurface fluid property changes caused by fluid flow (e.g. from production/injection wells or groundwater inflow).

However, resistivity monitoring during production or injection activities, has, in certain circumstances, provided evidence of resistivity change that can be useful for mapping the lateral extent of mixing fluids of different salinity and temperature. An example has been documented at Ohaaki (Bromley, 2001), where reinjection of 150 ºC brine (1200 ppm Cl) at 300m depth into a cool, low-Cl aquifer near the NW edge of the Ohaaki geothermal system, caused a progressive reduction in resistivity by up to 50%, at up to 200-300 m radius, over a 5-year period. The data was interpreted to indicate an outward flow of hot saline injectate, preferentially oriented NE from the injection well (BR41), which decreased resistivity by displacing and mixing with cooler groundwater hosted in a permeable and porous rhyolite aquifer. The value of this information was to provide supporting evidence that the injected fluid was dispersing within the edge-field aquifer and along the resistivity-mapped boundary zone, rather than funneling back rapidly into the central production zone. This shallow edge-field injection strategy has now been successfully utilized for 24 years.

Another, more recent, example is documented in Didana et al (2017) at Habanero-4 well in Cooper Basin, Australia. Here, MT resistivity monitoring during a 2012 stimulation injection experiment revealed a pattern of decreasing apparent resistivity (-5%) at periods greater than 10 seconds along north-south oriented conductive fractures. This was found to be in agreement with the orientation of MEQ events observed during fluid injection, and was likely indicating anisotropic permeability generated by the hydraulic stimulation. Abdelfettah et al (2018), however, point out the difficulties with MT monitoring, with an example from Rittershoffen, France. Apparent resistivity time variations are strongly influenced by changes in the magnitude and direction of the inducing magnetic field, creating a significant change over time in uncertainty.

6. DEFORMATION CHANGE (SUBSIDENCE)

Subsidence and deformation observations and mechanisms in New Zealand geothermal fields (Wairakei, Ohaaki, Kawerau, Rotokawa and Mokai) were summarized in Bromley et al (2015a). Local subsidence anomalies show associations with relatively shallow, anomalously-compressible, porous formations, weakened by hydrothermal alteration from boiling fluids that passed through shallow outflow structures.

Sepulveda et al (2017) provided an update of the integrated interpretation and analytical modelling of the world's deepest geothermal production-induced subsidence anomaly (15m maximum) located near the eastern boundary of Wairakei field. The key points of this update were that the anomaly is centered in an area of compacting segments of anomalously compressible clays (largely consisting of yielding and swelling smectite) between about 100 and 300 m depth. These layer segments had been affected naturally by an outflow of boiling fluid to a hot spring discharge area nearby (Geyser Valley), and by slow upward diffusion of an induced reservoir pressure decline from decades of accumulated net mass extraction (see Table 1). The subsidence rates are sensitive to reservoir pressure trends. Rising pressure between 1999 and 2011 from increased deep reinjection resulted in a levelling of subsidence rates. Therefore, a targeted injection mitigation scheme could be deployed if necessary, but to date the surface deformation effects have not been sufficient to justify this, given the unknown risks of other adverse effects possibly arising from shallow injection near the original borefield area.

6.1 Coupling of Deformation and Other Processes

Integrated interpretation of changes in ground deformation and micro-gravity results promises some benefits in terms of better understanding of the principal mechanisms behind each process. Gravity and level changes across Wairakei-Tauhara system (see Table 1) have been well documented for 60 years, and although the respective anomalies are not coincident in time or location, there is some overlap and a suggestion of a coupling between the dominant mechanisms. Changes in saturation through a vertical sequence of perched boiling aquifers are caused by initial deep pressure drawdown generating upflows of high pressure steam, followed by inflows or downflows of cooler groundwater, cooling condensation and saturation increase. Gravity is affected by pore fluid density and saturation changes, while deformation is influenced by pressure changes in the different perched aquifers and temperature effects (expansion and contraction). Efforts are currently underway at one of the local subsidence anomalies, where changes in saturation state of several 2-phase zones are most likely, in order to investigate this hypothesis by continuously monitoring gravity and deformation, aquifer pressures and temperatures.

An investigation at Brady's, Nevada, by Davatzes et al (2013), of surface deformation (using InSAR) and MEQ activity during high pressure pumping tests, when combined, provided useful information on reservoir structure; both data sets followed the general structural trend, although the seismicity was scattered across a wider area than the deformation.

Powell (2011) showed the evidence for natural subsidence occurring at Rotokawa, New Zealand, prior to exploitation (i.e. 1950 to 1997), and interpreted the cause to be natural mass removal from the reservoir by hydrothermal alteration (dissolution) and silica-rich hot spring discharge. Depletion of silica in buried andesite lavas by up to 15% through high temperature water-rock interaction causes an increase in matrix porosity. The natural subsidence is inferred to be due to the gradual collapse of a proportion of this created pore space. Permeability evolution through time could also be influenced by the selective brittle failure of shallower silica-enriched formations (from deposition processes), caused by the stress change induced by alteration compaction. This likely coupling of natural subsidence and reservoir processes constitutes another potentially useful tool when exploring for, and assessing, the probable extent of hidden geothermal systems.

7. REMOTE SENSING (SURFACE HEAT LOSS)

Surface heat loss is an important measurement used in calibrating reservoir models to account for mass and heat flux passing through the system. The natural and induced fluid and heat recharge entering the base and sides of the system are important parameters in the model for assessing the long-term sustainability of a chosen energy extraction scenario. Hence, the benefits of a heat-loss monitoring method are that a better calibrated model, using observed changes in surface heat loss from natural geothermal features, leads to a more robust prediction of resource sustainability.

Repeat thermal infra-red surveys, using remote sensing platforms (satellite, aircraft or helicopter-mounted sensors) help map changes in ground surface temperature, and have the potential to detect relative changes in surface heat loss, particularly when supported by ground-based calibration measurements using a calorimeter and ground temperature probes (e.g. Seward et al, in press, Bromley et al, 2015b). In addition, thermal infrared surveys can map the extent of thermal plumes across the surface of cold lakes resulting from hot seeps or springs. These surface temperature anomalies can be used to quantify heat loss changes from such seeps if a hot water discharge site of known temperature and flowrate is available for calibration purposes (e.g. Bromley et al, 2011).

Another good example of the use of repeat airborne thermal infrared surveys for monitoring undeveloped hydrothermal areas is documented in Heasley and Jaworowski (2018) from the Norris Geyser Basin of Yellowstone National Park, USA. This study illustrated the variations that can be expected in natural feature activity, over seasonal and multi-year time scales. Once the causes for these natural variations are fully understood they may provide another source of historical change data that can be used to improve and calibrate reservoir models.

8. CONCLUSIONS

By combining knowledge from geophysical monitoring tools, improved conceptual models of geothermal resources can be constructed, thereby assisting development of more accurate reservoir simulations, and enhancing exploration strategies. Permeability is a key parameter which varies with time. Saturation change in 2-phase reservoirs is also an important variable to track, along with mapping the changing flow paths of injected or recharging source fluid. Understanding what causes such changes is important for robust simulations.

In many geothermal reservoirs, modern MEQ monitoring generates large datasets of micro-seismic events distributed within and around the reservoir volume. Consequently, tomography based on Vp, Vp/Vs, attenuation (1/Q), and Poisson's ratio, and shear-wave analysis from these datasets, can provide useful tools for determining anisotropic structures (fluid barriers and conduits) and reservoir phase changes (in time and space). This information is helpful for siting make-up wells, or exploration (expansion) targets and choosing reinjection sites. Monitoring of fluid phase changes (liquid and vapor) by combining MEQ with micro-gravity results also provides useful information for reservoir management, that is, for planning reinjection and production strategy. Combining MEQ with resistivity (MT) inversions may provide useful knowledge on the likely heat source and deep upflow locations. Resistivity monitoring may, in specific circumstances, also illuminate the pathway of injected fluid flow. Deformation monitoring (subsidence) provides useful information on rock mechanical properties, which may also be useful when interpreted in conjunction with gravity change, MEQ results and hydrothermal alteration processes, such as silica dissolution or deposition. These water-rock interactions affect formation porosity, compressibility and brittleness. Finally, monitoring of surface heat-loss changes using remote-sensing methods can illuminate changes in natural and induced reservoir processes which are important to re-construct and history-match using reservoir simulators.

The ultimate benefit of this improved understanding of reservoir processes, based on integration of geophysical monitoring information, is an improvement in conceptual models of all under-developed geothermal resources, including the likely dynamics of reservoir property changes over utilisation time-frames, and therefore better projections of their long-term sustainable energy extraction capacity and recharge parameters. Such knowledge can also be applied to exploration and expansion strategies to provide better drilling targets and improved production-reinjection strategies for mature geothermal developments.

REFERENCES

Abdelfettah, Y., Sailhac, P., Larnier, H., Matthey, P.-D., and Schill, E.: Continuous and time-lapse magnetotelluric monitoring of low volume injection at Rittershoffen geothermal project, northern Alsace – France, *Geothermics* 71, 1-11, (2018).

Asanuma, H., Tamakawa, K., Soma, N., Niitsuma, H., Baria, R. and Häring, M.: Reflection Imaging of EGS Reservoirs Using Microseismicity As a Source, *Proceedings,* 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA., (2011).

Bannister, S., Bourguignon, S., Sherburn, S., and Bertrand, T.: 3-D Seismic Velocity and Seismic Attenuation in the Central Taupo Volcanic Zone, New Zealand: Imaging the Roots of Geothermal Systems, *Proceedings,* World Geothermal Congress 2015, Melbourne, Australia, (2015).

Bertrand E.A., Caldwell, T.G., Bannister, S., Soengkono, S., Bennie S.L., Hill G.J., and Heise, W.: Using array MT data to image the crustal resistivity structure of the southeastern Taupo Volcanic Zone, New Zealand, *Journal Volcanology & Geothermal Research*, 305, 63-75, (2015).

Bromley, C.J., Currie, S., Jolly, S., and Mannington, W.: Subsidence: an Update on New Zealand Geothermal Deformation Observations and Mechanisms, *Proceedings,* World Geothermal Congress 2015, Melbourne, Australia, (2015a).

Bromley, C.J., Ashraf, S., Seward, A.M., and Reeves, R.: Monitoring and quantifying heat loss from significant geothermal areas via remote sensing. *Proceedings,* 37th New Zealand Geothermal Workshop, Taupo, New Zealand, (2015b).

Bromley, C.J.: Tracking the movement of externally reinjected geothermal fluid (out-field) using repeat resistivity. *Proceedings,* 22nd Annual PNOC-EDC Geothermal Conference, Manila, Philippines, 191-198, (2001).

Bromley, C.J., and Majer, E.L.: Geothermal induced seismicity: risks and rewards. *Proceedings,* 34th New Zealand Geothermal Workshop, Auckland, New Zealand, (2012).

Bromley, C.J., and van Manen, S.M., Mannington, W.: Heat flux from steaming ground: reducing uncertainties. *Proceedings,* 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-191, 925-931, (2011).

Davatzes, N.C., Feigl, K.L., Mellors, R.J., Foxall, W., Wang, H.F, and Drakos, P.: Preliminary investigation of reservoir dynamics monitored through combined surface deformation and micro-earthquake activity: Brady's Geothermal Field, Nevada. *Proceedings*, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2013).

Didiana, Y.L., Heinson, G., Thiel, S., and Krieger, L.: Magnetotelluric monitoring of permeability enhancement at enhanced geothermal system project. *Geothermics* 66, 23-38, (2017).

Fang, Y., Elsworth, D., and Cladouhos, T.T.: Reservoir permeability mapping using microearthquake data. *Geothermics* 72, 83-100, (2018).

Heasler, H. and Jaworowski, C.: Hydrothermal monitoring of Norris Geyser Basin, Yellowstone National Park, USA, using airborne thermal infrared imagery, *Geothermics* 72, 24-46, (2018).

Heise, W., Caldwell, T.G., Bertrand, E.A., Hill, G.J., Bennie, S.L., and Palmer, N.G.: Imaging the deep source of the Rotorua and Waimangu geothermal fields, Taupo Volcanic Zone, New Zealand, *J. Volcanology & Geothermal Research*, 314, 39-48, (2016).

Hunt, T.M., Graham, D.J.: Gravity changes in the Tauhara sector of the Wairakei–Tauhara geothermal field, New Zealand, *Geothermics*, 38 (1), 108-116, (2009).

Lin, G. and Wu. B.: Seismic velocity structure and characteristics of induced seismicity at the Geysers Geothermal Field, eastern California, *Geothermics,* 71, 225-233, (2018).

Nordquist, G.A., Acuña, J., and Stimac, J.: Precision Gravity Modeling and Interpretation at the Salak Geothermal Field, Indonesia, *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia, (2010).

Nordquist, G.A., Protacio, J. A., Acuña, J.: Precision gravity monitoring of the Bulalo geothermal field, Philippines: independent checks and constraints on numerical simulation. *Geothermics* 33, 37-56, (2004).

Powell, T.: Natural subsidence at the Rotokawa Geothermal Field and implications for permeability development, *Proceedings,* 33rd New Zealand Geothermal Workshop, Auckland, (2011).

Sepulveda, F., Bromley, C.J., Hanik, F., Bixley, P.F., A Nishar, A., and Mannington, W.: A refined conceptual model for subsidence at Wairakei, New Zealand, Geothermal Resources Council Transactions, 41, (2017).

Sepulveda, F., Siega, C., Lin, Y.W., Urgel, A., and Boese, C.: Observations of Deep and Shallow Seismicity Within the Wairakei-Tauhara Geothermal System, *Proceedings,* 38th New Zealand Geothermal Workshop, Auckland, New Zealand, (2016).

Seward, A., Ashraf, S., Reeves, R., and Bromley, C.J.: Improved Environmental Monitoring of Surface Geothermal Features through comparisons of Thermal Infrared, Satellite Remote Sensing and Terrestrial Calorimetry, *Geothermics,* Virtual Special Issue on Environmental and Social Aspects (in press, 2018).

Sewell, S., Savage, M., Townend, J., Bannister, S., and Hutchings, L.: Preliminary investigation of seismic velocity variation at the Rotokawa and Ngatamariki Geothermal Fields *Proceedings,* 39th New Zealand Geothermal Workshop, Rotorua, New Zealand, (2017).

Sherburn, S., Bromley, C.J., Bannister, S., Sewell, S., and Bourguignon, S.: New Zealand Geothermal Induced Seismicity: an overview, *Proceedings,* World Geothermal Congress 2015, Melbourne, Australia, (2015).

Simiyu, S.M.: Geothermal reservoir characterization: Application of micro-seismicity and seismic wave properties at Olkaria, Kenya rift, Journal of Geophysical Research, 105, B6, 13779-13795, (2000).

Tezel T., Julian B.R., Foulger, G.R., Nunn, C., and Mhana, N.: Preliminary 4D Seismic Tomography Images for The Geysers, 2008-2014, *Proceedings,* 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2016).