NZGW
New Zealand
Geothermal Workshop

43rd New Zealand
GEOTHERMAL WORKSHOP 2021

Handbook

2-3 February 2022

ISSN 2703-4275

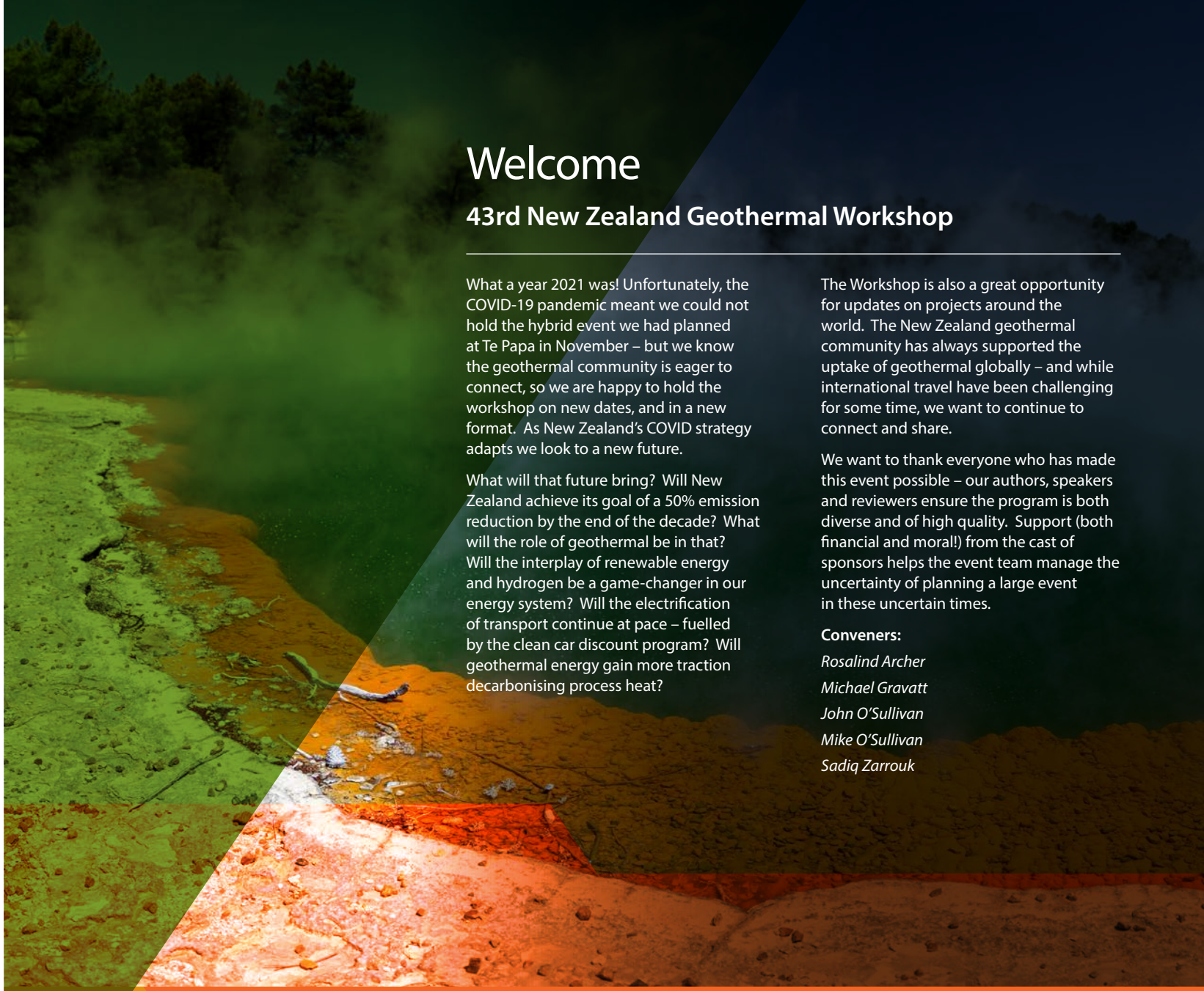
Contents

Virtual Platform Information

For the NZGW Workshop 2021 we will be using the OnAir platform.

You will receive a final access email 24 hours prior to workshop start, which will include your personalised log-in and all-important information you will require to enjoy the workshop. Upon receiving this email, the platform will be 'live' and able to be accessed. We encourage you to log-in and watch the Welcome video which will assist you in navigating the platform. There will be live support assistance throughout the workshop to support you with your technical enquiries.

Please find the full attendee guide attached to your email.



Welcome

43rd New Zealand Geothermal Workshop

What a year 2021 was! Unfortunately, the COVID-19 pandemic meant we could not hold the hybrid event we had planned at Te Papa in November – but we know the geothermal community is eager to connect, so we are happy to hold the workshop on new dates, and in a new format. As New Zealand's COVID strategy adapts we look to a new future.

What will that future bring? Will New Zealand achieve its goal of a 50% emission reduction by the end of the decade? What will the role of geothermal be in that? Will the interplay of renewable energy and hydrogen be a game-changer in our energy system? Will the electrification of transport continue at pace – fuelled by the clean car discount program? Will geothermal energy gain more traction decarbonising process heat?

The Workshop is also a great opportunity for updates on projects around the world. The New Zealand geothermal community has always supported the uptake of geothermal globally – and while international travel have been challenging for some time, we want to continue to connect and share.

We want to thank everyone who has made this event possible – our authors, speakers and reviewers ensure the program is both diverse and of high quality. Support (both financial and moral!) from the cast of sponsors helps the event team manage the uncertainty of planning a large event in these uncertain times.

Conveners:

Rosalind Archer

Michael Gravatt

John O'Sullivan

Mike O'Sullivan

Sadiq Zarrouk

2021 Sponsors

2021 Best Paper Awards

New Zealand Geothermal Association

Best Paper

Best Student Paper

Best Student Poster

Keynote speakers

Gioia Falcone

Professor of Energy Engineering
University of Glasgow, Scotland

Session:
Wednesday 2nd February 9.00am NZST

Gioia Falcone is Rankine Chair, Professor of Energy Engineering at the University of Glasgow, where she leads the Energy and Sustainability Research Group and is Associate Director of the Centre for Sustainable Solutions. She is also Visiting Professor at Department of Earth Science and Engineering at Imperial College London. Until June 2018, she was Professor and Head of the Geo-Energy Engineering Centre at Cranfield University. Between 2011 and early 2016, she held the Endowed Chair and Professorship in Geothermal Energy Systems at Clausthal University of Technology, Germany, where she was also the Director of the Institute of Petroleum Engineering. Gioia was formerly an Assistant and then Associate Professor in Petroleum Engineering at Texas A&M University, Chevron Corporation Faculty Fellow and faculty member of the Ocean Drilling and Sustainable Earth Science partnership. Prior to joining academia, she worked with Eni-Agip, Enterprise Oil UK, Shell E&P UK and Total E&P UK, covering both offshore and onshore assignments.
She holds a *Laurea Summa Cum Laude* in Environmental-Georesources engineering from Sapienza University of Rome, a M.Sc. degree in Petroleum Engineering from Imperial College London and a Ph.D. in Chemical Engineering from Imperial College London. She is Vice-Chairperson of the Bureau of the Expert Group on Resource Management of the United Nations Commission for Europe (UNECE), Member of its Renewables Sub-Group and its focal point for the UNECE Pathways to Sustainable Energy & Carbon Neutrality Project. She sits on the BEIS (UK Government Department of Business, Energy & Industrial Strategy) Energy Working Group, chaired by the Chief Scientific Advisor to BEIS, advising on the development of Technical Screening Criteria in the energy sector for the UK Green Taxonomy. She serves on the 2020-2023 Board of Directors of the International Geothermal Association (IGA) and is Chair of the IGA UNFC Ad Hoc Committee. She serves on the Directorate of Scottish Carbon Capture and Sequestration (SCCS) and on the Board of the Energy Technology Partnership (ETP). She is member of the Academic Panel of the Net Zero Technology Centre, of the European Geothermal Energy Council (EGEC) and of the UK Carbon Capture and Storage Research Centre (UKCCSRC). She serves on the Scientific Committee of the 2022 European Geothermal Congress (EGC) and on the Scientific Committee of the 2021 International Conference on Multiphase Flow and Heat Transfer (ICMFHT'21).

Jacqui Nelson

Chief Development Officer
Contact Energy Ltd, New Zealand

Session:
Wednesday 2nd February 1.00pm NZST

Jacqui has been with Contact Energy for over 15 years taking the role of Chief Development Officer in October 2021. As Chief Development Officer she has responsibility for the company's development and demand growth activities aligned with its Contact26 strategy. Previously Jacqui has held a wide range of roles within Contact across finance, resource management, trading and most recently as Chief Generation Officer where she was responsible for the electricity Generation and Trading, and Sustainability functions of the business which deliver 80% of Contact's EBITDAF.

Prior to her current role Jacqui has headed up trading, the land consenting and environment group and was Company Treasurer from 2004 to 2010. In the years before Contact she was Treasury Adviser at Airways for nine years and prior to that worked at ANZ Banking Group.

More broadly she has in recent years undertaken a number of external governance roles as Chair and Trustee of the New Zealand Red Cross Foundation (appointed Chair Aug 2020), she is a Director of the New Zealand Geothermal Association and is Chair and Trustee of the Performance Arcade.

Jacqui has received a number of external awards recognising her work and capability including the 2019 US Energy Association - Women in Energy Feature for Exemplary Leadership (https://www.usea.org/article/women-energy-jacqui-nelson) and the 2018 US Energy Association Corporate Volunteer Award for her work with Ngati Tahu in helping the Masai in kenya. (https://www.thinkgeoenergy.com/contact-energy-and-ngati-tahu-win-international-award-on-geothermal-engagement-work-in-kenya/).

Jamie C. Beard, Esq.

Executive Director Geothermal Entrepreneurship Organization (GEO)
University of Texas, USA

Session:
Thursday 3rd February 9.00am NZST

Jamie serves as the Executive Director of the Geothermal Entrepreneurship Organization (GEO) at the University of Texas at Austin, an organization she founded in 2019. She also organizes and curates the *PIVOT – From Hydrocarbons to Heat* conference series, a gathering dedicated to engaging the oil and gas industry in challenges associated with exploring and drilling for geothermal energy. An energy, regulatory and environmental attorney by training, Jamie is a passionate advocate for geothermal energy as the baseload capable clean energy of the future. She delivered a TED talk on the subject of geothermal and the oil and gas industry in August, 2021. www.texasgeo.org

Chris Bromley

Consultant, Geophysicist

GNS

New Zealand

Session:
Thursday 3rd February 1.00pm NZST

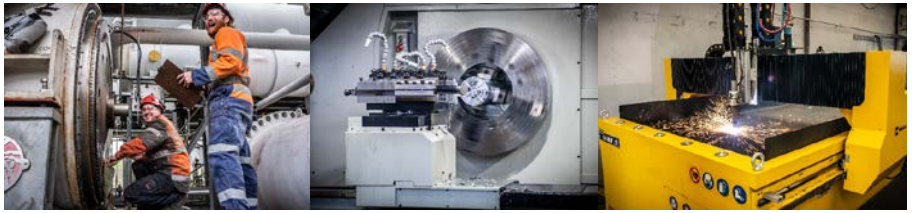
Chris Bromley is a 'semi-retired' senior researcher, geophysicist and consultant, with 42 years of international geothermal experience including the past 31 years at GNS Science. He is well known for his practical geophysical exploration, resource assessments, and environmental studies of geothermal fields in Indonesia, Philippines, Japan, Taiwan, Thailand, Kenya, Iran, Chile, Australia and New Zealand (NZ). He was Chairman of the 'IEA-Geothermal' TCP (2007-2015), is currently vice-chairman, NZ's representative, and leader of three research collaboration working groups on environmental, deep roots and induced seismicity topics. He is also currently Editor-in-Chief of the Journal 'Geothermics'(2014-). In 2010, Chris was a Lead Author of the geothermal chapter of the IPCC renewable energy report (SRREN), in 2014 won the prestigious NZ Geoscience Society Hochstetter Lecturer Award, and in 2020 the NZ Geothermal Association Contribution Award. He has been a session chairman and keynote speaker at 24 meetings and workshops in 16 countries, and he also peer reviewed operational management of 3 NZ geothermal fields (Wairakei, Rotokawa and Mokai). Chris has convened 5 international geothermal workshops and presented at 100 conferences, so his efforts are familiar to both commercial and research workers within the global geothermal community. Along with numerous other consulting roles, Chris spent 2 years in Indonesia (Kamojang 1979-1981) and 4 years in the Philippines (PNOC-EDC 1981-1985) working as an advisor on geothermal resources specializing in geophysics and reservoir engineering and has since undertaken due diligence assessments and development strategy studies of 6 geothermal resources in the Philippines and 2 in Indonesia.

MB Century

MB Century is one of the largest energy service specialists in the Asia Pacific region. We have a long history of providing world leading, innovative service to the energy sector, employing over 150 people. We provide award winning services to the renewable energy sectors in New Zealand, Australia and South East Asia.

With more than 70 years experience, we are well positioned to undertake a wide range of geothermal and hydro energy challenges, including design and build solutions. MB Century offer the following services:

- Geothermal drilling
- Reservoir data logging
- Enviromental monitoring and analysis
- Pipeline/steamfield and in-plant piping design
- Process engineering, including pump station and seperator design
- Hydro, geothermal and general engineering consultancy including feasibility studies
- Geothermal plant operation and maintenance
- Class 4 hydro power station maintenance and overhauls
- Precision machining (including mobile line boring / mobile milling)
- Industrial coatings
- Fabrication services including stainless steel
- Pipeline/steamfield construction
- Steam Turbine Specialists



Contact: mbcentury.com or Info-nz@mbcentury.com

New Zealand Geothermal Workshop 2021 Virtual Programme

Friday 28 January				
15:00	**Virtual Platform Open**			
Wednesday 2 February				
8:30	**Welcome & Mihi |** Rosalind Archer			
9:00	**Keynote Speaker |** Gioia Falcone, Rankine Chair, Professor of Energy Engineering, University of Glasgow, Scotland			
9:45	**MB CENTURY | INDUSTRY UPDATE |** Ben Rasdall			
10:00	**Morning Tea**			
10:25	**Session 1.1 - Industry Update 1**	**Session 1.2 - Social & Community**	**Session 1.3 - Reservoir Modelling 1**	**Session 1.4 - Geochemistry, & direct use**
	Stream 1	**Stream 2**	**Stream 3**	**Stream 4**
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10:30	**SCHLUMBERGER | INDUSTRY UPDATE |** James Bayley	36 | REGIONAL GOVERNMENT STRATEGY FOR THE SUSTAINABLE USE AND DEVELOPMENT OF THE KAWERAU GEOTHERMAL FIELD BY MULTI-TAPPERS IN NEW ZEALAND - Jason Laurent	69 | COMPARISONS OF AUTOUGH2 AND WAIWERA ON REAL GEOTHERMAL FIELDS - John O'Sullivan	17 | GEOTHERMAL PROSPECTIVITY OF THE TARANAKI SEDIMENTARY BASIN - Agnes Reyes
10:45	**AECOM| INDUSTRY UPDATE |** Peter Geoghengan	45 | RESIDENTIAL HEATING FROM LOW GEOTHERMAL TEMPERATURES - Celia Wells	113 | PRACTICAL WORKFLOW FOR TRAINING IN GEOTHERMAL RESERVOIR MODELLING - Théo Renaud	5 | EXPERIMENTAL STUDY ON RARE EARTH ELEMENT MOBILITY DURING GREYWACKE - WATER INTERACTIONS - Lucjan Sajkowski
11:00	**SOLENIS | INDUSTRY UPDATE |** Peter Slijp	9 | PRODUCTIVE AND ALLOCATIVE EFFICIENCY - ROTORUA GEOTHERMAL FIELD - Mariana Zuquim	82 | MODELLING TRACER BREAKDOWN UNDER GEOTHERMAL CONDITIONS - John Burnell	51 | COFFEE DRYING SYSTEM DESIGN FOR GEOTHERMAL DIRECT USE APPLICATION IN FLORES ISLAND - Pradana Vian Prasetyo
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	24 | Distributed temperature measurements at an active plate-bounding fault using fiber optic sensors - Haneef			
	60 | Experimental Studies of Supercritical Fluid-Rock Interactions Geothermal: The Next Generation - Rendel			
	89 | Porous Materials for CO2 and H2S capture in geothermal systems - Fernandez			
	96| Geothermal Well Control Equipment Application for Mining Drilling in Geothermal Environment - Irwansyah			
	101 | Selecting the Most Potential Geothermal Direct Use in Eastern Indonesia, Flores Island, Mataloko - Rachmadani			
	102 | Integrated geotourism in Dieng - Putri			
	103 | Geothermal Drilling Performance Improvement through a Comprehensive Non-Productive Time Analysis - Putri			
	105 | One sheet program for Integrated Project Services at Laguna Colorada Geothermal Field - Aparicio			
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13:00	**Keynote Speaker |** Jacqui Nelson - Chief Generation Officer, Contact Energy Ltd, New Zealand			

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	Stream 1	Stream 2	Stream 3	
	Chair | Mike Allen	Chair | Sadiq Zarrouk	Chair | Ru Nicholson	
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	Stream 1	**Stream 2**	**Stream 3**	**Stream 4**
	Chair | Brian White	Chair | Sadiq Zarrouk	Chair | John O'Sullivan	Chair | Rosalind Archer
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16:00	**JACOBS | INDUSTRY UPDATE |** Alex Batten	116 | WHANGAIROROHEA GEOTHERMAL AREA AND THE DEMISE OF A HIGH TEMPERATURE TVZ GEOTHERMAL SYSTEM - Andrew Rae	6 | VOLSUNG: INVERSE MODELLING AND UNCERTAINTY ANALYSIS USING PEST - Peter Franz	16:05-16:25: 119 | NGĀ WAI ARIKI O ROTORUA:HE KOHIKOHINGA (A HAU KAINGA PERSPECTIVE ON ROTORUA GEOTHERMAL) - Lani Kereopa
16:15	**CONTRACT RESOURCES | INDUSTRY UPDATE |** Jeffrey Kerferd & Mark Geldenhuys	86 | HYDROTHERMAL ALTERATION AND EVOLUTION OF THE ROTOKAWA GEOTHERMAL SYSTEM - Mark Simpson	43 | A NEW NUMERICAL MODEL OF THE OHAAKI GEOTHERMAL FIELD - Michael O'Sullivan	
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Thursday 3 February				
8:45	**Housekeeping |** Rosalind Archer			
9:00	**Keynote Speaker |** Jaime Beard - Executive Director Geothermal Entrepreneurship Organization (GEO), University of Texas, USA			
9:45	**Morning Tea**			
10:10	**Session 4.1- Industry Update 4**	**Session 4.2 - Production and Management 2**	**Session 4.3 - Geophysics**	**Session 4.4: Drilling & Well Testing 2**
	Stream 1	**Stream 2**	**Stream 3**	**Stream 4**
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11:00	**GEOTHERMAL INSTITUTE | INDUSTRY UPDATE |** Rosalind Archer	3 | INVESTIGATION OF COOLING WATER CHEMICAL DOSING: THE OHAAKI GEOTHERMAL POWER STATION COOLING TOWER - Morris Young	58 | MACHINE LEARNING INVESTIGATION OF INJECTION-SEISMICITY IN ROTOKAWA GEOTHERMAL FIELD - Pengliang Yu	99 | COMPARISON OF GEOTHERMAL WELL COST FOR SLIMHOLE EXPLORATION VERSUS BIGHOLE EXPLORATION - Vicki Agustino
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11:30	**GEOTHERMAL INSTITUTE | INDUSTRY UPDATE |** John O'Sullivan	33 | STEAM PURITY TROUBLESHOOTING: THE BERLIN STEAM FIELD, EL SALVADOR - Cristo Umanzor	29 | PHYSICAL, GEOCHEMICAL AND MINERALOGICAL CHARACTERISTICS OF THE ALTERATION AND DEFORMATION HALO ABOVE THE DIORITE-TONALITE INTRUSIVE AT NGATAMARIKI - Steven Sewell	94 | HYDRAULIC RIG AND ITS CHALLENGE TO CONDUCT SLIMHOLE GEOTHERMAL EXPLORATION DRILLING - Hafni Wiharlan
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12:00	**Lunch**			
12:50	**Welcome Back |** Sadiq Zarrouk			
13:00	**Keynote Speaker |** Chris Bromley, GNS, Auckland			
13:40	**Session 5.1 - Industry Update 5**	**Session 5.2 - Reservoir Modelling 3 & Future**	**Session 5.3 - Scaling and Corrosion**	**Session 5.4 - Production and Management 3**
	Stream 1	**Stream 2**	**Stream 3**	**Stream 4**
	Chair | Scott Henderson	Chair | Jeremy O'Brien	Chair | Ru Nicholson	Chair | Brent Young
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14:00	**NZTE | INDUSTRY UPDATE - Philippines |** Maricon Popanes-Lim	18 | CARBON NEGATIVE GEOTHERMAL: THEORETICAL COMBINED GEOTHERMAL-BIOMASS CO2 INJECTION CYCLE - Karan Titus	110 | CHEMICAL REMOVAL OF FORMATION SCALE IN GEOTHERMAL PRODUCTION WELLS - Katie Mclean	121 | LOST IN THE JUNGLE - A REVIEW OF THE STILL-RADICAL GEOTHERMAL DEVELOPMENT AT KIABUKWA, DR CONGO - Brian White
14:15	**NZTE | INDUSTRY UPDATE - Japan |** Yoshifumi Imamura	64 | NEW ZEALAND'S PATHWAY TO SUPERCRITICAL GEOTHERMAL ENERGY USE: MOVING FORWARD TO EXPLORATION DRILLING - Brian Carey	28 | TURNING THE PRESSURE ON FOR THE NANO-STRUCTURED CALCIUM SILICATE HYDRATE (CASIL) SOLUTION TO SILICA SCALING - Thomas Borrmann	92 | GENERATOR, TURBINE AND THERMAL EFFICIENCY OF LUMUT BALAI GEOTHERMAL POWER PLANT - Erwandi Yanto
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15:05	**Workshop awards and close** Sadiq Zarrouk | Leighton Taylor | Ted Montague | John O'Sullivan			

Abstracts

2 | NEAR-SURFACE GEOTHERMAL MAPPING – TESTING THE TTEM GEOPHYSICAL TECHNIQUE IN THE ROTORUA GEOTHERMAL FIELD

Robert Reeves[1], Jesper Pedersen[2], Thomas Brakenrig[1], Pradip Maurya[2], Rune Kraghede[2], Frederik Christenson[2], Liam McGovern[1] and Brian Moorhead[3]

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Keywords: *Rotorua geothermal Field, tTEM, Geophysics, permeability, resistivity, geothermal mapping.*

The towed transient electromagnetic (tTEM) geophysical technique enables high-resolution near-surface resistivity measurements to be collected in a timely manner, resulting in a better understanding of the near surface (approx. top 100 m). The tTEM system in development by Aarhus University is tested in the Rotorua Geothermal Field, New Zealand. The aims of the work are to test the equipment in a low-resistivity environment where abrupt changes in resistivity may occur over short distances and to better define subsurface areas of geothermal activity and provide insights into the permeability structure between the groundwater aquifers and geothermal surface features.

tTEM data collected from two sites show that the tTEM method can successfully define shallow resistivity targets and provide insights into the near-surface permeability structure. Areas of low resistivity correlate well with mapped geothermal surface features and suggest that subsurface areas of geothermal influence are larger than what is seen at the surface.

A large amount of the tTEM data collected in part of the study had to be discarded because they were of poor quality – probably affected by cultural effects such as electric power lines and buried objects. However, the poor data was largely constrained to one part of the study area, so a good resistivity model could be generated in other parts of the study area and achieve the projects aims.

Session: 4.3

3 | INVESTIGATION OF COOLING WATER CHEMICAL DOSING: THE OHAAKI GEOTHERMAL POWER STATION COOLING TOWER

Morris Young [1, 2] and Sadiq J. Zarrouk[2]*

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Keywords: *Cooling water, microbiological control, algae, biocides, Sulphur Oxidising Bacteria, Ohaaki, cooling tower.*

The Ohaaki power station is the only geothermal power station in New Zealand with a natural draft cooling tower. The concrete construction of the cooling tower influenced the locations vulnerable to attack from condensate/cooling water pH and from microorganism growth, and this altered the way chemical biocide was applied compared to forced draft cooling towers found in other flash steam power stations. Biocide was routinely sprayed directly onto the internal shell walls of the tower while the basin cooling water was only dosed seasonally.

This work presents a review of the chemical dosing history at the Ohaaki cooling tower, investigation into the effectiveness of the dosing regime and improvements to the understanding and monitoring of the degradation and control mechanisms.

Session: 3.3

4 | SINTER MORPHOLOGY AND THERMAL INFRARED IMAGERY: A DUAL APPROACH TO TRACKING HYDROTHERMAL CHANGES AROUND OLD FAITHFUL GEYSER, YELLOWSTONE, USA

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Keywords: *Old Faithful Geyser, siliceous sinter, depositional processes, post-depositional overprinting, Thermal Infrared imaging.*

Geysers are among the world's most dynamic geothermal features. Our research, combining Scanning Electron Microscopy (SEM) with Thermal Infrared (TIR) imagery, demonstrates that Old Faithful Geyser in Yellowstone National Park, USA, varies at time scales well beyond eruption intervals. In 2015, we collected 13 siliceous sinter samples from the sinter apron surrounding Old Faithful Geyser, Yellowstone National Park, USA. These were the first sinter samples to be collected in 22 years from this area. Samples were examined using a Scanning Electron Microscope (SEM) to observe the sinter morphology. SEM results indicated three samples experienced on-going deposition of opal-A silica, while three other samples revealed intermittent deposition of opal-A silica. Four samples displayed mild, moderate or aggressive dissolution features indicating post-depositional overprinting via acidic steam condensate. One sample indicated both intermittent deposition of opal-A silica and dissolution textures. A further two samples revealed the sinter was altering to clay. We then compared the SEM information with calibrated and georectified 2007-2012 airborne night-TIR images. This dual process identified that samples in a northeast-southwest alignment have significantly higher ground temperatures than those indicated in the airborne night-TIR images. The combination of these unique samples with the publically available 2007-2012 airborne night-TIR images has provided useful information on the changing hydrology of the area surrounding Old Faithful Geyser.

Session: 3.2

5 | EXPERIMENTAL STUDY ON RARE EARTH ELEMENT MOBILITY DURING GREYWACKE - WATER INTERACTIONS

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***Keywords:** REE, flow-through experiments, water-rock interactions, greywacke.*

Due to the increase demand in Rare Earth Elements necessary in solar panels or wind turbine magnets, the source and mobility of REE in geothermal fluids is becoming increasingly interesting. Previous studies of geothermal fluids from Taupo Volcanic Zone (TVZ) indicate that some REE are released during the breakdown of primary phases due to hydrothermal alteration. However, there is limited experimental data on the processes controlling the behaviour of REE in geothermal systems of Aotearoa New Zealand. The results presented here comprise part of a larger project that aims to broaden the understanding of the chemical exchange between geothermal fluids and reservoir rocks occurring during recharge of the geothermal plume.

In this preliminary study, we have investigated experimentally the release of REE during fluid-rock interaction using a continuous flow apparatus under hydrothermal conditions. The experiment used a "unaltered" greywacke as a proxy for the dominant basement rock in the Taupo Volcanic Zone. Distilled water was used as the fluid. The greywacke was progressively heated from ambient temperature to 400°C in 50°C increments over a period of 126 days. The fluid flow rate was 1 ml hr-1 for the entire experiment.

Results indicate that measurable concentrations of REE are released to the fluid from the greywacke. The similarity of REE patterns to other species present in the solution (i.e. Fe, H2S, SO42-) suggests that their trends are controlled mainly by mineralogy. However, the concentration of REE is strictly dependent on temperature and pH. These results show that the basement greywacke in the TVZ does influenced the REE composition of the geothermal fluid. The research findings are discussed and compared with available historical data.

Session: 1.4

6 | VOLSUNG: INVERSE MODELLING AND UNCERTAINTY ANALYSIS USING PEST

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***Keywords:** Volsung, Geothermal, Simulation, Inverse Modelling, PEST, Cloud Computing*

The PEST suite of tools has long been established as a standard toolkit in groundwater and other geoscience modelling. Its inverse modelling and uncertainty analysis capabilities allow modelers to greatly shorten model development time, improve model calibration, quantify uncertainty in model parameters and determine confidence in model predictions.

PEST tools have been used in the geothermal context, in particular in combination with TOUGH2; another noteworthy tool in this arena has been iTOUGH2. However the use of these tools has been greatly hampered by the complexity in setting up and running these types of simulations and the nature of TOUGH2 models. In particular, extraction of model observation data has been a really difficult task; in order to match real-world observations up to four dimensional interpolation has to be used. Since TOUGH2 does not store grid geometry this difficult task was left to the individual user. Further, parallel run management, i.e. the deployment of "workers" on different computational nodes, was also left to the individual modeler.

In this work we introduce a universal coupling between the Volsung suite of reservoir and wellbore simulators and the PEST suite. It is universal in the sense that any model parameter and any model observation is accessible to the inverse modelling process. It fully supports data interpolation, i.e. the modeler can simply enter data by location/type and time. The modeler can select the adequate PEST tool for the task and use the graphical user interfaces to setup the inverse modelling problem. Run management is fully automatic and can create clone workers on cloud service platforms like Amazon Web Services (AWS). This reduces barriers to greater use of inverse modelling and uncertainty analysis in the geothermal industry.

Session: 3.3

8 | IAN THAIN (THE 9TH OF JULY, 1937 – THE 4TH OF APRIL, 2021)

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***Keywords:** Ian Thain. NZGA, IGA,*

OBITUARY

Ian Alexander Thain was born in Scotland on the 9th of July 1937. His mother, Alexandrina, and his father Alexander were Psychiatric nurses at Montrose Hillside Psychiatric Hospital.

Ian's schooling was at Hillside Primary and then Montrose Academy. Ian was a self-made man. He got an apprenticeship as a fitter and turner with Coventry Gauge and Tool Company. Ian attended night school to get a mechanical engineering qualification. He cycled from Hillside to Dubton Station, left his bike there and took the train to Dundee where he studied.

As a young man, Ian enjoyed cycling, scuba diving and hill walking. He loved to travel and went on a bike trip across the channel to Holland and Belgium.

9 | PRODUCTIVE AND ALLOCATIVE EFFICIENCY - ROTORUA GEOTHERMAL SYSTEM

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***Keywords:** Rotorua Geothermal System, productive efficiency, allocative efficiency, geothermal flow metering.*

The Rotorua Geothermal System is managed under the Rotorua Geothermal Regional Plan (1999), to protect its rare and vulnerable surface features. The current plan has strong imperatives to support efficiency in the use and allocation of the geothermal resource. The effectiveness of these policies, and their implementation, has been assessed as part of a review of the regional plan. This work identified the typical efficiency issues in the geothermal production and distribution systems in Rotorua, and at the user end. To improve efficiency in allocation, the Bay of Plenty Regional Council is developing a robust process and an allocation App to calculate the heat and mass (geothermal fluid) load for benchmarking efficient use and allocation of the resource. There are limited suitable methods or technologies for accurate and continuous measurement of the geothermal fluid take in Rotorua due to its unique settings (i.e. geothermal fluid properties, mixed use and shared schemes, and environmental and regulatory constraints). Those challenges were overcome with the development of a movable flow loop, and trials showed that over 50% of the users may be using less than 30% of their allocated geothermal fluid. Increasing certainty around the actual heat and mass production from the system will reduce the risk of over-allocation while making better use of the estimated sustainable resource available. Wasteful practices are expected to be minimised mostly through allocation for efficient use coupled with tighter take monitoring. Most importantly, improved allocation and use will contribute to the sustainable management of the resource and protection of its unique surface features.

Session: 1.2

10 | MEASURING HEAT FLUX DYNAMICS THROUGH THE CLAY CAP IN THE WAIRAKEI-TAUHARA GEOTHERMAL FIELD

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Keywords: Magnetotelluric (MT), Methylene Blue (MeB), temperature, heat flux, AUTOUGH2, Wairakei-Tauhara.

This paper develops a multidisciplinary analysis of the extent, stratigraphic context, and thermal structure of the hydrothermally altered clay cap in the Wairakei-Tauhara geothermal field of New Zealand. We recovered unprecedented information on the clay cap geometry and heat transfer dynamics that helps in the understanding of these complex hydrothermal systems.

First, using a joint inversion of magnetotelluric (MT) and methylene-blue (MeB) data, we imaged a ~300 m thick conductive clay cap that tracks the primary aquiclude overlying a distinct reservoir unit. Then, by mapping wells temperature and lithology into this structure, we differentiated contemporary hydrothermal clays from relict clays as well as those formed under diagenetic alteration. Also, we confirmed a broad temperature formation range of between 59±15 °C and 199±20 °C for the electrically conductive smectite clay. Finally, by applying a simple heat transfer model that captures vertical conductive and advective heat flow through the inferred clay cap, we estimated a lower bound of 380±21 MW for the system heat output.

Additionally, we tested the incorporation of the clay cap inferred from MT inversions into geothermal reservoir simulations. The inferred clay cap was mapped to a reservoir permeability model to simulate temperatures with the reservoir simulator AUTOUGH2. Modelled temperatures were then compared to observed temperature logs as well as prior models using standard techniques (i.e., without MT information). We applied this scheme to a calibrated permeability model for the Wairakei-Tauhara geothermal field. Results indicated that our inclusion of the low permeability structure led to reductions in the model misfit to temperature logs.

The developed methods allow studying uncertainties when inferring clay cap properties in high-temperature geothermal fields. Imaging the clay cap serves as a guide for developing conceptual models and for defining drilling targets, so the uncertainty inferred for these estimations is of great importance.

Session: 4.3

11 | A REVISED TECTONIC MODEL OF MINAHASA DISTRICT BASED ON LIDAR, IMAGE LOG AND FRACTURE STABILITY ANALYSIS IN TOMPASO

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***Keywords:** Tompaso, Sulawesi, Tondano, tectonic, permeability, geology, geothermal system, structure, geomechanics*

This paper investigates the tectonic setting of the Minahasa district by using the updated surface and subsurface data of the Tompaso geothermal field, North Sulawesi, Indonesia. The update includes a detailed analysis of the high-resolution surface topographic map, a borehole image structural interpretation, feedzone identification from the well-test, and stress analysis from the geomechanics study. These methods lead us to a new tectonic concept of the Minahasa district, which consistent with the geothermal conceptual model in the Tompaso area. In line with this, we also evolve the previous well-known literature of Minahasa district tectonic as we used more detailed surface and subsurface data.

This paper assesses subsurface geology uncertainty in the Minahasa district, which is mainly hindered by surface interpretation. We argue the local ENE-striking fault existence that suggested by previous literature. We define the local Minahasa district on surface and subsurface, dominantly controlled by NE-striking fractures due to North Sulawesi subduction and East Sangihe subduction. The geomechanics study describes the regional and local stress direction to construct our tectonic concept and corroborates the local Tompaso area's structural framework. This interpretation also supports the mechanism of Tondano Caldera forming explanation as a classic ellipsoidal natural collapse caldera that follows the maximum horizontal stress trend, rather than occurring as a result of the step-over mechanism. Our permeability investigation through detailed integrated analysis of the borehole image with the injection spinner data suggests the NE-trend fluid flow direction, either from reservoir scale or well scale without showing a robust existence of ENE-striking fractures.

Session: 3.2

12 | PERFORMANCE OF A GEOTHERMAL SYSTEM IN PETROLEUM FIELDS OF THE TARANAKI REGION, NEW ZEALAND

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Keywords: *Petroleum fields, geothermal system, fractured reservoir, energy extraction, lifetime performance, Volsung*

Extracting energy from petroleum fields is an attractive topic for research. In the Taranaki region, some of the depleted oil and gas reservoirs are prospective candidates for low-temperature geothermal development. This is because the hydrocarbon wells produce a large amount of coproduced water at the surface.

Therefore, we analyse one of the hydrocarbon fields encountering fractured reservoirs in the Taranaki region. We aim to estimate the production rate and well separations to sustain generation capacity from the field for 10 years.

We used the Volsung reservoir simulator to simulate the reservoir models using the MINC (the Multiple Interacting Continua) formulations and representative rock properties. Then we analysed the behaviour of the petroleum reservoir over time with the extraction of geothermal energy.

It was found that a flow rate of 180 kg/s is sufficient to produce 6 MW of electricity and could be sustained for at least 10 years. The work suggests that the theoretical maximum production rate between production and reinjection well separated by 500 m would be 220 kg/s before the production enthalpy declined below 20% of the initial value. But the field has several wells and larger separation between the production and injection wells. The model of the field has seen production rates of 180 kg/s to sustain a generation capacity of more than 6 MW without the evidence of any thermal breakthrough from the injection well over a period of 10 year. The model demonstrates the effective movement of the warmer fluids from the lower formations to the upper reservoir for higher production rates before the arrival of the cold waterfront from the reinjection well.

For future analysis, it is recommended to conduct optimisation of the operation strategy in the field. A detailed thermo-economic study could also be performed to analyse the benefits of ultimate oil recovery, aquifer effect, and the onsite power demand.

Session: 1.3

13 | RECOVERY OF REINJECTION WELL CAPACITY USING ONLINE DISSOLUTION

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Keywords*: online dissolution, silica scaling, reinjection well*

There are several methods available for cleaning a scaled-up geothermal well. These can either be mechanical or chemical. A typical chemical method is usually acidizing, which objectively is simply a tubular process or cleaning the vicinity of the wellbore to improve the well's productivity or injectivity.

Similar to acidizing, a novel method being explored by Nalco Water is Online Scale Dissolution targeted to dissolve scales in a reinjection well. This method involves injecting GEO991, a strong acid alternative, to the condensate or brine for a specified period of time to be able to dissolve scales in the wellbore; thus, improving well acceptance rate.

Prior to deploying the dissolution program in the field, scale samples from the reinjection well were subjected to dissolution tests using different dissolvers to determine the extent of dissolution that can be achieved and the suitable dissolver. From the results of the test, the most suitable dissolver is GEO991 with 100% scale dissolution affecting Si, As and Fe components. Online dissolution sidestream test was done to better understand and evaluate the product performance in a realistic and controlled environment. It was found that GEO991 can dissolve scales composed of 60-70% silica and 20% iron-bearing compound. Observations supporting this claim include the 5.32% reduction in the total weight of the scales, minimal silica crystal observation in the dosed line coupon, higher levels of silica and iron measured in the dosed line. No additional scaling was also confirmed as manifested by the following: constant flowrate maintained in the dosed line, a more stable line pressure and minimal to non-existent scaling in the pipe holder. The study gave us enough information and confidence for a commercial trial to proceed.

Full-scale commercial run happened in two phases on the target reinjection well. First phase lasted for 33 days improving the well acceptance rate from 3.74 kg/s (baseline) to 10.1 kg/s. The second phase of the trial lasted for 16 days and was able to reach 35 kg/s final well acceptance rate which was the original acceptance rate. The study was able to confirm that GEO991 dosing can be a favorable alternative to traditional rig and non-rig well intervention techniques based on the capacity recovery achieved, cost, ease of deployment and reduced to eliminated well downtime.

Session: 5.3

14 | LESSONS LEARNED AND PERFORMANCE IMPROVEMENT: DRILLING CASE STUDY FROM SARULLA GEOTHERMAL OPERATION, NORTH SUMATRA

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Keywords: *Geothermal Drilling, Performance Improvement, Drilling Performance, Lost Circulations, Drilling Fluid, Integrated Project Management.*

A lessons-learned and continuous improvement approach used to improve drilling performance significantly during a five-well drilling campaign on one drilling pad at the Sarulla geothermal development field in North Sumatra, Indonesia. Drilling times were reduced by 73%, and costs decreased by 64% from the first to the fifth well. Drilling challenges on this pad included severe lost circulation, high vibration when drilling the surface hole sections, soft and swelling clays in shallow sections, along with sloughing Paleosol formations in the deeper section, and a corrosive drilling fluid environment, which resulted in drill pipe (DP) washouts and twist offs.

Optimized intermediate casing setting depths were developed to manage the sloughing formation issues. The use of nested liners was employed to stabilize the difficult hole sections already drilled but allowing drilling to commence safely with smaller hole sizes deeper. To help prevent intercepting previous wells and kickoff issues in the soft clay formation, the 26-in. surface hole section was "nudged" using directional drilling techniques. Formation clay samples were tested using the linear swelling method (LSM) and X-ray diffraction (XRD) to optimize drilling fluids formulations specific for each section, and a set of best practices for drilling these formations was developed.

Other performance improvements that were applied include the following:

- Using a shock sub in the surface section
- Replacing drilling stabilizers with roller reamers to reduce the torque while drilling in the reservoir
- Using casing running tools (CRTs) to increase efficiency and safety of casing operations
- Using a custom-designed and built polycrystalline diamond compact (PDC) drill bit to help enhance the rate of penetration (ROP)
- Modifying tubular inspection procedures to detect internal DP flaws

Session: 2.2

16 | LOW-TEMPERATURE THIXOTROPIC CEMENT DESIGN OVERCOMES SURFACE SECTION DRILLING CHALLENGES – DEEP GEOTHERMAL EXPLORATION PROJECT, JAVA – INDONESIA

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Keywords: *drilling, cement slurry design, thixotropic cement, drilling challenges, unconsolidated andesitic lava, boulders, loss circulation, hole problem.*

A low-temperature thixotropic cement design was utilized to successfully overcome surface drilling challenges in a deep geothermal exploration well in Java island - Indonesia. This solution was provided for the second exploration well after unexpected surface challenges were encountered during drilling of the surface hole section, where hole destabilization and total loss of circulation occurred because of unconsolidated Andesitic Lava Boulders, also encountered in the first well. The other challenge was a low surface temperature because of the high elevation of the well pad, which was higher than 2,000 feet above sea level.

Before this low-temperature thixotropic cement design was implemented, several cementing plugs had been pumped to stop the losses and stabilize the formation, with no significant result. Therefore, a decision had been made to perform a plug and abandonment (P&A) operation on this first well.

To avoid this P&A outcome, a low-temperature thixotropic cement was designed to have a slurry that would enable the operator to stabilize the surface hole so that the surface casing could be run and set at bottom-hole. The processes involved leading up to the utilization of this effective slurry design to stabilize the hole are listed below:

- Met with all parties to discuss options for thixotropic material that could be added to the slurry
- Selected two possible thixotropic additives (Material A and Material B)
- Performed a total of 58 lab tests to determine the thickening time and thixotropic properties of each slurry, as well as their different weights, concentrations, and temperatures
- Selected the slurry that had a thickening time below 90 minutes

Upon successfully inventing the most effective slurry, the operator was able to drill the surface section to target depth, and the surface casing was set at maximum depth. The drilling was continued in the well to a planned total depth (TD) at 11,300 feet. At the time of the writing of this publication, this well was the deepest geothermal well in Indonesia.

Session: 4.4

17 | GEOCHEMISTRY AND GEOTHERMAL PROSPECTIVITY OF THE HYDROCARBON-PRODUCING TARANAKI SEDIMENTARY BASIN

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***Keywords:** Taranaki, petroleum, geothermal prospectivity, geochemistry*

In a previous nation-wide study of low-enthalpy geothermal systems in New Zealand, the Taranaki peninsula was deemed sixth of the six regions in New Zealand with the highest geothermal prospectivity, albeit the only one where the minimum estimated recoverable heat (0.54 PJ/a) and estimated temperature range (<100-200oC) are based on data from abandoned subaerial oil and gas wells. This submission examines fluid geothermometry in more detail as part of a study on the geochemical compositions of oil and gas well discharges and their effects on future geothermal exploitation. Bottomhole temperatures (BHT) of wells in Taranaki vary from <50oC to about 175oC. The highest subsurface temperatures (>150oC) based on solute chemistry occur at New Plymouth, Kapuni and Stratford, with moderate temperatures (100-150oC) at Onaero, Kaimiro, Ngatoro, McKee and Waihapa, and the lowest in the west at Te Kiri (<100oC). High temperatures at New Plymouth may be related to the shallowing of the upper mantle but high temperatures at Kapuni and Stratford may be due to rapid ascent of hot fluids via deep faults. Subsurface temperatures at Taranaki show that geothermal energy can be harnessed for power generation and direct heat use. Because of the likelihood of liquid condensation, the presence of gases >C6 would require a different distribution system for geothermal fluids for power or direct heat use if fluids from petroleum wells are directly harnessed for geothermal energy. However, the use of deep borehole heat exchangers at Taranaki may obviate the problem of hydrocarbon gas condensation and hydrocarbon solidification during geothermal production.

Session: 1.4

18 | CARBON NEGATIVE GEOTHERMAL: THEORETICAL COMBINED GEOTHERMAL-BECCS INJECTION CYCLE

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Keywords: geothermal, hybrid, biomass, dissolved CO2, BECCS, forestry waste, reinjection, non-condensable gases

Geothermal energy is a mature and established technology in Aotearoa New Zealand. In 2019, it provided 17% of total electricity generation. However, power production from geothermal resources is often limited by heat transfer and conversion efficiencies, which are especially restrictive for low-temperature resources. For almost a century, there has been interest and research in superheating geothermal fluid with an ancillary fossil fuel boiler to improve efficiencies. Hybrid geothermal-solar and geothermal-biomass plants have been considered as carbon neutral solutions in a similar vein. The latter is of particular relevance in New Zealand due to the colocation of the Taupo Volcanic Zone (TVZ) with a large forestry industry. This work assesses the feasibility of using a biomass boiler coupled with carbon capture and storage in geothermal power generation in New Zealand. The superheating of geothermal fluid with bioenergy has been adopted in other parts of the world, and has been shown to result in an increase in energy output when retrofitting existing power stations.

Coupling bioenergy with carbon capture and storage (BECCS) technologies at geothermal plants is a pathway for net carbon negative generation. Since geothermal plants typically require reinjection wells as part of reservoir pressure management, part of the infrastructure for reinjection of CO2 is already present. A simple systems model was constructed to explore end-member energy cycles and determine, per unit mass rate of geothermal fluid, both the biomass fuel requirements for superheating and associated CO2 emissions. The model also quantifies the proportion of CO2 that can be dissolved in the condensate streams for reinjection. As this CO2 originates as atmospheric carbon that is locked in the biomass fuel during growth, the result is a carbon sequestering energy cycle (net carbon negative).

We apply the model to a theoretical geothermal doublet producing at 150 to 195 °C with a condensing turbine and optional wellhead separator. We showed that superheating the separated steam with biomass can yield electricity gains of about 50% and full emissions capture. If no wellhead separator is used and total production fluid is superheated, power output is increased two orders of magnitude, with emissions capture exceeding 30%. With only 1 kg/s of geothermal fluid flow, this energy cycle could sequester almost 2 kT of CO2 per annum for each MWe generated. However, understanding the challenges of large-scale dissolved CO2 injection remains a key uncertainty in determining the viability of carbon negative geothermal cycles.

Session: 5.2

20 | THEORETICAL MODELS OF MAGMA ASCENT THROUGH A GEOTHERMAL BOREHOLE

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***Keywords:** Magma, geothermal, drilling, eruption, borehole, fluid dynamics, crystallization.*

As drilling technology improves and shallower resources become tapped, interest is growing in deeper, hotter geothermal resources. In volcanic settings, the possibility of encountering a magmatic intrusion increases with each metre of borehole. Such intrusions may not be resolved by surface geophysical surveys, particularly if they are small, deep or sit beneath other bodies that shadow their presence. Further, if the intrusion contains a mobile fraction of partial melt, this could enter the borehole and begin to ascend.

Magma has been encountered at least three times during geothermal drilling: in Iceland, Kenya and Hawai'i. In the latter instance, dacitic magma at a depth of 2.5 km entered the borehole and ascended 5.5 m over several minutes before stopping. Several international projects have proposed to drill shallow magma bodies or their thermal aureoles for scientific inquiry, energy generation or hazard mitigation. However, the possibility of uncontrolled magma ascent within a wellbore has not been quantitatively addressed.

Here, we present an analysis of the competing time scales controlling the thermal survival of a magma column ascending the borehole. Rise time is most rapid for low viscosity magmas (like basalts) under large overpressure that are encountered at shallow depths in large-diameter boreholes. This magma must reach the surface before it is stalled by crystallization – either through radial cooling or growth of a crystal plug that exerts a drag on the borehole wall. Magma rise is also rapidly accelerated in the presence of a low-viscosity outer annulus of degassed volatiles, although it is not clear if this configuration could persist stably.

Investigating a typical parameter range, we show that rhyolite magmas are too viscous to feasibly ascend wellbores, which is consistent with the experience at Hawai'i and Iceland. In exceptional circumstances, low-viscosity basaltic magmas could reach the surface before freezing, such as occurred in Námafjall geothermal field in 1977 during the Krafla Fires.

Session: 4.4

23 | ACCURACY AND RELIABILITY ANALYSIS OF TRACER FLOW TESTING IN GEOTHERMAL SYSTEMS

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***Keywords:** Geothermal, Tracer Flow Testing, Isopropanol, Benzoate.*

As a critical resource management tool, tracer dilution techniques have been used to measure steam and brine flow and total enthalpy in geothermal industries for many years. Standard operations have become part of a routine monitoring program in many geothermal fields throughout the world. Different types of tracer for gaseous and aqueous phases have been developed and used in many different geothermal fields. Tracer injection equipment, sample collection systems and tracer analyzing methods have also been developed and gradually improved over past decades. The accuracy and reliability of testing results vary depending on types of tracer, injection and collection techniques, tracer analysis methods, and testing operation procedures. This paper summarizes our many years' experience on utilizing sodium benzoate and isopropyl alcohol as tracers for flow testing in geothermal systems in New Zealand and overseas and analyses the accuracy and reliability of the available testing results.

Single gaseous and aqueous tracers have also been used to measure steam or water flow rates in single phase pipelines to verify permanent flow meters at geothermal plants. An innovative tracer testing procedure to evaluate the performance of steam purifiers has also been developed with consistent results achieved. Particular emphasis will be placed on quality control system to ensure more accurate and reliable results are achieved.

Session: 4.2

24 | DISTRIBUTED TEMPERATURE MEASUREMENTS AT AN ACTIVE PLATE-BOUNDING FAULT USING FIBRE OPTIC SENSORS

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***Keywords:** Raman Scattering, Fibre optic sensors, Distributed temperature sensor (DTS)*

New Zealand attracts people for its liveliness, but its geography produces more seismic events and the Southern Alpine Fault is one of the largest sources of such activities. Deep fault drilling project -2B was commissioned to explore and understand the geophysical properties of the fault at depth. This involves the distributed temperature monitoring along the depth of the boreholes in the Whataroa valley. Here, we report the development and field deployment of the Raman based distributed fibre optic temperature sensor. The temperature profiles and its gradient are estimated using the indigenous interrogator and results compared to those of the commercial DTS interrogator.

Session: Poster

25 | NUMERICAL INVESTIGATION OF COUNTER-FLOW PROCESSES IN GEOTHERMAL WELLS

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Keywords: *Transient, wellbore, simulation, counter flow, heat up*

One of the complex transient phenomena that can occur within geothermal wellbores is counter-flow. In geothermal wells, counter-flow occurs when steam flows up the well while water flows down. Here we discuss numerical experiments with a recently developed transient geothermal wellbore simulator that is capable of modelling counter-flow scenarios.

We use our simulator to investigate the role of counter-flow in two test cases involving shut-in geothermal wells. In the first test case, counter-flow occurs as a shallow geothermal well heats up and a vapour cap is formed. The results of this simulation suggest that the vapour cap develops because of the heat transport in a counter-flow zone that occurs in the two-phase fluid. For this reason, counter-flow processes cannot be ignored when simulating flow in a shut-in geothermal wellbore, even though the mass flows that occur during this process are small. A second test case simulates the opening of a multi-feed well to flow, starting with realistic shut-in initial conditions. These initial conditions, which were found using simulation, involve inter-zonal flow and counter-flow processes. They demonstrate that temperatures in the well differ from those in the reservoir when these processes occur. Additionally, this second test case highlights that counter-flow capabilities are required to fully model many transient wellbore processes, even something as fundamental as opening a well to flow.

The test cases show that simulation can be used to help in the interpretation of data from shut-in wells. However, the investigation shows that if a wellbore simulator is to be used in this capacity it must be able to model counter-flow processes.

Session: 5.2

26 | MODELLING DISCHARGE STIMULATION USING A TRANSIENT WELLBORE SIMULATOR WITH AN AIR-WATER EQUATION OF STATE

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Keywords: *discharge stimulation, air-water EOS, transient, wellbore simulation, gas lifting, air compression.*

Simulation of transient flow in geothermal wells is an important reservoir engineering task. Previously, we discussed the development of a wellbore simulator capable of modelling complex transient processes in geothermal wells. However, its applicability was restricted to flows of pure water. This paper discusses the implementation of an air-water equation of state in our transient wellbore simulator. The simulator's capabilities are demonstrated by modelling two discharge stimulation methods, airlifting and air compression. A case study well is considered with a water level approximately 300m below the wellhead.

Session: 3.3

28 | TURNING THE PRESSURE ON FOR THE NANO-STRUCTURED CALCIUM SILICATE HYDRATE (CASIL) SOLUTION TO SILICA SCALING

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Keywords: *Silica, silica scale prevention, calcium silicate hydrate, solid liquid separation, lamellar separation, steam carry-over*

The nano-structured calcium silicate hydrate (CaSil) technology has been shown to prevent the formation of hard intractable silica scale. Such scale forms due to the supersaturation and precipitation of silica from geothermal water during energy production. Using the CaSil technology suspended silica is converted and precipitated as calcium silicate hydrate, which does not stick to surfaces and can be recovered via solid-liquid separation to yield useful products. Additionally, CaSil can capture and trap calcium carbonate species formed in parallel. So far, this technology has been employed after flashing processes with the recovery happening at atmospheric pressure and below boiling temperatures.

Feedback from the geothermal industry suggested that it would be very interesting to capture and transform the silica prior or during the flashing process. Doing so would offer a significant advantage. Currently during flashing silica can be carried over with the steam and damage sensitive equipment. Transformation of the silica into a non-volatile and particulate silicate hydrate reduces the carry-over. Furthermore, applying the CaSil technology under pressure would allow to retain elevated pressure at the end of the process, which aids in the transport of liquids over distances and reinjection.

In this article we present preliminary findings regarding employing the technology at elevated pressures. We have investigated and answered several research questions. The CaSil process does not significantly change the vapour pressure or lower the temperature of the geothermal water. It significantly reduces the carry-over of silica into the vapour phase depending on the extent of treatment. Lastly, the lamellar separation process can be carried out at elevated pressure. Elevated temperature has a larger impact on the efficiency of a lamella separator than pressure.

Session: 5.3

29 | GEOPHYSICAL, GEOCHEMICAL AND MINERALOGICAL CHARACTERISTICS OF THE ALTERATION AND DEFORMATION HALO ABOVE A DIORITE-TONALITE INTRUSIVE COMPLEX AT NGATAMARIKI GEOTHERMAL FIELD

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Keywords: *Ngatamariki, geophysics, intrusive, hydrothermal minerals, rock chemistry*

To understand what controls the geophysical properties at the Ngatamariki geothermal field, New Zealand, particularly seismic velocity, an analysis of geophysical logs was undertaken. The geophysically-logged interval in the south of the field (well NM10) spans the propylitic altered, tuff-dominated, Tahorakuri Formation volcaniclastics and andesite. In contrast, the logged interval in the north of the field (NM9) spans the Tahorakuri Formation that experienced an earlier phase of potassic, advanced-argillic and phyllic alteration related to intrusion of a tonalite-diorite intrusive complex. Geochemical analyses of drill cuttings using portable X-ray fluorescence (pXRF) were obtained at a 5m depth interval spanning the logged intervals in each of the wells. These were combined with automated mineralogy using a Tescan Integrated Mineral Analyzer (TIMA) and quantitative X-ray diffraction (XRD) data on selected samples that provided quantitative mineralogy data. The geochemical and mineralogy data were then used to interpret the factors that affect the geophysical properties of the rocks. The Tahorakuri Formation was found to have markedly different geochemistry, mineralogy and petrophysical properties in the north of the field (NM9) compared to the south of the field (NM10) which we interpreted as due to the wide-spread quartz deposition and ductile deformation that took place during the intrusion of the tonalite-diorite complex. These processes reduced porosity within the Tahorakuri Formation in the north of the field, resulting in higher seismic velocity, higher density and higher resistivity relative to the south of the field (north (NM9) –average porosity of 7.5%, average P-wave velocity (Vp) 4.59 km/s, average density 2.64 g/cm3, average resistivity 118 ohm.m versus south (NM10) – average porosity 18%, average Vp 3.78 km/s, average density 2.47 g/cm3, average resistivity 20 ohm.m). The approximately 400m thick interval of Tahorakuri Formation in NM9 that overlies the intrusive has particularly low porosity (<5%) and consequent high seismic velocity (4.5–5.5 km/s), density (2.6–2.8 g/cm3) and resistivity (500–1000 ohm.m). Abundant andalusite at the top of this interval provides evidence that the rock in this zone was >350 °C during the intrusive event. The inferred temperature, as well as deformation textures observed in an FMI log over this interval, suggest that the very low porosity is the result of ductile deformation. The interval between the andalusite altered tuff and the intrusive body appears to be relatively unaltered with abundant plagioclase and only subtle potassic alteration. Abundant small aperture (<0.1 mm), low-angle (<20° dip) fractures occur within this interval which are interpreted as being due to hydraulic fracturing due to pressure-transients that occurred within the lithostatic-pressured zone above the magma. The lack of alteration within this interval is interpreted as being due to the fluid within this zone being supercritical when the intrusive was emplaced with the low porosity/permeability that resulted from ductile deformation preventing further alteration as the magma cooled and during the present-day geothermal activity. The dataset provides insights into the changes in geophysical properties that occur close to intrusive bodies and has potential implications for geophysical imaging of magmatic intrusions and supercritical zones.

Session: 4.3

30 | IMAGING THE ALTERATION AND DEFORMATION HALO ABOVE THE DIORITE-TONALITE INTRUSIVE AT THE NGATAMARIKI GEOTHERMAL FIELD.

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Keywords: *Ngatamariki, Rotokawa, seismic tomography*

An expanded seismic array of ~55 seismometers deployed across the Rotokawa and Ngatamariki geothermal fields during 2017 and 2018 was used to derive 3D seismic velocity models via local earthquake tomography using P and S wave traveltimes from a set of 302 microseismic events. These events were mostly from three clusters of seismic activity around injection wells within the fields. The P and S arrival times used in the inversions were from both manual picking (90 events) and high-quality automatic picking (261 events) with estimated arrival times accurate to approximately ± 0.05 s for P and ± 0.1 s for S. The tomography code tomoDD was used for the inversions that progressed from 2D to coarse to fine inversion grids in order to examine the improvement in traveltime residuals with increasing model discretization. A 1D constant-velocity starting model previously determined using Monte Carlo VELEST was used for most models. In addition to this, a further fine inversion grid was constructed with a 3D starting velocity model based on available well-logging data (checkshot and sonic logs) and geological information. Model solution robustness and spatial resolution were assessed using derivative weight sum (DWS) values that provide a measure of ray-path coverage in conjunction with synthetic recovery tests (spike test and interpretation model test). The inversion models strongly indicate that a west to east, high to low-velocity variation of at least ±10% Vp and Vs exists across northern Ngatamariki. The high velocity in the west is interpreted to be due predominantly to the very low porosity that formed within the Tahorakuri Formation due to high temperature alteration and ductile deformation during intrusion of a diorite-tonalite magma approximately 600 thousand years ago. The location of the transition from high to low velocity agrees well with a transition from high to low gravity from the publicly available gravity data in the area and a transition from high to low resistivity from a 3D inversion of magnetotelluric (MT) data. Relatively low Vp and Vs is imaged in the east of Ngatamariki and is most likely due to either a greater proportion of porous volcaniclastics and sediments and less rhyolite lava in the upper 1 km and/or deeper smectite and smectite-illite clay alteration in that area, as suggested by magnetotelluric data. High Vs is observed at Rotokawa, which is interpreted as being due to the shallower contacts of the andesite and greywacke. An alternative explanation is that there is less volcaniclastics/sediments and more rhyolite lava in the upper 1 km. Since the magmatic alteration and deformation in the north of Ngatamariki is associated with low-permeability wells, the tomography results can be used to inform future well targeting and numerical modelling of the field.

Session: 4.3

32 | DOUBLE ENERGY INPUT, A PROPOSAL FOR A NOVEL SOURCE OF ELECTRICAL ENERGY, NON-OPEN PIT MODEL.

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Keywords: *DEI, Double Energy Input, Hydroelectrical, Seawater, Open Pit Mine, Geothermal, Supercharging, novel source of electrical energy, Sonora, Guaymas, Mexico renewables production.*

In order to slow down adverse global anthropogenic effects such as global climate change and the destruction of ecosystems, alternative energy sources that are clean, renewable, and efficient are needed to replace the existing energy sources.

Double Energy Input is a novel invention that gathers two renewable energy resources: hydro-electrical power and geothermal power. This invention utilises the sea as its reservoir, the dam is a wall of a big pit hole, and in the base of such pit, we will use the geothermal power for ridding off the water.

This model is designed to generate between 1,200 – 1,500 MW of power in the hydro-electrical phase and will generate about 4.86 tons of salt per second. An additional 800 MW of energy will be produced by supercharging the hot water at the bottom with heat and pressure and running a vapour power plant.

This model provides an alternative means for producing clean and renewable energy with two abundant resources, sea-water and geothermal heat.

Session: 5.4

33 | STEAM PURITY TROUBLESHOOTING: THE BERLIN GEOTHERMAL STEAM FIELD, EL SALVADOR

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Keywords: *Steam Purity, Berlin Geothermal Steamfield, El Salvador, Steam Scrubbing.*

Moisture carried with the geothermal steam at the turbine inlet can cause millions of dollars lost in electricity generation. These revenue losses occur due to frequent power plant overhauls, retrofitting and extended turbine maintenance required to remove the scaling out of the turbine blades and diaphragm or replace expensive turbine components (e.g. turbine shaft) damaged by entrained liquid droplets impacting the surfaces at high velocity.

Several technical articles, published since the onset of the geothermal industry, describe practical design techniques and recommendations to improve the steam field design effectiveness, to deliver dry and clean steam to the turbine. These criteria fundamentally refer to primary separation efficiency and steam line scrubbing (or secondary separation). Some of the design recommendations might be valid within a range of physical conditions (e.g. steam pressure or velocity) or applicable only to a specific steam field configuration. The authors consider an opportunity to combine all the design techniques, criteria, and experiences published to date into an integrated thermofluid model to either validate the well-known recommendations or optimise their results.

The Berlin Geothermal Steamfield (El Salvador) is presently experiencing problems with one of its turbine units due to impurities carried by the steam. LaGeo and the University of Auckland are working together to analyse the problem, develop and calibrate a model to simulate the current steam field, and assess optimisation scenarios to mitigate the steam purity problem.

This paper presents the findings, modelling results, and provide recommendations.

Session: 4.2

35 | CASE STUDY OF MASS FLOW DECLINE IN PRODUCTION WELL NM11

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Keywords: *Ngatamariki, New Zealand, calcite scale, production well, geology, geochemistry, reservoir engineering*

NM11 is an inactive production well at Ngatamariki geothermal field drilled 3km deep. It is a large diameter well with an 18-5/8" production casing. The well was first flowed in 2013, initially providing approximately 1000t/h. A few months after starting production, the mass flow from the well began to decline. Calcite scale was detected in the well 10 months after beginning production. Managing calcite scale in production wells and power plants is a major challenge in geothermal field operations. The well was ultimately rendered unproductive and understanding the mechanism will lead to appropriate management options for future wells.

Geological, reservoir engineering, and geochemical data are investigated to determine possible causes for the decline observed in the well's productivity. The geology of the well and characteristics of two cores are inspected and compared to neighboring wells. PTS results before production and after 6 months of production show significant permeability reduction in all feedzones over the first 6 months of production. Wellbore models are used to match the PTS results and give modelled productivity index (PI), pressure, and enthalpy for each of the 9 feedzones. Geochemical data showed the well had calcite scale deposition occurring. Calcite scaling is induced by flashing, typically at inferred flash point depth. Scaling is a likely cause of productivity decline in shallow feedzones but does not explain the productivity index in lower feedzones which have not experienced flashing. Thermal expansion and collapse of weak formation are possible contributors to the observed permeability decline.

36 | REGIONAL GOVERNMENT STRATEGY FOR THE SUSTAINABLE USE AND DEVELOPMENT OF THE KAWERAU GEOTHERMAL FIELD BY MULTI- TAPPERS IN NEW ZEALAND

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Keywords: *Kawerau, Geothermal, Multi-Tapper, System Management Plan*

The Kawerau Geothermal System in the North Island of New Zealand was first utilised for power generation in 1957. At this time all electrical power generation was controlled by the New Zealand Government. Over the next few decades the system was extensively developed by the Government.

More recently, electricity production has devolved from a State-owned activity towards private ownership. Notably in 2005, Ngāti Tūwharetoa Geothermal Assets (NTGA) purchased substantial Crown assets (as part of a historical settlement with the Crown) relating to the Kawerau Geothermal System. There are now four major consent holders using the geothermal resource, including Mercury NZ Ltd, NTGA, Geothermal Development Ltd, and Te Ahi O Māui Ltd.

Sustainable management of the resource is administered by the Bay of Plenty Regional Council (BOPRC) under the Resource Management Act 1991 (RMA). It allocates use of the resource through consents, with each consent holder having specific rights and obligations around the use of the resource, for a specific period of time.

The Kawerau geothermal resource is now one of New Zealand's largest developed geothermal resources. The field has consented takes of close to 200,000 tonnes per day with generation of close to 400MWe of electricity and a further 1000 MWth for direct industrial use.

To ensure cooperation between the multiple resource consent holders, and that the Kawerau Geothermal System is managed in an integrated and sustainable manner, BOPRC has worked with consent holders to develop a System Management Plan (SMP). The SMP is intended to provide an integrated approach to sustainable management of the Kawerau Geothermal System, and offer guidance to BOPRC in its decision making processes, in both the administration of existing consents, and the processing of new resource consent applications. This includes agreed operational protocols both amongst consent holders and between consent holders and BOPRC.

Session: 1.2

38 | INVESTIGATING CONTROLS ON GEOTHERMAL UPFLOW BENEATH THE ROTORUA LAKES

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Keywords: *TOUGH2, geothermal reservoir modelling, Rotorua lakes, Okataina Volcanic Centre, convective fluid flow, structural controls.*

Seven of the 11 largest lakes in the Rotorua region have geothermal manifestations. All seven are associated with collapse caldera features, while the other four which do not have any identified geothermal manifestations are situated some distance from any caldera structures. Six of the geothermally influenced lakes are close to the boundaries of the Okataina Volcanic Centre (OVC), which is a composite caldera collapse feature partly filled with lava domes. Lake Rotorua, the seventh, sits to the west and fills the centre of a single volcanic caldera. In this project, we use heat and fluid flow models to explore the role the OVC might play in determining the locations of upflow beneath the Rotorua lakes.

We created highly simplified TOUGH2 models to identify individual processes that could affect upflow locations. The model area encompasses the six lakes that lie close to the OVC boundary and the four cold lakes to the west and south. The base of the model is a uniform hot plate with 700 mW/m2 heat input. The top of the model follows water table elevation, which is a slightly muted reflection of topography. The model initially had uniform rock properties, with permeability variations added later to replicate an OVC boundary that acts as a barrier or conduit to flow.

Model results show that topography alone can drive convection so that geothermal upflows occur beneath Lakes Tarawera, Rotomahana and Okataina, along the western edge of the OVC boundary. Upflows were too far to the north for Lakes Rotoiti, Rotoehu and Rotoma, but if a barrier to horizontal flow was included at the inferred location of the OVC boundary, model upflows occurred in approximately the right places. It therefore appears that geothermal manifestations beneath the Rotorua Lakes are influenced by a combination of topographically-driven convection and structural controls related to the OVC boundary.

Session: 3.2

39 | NUMERICAL MODELLING FOR CARBON ACCOUNTING FROM GEOTHERMAL POWER PLANTS

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***Keywords:** Reservoir modelling, Emissions, Geothermal, Carbon accounting, Emissions Trading Scheme.*

Geothermal fields naturally emit greenhouse gasses through surface expression. When a geothermal power plant is installed on a geothermal field, the fluid extracted contains these gases, but generally, the reinjected fluid does not. For this reason, power companies producing from geothermal fields are considered an 'emitter' within the Emissions Trading Scheme (ETS) in New Zealand. They are hence liable to purchase carbon credits to offset emissions. At present, emissions are naively calculated from the emissions from production but do not consider the system as a whole.

When fluid is taken from a geothermal system, the pressure in the system is reduced, and some of the natural surface manifestations such as hot pools, fumaroles and steaming ground may decrease. This process lowers the natural emissions from the system, but this change is neglected in current emission calculations in the ETS. Numerical modelling of geothermal reservoirs provides a mechanism for more accurately accounting for total emissions provided the model has been well-calibrated to the emissions from the field. Numerical models solve conservation equations across the entire domain. Therefore, they can quantify emissions from geothermal wells and surface feature

Session: 3.4

42| A REVIEW OF GEOTHERMAL RESOURCE MANAGEMENT UNDER THE RMA 1991 WITH A VIEW TO THE FUTURE

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***Keywords:** sustainable management, integrated management, Māori partnerships, spatial planning, environmental limits*

As one of the world's major geothermal nations, New Zealand is a leader in geothermal resource management through the framework of the Resource Management Act 1991 (RMA) and the Central Government's devolution of geothermal resource management to Regional Councils. In the 30 years since the RMA was enacted, the geothermal policy developed by the Bay of Plenty and Waikato Regional Councils has managed the competing interests of large-scale energy development and the protection of rare and vulnerable geothermal features and landscapes for 90% of the national geothermal resource.

Pending Government reform of the resource management system, we review issues that have arisen in the last 30 years and to what extent the two Councils' broadly similar policies have been successful in managing the resource. We highlight RMA strengths, such as the goal of sustainable management and community participation. We identify challenges, gaps and future opportunities to develop and integrate resource management policy. Emerging issues include advancing technology to better understand geothermal resources, new techniques to access the deeper resource, and the further extraction of minerals from geothermal fluid. Partnerships and shared decision making with Māori will also increase in the management of geothermal taonga for the benefit of their communities.

As we transition to a zero-carbon future, extractive uses of geothermal resources will increase, while the need to protect and preserve our remaining geothermal features and ecosystems, and the need to honour the Crown/Māori relationship, will remain.

Session: 3.4

43 | AN UPDATED NUMERICAL MODEL OF THE OHAAKI GEOTHERMAL FIELD

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***Keywords:** Reservoir modelling, Geothermal, Ohaaki, Broadlands, Leapfrog, conceptual modelling.*

The first well was drilled at the Ohaaki geothermal field in 1965 and not long afterwards the University of Auckland began a long collaboration with Contact Energy and its predecessors in modelling the Ohaaki reservoir. The succession of models has been used to inform decision making and aid consent applications. The permeability distribution in the model has evolved over the years to match data, particularly pressure and temperature trends. As the conceptual understanding of the field changes new versions of the model must reflect these changes.

In recent years, we have been developing a modelling framework that can better capture the fault structures, the geology and the geophysics in a numerical reservoir model. This framework is based on mapping a geological model from Leapfrog Geothermal® into an AUTOUGH2 (or Waiwera) computer model. This paper shows how we imposed this framework on to a model of the Ohaaki geothermal field. We have employed techniques to maintain the state of calibration that has been developed over several years in the current numerical model but also allows new rock types to be added easily as our conceptual understanding of the field evolves. In this paper we discuss our techniques for maintaining the match to data while changing the underlying rock distribution. We also demonstrate how we can change the fault structure, geology, alteration model or model grid without too much effort. A new grid structure is used to allow the model to be run in either AUTOUGH2 or Waiwera, in the latter case benefitting from the improved computational speed.

The aim of this work is to increase the transparency of numerical modelling without compromising the complexity that is needed to match the behaviour of the reservoir. Having a numerical model that is closely linked to the languages used by geologists, geophysicists and reservoir engineers allows a complex model to be explained more easily.

Session: 3.3

44 | USING ELECTROMAGNETIC TELEMETRY FOR ABANDONMENT CEMENT SLURRY DESIGN ON COILED TUBING

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Keywords: *Electromagnetic, Measure While Drilling (MWD), Geothermal Cementing, Geothermal Coiled Tubing*

For many years the Coiled Tubing (CT) industry has been developing Electronic Bottom Hole Assembly Technology (E-Coil) where fibre-optic or wireline cable convey operating parameters and sensor readouts from the tools downhole through the CT and back to the surface unit where they can be interpreted. This technology requires a high setup cost to install the telemetry cable, purchase the electronic tools and costly reel management programs to prevent failures of the cable inside the string.

Using Electromagnetic (EM) technology from the drilling world, signals containing packets of information can be sent directly from the downhole tools to the surface through the formation rock and existing well casings. This technology requires limited setup cost, and tool purchase is much lower than the e-coil equivalents. The use of new EM technology in conjecture with the right operational planning provided a cost-effective solution to reducing the risk of the flash setting of cement during geothermal plug and abandonment operations with CT. There are limitations of the system due to signal delay, but in the instance of determining the downhole temperature of a static fluid column prior to cementing or to prevent damage to BHA components due to exposure to a temperature above the rated limits, the technology is more than capable of providing this data in nearly real-time. This available signal technology displaces the alternative practice of running memory gauges that could not be cemented through and required an additional CT cycle out of the hole to interpret the data and run back in to perform the cementing operation.

In our experience, the tools are designed to be run on large diameter equipment that is standard in geothermal environments. Building custom made components to adapt the tools to be run on the coiled tubing was a challenge but accomplished using proven industry components as well as new innovations. Limitation on the tool is defined by the battery limitations with the electronic components capable of being flasked to prevent damage in extreme environments.

Session: 4.4

45 | DISTRICT HEATING SCHEME CASE STUDY, TAUPŌ, NEW ZEALAND

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Research from Europe demonstrates the multi-faceted benefits for society from investing in district heating schemes. The technology provides reliable heating and cooling that has proven positive impacts on health and wellbeing. As the source of energy is the earth as opposed to an electricity provider, it addresses growing energy poverty hardship as there are minimal running costs to maintain a high level of comfort year-round. The reduced burden on the electricity grid also contributes to the government's sdecarbonisation and 100% renewable electricity generation targets by reducing the overall total of how much is produced.

A GNS facilitated a workshop in Taupō in July 2021 will explore the opportunities and barriers for investing in residential heating technology in New Zealand. A wide range of stakeholders were invited to the discussions: central and local government, iwi, engineers, developers and green finance. Discussions centred around an actual case study (a 2,200 lot subdivision and retirement village in Taupō), but the technology discussed is scalable and replicable across New Zealand.

This paper will summarise the workshop findings and analyse the barriers and opportunities to extending this initiative to other parts of the country.

Session: 1.2

46 | NGAWHA OEC4 GEOTHERMAL FLUID SEPARATION – HORIZONTAL SEPARATOR SELECTION AND PERFORMANCE

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Keywords: *Horizontal geothermal separator, steam purity, steam scrubbing performance.*

New Zealand has a long history of developing higher enthalpy geothermal fields. This has meant that the cyclone type separator design has been preferred. The Ngawha geothermal field has a low enthalpy when compared to all New Zealand's other developed fields. A horizontal separator was selected for Ngawha OEC4, primarily because of low pressure loss when compared with the cyclone type. The separator was easy to commission. The separator performance was tested using sodium as a tracer. Separation efficiency is like what is expected for a cyclone separator. The performance of condensate drop-pots designed for steam scrubbing was also compared to condensate drop-pots intended to capture excess condensate only. The results show that the first condensate drop pot makes a significant difference to the steam purity, but the downstream condensate pots do not irrespective of the steam velocity.

Session: 2.3

47 | CORROSION RATE ESTIMATION OF CR CASING STEELS AT HIGH TEMPERATURE ACID CONDITIONS

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Keywords: *Material corrosion, Acid fluid, High temperature*

To develop a geothermal power plant risk assessment system for high-temperature acidic hot fluid, we carried out the material corrosion tests using a flow-through autoclave at GNS Science, New Zealand. A test piece, having a diameter of 8 mm and a length of 13 mm, was isolated with zirconia beads inside a pressure vessel. Measurement of the corrosion rate under the conditions from 150 to 350 ºC was carried out for the two chromium (Cr) type materials, Super 13Cr, and 17Cr. The test brine had a pH of 3.0 at room temperature and contained non-condensable gases (Total 3%, CO2: 96%, H2S: 4%) and chloride ion (10,000 ppm).

The corrosion rate was calculated from the change in weight before and after the test, obtained after removing the corrosion product present on the sample surface. We estimated corrosion rates from the dissolved metal concentrations in the experimental effluents, and we estimated corrosion rates using Cr equivalent, pH and temperature using models proposed by Kurata et al. (1992).

With brine and pH adjusted to 3.0 by addition of sulfuric acid at room temperature, the measured corrosion rate from weight change and dissolved metal concentration showed the highest value at 250 ºC and was higher than the testing at 350 ºC. The reason for this result was hypothesized to be the change of pH at higher temperature, for example, 3.38 at 250 ºC and 4.5 at 350 ºC based on geochemical simulator modelling. Comparing the results for the two alloys tested, the relative corrosion rate of Super 13Cr/17Cr was lower in the higher temperature exposure testing than the 1.6 ratio value that would be predicted based on Cr equivalent. Analysis results suggest that that the Super 13Cr performed better than predicted by the Cr equivalent because of the better formation of adherent and protective corrosion products on this alloy at the higher pH encountered at the higher temperature.

Session: 5.3

51 |COFFEE DRYING SYSTEM DESIGN FOR GEOTHERMAL DIRECT USE APPLICATION IN FLORES ISLAND

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Keywords: *Geothermal Direct Use, Coffee Drying System, Dryer, Shell and Tube, Piping Material, CO2 emission reduction.*

Mataloko is one of the areas in Ngada District, East Nusa Tenggara Province where there is a geothermal power plant operating with 2.5 MW capacity. The type of reservoir is brine-dominated. In addition to geothermal sources from the powerplant, there is a geothermal resource that is coming from surface manifestation around the powerplant. Moreover, Mataloko is not only a geothermal area but also an agricultural and plantation area where coffee is the biggest plantation commodity with the cumulative harvest in every year reaching 3,000 tonne. Current practice for drying the coffee fruit or cherry on the open air (conventional) is a challenge for farmers. This practice cost and requires significant time for producing high quality green beans. A geothermal direct use of drying system has been designed for coffee commodity in Mataloko. The drying system scheme utilizes a Shell and Tube type of Heat Exchanger to produce 50oC for the final air temperature. Meanwhile, this system will use Tray Dryer with capacity of 500 kg. At this capacity, the energy required by the dryer is 240 kWh per 500 kg batch (8 hours). The amount of energy from the dryer will save 0.18 metric tons CO2 emission per 500 kg batch that equivalent to CO2 emissions from the same drying process when compared to diesel fuel.

Session: 1.4

53 |LESSONS LEARNT IN USAGE OF PRESSURE WHILE DRILLING (PWD) TO JUSTIFY DRILLING DECISIONS

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Keywords: *Pressure While Drilling, Well Capacity, Injectivity Index*

Pressure-While-Drilling (PWD) is a pressure sensor installed as part of the bore hole assembly (BHA) on the drill string. The PWD tool provides real time measurement of the pressure in the annulus at depth and can be used to monitor hole conditions such as the clearing of cuttings or used in early detection of well control issues. During Mercury's previous drilling campaign in 2016-2017, a methodology was developed by the reservoir engineering team to use the data obtained from PWD to quantitatively determine well capacity in real time. This information can then be used in lieu of the traditional stage test (which can induce additional cost for rig time) to drive drilling decisions such as side-tracking, deepening or early completion of the well. The PWD methodology yielded useful results during the 2016-2017 drilling campaign and therefore, the similar methodology was applied in the 2019-2020 campaign on two production wells and one injection well drilled.

This paper presents the lessons learnt from the usage of PWD in Mercury's 2019-2020 drilling campaign and provides specific examples of the drilling decisions that were made based on the PWD methodology. This paper also highlights the limitations of the PWD methodology and covers recommendations to improve the speed and accuracy to translate the PWD results into well capacity during a drilling campaign.

Session: 2.2

54 | SYNERGIES BETWEEN GEOTHERMAL AND SOLAR PV GENERATION

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***Keywords:** geothermal, solar, PV, co-locating, variable, renewable, generation*

By virtue of its infrastructure, each developed geothermal field represents an option to install solar power. Indeed, solar farms are steadily appearing as co-generation sources in geothermal fields internationally.

As New Zealand progressively increases the share of interruptible, renewable generation, the consequential difficulties for grid stability and supply are impolitely "hatching out." The question thus arises: are there configurations of baseload and a variable-load generation that can help manage these emerging issues?

This paper examines a general business case for co-locating solar PV generation with an existing baseload geothermal plant. The assessment considers economic synergies with the existing site (consents, land, infrastructure & capabilities), speed to market, direct customers, external (non-rival) benefits to the grid, as well as interconnection and regulatory constraints. The results suggest there will be net benefits to co-locating variables with baseload generation where conditions permit and as electrical consumption increases rapidly with decarbonisation. Furthermore, the concept is applicable to other baseload renewables such as hydro generation and other forms of variable renewable energy (VRE).

Session: 5.2

55 | NUMERICAL MODELLING OF FLUID FLOW AND HEAT TRANSFER IN A DUAL-POROSITY DOMAIN IN THE SHALLOW ZONE OF THE NESJAVELLIR GEOTHERMAL SYSTEM

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***Keywords:** Numerical modelling, Dual porosity, MINC, Geothermal reinjection.*

A numerical model of the warm wastewater re-injection zone was developed for the Nesjavellir geothermal field in Iceland. A detailed shallow 3D geological model was built to constrain the numerical model, with a dual-porosity based on Multiple Interactive Continuum (MINC) was considered as fracture model. The calibration method used was underground water temperature data measured between 1998 - 2019, along with tracer test data carried out in the area between 2018 - 2019. The temperature simulation showed acceptable results matching with the temperature field, and the tracer model closely matches the overall tracer return in the most of the monitoring stations. With the model calibrated we proceeded to simulate two future scenarios for a period of 20 years. The first scenario assumes that the injection continues, and in the second scenario the injection is completely stopped. The numerical model in this study allowed a better characterization of the fracture matrix interface and the porosity of postglacial lava flows, along with a clearer understanding of the connections between injection wells and monitoring stations,

providing solutions for sustainable management of the geothermal resource and the surrounding environment.

Session: 3.3

56 | TECHNO-ECONOMIC ESTIMATION OF THE GEOTHERMAL POTENTIAL OF EXISTING COLOMBIAN OILFIELD PRODUCTION WELLS

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***Keywords:** Organic Rankine Cycle, Low temperature utilization, Co-produced fluid.*

Using co-produced hot water from oil and gas wells and binary power plant technology for power generation purposes has been piloted in oilfields worldwide with profitable results. In Colombia these geothermal resources associated with oilfields are available with geothermal gradients up to 65°C/km. Oil and gas producers have expressed interest in technologies that enable decarbonization of oilfield operations. With this in mind, the development of this type of project could be economically and environmentally beneficial.

This work analyses data from oil and gas wells in Colombian oilfields to evaluate the feasibility of implementing a binary plant using the available co-produced water. The numerical calculations included economic and thermodynamic analysis of Organic Rankine Cycle (ORC) specifications for different working fluids and geothermal fluid supply temperatures. It was determined that n-pentane is the most appropriate working fluid at the conditions of 90°C brine supply temperature and 27°C ambient temperature. This finding is supported by industrial realities, but it is notable that it is not impacted by high ambient temperatures. Economic analysis showed a levelised cost of energy of 55 USD/MWh with a 7-year payback time.

This work supports proposed geothermal development in Colombia. Small scale, low risk, profitable projects like this can catalyse the industry and spur development.

Session: 4.2

57 | THE POTENTIAL OF GEOTHERMAL EMISSIONS STORAGE IN THE TAUPŌ VOLCANIC ZONE, NEW ZEALAND

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Keywords: *CCS, CO2 mineral storage potential,Wairakei, Kawerau, Rotokawa, CarbFix*

New Zealand's low carbon aspirations are in line with the goals of the Paris Agreement to constrain anthropogenic warming to 1.5–2°C. The enhanced utilisation of renewable geothermal resources is crucial to reduce the greenhouse gases emissions sourced from the energy sector that is the third largest industrial emitter in the country after national transport and manufacturing industries. Although more than a magnitude lower in CO_2 release comparing to coal-burning power plants, New Zealand geothermal power stations emit on average 76 gCO_2eq/kWh, which equals to about 530 $ktCO_2/yr$. As a result, necessary efforts must be undertaken to transform the geothermal industry into a neutral or negative carbon emissions energy source. Two solutions are currently developed worldwide to mitigate anthropogenic geothermal CO_2. The first one is the reinjection of the emissions back to the reservoir with the reinjection waters. The second one that is yet to be tested in New Zealand is the CarbFix mineral storage method. The latest is currently developed in Iceland where about 12 kt of CO_2 and 8 kt of H_2S are captured and injected annually into the subsurface. The CO_2 and H_2S are mineralised into carbonate and sulphide minerals as a result of interaction between the reinjected gases and the basaltic host rock that is enriched in divalent cations (Ca, Mg, Fe).

This study aims to investigate three geothermal areas for their CO_2 and H_2S storage potential: Wairakei, Kawerau, and Rotokawa geothermal fields, all located in the Taupō Volcanic Zone, New Zealand. In contrast to the basaltic reservoir at the CarbFix injection site, here, the subsurface consists of silicic tuff, andesitic greywacke, andesite, and rhyolite that are depleted in divalent cations, possibly limiting the CO_2 mineral storage. To address these limitations, geochemical reaction path models were created using the compositions of the geothermal reservoir fluids and rocks. The outcome of the simulations was used to assess the maximum mineral storage capacity of these geothermal sites.

Session:1.4

58 | MACHINE LEARNING INVESTIGATION OF INJECTION-SEISMICITY IN ROTOKAWA GEOTHERMAL FIELD

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Keywords: *Microseismicity, injection, time series feature engineering, seismicity rate, significant features, p-value*

Understanding the injection-seismicity relationship in geothermal reservoirs can provide insight into reservoir connectedness. One challenge is that, in real fields, fault and reservoir complexity make it difficult to apply simple analytical models to understand the data. Here, we use a machine learning technique called time-series feature engineering to study relationships between aspects of fluid injection and microearthquakes in Rotokawa geothermal field, New Zealand. We took four years of injection data between 2012 and 2016 and sliced it into smaller sub-windows. For each window, the average seismicity in a look-back period was computed, and then binary label of 1 was assigned if it exceeded a threshold. Automatic time series feature extraction from the raw and transformed injection data in each window was performed using Python package tsfresh. Significant features of the data were identified on the basis of distribution discrepancy between the two labels. The results show that the injection rate at some wells is a predictor of long- term (fortnightly) earthquake rates. At other wells, there is a poor correlation between injection rate and seismicity. We have been unable to find any link between rapid changes in injection rate and seismicity spikes, as suggested by some theoretical models.

Session: 4.3

59 | DATA-WORTH ANALYSIS: DESIGNING A MONITORING PLAN FOR ROTORUA THAT REDUCES UNCERTAINTY

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Keywords: *Reservoir modelling, Rotorua, Uncertainty quantification, Data-worth analysis*

Developing an accurate geothermal model requires model calibration to match available data. The data is expensive to gather and, therefore, usually sparse. It is common to use geothermal models to make predictions that aid in managing the geothermal field sustainably. However, these model predictions are uncertain due to model complexity and sparse data. This paper discusses how we can quantify that uncertainty and how we can design monitoring plans to reduce the uncertainty in model predictions in the context of the Rotorua geothermal field. The design of monitoring plans for uncertainty reduction falls under the area of data-worth analysis.

From 1950 to 1986, the state of the reservoir of Rotorua was deteriorating. Therefore, the government and the Bay of Plenty Regional Council collected valuable monitoring data that helps to sustainably manage the geothermal field. There are many individual users of the geothermal reservoir, and it is not known exactly how much production has occurred in the past from various users. Uncertainty in production rates is an unusual situation compared to other geothermal reservoirs, as usually the production and reinjection are known. We have hence developed a new geothermal model for Rotorua that considers the uncertainty in production and reinjection. Using the new model, we can make model predictions that have uncertainty bands that provide better information for reservoir management.

In this paper, we consider uncertainty and data-worth analyses for Rotorua using our new model. We present three scenarios of monitoring plans for taking additional measurements in Rotorua and compare how measuring new data in different locations reduces the uncertainty in model predictions. The results of these monitoring scenarios show the benefit of data-worth analysis using simulation models: we can assess the possible effect of new monitoring plans before spending any money on these further measurements.

Session: 3.3

60 | EXPERIMENTAL STUDIES OF SUPERCRITICAL FLUID-ROCK INTERACTIONS - GEOTHERMAL: THE NEXT GENERATION

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Keywords: *geothermal, supercritical, fluid-rock interaction, geochemistry.*

The MBIE research programme Geothermal: The Next Generation (GNG) is investigating New Zealand's supercritical geothermal resource potential. NZ's unique tectonic setting delivers an exceptional opportunity for the development of these resources and has the potential to provide an unlimited source of renewable energy while minimising carbon emissions.

The exploration and utilisation of supercritical fluids is dependent on accessible and high-quality thermodynamic data. Currently, there is a knowledge gap regarding fluid-rock interactions under the physicochemical conditions which exist under supercritical fluid conditions. This lack of knowledge needs to be addressed.

The GNG programme delivers vital geochemical data to understand the effect of fluid-rock interactions at supercritical conditions. Understanding these processes will provide thermochemical constraints that will be incorporated into numerical models. Such models will facilitate enhanced resource definition and prediction.

To perform fluid-rock interaction experiments at supercritical conditions is technically difficult because of the high temperatures involved. At GNS we have built a unique experimental system to address these challenges. Our continuous flow reactor allows the study of interactions between geothermal brines and NZ reservoir rocks at temperatures and pressures up to 650˚C and 230 bar.

The experimental system will allow the study of the complex reactions that occur when supercritical fluids react with rocks. The results will be used to understand, interpret, and predict the implications of geochemical processes to infrastructure and subsurface conditions.

Session: Poster

61 | MODELLING AND OPTIMISATION OF A BINARY POWER PLANT UTILISING A LOW TO MEDIUM TEMPERATURE GEOTHERMAL RESOURCE

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Keywords: *Geothermal binary plant, modelling, and optimisation*

To help achieve sustainable geothermal energy development, one should also improve efficiency in the existing energy system. The latest state of the art in the development of models to assist the achievement of this goal is the combination of a reservoir model and surface modeling of the geothermal plant. A successful attempt has previously been made to create such a combined model as part of a digital twin technology application pathway for an existing geothermal binary plant for planning purposes. This work focuses on creating a high-fidelity digital process plant model of a geothermal binary plant using commercial process simulation software for optimisation.

By creating a thorough process model, one can achieve more value from the geothermal binary plant. The model would be a valuable tool in the detailed engineering design phase to predict operational problems before the plant is built. Instead of designing a binary plant that is ideal only for initial conditions, the binary plant can be designed to withstand the changes of reservoir conditions and operational parameters over the lifetime of the plant. That way, the plant can be more robust to changes, and operators can prepare ahead.

The binary plant process model is intended to be a master planning tool in geothermal binary plant development and become a framework for low to medium geothermal resource utilisation. This paper investigates the effect of operational parameter changes over the power plant's lifetime and conducting a sensitivity analysis on the model plant performance.

Session: 4.2

62 | EVOLUTION OF GEOTHERMAL DIRECTIONAL DRILLING IN INDOENSIA THROUGH FIT-FOR-PURPOSE ENGINEERING WORKFLOWS AND TECHNOLOGY MAPPING

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Keywords: *geothermal, directional drilling, sliding, torque and drag, hole cleaning, well trajectory.*

Environmentally sustainable growth is strengthening the momentum of the global energy transformation. Renewable energy costs decline, production efficiency improvement and technology advancement are driving the future energy shift within reach. Located in the "Ring of Fire," Indonesia is home to 147 volcanoes, with 120 of them classified as active. Drilling geothermal wells in this area possesses unique operational challenges from surface to reservoir section. One of the significant challenges faced is the total mud loss circulation, which results in several operational complexities, including insufficient hole cleaning, high torque and drag, and hole instability, leading to a high risk of stuck pipe. Directional drilling companies have become technological partners for geothermal operators in search of solutions to address these problems. Over the past five years, geothermal drilling in Indonesia has seen an exponential learning curve through fit-for-purpose BHA design and technology mapping workflows. Electro-magnetic MWD technology, and high-performance mud motors in aerated drilling, have enabled significant enhancements in operational efficiency. The application of finite element analysis simulators has been instrumental in predicting the directional tendency response of dumb iron BHAs, which, combined with 24/7 operational surveillance through the real-time decision centre has enabled operators to prevent unexpected bit trips and reduce operational risks.

Located 40 km south of Bandung in West Java, Wayang Windu Power Generation is operated by Star Energy Geothermal (SEG) Limited a wholly-owned subsidiary of Star Energy. SEG has drilled more than 45 wells in the Wayang Windu field to supply steam to the two generating unit, namely Unit 1 and Unit 2. In 2019, SEG started a drilling campaign to provide steam as a make-up capacity. The wells were planned to be drilled from the existing pads to aim at subsurface targets that were not vertically beneath the pad. The directional well path had to be designed to penetrate the subsurface targets, and hence steam could be produced as per the subsurface department's objectives. The well path had to be drillable safely, and casings could be run to each section depth.

Session: 4.4

63 | MODELLING TRACERS USING THE WAIWERA GEOTHERMAL FLOW SIMULATOR

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Keywords: *Reservoir models, numerical modelling, flow simulator, tracer*

The Waiwera parallel, open-source geothermal flow simulator now includes the ability to model the movement of passive tracers in geothermal flows. A new algorithm is used which offers greater flexibility and higher efficiency. Rather than creating special equation-of-state modules for tracers, the tracer equations are solved separately from the flow equations, and as they are linear, this can be done using only a single linear equation solution per time step. This approach also allows arbitrary numbers of tracers to be modelled in conjunction with any equation of state. Either liquid-phase or vapour-phase tracers can be simulated, and temperature-dependent Arrhenius decay can be included.

In this paper we describe Waiwera's new tracer capabilities and demonstrate their performance via benchmark test problems and by application to a field-scale geothermal reservoir model.

Session: 1.3

64 | NEW ZEALAND'S PATHWAY TO SUPERCRITICAL GEOTHERMAL ENERGY USE: MOVING FORWARD TO EXPLORATION DRILLING

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Keywords: *supercritical geothermal energy, strategic approach, renewable energy, green hydrogen, exploratory geothermal drilling, geothermal energy investment, regulatory framework, supercritical, well design, Geothermal: The Next Generation (GNG)*

Where is the best location to drill Aotearoa New Zealand's first supercritical geothermal exploratory well? The answer will soon be needed in working to define New Zealand's supercritical geothermal energy opportunity and to advance exploratory supercritical geothermal well drilling.

Early supercritical projects are expected to have long lead times, thus additional research and inquiry should be embarked upon now to ensure future supercritical geothermal developments can align with New Zealand's low carbon economy and energy sector aspirations. Sector-wide roll out of supercritical geothermal operations ideally needs to occur before 2050. Working backwards, pilot and scale up demonstration of supercritical energy production would be needed by about 2040, and thus, the first exploration wells need to be drilled by 2030 or soon after.

This paper outlines preparatory and pre-planning work for drilling a supercritical exploration well. Unknowns include drilling location, well design, drillability, fluid handling, appropriate surface facilities for energy transformation, consenting and more. Traditionally large geothermal operations would have an electricity production focus, but there may be other drivers to undertake the energy transformation, which produce carbon friendly energy. Best practice information for engagement, planning and regulatory framework, and the handling and use of supercritical fluids should be developed as part of determining if supercritical geothermal is a viable industrial energy opportunity for Aotearoa New Zealand. The aim is to advance understanding and knowledge of the nation's supercritical geothermal potential for existing and potential new users of high enthalpy geothermal heat resources.

Session: 5.2

65 | ANALYSIS OF THE IMPACT OF THE REINJECTION OF GASES ON THE MASS FLOW RATE FROM PRODUCTION WELLS AT VARYING RESERVOIR CONDITIONS

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***Keywords:** Greenhouse gases, emissions, reservoir, geothermal fields, production, wellbore, reinjection.*

Greenhouse gas emissions from geothermal power plants are a barrier to the growth of geothermal energy at present and in the future. The discharge of the gases associated with the electricity generation process from geothermal fluids to the atmosphere contradicts New Zealand's target to achieve net-zero emissions by 2050. These gases are dominated by carbon dioxide. Reinjecting the gases back into the reservoir by dissolving them in the separated brine could be one way of reducing emissions from the geothermal electricity generation process. Besides reducing greenhouse gas emissions, reinjection may help in mitigating silica scaling problems by making the reservoir fluids more acidic. This helps in the dissolution of minerals, which further helps in improving the permeability of the reservoir and contributes to variation in output from the production well.

This paper discusses an analysis of the impact of the concentration of gases present in the reservoir on the mass flow rate from the production well. This is a result of changes in the thermodynamic properties of the fluid present in the reservoir. The analysis of the main parameters that contribute to the predicted mass flows will be presented. Well flows are estimated from production wells over the range of conditions found in New Zealand's geothermal production fields. It demonstrates the impact of reinjection of gases on different types of geothermal reservoirs through changes in mass flow rate from the production well.

Session: 4.2

67 | LINEAMENT EXTRACTION AND ANALYSIS USING REMOTE SENSING IN NORD-GHOUBBET GEOTHERMAL FIELD, DJIBOUTI

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***Keywords:** Remote sensing, lineament, rose diagram, a geothermal field*

Remote sensing is useful at the pre-feasibility stages of geothermal exploration. Lineament study is one of the most important assets for geothermal resource exploration. Several surface manifestations, in particular, fumaroles occur in Nord-Ghoubbet geothermal field and have not yet been examined by lineament extraction. Therefore, this study aims to quantify the spatial density of lineament and examine a correlation between surface geothermal manifestations and lineament distribution by remote sensing techniques for the Nord-Ghoubbet geothermal area as a preliminary investigation. Lineament extraction was performed manually in this study. For manual lineament extractions, the shaded relief technique (the lineaments were extracted from 6 different azimuth angles (0° 45°, 90°, 180°, 200°and 315°), the filtering operation (based on a directional edge detection by different directions (NS, EW, NW, NE)), and image processing (False-color composite (FCC), a combination of band ratio methods, and principal component analysis (PCA)) were used to guarantee an impartial mapping of all lineaments in the study area. All manual lineament extractions were performed using QGIS. All lineaments obtained were overlain into a single shape file. After duplicate lineaments were removed, the final manual lineament map was created. This was accompanied by some lineament evaluation techniques such as lineament density and orientation to extract additional lineament information. NW-SE trend, one of the main trends extracted here, is the general orientation of the faults in the study area. Conversely, N-S and WNW-ESE to E-W trends were less pronounced in the study area. The results of lineaments density were extracted manually. The analyses showed that the fumaroles are mainly located in high and medium density areas, suggesting that the structures may control the surface manifestation distribution.

Session: 3.2

69 | COMPARISONS OF AUTOUGH2 AND WAIWERA ON GEOTHERMAL FIELDS

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***Keywords:** Geothermal, reservoir modelling, flow simulator, AUTOUGH2, Waiwera.*

One of the main constraints of geothermal reservoir model development is the time it takes to calibrate geothermal models. Model calibration requires running the model for each change in parameters made to improve the match to available data. In recent years, Waiwera, a parallelised geothermal simulator, has been under development with the aim of speeding up geothermal model runs. While drawing on our experience with AUTOUGH2 (a serial geothermal simulator), Waiwera exploits parallelisation and has been coded with better underlying numerics, which means the speed-up achieved is very significant.

Previously, we presented benchmark comparisons between AUTOUGH2 and Waiwera. Here we offer comparisons on models of real geothermal fields, both in terms of results and run-time. We now use Waiwera in most commercial and research projects, including Lihir, San Jacinto, Ohaaki, Wairakei, Monserrat and Rotorua. With certain settings, when run on 40 cores, we see a speed-up of up to sixty times, meaning a model that took seven hours to run on AUTOUGH2 now takes seven minutes to run on Waiwera. This speed-up has four main advantages: model calibration is faster, more refined grids can be used, larger systems can be modelled such as the whole of the Taupo Volcanic Zone and uncertainty quantification of model forecasts is more efficient. AUTOUGH2 and Waiwera results for the simulation of a synthetic high enthalpy geothermal system are presented alongside those for a model of the San Jacinto geothermal field in Nicaragua developed by Polaris Energy Nicaragua S.A..

Session: 1.3

70 | CHALLENGES OF GEOTHERMAL DEVELOPMENT IN SMALL ISLAND DEVELOPING STATES (SIDS)

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***Keywords:** Geothermal Energy, SIDS, Small Island Developing States, Development Finance, Climate Change.*

Driven by all the competing factors of sustainable development, the Governments of Small Island Developing States (SIDS) are looking to renewable energy as a way of meeting their climate change obligations whilst simultaneously developing the economy and improving social outcomes. Typically, these islands rely on imported diesel fuel for power generation resulting in high power prices, proving to be a drain on foreign capital, and making a significant contribution to their annual carbon emissions (from both transportation and consumption of the fuel).

Globally, there are many Small Island Developing States with geothermal energy potential, from the Pacific (Vanuatu, Solomon Islands) to the Eastern Caribbean (Dominica, St Lucia, St Vincent, Grenada), outer islands of Indonesia and coastal Africa (Comoros). A small geothermal project (e.g., 10MW) holds the potential to transform a small nation and supply much of the country's power needs from an indigenous, low carbon, a renewable resource. Whilst some renewable energy options are cheaper, faster and easier to implement, the geothermal promise remains enticing and a key component of transforming a nation to be 100% renewable in the most reliable and affordable way.

The Governments of Small Island Developing States have recognised the potential of geothermal energy and utilised various approaches to attract public and private sector support to realise the geothermal promise. The New Zealand Aid Programme and many other donors have provided technical, legal and financial assistance to partner governments, yet to date, an operating geothermal power plant remains elusive. In this paper, we discuss the unique challenges that geothermal developments encounter in Small Island Developing States and approaches to overcome these.

Session: 1.2

73 | NEW ZEALAND SUPPORTING CAPABILITY FOR GEOTHERMAL DRILLING IN EAST AFRICA

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***Keywords:** Africa, Geothermal, Drilling, Development Assistance, Ethiopia, Djibouti, Tanzania.*

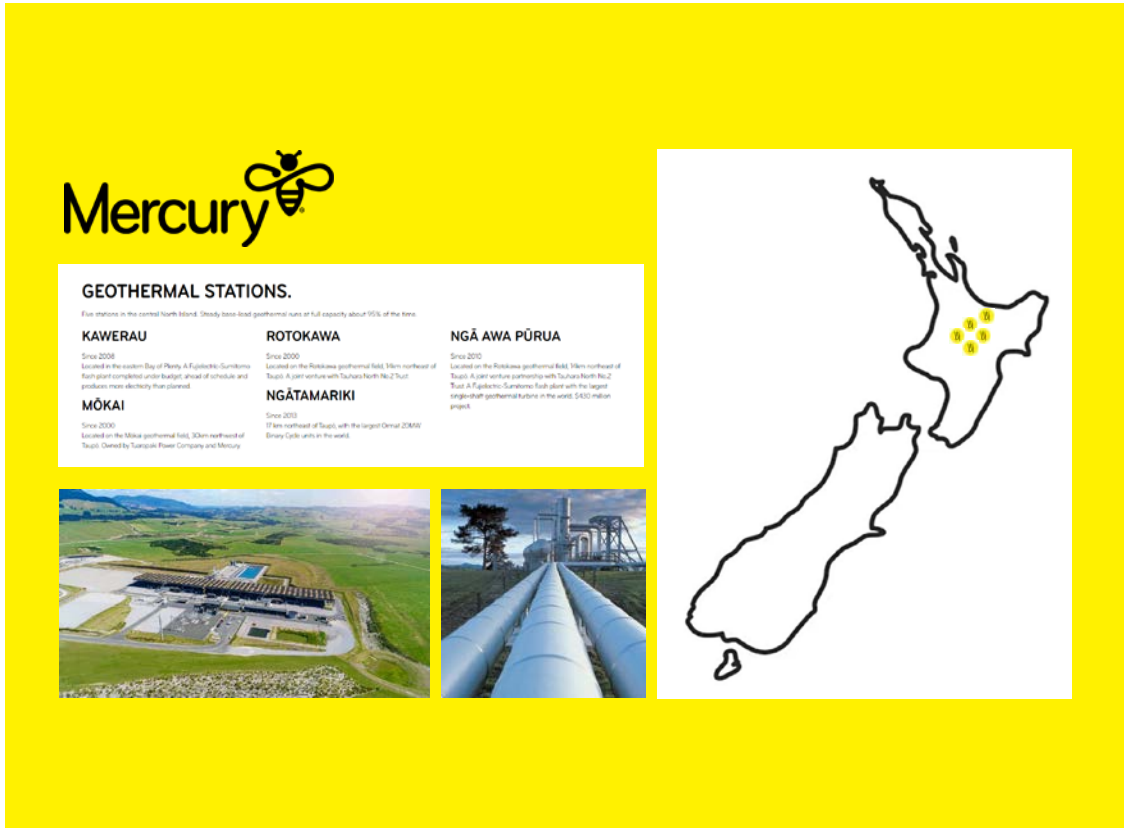
A niche area where New Zealand expertise excels is developing and delivering successful drilling programs both for exploration and exploitation. This expertise has been sought after in many countries around the world, including east Africa, where commitment to geothermal development goes back to the late 1970s.

This current project "East Africa Drilling Support" is provided by the African Geothermal Facility (AGF) which is a partnership programme between the Ministry of Foreign Affairs and Trade (MFAT) and the Africa Union (AU). The goal of this project is building human and institutional capacity focused on technical knowledge and good decision making, not just delivering technical or commercial knowledge to the projects. This is not only critical for the sustained successful execution of the Aluto geothermal project and for the planning of future drilling in Djibouti and Tanzania, but also long-term sustainability and effectiveness of the Partner organisations.

The key short-term outcome for this project are for the Partners and their drilling teams, to grow in confidence to manage drilling programs and display an increased understanding and competence in project management. An essential component has been the engagement from the wider teams within the Partner organisations, in particular the inputs and data from the various geoscience disciplines on which the drilling exploration programmes are built. The aim being to look critically at their concept models, consider alternatives and range of outcomes and thus optimising exploration drilling success. This is in conjunction with specific drilling activities such as well design, drilling risk, drilling contracts and drilling management to name a few.

The long-term outcome is successful implementation of the Partner's respective geothermal projects and thus new low-carbon electricity generation in their countries. The technical support and capacity development within this project is intended to help them on this journey of self-reliance but also continue to cement the ongoing relationship and value New Zealand has had in the region for 50 years.

Session: 1.2



75 | DISTRIBUTED TEMPERATURE SENSING IN FRACTURED LOW-TEMPERATURE RESERVOIRS – LESSONS LEARNED IN NEW ZEALAND AND CENTRAL EUROPE

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***Keywords:** DTS, fibre-optic cable, geothermal gradient, heat flux, permeable fractures*

DFDP-2B is a ~900 m-deep borehole drilled in 2014 in the hanging-wall of the Alpine Fault, in the South Island of New Zealand. PVGT-LT1 is a 2 km-deep hole drilled in 2007 in the Bohemian Massif, in the town of Litoměřice, Czech Republic. Both boreholes intersect foliated metamorphic rocks and are equipped with a fibre-optic cable that has been used for temperature monitoring and locating permeable fracture zones. By comparing data from the two boreholes we identify common problems and develop best practices for downhole applications of Distributed Temperature Sensing (DTS).

DTS measurements are sensitive not only to intrinsic properties of the optical fibre and the measuring unit, but also to ambient temperatures surrounding the measuring unit. A drift may occur in the recorded data if the temperature of the logging unit is not uniform, and here we describe different corrections (linear, polynomial) to this drift. The resulting data are also sensitive to filtering and time-averaging. Results from the two boreholes suggest that setting a longer sampling interval in the DTS unit generates less noise, although longer durations of measurement (1 hour or more) and averaging can effectively reduce the noise.

Our results highlight how different filtering techniques are appropriate depending on the scale of interest. For example, a 5 m moving window is useful for identifying individual fractured zones whereas a 100 m moving window enables zones of conductive heat transfer to be distinguished.

We show that DTS can provide reliable continuous downhole temperature measurements in fractured metamorphic rocks with accuracy ±0.5°C and <5 m spatial resolution, provided that the temperature of the measuring unit is kept stable or appropriate corrections made to correct for drift. This is sufficient for monitoring dynamic temperature changes in boreholes and more convenient than conventional logging for acquiring data on an on-going basis.

Session:4.3

78 | DATA-SPACE INVERSION FOR EFFICIENT GEOTHERMAL RESERVOIR MODEL PREDICTIONS AND UNCERTAINTY QUANTIFICATION

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***Keywords:** Data-space inversion, reservoir modelling, geothermal model calibration, uncertainty quantification, data-worth analysis*

The ability to make accurate predictions with quantified uncertainty provides a crucial foundation for successfully managing a geothermal reservoir. The standard, state-of-the-art approach to delivering accurate predictions for a geothermal model requires two steps. First, the underlying uncertain parameters (such as subsurface permeability, strength, and location of deep upflows, etc.) are estimated (i.e., calibrated), as well as the associated posterior uncertainty based on measured field data. Second, this uncertainty is propagated from the parameters to the predictions using linear uncertainty analysis or full nonlinear model runs. In most cases, calibrating the unknown parameters accounts for most of the computational costs and time. However, these parameters, and their associated uncertainty, are not always of direct interest. Instead, we are often only interested in the predictions themselves.

The so-called data-space inversion (DSI) methodology provides a solution to this problem. It effectively bypasses the need to calibrate the unknown parameters and directly provides approximate posterior predictions, i.e., model predictions conditioned on the measured field data. Here we review the DSI framework and demonstrate its effectiveness and robustness on several geothermal problems. We find that the DSI approach can lead to significant savings in both computational resources and time, providing an attractive alternative to the more conventional calibration-based approach.

Session: 3.3

80 | PASSIVE NCG REINJECTION AT TE HUKA GEOTHERMAL BINARY POWER PLANT

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Te Huka power plant is part of the Tauhara geothermal field in Taupo New Zealand. This 24 MWe binary plant started operation in July 2010. With 2 production wells and 2 injection wells it has produced around 209 GWh of electricity per year. As is the case for all geothermal reservoirs, Non-Condensable Gases (NCGs - CO2, CH4 and H2S) are naturally occurring in the hot geothermal fluids underground and are released in gaseous form during the power generation process. However not all NCGs are released at Te Huka (and many other binary stations) - due to the relatively high pressure at which the geothermal steam is condensed. Approximately

18.8 % of NCGs are dissolved in the geothermal condensate, which is combined with the separated geothermal water and reinjected back into the reservoir where it came from. We refer to this process as "passive" NCG reinjection – where "active" NCG reinjection refers to an additional process of actively redirecting the NCG gas stream at the surface and dissolving those gases back into the geothermal fluid in the reinjection line.

This paper discusses the reinjection history at Te Huka and the effect of NCG reinjection on mineral precipitation and dissolution at the reinjection well feed zones. Reactive transport modelling with TOUGHREACT has been used to compare passive NCG reinjection to active reinjection. The modelling results are used to illustrate the advantages of passive and active NCG reinjection at Te Huka.

Session: 1.3

81 | THE USE OF HIGH RESOLUTION ULTRASONIC WELL LOGGING TOOLS TO ENHANCE WELL INTEGRITY MANAGEMENT

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***Keywords:** Casing, Coal Seam Gas, Corrosion, Geothermal, Well Integrity, Well Logging, Ultrasonic*

Quest Integrity has been operating its proprietary ultrasonic intelligent pigging technologies for the inspection of pipelines and tubular assets operated in the energy sectors for the past 20 years. Building on this technology platform, Quest Integrity has developed Quest Well Integrity X-CalliperTM (QWIXTM), a unique well logging tool that collects high resolution ultrasonic metal loss and geometry data sets for well casings. Opportunities to apply the technology in geothermal wells will provide a step change in the resolution and coverage of logging data available for the integrity management of geothermal well casings. The QWIX technology collects millions of data points per log to provide 100% high resolution coverage of the production casing for both internal and external surfaces. The coverage and quality of the data collected allows for the immediate evaluation of casing condition, accurate measurement of corrosion growth rates with multiple logs over time and enables the performance of fitness-for-service and remaining life assessment calculations. This paper presents an overview of the well logging technology along with a case study covering its application in the inspection and engineering assessment of Coal Seam Gas wells.

Session: 2.2

82 | MODELLING TRACER BREAKDOWN UNDER GEOTHERMAL CONDITIONS

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***Keywords:** Tracers, NDS, Reservoir Modelling. Reaction Modelling*

Geothermal tracer tests are widely used in the industry to identify flow pathways between production and reinjection zones. The results of these tests are often used to predict the potential for thermal breakthrough of cooler reinjection fluids. This is usually done by using the tracer test data to constrain the flow paths through which reinjection fluids travel in numerical reservoir models.

Recent experimental studies by Mountain and Winnick, and Sajkowski et al have shown that naphthalene sulfonates that are widely used in the geothermal industry as tracers have temperature limits. These studies have measured the rates of the thermal breakdown reactions that these compounds undergo. These breakdown rates have been shown to depend on temperature and pH.

This paper presents work to model the breakdown of different types of geothermal tracers and incorporate the reactions into transport models of tracer flow in a geothermal reservoir. The ultimate purpose is to estimate temperatures along the paths that tracers flow within the reservoir. We will present models of the reaction kinetics of some naphthalene sulfonate and alcohol tracers and the findings of incorporating these reactions into numerical models of reservoir tracer tests.

Session: 1.3

83 | AN INSIGHT OF THE SUBSURFACE THROUGH BOREHOLE IMAGES CASE STUDY OF MW-34 MENENGAI GEOTHERMAL FIELD, KENYA.

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***Keywords:** Borehole images, Fractures, Subsurface, Menengai.*

Borehole imaging has been one of the fast-evolving technologies in well logging. The understanding of geological formations and logged formations below the surface has greatly improved since the advent of borehole imaging tools. The presence of natural fractures provides important pore spaces and fluid flow conduits. Insights can be provided into the subsurface fracture (natural and induced) detection and characterization using image logs. Menengai Geothermal field is quaternary volcano located in the central part of the Kenya rift which hosts a high temperature geothermal system. No core has been acquired from any of the wells drilled in this field. Therefore, to have a better understanding of the subsurface, a few wells were selected for borehole imaging. There are different methods of acquiring borehole images that include; Optical , acoustic and micro-resistivity. In this study, acoustic borehole-imaging devices were used to image MW-34, a vertical well drilled in NE part of the Menengai Geothermal field in Kenya. with the QL 43 ABI device. This device is also known as "borehole televiewers." It operates with pulsed acoustic energy so that it can image the borehole wall within drilling fluids. Using WellCad Software to analyze the borehole image we were able to recognize structures through irregularities on the borehole wall. The structures were captured from the image by fitting sinusoids to discontinuity traces. Numerous low acoustic amplitude fractures, which appeared as dark sinusoids, were noted in the depths ranging from 1370-1380 m and from 1530-1550 m. A few large apparent apertures fractures have been noted with the largest of 1160.69 mm in size, some lithological contacts have also been noted and appear to be low acoustic amplitude at 1180 m and 2275 m among other depths. Generally, the fracctures have a strike orientation of NE-SW.

Session: 3.2

84 | GEOTHERMAL AND HYDROGEN: COULD HYDROGEN MAKE SOME GEOTHERMAL PROJECTS VIABLE?

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Keywords: *Geothermal, Green Hydrogen, Carbon Emissions, Stranded Geothermal, Baseload*

The production of hydrogen via geothermal has seen a growing interest worldwide in recent times, and for a good reason. There is much potential for geothermal to act as a source of energy in the production of hydrogen. Hydrogen from geothermal could displace a significant amount of emitted carbon, especially in countries struggling to reduce their carbon footprint or in countries abundant in geothermal resources that can produce hydrogen for export. The economics, the desire and the timing must be right, however. This paper presents a comparison of hydrogen generation from a dedicated geothermal plant with that produced from solar and solar plus battery storage. This is to test and illustrate the value of baseload generation that is achievable from geothermal in comparison with alternative renewables that are normally considered 'lower cost'.

Session:5.2

86 | HYDROTHERMAL MINERALS AND HYDROLOGIC EVOLUTION OF THE ROTOKAWA GEOTHERMAL SYSTEM, NEW ZEALAND

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Keywords: *Hydrothermal minerals, hydrothermal eruptions, SWIR reflectance spectroscopy, XRD, fluid inclusions, Rotokawa.*

The Rotokawa geothermal system in the Taupō Volcanic Zone is ~28 km2 in areal extent and has been the site of eight large hydrothermal eruptions. This study documents hydrothermal minerals for 15 wells (3,242 samples). Quartz, chlorite, albite, calcite, pyrite, and illite are the most common hydrothermal minerals. Epidote and smectite are less common. Kaolinite is uncommon. Smectite occurs as a 250 to 900 m thick carapace overlying illite and separated by a narrow intervening interval of mixed-layered illite-smectite. Chlorite is generally ubiquitous at depths ≥700 m, calcite is most common at >750 m, and epidote >1,000 m. Hydrothermal albite is present in all wells, whereas rarer adularia is patchily distributed. Chalcedony unusually occurs at >1200 m depth. Kaolinite patchily occurs at surface and locally to 200 m depth. Kaolinite further occurs up to 1,150 m depth in two wells bordering the resistivity margin. Dickite and / or kaolinite ± alunite is present in three wells (same pad) between 475 and 585 m depth.

Hydrothermal minerals correlate with fluid types. Quartz, chlorite, albite, adularia, illite, calcite and epidote coincide with alkali chloride waters. Shallow kaolinite ± sulfur coincide with acid sulfate condensates. Dickite / kaolinite ± alunite at depth are interpreted to have formed from in-situ acid sulfate condensates. Whereas deep marginal kaolinite is inferred to have formed from steam-heated CO2-rich waters. Fluid inclusion and hydrothermal mineral inferred temperatures generally match measured temperatures, but the northern and north-eastern wells are cooler (up to 55°C to 1.5 km depth). A 3-stage hydrologic model is proposed relative to hydrothermal eruptions that occurred between ~20,000 and 3500 years ago. 1) Pre-eruption, with hotter and greater fluid flow to the north. 2) Syn-eruptions with creation of greater permeability in the south. Associated decompressive boiling resulted in chalcedony deposition at depth. Local transient temperature changes resulted in pressure draw down and formation of anhydrite (to 500 m depth).

3) Post-eruptions to present day with enhanced permeability in the south. Greater fluid and heat transfer in the south coupled with reduced fluid and heat transfer elsewhere has resulted in cooler conditions in the north to <1.5 km depth.

Session: 3.2

89 | POROUS MATERIALS FOR CO2 CAPTURE IN GEOTHERMAL SYSTEMS

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***Keywords:** CO2 capture, MOFs, COFs*

The manifestation of the effects of climate change has underlined the need to curb down the levels of carbon dioxide (CO2) emitted in the atmosphere. The shift towards renewable energy (RE) sources has significantly decreased global CO2 emissions. While a zero carbon emission for the energy sector is unrealistic considering a full life cycle assessment; geothermal energy, which remains a reliable RE, has the highest CO2 emission equivalent per kilowatt-hour (kWh) during operations, compared to the other RE sources. Thus, there is a continuing movement within the geothermal industry for decarbonization. Present carbon capture and storage (CCS) methods include injecting CO2 into a porous reservoir below an impermeable caprock whether as a supercritical fluid or dissolved in either freshwater or geothermal brine. While these technologies effectively decrease CO2 emissions, they are energy intensive, require additional infrastructure and specific geological conditions. Thus, there is a need to look for alternative methods to help the decarbonization of the energy sector. Porous materials are being studied as alternatives to selectively capture CO2 from flue gas emitted from traditional thermal energy power plants. Metal organic frameworks (MOFs) and covalent organic frameworks (COFs) belong to this class of materials that use their high porosity and surface area to capture CO2 either by chemisorption or physisorption. MOFs and COFs can also be designed not only to store CO2 but convert it into other useful compounds. It is therefore proposed to explore the use of MOFs and COFs to capture CO2 in geothermal systems.

Session: Poster

90 | TESTING SPATIALLY FLEXIBLE BOTTOM BOUNDARY PARAMETER SCHEMES AND PRIORS FOR GEOTHERMAL RESERVOIR MODELS

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***Keywords:** Geothermal model calibration, boundary conditions, uncertainty quantification, ensemble-based methods, parameterisation, reservoir modelling.*

Geothermal reservoir models require suitable bottom boundary conditions to account for the influence of deep geothermal energy sources. When applying mass- and heat-flux boundary conditions to a model, it is standard practice to assign mass upflows to fixed locations on the bottom boundary. That is, during automatic model calibration, each boundary mass-flux region does not change its position, area, or shape. This rigidity in boundary source locations may limit 1) how well automatic calibration methods can match field data, and 2) how well model uncertainty is quantified. Here we consider more flexible parameterisation schemes and parameter priors to address those issues. The parameterisation schemes we use are based on sampling from multivariate Gaussian prior parameter distributions and applying thresholding to generate boundary regions that act as sources of geothermal fluid. Unlike the standard approach, the schemes proposed here allow upflow regions to appear on parts of the bottom boundary in keeping with field observations. This spatial flexibility not only enables upflow regions to appear or grow in order to better match observations but, in the context of uncertainty quantification, also allows the existence, geometry, and extent of upflow regions to vary between posterior sampled models. We demonstrate our parameterisation methods by applying them to uncertainty quantification of synthetic test models, including a model which is based on the Montserrat geothermal field.

Session: 3.3

91 | ASSESSING THE VIABILITY OF GEOTHERMAL PROJECTS USING PUMPED WELLS

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***Keywords:** Low temperature, pumped wells, exploration.*

The common assumption within the world of high-temperature geothermal development has been that the economics of geothermal projects producing from resources below 200 ºC are so poor that such resources are generally not considered viable for power production and given a low priority for attention. While a very high tariff in selected locations such as Germany has enabled some deep, low-temperature power projects to be built in the last decade, these projects indeed are high cost mainly due to the depth of wells required to produce from warm aquifer sources in deep sedimentary basins for power. However, a substantial number of projects tapping resources in the 145 to 160 ºC range have been developed in the USA in the last eight years in a relatively low tariff environment and an absence of major subsidies.

Through Jacobs' work assisting with inventory studies for the government agencies in Indonesia, we have had to look closely at lower temperature systems that surprisingly form the bulk of the new systems now being identified in Indonesia. The accessible, high- temperature systems have primarily been identified and claimed, and these lower temperature systems comprise much of the future pipeline for geothermal exploration. We have had to apply global experience from the low-temperature sector of our industry to analyse the well pumping technology required to achieve economic well production and other key factors that may make these projects surprisingly viable. We share these learnings, and we also suggest some opportunities for the New Zealand geothermal industry to evaluate and possibly adopt this technology.

Session: 2.3

92 | GENERATOR, TURBINE AND THERMAL EFFICIENCY OF LUMUT BALAI GEOTHERMAL POWER PLANT

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Keywords: *Geothermal Power Plant, Thermal Efficiency, Turbine Efficiency, Generator Efficiency.*

Lumut Balai Geothermal Power Plant is a single flash plant which take high-pressure hot water from the reservoir into the low- pressure tank then using the resulting steam to turn the turbine. After turning the steam turbine condensed using a direct contact condenser before injection back into the reinjection wells, the condensation process is assisted by using Cooling Tower as Recirculating Cooling Water. During the operation, it is fundamental to calculate the efficiency of plant parameters to manage the production reliability in Lumut Balai geothermal field. Based on the integrated formulation during daily monitoring, there can be concluded that Lumut Balai Geothermal Power Plant has thermal efficiency is 2.35%, generator efficiency of about 84.39%, and turbine efficiency is 85%.

Session: 5.4

93 | THE POTENTIAL AND SOCIOECONOMIC IMPACTS OF GEOTHERMAL DIRECT- USE ON MATALOKO, FLORES ISLAND, NUSA TENGGARA TIMUR, INDONESIA

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Keywords: *Geothermal, Direct use, Socioeconomics, Mataloko, Flores, Indonesia*

Geothermal heat is naturally generated deep below the earth's surface and is one of the world's largest sources of continuous renewable energy. The most prevalent application of high geothermal temperature is used for power generation. Apart from electricity generation, geothermal energy can be utilized for direct use applications, such as room heating or cooling, drying, agriculture, aquaculture, and tourism.

Indonesia has the most extensive geothermal potential in the world, estimated at 29,000 MW. About 800 MW of that potential is located in Flores Island, Nusa Tenggara Timur. Therefore, in 2017, the Government of Indonesia designated Flores Island as a geothermal island (Flores Geothermal Island) to optimize the use of its geothermal energy as an electricity and non-electricity source.

This research aims to achieve a deeper understanding of geothermal direct-use application and how it would impact the people socially and economically in the area of Mataloko, Flores Island, Nusa Tenggara Timur. The paper also investigates the current local commodities and demographic conditions in Mataloko. The research of geothermal direct-use application, specifically on Flores Island, has been limited. Thus, this paper intends to fill the gaps in this field and can be utilized to improve the socioeconomic welfare on Mataloko and other regions in Indonesia.

Session: 1.2

94 | HYDRAULIC RIG AND ITS CHALLENGE TO CONDUCT SLIMHOLE GEOTHERMAL EXPLORATION DRILLING

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Keywords: *geothermal, drilling, hydraulic rig, exploration, Indonesia.*

Exploration and drilling activity is required to prove the existence of geothermal sources. The result of drilling activity can be used to assess the feasibility of the project. Though, the resource uncertainty, drilling risks, and high costs during exploration activities make investors reluctant to invest. One of the alternatives is by using slim hole drilling instead of big or standard hole drilling. Slim hole drilling has the potential to minimize drilling costs significantly because the equipment, long lead item, and the requirement is less than a big or standard hole.

The hydraulic rig is commonly used in mineral drilling activity and potentially to be utilized in geothermal exploration since the well construction of mineral exploration well is similar to a slim hole well. The capability of the hydraulic rig needs to be assessed to execute slim hole drilling activity. This paper aims to give an overview of hydraulic rig capability to drill the slim hole well. The aspect that will be assessed is the hoisting system, circulating system, foot clamp opening, make-up tool equipment, substructure height, material handling, cementing equipment, and driller's panel or console. The assessment result can provide an alternative and more economical option for drilling exploration in geothermal development, specifically in Indonesia.

Session: 4.4

96 | GEOTHERMAL WELL CONTROL EQUIPMENT APPLICATION FOR MINING DRILLING IN GEOTHERMAL ENVIRONMENT

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***Keywords:** Well Control, Well Control Equipment, BOP, Kick, Geothermal Drilling, Mining Drilling.*

One of the considerations during the planning of geothermal drilling is the selection of the well control equipment or Blowout Preventer (BOP). The BOP is used to shut in the well when the first barrier of the drilling operation, drilling mud, cannot withstand the well pressure. The pressure of the well itself originates from the Boiling Pressure Depth (BPD) profile which is controlled by the well temperature. Thus, all drilling operations inside the geothermal environment, including mining drilling, have the same risk on the well control side. Normally, well control equipment is not required in mineral/mining drilling exploration. But for some mineral coring operation that intersect a geothermal area, high temperature of water/steam and/or gases could be encountered during the drilling operation. In order to safely conduct drilling, we need to consider the use of well control equipment for mineral/mining drilling operations in geothermal areas. This paper will describe the assessment of well control equipment that is commonly used in geothermal drilling for mining drilling operations in a geothermal environment. The assessment will discuss the well design configuration, BOP stack configuration and BOP operation appropriate for the mining drilling equipment (drilling rig and BHA).

Session: Poster

97 | ANISOTROPIC GEOTHERMAL HOST ROCK? CASE STUDY OF NEVADO DEL RUIZ, COLOMBIA

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***Keywords:** Anisotropy, Colombia, metamorphic rocks, Nevado del Ruiz, ultrasonic waves.*

To date, geothermal exploration at Nevado del Ruiz (NRV) volcano suggests that metamorphic formations are the possible hosts of a geothermal reservoir. Measurements of ultrasonic elastic waves on metamorphic rock samples collected from outcrops and the well Nereidas-1 at in-situ pressure conditions. We find that elastic wave anisotropic is influenced by foliation and vein hydrothermal alteration at all effective pressures of interest. The presence of elastic wave anisotropy is crucial to correct seismic travel times for earthquake location, seismic tomography, monitoring, and design of future geothermal boreholes.

Session: 4.3

98 | DE-RISKING GEOTHERMAL PROJECTS BY RE-THINKING WELL DESIGN AND THE WELL CONSTRUCTION MINDSET

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***Keywords:** Completions, well optimization, drilling, critical path, well design, well construction, flow control, capital expenditure.*

To optimize well output, prevent premature failures, and extend the lifespan of geothermal wells, a new and holistic interdisciplinary approach is required in project management to ensure enhanced recovery and efficient performance become the new status quo.

This paper proposes solutions that in the past could have been perceived as not economically viable; the aim is to foment discussion around the standard approach to well design and challenge ourselves to adopt a more holistic, strategic, and innovative way of planning well construction.

This can be achieved by integrating data acquisition not only during appraisal stages but also within well construction and production/injection phases with permanent monitoring systems, proper material selection to mitigate structural and flow-assurance issues, and use of well engineering technological solutions rather than compartmentalizing disciplines and reducing them to so-called drilling challenges.

Based on experience, but starting with zero-scope, we can begin to establish minimum requirements and identify appropriate solutions that could increase success rates with the lowest budget increment, consequently reducing overall project risk.

Good practice would be to increase the involvement of geoscientists to optimize the positioning, trajectory, and quantity of wells, and this can lead to better, smarter, and more efficient decision-making to extricate some of the most challenging geothermal projects. To do this, it is crucial to ensure continuous proactive communication over the different sub-surface development stages, and not reduce any aspect to a trivial afterthought.

Session: 2.2

99 | COMPARISON OF GEOTHERMAL WELL COSTS FOR SLIM-HOLE EXPLORATION WELLS VERSUS BIG-HOLE EXPLORATION WELLS

Vicki Agustino[*1], *Gilang Rifki*[1] *Septa Ratnasari*[1], *Frilla Ranti*[1]

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Keywords: *slimhole, exploration, well cost, geothermal, drilling, Indonesia*

in the geothermal industry in Indonesia, many geothermal operators using big-hole wells for exploration. understand that well and drilling infrastructure costs for standard and big-hole exploration wells are quite high. High exploration costs and the risks of exploration itself are causing the slow development of geothermal fields in Indonesia. Slim-hole exploration wells in geothermal is one option that can be used to confirm the resource in certain geothermal fields.

Two emerging questions are: (i) whether a slim-hole well can deliver the exploration objective and how economic is the cost, (ii) is the use of slim-hole wells an option for exploration planning strategy in the geothermal industry in Indonesia. To answer these questions, we have conducted a literature study regarding the past operation of drilling in exploration projects in Indonesia. We will break down the cost of drilling services and material in the past operations in Indonesia to get the unit rate data and will adapt these data to calculate the cost of current geothermal slim-hole designs. This paper aims to summarize the information in the literature on slim-hole well costs compared with the cost of big-hole wells using the same subsurface data such as lithology, casing setting depth, reservoir zone, etc. This calculation was conducted by authors over the past several months.

Finally, this paper is expected to trigger more discussion among geothermal practitioners about the economics of slim-hole drilling. It is hoped that with the same amount of budget slim-hole wells could deliver more data and increase confidence about the geothermal resource in the area of interest.

Session: 4.4

101 | SELECTING THE MOST POTENTIAL GEOTHERMAL DIRECT USE IN EASTERN INDONESIA, FLORES ISLAND, MATALOKO

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Keywords: *Direct use, geothermal, indonesia, flores, mataloko, coffee, drying*

Flores island is located in eastern Indonesia and part of East Nusa Tenggara province. Known with the big potential geothermal reserve that spread in the 17 locations with approximately 402.5 MWe and 527 MWe reserve backup. According the big potential reserve, government arrange Flores as the island of geothermal. The aim of this arrangement is to fulfill the electricity demand by maximize the potential geothermal reserve, also with direct utilization to increase the agriculture, plantation, and tourism result. Geothermal energy can be used indirectly or directly. Geothermal can be indirectly used to produce electricity. Direct-use applications exist on a scale ranging from heating and cooling. The direct use of geothermal energy has significant economic, environmental, and social benefits, chiefly because it reduces electricity demand as it replaces electric-driven heating and cooling applications. The focus location is in Flores, Mataloko. This is a sub-district that located in Golewa district, Ngada city, in Nusa Tenggara Timur province. This district has 3.5 km2 land area or about 4.73% from the total area from Golewa district is Mataloko sub-district. This study describing about overview of the location, understand about the existing potential, identify all the possibilities that can be implemented for the best option of geothermal direct use in Mataloko.

Session: Poster

102 | INTERGRATED GEOTOURISM IN DIENG

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Keywords: *Geotourism, tourism facilities, Indonesia, Dieng*

Geotourism is one of the most popular concepts in the tourism sector. Geotourism is a broad concept that covers many aspects of various tourism activities, such as transportation, accommodation, destination facilities, recreation, planning, and management. Along with the growth of geotourism, there has been an explosion in the number of geotourism sites in the world. Dieng is an example of an area that has geotourism potential. Dieng has unique geology and dynamic natural scenery which has long attracted many tourists to the area. Most of Dieng's people live from agriculture and tourism. The main agricultural commodity in this area is potatoes, while the tourist objects are volcanic craters, surface manifestations, caves, and temples.

This study begins with a literature study and mapping the existing geotourism in Dieng, especially that related to existing facilities surrounding Dieng area. This summary of the results of geotourism in the geothermal prospect area will later explain the problems in the utilization and development of geothermal energy in the agricultural industry which can provide long-term improvements for development in Dieng.

Session: Poster

103| GEOTHERMAL DRILLING PERFORMANCE IMPROVEMENT THROUGH A COMPREHENSIVE NON-PRODUCTIVE TIME ANALYSIS

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***Keywords:** Geothermal, Drilling Operation, Non-Productive Time, Root Cause Analysis, Standardize Drilling Report.*

In the development of geothermal projects, one of main thing that has the greatest level of challenge and high costs are drilling operations. Drilling operations planning must be carried out properly and precisely so that the well can be completed effectively and efficiently in term of depth, time and cost.

However, in carrying out drilling operations problems cannot be eliminated. Operational problems can be categorized into surface and subsurface problems. All these problems lead to unplanned operational time in geothermal well construction, commonly defined as Non-Productive Time (NPT). NPT has a direct relationship to the cost overrun of wells.

Processing standardized daily drilling reports is the main information in identifying existing NPT, which explicitly stated as NPT or sometime disguised in Productive Time (PT). All these NPTs are then classified and analyzed to get the root cause and define ways to improve the performance during drilling campaign.

This paper aims to describe a comprehensive NPT analysis of all operating times to improve geothermal well performance. The proper NPT analysis can minimize problems in drilling, improve the drilling performance and in the end increase the economic value of geothermal development projects.

Session: Poster

105| ONE SHEET PROGRAM FOR INTEGRATED PROJECT SERVICES AT LAGUNA COLORADA GEOTHERMAL FIELD

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***Keywords:** One sheet program, integrated services, Liner, Casing, ENDE.*

ENDE, the national electricity company of Bolivia is planning to build a 100 MW power plant in the Sol de Mañana geothermal field. There already are 5 drilled wells (they will make up) and nowadays ENDE is planning to drill 25 new wells (16 production wells and 9 reinjection wells) to extract geothermal energy in two units (50 MW each one). In order to achieve this ambitious goal, it will be required to hire a company that is supposed to manage all the drilling operations on the field (Building and design of the access roads, pads, drilling, well-testing, etc.), this service is known as Integrated Drilling Services. In order to help find the best and more suitable company for this project, a one sheet program has been developed to show and illustrate to companies the key points of the services they must carry out. It is divided into two pages, the front face shows all the operations for the drilling service such as general information of the field, depth of the geological structures, well diameter, BHA, cement program, casing configuration, drilling fluids, and risks. This part gives an understandable summary of the drilling sequence and basic considerations. The back face shows all the well-testing procedures and equipment, wellheads, triaxial stresses for the casing, and a detailed scheme of all the services that will be required to perform this enormous project. This program is just a brief compilation of the main operations required for ENDE. Besides, this illustrative piece of paper is needed for a quick understanding of the necessities and as an advantage it could be carried everywhere.

Session: Poster

107 | THE USE OF VENTURI DURING BINARY PLANT PENTANE EVACUATION

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***Keywords:** Venting, Binary plants, Eductors, Evacuation, Ngawha, Vacuum pump, Nitrogen, Purge.*

The use of a binary cycle to extract energy from geothermal fluid for power generation is a well-established method. The main Achilles heel with these systems is the common use of a hydrocarbon based motive fluid in the process and the accompanying risks which are present when managing a flammable substance. One such instance of exposed risk occurs during maintenance work when breaking into the closed system. It has now become common in NZ to demand a full pentane evacuation and inert gas purge, utilising a vacuum pump and nitrogen gas generation plant, before a permit is issued to the work party; In doing so, striving for a full elimination mindset of workplace risk reduction.

An additional method has been developed by Ngawha Generation Limited which can be used in conjunction and complements existing practices to reach desired Lower Explosive Limits. The utilisation of an air driven Venturi known as an Air Horn or Eductor has been trialed. These are commonly used in meeting confined space ventilation requirements for underground storage tanks in the industrial and wastewater sectors. In the application it was used at Ngawha, the eductor was placed on the shell side of the recuperator vessel just downstream of the turbine outlet spool. During the works involving the removal and re-installation of the spool piece the eductor drew in air at the work front and expelled it to a safe location using ducting. The air carried away any pentane vapor that was still being liberated. The large volume of air displacement compared to that of pentane vapor resulted in a vented mixture which did not reach lower explosive limits at the discharge point. No hydrocarbons were detected at the work front, which is something current methods often fail to achieve.

Session: 2.2

108 | COILED TUBING LIVE WELL CLEANOUT

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Keywords: *Coil Tubing, Live Well Cleanout, Workover, Calcite, Silica, Scale removal, Air hammer, DTH hammer, CTH hammer*

Contact Energy Limited (CEL), with their partners Western Energy Services (WES) in New Zealand, have been pioneering live well cleanouts on production wells and reinjection wells. The most obvious advantage of live well cleanouts is very minimal production (or reinjection) downtime, and other advantages in production wells include avoiding thermal cycling of the casing and removing the wellbore scale fragments to the surface, which prevents blocking the reservoir. In 2018 CEL successfully cleaned out one reinjection and six production wells and gained back 34.3MWe of generation at only a fraction of the cost of a traditional rig workover. Since its inception, CEL and WES have cleaned out a total of 30 wells (3 reinjection wells and 27 productions) at several geothermal fields. CEL and WES are continuously developing the method and pushing the boundaries on what can be achieved.

Initial concepts for using coiled tubing in geothermal wells were developed from oil and gas technology which was then adapted to suit the harsh geothermal environment. In this environment, the highly destructive high-temperature geothermal fluid proved to be the biggest hurdle for job design and tool suitability. Our team first selected a variable vane style mud motor to power a milling bit to mechanically remove the scale from the wellbore. Although successful in multiple wells with apparent soft scale, the limited motor life resulted in poor performance for harder scale and extended milling section operations. Despite an initial success rate of less than fifty per cent over the first five attempts, both CEL and WES retained a clear appetite for innovation, fueling a path to broader thinking and design alterations that have led to recent successes. Trials on multiple candidate wells have demonstrated the suitability of coiled tubing for this purpose. Through pushing traditional boundaries, this technology continues to evolve as a trusted and reliable method to remove scale in geothermal wells. The technology has been utilised to clean out production and reinjection wells to a diameter of 14.5" ID (16" casing) and depths of up to 3000m.

Session: 4.4

109| CASE STUDY: ONLINE GEOTHERMAL WELL STIMULATION AND SILICA-BASED FORMATION SCALE REMOVAL

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Keywords: *Online Chemical Cleaning, Silica Scaling, Reinjection Wells, Geothermal Well Stimulation*

Silica remains one of the prominent problems that cause the loss of capacity in geothermal reinjection systems. Until recently, no solutions were available to stimulate or completely recover reinjection capacity if the formation beyond the wellbore was scaled with silica or silicon-based deposits.

Historically, in New Zealand, hydrofluoric acid (HF) or mud acid was used to try to improve and recover reinjection well capacity; however, the risk to the assets, the cost of the application, the risk to the environment, and the risk posed to the people doing the job did not warrant the short-term and marginal results achieved using the HF intervention.

Recently, an application approach and chemistries that often enable geothermal operators to recover the full capacity of their reinjection systems were developed. This new technique has many advantages over traditional methods. Advantages include avoiding the need to shut down the well; reducing cleaning time to two days during full and normal operation; using far lower concentrations of chemicals; and recovering, in many cases, well capacity that exceeds 100% of the full historical capacity.

One of the world's leading geothermal operators invested significant resources into the understanding of this new method and thus has been able to contribute to the collaborative advancement of this technique to the wider geothermal industry.

This paper documents three case histories using this new online well stimulation process and includes a comparison with offline cleans using HF. The geothermal company reviewed the two methods and found that the online method was at a minimum 13 times better in terms of ROI and benefits than offline techniques.

Session: 5.3

110| CHEMICAL REMOVAL OF FORMATION SCALE IN GEOTHERMAL PRODUCTION WELLS

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Keywords: *Geothermal production well, formation scale, chemical cleaning, well recovery, stimulation.*

It is common for geothermal production wells to suffer from scaling while in operation, which can drastically decrease or halt production. The scale is usually calcite and can also contain silica which makes the scale harder and more difficult to remove. In reservoirs with significant silica in the fluids, the loss of production can be due to silica as much as calcite. In high enthalpy production wells flashing and scaling occur in the formation, and this is a much more difficult challenge than scaling in the wellbore, as formation scale can only be accessed with chemicals and not mechanical methods.

Traditional chemical methods of trying to recover such wells use hydrochloric acid (HCl), and whilst this impacts calcite, silica and silica-based deposits are not soluble in HCl. Some companies have tried using mud acid applied through a coil tubing unit. However, there are significant risks involved due to the strength and aggressiveness of the acids (corrosion, human and environmental risks), and results have been varied, so this approach has mostly been abandoned.

A partnership between Contact Energy, Solenis and Thermal Clean Ltd has developed and successfully applied new technologies to chemically clean formation scale in production wells using a combination of acid and caustic to remove both calcite and silica. This is the only viable method to recover production well formation scaling and has been successful in restoring dead production wells to 100% of maximum historical capacity. There are also indications the method could be a stimulation technique, dissolving formation minerals rather than just scale. Examples are given from New Zealand and Mexico.

Session: 5.3

111| GEOTHERMAL GREENHOUSE GAS EMISSIONS IN NEW ZEALAND IN 2020: LIFECYCLE AND OPERATIONAL EMISSIONS

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***Keywords:** Carbon dioxide, methane, geothermal, operational emissions, lifecycle emissions.*

Greenhouse gas emissions from fourteen New Zealand (NZ) geothermal power stations in the calendar year 2020 are presented in this paper. Source data is given, verified against alternative sources, and used to calculate the overall geothermal emissions intensity for each power station as gCO2e/kWh(net). Statistical analysis of the results gives a representative emissions intensity for NZ geothermal electricity generation overall for 2020. Comparison of this to previous years shows a continuing decline in emissions intensity.

The emissions intensities presented in this paper are operational emissions only, those that are released directly during the operational phase of the plant life. This, however, only represents one portion of the total emissions over the full lifecycle of the plant. Life cycle analysis (LCA) "life-cycle emissions" take account of all emissions over the full life cycle of the plant, including materials and construction, operation and maintenance, and decommissioning. Accounting for the full life cycle will increase geothermal emissions intensity above the operational emissions by 20% on average for the NZ stations. Statistical comparison to life cycle emissions from other energy sources shows that NZ geothermal has the highest emissions intensity of the renewables, followed by solar PV, concentrating solar, hydro and then wind with the lowest. All renewables have life cycle emissions, an order of magnitude less than fossil fuel energy sources.

Session: 3.4

113 | PRACTICAL WORKFLOW FOR TRAINING IN GEOTHERMAL RESERVOIR MODELLING

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***Keywords:** Geothermal reservoir simulation, TIM, teaching, AUTOUGH2.*

Geothermal reservoir modelling is a complex and time-consuming task. While the theoretical background is generally reserved for professionals and academics, with the right training geothermal modelling is more generally accessible. Here we discuss practical and advanced simulation exercises, including idealised case studies, that can be used to introduce geothermal modelling.

Based on a synthetic high temperature geothermal case study, typical of a volcanic area, a reservoir modelling workflow has been developed for teaching the sequential steps of geothermal simulation. The students are introduced to the key stages of reservoir modelling using the geothermal simulator AUTOUGH2. An important part of the process is the use of a good visualization and post-processing tool such as TIM, for enhancing their understanding of geothermal simulation. Standardized reports are produced with compiled Python scripts to reduce the complexity of dealing with model outputs and allow the students to focus on model calibration. This allows the students to spend more time understanding how changing parameters like permeability and deep upflows affects the match between the model results and the observed data. The use of a synthetic geothermal field gives a practical example of what calibration, data analysis, production history simulation and future scenario simulation with make-up wells mean in a model with some complexity, but which is simple enough to run in a short time. This teaching material provides a valuable resource for getting students familiar with geothermal modelling and improving their understanding of the concepts of geothermal reservoir behaviour.

Session: 1.3

116 | WHANGAIROROHEA THERMAL AREA AND THE DEMISE OF A HIGH TEMPERATURE TVZ GEOTHERMAL SYSTEM

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***Keywords:** Whangairorohea, Te Kopia, Paeroa Fault, fossil sinter, extinct geothermal*

Whangairorohea, Taupo Volcanic Zone (TVZ), New Zealand, occurs on the Waikato River approximately 7 km directly west of Ohaaki and 5.5 km east-northeast of Ngatamariki geothermal fields. Several warm seeps occur along a 1.2 km stretch of the northern bank of the river. There are also extinct silica sinters and silicified surface deposits, as well as a few small circular warm and cold pools (20-50 m diameter). These surface features are evidence that the area once hosted a high temperature (>210°C) geothermal reservoir, with vigorous surface activity, that has since waned. The area is situated on the southern Paeroa block, an asymmetric horst feature that has been displaced by the Paeroa Fault, the most active fault in the TVZ and one that defines the eastern edge of the Taupo Fault Belt. Recently published geological mapping in the area north of Whangairorohea shows additional sinter and hydrothermal eruption deposits that demonstrate geothermal activity was once more widespread (an area approximately 10 x 5 km). Aeromagnetic data suggests a subsurface, shallow rhyolite body has been locally demagnetised by hydrothermal alteration. This work proposes that Whangairorohea geothermal area was once part of a high temperature geothermal reservoir with vigorous and widespread surface manifestations. Its demise resulted from vertical displacement of the Paeroa block, which affected reservoir fluid pathways and deepened aquifers, and demonstrates how high temperature TVZ geothermal systems are prone to irreversible change from active faulting.

Session: 3.2

118 | A SUPERCRITICAL JOURNEY INTO TE AO MĀORI

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Keywords: *mātauranga Māori, indigenous knowledge, western science, kaupapa Māori research methodology, Taupō Volcanic Zone, Geothermal: The Next Generation (GNG), diversity in science, stakeholder engagement*

More equitable partnerships are needed in Aotearoa New Zealand with Māori, to better inform decision-making and advance economic, social and environmental goals. Increasingly mātauranga Māori is being consulted, aligned with and/or brought into conversation with science. Yet, many non-Māori researchers are still uncertain how to engage with Māori. What can we do to build trust and long-term mutually beneficial relationships? How we can be good partners?

Within our geothermal community, there is a need to better connect Te Ao Māori ki te ao rangahau (the world of Māori to the world of research) to facilitate more culturally responsive and effective approaches for undertaking geothermal research and resource development.

In the Geothermal: The Next Generation research programme we are taking a Māori-first approach to engagement, recognising that Māori are key players in Aotearoa's next generation of geothermal development and custodians of geothermal resources. Supercritical geothermal is a long-term prospect. This means it will be future generations, particularly Māori groups with geothermal interests, who will determine the use of supercritical resources, making the decisions and leading the way.

Given the long lead times, we have a chance to do things differently — in our stakeholder engagement, research design and interweaving of knowledge systems. In this presentation, we will share our engagement approach, including some key projects, hui and wānanga, and share the feedback we have received from Māori groups, our learnings (spoiler: we don't always get it right!) and how our thinking has evolved. It is our hope that this presentation offers inspiration and encouragement for inter-weaving western science and mātauranga Māori, and leaves attendees feeling empowered build relationships.

Mā te kimi ka kite, Mā te kite ka mōhio, Mā te mōhio ka mārama

Seek and discover. Discover and know. Know and become enlightened.

Session: 3.4

119 | NGĀ WAI ARIKI O ROTORUA: HE KOHIKOHINGA

Lani Kereopa, Nga Wai Ariki Ki Rotorua: Ahi Kaa Roa Roopu

Te Ahi Kaa Roa are a collective of representatives from the hapū and iwi who have maintained continuous occupation of Ōhinemutu, Whakarewarewa and Ngāpuna villages in Rotorua since pre-European times. Ahi Kaa refers to the 'burning fires of occupation', and the whānau who reside in these villages have a long and unique relationship with the geothermal resources, features and activity around them. Because of their intergenerational knowledge and experience, Bay of Plenty Regional Council (Council) initiated the establishment of the group as one way to ensure a tangata whenua lens or perspective regarding the management of the Rotorua Geothermal System and that mana whenua are afforded a clear voice in the development of the Rotorua System Management Plan and the review of the Rotorua Geothermal Regional Plan. While not the sole focus of the group, a key output of this relationship has been the collation of cultural views, perspectives and observations of the current health of Rotorua Geothermal, and past and current uses, in the report Ngā Wai Ariki o Rotorua: He Kohikohinga. This presentation will present a Te Ao Māori perspective on how we measure mauri or health of geothermal and describe the significant change in geothermal use and management due to the intergenerational impacts of colonisation and resultant loss of control over their natural resources. Principles of management are proposed, including matters such an intergenerational equity, embedding Mātauranga Māori in decision making, reciprocity, and prioritization of uses of geothermal for the benefit of the community. A unique and challenging view on future management opportunities will be presented.

Session: 3.4

120 | STEAM SEPARATOR SELECTION FOR A GEOTHERMAL POWER STATION

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Keywords: *Horizontal Separator, Geothermal Separator, Separator Performance, Separator Design, Rotokawa, Rotokawa Upgrade, Nga Awa Purua, Enthalpy Decline*

Mercury operates the Rotokawa and Nga Awa Purua geothermal power plants on the Rotokawa geothermal field located in the North Island of New Zealand. As part of the Rotokawa Upgrade project, Mercury installed two horizontal steam-brine separators in 2021. The horizontal separator design was a first for Mercury and two of only a few of those installed within the New Zealand Geothermal industry. This paper discusses the analysis and decision-making process undertaken to select the horizontal separator design over a more traditional vertical separator. The separators were commissioned in mid-2021, and the paper presents preliminary results on their performance.

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121 | LOST IN THE JUNGLE – A REVIEW OF THE STILL-RADICAL GEOTHERMAL DEVELOPMENT AT KIABUKWA, DR CONGO

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Keywords: *Kiabukwa, sub-atmospheric flash, geothermal development, low temperature.*

In 1951, tin miners in what was then Belgian Congo needed electricity for their plant, but faced cost and logistic challenges around bringing fuel to site. There was a 91oC large flow hot spring near the site so they sought engineering help to develop this. This request would still be thought of as a development challenge today, especially in a tropical environment, even with the present availability of binary cycle technology. The resulting 250kW Kiabukwa geothermal station, which ran for several years before Wairakei, was developed in this purely commercial context.

This paper reviews the still-radical solutions employed by the English designer/manufacturer in this largely forgotten pioneering project, particularly its use of sub-atmospheric flash technology.

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122 | EMPOWERING INDIGENOUS EPISTEMOLOGIES IN GEOTHERMAL DEVELOPMENT

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Keywords: *Decision Support Tool, Holistic Geothermal Assessment, Indigenous Knowledge, Mauri Model Decision Making Framework.*

Epistemologies are ways of knowing. Indigenous Peoples are aware that they do not perceive and experience the world in the same way as others. So it is important when empowering Indigenous epistemologies, such as that of the New Zealand Māori, to also be able to represent a scientific understanding within the same analysis. A geothermal development assessment tool has been developed by adapting the Mauri Model Decision Making Framework. Mauri is a metric that is capable of representing the change in life supporting capacity of things and collections of things. The Mauri Model is a method of grouping mauri indicators as dimension averages in order to allow holistic assessment and also to conduct sensitivity analyses for the effect of worldview bias.

R-shiny is the coding platform used for this Vision Mātauranga research which has created an expert decision support tool (DST) that combines a stakeholder assessment of worldview bias, with an impact assessment of mauri based indicators to determine the sustainability of proposed geothermal development. The initial intention was to develop guidelines for quantifying mātauranga Māori impacts related to geothermal resources. To do this three typical scenarios were considered:

1. A resource owner wishing to assess the potential for a new geothermal development;
2. Another party wishing to assess the environmental and cultural impacts of a proposed development;
3. An assessment that focuses on the holistic sustainability of the resource including its surface features.

Indicator sets and measurement thresholds were developed that are considered necessary considerations for each assessment context and these have been grouped to represent four mauri dimensions that mirror the four well-being criteria used for resource management in Aotearoa New Zealand.

Two case studies have been conducted to test the DST suitability for quantifying mātauranga Māori and other bio-physical factors related to a geothermal system. This involved estimating mauri0meter values for physical features such as temperature, flow rate, frequency and colour. And developing indicators to also quantify qualitative observations about the geothermal system made by Māori. A retrospective analysis has then been conducted to verify different understandings of the geothermal system. The case studies found that the expert DST is useful for geothermal development assessment, especially where hapū (indigenous sub-tribal grouping) are conflicted regarding the benefits and disadvantages of their' and others' geothermal developments.

These results have been supplemented with evaluations for the cumulative impacts of geothermal developments experienced by different parties using integration techniques applied to the time history curve of the expert DST worldveiw bias weighted plotted against mauri0meter score. Cumulative impacts represent the change in resilience or potential of geothermal systems, which directly assists with the holistic interpretation of change from an Indigenous Peoples' perspective.

Session: 3.4

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