Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Hydrothermal Alteration: Separating Fact from Hyperbole

Sarah D. Milicich[1], Isabelle Chambefort[2] and Greg Bignall[2]

[1]GNS Science, Lower Hutt 5040, New Zealand

[2]GNS Science, Wairakei Research Centre, Taupo 3384, New Zealand

s.milicich@gns.cri.nz

Keywords: hydrothermal alteration, hydrothermal minerals, petrology, exploration

ABSTRACT

The value of information that can be gleaned from hydrothermal mineral studies in geothermal exploration and development projects is well known. Identification and interpretation of hydrothermal mineral assemblages is an important aspect of surface and subsurface geothermal exploration, as it may provide insight into the present and/or past nature of the geothermal reservoir. Observational and analytical tools available to the exploration geothermal geologist are wide and increasingly sophisticated. For several decades, the significance of mineral occurrences (e.g., indicators of temperature conditions at the time of mineral formation), textural relations (e.g., insights into system longevity and evolution, or influx of cool marginal fluid ingress) and chemistry (e.g., indicators of low pH conditions, potential for natural self-sealing or development-induced scaling etc.) has been recognised. However, at a time of geothermal renaissance in many parts of the World, it is a concern that the petrological skills are not used to their maximum potential, or are even being ignored. Low petrological skills of entrance-level geologists, and poor geothermal exploration and drilling practice knowledge of decision-makers new to the geothermal industry, mean potentially vital exploration and development information is being overlooked or superficially considered. This is of concern because petrological information could help resolve the conceptual hydrological-chemical (e.g., past vs. present reservoir characteristics) and geophysical-geological (evolution) framework of a system.

This paper provides an opportunity to highlight proven petrological practices and insights, including conventional techniques and recently developed tools, and knowledge that can be gleaned from hydrothermal minerals studies that, to some degree, are at risk of been lost or devalued. Whilst highlighting the value of information that can be obtained, we also discuss the pitfalls, mineralogical misrepresentation and ambiguities within the exploration and development-stages of the conceptual model.

1. INTRODUCTION

During the last twenty years worldwide utilisation of geothermal resources has accelerated, and the geological tools available to support exploration and development activities have become increasingly sophisticated. This is highlighted by the development of new or optimised geophysical techniques, such as seismic array (i.e. Bannister et al., 2010, Rawlinson et al., 2012, Sewell et al., 2013) and magnetotelluric (i.e., Heise et al., 2008, Bertrand et al., 2013) data acquisition. Whilst workers in the early days of geothermal exploration recognised the value of information that might be gained from the study of hydrothermal alteration minerals and their host geology (Browne, 1970), there is now a distinct focus on geophysical methods for the exploration of geothermal systems. At a time when geothermal exploration is being initiated in many places around the World, it is of concern that invaluable exploration and development information that might be gleaned from the alteration assemblage is being overlooked or misinterpreted. In some cases, this may be due to inexperience of entry level geologists, but also an oversight by some decision-makers who devalue petrological skills within the exploration / development team, and the information that may be obtained.

The interaction between hydrothermal fluids and the host rocks in a geothermal system strives to achieve a state of equilibrium between the fluids, primary minerals and secondary (alteration) minerals, whereby the mineralogy and fluid chemistry are modified to reflect the prevalent temperature and fluid composition (Browne, 1978). As geothermal petrologists know, the formation of the alteration minerals is dependent on a combination of temperature, permeability, pressure, fluid composition and initial composition of the rock at the time of mineral formation. Petrographic studies of hydrothermal alteration minerals are an effective means of gaining information that can help resolve the conceptual hydrological-chemical (e.g., past vs. present reservoir characteristics) and geophysical-geological (evolution) framework of a hydrothermal system. It is vital to gather this information from early stages in exploration to set a baseline before future utilisation of the geothermal resource.

Regrettably, it is our experience that detailed geological investigations (petrology, hydrothermal mineralogy, assessment of correlative / stratigraphic relationships, including high-precision dating, and structural studies) have become a less visible consideration in the exploration of geothermal resources over the last two decades, often due to real or perceived budgetary constraints. Most evident, particularly in New Zealand, is the prevalence of rotary drilling practices, drive for minimised exploration / drilling budget, and time issues associated with core retrieval that have impacted detailed geological investigations.

The geosciences cannot always answer resource uncertainties to the satisfaction of exploration and field development managers. What is essential is that the information that is obtained from geological investigations is presented accurately, and in context with other relevant information such as geophysical data. In so doing, resource exploration and development managers will have greater confidence in their decision-making. In this paper we present case studies that highlight the value of geological data that is obtained during geothermal exploration and resource delineation projects, and pitfalls of 'over interpreting' geological findings.

2. CASE STUDIES

Geology is by definition the science that deals with the dynamics and physical history of the earth, the rocks of which it is composed, and the physical, chemical, and biological changes that the earth has undergone or is undergoing. It is the most effective science to apply for exploring the potential of a geothermal site or developing an already established field. In the case of geothermal exploration and resource delineation, geology results from the observation of the mineralogical effects of natural or induced processes and conditions currently occurring, or prevalent in the past, but cannot be used to definitively predict what will happen in the future. For example, a geologist can identify minerals from well samples that form under a specific range of temperatures, but we cannot be sure that in the future the temperature in the well will be in that range.

Here we present a series of case studies, based on real world examples and situations from geothermal developments in a range of geological settings, that highlight how a clear understanding of hydrothermal alteration, and processes by which the secondary mineral assemblage formed, provide insights to engineers and field developers that can positively guide their exploration and development strategy. Conversely, not recognising the implications of the alteration mineralogy observed, can also have consequences. While not exhaustive, we present examples where temperature, fluid chemistry, lithological identification, clay mineralogy, and surface features have influenced drilling in a geothermal field.

2.1. The case of "not seeing is believing"

An exploration well was being drilled in a new/prospective resource delineated by geophysical methods. Extensive silica sinters and near-boiling chloride springs suggested the area drilled was in the main, high-temperature upflow of the geothermal system. Fluids in the system were inferred to be high in CO_2. Drilling proceeded to ~1600 m drilled depth, or about 400 m below the inferred cap to the reservoir. The rig geologist noted the rocks contained abundant calcite, common white clay, adularia, quartz, and possible wairakite. Field developers were concerned, however, as drilling was targeting the predicated high-temperature part of the system, yet no hydrothermal epidote had been reported which would "typically be indicative of high-temperature conditions" (i.e., >240 ºC; Browne and Ellis, 1970). Their concerns prompted debate that the drilling programme might be abandoned. The geologist explained, in this case the absence of epidote should not be regarded as fatal to the drilling programme, as calcite can be expected to form in high-CO_2 systems in preference to epidote (Browne and Ellis, 1970). A decision was made to continue drilling. The well was completed successfully, and provided important resource information, with the exploration programme proceeding as planned.

Lessons: Although epidote is commonly used during drilling as an indication that high-temperature conditions, it should not be assumed its absence means temperatures are now low. In this example, communication from geologist clarified that other mineral indicators (e.g. wairakite, 200 – 250 ºC; Fig. 1; Steiner, 1977; and subsequent XRD confirmation that the white clay was illite), knowledge of typical mineral formation temperatures and stabilities, combined with information from measured parameters (T_{in}/T_{out}) during drilling, were consistent with a "gassy", high-temperature resource.

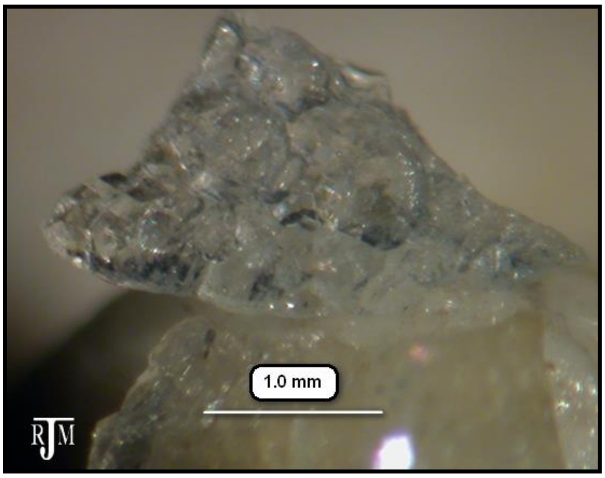

Figure 1. Wairakite, indicative of temperatures 200 – 250 ºC (Steiner, 1977). Photo courtesy of Rod Martin.

2.2. Recognising "timing is everything" – the truth is in the detail!

Drilling of a delineation well, as part of possible field-expansion, was proceeding from 1400 – 1600 m drilled depth through a strongly altered ignimbrite. The well was located in part of the field where geochemical indicators of reservoir temperature were ambiguous, although results of a recent MT survey covering the area were optimistic. The rig geologist reported an alteration assemblage that included abundant epidote (Fig. 2D; indicative of >240 ºC) and flakes of clay, which were initially assumed to be illite (Fig. 2A,B; indicative of >220 ºC; Browne, 1978). However, XRD analysis requested by the rig geologist indicated the clay was disordered interlayered illite-smectite (Fig. 2C,D), which typically forms at <200 ºC (Browne, 1978). The apparent disequilibrium epidote-clay assemblage lead the geoscience team to quickly conclude this part of the system had cooled, and the high-temperature epidote-bearing alteration assemblage was relict.

Lessons: It was not initially recognised by the geologist that the epidote was relict, as there was optimism delineation drilling would prove successful in identifying a large, high temperature resource. The geologist followed up their initial uncertain mineral identification by clarifying clay-type and relict nature of the epidote. This resulted in a changed drilling strategy, whereby a second delineation well was delayed until comprehensive testing of the first well was completed. Information obtained from analysis of downhole samples and well completion data, combined with reinterpretation of the geophysics data, prompted a cessation of the delineation drilling programme. Although expansion plans were shelved, the findings prompted reconfiguration of the reservoir model of the system. The existing plant continues to operate efficiently.

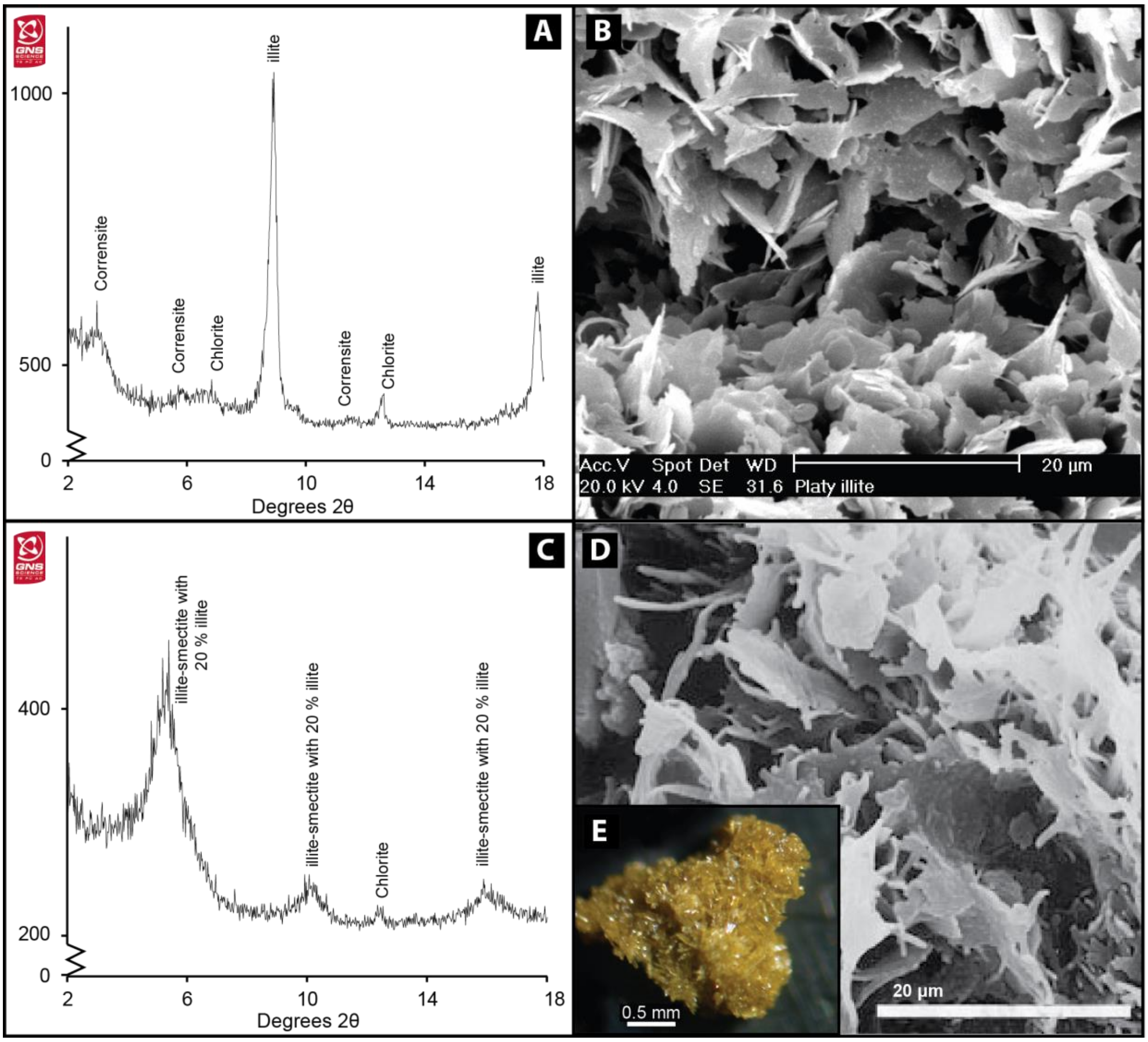

Figure 2. A. XRD diffractogram of sample with abundant illite. B. SEM image of ordered, crystalline illite. C. XRD diffractogram of sample with common disordered interlayered illite-smectite. D. SEM image of disordered, poorly crystalline, interlayered illite-smectite. E. Well crystalline epidote collected from cuttings. SEM images reproduced from the 'Images of Clay Archive' of the Mineralogical Society of Great Britain & Ireland and The Clay Minerals Society. Epidote image courtesy of Rod Martin.

2.3. The unexpected hydrothermal mineral assemblage

Drilling of a new well had been undertaken in a geothermal system located on the flank of an andesite volcano. Drilling proceeded through a sequence of andesite and volcanic sediments. The rig geologist had reported a sequence of prograde alteration to well bottom, albeit with a zone at 810 – 830 m drilled depth where alunite (Fig. 3) and pyrophyllite was unexpectedly encountered in the cuttings. This alteration assemblage is an indicator of high-temperature, acidic fluids (Reyes and Giggenbach, 1992). The alteration was considered anomalous, and described in drill reports as relict alteration. The well was successfully completed, with production liner run to 1500 m. After several months, the liner at around 800 m showed evidence of corrosion. On further consideration of the field hydrology, it was realised acid fluids from higher levels in the system was percolating to lower elevations via fractures in the host rocks. This was creating a zone of acid fluid, masked by the dominantly neutral pH fluids found in the reservoir.

Lessons: Recognition that geological structures can channel acid fluids some distance from source proved crucial to understanding the hydrology of the magmatic-hydrothermal system. Failure to recognise the nature of the acid mineral assemblage had implications for the long-term viability and performance of the well. Whilst early recognition of the acid alteration may not have impacted the design and completion of the well, it would have been taken into account in the design and casing plan of future wells. This would have resulted in the production area being target by deviated wells, which avoided the acid zones, rather than the vertical wells that comprised the planned drilling programme and which were subsequently impacted by acid fluids.

Figure 3. Image of alunite, which has formed under low pH conditions associated with magmatic-sourced fluids. Photo courtesy of Rod Martin.

2.4. The case of the misidentified breccia

During drilling of a production well, production casing was set at 1200 m drilled depth. Drilling continued to 2000 mVD, leaving 800 m of open hole while drilling. Drill cuttings were collected at 5 m intervals. Lithologies coinciding with the open hole section included flow banded rhyolite, tuff, siltstone and sandstone layers. From 1850 – 1970 m drilled depth, the lithology encountered was a tuff (Fig. 4A). At 1950 m, the drilling engineer reported problems that resulted in the drilling assembly being raised ~100 m to clear an inferred blockage. When drilling resumed, the cuttings from 1970 – 1985 m included a mix of rhyolite, tuff, siltstone and sandstone, in what was interpreted to be a tuffaceous matrix (Fig. 4B). These cuttings were initially assigned to a polymict breccia. On further examination, it was determined cuttings from 1970 – 1985 m derived from the shallower zone of caving.

Lessons: Geology staff should be aware that cuttings may not be representative of the depth of drilling. Here, mixed lithologies may have pointed to a breccia having been encountered, a sequence of alternating rock layers, or could have been related to caving from an uncased zone. Interpretation of breccia type and origin can be problematic, but may have been more straight-forward, and helped to identify the zone of collapse, if better recording of the lithologies and stratigraphic relationships had been undertaken, and considered in discussion with drilling staff. Identifying the potential for unconsolidated layers to cave into uncased hole should be communicated to the drilling staff.

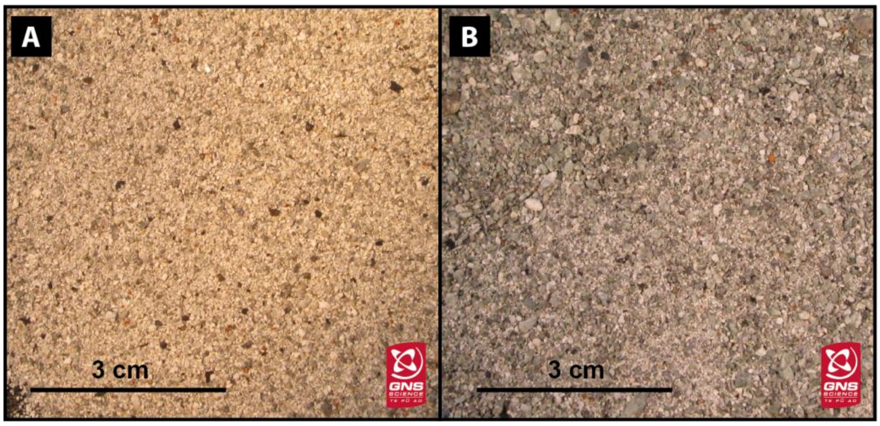

Figure 4. A. Cuttings collected from altered tuff. B. Cuttings collected from a zone contaminated with cave-ins.

2.5. The case of the "sticky" clay…

During exploration well drilling a sequence of volcaniclastic sediments and ignimbrite were encountered at 600 – 700 m drilled depth. The rig geologist noted the rocks contained moderately abundant low rank clays, zeolite, minor calcite and quartz. Drilling proceeded to ~1000 m where a bit change was programmed. The bit change was undertaken with standard procedures followed to maintain integrity of the hole and to manage inferred high temperature / pressure BPD geothermal conditions. The drill assembly was successfully removed from hole, although "sticky" conditions were noted at "some depth" below the 400 m anchor casing shoe. Following the bit change, that took somewhat longer to complete than usual, it proved difficult for the drillers to run back into hole and an obstruction or cave-in was suspected at ~650 m. At this time, the geologist reconsidered the nature of the clay alteration and found (by methylene blue testing; Fig. 5; Gunderson et al., 2000, Harvey et al., 2000) it to be a "predominantly swelling-type" (smectite). The geologist advised the senior drilling engineer who implemented modification to circulating downhole (drilling) fluids to inhibit swelling of the clays. The well was completed safely, and remains on-line and a good producer.

Lessons: Proactive consideration by the geologist to understand the nature of the hydrothermal alteration in a depth zone implicated in difficult drilling operations identified a possible cause of problem. MeB testing (subsequently adopted as "standard practice") during the drilling programme may have identified a "problem zone" earlier. However, prompt and effective communication with driller resulted in changed operational activities which resulted in a resolution of the problem.

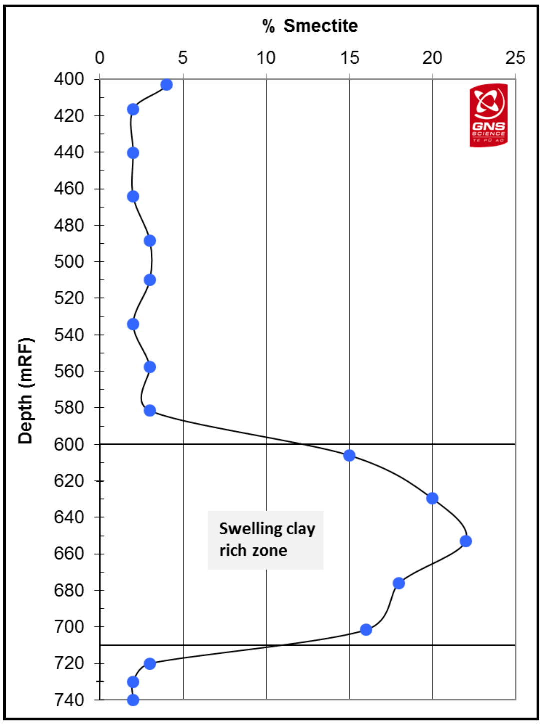

Figure 5. Methylene blue analyses indicating a zone rich in swelling clay from ~600-700 m.

2.6. More from the clay files ….

Drilling of a subsequent exploration well, in a previously undrilled part of the field, was proceeding without issue through an interval of volcaniclastic sediments at 400 – 600 m drilled depth. The geologist correctly reported a number of clay-rich intervals through this interval. Drilling staff, influenced by past experiences, and concerned by the presence of possible swelling clays that might detrimentally impact hole security, considered deviating from their initial drilling programme and proposed setting anchor casing shallower than planned. Such action, a prudent consideration in regard to safe drilling practice, would have resulted in the well being completed shallower than the original target depth. However, by being part of the decision-making process, the geologist clarified that the clay was detrital clay, associated with competent sedimentary units (Fig. 6), and (confirmed by MeB testing) the clays were not swelling-type.

Lessons: An assumption was made by the geologist that everyone reading their provisional geological log (during drilling) would appreciate the clays were sedimentary origin. Clearer communication from the geologist to the drilling engineer regarding the nature of the volcaniclastic sediments and its constituent clay minerals, helped the decision-making process to continue drilling the well, which was completed safely and achieved its exploration goals.

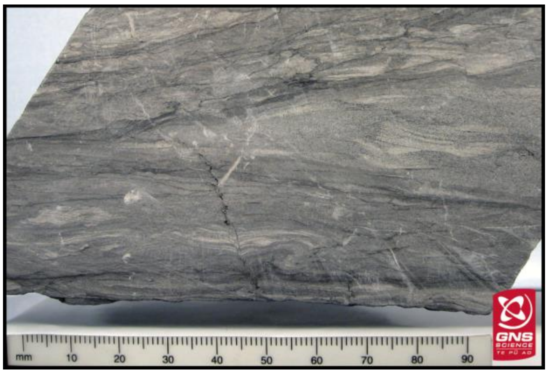

Figure 6. Drill core of sedimentary rock, rich in detrital clays.

2.7. And more clay ….

A production well was drilling as through a sequence of tuffs at 900 – 1200 m drilled depth. The rig geologist noted the rocks contained abundant clay, adularia, quartz, calcite and epidote. The drilling engineer queried the nature of the clays, and whether their high abundance may pose problems during further drilling. The response from the geologist clarified that the clay was illite, which had no swelling characteristics (confirmed by MeB testing), was a positive indicator of resource potential, and did not pose a drilling risk.

Lessons: A timely response to the drilling engineer from the geologist as to the nature of the clays present allowed drilling to be completed within the budgeted/programmed timeframe. This communication included the reminder that the presence of "clay" does not necessarily mean they are of the swelling variety, as not all hydrothermal clays are 'swelling clays'.

2.8. The case of "what used to be, no longer….?"

Over the last 5 years, a production well drilled in the 1980's as part of an extensive field development programme showed a steady decline in productivity and deterioration of its near-surface casing. It was decided to drill a make-up well from the same pad, targeting the same part of the resource that had been tapped by the earlier well. Geologists logging cuttings from the original well reported prograde alteration, with a secondary mineral assemblage at ~500 m depth of illite-smectite, quartz, albite, pyrite, titanite, zeolite and minor calcite. In the make-up well, geologists also noted a prograde alteration assemblage, albeit with co-existing smectite and illite-smectite, abundant calcite (Fig. 7), minor quartz, siderite and pyrite.

Lessons: Although a geologist reviewed the drilling results, the discrepancy in the style and intensity of alteration encountered by the two wells was not recognised. Subsequently, concern injection fluids might be contaminating near-surface aquifers, possibly via vertically connected faults and fractures through the system's clay cap, prompted further revision. The contrasting alteration assemblage provided evidence of hydrological change within the system, which might have prompted a revised injection strategy had the impacts been recognised earlier.

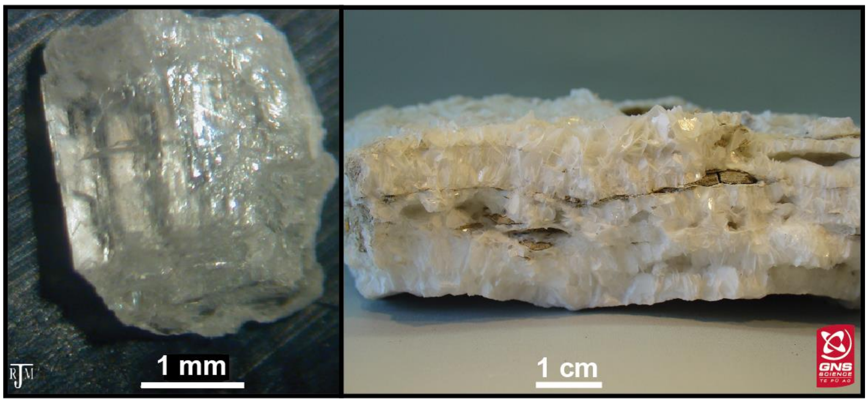

Figure 7. Calcite precipitating in reinjection areas.

2.9. "Something in the cuttings …."

Drilling of a production well was proceeding as programmed, with production casing set at 1100 m depth, and slotted liner below this depth to TD depths. The rig geologist reported generally prograde hydrothermal alteration with depth, but with common iron oxide in highly fractured rhyolite lava at 800 – 1000 m depth (Fig. 8). The presence of iron oxide can indicate the presence of cool, oxygenated water (Reyes, 1990). On consideration of the fractured nature of the host rock, it was considered likely that the iron staining was associated with the ingress of oxygenated waters. This information was communicated to the drilling engineer, who decided to set the production casing shoe at an appropriate depth to case off any zone of cool inflow.

Lessons: Prompt communication by the geologist of inferred fluid conditions indicated by alteration mineral assemblage allowed for a revision of the drilling programme and well design.

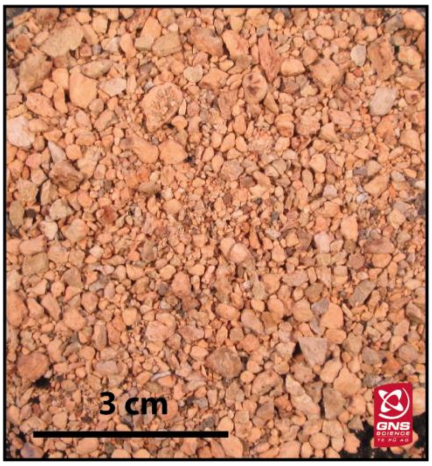

Figure 8. Cuttings with iron oxide alteration can indicate inflow of (cool?) oxygenated water.

2.10. Surface indicators

Surficial alteration and manifestations provide important resource information, and may be linked to either active or relict (fossil) geothermal activity. For example, the presence of silica sinter is a good indicator of well-connected vertical permeability within a high-temperature (>240 ºC) reservoir. However, the sinter needs to be confirmed as actively depositing (Fig. 9A), and not relict. There are many examples of extensive surface sinter deposits in areas where there is no longer hydrothermal activity, or hot springs that have reduced from high flow springs to minor seeps (Fig. 9B), where the near-surface plumbing has changed (due to self-sealing of the fracture or fault-controlled permeability).

Petrological analysis of surface alteration products can provide crucial information for well siting and design. For example, surface acid alteration can indicate the presence of acidic fluids in the near surface (Fig. 9C). Areas prone to acidic fluids are avoided, but can cause major problems with casing corrosion, and need to be considered in selection of casing. The presence of steaming ground can also be an indication of near-surface boiling (Fig. 9D). This needs to be taken into consideration by well designers due to the potential for vapour zones in the near surface, with appropriate well design implemented to mitigate for shallow blowouts.

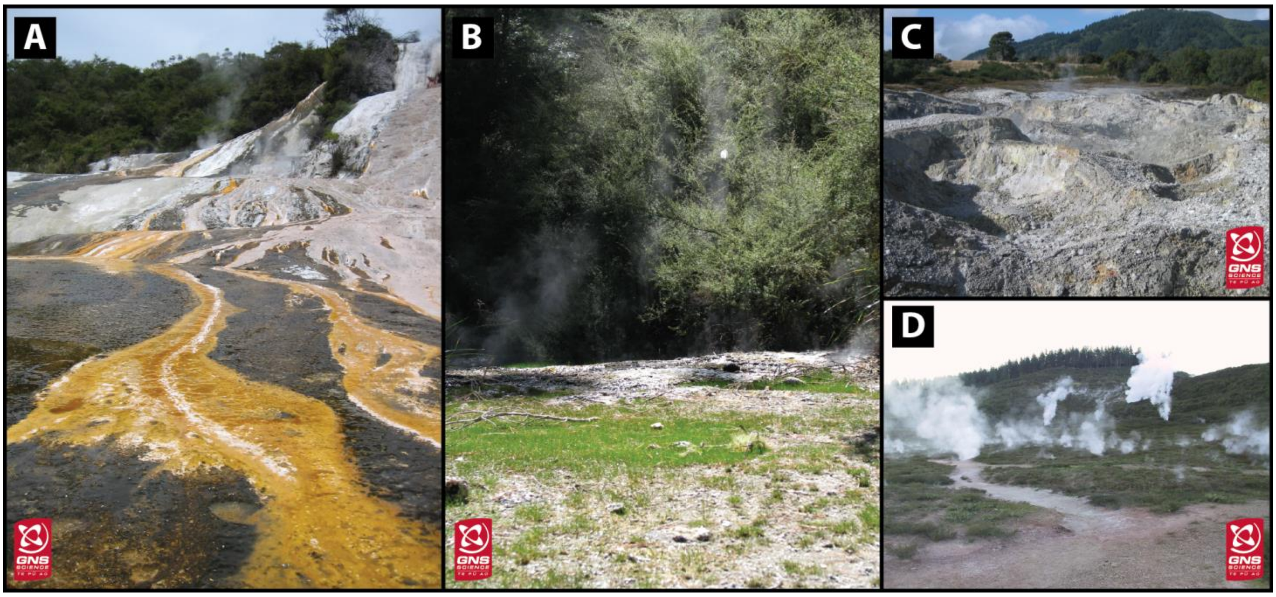

Figure 9. A. Actively depositing sinter associated with a high temperature resource. B. Inactive sinter in a cooled part of a system. The high temperature resource is located at some distance away. C. Acid alteration at surface. D. Steaming ground.

3. CONCLUSIONS

Geology is an applied science. In combination with geophysical insights and applications of geochemistry, geology is an important contributor to understanding the character and evolution of hydrothermal systems, and processes therein. However, the information available to the geologist, obtained from the study of well samples or surface exposures, is typically incomplete or ambiguous, and may not completely resolve an issue (or concern) to the geothermal exploration / resource delineation / drilling team. It is essential that the geologist is thorough in their observations and/or acquisition of data, but similarly rigorous in its interpretation. The findings and observations need to be conveyed, particularly to non-geoscientists, in a clear and unbiased fashion. This must include full disclosure of uncertainties and reservations, and not with over-interpreted or with extrapolated views.

The study of hydrothermal minerals, their formation and relationships is a specialist geoscience area. Many in the geothermal industry do recognise information gleaned from mineralogical studies can be valuable to the successful completion of a well, an exploration strategy, or achieving the goals of a resource delineation project. However, we hope through this paper to have drawn the attention of the wider geothermal community to the value mineralogical studies can have to their projects. Also, to challenge universities to address the general dearth in competent mineralogists and petrologists in the geothermal sciences, by providing their students with skills to undertake both fundamental research on active hydrothermal systems, but also to engage effectively with non-geologists and have influence in geothermal exploration and developments projects if they choose an industry career path.

REFERENCES

Bannister, S., Sherburn, S., Bourguignon, S., Parolai, S., and Bowyer, D.: Preprocessing for reservoir seismicity location: Rotokawa Geothermal Field, New Zealand, *Proceedings of the World Geothermal Congress*, (2010).

Bertrand, E.A., Caldwell, T. G., Hill, G.J., Bennie, S.L., and Soengkono, S.: Magnetotelluric imaging of the Ohaaki geothermal system, New Zealand: implications for locating basement permeability, *Journal of Volcanology and Geothermal Research*, **268**, (2013), 36-45.

Browne, P.R.L.: Hydrothermal alteration as an aid in investigating geothermal fields, *Geothermics*, **2**, (1970), 564-570.

Browne, P.R.L.: Hydrothermal alteration in active geothermal fields, *Annual Review of Earth and Planetary Sciences*, **6**, (1978), 229-250.

Browne, P.R.L., and Ellis, A.J.: The Wairakei-Broadlands hydrothermal area, New Zealand: mineralogy and associated geochemistry, *American Journal of Sciences*, **269**, (1970), 97-131.

Gunderson, R., Cumming, W., Astra, D., and Harvey, C.C.: Analysis of smectite clays in geothermal drill cuttings by the methylene blue method: for well site geothermometry and resistivity sounding correlation, *Proceedings of the World Geothermal Congress*, (2000), 1175-1181.

Harvey, C.C., Gunderson, R., and Cumming, W.: Methylene blue adsorption: a real time rig geologist tool for estimating geothermal reservoir temperatures and forecasting drillhole stability problems, *Proceedings of the New Zealand Geothermal Workshop*, (2000), 151-155.

Heise, W., Grant C., Hugh, B., and Stephen, B.: 3-D modelling of magnetotelluric data from the Rotokawa geothermal field, Taupo Volcanic Zone, New Zealand. *Geophysical Journal International*, doi: 10.1111/j.1365-246X.2008.03737.x (2008).

Rawlinson, Z. J., Townend, J., Arnold, R., and Bannister, S.: Derivation and implementation of a nonlinear experimental design criterion and its application to seismic network expansion at Kawerau Geothermal Field, New Zealand, *Geophysical Journal International*, **191**, (2012), 686-694.

Reyes, A.G.: Petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment, Journal of Volcanology and Geothermal Research, **43**, (1990), 279-309.

Reyes, A.G., and Giggenbach, W.F.: Petrology and fluid chemistry of magmatic-hydrothermal systems in the Phillipines, Water-Rock Interaction. Kharaka and Maest (eds). Balkema, Rotterdam. (1992).

Sewell, S.M., Cumming, W., Bardsley, C., Winick, J., Quinao, J., Wallis, I.C., and Sherburn, S.: Interpretation of Microearthquakes at the Rotokawa Geothermal Field, 2008 To 2012, *Proceedings of the New Zealand Geothermal Workshop*, (2013).

Steiner, A.: The Wairakei geothermal area, North Island, New Zealand, *New Zealand Geological Society Bulletin*, **90**, (1977), 136p.