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

Permeability Mapping

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Keywords: Injectivity Index, II, Productivity Index, PI, field, reservoir, boundary, permeability, feedzone

ABSTRACT

This paper introduces a permeability parameter called the Total Initial Injectivity Index Linear Density Average (TIIILDA, pronounced "tilde") defined as the initial total well II as measured during a stage test or completion test divided by the length of open wellbore in km (t/h/bar/km), the natural units of which is time. Mighty River Power's four operating geothermal reservoirs typically have values corresponding to an outer boundary of ~1 microsecond (µs), an injection area of <5 to 10 µs, and a production area of >5 to 10 µs. This metric can aid targeting of injection wells in all geothermal fields as well as production wells in mainly single-phase, compressed-liquid reservoirs like Ngatamariki. It also allows for simple identification of field geometry and boundaries using an objective measure.

1. INTRODUCTION

Permeability in geothermal reservoirs is usually encountered in discreet feedzones and is not readily mappable. Lithology often controls feedzone density and permeability, and permeability tends to decline with depth. A feedzone's permeability can be characterized by an Injectivity Index (II) and a Productivity Index (PI), and a well's total II and PI can be calculated either through downhole measurement of pressure changes during injection and production or by using a wellbore model. Targeting individual feedzones with drilling has had mixed success and predicting feedzones based on lithology is often complicated by lack of lithologic information due to total lost circulation while drilling.

Coutts (2013) studied feedzones at Ngatamariki and analyzed feedzone linear density, thickness and capacity (i.e. II or PI), depending on the behavior of the feedzone during testing. A strong correlation was found between these parameters and lithology. Deep andesites, Tahorakuri ignimbrite and Tahorakuri tuffaceous rhyolite breccias host lower-density, higher-II feedzones, while the Tahorakuri Tuff hosts higher-density, lower-II feedzones. Normalized to the average thickness of the formations across the reservoir, the andesite has the greatest total permeability, followed by Tahorakuri ignimbrites, volcaniclastics, and rhyolite breccias, in that order (**Figure 1**). The implicit conclusion was that wells should target the higher-permeability formations, and given that the andesite has good permeability, wells should be targeted deep enough to reach it.

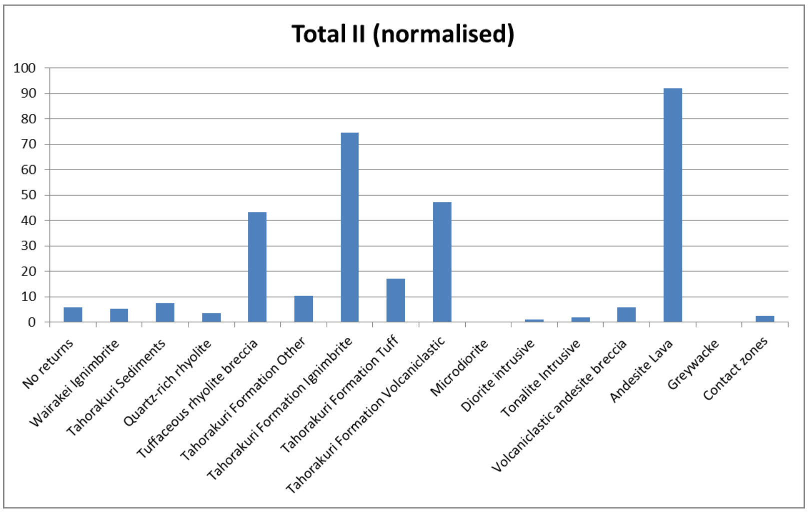

Figure 1: Total Injectivity Index (t/h/b) for each formation at Ngatamariki, normalised to the average thickness of the formation across the field. After Coutts (2013).

2. PERMEABILITY DATABASE

Completion and stage test reports were consulted for all wells for which MRP has information, including Crown reports, consultant reports and internal MRP reports. Many of the older reports have not been digitized and only exist in hard copy in MRP's library. Some of the completion reports give a range of values for the II, or state that the curve becomes non-linear at high flow rates. This non-linearity may be associated with improvement in skin factor, stimulation of feedzones, or opening of fractures due to the increased pore pressure during high-rate injection. In these cases a middle value, or the value for the linear part of the curve is used.

3. PI TO II CORRELATION

It has been observed that PI and II correlate in geothermal reservoirs, with PI generally equal to or lower than II for liquid feedzones, according to Grant and Bixley (2011). They stated that drilling in New Zealand has indicated that II is around three to five times PI, with wide scatter.

Combs and Garg (2000) reviewed this correlation for four Japanese geothermal fields and found a positive correlation, with the indices approximately equal to each other within an order of magnitude (**Figure 2**). Dual-phase feedzones, however, exhibit much more complicated nonlinear behavior than liquid feedzones (**Figure 3**) and the correlation is not as strong.

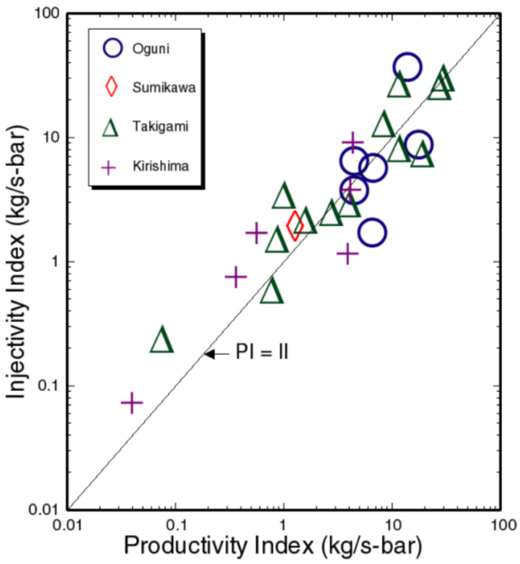

Figure 2: Injectivity Index (II) versus Productivity Index (PI) for Oguni, Sumikawa, Takigami, and Kirishima Boreholes with Liquid Feedzones. From Combs and Garg (2000).

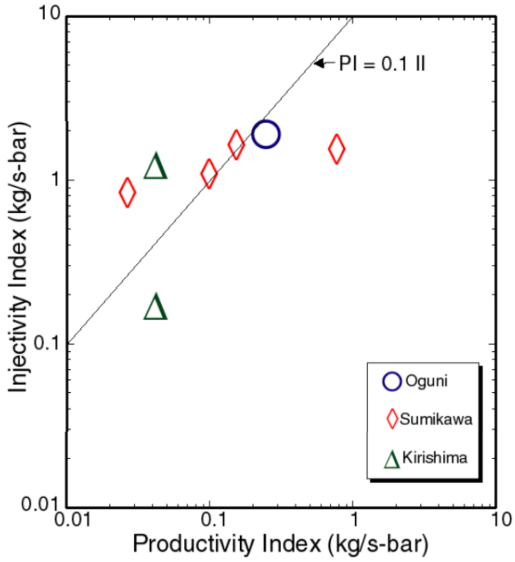

Figure 3: Injectivity Index (II) versus Productivity Index (PI) for Oguni, Sumikawa, and Kirishima Boreholes with Two-Phase Feedzones. From Combs and Garg (2000).

Comparison of initial II and PI values calculated from completion tests at Ngatamariki indicate a very good correlation, corresponding to a PI to II ratio of ~0.6 (**Figure 4**). Note these II values are measured prior to significant injection stimulation, but that all geothermal wells may stimulate somewhat during drilling if their reservoir sections are drilled with cold water.

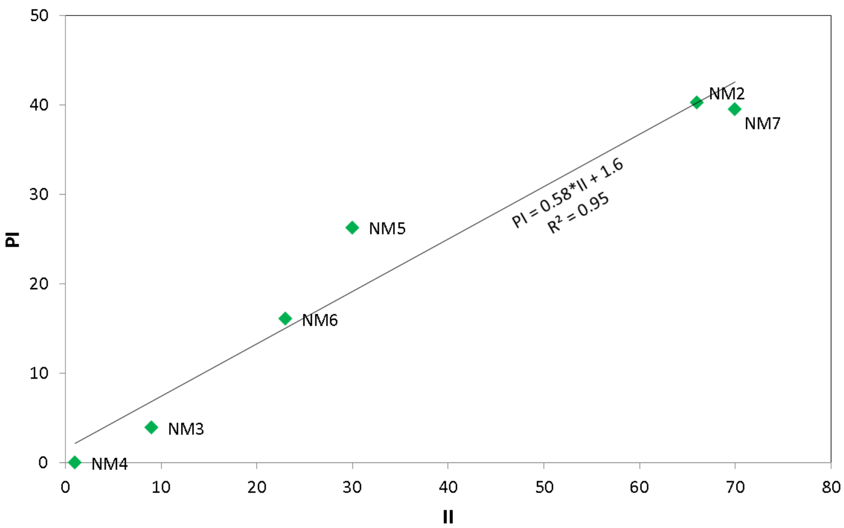

Figure 4: Initial PI vs II (t/h/bar) for the six Ngatamariki wells where both values were measured during completion tests. Note that NM4 was unable to produce and is assigned a PI of 0.

4. TIIILDA

The Total Initial Injectivity Index Linear Density Average (TIIILDA) is defined here as simply the total initial II of a well divided by its open length. It gives a single value for a well indicating the average permeability the well intersected. For some, the most useful conceptual units for this parameter may be II/km, although the natural units are time (1 t/h/bar/km reduces to ~3.6x10^{-8} s). TIIILDA values on the order of microseconds are typical for MRP's geothermal reservoirs. This time value can be thought of as an average feedzone residence time for a particle of injecting water moving from the wellbore through the porous and fractured feedzone to the reservoir, just as water flowing from a lake to the sea through a stream spends less time moving through a given distance in a narrow creek than in a wide river. Smaller values correspond to shorter residence times, lower permeability, and perhaps more constricted feedzone volumes. Larger values correspond to longer residence times, greater permeability, and perhaps greater feedzone volumes. This number can be skewed upwards in shallow wells that encounter good permeability immediately out of the shoe, and downward in deep wells that have long dead legs.

5. MAPPING PERMEABILITY

TIIILDA is contourable and mappable. This parameter has been mapped for MRP's five operating geothermal fields and consistently shows a concentric pattern of permeability with the highest values in the center of the field and the lowest values on the edges. Occasionally, well-defined low-permeability zones exist in the centers of fields (Wilmarth, 2014).

TIIILDA can be plotted on maps using the time value in microseconds (µs) contoured at values of 1, 5, and 10. This is used rather than II/km (t/h/bar/km) because the values conveniently correspond to meaningful reservoir distinctions: the edge of MRP's fields are usually ~1 µs, the injection areas are generally less than 5 to 10 µs, and the production areas are generally higher than 5 to 10 µs. However, values can be much higher than 10 µs (>100 µs for some fields). The conversion factor to II/km is to multiply µs by ~3.6. The value is plotted at the wellhead for vertical wells and at the midpoint of the open-hole section of a well bore track for deviated wells.

6. STATISTICS AND TRENDS

Analysis of MRP's fields indicates that both II and TIIILDA are log-normally distributed with a few wells having very large values, up to two standard deviations above the median value or even more. Histograms of TIIILDA for Ngatamariki and Rotokawa are presented in **Figure 5**. Rotokawa has approximately three times as many wells as Ngatamariki and five of these have much larger permeabilities than the median. At Ngatamariki, no well has encountered this anomalously large permeability to date (Azwar, 2012), but if the distribution of well permeabilities is similar to Rotokawa, one might expect that future wells will.

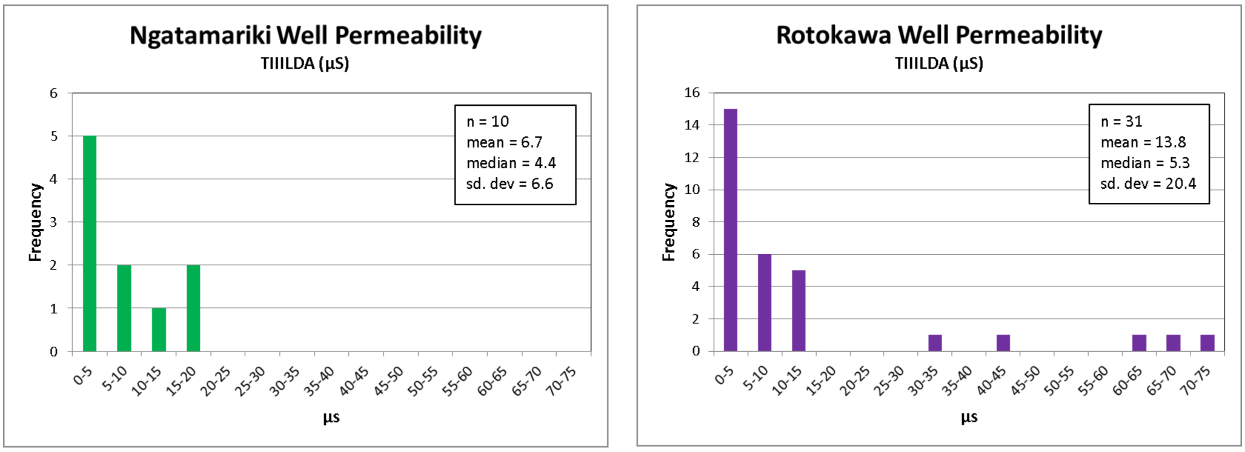

Figure 5: Histograms of well permeabilities for Ngatamariki and Rotokawa.

7. CONCLUSIONS

Mapping permeability may seem like simply an academic exercise, but it is not. While temperature maps are often used in geothermal development, permeability maps are not common. This may be because total II and PI information are not typically available. A search of the literature located no publically available collations of this kind of data for any geothermal field.

It is recommended that reservoir development plans utilize detailed conceptual models and 3D modeling of the distribution of feedzones. However, mapping permeability as described in this paper can help visualize the geometry and boundaries of geothermal fields including where new drilling may be warranted. While initial II does not seem to correlate as strongly with PI in two-phase reservoirs, predicting II is very useful for targeting injection wells in these fields. In single-phase, compressed-liquid reservoirs like Ngatamariki, this tool may additionally help target production wells.

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