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G.N. KILGOUR, M.D. ROSENBERG, A.J. RAE, G. BIGNALL

GNS Science, Wairakei Research Centre, Taupo, New Zealand

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Full addresses/phone/fax

GNS Science, Wairakei Research Centre, 114 Karetoto Rd, Wairakei, Taupo, N.Z.
Ph. (07) 374 8211 Fax (07) 374 8199

TARGETING FORMATION-HOSTED PERMEABILITY IN GEOTHERMAL SYSTEMS OF THE TAUPO VOLCANIC ZONE

G.N. KILGOUR, M.D. ROSENBERG, A.J. RAE, G. BIGNALL

GNS Science, Wairakei Research Centre, Taupo, New Zealand

SUMMARY – Production drilling targets in geothermal wells are often biased towards faults and fracture zones. In some of New Zealand's geothermal fields, this approach is warranted. However, in ignimbrite-dominated systems, formation-hosted permeability can provide excellent production. To illustrate the potential of targeting wells to intersect formation-hosted permeability, we use the results from the 2003-2004 drilling at Mokai Geothermal Field as a case study. Six wells (MK10-MK15) were radially drilled from one wellpad to specifically target ignimbrites and sediments, and the contact zones between them. Each well intersected feedzones hosted within and/or between one or more of Ignimbrite D, Whakamaru Ignimbrite, un-named volcaniclastic sediments and Ignimbrite F. Completion test data indicated that non-welded ignimbrite units hosted diffuse feedzones, whilst welded ignimbrite units hosted discrete, joint-controlled feedzones. All wells were regarded as successful, and highlight the potential of targeting permeability within, or on the margins of distinct ignimbrite flow units.

1. INTRODUCTION

Production well drilling in geothermal systems often targets known or inferred permeability in fault-related fracture zones. In some fields, targeting fault/fracture zones is necessary, as the production reservoir is hosted in rock that has very low inherent permeability, such as andesite lava (e.g. Rotokawa) or greywacke (e.g. Kawerau). However in ignimbrite-dominated geothermal fields such as Wairakei-Tauhara, Mangakino and Mokai, formation-hosted permeability plays a much greater role in providing pathways for production fluids than faults/fractures.

Here, we present results primarily from the Mokai Geothermal Field where from 2003 to 2004, GNS Science (along with a small geoscientific/drilling team including MAGAK, SKM and GCNZL) provided advice for well targeting and design of 6 wells (MK10 - MK15) in the southern part of the field. The 6 wells were drilled to supply steam for the second stage of power station development, in conjunction with the landowners - Tuaropaki Trust.

The first well (MK10) was deviated to intersect a likely fault (prognosis by SKM Ltd.), but completion test and drilling data showed that the production zones were located at a formation boundary and within an ignimbrite, rather than through an unequivocally defined fault/fracture plane (Figure 1). As the MK10-MK15 project progressed, cumulative drilling and completion data encouraged revised permeability targets that favoured likely *intra*-formational fractures and bulk-rock permeability, and *inter*-formational contacts where brecciated rock was inferred to provide fluid pathways. Zones of production potential were consistently found within Ignimbrite D, at the contact of Ignimbrite D and Whakamaru Ignimbrite, within Whakamaru Ignimbrite and deeper, at the contact between volcaniclastic sediments and Ignimbrite F (c.f. Wood & Rosenberg, 1998) (Figure 2).

2. STRATIGRAPHY

All wells in the 2003-2004 Mokai drilling project exceeded the 1245 mVD (vertical depth) drilled by MK12, with the deepest wells (MK11, MK14 and MK15) being over 2000 mVD

A study of drillcuttings and drillcore from each of the wells was carried out by GNS Science, which built on a good understanding of the stratigraphy and inferred structure of the southern part of the Mokai Geothermal Field from previous DSIR and IGNS studies of MK3 (Wood, 1983a), MK5 (Wood, 1983b), MK6 (Wood, 1984) and MK7 (Wood & Rosenberg, 1998).

The stratigraphy is dominated by a sequence of variably welded ignimbrites, rhyolite lavas, pumiceous fall deposits and volcaniclastic sediments (Kilgour & Rosenberg, 2004a; 2004b; 2004c; Rosenberg & Kilgour, 2004a; 2004b).

Ignimbrite D is a weakly welded ignimbrite. It is >250 m thick, and recognised only in Mokai geothermal wells. The absolute age has not been determined and its stratigraphic position affords only a relative age of <320 ka (Wilson et al., 1995). The ignimbrite is pumice-rich, and crystal- and lithic-poor. The crystal fraction is dominated by feldspar with subordinate partially resorbed quartz. Lithic fragments in the ignimbrite include rhyolite lava, mafic lava and rare granitoid rock.

Whakamaru group ignimbrites are regionally extensive, in surface outcrop and at depth in all explored geothermal fields in the central part of the Taupo Volcanic Zone. The ages of the ignimbrites are ~340 - 320 ka and their cumulative volume exceeds 1000 km^3 (Wilson et al., 1995). In MK10-MK15, the nominal Whakamaru Ignimbrite has two distinct welding zones: 1) an upper ~250 m porous and non-welded zone and 2) a dense and strongly welded zone up to ~350 m thick.

A unit of strongly indurated volcaniclastic sandstone and siltstone was encountered below the Whakamaru Ignimbrite in MK11, MK13, MK14 and MK15. The unit is relatively impermeable and may provide sufficient contrast in texture to the ignimbrites above and beneath to focus fluid flow in lateral directions.

Ignimbrite F was encountered in only the deepest of the six wells (MK14, MK15, and possibly M11). This rock is a hard, dense, welded ignimbrite with a lenticular fabric, low crystal content (feldspar, quartz, pyroxene and accessory zircon) and common greywacke, mafic lava and rhyolite lava lithic fragments throughout. High rock strength and hardness make fracture dominated permeability likely, although evidence from MK14 and MK15 favours at least some inter-formational feed zones.

3. HYDROTHERMAL ALTERATION

Hydrothermal alteration minerals present in the southern part of the Mokai Geothermal Field exhibit a general sequence of argillic alteration (smectite, illite/smectite, hematite, calcite and quartz) overlying a higher rank propylitic mineral assemblage, including chlorite, illite, calcite, epidote, wairakite and quartz. The transition between the two alteration assemblages occurs at ~500 drilled depth (close to the boundary between an undifferentiated package of tuffs and Ignimbrite B).

Completion test formation temperature data (Grant, 2004) and the distribution of hydrothermal mineral indicators of reservoir temperature are in good agreement. For example, epidote is present in varying proportions (from ~550 mVD) as a replacement of plagioclase and ferromagnesian minerals. Its occurrence and habit implies formation temperatures >260° C (Browne and Ellis, 1970). Well temperatures reach and exceed 300° C in several wells.

In the production part of the Mokai wells, zones of intense propylitic alteration occur where the ignimbrites are non-welded to partially welded (e.g. Ignimbrite D; in the non-welded zone of Whakamaru Ignimbrite; and in Ignimbrite F). These intensely hydrothermally altered zones are characterised by common chlorite and epidote, and sporadic illite, calcite and quartz. In contrast, the welded zone of the Whakamaru Ignimbrite is weakly altered, with fractures/joints commonly filled by epidote and chlorite.

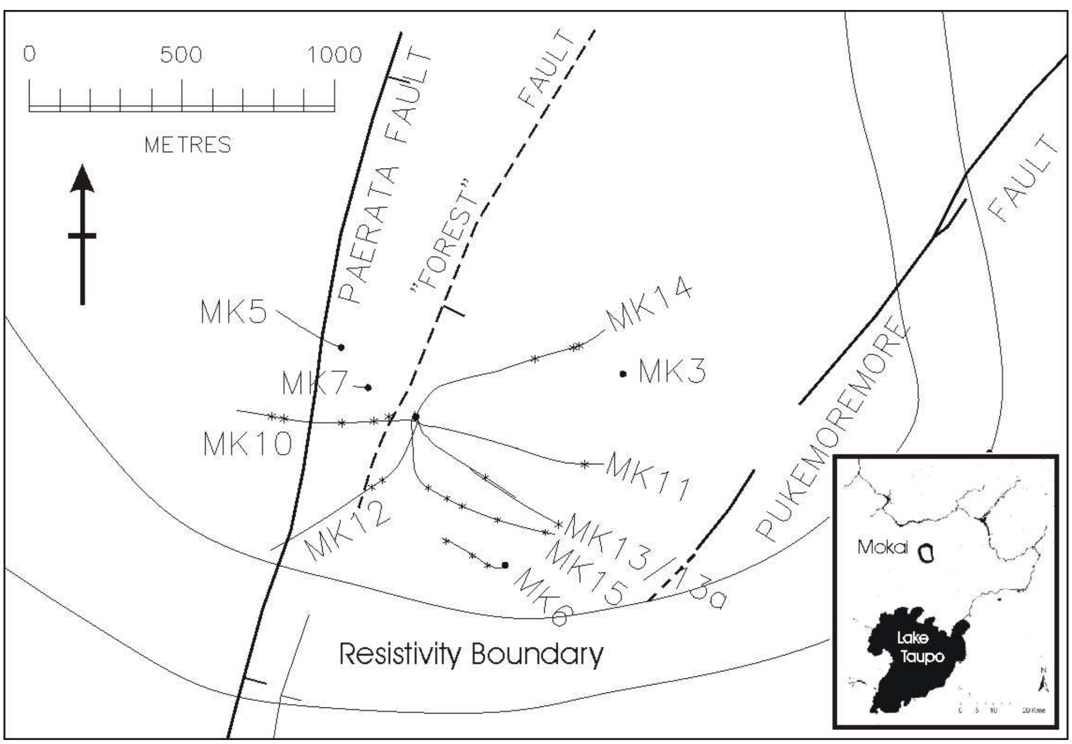

Figure 1. Location of MK10-MK15 as part of the 2003-2004 drilling program at Mokai Geothermal Field. Nearby existing wells and surface fault traces are also shown. Stars indicate production zones determined by completion tests.

4. FEEDZONE LOCATIONS

Based on completion test data (Grant, 2004) and geological logging of cuttings and core, the location of major feedzones in Mokai wells MK10-MK15 were correlated with Ignimbrite D, Whakamaru Ignimbrite and Ignimbrite F, and the boundaries between these rock units. Using MWD survey data we plotted the 3-d location of feedzones in these wells, and by doing so discounted a common fault plane as the source of the major feedzones. Therefore, as the well programme progressed, greater understanding of the location of feedzones allowed us to target formation-hosted permeability in preference to targeting faults It is important to note, although permeability appears mostly to be formation-controlled at Mokai, that there is inherent diversity within the productive rock units and as a consequence each well encountered variable success (as measured by mass flow output)

Feedzones located in Ignimbrite D occur throughout the formation and it is likely that the ignimbrite has significant bulk permeability as evidenced by the high (25 – 30%) apparent porosity measured from Ignimbrite D (Kilgour & Rosenberg, 2004a). The ignimbrite does not have zones of significant hydrothermal veining, and instead, the pervasive nature of the alteration implies that the rock matrix is permeable.

Two distinct permeability pathways were identified through the Whakamaru Ignimbrite by completion testing. The non-welded upper zone is pervasively altered and hosts feedzones throughout, probably due to its inherently high bulk porosity. The densely welded zone of the Whakamaru Ignimbrite is weakly altered, due to its relatively impermeable matrix. Joint patterns in surface outcrop point to well feedzones in the welded zone being restricted to the zones of inferred discrete, sub-vertical joint sets, created during post-emplacement cooling. Both the non-welded and welded zones of the ignimbrite provide feedzones to MK10, MK13 and MK15, whilst only the non-welded zone contributes fluid in MK7 and MK12, and the welded zone solely in MK5 and MK14.

A package of volcaniclastic sediment immediately underlying the Whakamaru Ignimbrite is moderately consolidated and in parts, pervasively silicified. The measured bulk porosity is relatively low. but there are no obvious signs of hydraulic or other fracturing seen in core from this unit to account for enhanced permeability within a upper few tens of metres of this formation in MK15. It is likely that the permeable zone is more likely related to the contact between the sediments and the overlying ignimbrite, rather than the inherent permeability of the sediments themselves.

Ignimbrite F is a densely welded ignimbrite that does not exhibit variations in welding intensity over its drilled depth (>270 m in MK14). This ignimbrite hosts extensive sub-vertical veinlets and veins (seen in core) that are filled by chlorite and epidote. The width of veins (and therefore fractures) ranges from <1 mm up to 3 mm wide which, given the low bulk porosity of the ignimbrite, is likely evidence of fluid channelled through these fracture sets.

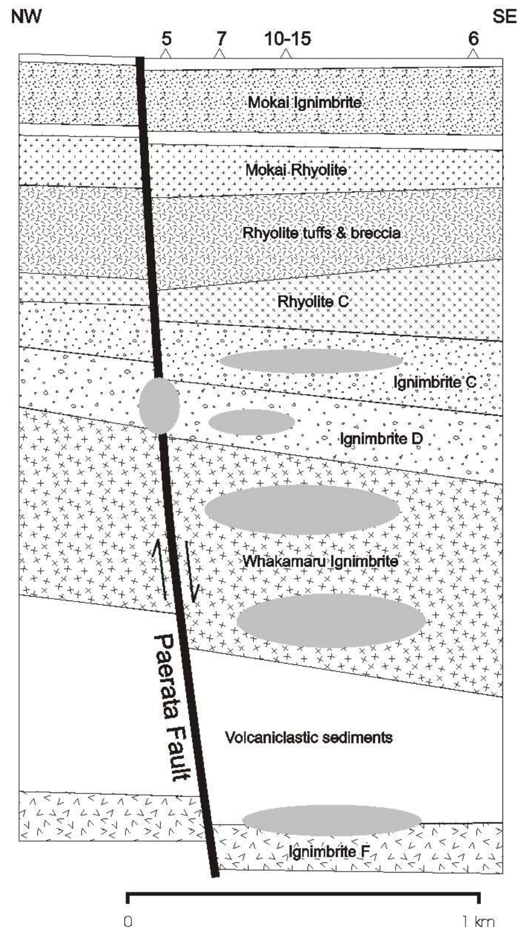

Figure 2. Indicative cross section, of the southern part of the Mokai Geothermal Field using data from the 2003-2004 drilling program. Light grey zones are indicative locations of productive feedzones encountered in one or more wells.

5. DISCUSSION

The 2003-2004 drilling at Mokai Geothermal Field has afforded reinterpretation of the location and rlithological controls on permeability in ignimbrite-dominated geothermal fields. Prior to the 2003-05 Mokai drilling programme, MK5 was considered to derive its main production from feeds in the Paerata Fault (Wood, 1983b). However, the 2003-2004 drilling program (MK12 and MK10 in particular) tested that assumption, and showed that not all wells deviated towards this fault target have production zones coinciding with the inferred fault plane. It could be that the fault is structurally inactive and partially mineral-sealed, as the completion test data for MK10 showed that permeability coincides with inherent bulk rock permeability in the ignimbrite, rather than a steeply dipping fault plane.

Soengkono (2000) provided an assessment of the fault structure at Mokai Geothermal Field. That study showed that there are three main faults, oriented NW, N and NE. The faults were considered to be supplying the main upflow for the geothermal field.

In asserting that most of the feedzones encountered in MK10-MK15 are related to formation-hosted permeability, it is necessary to examine the potential for common lithological characteristics and/or the location of feedzones at similar stratigraphic positions within each ignimbrite. The lithological characteristics of Ignimbrite D throughout MK10-MK15 are similar, i.e., there are no significant alteration and/or lithological differences that could account for the variation in feedzone potential. The results from Ignimbrite D indicate that feedzones are randomly distributed throughout the ignimbrite. For example, feedzones in MK7 are located throughout the ~300 m thickness of Ignimbrite D; in MK10 and MK12 feedzones are limited to the upper part of the ignimbrite; while in MK13, MK14 and MK15, feedzones are located throughout the ignimbrite, but make negligible contribution to the well flow. In MK5, major feedzones occur in a narrow depth interval, within Ignimbrite D, and have been attributed to the well intersecting the Paerata Fault (Wood, 1983b).

Formation-hosted permeability located in the Whakamaru Ignimbrite can be delineated into two separate locations and types. There is no compelling evidence to suggest feedzones located in either welding zone are related to the Pukemoremore Fault (Figure 1) in the southern part of Mokai Geothermal Field. Due to the non-welded nature of the upper part of the ignimbrite, the primary flow in this zone is likely to be relatively consistent throughout. The high bulk porosity is inferred to allow continuous flow (assuming limited mineralisation). However, the sub-vertically fractured welded zone is likely to provide rapid flow along fracture/joint spaces.

Only MK11 and MK15 were drilled deep enough wells to intersect Ignimbrite F (the deepest formation encountered). Previously, MK6 had also reached Ignimbrite F and also found contributing feedzones throughout this ignimbrite. The nature of this welded ignimbrite is of an intensely fractured (and hence veined) rock with sub-vertical to sub-horizontal fracture planes. Therefore, similar to the densely welded zone of the Whakamaru Ignimbrite, Ignimbrite F is likely to host relatively rapid vertical flow with limited horizontal flow. Due to the limited number of wells that have intersected Ignimbrite F, the thickness of this unit is difficult to assign, however according to the results from MK11 and MK15, this ignimbrite is at least 100 m thick.

Future drilling at Mokai Geothermal Field could be economically achieved in a similar way to the 2003-2004 drilling program, ie. a single wellpad with a number of deviated well tracks. This type of drilling program enables a number of targets to be explored in various locations of the field whilst still producing from consistently productive formations, such as Ignimbrite D and Whakamaru Ignimbrite. Furthermore, drilling at a similarly ignimbrite dominated field eg. Wairakei-Tauhara and possibly Mangakino could be explored with a number of deviated wells from one well pad. As MK10-MK15's drilling program progressed, it was possible to refine targets based on lithology and alteration mineralogy and recently acquired completion test data.

Completion test data provided an estimate of the production potential for each well. All wells in this program were moderate to very good producers, ranging from 100 to 300 t/h steam capacity. All wells have less potential output than MK5 (~450 t/h).

6. SUMMARY

The 2003-2004 drilling programme at Mokai Geothermal Field resulted in the completion of six productive geothermal wells (MK10-MK15) to a maximum depth of -1747 mRL.

Each well encountered feedzones that were related to distinct formation permeability and/or permeability related to the margins of rock units. Some productive zones were common between wells, but others differed possibly due to local lithological conditions.

MK10-MK15 provided new information on the location and character of formation-hosted permeability in an ignimbrite-dominated geothermal field. The results from the drilling programme show that it is viable to target permeable formations as the most prospective, and/or secondary target, compared to fault-related permeability.

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8. REFERENCES

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

Grant, M.A. 2004. MK10 to MK15 completion test reports: November 2003 – July 2004. MAGAK consultant reports to Tuaropaki Trust.

Kilgour, G.N., Rosenberg, M.D. 2004a. Geology of production well MK10 at Mokai Geothermal Field. GNS Client Report 2004/42.

Kilgour, G.N., Rosenberg, M.D. 2004b. Geology of production well MK11 at Mokai Geothermal Field. GNS Client Report 2004/43.

Kilgour, G.N., Rosenberg, M.D. 2004c. Geology of production well MK12 at Mokai Geothermal Field. GNS Client Report 2004/44.

Rosenberg, M.D., Kilgour, G.N. 2004a. Geology of production wells MK13 and MK15 at Mokai Geothermal Field. GNS Client Report 2004/145.

Rosenberg, M.D., Kilgour, G.N. 2004b. Geology of production wells MK14 at Mokai Geothermal Field. GNS Client Report 2004/46.

Soengkono, S. 2000. Assessment of faults and fractures at the Mokai Geothermal Field, Taupo Volcanic Zone, New Zealand. Proceedings of the World Geothermal Congress, Japan.

Wilson, C.J.N., Houghton, B.F. McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M. 1995. Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. Journal of Volcanology and Geothermal Research 68:1-28.

Wood, C.P. 1983a. Stratigraphy and petrology of MK3 Mokai Geothermal Field. N.Z. Geological Survey Report.

Wood, C.P. 1983b. Stratigraphy and petrology of MK5 Mokai Geothermal Field. N.Z. Geological Survey Report.

Wood, C.P. 1984. Stratigraphy and petrology of MK6 Mokai Geothermal Field. N.Z. Geological Survey Report.

Wood, C.P., Rosenberg, M.D. 1998. Geology of production well MK7 at Mokai Geothermal Field. GNS Science Client Report 71775C.10A.