WHAT DEFINES A SEPARATE HYDROTHERMAL SYSTEM?

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SUMMARY - Separate hydrothermal systems can be defined in a variety of ways. Criteria which have been applied include separation of heat source, upflow, economic resource and geophysical anomaly. Alternatively, connections have been defined by the effects of withdrawal of economically useful fluid and subsidence, effects of reinjection, changes in thermal features, or by a hydrological connection of groundwaters. It is proposed here that: "A ***separate hydrothennal system is one that is fed by a separate convective upflow of fluid, at a depth above the brittle-ductile transition for the host rocks, while acknowledging that separate hydrothennal system can be hydrologically interconnected at shallower levels***".

1.0 INTRODUCTION

To a large extent the problem of establishing if adjacent hydrothermal systems are separate is one of definition. Although there have been numerous papers describing the boundaries of hydrothermal systems, surprisingly little attention has been given to the question of what constitutes a separate system. In relation to the numerous systems of the Taupo Volcanic Zone (TVZ), comments relevant to the topic have been made by Houghton *et al.* (1980), Bixley (1994) and Bibby *et* al. (1995). Despite this, it is difficult to find a clear definition in the literature. Yet this is becoming an important topic in New Zealand, as the Resource Management Act (RMA) forces potential developers to address questions of interference and sustainability.

2.0 DISCUSSION

Part of the difficulty is that it is necessary to state what is being defined quite closely. For example, there may well be different answers to the following questions:

1. Are systems A and B supported by the same heat source?

2. Are systems A and B fed by separate upflow zones?

3. Are areas A and B part of the same economic resource?

4. Do areas A and B lie within the same geophysical anomaly?

5. Will exploitation of area A withdraw economically useful fluid from area B?

6. Will reinjection from area A detrimentally affect area B?

7. Will exploitation of area A cause detectable effects such as subsidence or changes in thermal activity at field B?

8. Are areas A and B hydrologically connected though groundwater?

All of these criteria have been used at different times to demonstrate "interconnectedness" of adjacent hydrothermal systems, without necessarily clearly defining the term "interconnectedness". This can lead to the inappropriate application of scientific statements, otherwise quite valid in context, to legalistic definitions, as required for instance under the RMA.

Consider, for example the review of the New Zealand thermal areas by Houghton *et al.* (1980), whose paper has been widely quoted when comparing the relative conservation importance of different thermal areas, and has become almost a de *facto* standard for that purpose. From the conservation aspect, most views stated in that paper would probably be widely supported. At the same time, the paper suggests a degree of interconnectedness of some geothermal fields (e.g. Whakarewarewa-Tikitere; Rotokawa-Wairakei; Waimangu-Waiotapu-Reporoa-Waikite-Lake Tarawera-Golden Springs-Paukohurea; Ohaaki-Ngatamariki), that we consider to be an extreme point of view. Nevertheless, it is difficult to demonstrate that the interconnections suggested are not correct, because the criteria and evidence for "connection" are not stated, except in the case of Waimangu-Waiotapu.

We offer for consideration the following definitions and criteria, with the numbering in the following paragraphs relating to the questions raised above, and where appropriate using the Wairakei-Tauhara and Orakeikorako-Te Kopia geothermal areas as convenient case studies:

1. Interconnection of Heat Sources

At some depth, the heat sources for all of the hydrothermal systems of the TVZ are connected. However, this is at such great depth that exploitation of any particular field will not detract from the heat available to any other field. Bibby *et al.* (1995) suggest that this is at about 8 km, which they consider to be the maximum depth to which meteoric water penetrates. Thus this criterion becomes trivial, since exploitation at a much shallower level is most unlikely to affect the heat source at this depth. Even though the TVZ is anomalous on a world scale in terms of the close spacing of geothermal systems within it (Hochstein *et* al., 1993, Lawless *et al.,* 1995), a similar situation probably applies to the other great geothermal provinces worldwide.

2. Separate Upflows

When considering the "upflow zone" of a hydrothermal system, it is necessary to define the depth to which one is referring. Consider the example of the Wairakei-Tauhara area. Isotherms to drilled depth make it clear that despite the proven hydrological connections between the fields, Wairakei and Tauhara are fed by separate upflows with one associated with Mt. Tauhara (Dawson 1988), with that at Wairakei concealed by the largely impermeable Wairakei Ignimbrite. At a shallower level, the Wairakei field is probably fed by a number of separate, smaller upflows as fluid percolates where it can through the Wairakei Ignimbrite. Elsewhere, Bignall (1994) used mineralogical and fluid inclusion data to suggest that the Orakeikorako and Te Kopia geothermal areas may have a single, major upflow zone at some depth, with an interconnection that is presently less clear at the surface.

We propose the definition that:

"A separate hydrothennal system is one that is fed by a separate convective upflow of fluid, at a depth above the brittle-ductile transition for the host rocks (ie a temperature of about 330 °C in the TVZ (Sibson, 1989)), ***while acknowledging that separate hydrothennal systems can be hydrologically interconnected at shallower levels".***

The reason for defining the depth as the brittle-ductile transition is that this probably represents the limit of active, rapid downward percolation of groundwater and its convective upflow when heated. Pressure disturbances above this level in response to exploitation are unlikely to significantly propagate below this level, so in this restricted sense we are defining systems with separate heat sources. On this basis, Wairakei and Tauhara are probably separate systems, though hydrologically interconnected at a shallow level; Orakeikorako-Te Kopia may be one system, with presently little evidence of interconnection at shallow depths, Ohaaki is probably a single system, though with the East and West Bank upflows having separated at considerable depth; and Rotokawa and Wairakei are definitely separate systems.

Table 1
Connections Between TVZ Fields
on the Basis of Separate Upflows of Hot Fluid

	Tokaanu-Waihi	L. Taupo	Wairakei	Tauhara	Mokai	Mangakino	Rotokawa	Ohaaki	Ngatamariki	Orakei-Korako	Waikite	Te Kopia	Reporoa	Waiotapu	Rotorua	L. Rotorua	Tikitere	L. Rotoiti	Taheke	Tarawera-Rotoma	Kawerau
Ketetahi	O																				
Tokaanu-Waihi																					
L. Taupo																					
Wairakei																					
Tauhara																					
Mokai																					
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Rotorua																					
L. Rotorua																					
Tikitere																		O	O		
L. Rotoiti																			O		
Taheke																					
Tarawera-Rotoma																					

Key: ● Connection highly probable using this criterion
O Connection possible but unproven using this criterion

3. Connection of Economic Resources

What constitutes the economic resource of a hydrotherm-' system is the heat contained in the rocks, and to a less extent in the fluid, above a base temperature defined by economic limits and with a depth constrained by drilling limitations. A typical value for the base temperature for electricity generation, even if binary-cycle technology is to be used, would for most fields be over 180 °C. The applicability of a lower limit for non-electrical uses is acknowledged, but even so there are limits imposed on practical exploitation by silica deposition. The practical economic limit for drilling is about 3000 m vertically. The only way in which exploitation of one economic resource can directly subtract from another, therefore, is if the two areas form part of a contiguous body of hot rock, at economic drilling depth, above the base temperature.

On this basis Wairakei and Tauhara would marginally be considered part of the same resource, because temperatures in the area between them probably exceed

180 °C, though at greater depth than has yet been drilled. In the case of the Orakeikorako-Te Kopia area, the distinction is less clear as no drilling has been carried out in the intervening area. Certainly there are fossil geothermal manifestations between the present active areas at Orakeikorako and Te Kopia, although there is now a 'gap' of about 6 km that lacks any surface expression of an unproven hydrothermal interconnection between the two areas (Bignall, 1994).

Table 2
Connections Between TVZ Fields on the Basis of Separate Economic Resources

	Tokaanu-Waihi	L. Taupo	Wairakei	Tauhara	Mokai	Mangakino	Rotokawa	Ohaaki	Ngatamariki	Orakei-Korako	Waikite	Te Kopia	Reporoa	Waiotapu	Rotorua	L. Rotorua	Tikitere	L. Rotoiti	Taheke	Tarawera-Rotoma	Kawerau
Ketetahi	○																				
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Wairakei				●																	
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Te Kopia																					
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Rotorua																					
L. Rotorua																					
Tikitere																		○	○		
L. Rotoiti																			○		
Taheke																					
Tarawera-Rotoma																					

Key:
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○ Connection possible but unproven using this criterion

4. Geophysical Boundaries

A variety of geophysical "boundaries" have been used for different systems. These have been primarily resistivity boundaries, but magnetic anomalies have also proven significant (*e.g.* Soengkono *et al.*, 1993). When discussing the resistivity boundaries of adjacent areas, it is once again necessary to define the depth. For example, early shallow-penetrating surveys showed Wairakei and Tauhara to be separate, whereas later surveys demonstrated a connection at greater depth (Risk *et* al., 1984). In contrast, early surveys in the Waimangu-Waiotapu area could not disprove a connection as suggested by Houghton *et* al. (1980), but later surveys show a connection is unlikely (Bibby *et* al., 1995). However, given the potential for MT surveys to penetrate to depths at which all of the fields of the TVZ are undoubtedly connected by low resistivity, it is important to restrict considerations of interconnectedness on the basis of resistivity to no greater than economic drilling depth (*e.g.* Ingham, 1989) and certainly the Te Kopia area has been shown to be clearly linked to the northeast with thermal areas at Waikite (Bromley, 1992).

The most cogent point is that, while resistivity surveys are often taken to be a good indicator of the economic boundaries of a hydrothermal system there is not necessarily a direct correlation due to the possible presence of relict alteration. However, zones of high resistivity at economic depth lying between adjacent areas are probably good evidence they do not constitute the same economic resource and are probably not hydrologically connected except through groundwater.

Magnetic anomalies produced by demagnetisation are another geophysical method that can delineate hydrothermal systems, but as with resistivity the effect is a cumulative one and may not necessarily link systems which are active at the same time. The presence of a concealed non-magnetic body elongated in the SW-NE direction appears to be connecting Orakeikorako-Te Kopia (Soengkono et *al.*, 1993). Wairakei and Tauhara are also linked by an area of demagnetisation (Soengkono and Hochstein, 1992).

Table 3
Connections Between TVZ Fields on the Basis of Geophysical Boundaries

	Tokaanu-Waihi	L. Taupo	Wairakei	Tauhara	Mokai	Mangakino	Rotokawa	Ohaaki	Ngatamariki	Orakei-Korako	Waikite	Te Kopia	Reporoa	Waiotapu	Rotorua	L. Rotorua	Tikitere	L. Rotoiti	Taheke	Tarawera-Rotoma	Kawerau
Ketetahi																					
Tokaanu-Waihi																					
L. Taupo																					
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Mokai																					
Mangakino																					
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Ohaaki																					
Ngatamariki																					
Orakei-Korako												○									
Waikite												○									
Te Kopia																					
Reporoa														○							
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Rotorua																					
L. Rotorua																					
Tikitere																		○	○		
L. Rotoiti																			○		
Taheke																					
Tarawera-Rotoma																					

Key:
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○ Connection possible but unproven using this criterion

5. Inter-Connection of Economically-Useful Fluid

Two fields can be considered to be interconnected on this basis if withdrawal of hot fluids from one area will cause hot fluid to migrate to it from the other area. On this basis Wairakei-Tauhara are definitely part of the same economic resource, since pressure response and subsidence have occurred at Tauhara in response to exploitation (Allis, 1983) and it can be assumed that there has been flow of hot fluid from Tauhara to Wairakei. In contrast, while the substantial withdrawal of fluid from Rotorua has had significant effects on the Rotorua system itself, there is no evidence that it has withdrawn fluid from Tikitere and on this basis the connection suggested by Houghton et al., (1980) appears unfounded.

Table 4
Connections Between TVZ Fields on the Basis of Separate Economic Resources

	Tokaanu-Waihi	L. Taupo	Wairakei	Tauhara	Mokai	Mangakino	Rotokawa	Ohaaki	Ngatamariki	Orakei-Korako	Waikite	Te Kopia	Reporoa	Waiotapu	Rotorua	L. Rotorua	Tikitere	L. Rotoiti	Taheke	Tarawera-Rotoma	Kawerau
Ketetahi	○																				
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6. Reinjection Effects.

This criterion is somewhat different from the others, since it depends on what strategy is adopted for reinjection and is therefore under human control to a greater extent. For example there is the possibility that a decision will be made to deliberately reinject outside of the field, such that an adjacent field may be affected without there actually being any pre-existing connection. There are several separate but related issues to be considered: whether fluid will return from reinjection from exploitation of one field to the production area of another; how one would detect the arrival of such fluid, and whether the return of fluid causes any detrimental effects.

In relation to the first point, it is difficult to provide a definitive answer in advance of reinjection starting. Where tracer tests provide evidence for strongly anisotropic permeability, as at Otake-Hatchobaru in Japan (Inoue and Shimada, 1985), the rapid return of reinjected fluid can confidently be predicted if two adjacent fields lie along the geological structural grain. Where permeability is much more nearly isotropic, as at Wairakei-Tauhara, the return of reinjected fluid appears less likely, but it is not possible to give a definite assurance that it will not occur.

In relation to the second point, there is now accumulating a body of experience in the chemical detection of reinjection "fronts" in various fields worldwide (*e.g.* Malate and O'Sullivan, 1990, Seastres et al., 1995). The chemical signature of primary reservoir fluid and reinjected fluid are sufficiently different that they can generally be distinguished and mixing calculations done. The addition of chemical tracers can also yield additional useful information (*e.g.* Adams, 1995).

The question of whether reinjected fluid will cause detrimental effects to another resource is really one of time scale. The return of reinjected fluid, per se, is not necessarily harmful and may be beneficial in terms of maintaining reservoir pressures. Given that most of the heat in a geothermal resource is contained in the rocks, there is a need to re-cycle some fluid to extract it. Careful selection of reinjection strategy is part of the art of long-term reservoir management (Bernavidez et *al.*, 1985). Detrimental effects will only occur if the reinjected fluid returns to the production area rapidly enough that it does not become heated. This has taken place at Otake-Hatchobaru, as mentioned above (Inoue and Shimada, 1985). There is not enough history of reinjection in New Zealand to provide examples of the detrimental return of reinjected fluid.

7. Subsidence and Changes in Thermal Activity

It is clear from the example of Wairakei-Tauhara that subsidence in response to fluid withdrawal can take place over a wider area than would be predicted on the basis of the resistivity "boundary" of the field (Allis *et* al., 1989). However, it is a moot point whether such large-scale fluid withdrawal as has happened at Wairakei without reinjection would ever be permitted again. For future developments the net fluid withdrawal should be much less, and the extent of subsidence can probably be predicted with reasonable accuracy (Narasimhan and Goyal, 1984), although it should be noted that this has not been the experience at Ohaaki (Clotworthy *et* al., 1995).

With regard to changes in thermal activity, such effects can only occur if there is net transfer of heat or fluid from one field to another, with a resulting impact on field pressures. Thus this criterion can be expressed in terms of those already discussed. It can however yield useful additional information or corroborative evidence, as in the example of Wairakei-Tauhara, where Allis *et al.* (1989), on the basis of a lack of these effects in the Southern part of the field, postulate that there are two separate systems at Tauhara. A related issue is how induced changes in thermal activity can be distinguished from "natural" changes. This is a point of particular contention at Ngawha, where the thermal features have exhibited both considerable long- and short-term variation (Lawless 1993).

Table 5
Connections Between TVZ Fields on the Basis of Separate Upflows of Potential Surface Effects

	Tokaanu-Waihi	L. Taupo	Wairakei	Tauhara	Mokai	Mangakino	Rotokawa	Ohaaki	Ngatamariki	Orakei-Korako	Waikite	Te Kopia	Reporoa	Waiotapu	Rotorua	L. Rotorua	Tikitere	L. Rotoiti	Taheke	Tarawera-Rotoma	Kawerau
Ketetahi	○																				
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Ngatamariki																					
Orakei-Korako												○									
Waikite												○									
Te Kopia																					
Reporoa														○							
Waiotapu																					
Rotorua																					
L. Rotorua																					
Tikitere																		○	○		
L. Rotoiti																			○		
Taheke																					
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Key:
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8. Connection Through Groundwater

If one were to take the widest possible definition of connection of groundwater, then the only geothermal system in the TVZ which is *not* connected to the others might be Ketetahi, simply on the basis of elevation, although it has been suggested that the Tokaanu system is an outflow of Ketetahi (Robinson and Sheppard, 1986). It would be better, perhaps, to restrict this criterion by asking whether the shallow hydrology of adjacent areas is sufficiently connected that detectable changes in groundwater would be apparent on a human time scale in response to the largest conceivable artificial fluid withdrawal. This could be fairly easily evaluated by the Theiss equation. This is in contrast to the statement made in this context by Houghton *et* al. (1980: p 7), that: "Anything that changes ground water level is likely to affect hydrothermal system." It should be noted, however, that those authors follow that statement with a number of examples that do clearly demonstrate that in particular cases modification of the groundwater regime has affected surface hydrothermal activity (though not necessarily the underlying economic resource). It is also of interest to note the situation at Tauhara where despite changes in the thermal features and deep reservoir pressures much of the groundwater has been unaffected because it is perched.

3.0 CONCLUSIONS

The question of whether adjacent geothermal areas are connected, and thus constitute a 'single' system, is critically dependant on the definition used for "connectedness". We have proposed a definition of what constitutes a separate upflow zone, but this is not a sufficient basis for all questions that might be asked for the purposes of resource management. The accompanying tables present our current opinion regarding the degree of interconnectedness of the geothermal fields of the TVZ for different criteria. It is hoped that presentation of the criteria in this way will stimulate further discussion. Note that criteria (1) and (7) above, regarding connection to the ultimate heat source at depth, and connections through groundwater respectively, have not been included in these tables because on the basis of these criteria applied in the widest sense, all fields in the TVZ are connected to some extent. Criterion (6) has also not been included as there is an insufficient history of reinjection in the TVZ to be able to make useful assessments.

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