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The Geothermal Potential of the West Coast Region, South Island, New Zealand

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ABSTRACT

The North Island of New Zealand is renowned for its high temperature geothermal resources utilized for electricity generation, direct use applications and tourism. However, the South Island also has geothermal resources, albeit at lower temperatures, that manifest as warm springs at several locations within the mountainous Southern Alps. These are currently used for bathing, from non-commercial pools to tourist-level commercial developments. With the New Zealand Government encouraging regional development and use of renewable energy sources, local stakeholders of South Island West Coast Region are investing to assess and quantify the geothermal resources for potential use.

The western Southern Alps are characterized by steep relief, high mountains and deep river valleys. The mountain ranges are densely vegetated, with remote and isolated areas covered in native forest. The area is sparsely populated with most settlements on the western side of the mountain range. Sedimentary basins west of the Alpine Fault also offer potential for heat use, albeit with lower temperatures and thermal gradients. While rich in coal resources, development of geothermal energy for direct heat use and small local electricity generation would secure local energy supplies and promote some economic development in the region.

Two geothermal domains have been identified for the West Coast Region, that being the Alpine Fault domain and the Sedimentary Basin domain. Using the geological and structural characteristics from both, along with fluid flow estimates and heat source processes, as they are currently understood, geospatial analysis of each domain has identified the most prospective geothermal areas. With a focus on usability of the resource, other spatial parameters considered in the analysis include potential surface limitations, such as steep local topography, land-use, land-cover, land-ownership, conservation status, and distance to heat prospects. Energy demand estimates and supply temperature requirements are also important considered parameters.

This paper shows how GIS geospatial analysis can be a useful tool for defining and prioritizing geothermal prospect areas. However, the analysis is underpinned by well developed geoscientific conceptual models, along with clear understandings of end-user energy requirements and surface infrastructure and land constraints. The preliminary investigation on the West Coast identified and substantiated possible utilization of low temperature (<160°C) geothermal heat with potential end-uses for the region.

1. INTRODUCTION

The North Island of New Zealand is renowned for its high temperature geothermal resources utilized for electricity generation, direct use applications and tourism. However, the South Island also has lower temperature geothermal resources that manifest as warm springs at a number of locations within the mountainous Southern Alps. These are currently used for bathing, ranging from non-commercial pools to tourist-level commercial developments. With the New Zealand Government encouraging regional development and use of renewable energy sources, local stakeholders of the South Island West Coast Region are investing to assess and quantify the geothermal resources for potential geothermal use.

The Southern Alps are bounded to the west by the Alpine Fault, an active transpressional fault between the Australian and Pacific Plates. The landscape and geohydrology of the West Coast Region are dominated by the Alpine Fault, as the combination of tectonic (i.e., rapid uplift) and surface processes (i.e., rapid erosion) resulting from the collision of the tectonic plates have produced regions on both sides of the Alpine Fault with elevated subsurface geothermal temperature gradients (>30°C/km).

The West Coast climate is dominated by the orographic rainfall effect of the Southern Alps, which strongly influences erosion rates. The mountains perturb the prevailing moisture-laden westerly winds, causing orographic rainfall on the western side of the Alpine range, leading to an extreme contrast in precipitation between the western and eastern sides of the ranges (Griffiths and McSaveney 1983; Henderson and Thompson 1999; Tait and Turner 2005). West of the ranges experiences rainfall in excess of 10 m/yr, resulting in erosion rates along the base of the mountains, adjacent to the Alpine Fault, sufficient enough to maintain an approximately steady state sea-level elevation despite the rapid uplift rates (Koons 1990; Norris et al. 1990). Consequently, the western Southern Alps are characterized by steep relief, high mountains and deep river valleys. The mountain range is densely vegetated, with remote and isolated areas covered in native forest. The area is sparsely populated with most settlements on the western side of the mountain range. Development of geothermal energy for direct heat use and small local electricity generation would secure local energy supplies and promote some economic development in the region.

2. WEST COAST GEOLOGY

The South Island of New Zealand marks the tectonic plate boundary between the Pacific and Australian plates (Figure 1 inset), where strike-slip (~39 mm/yr) and convergent (7-9 mm/yr) motions are engaged at the Alpine Fault (DeMets et al. 1994; Norris and Toy

2014). In the north of the island, plate motion is split into a set of smaller dextral strike-slip faults, known as the Marlborough Fault System, which transfers displacement between the Alpine Fault and the Hikurangi subduction zone to the northeast (Figure 1, inset) where westerly subduction of the Pacific plate occurs. In the south, the Alpine Fault diverges from the western coastline as plate motion becomes predominantly convergent with the eastwards subduction of the Australian Plate beneath the Pacific Plate.

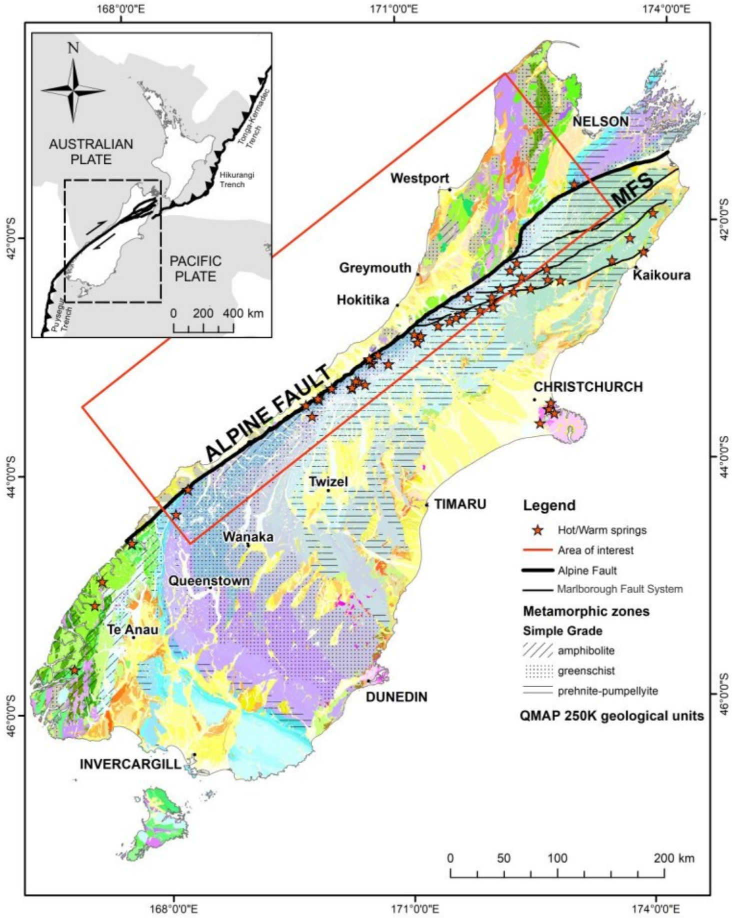

Figure 1: Simplified geological map of the South Island with the major faults and hot spring locations highlighted ((c) GNS Science 2018). This study's area of interest is within the red polygon. MFS = Marlborough Fault System. Inset: plate boundary setting. For the full geological map codes, refer to https://data.gns.cri.nz/geology/.

The eastern side of the Alpine Fault (Pacific Plate) is largely composed of sedimentary rocks deposited off the continental edge of Gondwana in the Late Carboniferous to Late Cretaceous periods (Cox and Barrell 2007). These rocks have been metamorphosed to varying degrees and are currently being deformed at the current plate convergence where deep crustal rocks are uplifted as the hanging wall to the Alpine Fault. Maximum localized uplift rates are up to 12 mm/yr (Cox and Barrell 2007; Norris and Cooper 2007) and averaging more than 5–10 mm/yr (Wellman 1979). The fastest uplift appears to be focused along the central section of the Alpine Fault (red area in Figure 2; Koons 1987; Little et al. 2005). The metamorphic grades shown in Figure 1 vary from amphibolite facies (maximum burial temperatures of ~600°C) adjacent to the fault, through greenschist (burial temperatures of ~400°C) to prehnite-pumpellyite facies (burial temperatures of ~300°C).

West of the Alpine Fault, between the Alpine Fault and the western coastline to the northwest, the geology consists of tectonostratigraphic basement terranes of Palaeozoic metasedimentary and plutonic rocks that are fragments of the Gondwanaland supercontinent. These rocks have been intruded by Middle Cretaceous plutons and are largely covered by Late Cretaceous and Cenozoic sedimentary rocks (Figure 1). Late Cenozoic tectonic shortening associated with the ongoing orogeny has resulted in uplift (0.4–2.0 mm/yr; Figure 2; Wellman 1979; Kamp et al. 1992) and development of N- and NNE-trending basin-and-range topography.

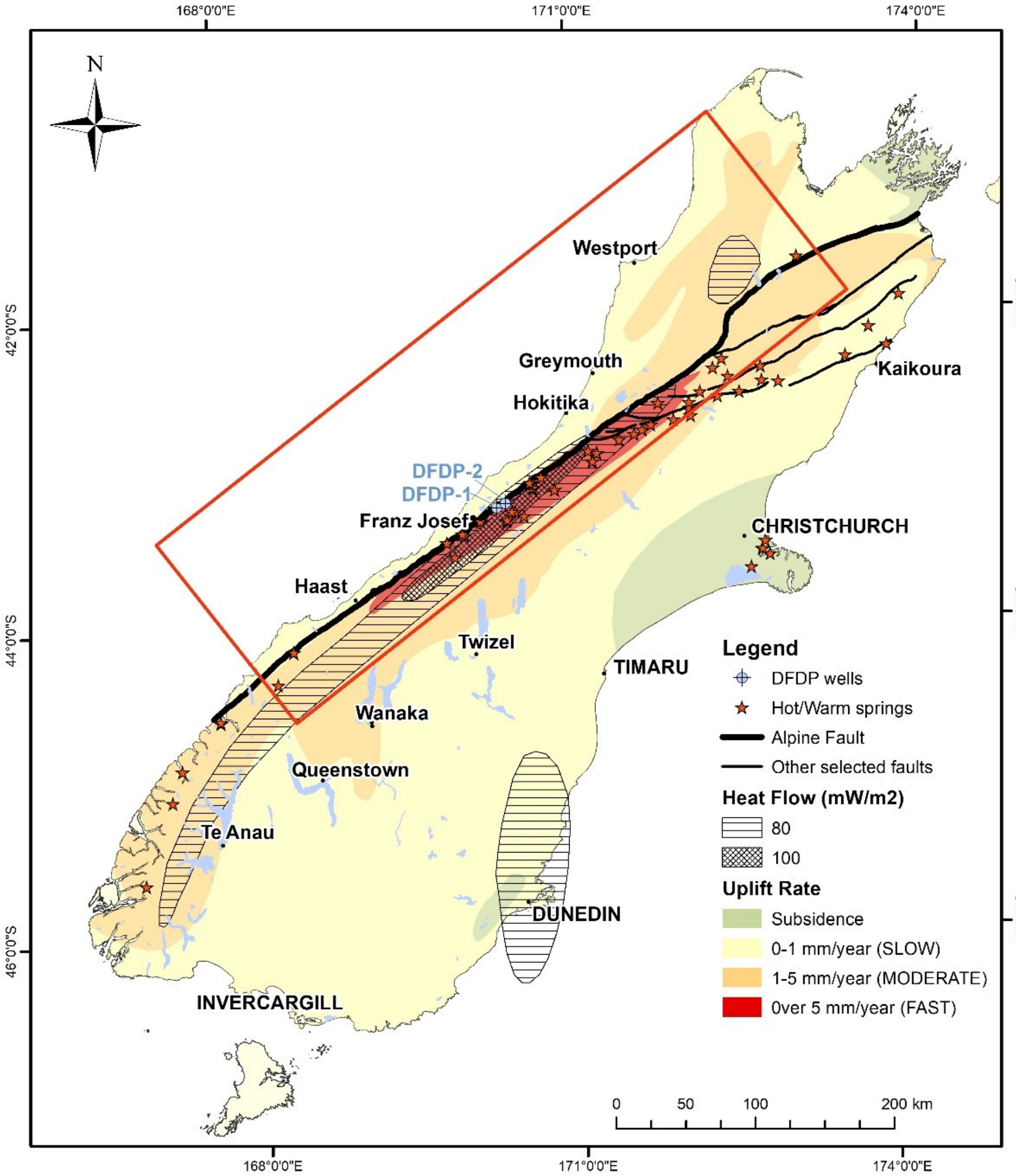

Figure 2: Map of uplift rates (modified from Wellman 1979) across the South Island with areas of elevated heat flow (>80 mW/m^2) (modified from Allis et al., 1998).

3. HEAT FLOW OF THE SOUTH ISLAND

Elevated heat flows with greater than average geothermal gradients (i.e., >30°C/km) occur either side of the Alpine Fault (Figure 2; Allis et al. 1998). Many hot springs that occur along the Southern Alps, east of the Alpine Fault (Figure 2), corroborate an elevated geothermal gradient within the hanging-wall of the Alpine Fault. Additionally, west of the Alpine Fault, exploration petroleum wells drilled in uplifted and eroded sedimentary basins of the Westland plains have encountered elevated heat flows (Townend 1999). Overall, there is general congruence that regions of high uplift also have elevated heat flows (Figure 2).

Drilling into the hanging-wall close to the Alpine Fault, in areas of highest uplift and heat flow, has confirmed the elevated heat flows. Boreholes drilled in the Franz Josef and Haast areas (Figure 2) during the 1990s indicate heat flows of 190 ± 50 mW/m^2 and 90 ± 25 mW/m^2, respectively (Shi et al., 1996). More recently, the Deep Fault Drilling Project (DFDP) provided further insights into the hanging-wall geothermal gradients (Townend et al. 2009). The datasets obtained from the boreholes (DFDP-1A, DFDP-1B and DFDP-2B) (Figure 2) confirmed the hanging-wall to be over-pressured with a high geothermal gradient (100° – 150°C/km in the upper metamorphic sequence) (Sutherland et al. 2017; Townend et al. 2017; Janku-Capova et al. 2018). A year after drilling DFDP-1A and -1B, an equilibrium geothermal gradient of 62.6°C ± 2.1°C/km was determined (Sutherland et al. 2012), whereas in DFDP-2B, the equilibrated bottomhole temperature is 110°C at 890 m drilled depth, with average geothermal gradient of 125°C ± 53°C/km providing a total heat flux of 721 mW/m^2 (Sutherland et al. 2017).

West of the Alpine Fault, exploration petroleum wells drilled into the Westland sedimentary basins show localized elevated geothermal gradients and heat flows (Townend 1999). Steady-state mean heat flows are calculated to be 76 ± 15 mW/m^2, with localized areas around Lake Brunner and Murchison (Figure 3) having >90 mW/m^2. The highest heat flows and geothermal gradients in these sedimentary basins occur close to anticlinal crests (Thrasher et al. 1996; Suggate and Waight 1999), such as the Kotuku Anticline (~50°C/km) in the Lake Brunner area (Figure 3).

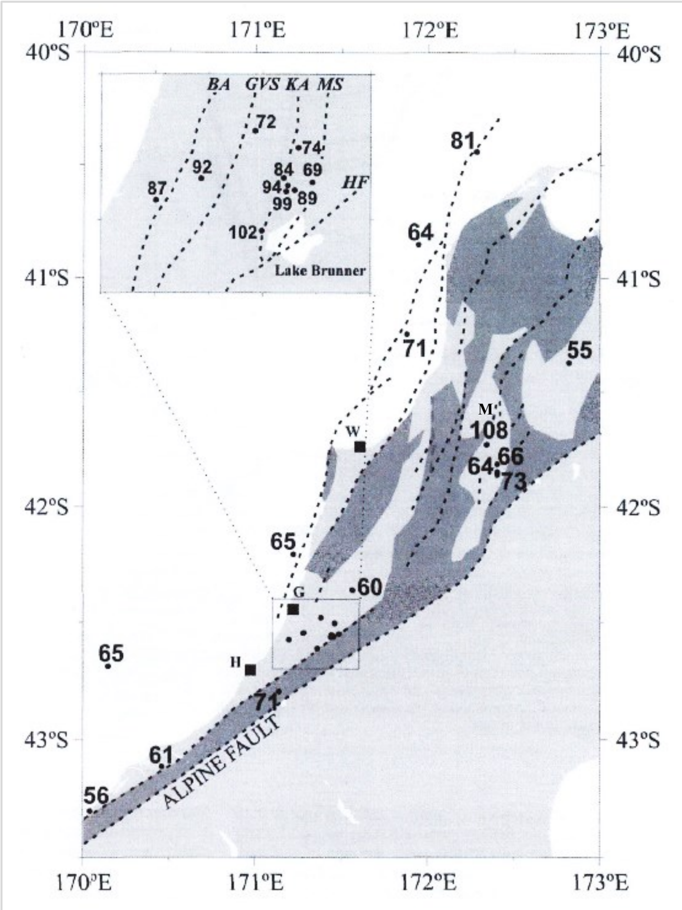

Figure 3: Steady state heat flows (in mW/m^2) for the Westland Plains, with sedimentary basins (pale grey) and basement (dark grey) geology, major faults (dashed lines). The inset shows folds and faults in the Brunner region: BA = Brunner Anticline, GVS = Grey Valley Syncline, KA = Kotuku Anticline, MS = Moana Syncline and HF = Hohonu Fault. From Townend (1999). H = Hokitika, G = Greymouth, W =Westport, M = Murchison.

4. GEOTHERMAL DOMAINS

4.1 Alpine Fault Geothermal Domain

The Alpine Fault rock sequence in the hanging-wall, immediately adjacent to the fault slip surface, has a relatively narrow zone (~50 m wide) of fault gouge and cataclasites (Norris and Cooper 2007). Above this is a sequence of ultramylonites, mylonites and protomylonites (Figure 4; Sutherland et al. 2015) that have been deformed at high strains and temperatures and are part of a deeper ~1 km thick ductile shear zone (Norris and Toy 2014; Sibson et al. 1979; Sutherland et al. 2012; Toy et al. 2008; Toy et al. 2017). The precursor rock to the mylonites is the high-grade Alpine Schist that is found structurally above the mylonites. It is foliated and finely laminated (Figure 4) with alternating quartz- and mica-rich layers that tend to fracture along the less robust mica-rich layers. Near the Alpine Fault this layering is steeply dipping, approximately parallel to the fault, and has important permeability implications for the geothermal fluid flow model.

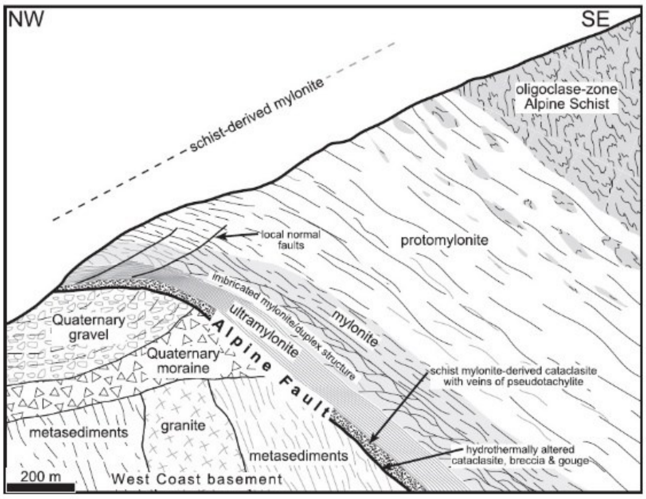

Figure 4: Summary of the geological sequence in the Alpine Fault Zone hanging wall. Reproduced from Norris and Cooper (2007).

The permeability of the bedrock is anisotropic with the schist foliation enhancing permeability approximately parallel to foliation planes, and hence to the Alpine Fault. Based on numerical modelling (Sutherland et al. 2017; Figure 5), the anomalously high thermal gradient along the western side of the Southern Alps arises from a combination of: a) rapid sub-vertical uplift that transports rock and heat from depth; b) rapid erosion that exposes hot mid- to lower crustal rocks to shallow geohydrological processes; and c) topographically-driven fluid movement that concentrates heat into valleys. As a result, the most prospective geothermal sites in the Alpine Fault domain will likely be on the floor of deeply incised valleys between the Alpine Fault and the crest of the alpine mountain range. Potential permeable zones will be fault damage zones in the hanging-wall, above and east of the mylonites (Figure 4). The conceptual model is driven by two flowpaths, one from the main divide toward the Alpine Fault (Figure 5b), orthogonal to the schist foliation planes, and a flowpath from side-ridges into the valleys (Figure 5b). The highest permeabilities are parallel to foliation planes, and broadly parallel with the Alpine Fault. Therefore, the flowpath from the side-ridges dominates the flow regime.

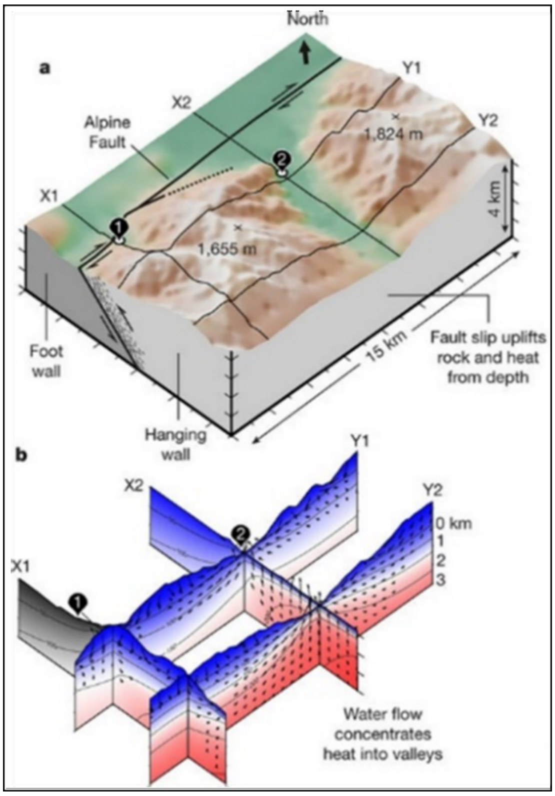

Figure 5a: DFDP-1 and DFDP-2 boreholes (labelled 1 and 2, respectively) relative to the Alpine Fault and topography. For locations see Figure 2. b: Temperature cross-sections with contours (°C) and fluid fluxes (arrows show fluxes >0.15 m yr^{-1}). From Sutherland et al. (2017)

Consideration of the Alpine Domain thermal spring chemistry shows that although there is isotopic evidence from the mid-crustal metamorphic rocks that meteoric fluids penetrated to depths of 6-8 km (Menzies et al. 2014; 2016; Upton et al. 1995)., these flow paths are likely to be slow enough for chemical equilibrium with the host rocks to be maintained. Reservoir geothermometer temperatures from the surface spring chemistry are best estimated using K-Mg cation and silica (quartz, chalcedony) geothermometers

(Reyes, 2015). The reasonable correspondence between these two geothermometers provides a degree of confidence that the equilibrium temperature of the fluid source is reliably estimated, and shows resource temperatures at shallow depths (<1 km) are most likely to be 70° – 100°C (Reyes, 2015). This approximates the measured 110°C at 890 m in DFDP-2B.

4.2 Sedimentary Basin Geothermal Domain

The stratigraphic sequence of the Westland plains (Nathan et al., 1986; Suggate and Waight, 1999; Nathan et al., 2002), west of the Alpine Fault, formed in relatively small fault-bound basins (Figure 6) in response to the changing tectonic forces across the Australian – Pacific Plate boundary. Sedimentary deposition occurred in small marine basins during periods of marine transgression from the latest Cretaceous to the Oligocene, followed by marine regression during the Miocene to Pliocene. Rapid deformation in the early Pleistocene resulted in crustal shortening and uplift. The result is a sedimentary sequence that is stratigraphically and structurally complex with many facies changes, with rock types ranging from fine mudstones to relatively coarse conglomerates.

The initial transgressive marine sequences resulted in deposition of coal measures and other hydrocarbon source rocks, making the region highly prospective for coal mining and oil exploration. This led to detailed geological mapping and geophysical (seismic) surveys, and exploration drilling. Much of the oil exploration was focussed in the Brunner and Murchison, with hydrocarbon source rocks including the Paparoa and Brunner Coal Measures (Late Cretaceous to Early Eocene).

A significant break in the Early Pleistocene sedimentary record is due to the continued rapid uplift of the Alpine Fault. Most of the district emerged from the sea, but development of high relief was arrested by high erosion rates. The associated compressive deformation, resulted in crustal shortening that lead to basin inversion of the Paparoa Trough, fault reversals, basin-and-range topography, and deformation of the Cretaceous to Cenozoic sedimentary basins into synclines (e.g., Grey Valley Syncline) and anticlines (Brunner and Kotuku Anticlines) (Figure 6).

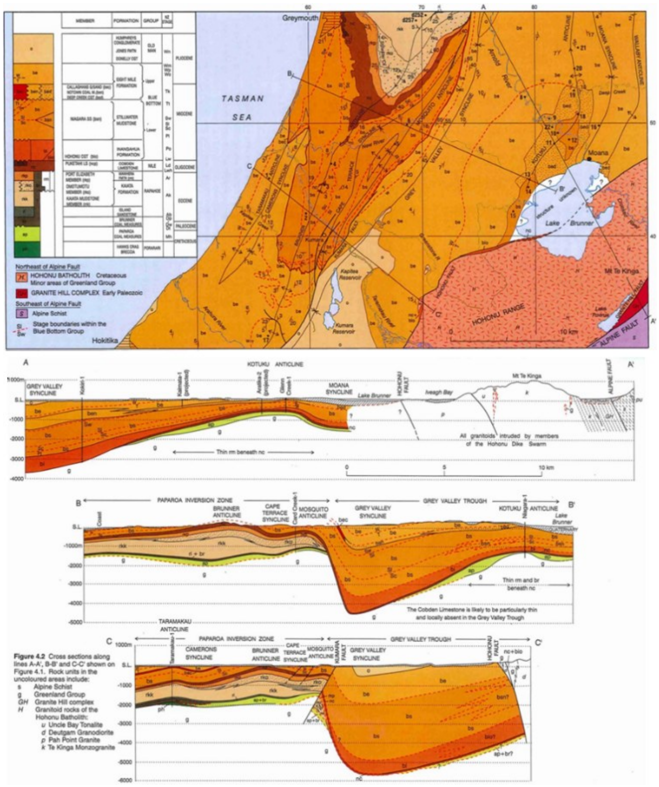

Figure 6: Top: Pre-Quaternary geology map, south and east of Greymouth, consists of folded sedimentary basin sequences. Bottom: Cross-sections through the sedimentary basin sequences as indicated in top figure. From Suggate and Waight (1999).

Tectonic deformation that caused crustal shortening and uplift, followed by rapid erosion, has resulted in higher geothermal gradients and increased heat flow (by 20-60%; Townend 1999) across parts of the West Coast. Areas with the greatest uplift and erosion are accentuated along the anticline crests, especially that of the Kotuku Anticline where as much as 500–700 m of material has been removed (Townend 1999). As a result, the areas with greatest geothermal gradient (i.e., ~50°C/km) are found along the anticlinal crests, such as the Kotuku Anticline (Suggate and Waight 1999). These represent the most prospective geothermal sites in the Sedimentary Basin domain and geothermal wells drilled to 1-2 km depth, located close to the anticlinal crests, and targeting any permeable sedimentary rock units should encounter temperatures between 50°C and 100°C.

5. POTENTIAL HEAT USE

The temperature of a geothermal resource available for utilization is important for any commercial geothermal venture. Low temperature geothermal reservoirs can supply heat energy used directly for a range of enterprises such as: bathing, spas and aquatic centers; horticultural greenhouses; aquaculture; and commercial/domestic space and water heating. Low temperature electricity generation is also possible but ideally source temperatures of about 100°C or greater are necessary.

Several West Coast stakeholders (Figure 7) were canvassed for information on their current heat use and heat generation systems. The largest heat user is Westland Milk Products, which has a boiler capacity of 35 MW thermal that currently demands about 70,000 tonnes of coal per annum. Other West Coast users are smaller, with capacities of 2 MW thermal or less. These uses are most commonly fueled by either coal or LPG. In some locations a geothermal heat supply might be used by multiple parties thereby establishing a larger heat load for that location. Table 1 is the suggested agglomerated heat load at likely locations where multiple parties might seek to utilize a geothermal heat source.

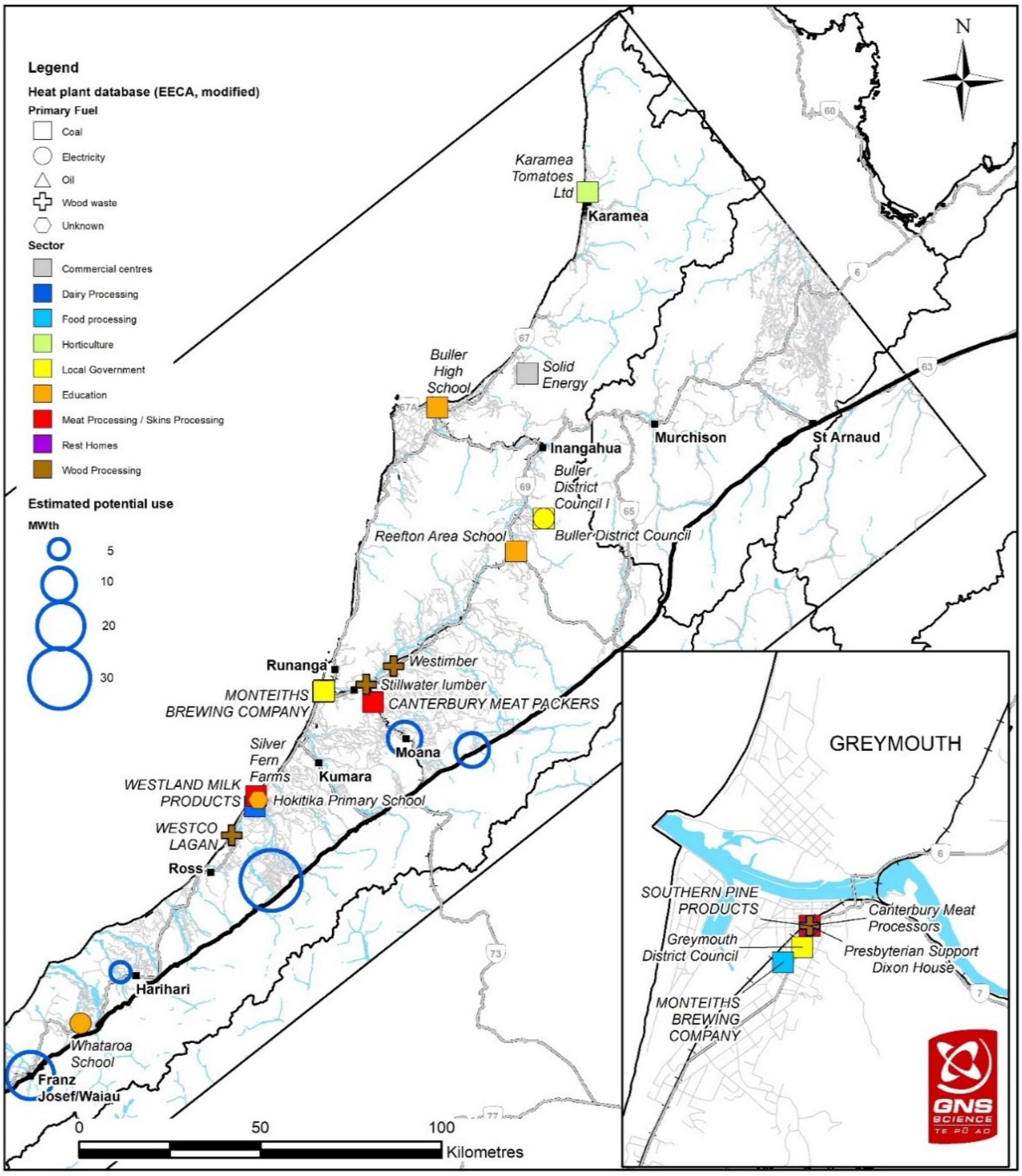

Figure 7: Existing heat users in the west coast region and suggested agglomerated heat load location.

Table 1: Agglomerated thermal loads at a given location

Location	Agglomerated MW Thermal
Franz Josef	40
Hokitika / East of Hokitika	>20
Haupiri	10
Brunner / Moana	5

The requirements of the smaller West Coast enterprises, with capacities less than 2 MW thermal, could realistically be met by the potential West Coast geothermal sources. However, the heat demands of a dairy factory require a significant amount of energy at temperatures about 100°C in excess of what could be reasonably expected from the geothermal sources. For the purpose of assessing the feasibility of the West Coast geothermal resources, a figure of 10 MW thermal has been arbitrarily suggested for the Westland Milk facility for preheating or lower temperature use.

Some small scale low temperature power generation might be possible, and an electrical capacity of up to about 3 MW is in the size range considered. The critical uncertainty of a West Coast geothermal resource is the reservoir temperature. Electricity generation is now considered viable over the temperature range of 70°C to 140°C and is highly dependent on the fluid flow volume, which is dependent on rock permeability. Temperatures of 120° – 140°C should be considered the maximum that might be encountered at drillable depths (2 km) for the Alpine Fault domain, whereas for the Sedimentary Domain, it would likely be no higher than ~100°C.

6.GEOSPATIAL DECISION SUPPORT SYSTEM FOR PRIORITIZATION OF PROSPECT AREAS

To automate the assessment of the geothermal potential of the West Coast, a geospatial decision support system has been developed (Figure 8). This computer-based procedure uses spatial analysis tools to generate geothermal favorability maps. The purpose of the procedure is to identify prospective geothermal areas and prioritize them for further investigation while considering the feasibility for development and end-user requirements. It is a semi-automated approach to geothermal development feasibility that combines data- and knowledge-driven models, integrating geoscientific and environmental data, and energy-use information, so that the best solution between potential locations and potential energy-use can be identified.

The strength of a computerized geospatial approach is the ability to combine multiple influential variables. One objective for this project is to test the rendering of distinct conceptual models (i.e. for each geothermal domain) by scoring and weighting geoscience-based thematic maps, or layers. The second objective was then to use environmental and economic factors in an algorithm to integrate the end users requirements and prioritize favorable areas.

Each layer is assessed and scored based on its influence on the geothermal potential of any given area from least (score 1) to most (score 5) favorable. While some layers can be easily scored (e.g. uplift rate, heat flow), others are transformed into qualifiable and quantifiable parameters (e.g. distance to a fault trace). Following discussions with West Coast stakeholders, parameters are weighted with respect to their respective influence and what stakeholders considered to be the most important from their perspective.

A conditional layer is created to represent each geothermal domain. West of the Alpine Fault is the Sedimentary Basin domain, and east of the Alpine Fault is the Alpine Fault domain. Some variables have influence in both (e.g. the density of faults), while others are domain-dependent (e.g. proximity to hot spring location for the Alpine Fault domain; proximity to anticlinal crest for the Sedimentary Basin domain).

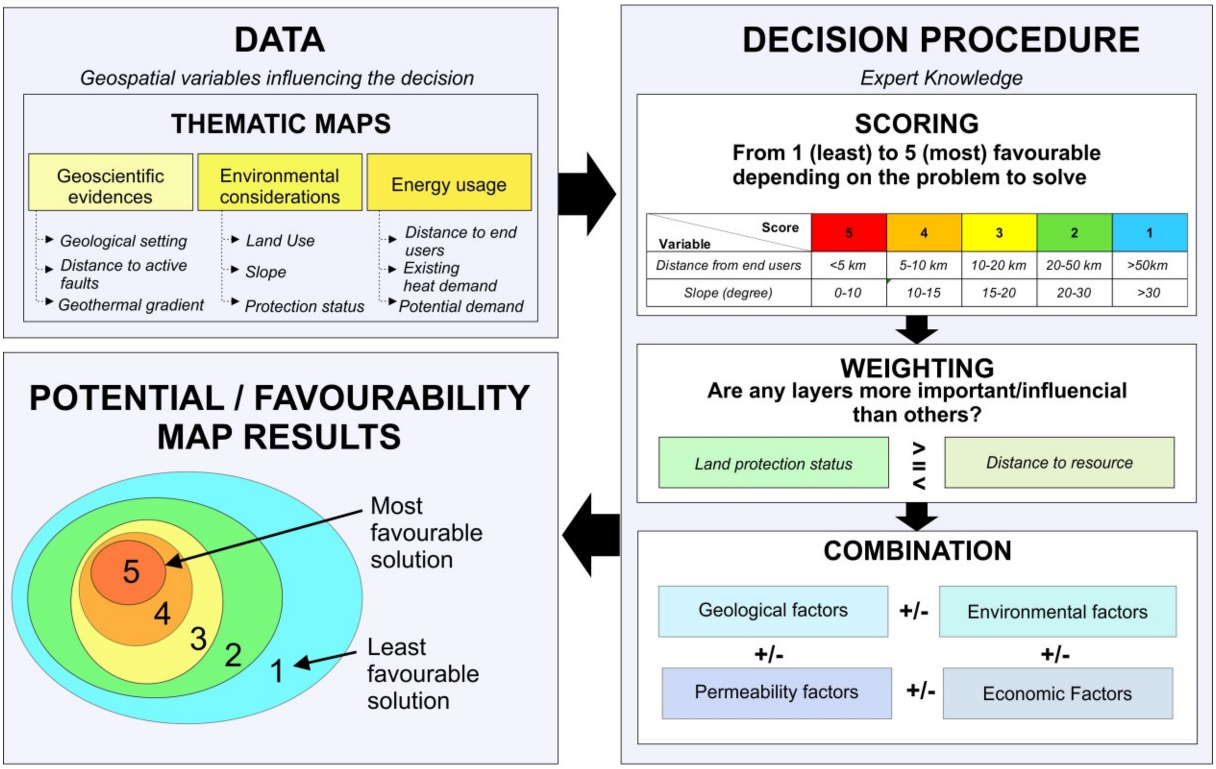

Figure 8: Illustration of the geospatial decision support methodology using spatial analyses. Examples are italicized.

6.1 Geoscientific Variables in the Alpine Fault Domain

Table 1 presents scores and weightings of each layer used to prioritize elements of the Alpine Fault domain. Structural indicators that can influence permeability and fluid flow pathways are derived from the location and density of faults, fault activity and earthquake locations. Similarly, the closer to existing warm spring, the better the possibility of fluid flow and temperature. The conceptual model of the Alpine Fault domain indicates that hot fluids are focused into the valley floors that incise across the Alpine Fault into the western Southern Alps. The distance to major rivers with these characteristics and the topographic gradient of their valley systems are used to identify preferential areas.

Table 2: Summary of key geoscientific variables used in the spatial analyses for the Alpine Fault domain

Parameter	Layer Weight	Score 5	Score 4	Score 3	Score 2	Score 1
Distance from the Alpine Fault	1	1–2 km	< 1 km	2–5 km	5–10 km	>10 km
Distance from active faults	0.5	< 500 m	500 m to 1 km	1–2 km	2– 5 km	> 5 km
Density of faults	1	>2	1.5–2	1–1.5	0.05–1	<0.05
Rate of uplift (estimation)	1	FAST	MODERATE		SLOW	SUBSIDENCE
Density of earthquakes events	0.5	>1	0.2–1	0.1–0.2	0.05–0.1	<0.05
Heat flow (estimation)	0.5	>100	80–100	60–80	60–40	<40
Slope (in degrees)	0.5	0–10	10–15	15–20	20–30	>30
Distance from hot springs	0.5	0–500 m	500 m to 1.5 km			>1.5 km
Distance to major rivers	1	<50 m	<100 m	<250 m	<500 m	>500 m

6.2 Geoscientific Variables in the Sedimentary Basin Domain

In the sedimentary basin domain, the same permeability indicators are used, though scores and weights are adjusted to best represent the conceptual understanding of heat transfer in the basins (Table 3). Of interest in this domain is the distance to the anticlinal crest axis, with the crest having the higher geothermal gradient.

Table 3: Summary of key geoscientific variables used in the spatial analyses for the Sedimentary Basin domain

Parameter	Layer Weight	5	4	3	2	1
Distance from active faults	0.5	< 500 m	500 m to 1 km	1–2 km	2– 5 km	> 5 km
Density of faults	1	>2	1.5–2	1–1.5	0.05–1	<0.05
Density of earthquakes events	0.5	>1	0.2–1	0.1–0.2	0.05–0.1	<0.05
Rate of uplift (estimation)	0.5	FAST	MODERATE		SLOW	SUBSIDENCE
Petroleum basin	0.5	In			Out	
Heat flow (estimation)	0.5	>100	80–100	60–80	60–40	<40
Distance to anticline	0.5			<= 500 m	500 to 1000 m	other

6.3 Other Variables

Surface constraints due to the local topography, land use, land cover, land ownership, conservation status, ease of access and distance to heat use prospects provide environmental criteria for preferred site selection (Table 4). For example, the topographic gradient imposes infrastructural and access limitations to any development. Conservation areas in the region have different protection status (e.g., National Parks, wildlife reserves) that impact the feasibility of a potential development. While the distance to the warm spring as a geoscientific factor is important (the closer being the most favourable), from an environmental point of view, any development should not impact the natural flow of the feature and should not be located too close to the springs. Also of consideration is the type of land cover. Areas covered by glaciers or prone to land slides are excluded as potential areas of development due to their intrinsic value and hazards associated.

The feasibility of any development is also largely constrained by the costs of development. Due to the rugged topography and isolation of parts of the West Coast region, the distance from roadways can constrain ease of access to a prospect area and the closer to populated areas the better for development and potential end-users. Should a development proceed, the proximity to railway transportation facilities is a favourable parameter for ease of distribution of end-products (e.g. green house vegetables).

Table 4: Summary of environment and end user requirements variables used in the spatial analyses

Parameter	Layer Weight	5	4	3	2	1
Slope (in degrees)	0.5	0–10	10–15	15–20	20–30	>30
Status of conservation (classification)*	1	Other	Other sections	s. 19	s.7, s. 12, s.18	s.3, s.4, s.20, s.13, s.14, s.23B, s.20
Land cover classification	0.5	All others		Transport infrastructure	River Surface mine or dump	Lake or pond Landslide Estuarine open water Permanent snow and ice
Distance from hot springs **	0.5	>1.5 km			500 m to 1.5 km	0–500 m
Distance from railway	0.5	<5 km	5–10 km	10–25 km	25–50 km	>50 km
Distance from roads and vehicle tracks	0.5	<1 km	1–5 km	5–10 km	10–20 km	>20 km
Distance from urban area and settlement	1	<2 km	<5 km	<10 km	10–20 km	>20 km

6.4 Favorability Map

A favorability map using the geoscientific parameters combined with the environmental and energy use factors (Tables 2 to 4) illustrates the most favorable areas for geothermal development. The results show that for the Alpine Fault domain, in accordance with the conceptual model, favorable areas are located along several the major river valleys that have incised into the western side of the Alpine range, for example at Haupiri (Figure 9). For the Sedimentary Basin domain, favorable areas are either located close to anticlinal crests or close to active faults.

The geospatial decision support system developed as part of this study provides an automated solution to assess the geothermal potential of areas in the West Coast region. Two distinct geothermal domains identified from the review of the geoscientific data can be assessed independently using scoring and weighting of different data-driven spatial layers. The combination of the geoscientific layers with the environmental constraints and some economic factors dictated by the stakeholders and potential end-users provided further refinement of the areas that should be prioritized for further investigation. The techniques could be applied to other prospect areas, however it can only be reliable when informed by a robust conceptual understanding of the processes constraining the resources.

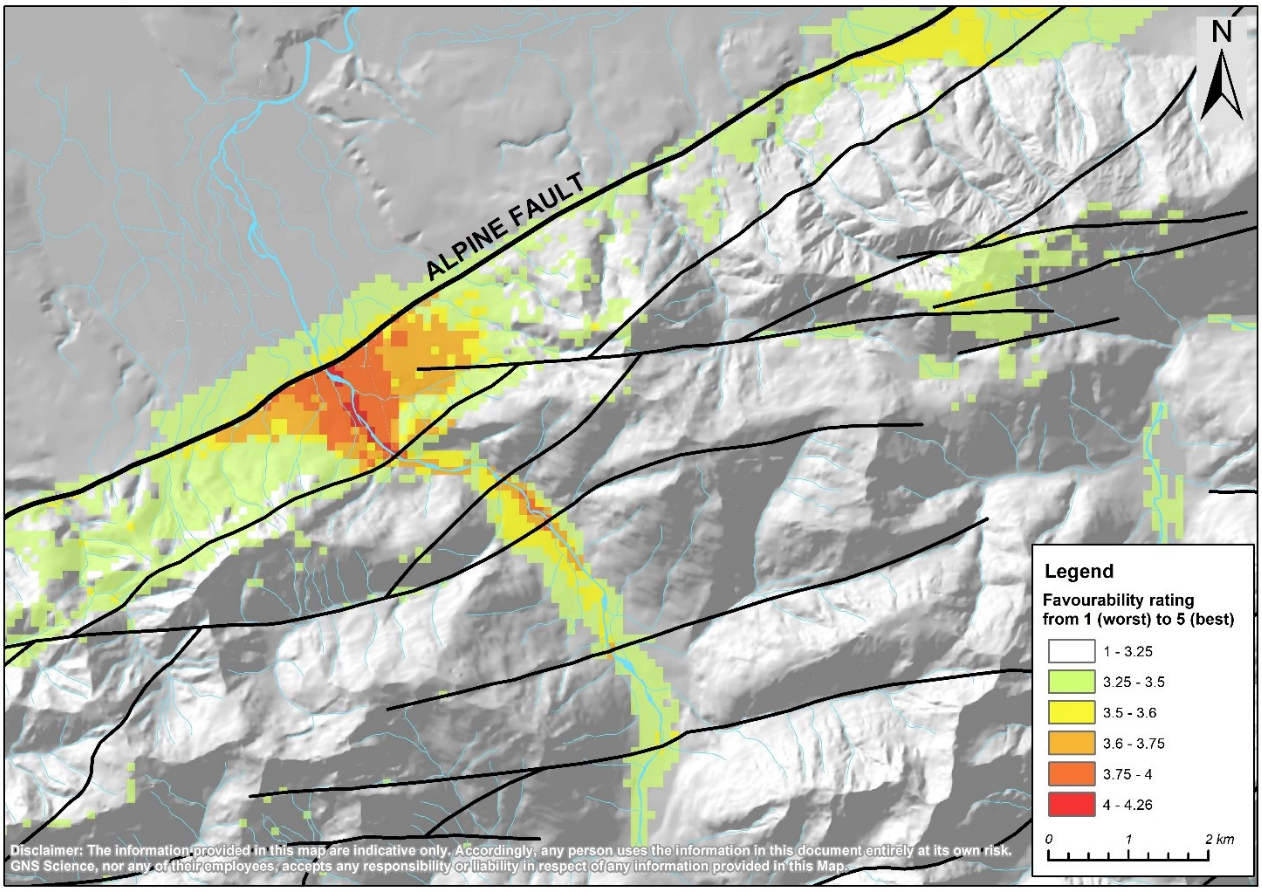

Figure 9: Favorability map of the Haupiri Valley (Alpine Fault domain), considering the geoscientific, environmental and economic factors for this location.

7. SUMMARY AND CONCLUSIONS

Two low temperature geothermal domains identified in the West Coast province of New Zealand's South Island are a result of uplift and erosion of geological rock sequences at the active Australian – Pacific Plate tectonic boundary. Rock exhumation exposes uplifted, hot, mid-crustal rocks to shallow geohydrological processes for both domains:

- **Sedimentary Basin domain**: geothermal prospects are associated with active faulting and crests of anticlines in folded and faulted sedimentary basin sequences that dominate the geology between the western coastline and the Southern Alps. Temperatures of approximately 60°C at 1000 m might be found in the Sedimentary Basin domain.
- **Alpine Fault domain**: active faulting and rapid erosion along the western side of the alpine crest has elevated geothermal gradients and heat flows that manifest as hot springs occurring in valleys along the Alpine Fault. Temperatures of ~130°C at 1000 m can be expected in the Alpine Fault domain.

To be useful as a geothermal energy resource requires a utilization load. This study identified potential uses and fluid temperatures for useful supply to hot bathing pools, green houses, aquaculture and domestic and commercial space heating. These can function with temperatures as low as 60°C. Some lower temperature industrial use and small scale electricity generation might usefully utilize temperatures in the range 100°C to 130°C. The higher potential temperatures are not hot enough to supply all the heat requirements to the largest West Coast heat user, Westland Milk Products.

With conceptual models providing insights into the feasibility of each geothermal domain, an automated geospatial analysis provided an objective methodology for defining geothermal areas with the highest prospectivity. The methodology is reliant on robust conceptual models defined by sound geoscientific studies and tested using numerical models. Also reliant on robust understanding of environmental and economical parameters, which are defined by end-user/stakeholders, and sound understanding of regulatory constraints, requirements and demands. The strength of the method is that it can be automated over large geographic areas. It relies on the availability of data, and can be refined and adjusted to preferred criteria defined by stakeholders.

For the Sedimentary Basin domain, preferred locations are either proximal to active faults or anticlinal crests, and have been chosen mainly for their potential for direct use thermal applications supplying heat for bathing, spas and aquatic centers; horticultural greenhouses; aquaculture; commercial and domestic space and water heating.

For the Alpine Fault domain, preferred locations are valley systems that incise the western side of the Southern Alps, between the Alpine Fault and the alpine ridge, such as at Haupiri. These valleys might be suitable for direct use thermal applications, as per the Sedimentary Basin domain, but also lower temperature industrial use (e.g., timber drying) and small scale electricity generation might be possible at some locations.

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