Supercritical Geothermal Systems Near the Brittle-Ductile Transition Zone

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ABSTRACT

Supercritical and superhot geothermal systems offer substantially higher energy density than conventional geothermal resources, but reaching high temperature is not sufficient to define a viable reservoir. This paper presents a lithology-based mechanical screening framework for supercritical geothermal exploration, developed from a comprehensive literature synthesis. The framework integrates laboratory deformation experiments, numerical modelling and global drilling evidence to evaluate whether a target interval is likely to remain brittle and fracture-permeable, become mixed brittle-ductile and stress-dependent, or compact and lose permeability before a producible resource is reached.

Three end-member scenarios are proposed. The Best Case applies to low-porosity, glass-poor mafic rocks where the temperature-controlled brittle-ductile transition (BDT) zone lies above the supercritical window. The Mid Case applies to the Quartzo-feldspathic crystalline basement where the transition overlaps the supercritical threshold. The Worst Case applies to porous or hydrothermally altered volcaniclastics where pressure-controlled pore collapse may destroy permeability. The framework is compared with IDDP-1, IDDP-2, Kakkonda, Larderello, a wider suite of granite-hosted enhanced geothermal systems, and selected high-temperature volcanic analogues, then applied provisionally to Rotokawa and the Taupō Volcanic Zone.

Attention is given to New Zealand's greywacke basement, where the Torlesse and Waipapa terranes may not be mechanically identical, and to the possibility, supported by regional geochronology, that the basement encountered by future wells includes intrusive or igneous material rather than a texturally uniform greywacke section. The main implication for New Zealand is that deeper drilling should be preceded by high-temperature deformation and permeability testing of Rotokawa Andesite, Torlesse and Waipapa greywacke, any recovered intrusive lithologies, and altered TVZ volcaniclastics, together with dynamic brittle-ductile transition zone modelling and deeper geophysical characterisation.

1. INTRODUCTION

Supercritical pure water occurs above 373.946°C and 22.064 MPa, while superhot geothermal targets are commonly discussed as geothermal environments with rock or reservoir temperatures above approximately 400°C. These conditions are attractive because supercritical or near-supercritical fluids can carry much greater heat per unit mass than conventional geothermal fluids, increasing the potential power output per well (Elders et al., 2014; Reinsch et al., 2017; Watanabe et al., 2019). However, field records show that comparable temperatures can yield very different reservoir outcomes depending on host lithology and mechanical state.

The central mechanical issue is the brittle-ductile transition (BDT) zone, where rock behaviour shifts from localised brittle fracture to distributed ductile flow or compaction (Violay et al., 2015, 2017). Above this transition, open fractures and faults can sustain fluid circulation. At or below it, fracture apertures may close, deformation may become distributed, and permeability can become limited or disconnected. The BDT zone is therefore not simply a geological curiosity; it controls whether a supercritical target is drillable and whether the fluid can be produced. Figure 1 illustrates this concept for a conventional high-enthalpy system, showing how the BDT zone sits between the exploitable reservoir and the deeper superhot resource that motivates this paper.

This paper presents a condensed version of a research project that reviewed laboratory rock mechanics experiments, simulation models, geophysical evidence, and deep geothermal drilling records. Its purpose is to develop a practical lithology-based screening framework for supercritical geothermal exploration, with particular attention to how the framework could guide future work in New Zealand's Taupō Volcanic Zone (TVZ), including the mechanical uncertainty posed by its greywacke basement and any intrusive rock it may contain.

Section 2 outlines the literature synthesis method. Section 3 presents the mechanical basis of the BDT zone and its lithological controls, including how permeability evolves near the transition. Section 4 develops the three-scenario framework, which is tested against global drilling evidence in Section 5. Section 6 applies the framework to New Zealand, with particular emphasis on Rotokawa's greywacke basement and the evidence for intrusive rock within it. Sections 7 to 10 discuss engineering implications, broader discussion, limitations and conclusions.

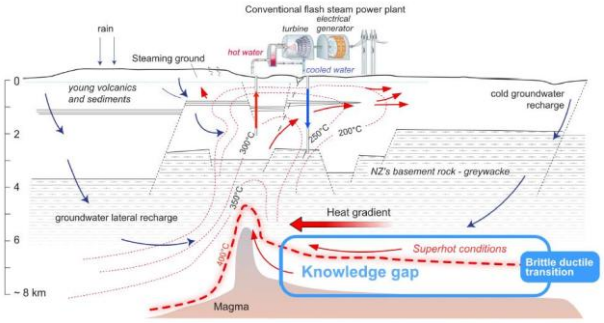


Figure 1: Conventional geothermal system showing the potential brittle-ductile transition zone (blue). (Modified from ESNZ, 2025, with permission).

2. METHOD

The study used a structured comparative literature synthesis rather than new laboratory or numerical work. Evidence was drawn from four source types: theoretical definitions of the BDT zone, laboratory deformation experiments, numerical models of supercritical resource formation, and field drilling or geophysical records from deep geothermal projects (Scott et al., 2015; Violay et al., 2012, 2017; Muraoka et al., 1998; Bertani et al., 2018). These evidence streams were compared by lithology, temperature, pressure (where reported), strain rate, alteration, permeability behaviour, deformation mechanism, and drilling response. New Zealand-specific sources on greywacke basement mechanics and TVZ geochronology were given particular attention, given their direct relevance to Rotokawa (McNamara et al., 2014; Melia et al., 2022; Milicich et al., 2020; Mortimer et al., 2023).

Where possible, evidence was weighted toward peer-reviewed laboratory and field studies, but conference proceedings and technical reports were retained when they provided primary temperature, pressure, lithology, or drilling data not available elsewhere, a common practice in this field reflected in the workshop proceedings cited throughout Sections 5 and 6. This introduces a degree of publication and reporting bias that is discussed further as a limitation in Section 9.

No single evidence stream was treated as sufficient on its own. Numerical models provide system-scale thermal context but commonly represent rock mechanics through simplified temperature-dependent permeability functions. Laboratory experiments provide lithology-specific deformation thresholds but use strain rates and sample scales that differ from those in natural crustal systems. Drilling records are field-scale tests, but they are site-specific and rarely isolate lithology, stress, alteration, fracture architecture and drilling practice from one another. The framework developed here, therefore, rests on agreement across multiple evidence streams.

The literature was interpreted using an evidence hierarchy. Direct field-drilling evidence was given the greatest weight when all available temperature, pressure, lithology, and permeability behaviour were available, as in IDDP-2 and Kakkonda. Geophysical evidence, including seismicity cut-off depths and magnetotelluric resistivity patterns, was treated as supporting evidence because it can help constrain high-temperature mechanical transitions before direct drilling confirmation, although these signals are not uniquely diagnostic of the BDT zone. Laboratory experiments were used to define the deformation mechanisms and relative brittle–ductile thresholds of each lithological group, while numerical models were used to examine how permeability structure and the position of the brittle–ductile transition influence the development and scale of supercritical geothermal resources.

A central methodological decision was to classify evidence by mechanism rather than by rock name alone. For example, basalt can behave as a high-strength mafic crystalline rock when glass-poor and low-porosity, but porous or partly glassy basalt can compact at much lower temperatures under fluid-saturated conditions. Similarly, granite and metamorphic basement are grouped because quartz and feldspar dominate the relevant deformation mechanisms, whereas porous volcaniclastics are grouped because pore collapse rather than crystal-plastic creep governs their permeability loss. The same mechanism-first logic is applied to New Zealand greywacke and any associated intrusive rock in Section 6, rather than if a single rock name describes a single mechanical behaviour.

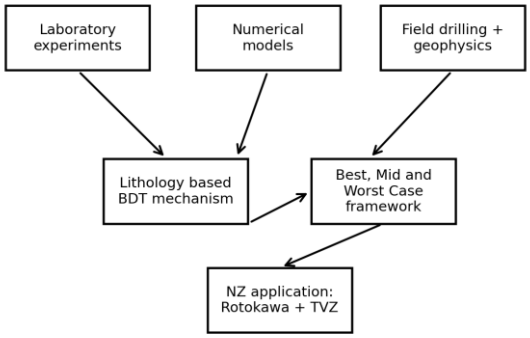


Figure 2: Evidence streams used to develop the lithology-based framework.

3. MECHANICAL BASIS

3.1 Supercritical conditions and the BDT zone

Supercritical geothermal systems commonly approach or exceed the pure-water critical temperature and pressure, but natural geothermal fluids contain salinity and dissolved gases that shift critical behaviour (Scott et al., 2017; Watanabe et al., 2019). The term superhot is therefore useful as a temperature-based descriptor for wells that approach the superhot regime alone, without pressure and composition fully establishing supercritical fluid conditions.

For geothermal engineering, the important question is not only whether a well reaches 400–600°C, but whether the host rock at that depth can sustain connected permeability. A superhot target that is ductile, compacting, chemically sealing or disconnected may be hotter than a conventional reservoir but still unusable. This shifts the screening problem from a purely thermal question to a coupled thermo-hydro-mechanical one.

3.2 Lithological controls

The reviewed experiments indicate that BDT zone behaviour depends strongly on lithology, texture and alteration, and in every group the same underlying question recurs: does the rock's structure preserve a connected flow path, or does deformation shut it down? In low-porosity, glass-poor basalt, high-temperature experiments show brittle and dilatant behaviour that persists to very high laboratory temperatures, with field extrapolations placing the basaltic BDT zone at around 550-650°C in the Icelandic crust (Violay et al., 2012, 2015). This favourable behaviour is itself structurally contingent rather than guaranteed by composition alone: low-porosity basalt remains dilatant and brittle to effective pressures of 200 MPa, whereas higher-porosity basalt (≥8%) transitions to permeability-destroying cataclastic compaction at effective pressures as low as 80 MPa (Zhu et al., 2016). Competent, low-porosity mafic crust is therefore the most favourable mechanical endmember, but it is porosity, not composition alone, that decides whether this favourable behaviour holds.

Granite and related quartzo-feldspar crystalline basement behave differently because quartz and feldspar activate crystal-plastic processes at lower temperatures than mafic minerals: quartz begins to deform by dislocation creep at approximately 300°C at laboratory strain rates, while feldspar undergoes hydrolytic weakening under hydrothermal, water-present conditions (Hirth & Tullis, 1992; Rybacki et al., 2006). Westerly granite experiments extrapolated to geological strain rates indicate a BDT zone around 400±100°C (Violay et al., 2017). This range overlaps with the supercritical water threshold, suggesting that granite-hosted superhot resources are likely to lie within a mixed brittle-ductile regime rather than clearly above or below the transition. Here, the controlling structural variable is different again: as Section 3.3 shows, it is not porosity but whether deformation localises onto a single fault or distributes through the rock mass that decides whether permeability survives the transition.

Porous tuffs, ignimbrites, hyaloclastites and hydrothermally altered volcaniclastics form a third mechanical group. Their controlling transition is not primarily temperature-controlled crystal-plastic creep but pressure-controlled cataclastic pore collapse. Experimental P* values in this group can be low enough that irreversible compaction and permeability loss may begin before a producible superhot resource is reached (Eggertsson et al., 2020; Heap et al., 2024; Farquharson et al., 2017). This makes porous altered volcaniclastics the highest-risk lithological group.

This distinction also explains why andesite and dacite cannot be assigned automatically to a single scenario. Dense, low-porosity andesite may remain mechanically strong under near-solidus laboratory conditions, while altered or porous andesite can undergo distributed cataclastic compaction and permeability loss. Intermediate volcanic rocks, therefore, require site-specific interpretation of porosity, glass content, alteration and stress state before they can be used as analogues for either favourable or unfavourable behaviour. New Zealand greywacke follows the same mechanism-first logic and is examined in detail in Section 6, because Torlesse and Waipapa greywacke are not necessarily mechanically identical to each other, nor are they necessarily identical to Westerly granite or to any intrusive rock the basement may also contain.

3.3 Permeability evolution near the BDT zone

A recurring and counterintuitive finding across the reviewed experiments is that permeability does not simply collapse at the BDT zone; rather, its evolution depends on whether deformation localises onto a single fault or distributes throughout the rock volume. In granite deformed under confining pressure with continuous permeability monitoring, samples in the brittle regime (200-400°C) showed permeability fluctuating around its initial value because strain localised onto a single fault that did not connect across the sample, whereas samples in the semi-ductile regime at 800°C showed roughly a thirty-fold permeability increase relative to the initial value, driven by distributed microcracking that generated a connected network through the bulk rock (Meyer et al., 2024). A related experiment on Westerly granite recorded an inversion during deformation: permeability initially decreased due to compaction, then increased again shortly before and after failure as interconnected fracture pathways developed (Petrini et al., 2021). Both results indicate that, in quartzo-feldspathic crystalline rock, crossing into the BDT zone can enhance bulk permeability rather than destroy it, provided deformation is distributed rather than confined to an isolated fault plane.

This behaviour is directly relevant to greywacke, discussed in Section 6, because it means that the BDT zone in Mid Case lithology should not be automatically modelled as a permeability cut-off. Whether a granite- or greywacke-hosted target is favourable depends on the structural context, principally fracture density and connectivity, rather than on temperature or nominal BDT zone position alone. Porous volcaniclastics behave differently again: because their controlling mechanism is pressure-driven pore collapse rather than crystal-plastic microcracking, permeability loss in that group is progressive and largely irreversible rather than potentially enhanced (Farquharson et al., 2017). Table 1 summarises the BDT zone constraint currently available for each lithological group discussed in this paper, including the provisional, untested status of greywacke.

Table 1: Summary of BDT zone constraints by lithological group referenced in this paper.

Lithological group	BDT zone constraint	Governing mechanism	Key reference
Low-porosity, glass-poor basalt	~550-650°C	Temperature-controlled crystal-plastic flow	Violay et al. (2012, 2015)
Granite / Quartzo-feldspathic crystalline rock	~400±100°C	Temperature-controlled crystal-plastic flow	Violay et al. (2017)
Porous tuff, ignimbrite, hyaloclastite	P* ≈ 10-110 MPa	Pressure-controlled pore collapse	Eggertsson et al. (2020); Heap et al. (2024)
Greywacke (Torlesse / Waipapa)	~400±100°C (provisional, untested)	Inferred temperature-controlled, by analogy to granite	This study, after Hirth & Tullis (1992)

4. LITHOLOGY-BASED SCENARIO FRAMEWORK

The framework classifies supercritical geothermal targets according to the position of the target interval relative to the relevant lithology-specific BDT zone mechanism. It is not a universal depth-prediction model. The same temperature may be favourable in one lithology and unfavourable in another because the controlling deformation mechanism changes.

Table 2 summarises the three end-member scenarios. The values are indicative synthesis ranges from the reviewed experimental and field evidence, not fixed boundaries. In practice, classification requires that lithology, porosity, glass content, alteration, stress state, fracture architecture, temperature, and pressure be interpreted together.

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Table 2: Lithology-based mechanical scenarios for superhot geothermal screening.

Scenario	Typical host	BDT mechanism	Engineering implication
Best Case	Low-porosity, glass-poor basalt or mafic crystalline crust	Temperature-controlled crystal-plastic flow, BDT around 550-650°C	Fracture permeability likely persists; the main risks are thermal, chemical, and casing-related.
Mid Case	Granite, granodiorite, greywacke or competent quartzo-feldspathic basement	Temperature-controlled BDT around 400±100°C	Permeability is likely affected by ductile transition in some cases, depending on stress conditions and fracture connectivity.
Worst Case	Porous tuff, unwelded ignimbrite, hyaloclastite and altered volcaniclastics	Pressure-controlled pore collapse; P* approximately 10-110 MPa depending on porosity and alteration	Compaction may irreversibly reduce permeability before a producible target is reached.

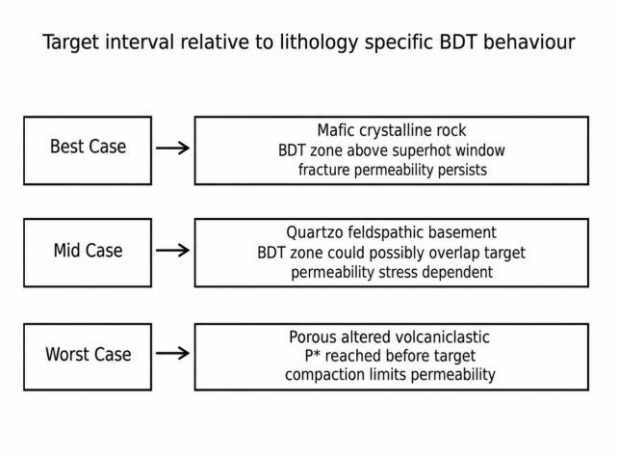


Figure 3: Mechanical position of the three supercritical geothermal scenarios relative to BDT behaviour.

Greywacke is included in the Mid Case row of Table 2 on compositional grounds only. As Section 6.2 sets out, New Zealand's two main basement terranes are not known to share a single BDT zone, and the basement a well actually encounters may not be greywacke at all. Greywacke should therefore be read as a provisional Mid Case placeholder pending direct testing, not as a confirmed member of that scenario.

5. FIELD COMPARISON

IDDP-2 at Reykjanes is the strongest field anchor for the Best Case. The well reached approximately 4.66 km in basaltic oceanic crust and recorded around 426-427°C after partial heating, with later estimates near 535°C. Circulation losses and interpreted feed zones indicate that fracture-controlled permeability persisted at very high temperature (Friðleifsson et al., 2017; Kruszewski & Wittig, 2018). The well also shows that a mechanically favourable setting is not operationally simple: total losses, stuck pipe, corrosion and damage still occurred. The Best Case should therefore be understood as favourable reservoir mechanics rather than low engineering risk.

IDDP-1 at Krafla is a useful cautionary counterpoint rather than a further Best-Case test. The well was intended to reach approximately 4.5 km, but instead intersected rhyolitic magma at around 2.1 km, and subsequent testing produced superheated steam at wellhead temperatures near 450°C before valve malfunction, casing collapse and silica scaling forced termination (Elders et al., 2014). The lesson for the Best-Case scenario is that even favourable basaltic settings can carry severe, largely unpredictable engineering risk where drilling approaches active magmatic bodies, independent of the BDT zone mechanism itself.

Kakkonda WD-1a in Japan provides the clearest Mid Case comparison (Muraoka et al., 1998). The well exceeded 500°C in the granitic basement, but field indicators place the BDT zone-affected interval around 350-380°C. Below this interval, the system became conduction-dominated and poorly connected to productive fracture permeability. The case supports the granite experimental prediction that supercritical temperatures overlap the BDT zone, making permeability strongly dependent on fracture connectivity rather than temperature alone.

Larderello adds an important metamorphic-basement analogue (Bertani et al., 2018; Reinsch et al., 2017). The DESCRAMBLE Venelle-2 well recorded temperatures above 500°C near the K-horizon, a reflector interpreted by some authors as a BDT-related boundary. They experienced circulation losses but did not recover representative native formation fluid. This asymmetric response suggests local fracture or vein porosity without a laterally connected productive reservoir, reinforcing the Mid Case interpretation that quartzo-feldspar-rich basement may be hot but poorly connected near the BDT zone.

The Kenyan Rift systems, especially Menengai and Olkaria, are useful high-temperature volcanic analogues rather than direct framework anchors. Menengai wells have recorded near-critical temperatures at shallow depths, and modelling suggests a deeper superhot or supercritical regime, but drilling has also intersected shallow magmatic material and severe instability (O'Sullivan et al., 2015; Reinsch et al., 2017). Olkaria, by contrast, generally remains high temperature but subcritical at conventional production depths, with deeper supercritical conditions inferred rather than directly drilled. Together, these fields show that heat-source depth and magmatic proximity strongly influence whether high temperature becomes a producible reservoir or a drilling hazard.

Granite-hosted enhanced geothermal systems (EGS) provide a broader, lower-temperature test of the Mid Case mechanism than Kakkonda alone, summarised in Table 3. At Soultz-sous-Forêts, France, fractured granite at 4.5-5 km and approximately 200°C sustains circulation through a small number of critically stressed fault zones rather than pervasive matrix permeability (Genter et al., 2010; Valley & Evans, 2007). At Basel, Switzerland, stimulation of granite at 4.8-5 km and 180-200°C triggered induced seismicity large enough to end the project, showing that permeability creation in this lithology is tightly coupled to fault reactivation rather than distributed cracking (Häring et al., 2008). The Cooper

Basin Habanero project in Australia stimulated granite at 4.2-4.5 km, and 230-264°C, and again relied on a small number of major fracture zones (Baisch et al., 2006). Fenton Hill, USA, the original hot dry rock experiment, created connected permeability in granitic and granodioritic rock at 2.8-4.4 km and 195-327°C by hydraulically stimulating and linking existing fractures (Brown, 2009). Utah FORGE extend this pattern into granite at 2.5 km and 175-225°C (Cladouhos et al., 2016; Moore et al., 2022), while the Japanese hot-dry-rock sites Hijiori and Ogachi confirm similar granodiorite behaviour at shallower depth and lower temperature (Tezuka & Watanabe, 2000; Kaieda et al., 2010). Across this temperature range, from 175°C to over 500°C at Kakkonda, quartzo-feldspathic crystalline rock consistently behaves as a Mid Case lithology: permeability is real but structurally controlled, concentrated on discrete fractures or faults rather than distributed through the rock mass, and often requires stimulation to become productive.

Table 3: Granite-hosted EGS analogues supporting the Mid Case mechanism across a wide temperature range.

Project	Depth (km)	Temp. (°C)	Lithology
Soultz-sous-Forêts (France)	4.5-5	~200	Granite
Basel (Switzerland)	4.8-5	180-200	Granite
Cooper Basin Habanero (Australia)	4.2-4.5	230-264	Granite
Fenton Hill (USA)	2.8-4.4	195-327	Granite / granodiorite
Utah FORGE (USA)	2.5	175-225	Granitic basement
Hijiori (Japan)	1.8-2.2	250-270	Granodiorite
Ogachi (Japan)	1.0-1.1	228-240	Granodiorite

Table 4 extends this comparison to the primary field evidence used to test the framework directly, spanning the Best Case, Mid Case, and high-temperature volcanic analogues discussed above, as well as the provisional New Zealand application developed in Section 6.

Table 4: Field evidence used to test the mechanical scenario framework.

Project or field	Lithology	Temperature evidence	Role in framework validation
IDDP-2, Reykjanes	Basaltic oceanic crust	427°C after partial heating; later near 535°C	Best Case anchor
IDDP-1, Krafla	Rhyolite-intersected basaltic system	~450°C wellhead after magma intersection at ~2.1 km	Cautionary example, not a further Best Case test
Kakkonda WD-1a	Volcanic succession over granitic basement	>500°C at depth; brittle to ductile transition indicators near 350-380°C	Mid Case anchor
Larderello, Venelle-2	Metamorphic basement with granitoid intrusions	>500°C near K-horizon (3km)	Mid Case analogue
Menengai and Olkaria	Trachyte, phonolite, pyroclastics and interpreted deeper intrusive rocks	Menengai near 390°C at ~2.1 km; Olkaria mostly subcritical at production depths	High-temperature volcanic analogue
Rotokawa and wider TVZ	Andesite, altered volcaniclastics, greywacke and possible intrusive basement	Superhot potential inferred rather than directly drilled	New Zealand provisional application

6. NEW ZEALAND APPLICATION

The framework is most directly relevant to New Zealand through the TVZ and Rotokawa, where superhot exploration is being considered, but site-specific high-temperature mechanical data remain limited (Rowland & Sibson, 2004; Massiot et al., 2021). The application should be treated as provisional because Rotokawa Andesite, Torlesse and Waipapa greywacke, possible intrusive basement rock, and altered TVZ volcaniclastics have not yet been tested across the full range of temperature, pressure, pore-fluid, and strain-rate conditions required to define their BDT behaviour.

6.1 Rotokawa geological context

Rotokawa hosts more than 170 MWe of installed geothermal capacity and one of the most extensively studied subsurface datasets of any TVZ field, making it the natural priority site for New Zealand's first supercritical exploration programme. The shallow to intermediate reservoir is dominated by Rotokawa Andesite, a sequence of andesitic lava and volcaniclastic rock that hosts the current production interval, underlain at depth by a Mesozoic basement conventionally described as greywacke (McNamara et al., 2016). Deep resistivity and thermal data indicate a hot upflow beneath the current production zone, and this deeper interval, rather than the shallow andesite reservoir, is the notional target for future supercritical exploration. However, both Rotokawa Andesite and the underlying basement have been mechanically characterised mainly at or near ambient temperature (Villeneuve et al., 2025; Siratovich et al., 2016); their behaviour under the temperature, pressure and pore-fluid conditions relevant to a supercritical target is not yet directly constrained.

6.2 Torlesse and Waipapa greywacke: a provisional Mid Case analogue

Greywacke is a Quartzo-feldspathic metasedimentary rock, and its bulk mineralogy places it closer to the granite Mid Case anchor described in Section 3 (approximately 400±100°C) than to basalt (Hirth & Tullis, 1992; Rybacki et al., 2006). No dedicated high-temperature deformation dataset exists for greywacke; therefore, this placement is inferred from composition rather than measured.

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New Zealand's basement is also not mechanically uniform. It comprises two main terranes, Torlesse and Waipapa, which differ measurably in strength according to their source rock: Waipapa Terrane greywacke, sourced from andesitic-dacitic volcanic detritus, is mechanically stronger at ambient conditions than Torlesse Terrane greywacke, which is sourced from more quartz-rich granite-rhyolite detritus (McNamara et al., 2014). This strength contrast has been linked to differences in basement permeability between the Kawerau field, which sits on Waipapa-derived basement, and the Ohaaki field, which sits on Torlesse-derived basement (Wallis et al., 2012). The inference drawn from this fracture-productivity contrast is that the more feldspar-rich Waipapa greywacke may sustain brittle, fracture-controlled behaviour to greater temperature and depth than the more quartz-rich Torlesse type, broadly consistent with the quartz crystal-plasticity evidence reviewed in Section 3.2 (Hirth & Tullis, 1992). McNamara et al. (2014) confirm the ambient-condition strength difference between the two terranes but do not test it at BDT-relevant temperature, so the distinction remains provisional rather than settled.

The mineralogical basis for this inference follows directly from the experimental evidence in Section 3.2. Quartz begins to deform by dislocation creep at markedly lower temperatures than feldspar (Hirth & Tullis, 1992), so a more quartz-rich greywacke would be expected to enter distributed ductile behaviour at a lower temperature than a more feldspar-rich, plagioclase-dominated greywacke, all else being equal. Torlesse greywacke, sourced from granite-rhyolite detritus, is comparatively quartz-rich; Waipapa greywacke, sourced from andesite-dacite detritus, is comparatively plagioclase-rich and quartz-poor. This mineralogical contrast provides a plausible mechanism for the strength and fracture-productivity differences reported by McNamara et al. (2014) and Wallis et al. (2012), but it has not been tested directly: no published study has deformed Torlesse or Waipapa greywacke at BDT-relevant temperature while monitoring permeability, so the mechanism remains an inference rather than a demonstrated result.

Separately, Melia et al. (2022) show that macrofractures in Waipapa greywacke retain measurable permeability above the confining pressure at which fractures would nominally close, sustain by fragment propping and asperity generation at confining pressures of 95-150 MPa. This suggests that permeability decline with depth in greywacke may be more gradual than a simple binary BDT cut-off would imply, consistent with the permeability-redistribution behaviour of granite described in Section 3.3.

6.3 Evidence for intrusive and igneous bodies within the TVZ basement

A further complication is that the basement interval encountered by a future deep well at Rotokawa may not comprise a simple, texturally uniform greywacke succession. Rotokawa-specific zircon U-Pb geochronology shows that the drilled succession includes locally derived andesite and rhyolite lavas together with shallow rhyolitic intrusions above a basal andesite lava pile resting on Mesozoic greywacke basement (Milicich et al., 2020). At the regional scale, crustal synthesis indicates that the TVZ basement is heterogeneous, with crustal intrusive bodies interspersed vertically and horizontally with greywacke, making intermediate- to silicic-intrusive rocks difficult to distinguish geophysically from greywacke (Mortimer et al., 2023). Consequently, the basement intersected by a deep Rotokawa well may comprise greywacke together with intrusive bodies rather than a laterally continuous greywacke sequence.

More broadly across the TVZ, the regional basement synthesis of Mortimer et al. (2023) shows that deep geothermal and magmatic systems interact with a heterogeneous Mesozoic basement rather than a simple, uniform greywacke succession. Outcrop-analogue studies of thermo-physical rock properties have accordingly characterised both exposed greywacke and intrusive lavas as representative TVZ basement rock types, rather than treating greywacke alone as representative (Mielke et al., 2016). Taken together, this basement-scale evidence, the Rotokawa-specific geochronology of Milicich et al. (2020) and the crustal-scale terrane synthesis of Mortimer et al. (2023) indicate that the assumption of a simple, uniform greywacke basement beneath Rotokawa is not well supported and should be tested directly rather than carried forward into deep well planning by default.

This matters mechanically because intrusive rock of andesitic to rhyolitic composition would not necessarily follow the granite-like, Quartzo-feldspathic BDT zone assumed for greywacke. Depending on its crystallinity, glass content and alteration state, an intrusive body could behave closer to the Best Case crystalline mafic group, the Mid Case quartzo-feldspathic group, or, if altered or vesicular, closer to the Worst Case porous volcaniclastic group described in Section 3. A single deep well at Rotokawa could therefore cross greywacke, an unrelated intrusive body, and altered volcanic material within a short depth interval, each with a different BDT zone mechanism. Until cuttings or core from the relevant depth are examined petrographically, the mechanical classification of the 'basement' target at Rotokawa should be treated as unresolved rather than assumed to be a single Mid Case greywacke interval.

The practical risk this creates is asymmetric. If future drilling assumes a uniform greywacke basement and instead encounters a substantial intrusive body, both the anticipated BDT zone position and the anticipated permeability structure could be wrong in either direction: a mafic intrusive body might be more favourable than greywacke, while an altered or glassy intrusive margin could be considerably less favourable. Because the cost of a deep supercritical well is dominated by fixed costs that are not strongly dependent on which of these outcomes eventuates, resolving the basement's lithological identity before final well design is a comparatively low-cost way to reduce that uncertainty.

6.4 Existing modelling and its limits

The most relevant published supercritical reservoir model for Rotokawa treats the BDT zone as a fixed no-flow boundary at approximately 6 km below sea level, an assumption adopted for computational convenience rather than derived from a measured Rotokawa BDT zone (Carson, 2020). Sensitivity testing of that model shows that deep fault-zone permeability, not the precise BDT depth, is the parameter with the greatest influence on predicted upflow temperature and mass flux, which is consistent with the greywacke evidence above, where permeability appears to be controlled primarily by discrete fracture-scale connectivity rather than matrix flow.

A thermally controlled brittle-ductile transition model for TVZ-like settings suggests that the transition shallows from roughly 14-15 km outside geothermal areas to 6-8 km beneath them in response to local thermal structure (Kissling et al., 2009), which implies that a fixed 6 km boundary is, at best, a local approximation. Independently, reliable magnetotelluric resolution at Rotokawa currently extends only to about 1 km above sea level (Sewell et al., 2012), leaving a gap of several kilometres between the depths that can be directly imaged and the depths at which the supercritical target and its BDT zone are modelled to occur.

6.5 Recommendations

The most important New Zealand recommendation is therefore targeted mechanical characterisation before relying on the global framework, or on greywacke as a single representative basement lithology, for drilling decisions. Priority tests include high-temperature triaxial deformation, simultaneous permeability measurement, pore-fluid pressure control, alteration mineralogy characterisation and multiple strain rates, applied separately to Torlesse greywacke, Waipapa greywacke, Rotokawa Andesite, and any intrusive or igneous lithologies recovered in cuttings or core from the target depth. These tests would reduce the current reliance on Icelandic basalt, Westerly granite, and Krafla tuff analogues, and the untested assumption that Torlesse and Waipapa greywacke behave identically under New Zealand-specific mechanical constraints.

A second recommendation is to improve dynamic modelling of the BDT zone. Existing supercritical models often impose the BDT zone as a fixed no-flow or permeability-reduction boundary (Scott et al., 2015; Kissling et al., 2009). For TVZ applications, the boundary should instead respond to lithology, local thermal gradient, pore pressure, stress state, permeability evolution and alteration, and should be able to represent a compositional change in basement lithology with depth rather than assuming a single rock type throughout. This would allow Rotokawa-style models to test whether the target interval remains fracture-permeable, becomes stress-dependent, or crosses into compaction-limited behaviour during drilling and production (Croucher & O'Sullivan, 2008).

A third recommendation is deeper geophysical characterisation designed specifically around BDT-zone interpretation. Existing seismic and magneto telluric data can be re-examined for evidence of a seismic cut-off depth, deep resistivity contrasts, and possible high-temperature dehydrated zones. These indicators should not be used alone, but they can identify where a planned well may cross from a brittle fracture-controlled interval into a stress-dependent or compaction-prone interval, or from greywacke into a distinct intrusive body or igneous interval.

Finally, the framework should be modified for New Zealand as a depth-stratified risk tool. A single TVZ well may cross multiple mechanical regimes: altered volcaniclastics in the upper section, andesitic reservoir rocks at intermediate depths, greywacke, intrusive igneous rock, or some combination of the two at deeper levels. The relevant question is therefore not whether Rotokawa is globally Best, Mid or Worst Case, but which interval belongs to which mechanical regime, whether that interval is genuinely greywacke or an unrelated intrusive body, and how the well design should respond to each.

6.6 Distinguishing greywacke from intrusive rock during exploration

Because the mechanical classification of the deep target depends on which rock is present, practical means of distinguishing greywacke from intrusive material during exploration and drilling are as important as the mechanical testing itself. Regional geochronology, principally U-Pb zircon dating, can help distinguish Mesozoic greywacke from younger intrusive or volcanic material at the formation scale and has already been used to establish the presence of local andesite and rhyolite bodies above the basement at Rotokawa (Milicich et al., 2020). At the well scale, cuttings and core description supported by whole-rock geochemistry can identify intrusive textures and compositions that differ from the quartzo-feldspathic sandstone and argillite that make up greywacke.

Wireline logs may also assist (although alteration can obscure primary lithological contrasts): intrusive igneous rock and metasedimentary greywacke may exhibit contrasting density, resistivity and natural gamma responses, so unexpected log character changes within a nominal 'basement' interval can flag a lithological change worth sampling directly, before it is simply logged as more greywacke. None of these methods needs to be developed specifically for this framework; the recommendation is to apply them systematically at the depths relevant to a supercritical target, and to feed the result back into the mechanical testing programme in Table 5 rather than assuming lithological uniformity in advance.

Table 5: Recommended pre-drilling evidence for adapting the framework to New Zealand.

Evidence needed	Priority lithology or dataset	Recommended method	Decision value
Basement lithological identity	Torlesse greywacke, Waipapa greywacke, possible intrusive/igneous bodies	Petrographic and geochronological analysis of cuttings/core (e.g. U-Pb, whole-rock geochemistry)	Confirms whether the 'basement' target is genuinely greywacke or includes younger intrusive rock requiring separate characterisation
High temperature strength and BDT zone behaviour	Rotokawa Andesite, Torlesse greywacke, Waipapa greywacke and any confirmed intrusive lithologies	Triaxial deformation at relevant T, Peff, Pp and multiple strain rates	Defines whether the deep target is favourable or compaction prone
Permeability evolution during deformation	Andesite, greywacke and altered volcaniclastics	Continuous permeability measurement during loading and thermal cycling	Tests whether permeability is created, redistributed, sealed or irreversibly lost
Alteration and pore collapse risk	Tuff, ignimbrite and clay altered volcaniclastic intervals	QEMSCAN or SEM mineralogy plus hydrostatic P* testing	Identifies weak intervals that may need special drilling design or avoidance
Dynamic BDT zone position	Rotokawa reservoir model and regional TVZ thermal structure	TOUGH2 or AUTOUGH2 style simulations with evolving permeability and stress dependent functions	Replace static no-flow BDT assumptions with field-specific mechanical scenarios

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Pre-drilling geophysical screening	Existing seismicity, MT and resistivity datasets	Reinterpretation for seismicity cutoff depth and deep resistivity contrasts	Provides early evidence of where mechanical transition may begin before well commitment

The testing sequence in Table 5 is deliberately staged. It begins with confirming basement lithological identity and rock-mechanics testing, because both are the largest current uncertainties, then moves to modelling and geophysics, so that those thresholds can be placed into the field context. This order avoids treating deep temperature as the primary target criterion before mechanical viability, even though the composition of the target rocks is unknown.

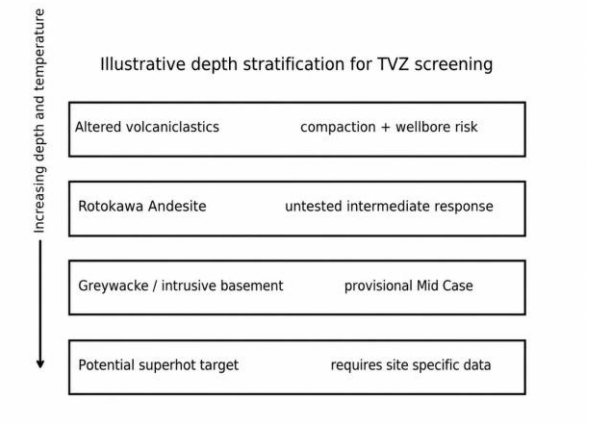


Figure 4: Illustrative depth stratification for applying the framework in the TVZ, including possible intrusive basement.

7. ENGINEERING IMPLICATIONS

The scenario framework translates geological interpretation into implications for drilling and reservoir engineering. In the Best Case, the main challenge is not creating permeability but managing extreme temperature, corrosion, scaling, thermal expansion, cement integrity and casing deformation. In the Mid Case, the main challenge is uncertainty: permeability may exist, but it may be poorly connected, stress-dependent or transient. In the Worst Case, the central risk is that permeability may be mechanically destroyed by pore collapse before stimulation can create a useful reservoir.

For New Zealand specifically, Mid Case uncertainty is compounded by basement heterogeneity: if the deep target at Rotokawa includes intrusive rock rather than, or in addition to, greywacke, its permeability response to drilling and stimulation cannot yet be anticipated from either the greywacke or the global granite evidence base. Well design and stimulation planning at Rotokawa should therefore allow for the possibility of an unexpected lithological or mechanical change with depth, rather than assuming a single Mid Case regime throughout the basement section.

Four screening indicators are especially useful before deep drilling. First, a threshold-like decline in permeability or poor productive fluid entry may indicate an approach to a BDT-affected interval. Second, seismicity cutoff depth provides a field-scale proxy for the lower limit of brittle failure. Third, deep resistivity contrasts may indicate zones of high temperature, dehydration, alteration, or reduced permeability, though these are not diagnostic without additional data. Fourth, wellbore instability, casing deformation, stuck pipe and persistent circulation anomalies provide operational evidence that the mechanical regime is changing. None of these indicators alone proves the BDT zone; their value lies in their combined interpretation.

These indicators can be strengthened where independent geophysical evidence is available. In Icelandic basaltic systems, magnetotelluric surveys typically show a shallow, smectite-controlled conductive cap giving way to a more resistive chlorite-stable zone around 230°C, with a deeper high-resistivity core interpreted to reflect mineral-dominated conduction as temperatures approach and exceed 400°C; where this deep resistive core coincides with the lower limit of local seismicity, both signals may jointly indicate approach to the BDT zone, although neither is diagnostic alone (Flóvenz & Vilhjálmsson, 2021; White et al., 2011; Ágústsson & Flóvenz, 2005). Equivalent resistivity and seismicity datasets already exist for parts of the TVZ and could be reinterpreted specifically for BDT zone proximity at comparatively low cost, as noted in Table 5.

8. DISCUSSION

The framework changes the way supercritical targets are screened. A purely thermal approach would rank systems by maximum temperature, pressure and proximity to a heat source. The evidence reviewed here shows that this is incomplete because the same 400-600°C temperature interval can occur in a brittle mafic system, a stress-dependent crystalline basement system, or a compacting volcaniclastic column. These settings have different drilling risks, stimulation needs and production potential. The screening question should therefore be reframed as: what is the deformation mechanism of the host rock at the target interval, and does that mechanism preserve or destroy connected permeability?

This shift matters for exploration economics. Deep wells are expensive, and supercritical drilling introduces high-temperature material limits, fluid instability, corrosion, and well-control risks. A well that reaches a very hot but sealed interval may prove the thermal resource while failing to establish a producible reservoir. Conversely, a slightly cooler but fracture-connected interval may be more valuable if it can sustain flow. The framework therefore supports a staged exploration workflow in which thermal targeting, lithological screening, geophysical evidence and mechanical testing are combined before committing to the deepest and most expensive drilling phase.

This has a direct bearing on how supercritical exploration risk is communicated to investment decision-makers. Framing a prospect purely in terms of temperature or resource size can overstate its readiness, because temperature alone says nothing about whether the fluid can be produced. Framing it instead in terms of a mechanical scenario, together with the specific evidence still required to confirm that scenario, gives a more defensible basis for staged investment: comparatively low-cost laboratory and geophysical work can substantially de-risk the decision to commit to an expensive deep well.

The three scenarios should not be interpreted as fixed labels for whole geothermal fields. They are interval-scale mechanical categories. A single well may pass through a Worst-Case shallow column, a transitional Mid Case reservoir interval and a more favourable deeper crystalline target. This is especially relevant in silicic volcanic provinces such as the TVZ, where shallow altered tuffs and ignimbrites may be mechanically weak even if the deeper target is stronger. In such systems, the drilling design must manage weak intervals and route to the target rather than classify the entire field as favourable or unfavourable.

The framework also helps clarify why field examples sometimes appear contradictory. IDDP-2 demonstrates that supercritical or near-supercritical temperatures can be reached in basalt while permeability remains, but it also shows that high-temperature engineering constraints can still limit utilisation (Friðleifsson et al., 2021). Kakkonda demonstrates that temperatures above 500°C do not guarantee a productive reservoir if the target has crossed into a poorly connected crystalline regime (Muraoka et al., 1998). Larderello demonstrates an intermediate response: high temperature, evidence for fracture or vein space, and fluid uptake without productive native return (Bertani et al., 2018). The wider EGS comparison in Table 3 shows the same Mid Case pattern recurring in granite from 175°C to over 500°C, across settings with very different tectonic histories. These outcomes are not contradictory once lithology, the BDT zone mechanism, and fracture connectivity are considered together.

For New Zealand, the implication is that supercritical exploration should avoid treating the TVZ, or even the Rotokawa basement alone, as a single lithological class. Rotokawa Andesite, Torlesse greywacke, Waipapa greywacke, altered volcaniclastics and possible intrusive intervals each require separate mechanical characterisation, and current evidence, principally the basement geochronology of Milicich et al. (2020) and the terrane-scale synthesis of Mortimer et al. (2023), cannot yet confirm which of these the deepest target interval will actually be. The global framework can identify the likely risk categories, but it cannot confidently assign them without New Zealand-specific data, and it certainly cannot assume that all TVZ basements will behave as a single generic 'greywacke' Mid Case analogue. The most useful near-term outcome is therefore not a definitive prediction of BDT zone depth, but a prioritised testing and modelling programme, beginning with confirming what rock is present at target depth, that reduces uncertainty before deep drilling.

9. LIMITATIONS

The framework is intentionally a screening tool rather than a predictive numerical model. It does not calculate the BDT zone depth for a specific field, nor does it replace site-specific geomechanical modelling. Its value lies in identifying which mechanical evidence is required to confidently classify a supercritical target.

The Best and Mid Case scenarios have field anchors, but the Worst Case remains experimentally supported and not field-confirmed at supercritical depth. This does not make it irrelevant; rather, it means that altered volcaniclastic risk should be evaluated through core testing, cuttings analysis, alteration mapping and modelling before drilling decisions are made.

The framework also does not explicitly model the loss of chemical permeability. Supercritical and superheated fluids can enhance permeability through thermal cracking, while silica scaling, mineral precipitation and alteration can destroy permeability over operational time scales. Future versions should couple mechanical permeability evolution with reactive transport and production-driven stress redistribution.

The granite EGS comparison in Table 3 also has a specific limitation: with the exception of Kakkonda, these systems were stimulated at temperatures well below the supercritical threshold, so their consistent Mid Case behaviour supports the granite BDT zone mechanism but does not by itself confirm how that mechanism behaves at true supercritical temperature and pressure.

A further limitation specific to the New Zealand application is that the mechanical distinction drawn here between Torlesse and Waipapa greywacke has not been validated by high-temperature deformation experiments representative of brittle–ductile transition conditions. Likewise, the possibility that Rotokawa's deep basement includes intrusive lithologies is supported by regional geological, geochronological and crustal studies together with analogue outcrop investigations, rather than by direct petrographic confirmation from the depths targeted for supercritical exploration. Both uncertainties should be addressed through analysis of future drill core or cuttings before they are incorporated as established inputs to Rotokawa-specific mechanical models.

10. CONCLUSIONS

- The BDT zone should be treated as a lithology-dependent mechanical transition rather than a universal depth or temperature. Superhot and supercritical temperatures are necessary for high-energy geothermal development but are insufficient to define a viable resource.

- The most favourable mechanical setting is low-porosity, glass-poor mafic crust where brittle-fracture permeability can persist into the superhot window. Quartzo-feldspathic crystalline basement forms an intermediate case because its BDT zone can likely overlap the supercritical threshold, permeability becomes strongly stress- and fracture-controlled, and, in some cases, can be enhanced rather than destroyed near the transition. Porous or hydrothermally altered volcaniclastics pose the highest risk because pressure-controlled compaction may irreversibly reduce permeability.

- Global drilling evidence supports the proposed Best and Mid Case scenarios through IDDP-2, Kakkonda, Larderello and a wider suite of granite-hosted EGS projects, but the Worst Case remains experimentally supported and field-unconfirmed. This is an important knowledge gap because many silicic volcanic systems, including parts of the TVZ, contain altered volcaniclastic intervals that may need to be drilled before stronger target rocks are reached.

- For New Zealand, Torlesse and Waipapa greywacke should not be treated as a single,

uniform Mid Case analogue: ambient-condition evidence suggests they differ in strength, and neither has been tested at BDT-relevant temperature. The basement interval encountered by a deep well may also include intrusive or igneous rock rather than, or in addition to, greywacke, with its own unknown BDT zone mechanism, as indicated by Rotokawa-specific geochronology and regional basement studies (Milicich et al., 2020; Mortimer et al., 2023).

- Distinguishing greywacke from possible intrusive rock during exploration is achievable with established methods, including regional geochronology, cuttings and core geochemistry, and wireline log character, and should be applied systematically at target depth rather than assumed from regional geological maps alone.

- The immediate next step for New Zealand is therefore not deeper drilling alone. It is targeted laboratory testing that first confirms basement lithological identity and then characterises its high-temperature mechanical behaviour, combined with dynamic BDT zone modelling and deeper geophysical characterisation, to adapt the global framework to Rotokawa's specific lithological sequence.

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REFERENCES

Ágústsson, K., & Flóvenz, Ó. G. (2005). The thickness of the seismogenic crust in Iceland and its implications for geothermal systems. *Proceedings World Geothermal Congress 2005*, Antalya, Turkey.

Baisch, S., Weidler, R., Vörös, R., Wyborn, D., & de Graaf, L. (2006). Induced seismicity during the stimulation of a geothermal HFR reservoir in the Cooper Basin, Australia. *Bulletin of the Seismological Society of America, 96*(6), 2242-2256.

Bertani, R., Büsing, H., Buske, S., Dini, A., Hjelstuen, M., Luchini, M., Manzella, A., Nybo, R., Rabbel, W., Serniotti, L., & the DESCRAMBLE Science and Technology Team. (2018). The first results of the DESCRAMBLE project. *Proceedings of the 43rd Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, SGP-TR-213.

Brown, D. W. (2009). Hot dry rock geothermal energy: Important lessons from Fenton Hill. *Proceedings of the 34th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California.

Carson, B. (2020). *Investigation of the Rotokawa Geothermal System and feasibility of supercritical fluid production within the TVZ through supercritical TOUGH2 numerical modelling*. Victoria University of Wellington Open Access Repository.

Cladouhos, T. T., Petty, S., Nordin, Y., Moore, M., Grasso, K., Uddenberg, M., Swyer, M., Julian, B., & Foulger, G. (2016). Results from Newberry Volcano EGS demonstration. *Proceedings, 41st Workshop on Geothermal Reservoir Engineering*, Stanford University.

Croucher, A. E., & O'Sullivan, M. J. (2008). Application of the computer code TOUGH2 to the simulation of supercritical conditions in geothermal systems. *Geothermics, 37*, 622-634.

Eggertsson, G. H., Kendrick, J. E., Weaver, J., Wallace, P. A., Utley, J. E. P., Bedford, J. D., Allen, M. J., Markússon, S. H., Worden, R. H., Faulkner, D. R., & Lavallée, Y. (2020). Compaction of hyaloclastite from the active geothermal system at Krafla Volcano, Iceland. *Geofluids, 2020*, Article 3878503.

Elders, W. A., Friðleifsson, G. Ó., & Albertsson, A. (2014). Drilling into magma and the implications of the Iceland Deep Drilling Project for high-temperature geothermal systems worldwide. *Geothermics, 49*, 111-118.

Farquharson, J. I., Baud, P., & Heap, M. J. (2017). Inelastic compaction and permeability evolution in volcanic rock. *Solid Earth, 8*, 561–581.

Flóvenz, Ó. G., & Vilhjálmsson, A. M. (2021). The relation between resistivity and temperature in the basaltic crust of Iceland. *Proceedings World Geothermal Congress 2020+1*, Paper 13051.

Friðleifsson, G. Ó., Elders, W. A., Zierenberg, R. A., Stefánsson, A., Fowler, A. P. G., Weisenberger, T. B., Harðarson, B. S., Mesfin, K. G., & Óskarsson, F. (2017). The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2, in the seawater-recharged Reykjanes geothermal field in SW Iceland has successfully reached its supercritical target. *Scientific Drilling, 23*, 1-12.

Friðleifsson, G. Ó., Elders, W. A., Zierenberg, R. A., Stefánsson, A., Fowler, A. P. G., Weisenberger, T. B., Harðarson, B. S., Mesfin, K. G., & Óskarsson, F. (2021). The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2 at Reykjanes: Drilling into the root zone of a black smoker analog. *Geothermics, 90*, 101931.

Genter, A., Evans, K., Cuenot, N., Fritsch, D., & Sanjuan, B. (2010). Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems. *Comptes Rendus Geoscience, 342*(7-8), 502-516.

Häring, M. O., Schanz, U., Ladner, F., & Dyer, B. C. (2008). Characterisation of the Basel 1 enhanced geothermal system. *Geothermics, 37*(5), 469-495.

Heap, M. J., Bayramov, K., Meyer, G. G., Violay, M., Wadsworth, F. B., & Lavallée, Y. (2024). Compaction and permeability evolution of tuffs from Krafla Volcano, Iceland. *Journal of Geophysical Research: Solid Earth, 129*, e2024JB029067.

Hirth, G., & Tullis, J. (1992). Dislocation creep regimes in quartz aggregates. *Journal of Structural Geology, 14*(2), 145-159.

Kaieda, H., Jones, R. H., Moriya, H., Sasaki, S., & Ushijima, K. (2010). Ogachi HDR project and future geothermal development in Japan. *Proceedings, World Geothermal Congress 2010*, Bali, Indonesia.

Kissling, W. M., Ellis, S., Charpentier, F., Bignall, G., & Bibby, H. (2009). Convective flows in a TVZ-like setting with a brittle–ductile transition. *Transport in Porous Media, 77*, 335–355.

Kruszewski, M., & Wittig, V. (2018). Review of failure modes in supercritical geothermal drilling projects. *Geothermal Energy, 6*, Article 28.

Massiot, C., Milicich, S. D., Miller, C. A., Bertrand, E. A., Villamor, P., et al. (2021). Scientific Drilling in the Taupō Volcanic Zone? Exploring Intense Volcanic and Geothermal Processes in a Rapidly Rifting Arc. *World Geothermal Congress 2020*.

McNamara, D. D., Faulkner, D., & McCarney, E. (2014). Rock properties of greywacke basement hosting geothermal reservoirs, New Zealand: Preliminary results. *Proceedings, 39th Workshop on Geothermal Reservoir Engineering*, Stanford University.

McNamara, D. D., Sewell, S., Buscarlet, E., & Wallis, I. C. (2016). A review of the Rotokawa Geothermal Field, New Zealand. *Geothermics, 59*, 281-293.

Melia, A., Kummerow, J., Bjørnerud, M., Faulkner, D. R., & McNamara, D. D. (2022). Physical property characterization of the Waipapa greywacke: An important geothermal reservoir basement rock in New Zealand. *Geothermal Energy, 10*, Article 11.

Meyer, G. G., Shahin, G., Cordonnier, B., & Violay, M. (2024). Permeability partitioning through the brittle-to-ductile transition and its implications for supercritical geothermal reservoirs. *Nature Communications, 15*, Article 7753.

Mielke, P., Weinert, S., Bignall, G., & Sass, I. (2016). Thermo-physical rock properties of greywacke basement rock and intrusive lavas from the Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research, 324*, 179-189.

Milicich, S. D., Chambefort, I., Wilson, C. J. N., Alcaraz, S., Ireland, T. R., Bardsley, C., & Simpson, M. P. (2020). A zircon U-Pb geochronology for the Rotokawa geothermal system, New Zealand, with implications for Taupō Volcanic Zone evolution. *Journal of Volcanology and Geothermal Research, 389*, 106729.

Milicich, S.D., Mortimer, N., Villamor, P., Wilson, C.J.N., Chambefort, I., Sagar, M.W., & Ireland, T.R. (2020). The Mesozoic terrane boundary beneath the Taupo Volcanic Zone, New Zealand, and potential controls on geothermal system characteristics. New Zealand Journal of Geology and Geophysics, 64(4), 499–520.

Moore, J. N., Simmons, S. F., Allis, R., Jones, C., Bartley, J. M., & McLennan, J. (2022). The Utah FORGE site: A laboratory for enhanced geothermal system development. *Proceedings, 47th Workshop on Geothermal Reservoir Engineering*, Stanford University.

Mortimer, N., Charlier, B. L. A., Rooyakkers, S. M., Turnbull, R. E., Wilson, C. J. N., Negrini, M., Bannister, S., Milicich, S. D., Chambefort, I., Miller, C. A., & Kilgour, G. (2023). Crustal basement terranes under the Taupō Volcanic Zone, New Zealand: Context for hydrothermal and magmatic processes. *Journal of Volcanology and Geothermal Research, 440*, 107855.

Muraoka, H., Uchida, T., Sasada, M., Yagi, M., Akaku, K., Sasaki, M., Yasukawa, K., Miyazaki, S., Doi, N., Saito, S., Sato, K., & Tanaka, S. (1998). Deep geothermal resources survey program: Igneous, metamorphic and hydrothermal processes in a well encountering 500°C at 3729 m depth, Kakkonda, Japan. *Geothermics, 27*(5–6), 507–534.

O'Sullivan, J., Kipyego, E., Croucher, A., Ofwona, C., & O'Sullivan, M. J. (2015). A supercritical model of the Menengai geothermal system. In *Proceedings World Geothermal Congress 2015*, Melbourne, Australia.

Petrini, C., Madonna, C., & Gerya, T. (2021). Inversion in the permeability evolution of deforming Westerly granite near the brittle-ductile transition. *Scientific Reports, 11*, Article 23633.

Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F., & Sanjuan, B. (2017). Utilizing supercritical geothermal systems: A review of past ventures and ongoing research activities. *Geothermal Energy, 5*, Article 16.

Rowland, J. V., & Sibson, R. H. (2004). Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand. *Geofluids, 4*, 259-283.

Rybacki, E., Gottschalk, M., Wirth, R., & Dresen, G. (2006). Influence of water fugacity and activation volume on the flow properties of fine-grained anorthite aggregates. *Journal of Geophysical Research: Solid Earth, 111*, B03203.

Scott, S., Driesner, T., & Weis, P. (2015). Geologic controls on supercritical geothermal resources above magmatic intrusions. *Nature Communications, 6*, Article 7837.

Scott, S., Driesner, T., & Weis, P. (2017). Boiling and condensation of saline geothermal fluids above magmatic intrusions. *Geophysical Research Letters, 44*, 1696-1705.

Sewell, S. M., Cumming, W., Azwar, L., & Bardsley, C. J. (2012). Integrated MT and natural state temperature interpretation for a conceptual model supporting reservoir numerical modelling and well targeting at the Rotokawa Geothermal Field, New Zealand. *Proceedings, 37th Workshop on Geothermal Reservoir Engineering*, Stanford University.

Siratovich, P. A., Heap, M. J., Villeneuve, M. C., Cole, J. W., Kennedy, B. M., Davidson, J., & Reuschlé, T. (2016). Mechanical behaviour of the Rotokawa Andesites, New Zealand: Insight into permeability evolution and stress-induced behaviour in an actively utilised geothermal reservoir. *Geothermics, 64*, 163-179.

Tezuka, K., & Watanabe, K. (2000). Fracture network modelling of Hijiori hot dry rock reservoir by

ISSN 2703-4275

deterministic and stochastic methods. *Proceedings, World Geothermal Congress 2000*, Kyushu-Tohoku, Japan.

Valley, B., & Evans, K. F. (2007). Stress state at Soultz-sous-Forêts to 5 km depth from wellbore failure and hydraulic observations. *Proceedings, 32nd Workshop on Geothermal Reservoir Engineering*, Stanford University.

Villeneuve, M. C., Jones, T. P. C., Heap, M. J., Kennedy, B. M., Cole, J. W., & Siratovich, P. A. (2025). Physical and mechanical depth relationships of rocks from the Rotokawa Geothermal Reservoir, Taupō Volcanic Zone, New Zealand. *New Zealand Journal of Geology and Geophysics, 68*(3), 474-492.

Violay, M., Gibert, B., Mainprice, D., Evans, B., Dautria, J. M., Azais, P., & Pezard, P. (2012). An experimental study of the brittle ductile transition of basalt at oceanic crust pressure and temperature conditions. *Journal of Geophysical Research: Solid Earth, 117*, B03213.

Violay, M., Gibert, B., Mainprice, D., & Burg, J. P. (2015). Brittle versus ductile deformation as the main control of the deep fluid circulation in oceanic crust. *Geophysical Research Letters, 42*, 2767-2773.

Violay, M., Heap, M. J., Acosta, M., & Madonna, C. (2017). Porosity evolution at the brittle–ductile transition in the continental crust: Implications for deep hydro-geothermal circulation. *Scientific Reports, 7*, Article 7705.

Wallis, I. C., McNamara, D. D., Rowland, J. V., & Massiot, C. (2012). The nature of fracture permeability in the basement greywacke at Kawerau Geothermal Field, New Zealand. *Proceedings, 37th Workshop on Geothermal Reservoir Engineering*, Stanford University.

Watanabe, N., Egawa, M., Sakaguchi, K., Ishibashi, T., & Tsuchiya, N. (2019). Cloud-fracture networks as a means of accessing superhot geothermal energy. *Scientific Reports, 9*, 939.

White, R. S., Drew, J., Martens, H. R., Key, J., Soosalu, H., & Jakobsdóttir, S. S. (2011). Dynamics of dyke intrusion in the mid-crust of Iceland. *Earth and Planetary Science Letters, 304*(3-4), 300-312.

Zhu, W., Baud, P., Vinciguerra, S., & Wong, T.-F. (2016). Micromechanics of brittle faulting and cataclastic flow in Mount Etna basalt. *Journal of Geophysical Research: Solid Earth, 121*, 4268-4289.