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EXECUTIVE SUMMARY

GNS Science has undertaken preliminary studies related to a proposed damsite (A7) on the Makaroro River in Central Hawke's Bay near Wakarara, with particular regards to issues concerning active faulting. The project was commissioned by the Hawke's Bay Regional Council (HBRC; the Client) through Tonkin & Taylor Ltd (T&T). The objective was to map potentially active faults in the vicinity of the A7 dam site and provide information on the potential for faulting in the damsite and area surrounding the site. After visiting the site, both GNS and T&T have recognised that the original brief was too simple in scope and that a broader, staged approach is required on behalf of the Client. A staged approach of investigations is required ahead of constructing a large dam in a moderately high tectonic environment such as the central Hawke's Bay ranges. For that reason, we have developed a medium term project philosophy and a detailed list of recommendations with priority given to work which will, at an early stage, define high risks to the viability of the project in regard to potential active faulting.

We have reviewed existing published and unpublished literature, undertaken analysis and mapping of a number of fault related features using aerial photographs, and LiDAR DEM and undertaken a 2-day field reconnaissance trip.

The damsite is located within a greywacke range known as the Wakarara Range or Wakarara Block. The block is bounded active faults that lay within c. 3 km of the proposed A7 Makaroro River damsite. Because the Wakarara Block displays bedrock structures that are favourably oriented to potential movement with the current tectonic regime, we have assessed aspects of primary fault rupture, as well as secondary deformations within the block. One potential bedrock lineament, mapped on the upcoming QMap Hawke's Bay sheet, is shown as intersecting the damsite.

Primary fault rupture along the main active fault is not likely to occur within the site area. However we cannot rule out potential secondary rupture at the damsite based on current information. Primary fault rupture will also produce strong ground shaking at the site.

We have mapped active fault traces, inferred fault traces, bedrock related features, lineaments, and folds, within 5 km of the site, to establish a fault movement model of the area to understand the different roles of the major active faults, and gain insights into possible secondary faulting within the Wakarara Block.

Based on our mapping and the kinematic model (model of fault motion), we conclude that primary fault rupture and large (Mw 6-7+) earthquakes will occur along the main active faults that bound the Wakarara Block. These are all within 3.5 km of the damsite and are the following:

- The Mohaka Fault, a NNE-striking, active dextral-slip fault within the North Island Dextral Fault Belt with a slip rate of c. 3-4 mm/yr.
- The Wakarara/Rangefront Fault, a pair of NNE-striking and west-dipping reverse-slip faults at the front of the Wakarara Range.
- The Mangataura Fault, a SE-striking active fault recognised on the LiDAR and during the field reconnaissance. Little is known about this fault, though we suspect it could be a strike-slip tear fault that separates the Rangefront and Wakarara faults along strike.

The proximity of the site to the major active faults suggests the possibility of uplift, folding and faulting within the block between the Mohaka and Wakarara faults. Independent failure of the Mohaka Fault and the Wakarara Fault, and/or concurrent co-seismic failure of both faults can produce deformation within the Wakarara Block, which must also be considered as a possible hazard to the A7 dam. Bedrock defects at, or close to, the site are favourably oriented to movement in conjunction with rupture of the major faults around the damsite.

Our main recommendation is that the Client works closely with T&T and GNS Science to develop a multi-staged work plan evaluating the feasibility of constructing the A7 Makaroro River dam. We recommended the following staged investigations:

- Phase 2a Investigations

We consider that the highest priorities for the next round of investigations are: (i) site investigations (paleoseismic trenches) that test whether there is an identifiable and measurable displacement hazard to the foundation of the proposed A7 damsite; and (ii) geologic mapping that furthers the understanding of bedrock structure and potential secondary deformation to the damsite and its surrounds.

- Phase 2b Investigations

We recommend that two lines of approach are considered for understanding the possibility of slip on secondary features adjacent to the Mohaka Fault. These are (i) further trench investigations across other bedrock/bedrock faults that have been identified as possible slip surfaces during Phase 2a mapping; and (ii) a synthesis of analogue historical surface ruptures to consider the extent and characteristics of secondary slip that occurred in association with those events.

- Phase 3 Investigations

If earlier phases of investigation do not rule out the viability of the A7 damsite then additional information of the nearby active faults will be needed for an updated seismic hazard analysis including local earthquake design spectra for the A7 damsite. Paleoseismic trenching of the Mohaka, Rangefront, Wakarara, and Mangataura faults would determine the timing, frequency, amount and style of slip for past rupture events on these faults.

1.0 INTRODUCTION

1.1 Project Outline and Brief

The Hawke's Bay Regional Council (HBRC; the Client) through Tonkin & Taylor Ltd (T&T) have requested that GNS Science (GNS) provide a report outlining issues concerning active faulting in the vicinity of a planned Water Augmentation Scheme in Central Hawke's Bay, and to provide recommendations concerning the proposed A7 damsite on the Makaroro River. The technical content of the project brief stated:

In Phase 1, our objective is **to map potentially active faults in the vicinity of the A7 dam site**. To achieve this, we have highlighted four tasks:

- 1a Review of existing literature, geological maps, topographic maps, digital elevation models (DEMs) and aerial photos of the site and surrounding area (within a 5 km radius of the proposed site) to identify geomorphic or geological features that could be active faults.
- 1b Mapping of potentially active fault lines at highest resolution possible to assess their location with respect to the site and/or their potential extension into the site. This will also entail geo-referencing of old aerial photos or other documents where potentially active faults can be identified.
- 1c Field reconnaissance of features identified in 1a and 1b to assess whether they are active faults. This reconnaissance took place over 2 full days.
- 1d Reporting on results with recommendations for further work if needed. The current report comprises Task 1d.

After visiting the site, both GNS and T&T have recognised that this brief is perhaps too simple to provide the client with best possible advice on how to develop a staged approach toward constructing a large dam in a moderately high tectonic environment such as the central Hawke's Bay ranges. Our goal is that the Client makes informed decisions and avoids both economic and natural risks associated with such a major project.

Therefore, as part of the scope of work GNS has agreed to write a medium term project philosophy and to develop a detailed list of recommendations with priority given to work which will, at an early stage, identify potential risks that could compromise the viability of the project. During the field reconnaissance GNS was also asked to provide advice on landsliding as a risk to the dam site and reservoir. At this point, we are not able to provide this information within the brief of this project.

1.2 The A7 Makaroro River dam site

The A7 Makaroro River dam is part of a wider Central Hawke's Bay Water Augmentation scheme that will bring water from the Makaroro and Makaretu (site D5) headwaters into 4 areas for storage and distribution for irrigation (Fig. 1). These two possible dams form the most significant hazard prone structures required for the proposed irrigation development.

The A7 Makaroro River dam site is located in Central Hawke's Bay District, 60 km southwest of Napier, near the locale of Wakarara at NZMS 260 U22/907537 (Fig. 1). The site is located

within a gorge section of the Makaroro River, a tributary of the Waipawa-Tukituki river system that drains to Hawke Bay. The site is located within the “Wakarara Block”, a narrow (5 km wide) greywacke range to the east of the Ruahine Ranges. The damsite is located in close proximity to a number of active faults including the Mohaka, Wakarara/ Rangefront and the Mangataura faults (Figs. 2, 3). Some of the geology and earthquake shaking hazards that could affect the district and in proximity to this damsite were outlined in an earlier GNS report (Langridge et al. 2010).

On the true left side of the valley, much of the land and approaches are through Smedley Station. On the true right bank the main access points to the site are from Wakarara Road and Rangimarie Station. The current plan is to construct a c. 70 m high dam for irrigation purposes, to be constructed as a Rolled Compacted Concrete (RCC), Concrete Faced Rockfill (CFRF) or Zoned Embankment dam. The left abutment of the dam is proposed to be sited in greywacke bedrock, in a steep sided face above the river. The right abutment of the dam will also be built on greywacke bedrock after excavation of alluvial terraces.

Preliminary studies by T&T at the A7 site include aerial photo analysis and interpretation, bedrock and shear mapping along the Makaroro River, and shallow geophysical studies across the high river terrace adjacent to the proposed right abutment of the dam. The A7 reservoir related to this dam will extend c. 5 km upstream and will flood farm land and overlap the trace of the active Mohaka Fault. Bedrock geology changes to the northwest of the Mohaka Fault, where folded Tertiary marine rocks predominate.

1.3 Hazards from Earthquakes

The proposed A7 Makaroro damsite occurs within the southwestern part of Hawke’s Bay region (Figs. 1, 2), to the east of the Ruahine Ranges and west of the Dannevirke or Ruataniwha Depression, an area of subdued topography and typically young surficial (Quaternary) geology with somewhat lesser tectonic activity compared to the ranges to the northwest and southeast of it (Fig. 3).

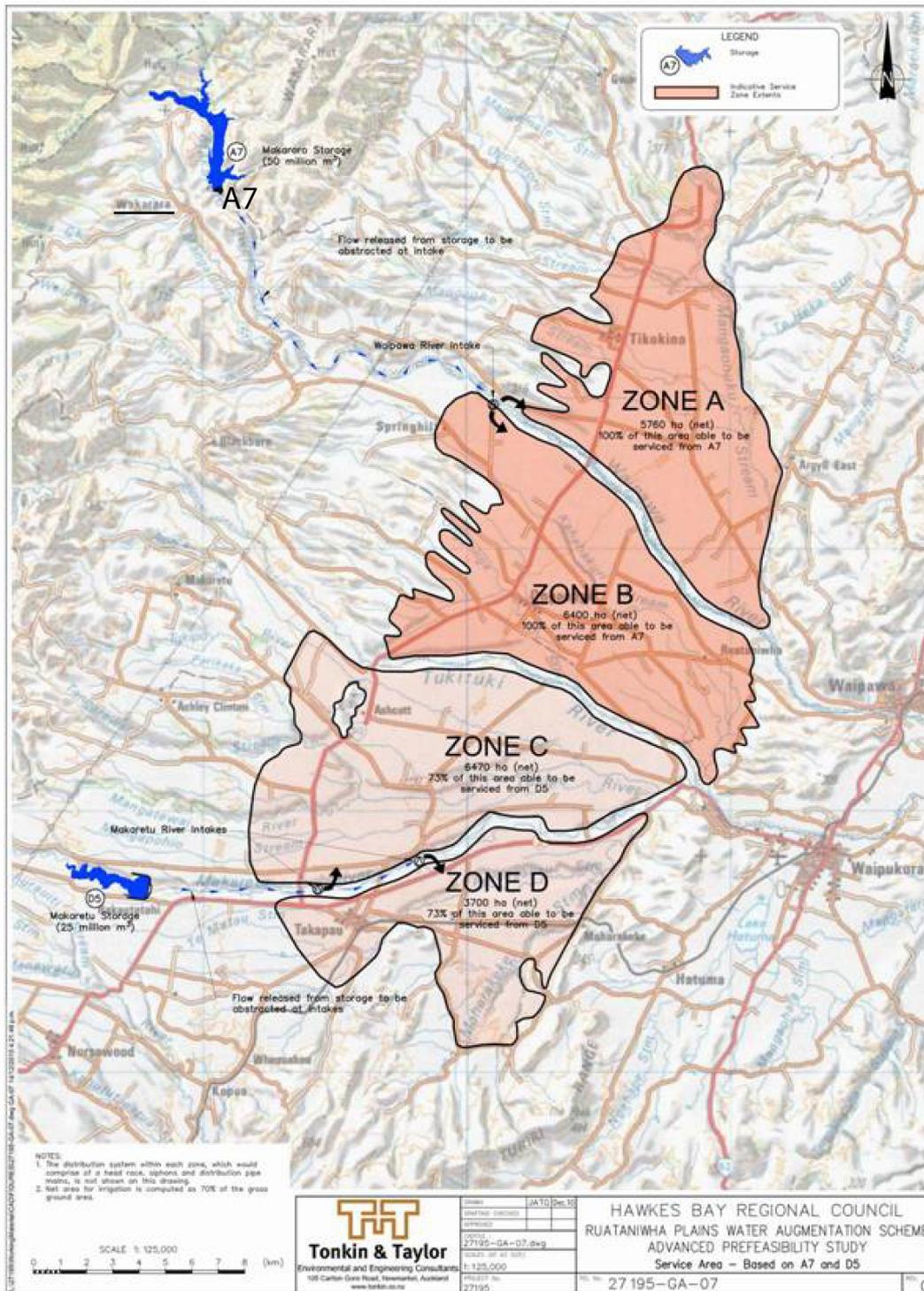


Figure 1 Regional plan for the Central Hawke’s Bay Water Augmentation scheme. The proposed A7 Makaroro River damsite and reservoir are located in the top left of the map near the locale of Wakarara (underlined).

1.3.1 Regional tectonic setting

New Zealand straddles the boundary of the Australian and Pacific plates, where relative plate motion (which varies from 30 to 50 mm/year) is obliquely convergent across the plate

boundary (Fig. 2). That relative plate motion is expressed in New Zealand by the presence of many active faults (Figs. 2, 3), a high rate of “small-to-moderate” earthquakes ($M < 7$), the occurrence of many “large” earthquakes ($M 7-7.9$), and one “great” earthquake ($M > 8$) in historical time (Fig. 4). The most recent moderate to large earthquakes in New Zealand’s historical record are the 2010 Darfield and 2011 Christchurch earthquakes (Gledhill et al., 2010).

The North Island is dominated by deformation related to the Hikurangi subduction margin. This margin is characterised by a northwest-dipping subduction zone and by a 450 km long zone of right-lateral oblique slip faulting, called the North Island Dextral Fault Belt (NIDFB; Beanland 1995). A significant proportion of the relative plate motion across North Island is accommodated by slip and large earthquakes on the faults of the NIDFB (Beanland et al., 1998). The proposed Central Hawke’s Bay Water Augmentation Scheme lies between the eastern edge of the North Island Axial Ranges and the western edge of the Hawke’s Bay coastal ranges, within one of the more tectonically active parts of this boundary zone (Fig. 3).

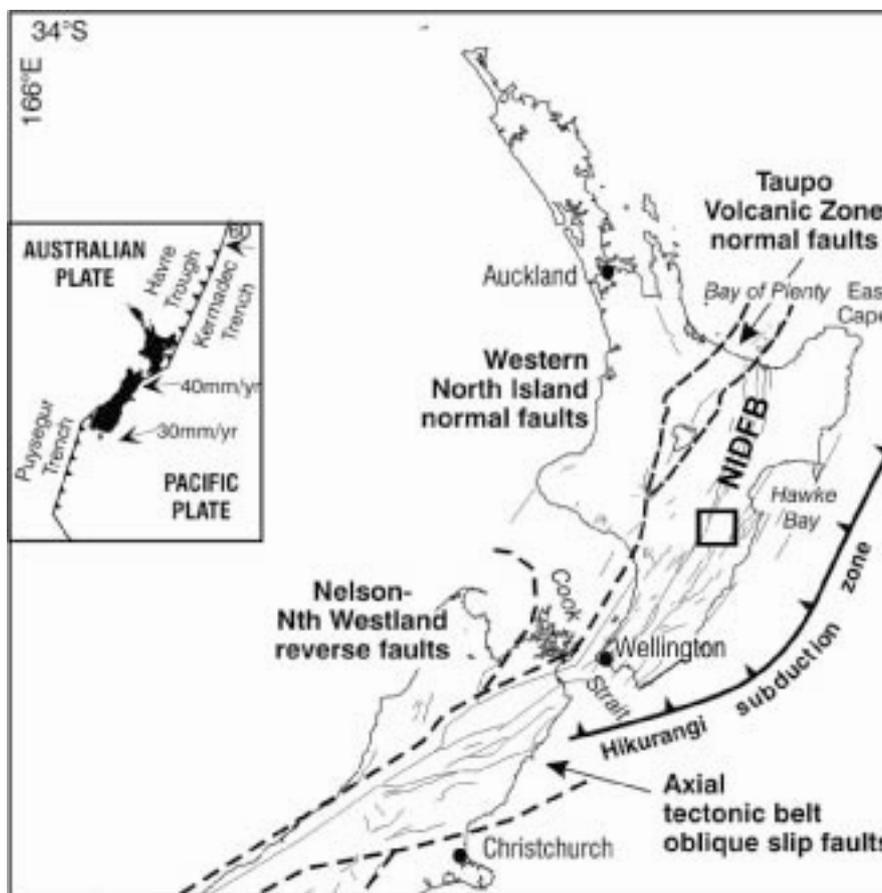


Figure 2 Plate tectonic setting of northern and central New Zealand showing the major tectonic zones in and the representative style of movement within the zones. Grey lines are active faults. The wider study area of Figure 1 in central Hawke’s Bay is outlined by a bold box.

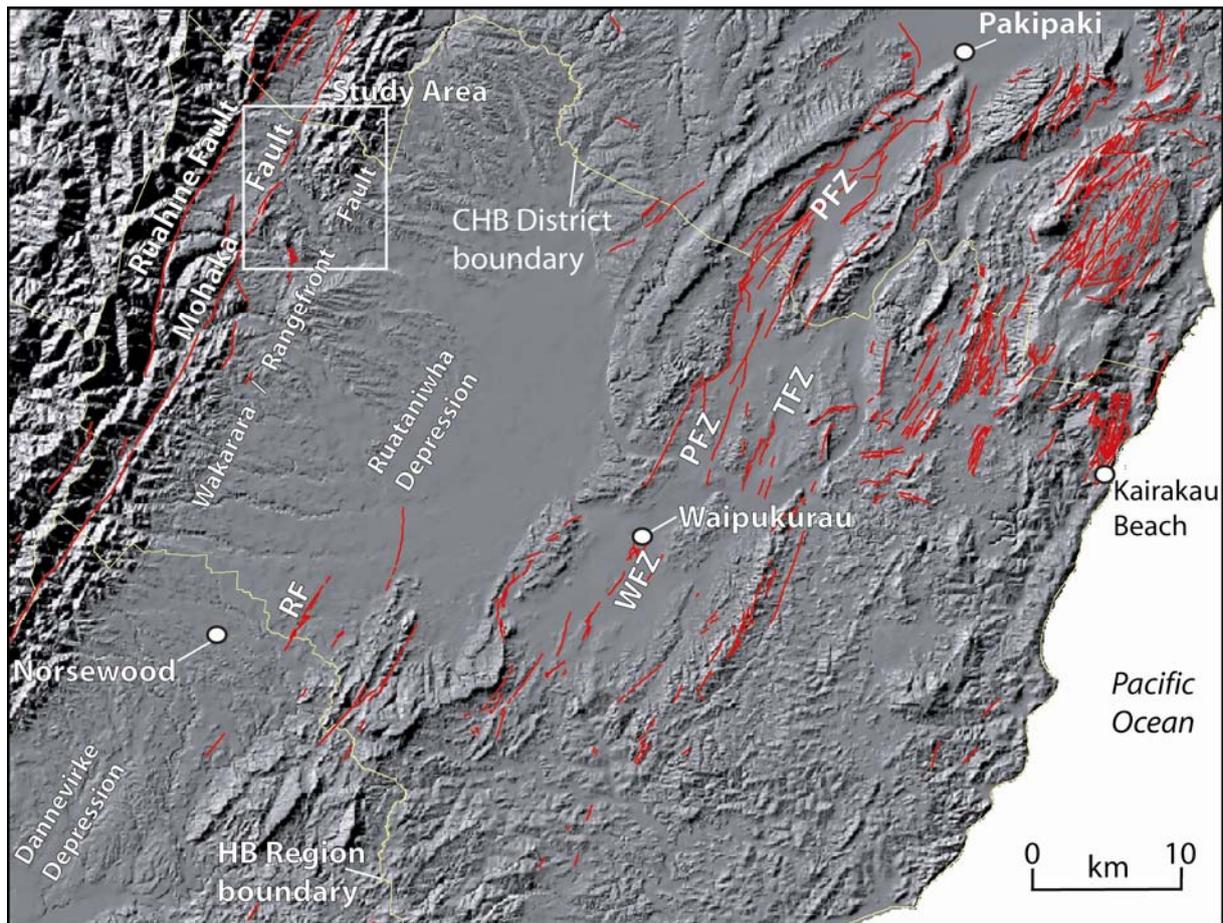


Figure 3 Active fault map of central Hawke's Bay and surrounds over a Digital Elevation Model. The area of the interest for the A7 Makaroro River dams site is shown by the white box. Red lines represent known active fault traces from the GNS Science Active Faults database (<http://data.gns.cri.nz/af/>), including the: RF, Ruataniwha Fault, WFZ, Waipukurau Fault Zone, PFZ, Poukawa Fault Zone, and TFZ, Tukituki Fault Zone. The regional and district boundaries are coloured yellow.

1.3.2 Regional seismicity

The Hawke's Bay region has a well-documented record of historical earthquakes (Fig. 4) that have been both damaging and destructive. Early in New Zealand's historic record, two significantly large earthquakes occurred between 1840 and 1870. A large event in 1843 has now been assigned to the area of the Axial Ranges in Hawke's Bay, based on shaking intensity contours. In 1863 the M 7.5 Waipukurau earthquake is believed to have occurred on a reverse fault source in the vicinity of that town (Grouden 1966; Downes and Dowrick, in prep.). These events and the M 8.2 1855 Wairarapa earthquake produced strong ground motions in the study area. During the early part of the 20th century, Hawke's Bay was rocked by a number of large earthquakes, including the M 7.8 1931 Hawke's Bay earthquake which killed 256 persons and destroyed the cities of Napier and Hastings. This event also caused damaging to very damaging (MM 7-8) ground motions in the vicinity of the study area. Other 20th century damaging earthquakes in the region include the M 6.9 1932 Wairoa, M 7.4 1934 Pahiatua, and M 7.2 1942 Masterton earthquakes (Downes 1995; Schermer et al. 2004).

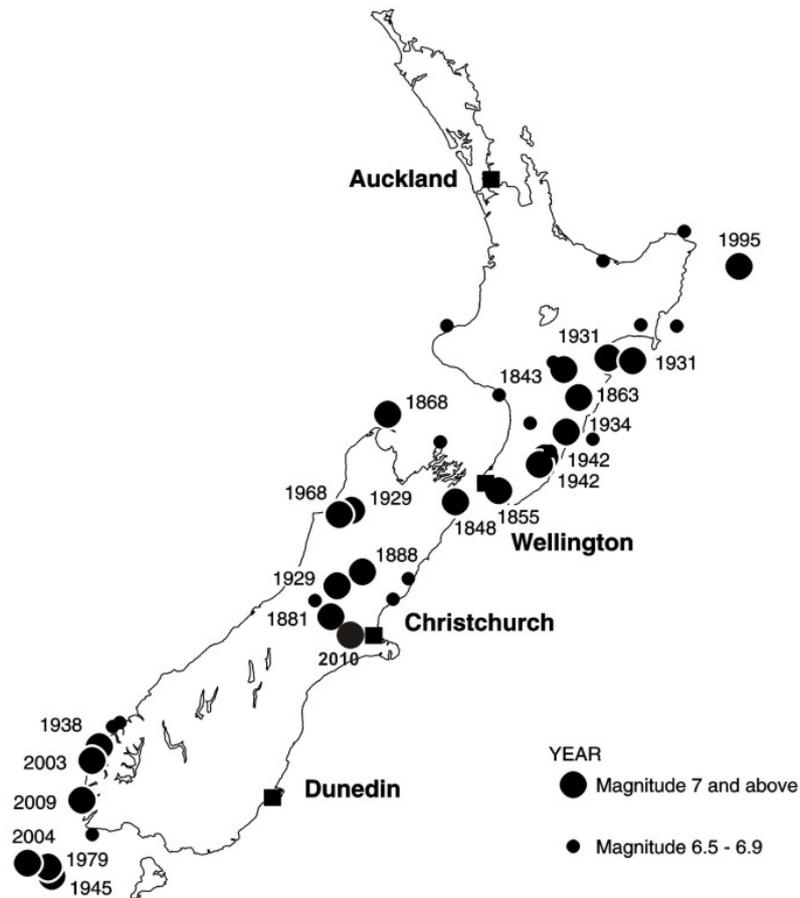


Figure 4 Epicentral locations of large earthquakes in New Zealand from 1848-2009 (<http://www.geonet.org.nz/earthquake/quakes/2178228g-shaking.html>).

1.3.3 Active faulting in Central Hawke's Bay

The large earthquakes in the region have been and will be associated with the major active faults. In addition to being underlain by the subducting Pacific plate (Fig. 2), the study area is traversed by a number of significant active faults (including the Mohaka Fault, Ruahine Fault, Ruataniwha Fault, RF, and Waipukurau Fault Zone, WFZ) (Fig. 3), with the ability to produce earthquakes of estimated magnitudes in the range of about M 6.8 to 7.6, and with average recurrence intervals ranging from <1000 years to in excess of 10,000 years (Berryman and Beanland 1991). These faults are also capable of generating large (i.e. metre-scale) single event surface rupture displacements and also pose a considerable seismic shaking hazard. The faults have a variety of structural styles, ranging from strike-slip, e.g. Mohaka Fault, to reverse or reverse-oblique slip, e.g. Ruataniwha Fault (Klos 2009).

1.3.4 Potential active faulting hazards at the proposed A7 damsite: primary and secondary faulting.

The proposed A7 damsite, is located within the Wakarara Block which is bounded by the Mohaka and Wakarara faults. These faults, together with the Mangataura Fault (Fig. 5), deserve attention in terms of potential surface fault displacement effects and strong ground motions as outlined in Langridge et al. (2010).

One of the major issues facing the viability of the A7 Makaroro site is whether there is evidence of, or potential for: (i) primary fault displacement (displacement along major active fault traces) through the footprint of the proposed damsite; or (ii) secondary displacement (minor displacement that occurs off the main fault trace) consequent on rupture of nearby active faults.

The potential presence of major faulting at a damsite is a clear hazard because of the metre scale displacement that the dam could be subjected to during fault rupture. Even if no major active fault were to be found at the proposed A7 damsite, the proximity of the site to these faults would imply the possibility that secondary deformation on fault-parallel structures and/or bedding within the bedrock could occur during co-seismic movements on nearby faults.

An important set of questions for the proposed A7 damsite are:

- (i) is it possible that significant fault displacements can occur in, or close to, the A7 site as a result of tectonic movements on either of the three major faults (Mohaka, Wakarara, Mangataura)?
- (ii) could secondary displacements occur as a result of internal deformation within the Wakarara Block as a consequence of movements on the major faults?; i.e. from bending, folding, uplift etc.; and
- (iii) if either (i) or (ii) occurs, what is the possible size, style and recurrence of the expected displacements?

In the following sections, we will describe our preliminary observations and insights into potential primary and secondary deformation at, or close to, the proposed site.

2.0 METHODOLOGY

In order to better characterise the important geological (active) structures and potential types of deformation near the dam site, the following mapping activities were undertaken: (i) compilation of existing GNS information such as QMap geology and the Active Faults database; (ii) analysis of LiDAR data made available to GNS by the Client; and (iii) a geological field reconnaissance to the site area to investigate faults, structures and lineaments.

2.1 Mapping of active faults and other lineaments

Fault mapping has been undertaken within a GIS onto LIDAR DEMs of the area surrounding the damsite. Hawke's Bay Regional Council supplied LiDAR data prior to this project that was used for earlier mapping of active faults in the central Hawke's Bay area (Langridge et al., 2006; 2010). As part of the current project, a small (60 km²) area of LiDAR coverage was acquired and added to pre-existing surveys to include the area of the proposed damsite and in order to have complete LiDAR coverage within c. 4 km of the damsite. In addition, aerial photographs have been analysed in conjunction with LiDAR to verify the nature of geological features observed on the DEMs and in the field.

Within the GIS a number of Shapefiles have been created to categorise the types of features that have been mapped. These features have been classified into:

1. Active Fault – a definite fault trace can be identified if it breaks an alluvial or hillslope surface creating a vertical scarp, e.g. the Rangefront Fault, or if the trace shows clear horizontal displacements, as the Mohaka Fault does in many places;
2. Inferred Fault – where an active fault cannot be seen but is inferred to occur based on extension of well-mapped active fault traces and/or other geological features. For example, where a river has removed evidence for the fault we infer the location of the fault from scarps on opposite banks of the river;
3. Lineaments – this is a broad category referring to geomorphic indications of linear features in the landscape. The term lineaments will include linear possible fault traces, secondary fault traces, or features of unknown origin. Sometimes such features may be man-made structures that parallel a local tectonic fabric, e.g. fences, roads, but cannot be conformed as faults indicate. The term 'lineaments' is also used for landscape-scale geomorphic features within the greywacke hill country, such as linear valleys and linear bumps within these valleys. We also include clearly linearly-oriented stretches of gorges in the Makaroro catchment under the term lineament.
4. Bedding-related features – this term refers mainly to features such as those observed where ribbed bedrock spurs form geomorphic lineations in the landscape. This category of features is mainly located adjacent to the parallel sections of the Makaroro River and Mohaka Fault upstream of the A7 damsite.
5. Folds – these linear features include active folds such as anticlinal warps that form on the upthrown side of active reverse fault traces, and also fold axes observed in Tertiary rocks, such as the Yeoman Syncline which can be seen in rocks on Rangimarie Station.

Finally, a Shapefile is developed to summarise our best estimate of the continuous nature of faulting along some active faults, such as the Mohaka Fault, that are shown to determine the probable extent of its continuous trace. This is typically a combination of 1 and 2 above.

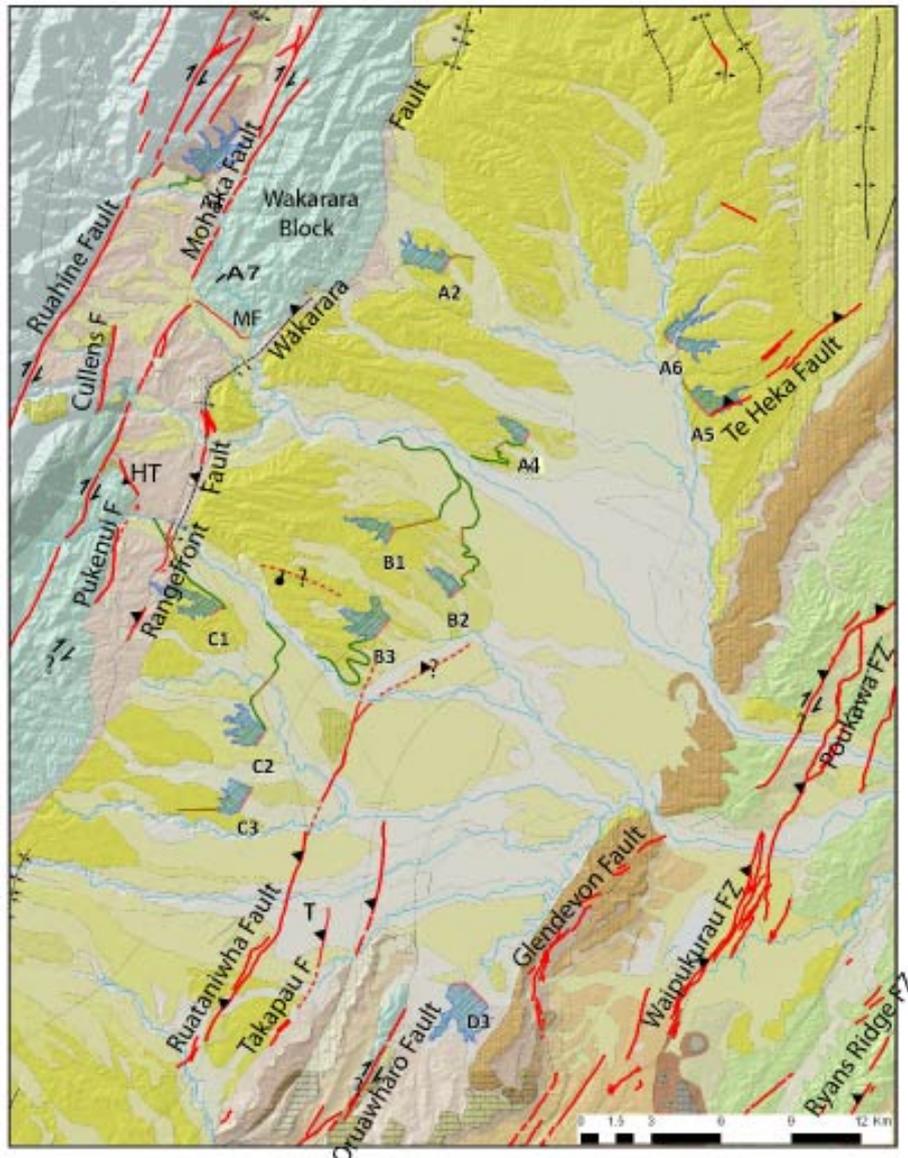


Figure 5 Known active fault (red) and active fold traces (black dashed lines) that are in proximity to the proposed scheme. From 1:250,000 scale geological map of the Hawke's Bay area (Lee et al. in press). In addition, possible fault (red dashed lines) and fold (thin black lines) locations are also included. Up-thrown side of reverse faults is shown with triangles; black arrows indicated sense of strike-slip movement; and tick/ball symbols indicate down-thrown side of normal faults. Proposed dam A7 occurs within the Wakarara Block. Abbreviations: HT Hinerua Thrust, MF Mangataura Fault. Yellow patterns indicate Quaternary sediments. A2 – C3 locations are other proposed dam sites within the Water Augmentation scheme.

2.2 Field reconnaissance

The report authors undertook a field reconnaissance of the proposed A7 Makaroro dams site area and surrounding region on May 12th-13th 2011 in order to appreciate the local site geology and active faulting. The first day was spent in conjunction with Bernard Hegan of T&T looking at features in close proximity to the proposed site, and was focused toward understanding the site and possible features of primary and secondary deformation. The second day focused on considering the location, sense of movement, activity and interactions between the main active faults (Mohaka, Wakarara/ Rangefront, and Mangataura faults) in proximity to the proposed dams site and reservoir.

3.0 PRIMARY DEFORMATION: MAJOR FAULTS AND FOLDS

This section includes summary information from published and unpublished studies of active faults and deformation within 10 km of the proposed A7 damsite, including observations and photographs from our field reconnaissance.

3.1 Mohaka Fault

The Mohaka Fault is a NNE-striking active strike-slip fault that runs through the entire length of the Hawke's Bay region (Fig 3; Beanland 1995). The Mohaka Fault, along with the Ruahine Fault, comprise the main faults within the western strand of the North Island Dextral Fault Belt (NIDFB) within the central sector of the eastern North Island (Fig. 2). The Mohaka Fault is the northern continuation of the Wellington Fault (Beanland 1995; Langridge et al 2005). North of Hawke's Bay region the Mohaka Fault becomes the Whakatane Fault (Mouslopoulou et al. 2007) and merges offshore in the Bay of Plenty with the Taupo Fault Belt (Fig. 2; Mouslopoulou et al., 2009).

The Mohaka Fault is characterised by right-lateral motion. The fault has a steep (85° dip) to the northwest (Beanland 1995). Regional estimates of slip rate range from 4.8 ± 2.4 mm/yr (northern Hawke's Bay; Beanland 1995) to 3-5 mm/yr near Dannevirke and the Big Hill area (Raub et al. 1987; Langridge, unpublished data; Zachariassen unpublished data). Sites which aid in the estimation of single-event displacement (SED) along the Mohaka Fault are sparse. Along the southern part of the Mohaka Fault the smallest displacements measured are c. 5 ± 1 m (Marden 1984). This is comparable to estimates of single-event displacement (4.5 ± 1 m) on the northernmost section of the Wellington Fault (Langridge et al., 2005).

Based on these slip rate and SED estimates, the average recurrence interval of faulting is c. 1250 yr (800-2000 yr). There have been several paleo-earthquake trenching studies undertaken along the Mohaka Fault. Raub et al. (1987) describe trenches near Wakarara and at Te Hoe in northern Hawke's Bay. The former site provides evidence for a single surface rupturing event since 1165 ± 50 yr Before Present (BP). The trench at the Te Hoe site provides evidence for 2 surface-rupturing earthquake during the last 1800 yr (i.e. since deposition of the Taupo Pumice). These two observations are consistent with a recurrence interval of c. 1000 yr. There are three other paleoseismic studies that have been undertaken along the Mohaka Fault since 1998, but this data remains largely unpublished (e.g. Hanson 1998). These studies find generally similar results to those listed above. At least along the southern part of the Mohaka Fault, it appears that the most recent faulting event occurred c. 300 yr ago (Hanson 1998; Langridge, unpublished data).

The Mohaka Fault is well-expressed on LiDAR and aerial photographs within ± 10 km of the A7 damsite. It is typically expressed by a clear, straight to slightly sinuous fault trace between Alder Road, near the Hinerua Thrust and Mangleton Road within the Gwavas forest. The fault can be mapped crossing hillslopes and alluvial terraces. In detail, the fault is often identified by an uphill-facing scarp that causes ponding to occur along the fault trace. Displaced streams are common along the fault trace. Many of the larger hillslope streams show total dextral displacements of 30-40 m (Beanland 1995; Fig. 6), indicating that there have been repeated movements along the fault during the late Pleistocene to Holocene (~ last 20kyr). During our field reconnaissance we located one site on Rangimarie Station which may indicate repeated dextral displacements of c. 4 m per event (NZMS 260 U22/899544).



Figure 6 Uphill-facing scarp of the Mohaka Fault on Rangimarie Station, marked by red arrows. At this locality a ponded basin has formed behind the scarp and the original drainage has been displaced from its source by 30-40 m and the scarp matches to the offset ridge with a large tree. Rounded to conical hillocks of greywacke occur on the east (far) side of the fault trace.

While the fault has been mapped in a general way for QMap at 1:250,000 scale (Lee et al., in press), the LiDAR DEMs have allowed us to clarify the location and complexity of the fault pattern on the ground (see Appendix 1). For example, an important observation in the Wakarara area is that the fault bifurcates to the south of the village near Pebbly Hill No.2 and steps to the left, creating a stepover of width up to c. 500 m south of Mangataura Stream. This western trace forms a single scarp across most of Rangimarie Station, but bifurcates again in the southern part of the Gwavas Forest. These observations indicate that the faulting is more complex than has been previously mapped and that the zone of deformation may be wider than previously considered.

3.2 Wakarara/ Rangefront faults

Faults such as the Rangefront Fault and Wakarara Fault are active reverse-slip faults that account for some tectonic convergence (shortening) at the front of the Ruahine Ranges. In this study the main frontal reverse structure has been divided into the Rangefront and Wakarara faults.

The Wakarara Fault replaces the name Wakarara Monocline of Raub (1985), emphasising that an active fault is responsible for the deformation observed at the front of the Wakarara Range. The Wakarara Fault is a NNE-striking, active range-bounding reverse fault characterised by greywacke to the NW and Tertiary rocks to the SE of the fault. The fault trace is discontinuous and displays scarps of up to 2 m height in places. The fault trace hugs the rangefront of the Wakarara Range and it bends upvalley at Poporangi Stream. This indicates that the sense of movement is reverse, characterised by uplift of the Wakarara Range. There are no indications at present that this fault produces a strike-slip component of deformation.

The dip of the fault has not been measured directly but is considered to be moderate to shallow (c. 30-45°) to the NW. The Wakarara Fault typically crops out 5 km to the SE of the Mohaka Fault. Models of fault movement that will be discussed later, suggest that these

faults must therefore converge at shallow crustal depths. As currently defined, the Wakarara Fault is c. 15 km in length.

The Rangefront Fault is the southwestern continuation of the Wakarara Fault. It strikes NNE and may be traced for at least 42 km into the Manawatu region as a range-bounding structure. Clear active traces of the Rangefront Fault can be traced on the available LiDAR over a distance of 23-28 km. Vertical fault scarps are clearly associated with this fault between Makaroro River and the Tukituki River headwaters, including Tukipo Stream. These fault scarps are preserved across likely Q2 (post-glacial, c. 15 ± 3 kyr; also called the Ohakean surface elsewhere in the southern North Island), younger (Q1 = Holocene; <12 kyr) and older (Q3?; 24-59 kyr) terraces in these areas (Lee et al., in press). There are no indications at present that this fault has a lateral component of movement. The sinuous, multi-trace outcrop pattern of the fault as seen across flat terraces suggests that the Rangefront Fault has a low to moderate dip.

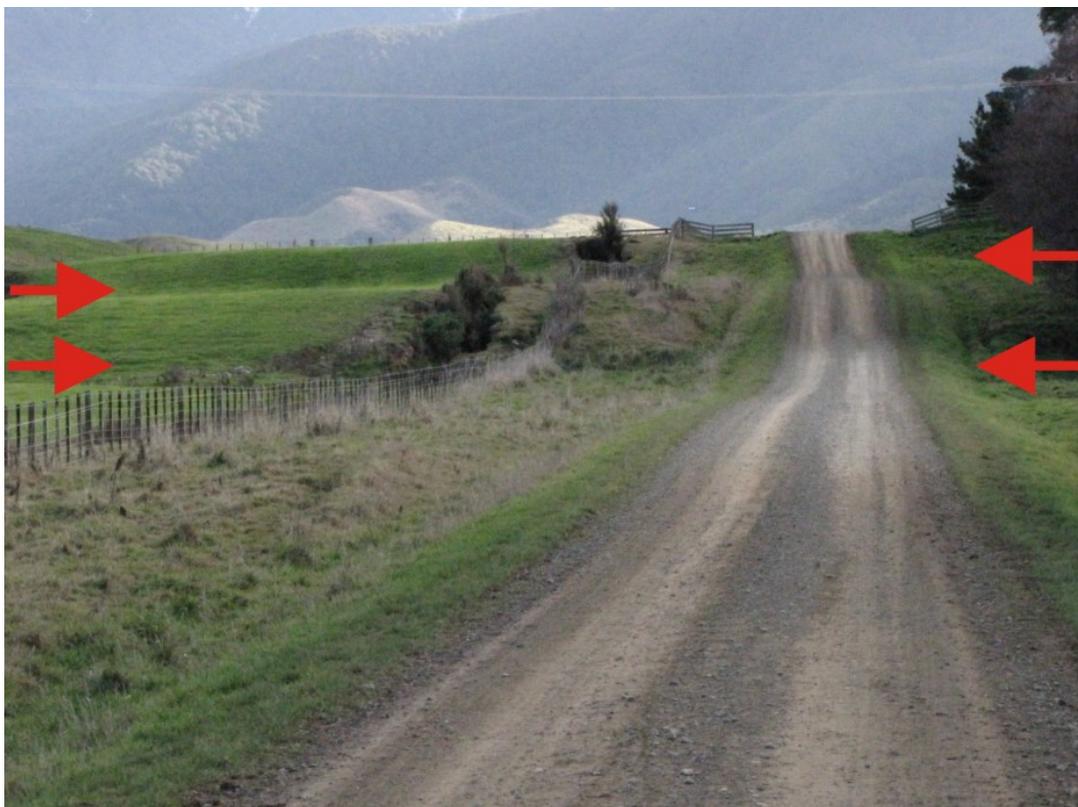


Figure 7 Pair of fault scarps of the active Rangefront Fault across Tukituki Road near the Ruahine Ranges (background). Here the fault is expressed across a probable Q2 or Ohakean ($\sim 15 \pm 3$ kyr old) alluvial terrace.

Based on the height of fault scarps, and the age of the Q2 alluvial aggradation surface (15 ± 3 kyr), it is possible to estimate the vertical slip rate of both the Rangefront and Wakarara faults. At the Tukituki Road site, the Rangefront Fault has a double scarp with an overall height of 4 m (Fig. 7). A broad, 2 m high scarp occurs at the Wakarara Road site at the northern end of the Rangefront Fault. These yield vertical slip rates in the range of 0.2-0.33 mm/yr, and 0.1-0.2 mm/yr, respectively for the Rangefront Fault. Scarps of up to 2 m in height along the Wakarara Fault are consistent with the lower slip rate for the Rangefront Fault.

3.3 Mangataura Fault

The Mangataura Fault was first identified by Kingma (1957) as an active fault that strikes SE from a junction with the Mohaka Fault into the Ruataniwha Depression near Springhill. The fault marks the boundary between greywacke rocks of the Wakarara Range and Tertiary marine rocks, to the south of it (Lee et al. in press). Kingma (1962) shows this fault as an up-to-the-northeast sense structure. In this study, the Mangataura Fault is defined as a c. 4 km long, SE-striking fault that runs between the active trace of the Mohaka Fault at Wakarara and the Wakarara/ Rangefront faults.

From our preliminary field reconnaissance, we suspect that the Mangataura fault has a sinistral (left-lateral) sense of movement. Geomorphically, the fault is defined by a broad (5-10 m wide and 2-4 m high) linear zone of deformation exhibited across a probable Ohakean alluvial surface (Fig. 8). Near its southeastern end, the fault crosses younger terraces of the Makaroro River, where the vertical height of the scarp is smaller. The sense of motion on this fault is difficult to assess, but near its southeastern end, we identified a potential left separation in a young terrace riser. In addition, the straight to sinuous bulged trace of this feature appears to indicate a strike-slip sense of motion.



Figure 8 View to the southeast along the scarp of the Mangataura Fault from Wakarara Road. The fault is characterised by a series of high, stepping mound-like traces up to 2 m high and 10 m wide across a probable Q2 surface. Greywacke slopes of the Wakarara Block are just visible at left.

The left lateral sense of movement on the Mangataura Fault is consistent with the right-lateral mode of shear for the Mohaka Fault and sub-parallel faults in the NIDFB, and also with reverse movement on the Wakarara and Rangefront faults. The dip and dip direction of the Mangataura fault are not known at this time, but we suspect it has a steep dip. The fault also represents a boundary between greywacke of the Wakarara Range to the north and Tertiary rocks to the south.

3.4 Other faults

In the wider area surrounding the Makaroro River catchment there are a several other active faults that have been mapped in previous studies and have been confirmed by Langridge et al. (2010) (see Fig. 4). These are not likely to cause a displacement hazard to the A7 damsite, but are mentioned here as further background to the site.

3.4.1 Ruahine Fault

The Ruahine Fault is an active dextral strike-slip fault that is located c. 4 km northwest of the Mohaka Fault. These two faults are the main structures in the western strand of the NIDFB. In this area the faults bound a thin block which is filled by Tertiary marine rocks known as the Ohara Depression (Fig. 5). The Ruahine Fault has a Holocene slip rate of 1-2 mm/yr and an estimated range of dextral single-event displacement of 2-5 m (Beanland and Berryman 1987).

3.4.2 Hinerua Thrust and Pukenui Fault

The Hinerua Thrust was identified by Raub (1985) as an active, NNW-striking fault that bounds the northern end of a narrow tectonic sliver of greywacke adjacent to the Mohaka Fault near Alder Road (Fig. 5). Greywacke of Folgers Hill marks the rangefront of this short (3 km) fault trace (see U22 topographic map). The active trace of the Hinerua Thrust shows down-to-the-south motion (Raub et al. 1987).

The Pukenui Fault was first described by Kingma (1962) and recognised during reconnaissance for the Langridge et al. (2010) report (Fig. 5). The Pukenui Fault is an active fault zone between the Mohaka and Rangefront faults in southern Hawke's Bay. The Pukenui Fault extends southward from the eastern end of the Hinerua Thrust. At least 2 active traces observed on LiDAR imagery were confirmed as faults during a field reconnaissance in 2010.

The Hinerua Thrust and Pukenui Fault are both range-parallel and range-normal faults that display activity in a location between the Mohaka and Rangefront faults and c. 10 km south of the proposed dam site (Fig. 4). This is important as these faults may be indicative of the style and activity of faults and fractures within the Wakarara Block, adjacent to the proposed A7 damsite.

3.5 Kinematic model of the A7 site area

In this section we present a model of fault motion (kinematic model) to explain possible interactions between the faults. Understanding the geometry and possible interactions of faults provide a basis for considering fault rupture hazards, including possible secondary faulting or other deformation on bedrock defects in the damsite. For this purpose, we have produced a map view of the potential interactions of key faults within 5 km of the A7 damsite (Fig. 9), and a simple cross section perpendicular to the regional grain and through the location of the site (Fig.10).

The proposed A7 dams site on the Makaroro River is located between three active faults and within the actively deforming Wakarara tectonic block (Fig. 9). The Wakarara Block is a 4-5 km wide area of greywacke bedrock bounded by the Mohaka, Wakarara and Mangataura faults. These faults have right-lateral, reverse and possible left-lateral movement, respectively.

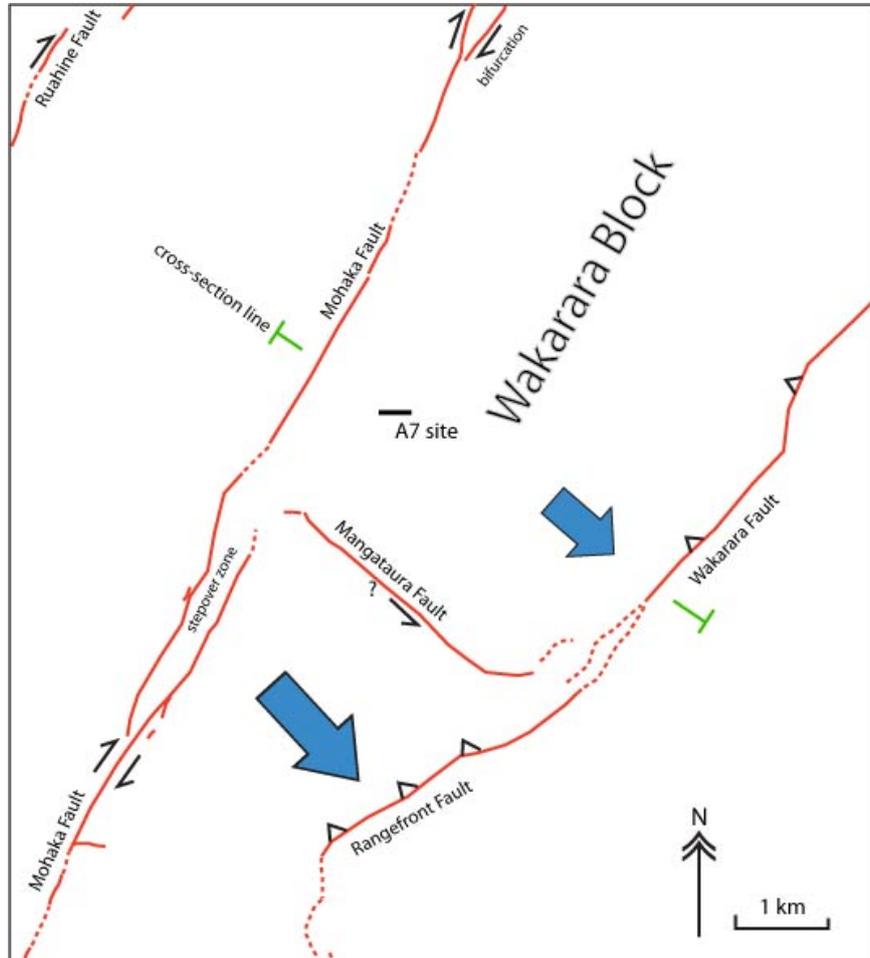


Figure 9 Simplified kinematic model involving the key active faults within 5 km of the proposed A7 dams site. The dextral-slip Mohaka Fault is both the closest and most active fault to the A7 dams site. The Mangataura Fault is interpreted as a left-lateral (sinistral) fault. The sinistral motion (single black arrow along the Mangataura Fault) is explained if the Rangefront Fault is more active than the Wakarara Fault, which will cause faster SSE movement of the southern side Mangataura Fault compared with movement of the northern side (shown by relative size of blue arrows).

The preliminary cross-section shown in Figure 10 includes these main structural elements. Projections of the linear, valley-forming NNE-trending structural grain in the Wakarara Range have been put on the cross-section, though the activity, dip and extent of these features are not known at this time. The Yeoman Syncline is a fold in Tertiary rocks on the west side of the Mohaka Fault (Kingma 1957).

The topography is consistent with continuing activity on the Wakarara Fault, with reverse-slip motion producing uplift and deformation near the rangefront (Figs. 9, 10). Geomorphically, the Wakarara Range is higher and steeper toward its eastern front with elevations up to 600 m a.s.l. The topography is a little more subdued to the NW flank of the Wakarara Block

because strike-slip movement on the steeply-dipping Mohaka Fault does not produce significant relief.

Two variations for the possible dip of the Wakarara Fault have been used to assess the closest distance of the Wakarara fault to the dams site (Fig. 10). Assuming the fault dip does not change in depth, the Mohaka and Wakarara faults would merge at depths of c. 2.5-3.0 km (case i) or c. 4.5-5.0 km (case ii). This would imply that the Wakarara Fault is at a minimum depth of c. 1.8 km depth beneath the proposed dams site.

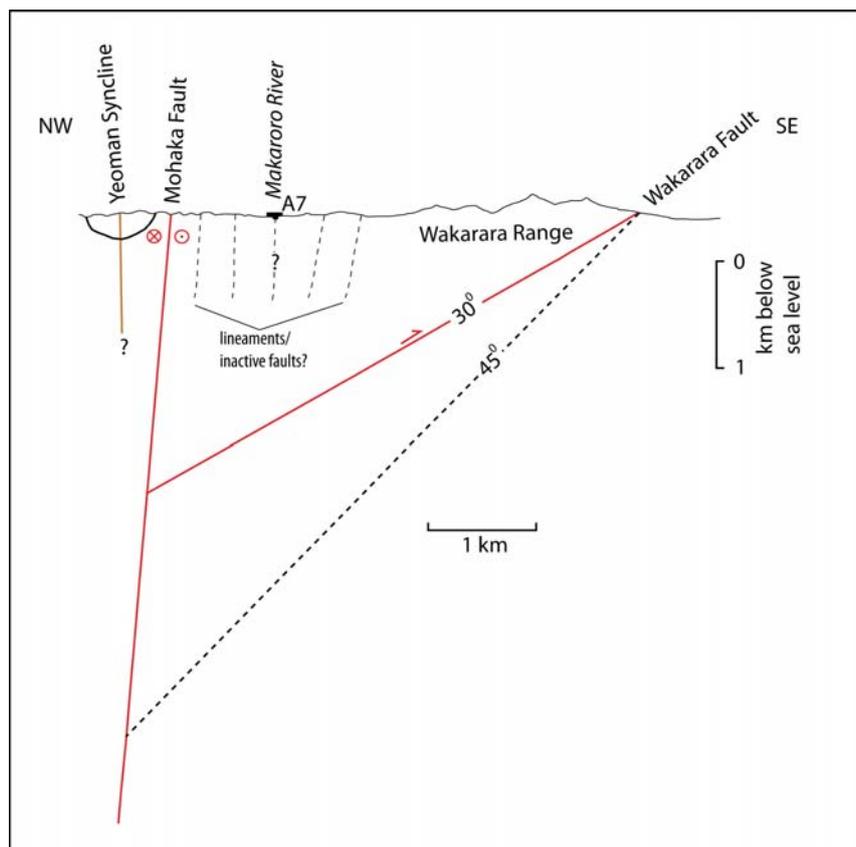


Figure 10 Simplified geologic cross-section running NW-SE through the proposed A7 dams site on the Makaroro River. Two models for the dip of the Wakarara Fault are shown; the first with a shallow (30°; preferred) dip (in red) and the second that has a moderate, 45° dip to the NW (in black). A series of geomorphic lineaments/valleys are marked in the vicinity of the Mohaka Fault and A7 site. Location of cross-section line is shown on Figure 9.

Movements on the Mangataura fault may be individual or related to movements on the Rangefront and/or Wakarara faults, i.e. reverse slip on either of these faults could potentially cause simultaneous movement on the Mangataura Fault. The Mangataura Fault could thus act as an “accommodation zone” to allow for differential movement between the Rangefront and Wakarara faults with different rates of movement (increase of activity on the Rangefront Fault as compared to the Wakarara Fault), as implied by larger fault scarps to the south of the study area. These statements are consistent with the Mangataura Fault being a left-lateral, which is also supported by the geomorphic expression of the scarp of the Mangataura Fault as observed during the field reconnaissance.

3.6 Location, size and timing of primary deformation in the study area

Primary deformation will take place along the trace of major faults. The closest faults to the A7 damsite are the Mohaka (1 km distant), Wakarara/Rangefront (2 km distant, based on Figure 10) and Mangataura faults (2 km distant).

With a short recurrence interval (c. 1000 yr), the Mohaka Fault is the most likely fault to rupture, causing dextral displacements of 4-5 m along its main trace. Because of the presence of lineaments parallel to the Mohaka Fault in close proximity to the fault, it is important to understand what would be the likely width of primary deformation associated with rupture along this fault, to assess if primary rupture could extent into the damsite.

The width of primary deformation associated with the Mohaka Fault must be considered to be proportional to the width (size) of fault complexities along the fault. In general, we observe a stepover zone SW of the damsite in the Wakarara area that is c. 330-450 m in width (Fig. 9). Four km to the north of the proposed A7 damsite, the Mohaka Fault bifurcates, so that deformation is split onto two sub-parallel traces. The width between these traces is c. 275 m, but this separation between the traces widens to the north to c. 1 km at the northern edge of the LiDAR coverage. Along the western boundary of the Wakarara Block, the Mohaka Fault is characterised by a single trace, adjacent to the proposed A7 site. Primary fault rupture of the Mohaka Fault is not likely to affect the damsite. However, because of the complexity of the fault trace further studies would be required to fully confirm the width of primary rupture.

Individual ruptures will probably also occur on the Rangefront and/or Wakarara faults with a recurrence that is unknown at present, but likely to be many thousands of years. The size of co-seismic displacement of the Rangefront and Wakarara faults is unknown. Because of the possible interaction (merging) of the Mohaka and Wakarara faults at depth it is possible that on occasions they could both rupture simultaneously.

The recurrence and displacement size of rupture along the Mangataura Fault is unknown. The fault could rupture individually or in association with rupture along the Mohaka and/or the Wakarara and Rangefront faults.

4.0 POSSIBLE SECONDARY DEFORMATION AT THE A7 DAMSITE: BEDROCK STRUCTURE

The presence of lineaments/inactive faults within the Wakarara Block, bounded by active faults, suggests that it is likely that there is active internal deformation within the block. Greywacke bedrock, exposed in the gorge of the Makaroro River, would form the foundation rock for the proposed A7 dam. Internal deformation within the block may be focused within hundreds of metres of the Mohaka and/or Wakarara faults, but the deformation may also extend throughout the block including the vicinity of the A7 damsite. The possibility of slip along these lineaments/inactive faults, and the presence of such features beneath the foundations of the A7 damsite, needs to be considered.

Primary rupture on the Mohaka and Wakarara faults may result in movement of weak planes in the greywacke rock mass at the damsite through:

- (i) Reactivation of old fault zones that are favourably oriented for displacement: These include both NNE to NE and E-W striking fault (shear) zones with strike-slip or reverse displacements, and E-W striking shear zones with strike-slip movement.
- (ii) Flexural slip or slip along basement beds: When rocks are folded sometimes brittle deformation (slip) can occur along favourably oriented bedding planes.
- (iii) Gravitational collapse: sometimes when tectonic blocks are uplifted, gravitational collapse can occur along favourably oriented weak planes (old fault or bedding planes) in the rock mass, along ranges and hills.

4.1 Bedrock attitudes

Secondary deformations within bedrock or on bedrock shear zones adjacent to major faults can potentially represent displacements ranging up to decimetres of vertical or horizontal displacement. Therefore, understating the location, orientation and type of bedrock structures is essential to assess the likelihood of secondary deformation, and its possible effects on dam feasibility/stability.

4.1.1 Form lines and attitudes in the region

As part of the QMap 'Geology of the Hawke's Bay region' project, bedrock form lines and attitudes have been collated region-wide at a scale of 1:50,000 (Lee et al. in press; GNS Science unpublished data). Bedrock form lines are indications of the strike of bedding from aerial photograph analysis. In general, form lines have been measured in areas of Torlesse greywacke basement throughout the area within 10 km of the proposed A7 dam site. Within the Wakarara Range, bedrock form lines are subparallel to the range-bounding Mohaka and Wakarara faults (average trend c. 020°) and do not vary significantly from this trend by more than $\pm 10^\circ$. Similar patterns of bedrock form lines are observed in nearby ranges comprised of Torlesse greywacke rock, e.g. Ruahine Ranges.

Bedrock attitudes (strikes and dips) have also been collated for QMap for the construction of the new 1:250,000 Hawke's Bay geologic map. This data comes from a wide variety of sources over many decades (e.g. Kingma 1957, 1962; Raub 1985; Erdman and Kelsey 1992). The strike of greywacke bedrock also follows the local (NNE-striking) tectonic grain,

however there is a much greater variation in the strike of bedding between c. north and northeast strikes (c. 000-045°). Although there are great variations in strike and dip across the Wakarara Block, the dips measured on greywacke beds in the east of the block dip steeply to the east, but change to dips of up to 70° in the NW toward the Mohaka Fault, i.e. dipping to the NW (Kingma 1957).

4.1.2 Bedrock attitudes in the vicinity of the dam site

As part of their preliminary damsite studies in the Makaroro River valley Tonkin & Taylor have undertaken geologic mapping of the bedrock in and around the river gorge where the A7 Makaroro dam and reservoir are proposed to be sited (see Appendix 2). Attitudes on greywacke bedrock and minor shear zones were collected within 300-850 m of the proposed A7 damsite (Appendix 2). Compared to regional trends from form lines and attitudes, these local strikes vary across all quadrants of the compass. Strikes on bedding tend to cluster between NNE strikes ($020 \pm 10^\circ$) or E-W strikes ($270 \pm 20^\circ$). These rocks are typically folded or multiply-deformed, so that dip direction is not consistent. Strikes on shear zones tend to also cluster around northerly strikes ($000 \pm 10^\circ$) and E-W strikes ($270 \pm 10^\circ$).

As outlined in Section 2.1 a range of features have been mapped onto the LiDAR and are collated in the GIS files, including faults, lineaments, inferred and possible faults, folds and bedrock features (Fig.11 and Appendix 1). Mapped bedrock lineaments typically follow the hillslope geomorphology within the Wakarara Range and include gully orientations, uphill-facing topography, remnant linear topography and aligned spurs. These features have dominant and subordinate trends that are consistent with the pattern of regional bedrock attitudes described above. There is a predominance of NNE- to NE-trending spur and gullies, such as Long Spur and Donovan Gully (see Fig. 11 & U22 topographic map) on the true left of the Makaroro River, northeast of the A7 damsite.

A second pattern of lineaments occurs in an E-W orientation in the southern part of the Wakarara Block. One lineament in particular is semi-continuous over a length of 1-2.5 km and typically appears to cross-cut the regional grain of NNE- to NE-trending geomorphology (just north of Makaroro River, Fig. 11).

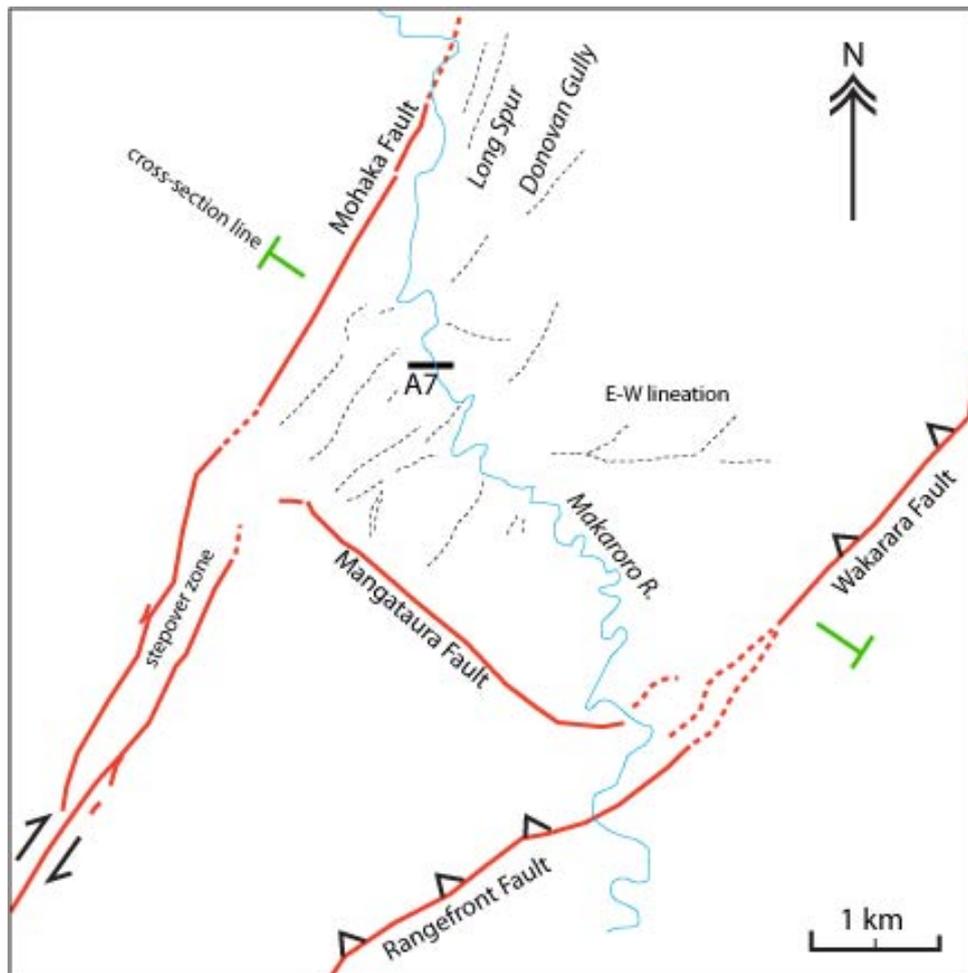


Figure 11 Kinematic map similar to Figure 9. In this case, bedrock and geomorphic lineaments within the Wakarara Block (dashed dark grey lines) compiled and/or mapped in this study are also shown. These lineaments tend to have NNE- or E-W trends and could potentially intersect the A7 damsite

4.2 Possible secondary deformation at, or close, to the A7 damsite.

The new QMap (1:250,000) geological map of the Hawke's Bay region (Lee et al., in press) describes the basement within the Wakarara Block as Cretaceous Waipapa terrane greywacke of the Torlesse Supergroup (Ktw). This map shows up to 5 sub-parallel NNE-striking bedrock faults within the Wakarara Block at spacings of c. 1 km within the block. The sub-parallel bedrock faults mapped coincide with NNE-trending valleys within the block.

Some of the bedrock features, <1000 m from the active traces of the Mohaka Fault, show signs of possible activity and may require further investigation. For instance, in Donovan Gully (NZMS U22/ 910545), c. 850 m from the active traces of the Mohaka Fault and <500 m from the damsite, there are definitive NNE-trending linear features including uphill-facing topography that may be the result of recent movement along bedrock faults or bedding. This site was visited during our reconnaissance and the topography appears to be both linear and late Pleistocene to Holocene in age (younger than ~20 kyr). Also, on the true left bank of the Makaroro Station on Smedley Station we observed evidence for possible fault-parallel deformation that could persist close to the A7 damsite (e.g. near NZMS U22/ 909555). In this part of the Makaroro River valley a series of NNE-trending, bedding and river parallel spurs occur in the greywacke within c. 600 m of the Mohaka Fault above the east bank of the river.

These observations offer the possibility that secondary deformation associated with the Mohaka Fault could persist out from the most active trace to distances of >0.5 km (the expected width of primary rupture based on observations presented above).

Of significant importance is the fact that one of the NNE-striking geologic faults shown by QMap as being within the Wakarara Block extends right through the foundations of the A7 damsite. This fault is shown as an inactive geologic fault that runs along the length of Donovan Gully, though the site and continues to the SSW until it meets the Mangataura fault. The relevance of this fault is not known at this time. However, it raises the question that a fault has been mapped continuously across the Q2 alluvial terrace and through the site. This will require investigation to either confirm or deny the relevance/activity of this feature.

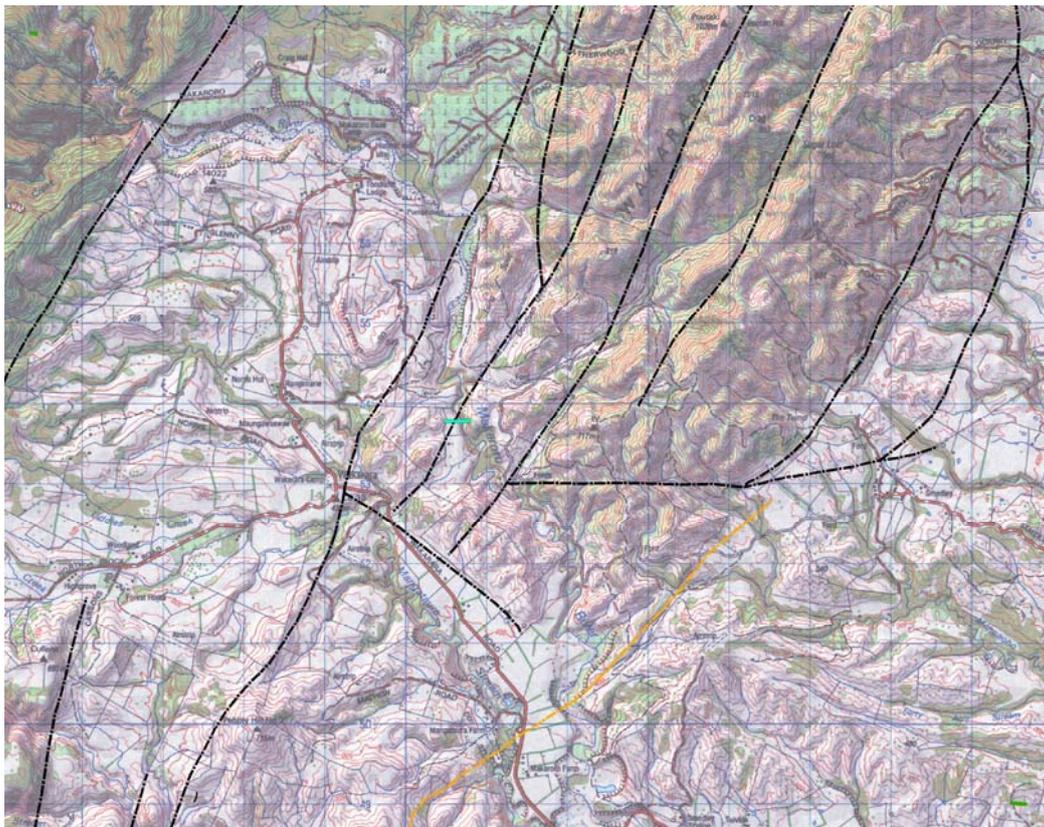


Figure 12 Geologic faults (black dashed lines) and folds (orange dashed lines) shown on the upcoming QMap Hawke's Bay geologic sheet (Lee et al., in press). The proposed A7 dam structure is identified by a blue bar at centre. A NNE-striking bedrock fault that runs up Donovan Gully is shown intersecting the A7 damsite.

A reasonable observation to make is that the Wakarara Block is an uplifting basement block that has been stripped of its Tertiary cover rocks (Kingma 1957). The block is squeezed between active strike-slip and thrust faults and is cut by at least 5 significant bedrock faults that are oriented parallel to the tectonic fabric. It is reasonable to suspect that some intra-block tectonic movement is occurring within the Wakarara Block. Uplift and shortening within the block associated with reverse movement on the Wakarara Block can reactivate NNE trending bedrock faults or bedding planes. In addition, secondary slip that is partitioned/ bled off the Mohaka Fault and into bedrock within c. 1 km of the damsite should be considered possible because of the presence of favourably oriented bedrock faults and bedding. Other E-W trending lineaments within the Wakarara Block (c. 1 km to the southeast of the A7 site) could be reactivated together with the Mangataura Fault.

At this time, it is not possible to confirm recent displacement of the bedrock faults or lineaments. However, the presence of topographically-controlled geomorphology suggests this has happened. Specific investigation including excavations at key sites would be required for this assessment. Field studies and/or desktop studies that investigate global examples of the width of, or probability of off-fault deformation (e.g. Petersen et al., 2011) can be useful in assessing the likelihood of off-fault deformation.

5.0 CONCLUSIONS

- GNS Science have undertaken analysis and mapping of a number of geological features using aerial photographs, and LiDAR DEM data supplied by Hawke's Bay Regional Council (HBRC; the Client), in conjunction with a GIS (ArcMap). Mapping differentiates active fault traces, inferred fault traces, bedding-related features, lineaments, and fold traces. Many of these features have NNE strikes or trends, consistent with the regional tectonic fabric.
- A 2-day field reconnaissance was undertaken by the authors to analyse geomorphology and fault-related deformation within 3 km of the damsite.
- Three active faults occur within c. 3 km of the proposed A7 Makaroro River dam site.
 - The Mohaka Fault is a NNE-striking, active dextral-slip fault with a slip rate of c. 3-4 mm/yr. The fault occurs at a distance of c. 1 km from the A7 site. Rupture of the Mohaka Fault will produce significant ground motions with a return time of c. 1250 yr.
 - The Wakarara/Rangefront Fault is a NNE-striking and west-dipping reverse-slip fault with active fault scarps across young (Q2; 15 ± 3 kyr) alluvial surfaces. The Wakarara Fault is the northern continuation of the Rangefront Fault. The Wakarara Fault is shorter and appears to be less active than the Rangefront Fault. The Wakarara Fault, crops out c. 3.5 km to the SE of, and dips to the NW beneath the location of the A7 Makaroro River damsite and could occur at a minimum depth of c. 1.8 km beneath the proposed site. The size and recurrence of fault rupture is not known.
 - The Mangataura Fault is a SE-striking active fault recognised on the LiDAR and during the field reconnaissance. Little is known about this fault, though we suspect it could be a left-lateral, strike-slip tear fault that separates the Rangefront and Wakarara faults along strike.
- Based on existing information and a kinematic model presented here, we interpret that concurrent co-seismic failure of the Mohaka and Wakarara faults and the ensuing deformation within the Wakarara Block must also be considered as a possible hazard to the A7 dam. Uplift, folding and faulting within the block between the Mohaka and Wakarara faults are likely to occur during rupture of the major faults, individually or concurrently.
- Defining the width of primary deformation of the Mohaka Fault is of critical importance to the damsite. In addition, the extent of secondary deformation away from the fault has been identified as a potential hazard to the proposed A7 dam. Based on the presence of bedrock faults/lineaments in the Wakarara Range and the strike and proximity of bedrock and shear planes within hundreds of metres of both the Mohaka Fault and the A7 damsite, we consider secondary displacement on bedrock lineaments and shear zones through the site is possible.
- Bedrock defects are favourably oriented to rupture together with major active faults. Greywacke bedrock attitudes within the Wakarara Range typically strike to the northeast. Bedrock dips moderately to the east near the front of the Wakarara Fault and dips steeply to the west near the Mohaka Fault. Bedrock and shear zone attitudes within 1 km of the damsite are more varied. These tend to fall into either N to NE strikes, or E-W strikes. The '*in press*' QMap Hawke's Bay geologic map identifies one potential NNE-striking bedrock fault/lineament within the Wakarara Block that intersects the A7 damsite.

6.0 RECOMMENDATIONS

In this section we list a number of recommendations and a forward approach to planning for the development of the A7 Makaroro River dams site.

6.1 Multi-staged work plan evaluating the feasibility of constructing the A7 Makaroro dam

Our first recommendation is that the Client works closely with T&T and GNS Science to develop a multi-staged strategy evaluating the feasibility of constructing the A7 Makaroro River dam. Both consultants recognise that there are significant natural and economic hazards for the Client in proceeding toward the instalment of a large dam and reservoir and wish for a sound process of investigation and planning. Geologic and related hazards include: fault displacement, local secondary displacement, landsliding, very high ground motions, and reservoir seiche. The economic costs of managing some of the potential geologic hazards posed by this site could be considerable.

We recommend that the Client together with the Consultants (T&T and GNS) hold a series of round table discussions to advance the project in a staged manner. GNS has a wealth of experience and an international reputation related to the seismic hazard posed to dam structures. These include seismic hazard upgrades for the Waitaki Power scheme, Clyde Dam, Waikato River scheme, and Matahina dam rebuild.

6.1.1 Phase 2a Investigations

We consider that the highest priorities for the next round of investigations are: (i) site investigations that test whether there is an identifiable and measurable displacement hazard to the foundations of the proposed A7 dams site; and (ii) geologic mapping that furthers the understanding of bedrock structure and potential secondary deformation to the dams site and its surrounds.

- (i) To confirm that there are no structures that have produced or have the potential to produce displacements through the dams site, we recommend that trenches be excavated in the vicinity of the proposed dams site. A wide terrace surface (probably Q2; 15 ± 3 kyr) occurs on the true right side of the valley and is in the area of the right abutment of the dam. Large trench excavations representing tens of metres in length and up to 10 m in depth are required to view the bedrock erosion surface beneath this terrace. A thorough examination of attitudes of the bedrock and potential shear planes needs to be undertaken. Such excavations should be a pre-requisite of siting the dam and should be undertaken at an early phase in the project to eliminate the possibility of significant defects in the foundation of the A7 dam, e.g., the geologic fault/lineament shown in Figure 12 (from QMap Hawke's Bay) must be investigated or further considered. If such geological structures are found, the size and recurrence of displacements should be assessed.
- (ii) We recommend the construction of a geologic map of the area within c. 5 km of the dams site in order to fully understand the bedrock structure near the site and potential active secondary deformation. GNS holds a preliminary dataset of bedrock attitudes in this area. Field mapping and checking of this data and construction of a map is a vital phase of this project.

6.1.2 Phase 2b Investigations

We recommend that two lines of approach are considered for understanding the extent of secondary faulting adjacent to the Mohaka Fault. These are (i) further trench investigations across bedrock/bedrock faults that have been identified as possible slip surfaces during Phase 2a mapping; and (ii) Synthesis of analogue historical surface ruptures and the extent of secondary faulting that occurred.

For (i): Phase 2a may identify or confirm linear geomorphic features such as those discussed in the text, e.g. linear ridges in Donovan Gully, and benched greywacke spurs opposite the Mohaka Fault on the true left bank of the Makaroro River. It is important to consider whether these are Holocene active features; when and how often they may have moved, and by what amount.

For (ii): Historical earthquake ruptures on strike-slip and reverse faults, e.g. 1992 Landers earthquake, demonstrate the likelihood and proximity of secondary deformation from large earthquakes. Historic earthquakes provide examples of how slip occurs across stepovers, on secondary faults and in areas of bedrock where faults have not been mapped (secondary deformation). A synthesis of analogue fault ruptures would provide a reasonable basis for assessing how much slip could occur at distances from the Mohaka Fault or on adjacent secondary structures.

6.1.3 Phase 3 Investigations

If earlier phases of investigation do not rule out the viability of the A7 damsite then additional information of the nearby active faults will be needed for an updated seismic hazard analysis including local earthquake design spectra for the A7 damsite. At that time, it would be useful to reconsider the seismic potential of the key faults within 5 km of the dam. Paleoseismic trenching of the Mohaka, Rangefront, Wakarara, and Mangataura faults would determine the timing, frequency, amount and style of slip for past rupture events on these faults. At that time it may be possible to assess whether there are co-incident ruptures of the Mohaka Fault and any of the other key faults, or secondary structures, or co-incident ruptures of the Rangefront and Wakarara faults.

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APPENDICES

APPENDIX 1 GIS LAYERS

ArcMap Shapefiles of features mapped within the vicinity of the A7 Makaroro damsite. (See attached CD).

APPENDIX 2 BEDROCK MAPPING UNDERTAKEN BY TONKIN & TAYLOR

The following are 3 images provided by T&T Ltd. to GNS Science. These show preliminary bedrock mapping with attitudes of bedding, shear zones and folds.

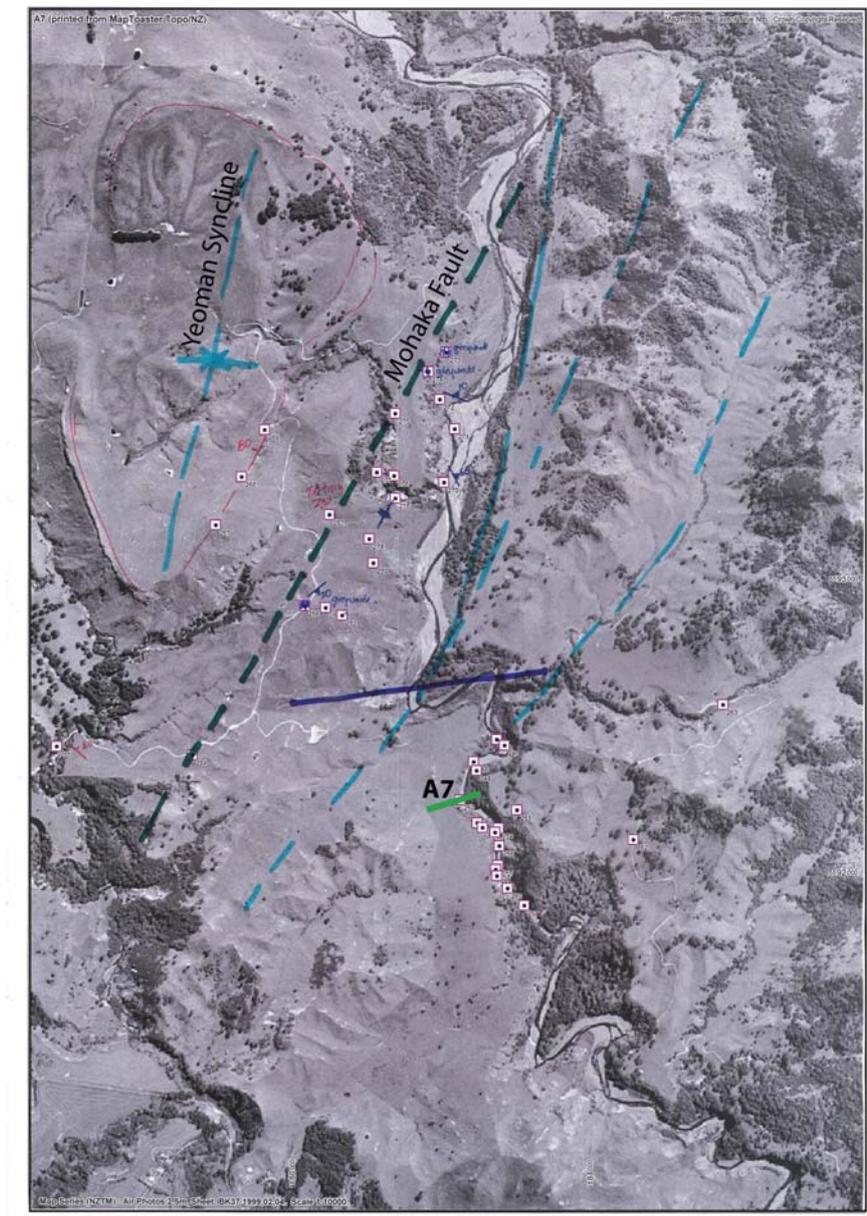


Image 1 Overview of the Makaroro River area. The A7 damsite location is shown by a green bar. The proposed reservoir extends to the northern edge of this image.



Image 2 Bedrock and shear zone attitudes immediately upstream of the A7 site



Image 3 Bedrock and shear zone attitudes in the immediate vicinity of the A7 site



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