

ASPECTS OF THE REGIONAL TECTONIC AND STRUCTURAL GEOLOGICAL MODEL OF THE TRANSMISSION GULLY PROJECT IN WELLINGTON, NEW ZEALAND FOR ROCK CUTTING SLOPE DESIGN

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ABSTRACT

The rocks of the Torlesse Composite Terrane in New Zealand are highly anisotropic and as such local to district scale geological structure patterns tend to orientate with respect to crustal anisotropy. Accordingly, a study of the tectonic setting and regional scale faulting is an important tool when evaluating structural domains for rock slope design in quarries and cuttings for road, rail and land development projects.

This approach has been adopted for rock cutting design at Transmission Gully in New Zealand which is a project to build a new 27 km, four lane motorway along SH1 north out of Wellington. The Transmission Gully alignment is dominantly located in Torlesse rocks and crosses several regional scale faults. Structural data for slope design was predominantly derived from borehole imaging. To guide engineering geological evaluation of local structural domain models a regional tectonic and structural geology study was undertaken to assist in predicting highway cutting scale structural patterns and guide interpretation of the borehole dominated structural database. This paper summarises key aspects of the study and illustrates how this approach is integral to managing design and construction risk.

1 INTRODUCTION

Transmission Gully is a new 27km, four lane motorway along SH1 north of Wellington currently under construction. The road provides an inland route between Wellington (Linden) and the Kapiti Coast (MacKays Crossing), and forms part of the Wellington Northern Corridor Road of National Significance.

The project is located in steep terrain with difficult access. A total of 135 permanent cut slopes have been designed along the alignment with some cut slopes exceeding 75 m in height. The alignment crosses several regional scale faults and tectonic structural zones which exhibit a range of rock mass and structural conditions.

At Transmission Gully the geological structural database for cut slope design was heavily reliant on borehole optical (OTV) and acoustic (ATV) televiwer surveys with limited outcrop mapping. A regional tectonic and structural geology study was undertaken to guide interpretation and evaluation of the structural database with a focus on understanding the key geological and tectonic controls on structural orientations, particularly at the individual cutting scale.

This paper examines structural patterns of the wider Wellington region and the Transmission Gully alignment. Regional scale structural patterns are assessed and the Transmission Gully alignment is divided into three tectonic zones based on simple 'textbook' style structural relationships. The division of the alignment into tectonic structural zones was undertaken to test the hypothesis that cutting scale structural patterns can be predicted by assessing the geometric relationship of major structure. This understanding is then used to interpret the structural database which is presented and compared to the orientation of major structure in each tectonic structural zone.

2 STUDY APPROACH

The study has been undertaken in three parts:

- 1) A simple literature review of the Torlesse rock mass and tectonic setting of the Transmission Gully alignment and wider Wellington region. The initial literature review was supplemented with a lineament analysis of the Transmission Gully alignment.
- 2) A division of the Transmission Gully alignment into tectonic structural zones based on the geometric relationship of major structure (mapped faults and lineaments). Each structural zone is assessed in detail which allows some prediction of cutting scale structure.
- 3) A comparison of borehole scale bedding and fault/shear orientations to the orientation of major structure in each structural zone.

3 GEOLOGICAL SETTING

3.1 HISTORICAL TECTONIC SETTING

The Torlesse Composite Terrane has undergone a complex tectonic history. Deposition of the Torlesse accumulated off

the coast of Gondwanaland into an active subduction zone as sediments in mid to deep water submarine fans, marine shelves or terrestrial environments (Cox & Barrell, 2007; Forsyth et al., 2008). Over several million years the sedimentary beds were buried, scraped, stacked and partially dragged down the subduction system within an accretionary wedge environment (Cox & Barrell, 2007). This resulted in the rock mass becoming folded, faulted and lightly metamorphosed (Forsyth et al., 2008).

Some 100 to 200 Ma (Jurassic to Early Cretaceous) the Torlesse rock mass was pushed and thrust upwards off the coast of Gondwanaland (Rangitata Orogeny). Large scale thrust faulting and fracturing is likely to have occurred during this period of uplift.

Around 90 to 25 Ma (Late Cretaceous to Late Paleogene) the New Zealand continent was involved in an extensional environment and broke away from Gondwanaland and Australia, with sea floor spreading along a continental rift forming the Tasman Sea.

Around 25 Ma (Late Paleogene) the Kaikoura Orogeny began which involved the development of a new plate tectonic margin through New Zealand (Walcott, 1987). The Pacific Plate began converging westward into the Australian Plate. At this time the plate boundary off the coast of the upper South Island and lower North Island was defined by active subduction. Approximately 4 Ma (Early Pliocene) subduction under the upper South Island and lower North Island ceased (McGinty et al, 2000; Vickery & Lamb, 1995) and the region began accommodating northeast-southwest tectonic strain between strike slip movement in the south (i.e. Alpine Fault) and continuing subduction in the north.

3.2 MODERN DAY TECTONIC SETTING

The modern day plate boundary comprises subduction of the Pacific Plate under the Australian Plate off the eastern coast of the North Island, becoming strike slip in the South Island and transitioning back to subduction of the Australian Plate under the Pacific Plate to the south of New Zealand, Figure 1. A number of authors suggest the plate interface beneath Wellington is locked and stress from the subducting slab is no longer accommodated along the plate interface. The coupling of the plates has given rise to the dominantly dextral, strike slip transfer zone through the upper South Island and lower North Island. The transfer zone actively accommodates tectonic strain between strike slip movement in the south and continuing subduction in the north.

The Transmission Gully alignment is located in the axial ranges of the coupled subduction system, Figure 1. It is characterised by steeply dipping, regional northeast-southwest faults. Typically axial ranges are in compression, and tend to accommodate a high proportion of thrust. The modern day movement on these structures is thought to be dominantly dextral strike slip with some degree of thrust.

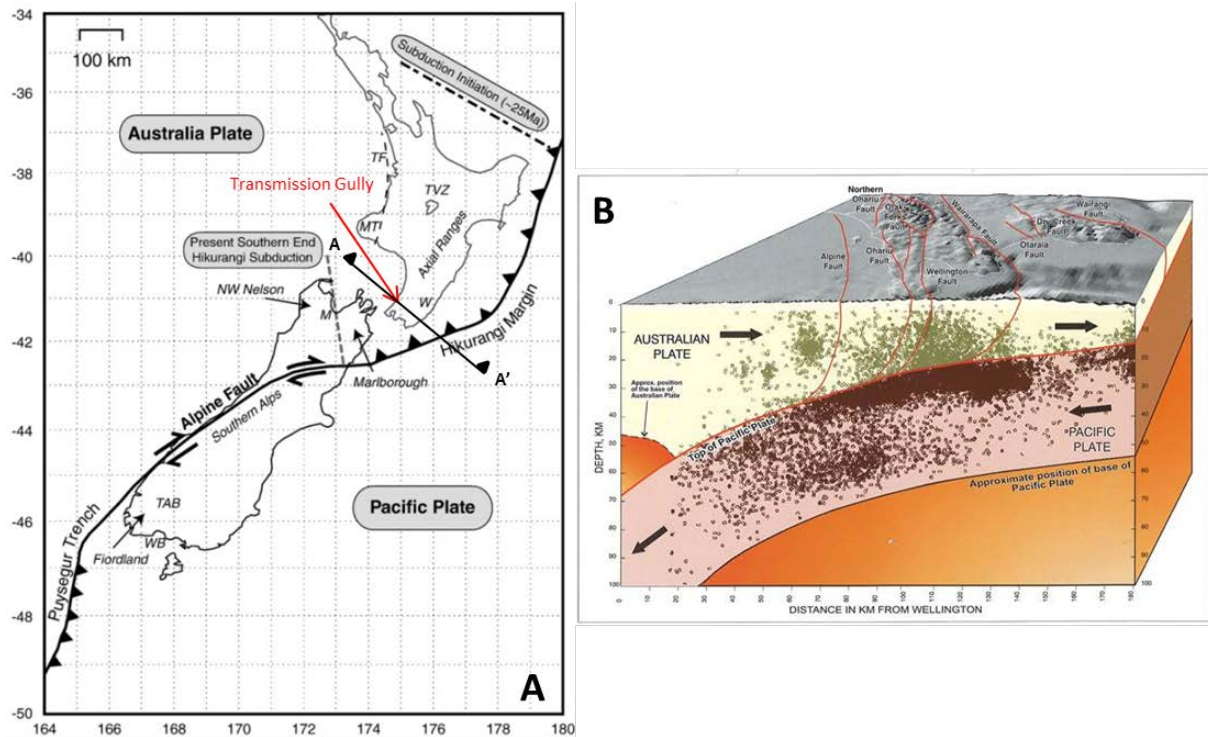


Figure 1: A – Tectonic setting of New Zealand modified from Furlong and Camp (2009). B – Lower North Island schematic cross section (Begg & Johnstone, 2000).

Figure 2 presents a plan of major faulting in the lower North Island and attempts to illustrate the different forces acting on the crust. It presents the average orientation of the plate boundary, the dip of the subducting slab, plate convergence and the principal stress axis (maximum crustal shortening) presented by different authors. It is noted Darby and Beavan (2001) observe a change in the principal stress axis between the east and west coasts of the lower North Island attributed to partitioning of fault-parallel and fault-perpendicular components of strain (Balfour, 2004).

It is evident in Figure 2 the structural grain of the region is not well aligned with the principal stress axis. Balfour et al (2005) highlight the angle between the maximum horizontal compressive stress axis and the average strike of major faults is substantially higher than the optimal 30° required for reactivation of a vertical strike slip fault. They suggest the suboptimal faulting geometry can be explained by crustal anisotropy, low fault plane friction or excess fluid pressures.

The fact these structures exhibit dominant dextral strike slip suggests the subducting slab is most likely coupled at the interface and the crust is anisotropic. It is suggested the subducting slab is acting as a stress guide, transferring and storing strain in the crust (McGinty et al, 2000). Nicol and Wallace (2007) support this theory by highlighting both margin parallel and margin normal motion is actively occurring. They suggest margin parallel motion has been taken up by dextral strike slip faulting and the rotation of tectonic blocks about vertical axes whereas margin normal motion is taken up by reverse faulting in the crust (overriding plate) and dip slip on the subducting slab.

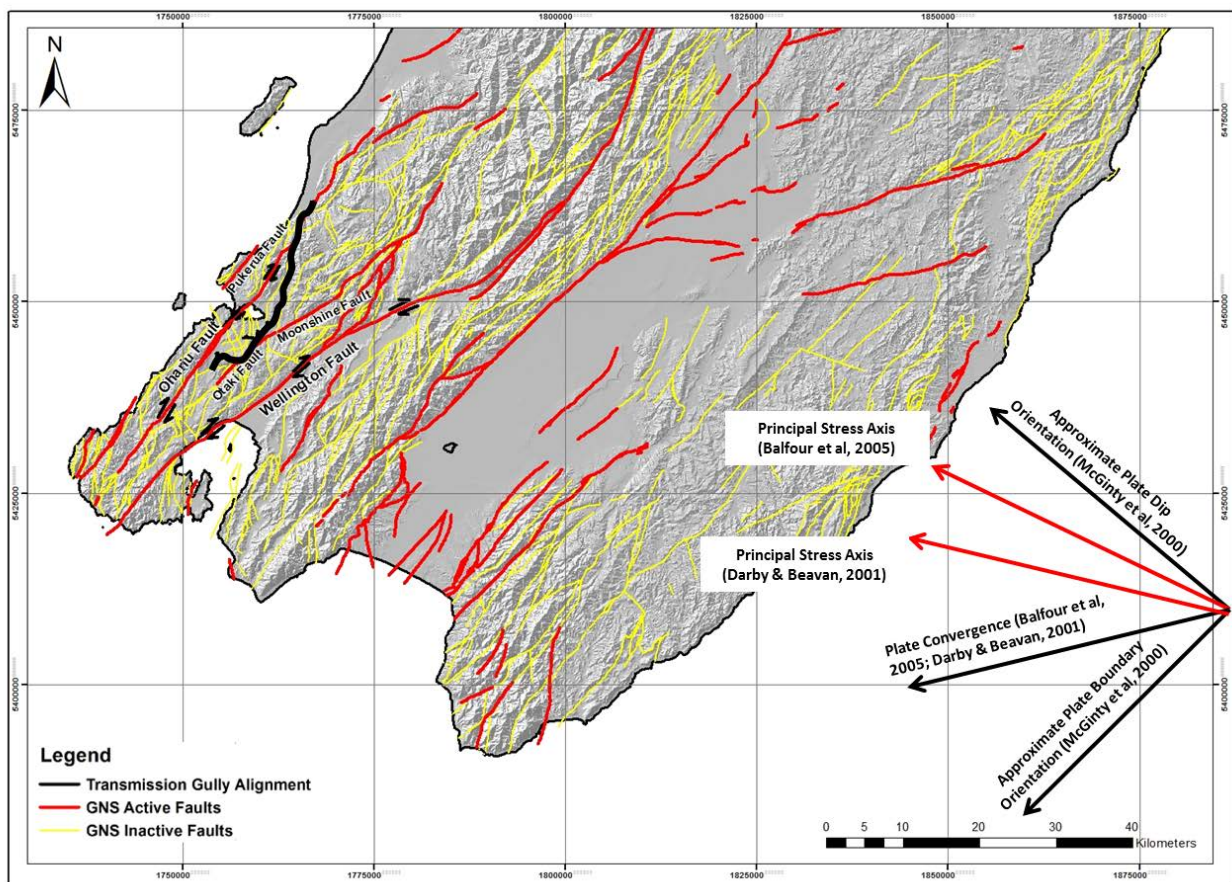


Figure 2: Wellington regional tectonic model. Fault data sourced from Heron (2014).

3.3 ROCK MASS

The Torlesse rock mass comprises a series of variably interbedded sandstone and mudstone (Mortimer, 2004). Several periods of tectonic deformation are recognised prior to the formation of the current plate boundary as summarised in Section 3.1. The rocks are highly folded, faulted and commonly out of sequence (Cox & Barrell, 2007). The result is an intensely deformed rock mass unit whose engineering characteristics can vary significantly over short distances.

The rock mass is heavily anisotropic. The mudstone beds are typically more susceptible to deformation and, as a result, significant layer parallel shearing is common along bedding. Irvine (2013) has previously demonstrated highly anisotropic rock mass strengths between the two members in Canterbury, New Zealand. The mudstone member is typically thinner, fragmented, exhibits lower intact strengths and is more sheared than the sandstone member.

Structural discontinuities can vary substantially in character. Bedding, faulting and shearing is typically steeply dipping with high persistence. Conversely, jointing is generally short and discrete. Previous authors (Read & Richards, 2007; Read et al., 2000) have described the nature of non-persistent jointing of the Torlesse rock mass in detail. The short discrete jointing acts to 'interlock' the rock mass usually resulting in high rock mass strengths at the cutting scale.

Intact rock strengths vary with weathering. At Transmission Gully, highly weathered rock encountered in the field are typically very weak to weak with UCS strengths < 20 MPa. In this case, global cut stability is often governed by the rock mass strength. In contrast, moderately weathered rock is typically weak to moderately strong. In this case, despite the fractured nature of the rock mass, intact strengths are generally high enough to prevent global rock mass failure. In moderately weathered rock or better it is anticipated rock structure will control global stability. Given the persistence of bedding and faulting/shearing these structures are the dominant control on kinematic failure mechanisms.

3.4 GEOLOGICAL SUMMARY

Given our understanding of the tectonic history, the rock mass and crustal anisotropy it is hypothesised major (fault) structure has formed preferentially along bedding, probably during subduction related processes. The plates have become locked and the principal stress axis has rotated away from the dip of the subducting slab to accommodate northeast-southwest strain between strike slip in the south and subduction in the north.

The modern day principal stress axis (Figure 2) is controlled by two mechanisms; northwest subduction slab pull and northeast-southwest strain transfer. It is well documented in the literature Wellington faulting is not well aligned to the principal stress axis.

The orientation of northeast-southwest dextral faulting suggests the subducting slab is most likely coupled, there is a degree of crustal anisotropy, and strain (parallel and perpendicular to the plate boundary) is accumulating in the crust. Carter (1988) suggests crustal strain is accommodated by deformation between major faults, dissipation along favourably orientated structure and by rotation of intra-fault blocks.

In the Torlesse, rock mass strength is anticipated to govern slope stability in highly weathered rock. In moderately weathered rock or better, slope stability is anticipated to be governed by structural kinematics, specifically persistent bedding and faulting/shearing. Jointing is sufficiently short and discrete that it is not anticipated to control stability in the majority of cases.

4 STRUCTURAL PATTERNS

4.1 REGIONAL STRUCTURE

A lineament analysis of the Transmission Gully Project and the wider Wellington region was carried out prior to interrogation of the Geological and Nuclear Science (GNS) fault database sourced from Heron (2014). The lineament analysis was undertaken to predict potential fault and structural patterns along the highway alignment and to supplement the GNS fault database.

The fault and lineament model is presented in Figure 3. To aid in the interrogation of major structure, faults and lineaments were divided into three Fault Orders dependant on strike length, Table 1. The division was carried out under the assumption major structures with greater strike lengths are likely to have a larger control on crustal stress/strain and subsequently have a wider zone of structural influence.

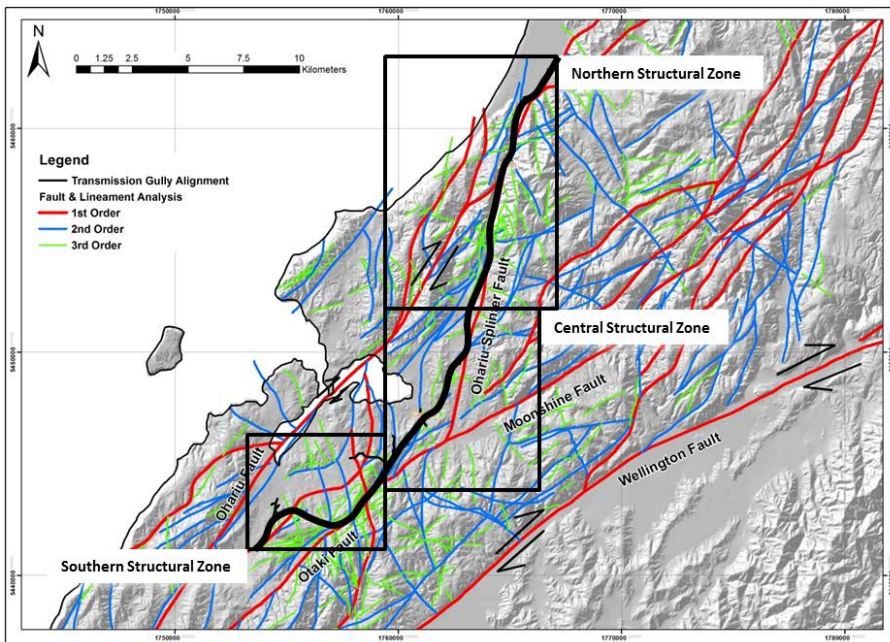
Figure 3 also presents the orientation of major structure plotted by Fault Order. The plots demonstrate heavy crustal anisotropy, particularly of First Order structure. The plot also suggests the propagation of Second and Third Order structure is influenced by First Order structure. Figure 3 attempts to explain this geometric relationship with a typical riedel shear model. Second Order structures are dominantly represented by type R and P shears, sub-parallel to the First Order. Conversely Third Order structures are represented by the range of shear types including perpendicular type R'.

Applying the philosophy of crustal anisotropy, we can infer an approximate bedding orientation based on the orientation of major structure. Furthermore, by applying the radial shear model we can infer faulting and shearing at different scales should preferentially align sub-parallel to major structure. This inference gives us a basis for predicting cutting scale structure at Transmission Gully and helps guide interpretation of ATV/OTV in a heavily fractured mass.

To test this idea, the Transmission Gully alignment was divided into three distinct tectonic structural zones defined by the geometry of major structure, Figure 3. The division of the alignment into tectonic zones allows us to infer cutting scale structural orientations for each zone based on the orientation and geometric relationship of major structure within that zone.

Table 1: Definition of fault orders

Order	Strike Length	Characteristics
First	> 10,000 m	Regional scale north to northeast striking, dextral active faulting.
Second	10,000 m – 2,500 m	District scale northwest to northeast striking. Structures are typically sub-parallel to the First Order. They tend to link the First Order and likely distribute strain between seismic events.
Third	< 2,500 m	Local scale structure orientated both parallel and perpendicular to First and Second Order structure. The Third Order commonly links the Second Order and likely accommodates intra-fault block strain.



Subsidiary R, R' and P riedel shearing about a major structure (Twiss & Moores, 1992)

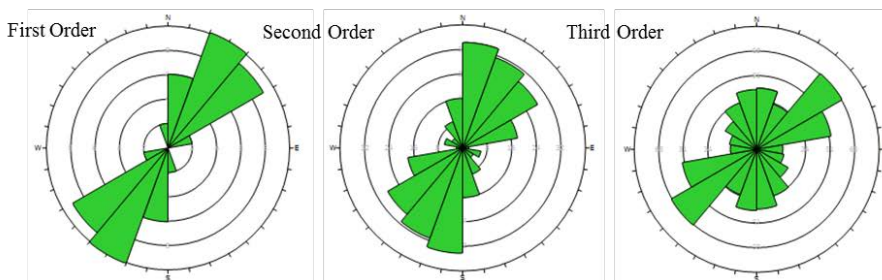
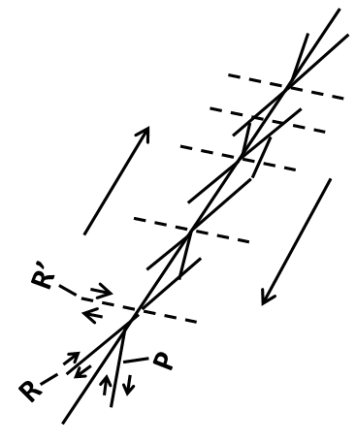


Figure 3: Orientations of First, Second and Third Order fault/lineament major structure. Faults sourced from Heron (2014) supplemented with an interpretation of topographic lineaments.

4.2 ALIGNMENT STRUCTURE

4.2.1 Northern Structural Zone

The Northern Structural Zone is characterised by two major structures, the active Ohariu Fault and the Ohariu Splinter Fault, Figure 4. The Ohariu Fault runs along a western valley parallel to Transmission Gully before stepping over onto the alignment at the Wainui Saddle. The Ohariu Splinter Fault runs along the Transmission Gully alignment in the Horokiri Valley before meeting the main Ohariu Fault at the Wainui Saddle (topographic high).

It is interpreted crustal stress in the Northern Structural Zone is controlled by the right hand step over of the active Ohariu Fault, Figure 4. The right hand step over creates a releasing bend and is anticipated to place a high portion of the Northern Zone in north-south extension. It is interpreted stress from the releasing bend is transferred onto First Order structure either side of the step over and onto Third Order east-west structure, Figure 4. The releasing bend is expected to contribute to a high degree of dip slip movement, particularly on east-west structure orientated perpendicular to inferred movement. It is documented in the literature north trending strike slip releasing bends have a tendency to produce east-west striking normal and thrust faults (i.e. Balfour et al, 2005).

The zone is anticipated to be highly disturbed due to the close proximity of major structure. The conceptual model suggests two dominant cutting scale structural orientations should dominate:

- Bedding and shearing sub-parallel to major structure i.e. north-south striking; and
- Shearing perpendicular to major structure i.e. east-west striking.

4.2.2 Central Structural Zone

The Central Structural Zone is defined by the Ohariu Fault to the west, the Ohariu Splinter Fault to the east and the Otaki Fault to the south, Figure 5. The structural grain of the zone is dominantly northeast-southwest orientated.

The structural zone is dominantly controlled by the Ohariu Fault. The Ohariu Fault exhibits a series of curves anticipated to create releasing/restraining bends that control the propagation of Second and Third Order structure.

Near the southwest of the zone the Ohariu Fault begins a gentle right hand curve resulting in a slight releasing bend. This corresponds with a topographic low (Porirua Harbour). Moving northward the fault curves back to the left creating a restraining bend and point of stress which corresponds to a sharp increase in topography.

Figure 5 attempts to relate the propagation of subsequent structure using point of stress theory, that is the idea that at a point of stress, stress field trajectories will bend, rotate and concentrate on the point resulting in structure propagating into the point of stress (Price & Cosgrove, 1990). In the central zone, a series of Second Order structures appear to propagate into the First Order restraining bend.

The southern and central portion of the zone exhibits gently rolling topography. The structure tends northeast-southwest at a similar orientation to the Otaki Fault. The Ohariu Splinter Fault runs against the structural grain in a north-northeast trend and is interpreted to control local scale structure near the fault trace. The trace runs parallel with the Transmission Gully highway alignment before joining the alignment near the middle of the structural zone.

Bedding and shearing is anticipated to strike sub-parallel with northeast-southwest structure throughout the zone. Some small scale north striking faulting is anticipated in close proximity to the Ohariu Splinter Fault.

4.2.3 Southern Structural Zone

The Southern Structural Zone is dominated by a series of high angle cross faults linking the Otaki and Ohariu Faults, and indirectly linking the Wellington and Ohariu Faults, Figure 6. It is interpreted high angle cross faulting is actively accommodating regional tectonic stress between the Wellington and Ohariu Faults. Both structures experience dextral movement which place the intra-fault block in convergence. As the structures converge toward the south there is less available rock volume to accommodate elastic strain. The result creates a series of fault bound blocks that link the major structures and accommodate intra-fault stress. Intra-fault block rotation is a recognised mechanism to accommodate crustal strain. Given the geometric relationship between the Wellington and Ohariu faults, and the high angle cross faulting, anticlockwise block rotation about a series of vertical axes is thought to be occurring, Figure 6.

The hypothesis of high angle faulting and intra-fault block rotation suggests bedding may have rotated from northeast to northwest and has preferentially aligned sub-parallel to cross faulting i.e. oblique-perpendicular to the alignment, rather than sub-parallel as inferred in other areas of Transmission Gully. Likewise, shearing is anticipated to propagate and align sub-parallel to cross faulting.

The degree of rotation from northeast to northwest is unknown but regardless the anticipated rotation from sub-parallel to oblique-perpendicular with the alignment is favourable for highway cut slope design. Some northeast-southwest striking structure is anticipated due to the close proximity of the Otaki Fault.

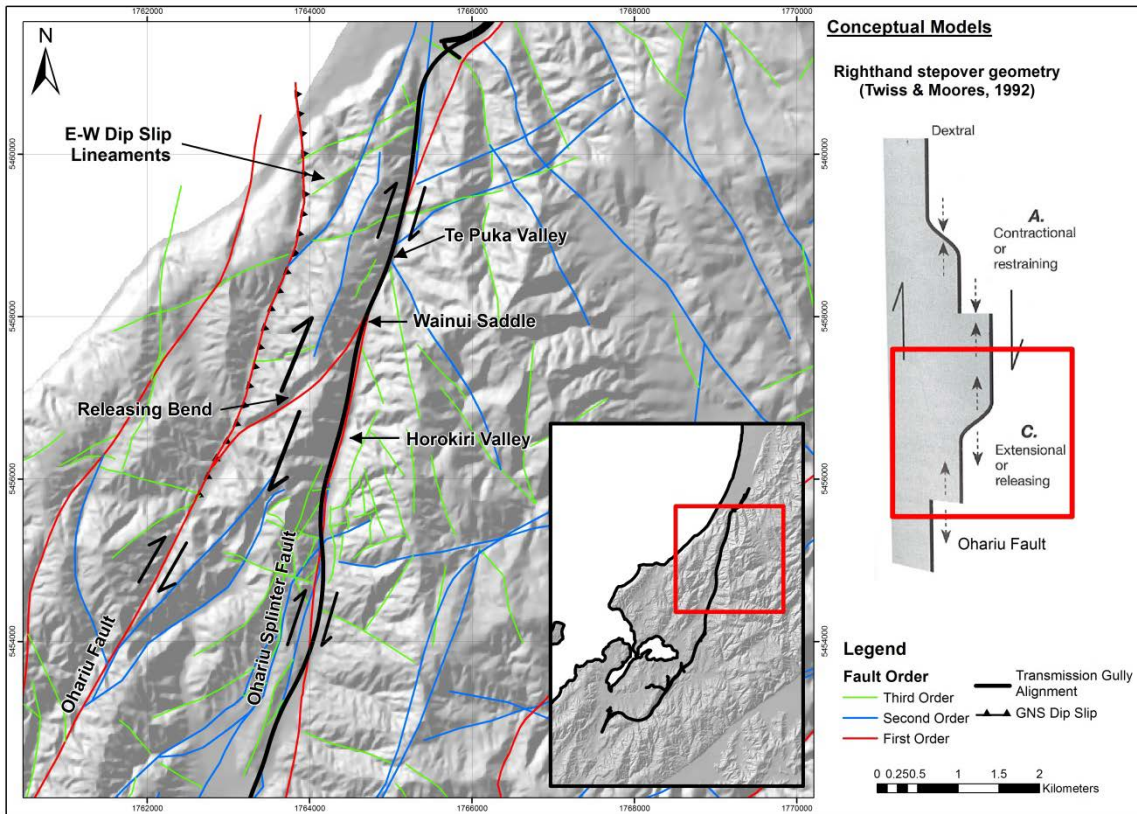


Figure 4: Northern Structural Zone and conceptual structural model. Faults sourced from Heron (2014, see Figure 2) supplemented with an interpretation of topographic lineaments.

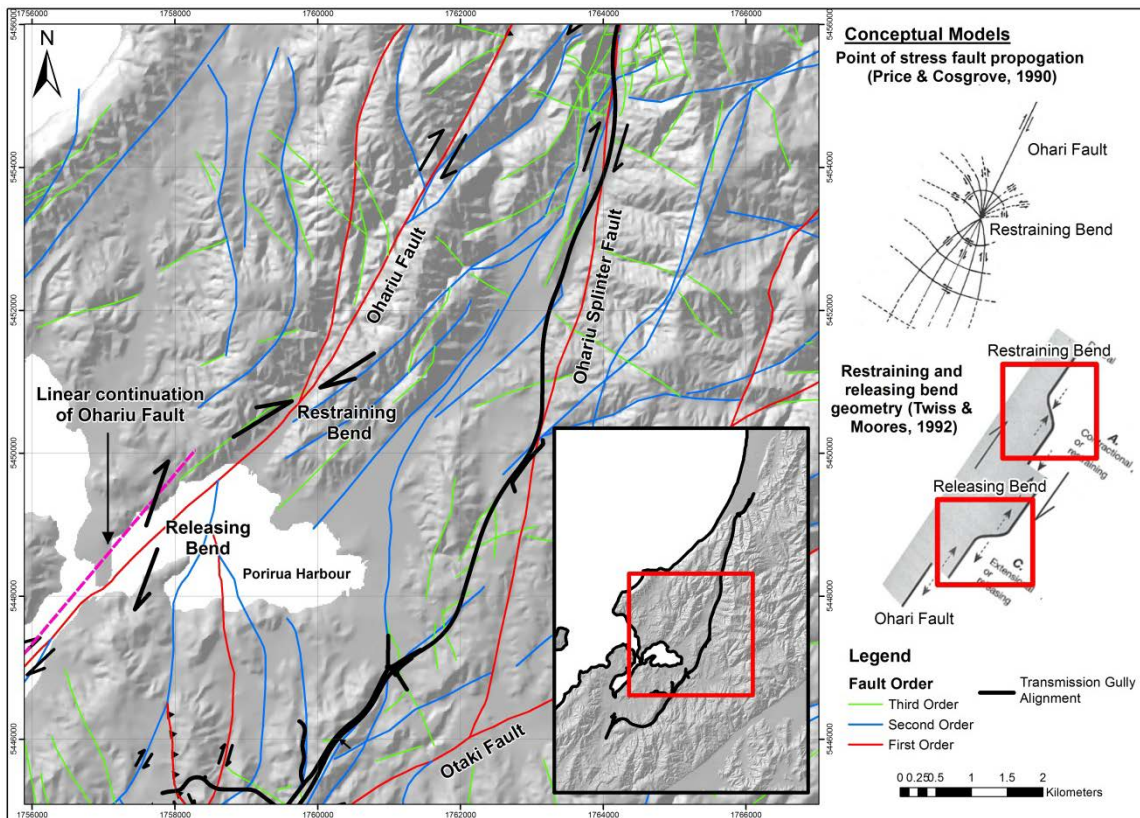


Figure 5: Central Structural Zone and conceptual structural model. Faults sourced from Heron (2014, see Figure 2) supplemented with an interpretation of topographic lineaments.

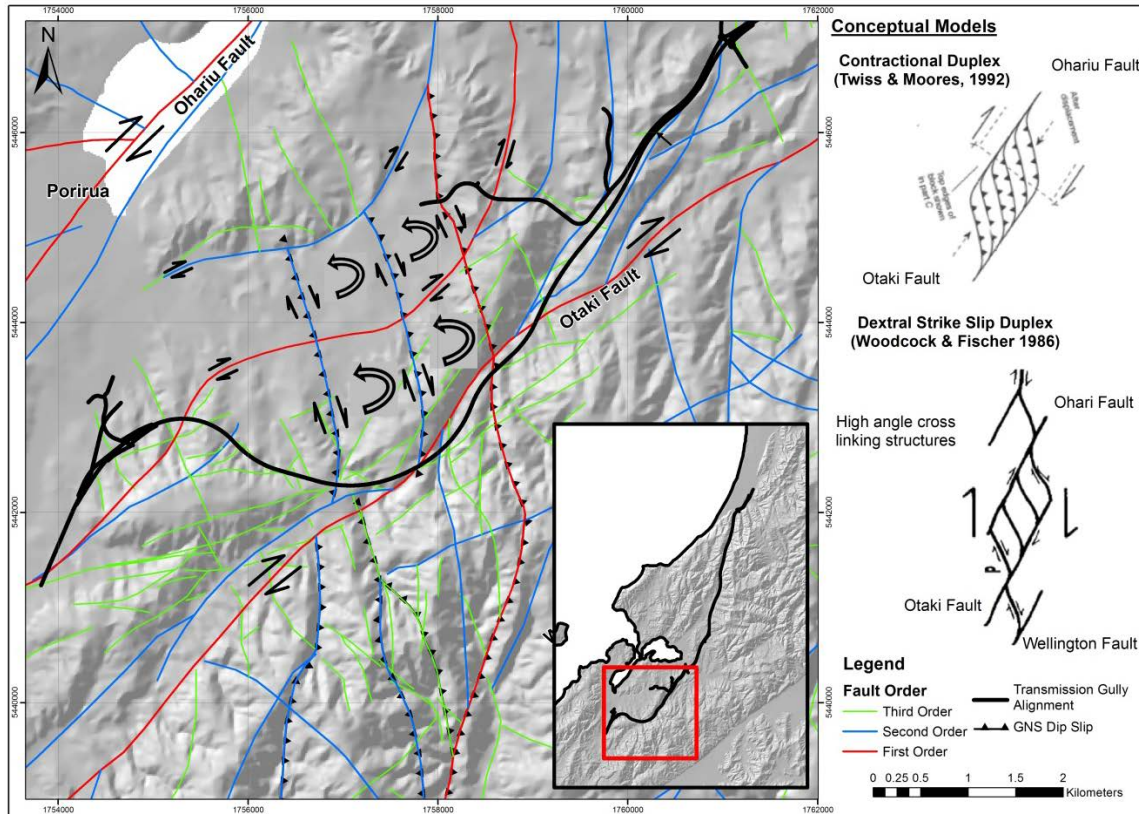


Figure 6: Southern Structural Zone and conceptual structural model. Faults sourced from Heron (2014, see Figure 2) supplemented with an interpretation of topographic lineaments.

4.3 COMPARISON WITH THE STRUCTURAL DATABASE

4.3.1 Bedding

Figure 7 presents stereoplots of bedding orientation for each tectonic structural zone, sourced from mapping and ATV/OTV interpretation. The average strike of major structure is presented on the plots for comparison. The figure demonstrates a clear relationship between major structure and the orientation of bedding. Typically, bedding strikes parallel to sub-parallel with major structure and tends to rotate in response to changing strike of major structure. At a local scale, folding and/or cross cutting of bedding is anticipated to produce some variation in bedding orientation.

It should be noted there is a lack of data in the centre of the Central Structural Zone. This is primarily due to limited cut heights and a deep weathered profile where global rock mass failure (rather than structural kinematic) is anticipated to govern stability. In this case, cuts are not anticipated to extend into structurally controlled rock.

4.3.2 Faulting and Shearing

Figure 8 presents stereoplots of fault/shear orientation for each structural zone sourced from mapping and ATV/OTV interpretation. The average strike of major structure is presented on the plots for comparison. The figure demonstrates only broad conclusions can be made between the orientation of major structure and borehole scale structure.

Due to the complex tectonic history of the Torlesse, faulting and shearing tends to present as recent 'systematic' defects that form sets and older 'non-systematic' defects which cross cut and create scatter. When interpreting ATV/OTV structural logs it is nearly impossible to distinguish between systematic and non-systematic faulting/shearing which leads to heavy scatter, as observed in Figure 8. Generally speaking, there are two systematic fault/shear sets that strike subparallel with bedding and major structure. Faulting and shearing in this orientation is expected to be younger and typically exhibit weaker (uncemented) infills. Other non-systematic defects that are randomly orientated or only form weak sets may represent older faults and shears whose infills have been annealed or semi-annealed over time.

Understanding the orientation of systematic faults and shears allows us to design for individual rock cuttings, however the randomness of faulting and shearing orientation in the Torlesse presents a risk to cut slope design. At Transmission Gully this risk is actively managed by adopting the observational method, including detailed geotechnical mapping and verification of design assumptions during cutting excavation.

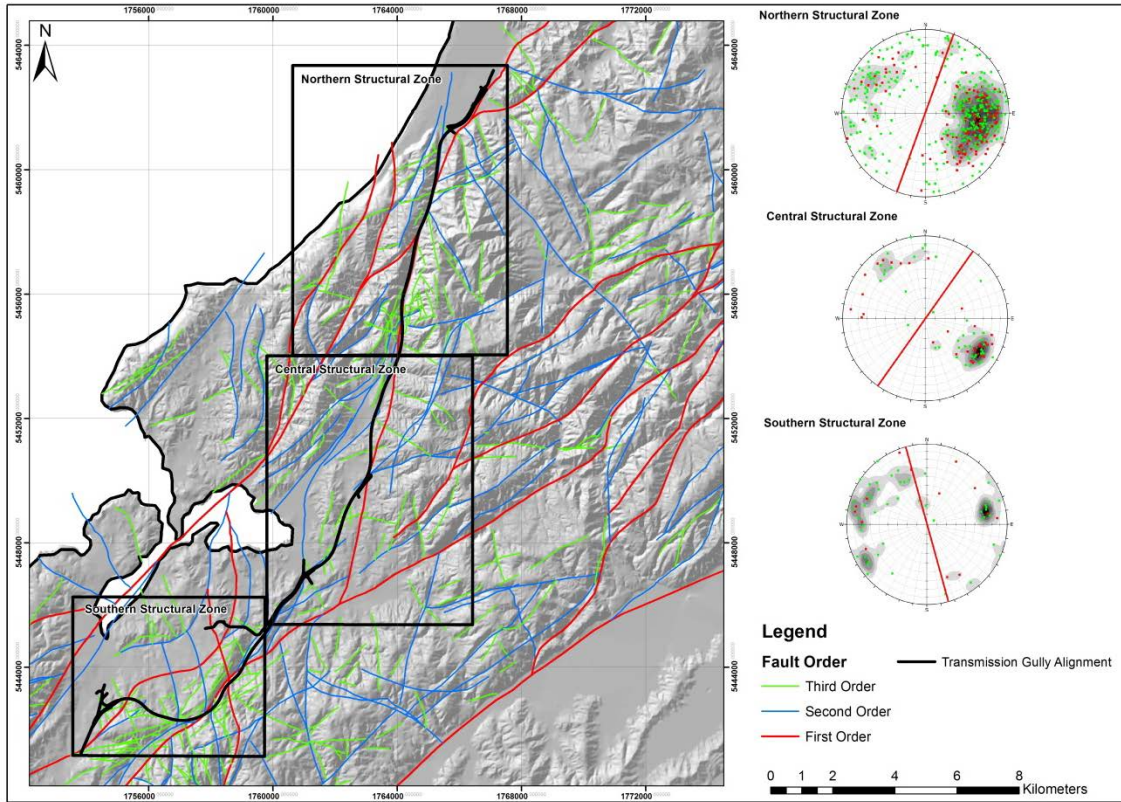


Figure 7: Comparison of bedding orientation to major fault/lineament orientation. Faults sourced from Heron (2014, see Figure 2) supplemented with an interpretation of topographic lineaments.

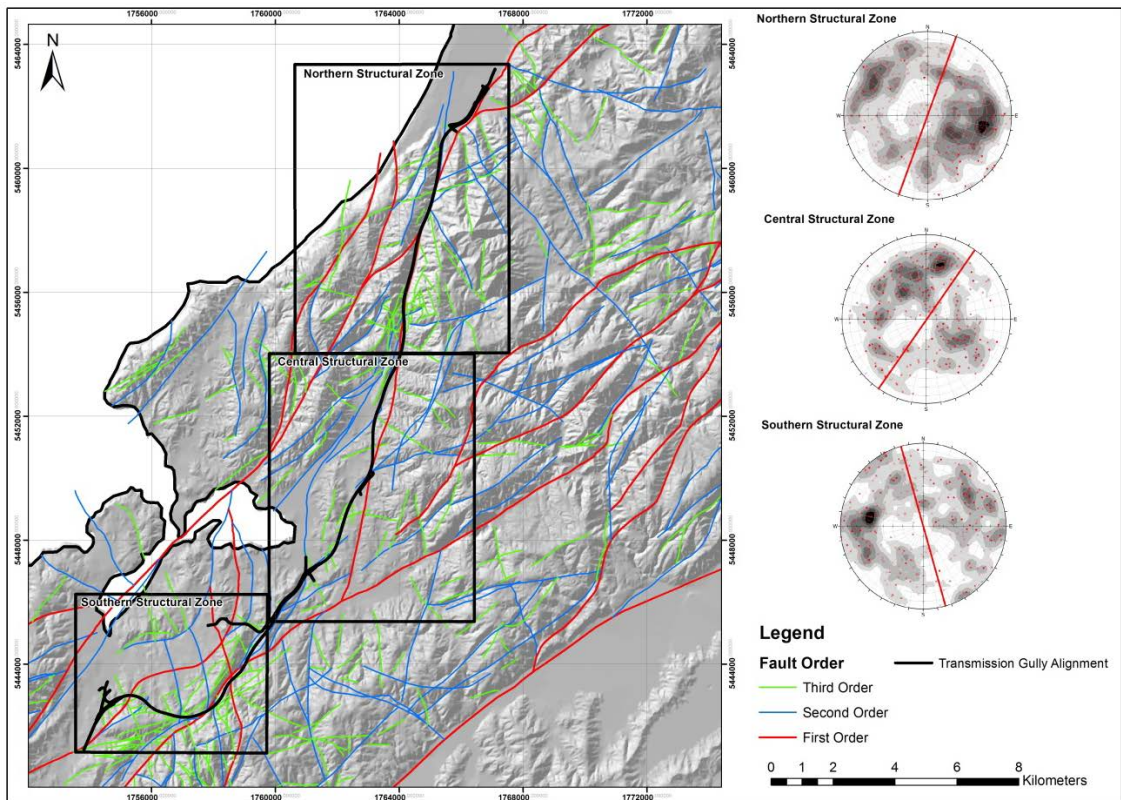


Figure 8: Comparison of shearing orientation to major fault/lineament orientation. Faults sourced from Heron (2014, see Figure 2) supplemented with an interpretation of topographic lineaments.

5 SUMMARY AND CONCLUSIONS

A simple tectonic study investigating the geometric relationships between major structures has been used to help predict cutting scale structural patterns and guide interpretation of the borehole dominated structural database. In the Torlesse rock mass of Wellington, this approach has proven to be a useful tool for predicting cutting scale structure and aiding in the dissection of the alignment into tectonic design domains.

The study has developed a conceptual tectonic and rock mass model for the Transmission Gully alignment and the wider Wellington region. The results indicate the region is undergoing stress from two mechanisms, the subduction of the Pacific Plate whose interface is locked and northeast-southwest transfer between strike slip in the south, and subduction in the north. The result is a principal stress axis which is not well aligned to the structural grain of the lower North Island. The misalignment suggests the tectonic plates are most likely coupled and there is some degree of crustal anisotropy that allows northeast-southwest dextral movement on unfavourably orientated structure.

Applying the philosophy of crustal anisotropy and employing simple 'textbook' style structural relationships the Transmission Gully corridor was separated into three tectonic structural zones. Structural relationships in each tectonic zone were assessed in detail allowing cutting scale structure, specifically bedding and faulting/shearing to be predicted. The prediction of cutting scale structure also allowed 'intelligent' interpretation of the ATV/OTV dominated structural database in a heavily fractured mass. The results indicate potential bedding and, to a lesser extent, faulting/shearing patterns at Transmission Gully can be inferred by assessing the geometric relationships of major structure.

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