HOW TECTONIC GEOMORPHOLOGY CAN BE USED TO FIND A HIDDEN FAULT ZONE: A CASE STUDY OF THE TE TATUA O WAIRERE FAULT ZONE, NEW ZEALAND

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ABSTRACT

A series of complex fault systems have recently been discovered within the Hamilton Basin, New Zealand. Though the first zone was unexpectedly exposed during construction excavations, other zones have been discovered due to their influences on the local geomorphology. In this paper we present evidence for tectonic geomorphic features that were first observed via high-resolution LiDAR images of the Hamilton Basin, then confirmed by geologic and geomorphic mapping. Exposed fault traces show evidence of significant fault splaying within the soft sediments and tephra deposits contained within the basin, causing the fault zones to cover a wide area and create a geomorphic system of complex linear ridges. At Stubbs Road, tectonic geomorphological features including rectangular drainages, stream knickpoints, aggradational/degradational zones, linearly aligned ridges and drainage systems, and abandoned river channels and outlets were observed in the LiDAR and bathymetric data of the Waikato River and surrounding area. Field investigations revealed offset geological outcrops concurring with geomorphic features found in both the LiDAR and bathymetric data. At this site the Waikato River begins bending 82° from N to NE. Electrical resistivity data reveal a discontinuity in the geological material and seismic reflection indicates a fault crossing the river. These features are evidence for the Te Tatua o Wairere Fault Zone and are being presented to exemplify the use of tectonic geomorphology in aiding in the discovery of tectonic structures that are either concealed due to poor exposure within young, unconsolidated material, or that contain planes that have yet to daylight.

1 INTRODUCTION

The Hamilton Basin is a depression located in the central North Island of New Zealand and is confined by the Pakaroa Ranges and Maungakawa Hills to the east, the Alexandra Volcanics and Kawhia Syncline to the west and the Hakarimata-Taupiri Ranges to the north (Fig. 1). The surficial geological units that fill the basin are Pleistocene-age Walton Subgroup consisting of primary and reworked non-welded ignimbrites and tephras, that are overlain by low angle, late Pleistocene age, volcaniclastic derived alluvial fan sediments of the Hinuera Formation (Selby and Lowe, 1992; Edbrooke, 2005; McCraw 2011). Until recently, geological research concluded that only two existing faults influence the Hamilton Basin - the N-S oriented Kerepehi Fault, located to the east in the neighbouring Hauraki Basin, and Waipa Fault located to the west inferred by the Junction Magnetic Anomaly (JMA). The Kerepehi Fault is an active normal fault, but the Waipa Fault is considered to be inactive. Information regarding the movement along the Waipa Fault suggests last activity occurred between the early Paleogene and the Oligocene with a predominantly normal movement. (Kear, 1960; Kear and Scholfield, 1978; King, 2000). A third E-W oriented fault located at the base of the Hakarimata-Taupiri Ranges was proposed by Hunt (1978), Kear and Schofield (1978) and Kirk (1991). Due to the approximate 30° displacement of the Hakarimata Anticline to the rest of the Kawhia Syncline it has been proposed by Kirk (1991) that strike slip movement may have occurred along the Waipa Fault.

Seismic hazards as defined by the National Seismic Hazard model for New Zealand, are considered to be relatively low for the Hamilton Basin due to the absence of known active faults (Stirling et al., 2010). However, two faults zones named the Kukutaruhe Fault Zone and the Te Tatua o Wairere Fault Zone have recently been discovered within the Hamilton Basin (Moon and de Lange, 2017; Campbell, 2017). Due to the soft sediment nature of the geological units within the Hamilton Basin, faults can be difficult to observe because the poorly consolidated deposits existing in the basin can be easily eroded, reworked and redeposited. With such challenging locations, tectonic geomorphology coupled with standard geologic mapping and geophysical data is key for evaluating the structural evolution of the area. This paper presents an example of the use of a multi-faceted geomorphic, geological, and geophysical investigation programme to elucidate the pattern of faulting in a previously un-recognized complex fault zone. The field area is a near Stubbs road, south Hamilton City, NZ (Fig. 1)

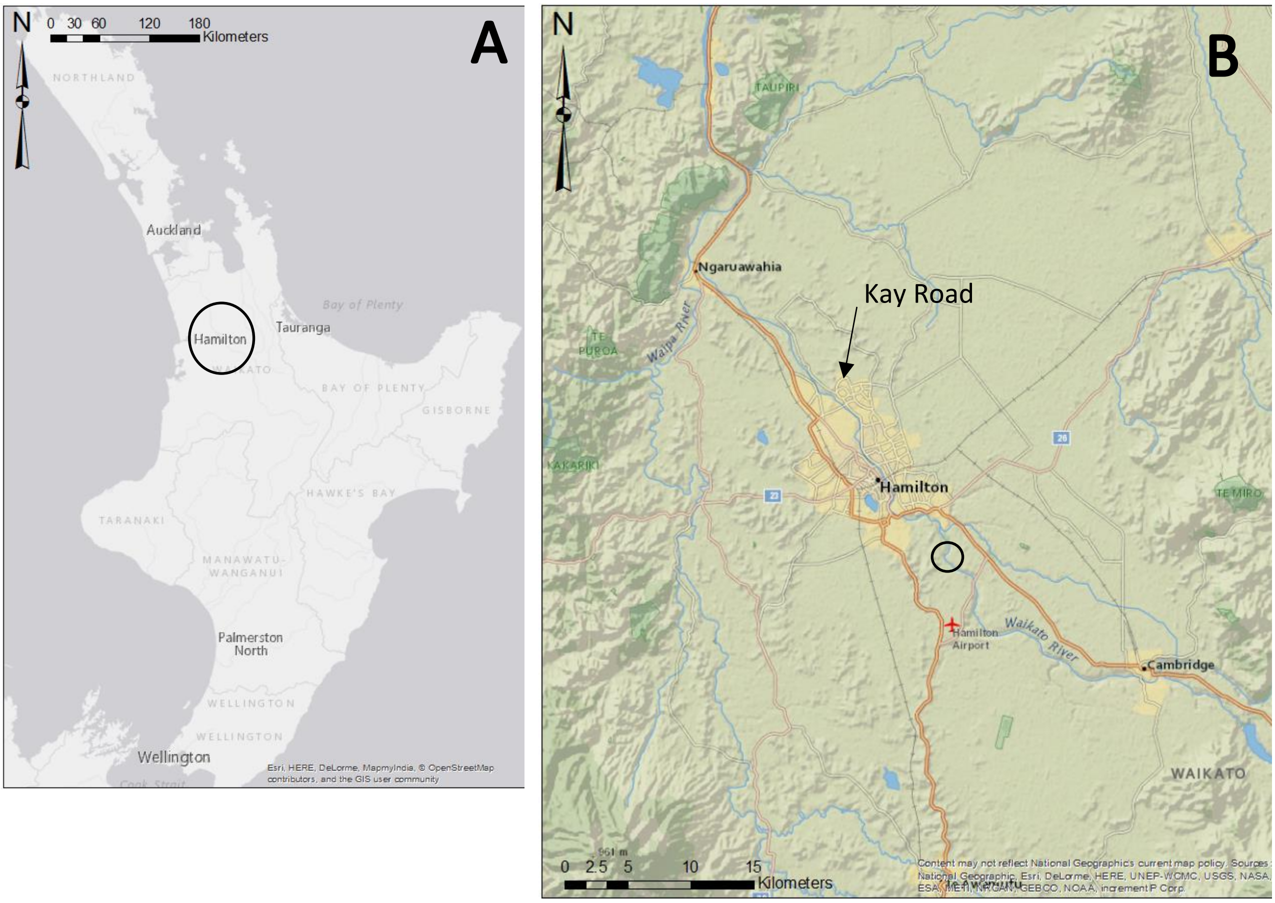

Figure 1. A) Map of the North Island of New Zealand. Hamilton's location is circled. B) Map of Hamilton with Kay Road marked by the arrow and Stubbs Road field area by the circle.

2 METHODS

It has been hypothesized that the current course of the Waikato River was formed when the river changed from a meandering braided system to an entrench river system after its sediment supply began to dwindle (Schofield, 1967; Selby and Lowe, 1992; McCraw, 2011). Sediment sources were supplied through the erosion of various ignimbrites and other volcaniclastic rocks in the Waikato Region, particularly those related to the Taupo Volcanic System (Hume et al., 1975; Manville, 2002; Manville and Wilson, 2004). It was believed that the geomorphology of the Hamilton Basin was marked by the various paths of the Waikato River while it meandered with the assistance of the post eruption break out floods supplying significantly large amounts of sediment (Manville and Wilson, 2004; Selby and Lowe, 1992; Hume, 1975). However, given the recent discovery of two fault zones within the Hamilton Basin, it has become clear that the tectonic influences encourage the current entrenched location of the Waikato River. Thus, the geomorphology of the Hamilton Basin needs to be revaluated.

The geomorphology of the basin was examined using LiDAR data provided by the Waikato Regional Council. The Waikato River is a particularly important geomorphic tool because rivers act as linear structures and create other linear features such as terraces, floodplains, and channels that give insight into temporal changes associated with land movements (Schumm et al., 2000; Jain and Sinha, 2005). With a basic understanding of fluvial geomorphology coupled with the use of LiDAR, resistivity surveys, and shallow seismic (CHIRP), multibeam imaging, and sidescan imaging of the Waikato River (Wood, 2006; Moon and de Lange, 2017) an evaluation of tectonic geomorphic signatures within the Hamilton Basin could be conducted. The results gathered from these remote sensing techniques were used in selected regions of interest for further investigation via field ground truthing. Standard geologic mapping techniques were conducted to map the selected regions along the Waikato River bank using boat surveys and foot access when available. Ground truth techniques included taking sketches, stratigraphic logs, and photographing landforms and outcrops. Fault plane orientations, stratigraphic dips, and dip directions were recorded using the mobile application GeoID; location parameters were recorded using GPS. Samples were collected from areas where lithology could not readily be determined in the field and used for preparation of thin section samples. A two-dimensional resistivity survey was undertaken at

Stubbs Road by Cummins (2016). The resistivity lines were positioned to target a fault zone identified in the seismic survey and intersect an abandoned channel inferred from the geomorphology.

3 RESULTS

3.1 GEOMORPHOLOGY

Fluvial systems are used as important tools to understand the interaction between tectonic influences and geomorphologic processes. In order to discuss results gathered from remote sensing and the field expeditions we must first consider key features of tectonic geomorphology and what they mean for the Hamilton Basin. Key geomorphological trends along the Waikato River observed from the LiDAR, field data, multibeam, and seismic results include a rectangular drainage system, abandoned channels, and knickpoints observed in the multibeam and seismic data.

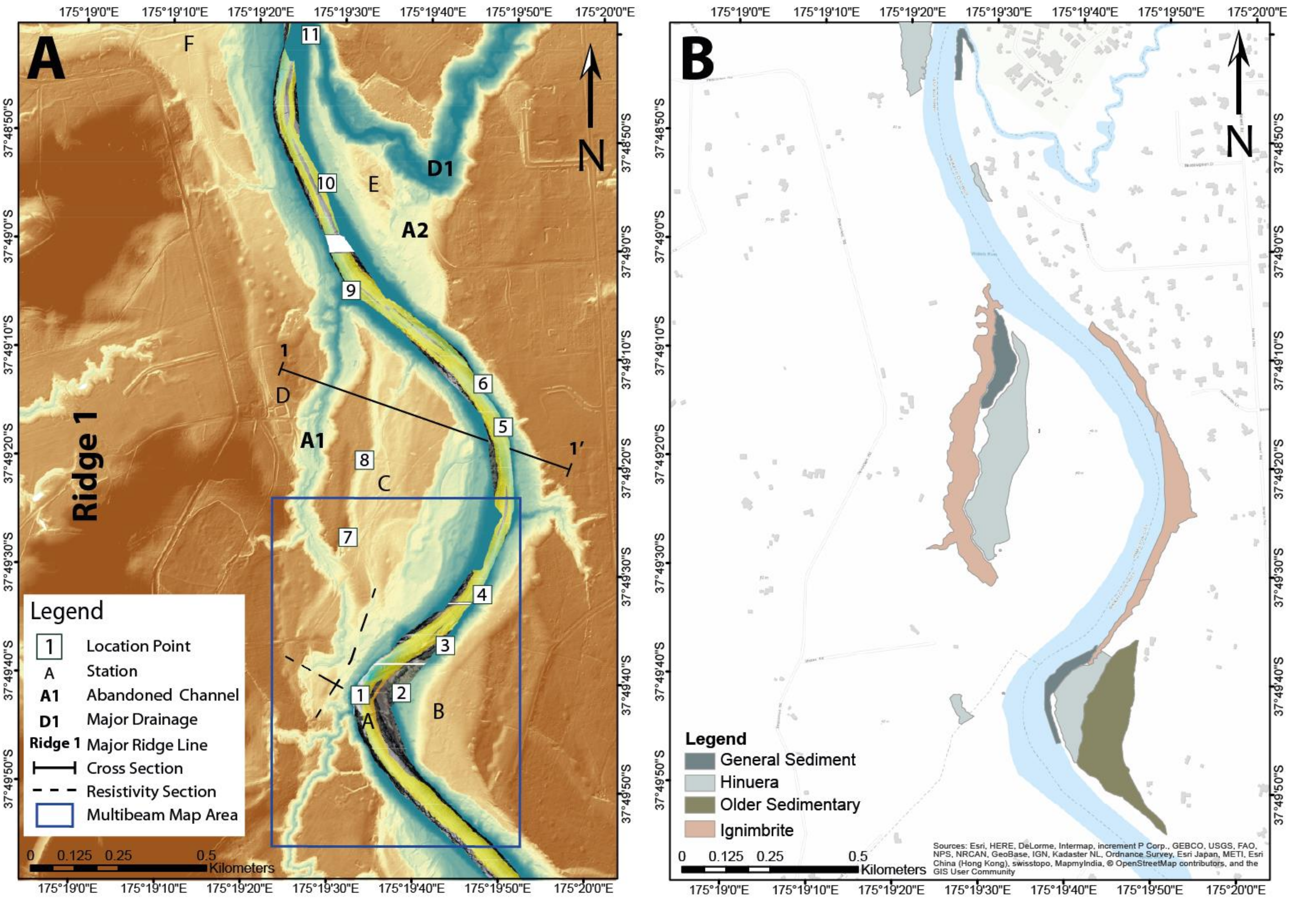

Figure 2. A) LiDAR map of the Stubbs Road field area with brown indicating high elevation and blue low elevation. B) Geologic map of the area based on data collected from field data.

There are eleven major river bends along the Waikato River in the Hamilton area with changes of bearing varying between 140° and 82°. Two of these major bends are located within the Stubbs Road field area, with the first major bend at Station A measuring approximately 82°, and the second occurring along the eastern side of Station C measuring approximately 139° (Fig. 2). As the Waikato River progresses downstream from south to north it maintains a NW direction until suddenly bending at Station A to the NE and then back towards the NNW at Station C, forming a large half-moon shaped terrace along the western bank. The Waikato River then maintains a N-S orientation for several kilometres until it reaches Station F (Fig.2A). Along the western side of the river is a large north-south oriented ridge, Ridge 1. To the east of Station A is a small one-sided terrace, marked by Station B, and along the western bank and slightly north is a larger single sided, half-moon shaped terrace marked by Station C. The large terrace at Station C is composed of three smaller terraces, T1-T3, decreasing in height from W to E (Fig. 3). A deep N-S oriented channel, A1, cuts into these terraces along the western outermost edge near T1 (Fig.2A and 3). The inlet of the abandoned channel begins at Station A near the orthogonal bend in the river and links to the Waikato River to the north at Location 9. This indicates the abandoned channel once followed a N-S alignment of the Waikato River, which can be observed toward the north near Stations E, F, and G. West of the channel at Station D the elevation of the surrounding ground is of similar elevation to the tallest of the three terraces, T1, at Station C. In the southern area near Station A the abandoned channel width measures between 30-50m and does not contain any major terraces. However, to the north near Location 9 the width of the abandoned channel increases to 50-100m and a set of terraces can be observed.

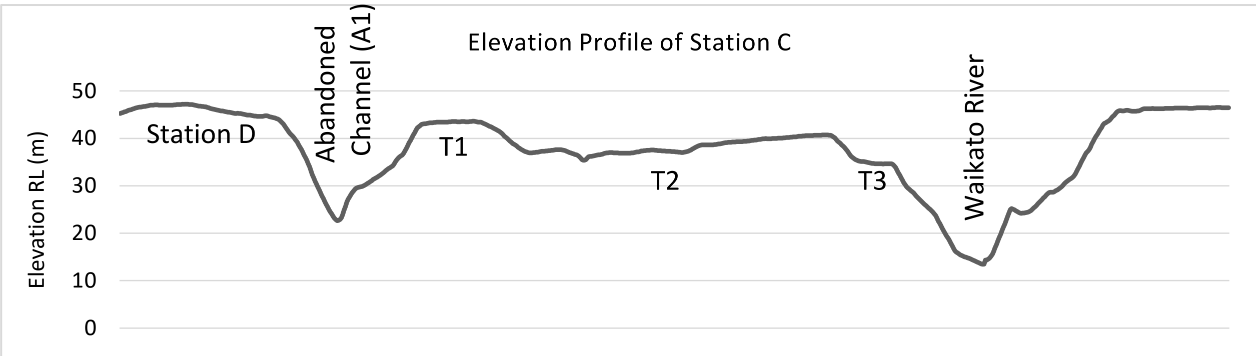

Figure 3. Elevation cross-section of the western bank of the Waikato River within Stations C and D from west to east. Note that Station D and the highest terrace (T1) have similar heights. The terraces at Station C decrease in height from W to E and are labelled tallest to smallest as T1 to T3.

3.2 FIELD RESULTS

Along the eastern bank at Station B recent fine to coarse grained river deposits were found along the lower portion of the terrace, with Taupo Pumice Alluvium occurring in one area marked by Location 2 (Fig. 2B). Sediments belonging to the Hinuera Formation dominate the rest of the terrace at Station B, except within the northern section, marked as Location 3, where a thinly bedded yellow-white outcrop of alternating silt and white-yellow clay layers is present along the slope leading from the bottom of the terrace to the top (Fig. 2 and 4A). The clay/silt beds are sub-horizontal and do not possess any cross bedding, indicating they are related to a locally reworked ignimbrite. The presence of ignimbrite along the eastern bank was confirmed by outcrops along the Waikato River, marked at Locations 4, 5, and 6 (Fig. 2) and related thin section samples gathered from these locations. An attempt was made to find the exact location of the contact between the Hinuera Formation and the ignimbrite, but the area of the potential contact was buried under disturbed Hinuera Formation sediments that have been pushed over the slope during construction for the existing homes and private river access paths. Ignimbrite continues to be present down the Waikato River until Station E, where the geology of the outcrops changes to Hinuera Formation, marked by Location 10, and Taupo Pumice Alluvium, marked by Location 11 (Fig. 2). The contact between ignimbrite and sediments of the Hinuera Formation/Taupo Pumice Alluvium near Station E was not be located due to the heavy vegetation along the river bank.

Figure 4. A) Photographs of the yellow-white alternating horizontal clay/silt bands found at Location 3 along the eastern terrace at Station B. B) Photograph of the Ongatiti Ignimbrite forming cliffs at Location 9. C) Image of the cross bedded sands and gravels of the Hinuera Formation found along the T1 terrace at Location 7.

Along the western bank at Station C the western abandoned channel, A1, is composed of massive white cliffs with large pumice clasts and felsic mineral crystals supported in a fine matrix. This unit was followed from N to S throughout the drainage area. The best exposure of this unit is present along the northern section, at Location 9, where the material makes up the steep cliffs surrounding a low level heavily vegetated terrace (Fig. 4B). Thin sections of samples collected from various locations throughout A1 and the cliffs at Location 9 show massive, poorly sorted glass and pumice-rich material, with little to no minerals, indicative of an ignimbrite, likely the Ongatiti Ignimbrite. Mineral content, when it was present, consisted predominantly of plagioclase and quartz. Hinuera Formation is present at Station C with outcrops marked by Location 7 and 8 (Fig. 2). At Location 7, a large exposed face along the SW side of the terrace shows fine to coarse sands and gravels that are cross bedded, horizontally laminated, and graded; all classic signatures of the Hinuera Formation (Fig. 4C). Field evaluation of the lower terraces, T2-T3, was unable to be conducted due to farm works taking place at the time of surveying. Heavy vegetation growth along the river banks also prevented close evaluation of the geology along these terraces during boat surveys. However, one area that was accessible, marked as Location 8, did show that sedimentary deposits were present along most of the western bank within Station C (Fig. 2).

Figure 5. Photographs of the faulted outcrop at Location 1. A) A close up of the precipitated iron pan within the fault line. B) The outcrop with the fault location traced by the red line. The location of photo A on the outcrop is indicated by the yellow box (Moon and de Lange, 2017).

A small fault, marked as\t Location 1 (37° 49' 38" S, 175° 19' 34" E), was discovered along the crest of the sharp river bend at Station A (Fig. 5). The outcrop consisted of alternating pale yellow to white clay layers topped by a band of medium pumiceous yellow sediments. Pumice clasts suspended in an ashy matrix, indicating an ignimbrite deposit, could be seen at river level. The offset on the clay beds measured 43mm and the fault orientation of 85/227 (dip/dip direction) which was marked by the ductile deformed clay beds, offset sediment beds and a precipitated iron pan along the plane (Fig. 5). Measurements between this outcrop and the ignimbrite outcrop across the river at Location 3 to the east shows a measured bearing of 66° from north between them (Fig 6A).

3.3 GEOPHYSICAL

Multibeam data shows a large ENE lineation between Location 1 and 2 with a bearing measuring 74° (Fig. 6A and B). This linear feature is present along the crest of the near orthogonal bend in the Waikato River and spans the width of the rivers. On the NW side of the lineation is a deep depression and to the SE the river depth is shallower (Fig. 6B).

Seismic survey data shows a narrow depression cross cutting the river as it moves from south to north (Fig. 6C). The geology along the southern section shows a higher density than the geology to the north as seen by five "layers" on southern section verses three to the north. A lineation can be seen cutting through the top layer within the north area and against the south wall of the depression, slightly offsetting these dense layers (Fig. 6C). The difference in density characteristics from the south to the north, indicates either a possible change in the lithology or a difference in the degree of induration.

From the fault outcrop along the river bank (river level ~14m elevation) we know the local geology is composed of weakly indurated siltstone to sandstone materials overlain by reworked volcanic sediments. A resistivity survey was undertaken along two approximately orthogonal lines along the southern western bank near the inlet to the abandoned channel near Station A (Cummins, 2016; Fig. 6A). The resistivity survey reflects similar findings showing a region of low resistivity (<50 Ω.m, blue colours) related to water saturated sands and gravels on top of a zone of high resistivity (> 100 Ω.m, yellow – red colours). The low resistivity zone stretches across the entire profile and extends to an elevation depth of approximately 20m. The high resistivity zone is present below the low resistivity area and extends to an elevation below 0m. A vertical gap between these layers can be observed in both these profiles (Fig 7; Cummins, 2016).

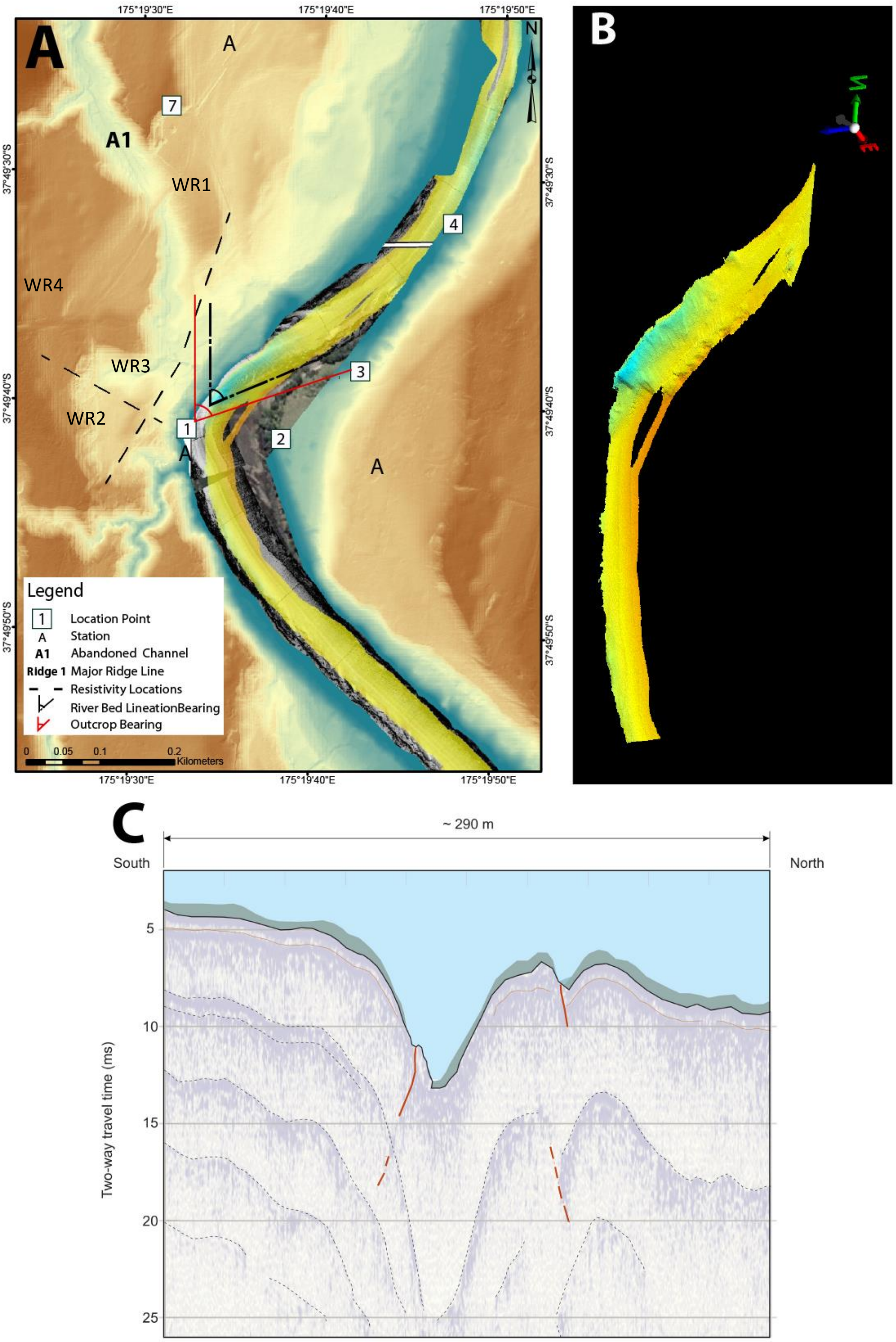

Figure 6. A) Close up LiDAR map of the near orthogonal bend in the Waikato River. The bearing between the fault outcrop at Location 1 and the ignimbrite at Location 3 is indicated by the red line. The bearing showing the orientation of the lineation feature along the riverbed is marked by the dashed lines. B) 3D multibeam image

of the riverbed geomorphology near Stations A and B. C) Seismic imaging data of the Waikato River from south to north at Station A. Dense material is marked by the grey planes and offset in these layers is marked by the orange lines. Dense materials will possess multiple grey planes.

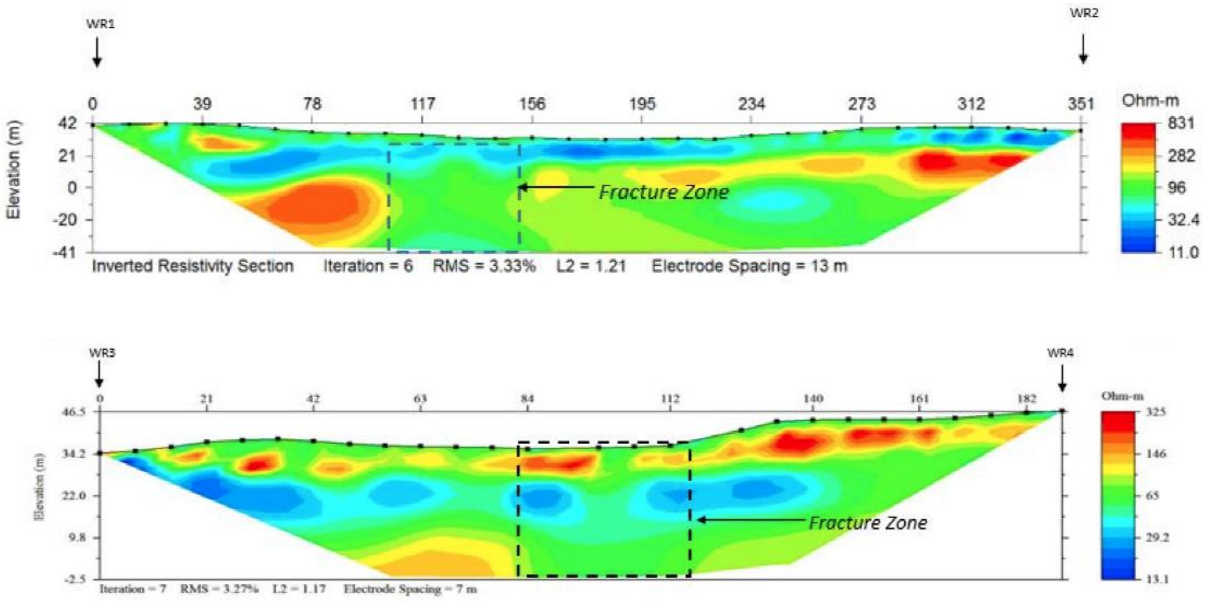

Figure. 7 Resistivity data with the blue area indicating low resistivity material and the red high resistivity material. Fracture area noted by dashed lines (Cummins, 2016).

4 DISCUSSION

We hypothesise that the abrupt orthogonal nature of the Waikato River bend along Stubbs Road is due the presence of a fault zone acting on the river's path. The geomorphology, field surveys, and an exposed fault outcrop along the western bank of the Waikato River give supporting evidence for this hypothesis. Further confirmation is supported by 3D multibeam images, seismic survey, and resistivity data (Fig. 9).

There are eleven major river bends in the Hamilton area with angles varying between 140° and 82° indicating that the Waikato River possesses a rectangular drainage pattern (Fig. 1; Howard, 1967). Two of these major bends are located within the Stubbs Road field area with the first major bend at Station A and the second occurring along the eastern side of Station C (Fig. 2A). River bends can form through different fluvial processes, such as interlocking spurs, damming, and erosion/undercutting of the existing geology. However, rectangular drainage patterns are unique because they are formed through the influence of joints, faults, or other discontinuities in the underlying geology often creating near orthogonal bends (Howard, 1967; Schumm et al., 2000; Jain and Sinha, 2005).

Looking at the geomorphology at Station C it can be observed that each of the smaller terraces have a similar orientation to that of the abandoned N-S channel, A1 (Fig. 2A). Field investigations and rock samples reveal that much of the western bank consists of ignimbrite, likely the Ongatiti Ignimbrite. The ignimbrite is topped by the Hinuera Formation along the tallest terrace (T1) at Location 7 and 8, whereas across the river on the eastern bank at Station B, Hinuera Formation and Taupo Pumice Alluvium were found along most of the terrace, except within the northern section at Location 3-6 where reworked ignimbrite and primary ignimbrite were found. The difference in geological formations when comparing the western to eastern terraces are evidence of disruption or even offset between geological units. The measured bearing of offset between the fault outcrop at Location 1 to the outcrop of the ignimbrite on the eastern terrace at Location 3 was approximately 66° from north. This bearing is in close alignment with the lineation found in the multibeam data which measured approximately 74° from north (Fig. 6A). Although there is an 8° difference between the lineation along the riverbed and the terrace offset, they are still within a reasonable proximity to one another, with error being contributed by the observed outcrop not being at the exact contact location, and alteration due to erosion and/or development.

The large N-S channel, A1, is interpreted as an avulsed river path that was once taken by the Waikato River, but was cut off either during a seismic event or by creep along the fault zone. Evidence for this interpretation can be observed in the west to east progression of the terraces T1 to T3. River terraces act as markers for where a river level and position once existed. The first terrace has a similar height to the terrace across the A1 gully marked by Station D, indicating the river once followed a N-S orientation, but then shifted to toward the east as marked by the T2 to T3 (Fig. 3). It is interesting to see that the abandoned channel contains Ongatiti Ignimbrite, but along the eastern bank the ignimbrite is only present along half of the bank between Location 3 to 6 before it changes back to sediments upriver near Station E (Fig. 2). This alternating nature of geologic deposits may indicate the potential of another fault nearby, suggesting that the system present at Stubbs Road may be a part of a larger fault system.

The small exposed fault plane located along the western bank of the Waikato River at the crest of the bend is further evidence of tectonic influences acting upon the Waikato River (Fig. 5). The plane is dips 85° towars 227° and is conjugate to the main fault trace inferred along the riverbed. Campbell (2017) found evidence of similar features and conjugate faulting at Kay Road, in northern Hamilton (Fig. 1B) indicating that the tectonic feature at Stubbs Road is possibly a small splay belonging to a larger fault zone system, specifically the Te Tatua o Wairere Fault Zone (Moon and De Lange, 2017).

Multibeam imaging at Station A shows a NE lineation across the river bed with a bearing angle of approximately 74°. To the north of the NE plane a scour hole can be observed, and what can be assumed as either harder or different material is present to the south (Fig. 6A). Although this hole was originally thought to be a scour depression formed by the erosional processes of the Waikato River, when paired with the seismic survey data it can actually be considered as a knickpoint. Knickpoints are drops in elevation along a river's longitudinal profile that form due to changes in geology. The changes in elevation can be influenced by different depositional processes in the geology. However, such changes can also be due to faults (Schumm et al., 2000; Jain and Sinha, 2005). The shallow seismic data also shows the presence of a knickpoint along the longitudinal profile of the Waikato River at Station B, where a large depression is present (Fig. 6C). The underlying lithologies show a difference in density between the north and south as shown by the number of dense planes in the survey image. The south shows a higher density as indicated by the five continuous multiples in the seismic imaging in comparison to the north which only has three non-continuous multiples (Fig. 6C). It is doubtful that these differences are due to deposition due to the non-uniformity between the layers in the north coupled with the offset observed in the upper layer. Given the geomorphic lineation along the river bed and the presence of a knickpoint, it can be interpreted that the difference in densities is more likely due to the presence of two different lithologies that are offset due to faulting. Further evidence for a fault can also be observed in the resistivity data where there is a significant discontinuity in the underlying lithologies as seen by the vertical gap between both the low and higher resistivity layers (Fig. 7).

From the geomorphic, field, multibeam, resistivity, and seismic data, it can be interpreted that tectonic influences are acting upon the Waikato River at Stubbs Road and influencing the river's overall drainage pattern. From the data it can be assumed that the Waikato River once took a more N-S path, but changed direction either from a seismic event or by creep along a fault. Such movement would have created an obstacle along the Waikato River's path. Over time the river would make its way around the obstacle and slowly erode it away, as seen by the eastwardly stepping terraces. Using the multibeam data we know the orientation of the fault pane is approximately 74° from north, a NE-SW orientation, and we can see the Waikato River Changes direction from NW to NE. There is no measurable evidence to help determine the main type of movement along this fault zone, but given evidence of the complex normal fault zones located in the north of Hamilton, it can be inferred that the dominant movement is probably normal faulting (Moon and de Lange, 2017; Spinardi et al., 2017; Campbell, 2017). However, due to the presence of a conjugate faulting system there is also potential for localised reverse faulting (Campbell, 2017). It can be postulated that the movement along this fault was within the last 20 ka because the uppermost terrace at Station C, which is composed of Hinuera Formation, has been eroded by the abandoned A1 channel and the other terraces. If a seismic event caused the Waikato River to change its direction it would mean, based on the erosion of Hinuera Formation Terraces that the event would have occurred after the Hinuera Formation was deposited, potentially classifying the fault as active.

4 CONCLUSION

Examining fault structures within poorly consolidated sediment filled basins poses many challenges due to the easily erodible and redeposited nature of the non-indurated and poorly cemented sediment. However, geologic structures can influence the geomorphology of such regions and shape their surface processes. Thus, the use of tectonic geomorphology paired with LiDAR mapping can be used to evaluate such structures that are otherwise hidden by poorly consolidated sediment. Rectangular river/drainage patterns, stream knickpoints, abandoned river channels, and linearly aligned ridges and drainage systems are all tectonic geomorphologic signatures found at Stubbs Road within the Hamilton Basin, New Zealand. The most distinct feature at Stubbs Road is a near orthogonal bend in the Waikato River at a location where an abandoned channel is also present. Field mapping and observations determine the existence of offset between geological units and the presence of a fault structure within a surveyed outcrop. Geophysical data from resistivity, seismic surveying, and 3D multibeam imaging aided in confirmation of a fault's existence and location. Offset between geological units on either side of the Waikato River had a similar orientation to the fault observed in the multibeam, seismic, and resistivity data. The orientation of the fault outcrop found in the field was determined to be a conjugate fault to the main fault found along the riverbed. Conjugate faults indicate that these features are possibly splay faults belonging to a larger complex fault zone, the Te Tatua o Wairere Fault Zone. It appears that the fault influences the change in direction observed in the

Waikato River and that movement occurred within the last 20,000 years given the erosion of the Hinuera Formation river terraces.

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References

Cummins, M., 2016. Investigating possible fault structures: Stubbs Road and Newell Road, South Hamilton. *Unpublished special topics project presented to the faculty of the School of Science and Engineering (Earth Science) at the University of Waikato.*

Institute of Geological & Nuclear Sciences (NZ) and Edbrooke, S.W., 2005. *Geology of the Waikato area* (Vol. 1, No. 250.000). Institute of Geological & Nuclear Sciences.

Howard, A.D., 1967. Drainage analysis in geologic interpretation: a summation. *AAPG bulletin*, *51*(11), pp.2246-2259.

Hunt, T., 1978. Stokes magnetic anomaly system. *New Zealand journal of geology and geophysics*, 21(5), 595-606.

Jain, V., & Sinha, R. 2005. Response of active tectonics on the alluvial Baghmati River, Himalayan foreland basin, eastern India. *Geomorphology*, 70(3), 339-356.

Kear, D., 1960. Sheet 4 Hamilton (1st Ed.) Geological Map of New Zealand, 1:250,000. *Department of Scientific and Industrial Research, Wellington, New Zealand*.

Kear, D., Schofield, J.C. & Couper, R.A., 1978. *Geology of the Ngaruawahia subdivision*, Wellington: New Zealand, Dept. of Scientific and Industrial Research.

King, P. R., 2000. Tectonic reconstructions of New Zealand: 40 Ma to the present. *New Zealand Journal of Geology and Geophysics*, 43(4), 611-638.

Kirk, P. A., 1991. Waipa Fault and the tectonic rotation of Hakarimata–Taupiri Block. Record—*New Zealand Geological Survey*, 43, 81-84.

Manville, V., and C.N.J. Wilson 2004: the 26.5 ka Oruanui eruption, New Zealand: a review of the roles of volcanism and climate in the post-eruptive sedimentary response. *New Zealand Journal of Geology and Geophysics*, 47: 525 – 547.

Manville, V. 2002: Sedimentary and geomorphic responses to ignimbrite emplacement: readjustment of the Waikato River after the AD 181 Taupo Eruption, *New Zealand. Journal of Geology*, 110: 519 – 541.

McCraw, J.D., 2011. *The wandering river: landforms and geological history of the Hamilton Basin*. Geoscience Society of New Zealand.

Moon, V. and de Lange, W., 2017. Final Report on EQC Potential shallow seismic sources in the Hamilton Basin Project 16/717.

Schumm, S.A., Schumm, S.A., Dumont, J.F. and Holbrook, J.M., 2002. *Active tectonics and alluvial rivers*. Cambridge University Press.

Schofield, J.C. 1967: Recent aggradation within the Waikato River, *Earth Science Journal*, 1:124 – 129.

Selby, M.J. and Lowe, D.J.; 1992: The middle Waikato basin and hills, In: J.M. Soons and M.J. Selby (eds), *Landforms of New Zealand*, 2nd edn, Longman Paul, Auckland, pp. 233-255

Spinardi, F., Campbell, B., Moon, D.V., Pittari, A., Fox, B.R.S. and de Lange, W.P., 2017, November. Unravelling Fault Structures of the Hamilton Basin. In *Proc. 20th NZGS Geotechnical Symposium*.

Wood, A.P., 2006. *Morphodynamic Channel and Stability of the Waikato River: Karapiro to Ngaruawahia Reach* (Doctoral dissertation, University of Waikato).