Development of the Whakatane Graben with a focus on structural blocks between Maketu and Whakatane

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ABSTRACT

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ABSTRACT

Geothermal resources within the Taupo Volcanic Zone (TVZ) currently supply 13% of the energy used in New Zealand, but could make up to one third of the total electricity used in this country if fully developed. Improvement in targeting of wells to intercept high-flux fluid pathways is a key component in geothermal development, and depends in part on a good understanding of the geometry of geological structures at depth. Here we present new geological and geophysical (gravity) data to develop an improved tectonic and structural model of the Whakatane Graben (WG), which hosts the Kawerau Geothermal Field. Interpretations of new gravity and published seismic data (Lamarche et al, 2006) indicate different evolutionary stages in rifting within the WG, including an eastward shift of its western shoulder. Sediment rates within the WG have increased significantly in the last 350 thousand years due to 1) a flare-up in ignimbrite eruptions and consequent supply of volcaniclastic sediment and 2) a constriction of the depocentre for the Whakatane, Rangitaiki and Tarawera Rivers as the WG itself became narrower. Results from field work in the Awatarariki stream behind the township of Matata and from Lamarche's (2006) offshore seismic reflection interpretation show that the accumulation of sediment and the subsequent thickness is largely fault controlled. As a consequence, applying average sedimentation rates across the whole graben (and to the full depth to basement rock) conceals a more intricate development of the WG with respect to the growth of faults and the creation and movement of discrete tectonic blocks over time. Here, we present a new picture for the evolution of the WG, and in particular, the structure and geometry of tectonic blocks with implications for what might lie beneath the Kawerau Geothermal Field.

1. INTRODUCTION

The central volcanic region of the North Island, New Zealand, and its associated volcanic zones (Coromandel and Taupo), result from more than 15 million years of arc magmatism and tectonism associated with roll-back of Hikurangi Subduction Margin. At its northernmost subaerial extent, the most recent manifestation of arc magmatism and rifting occurs within the Whakatane Graben (WG), which has been filled with Holocene alluvial deposits via the Rangitaiki flood plains. Recent structural, geophysical and geochronological investigations have advanced our tectonic understanding of the eastern shoulder to the WG (Mousopoulou et al., 2008,), the offshore Bay of Plenty (Lamarche et al. 2006; Davey et al., 1995), the Coromandel Volcanic Zone (CVZ) to the north (Christie et al., 2007; Mauk et al., 2011), and the central TVZ to the south (Wilson et al., 2010; Seebeck et al., 2010; Rowland et al., 2010) (Fig. 1). However, the western shoulder to the Whakatane Graben and its lateral connection to the CVZ have remained poorly studied, largely because post-320 ka ignimbrite deposits obscure much of the critical geological information. Nonetheless, the up-faulted geology on the shoulders and surroundings of the Whakatane Graben (WG) is integral to understanding the tectono-magmatic evolution of the Taupo Volcanic Zone (TVZ), and indeed the late-Miocene to Recent evolution the North Island. In addition, an improved conceptual model of the tectonic context of this region is of relevance to energy production within the Kawerau geothermal field (Fig. 1).

Flooding and landslides on May 18th, 2005, occurred in the Bay of Plenty region in the North Island of New Zealand. For geological studies, this event brought the opportunity to study newly exposed outcrops in the Awatarariki and Waitepuru Streams on the western shoulder of the WG (see Fig. 1). Various authors (O'Leary, 2007; Costello, 2007; Dunkerley, 2006; Bull et al. 2010) have investigated structure and slope stability of the area, and reconstructed paleo-environments for the last 550 ka, based on sedimentology (terrestrial versus marine), fossil content, and geochronology. Prior to this work, the accepted age of uplift of the western shoulder of the WG was ~1 Ma (Beanland, 1989; Beu, 2004). However, new age data and higher-resolution mapping of volcanic and sedimentary deposits demonstrate that most of the uplift occurred post ~370 ka (Gravley et al. in preparation), presumably in tandem with caldera-forming eruption(s) and an eastward jump in the the localisation of rifting within the broader central volcanic region. This observation provokes questions about the relation between onshore and offshore structure and sedimentation rate, and timing of fault activation (and deactivation) across the lateral extent of the Bay of Plenty. Here we present new structural field studies from the Maketu and Matata areas, and high-resolution gravity profiles from the upstanding Otamarakau basement block, all of which lie to the west of the WG. We synthesise our results with existing onshore and offshore data to develop an improved conceptual understanding of the tectonic evolution of the western shoulder to the WG.

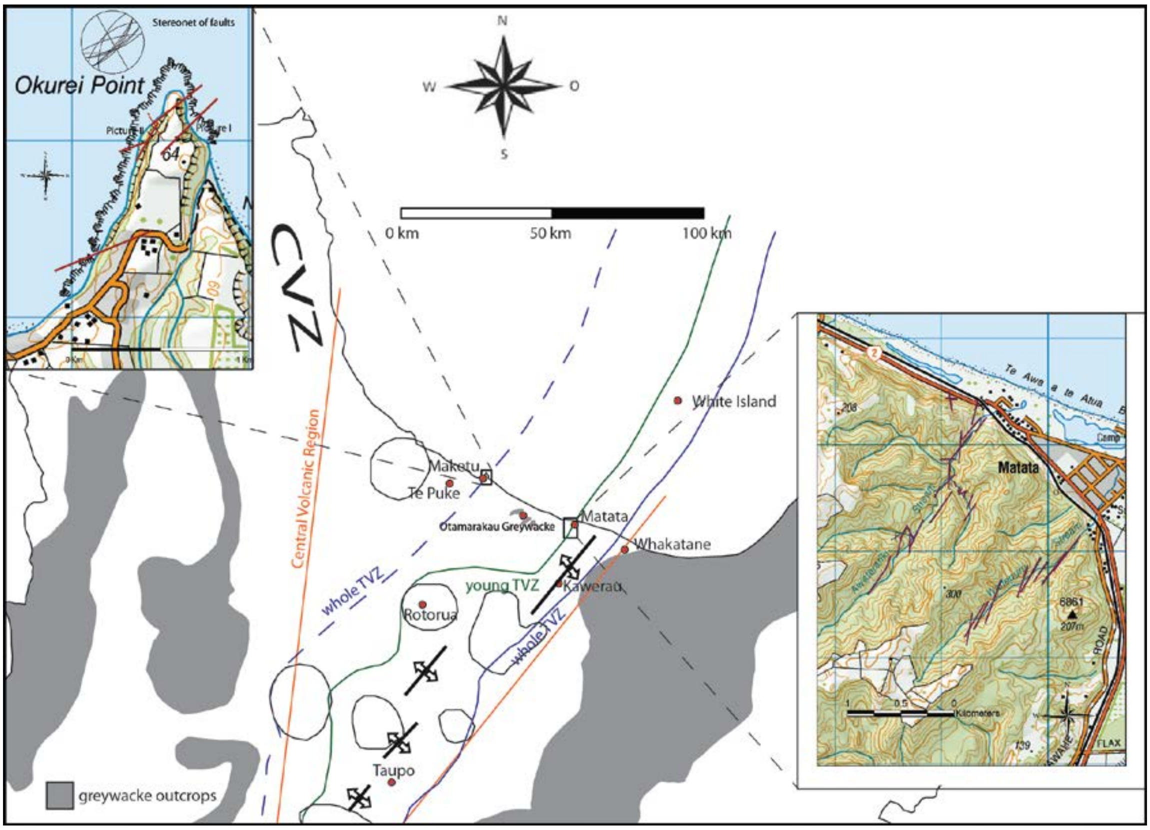

Figure 1: Overview of TVZ and location of Matata with Waitepuru and Awatarariki streams, Otamarakau Greywacke and Maketu.

2. Geologic Background

The main area of Pliocene to Quartenary volcanic activity in New Zealand occurs within the TVZ, a NNE-striking rifted arc associated with subduction of the Pacific plate beneath the Australian plate (Wilson et al., 1995). The TVZ can be subdivided into: 1) Old TVZ that was active from ca. 2 Ma (Davey et al., 1995); 2) Young TVZ, active from the first flare-up in volcanic activity (ca. 340 to 240 ka) through to 61 ka; and 3) Modern TVZ from 61 ka onwards (Wilson et al., 1995). The Young TVZ is the most active silicic volcanic system on earth, erupting 0.28 m^3s^{-1} rhyolite for the last 0.34 Ma (Wilson et al., 1995). Like most of the magmatically active rift systems worldwide, the TVZ shows a complex history of interactions between stress and magma emplacement, with extension accommodated by normal faulting and dike intrusion, and perhaps by episodes of rifting in association with large caldera-forming eruptions (Seebeck and Nico1. 2010; Rowland et al., 2010).

The entire TVZ is mechanically partitioned into discrete rift segments linked by accommodation zones (Rowland and Sibson, 2001). The WG is the northernmost subaerial rift segment and it extends from Matata in the east to Whakatane in the west. A SE-directed geodetic extension rate of 15 mm/yr has been measured using campaign GPS along the Bay of Plenty coast (Wallace et al., 2004). In contrast to the segments to the southwest, which comprise arrays of subparallel normal faults, within the WG fault zones strike NE and NNE (Fig. 2). Mouslopoulou et al. (2007, 2008) synthesised a comprehensive suite of geological and geophysical data from within the WG and along its eastern margin and concluded that the WG is linked kinematically to the right-lateral North Island Fault System (Mouslopoulou et al., 2007). Total displacement of the Mesozoic metasedimentary (greywacke) basement across the eastern shoulder is over 2500 m with a noticeable increase in displacement at ca. 0.3 Ma ago (Mouslopoulou et al., 2008), which is roughly the age of the Matahina Ignimbrite (320 Ka) (Leonard et al., 2010). Mouslopoulou et al. (2008) suggested that this correlates with the change from old to young TVZ.

On March 2nd, 1987, the WG was affected by the $\mathbf{M}_L$6.3 Edgecumbe earthquake. Seismic analysis of the event indicates that the main shock initiated at a source depth of 8 km on the western side of the WG, and the rupture propagated along and up the Edgecumbe fault, which dips 45±10° at seismogenic depths. Subsidence of 2 m and horizontal extension towards the southeast of 1.8 m accompanied this event (Anderson et al., 1990). Based on detailed seismic studies of this event, Cole (1990) developed a structural model of the WG (Figure 3). Paleoseismic studies reveal that the Edgecumbe fault has moved at least 3 times during the Holocene and produced a total vertical displacement of the basement of 1500 m in the last 1 Ma (Nairn, 1989, Beanland et al., 1998). Gravity profiles, seismic reflection data, and the distribution of seismicity associated with the 1987 earthquake suggest that the Edgecumbe fault roots in the greywacke basement (Mouslopoulou et al., 2008).

Prior to 1987, few fault scarps were recognised within the WG because resurfacing across the Rangitaiki flood plains keeps pace with fault growth. Begg et al., (2010) used high resolution digital elevation models derived from LiDAR data to improve the onshore fault map and revealed several en echelon fault zones, which are consistent in architecture with mapped fault zones in the offshore WG (Lamarche et al., 2006; Davey et al., 1995: Fig. 10). Inspection of the offshore 2D seismic sections reveals that these enchelon fault zones have small offset at the surface, reduce in geometrical complexity with depth, and root onto basement structures (Lamarche et al., 2006; Barnes et al. 2006).

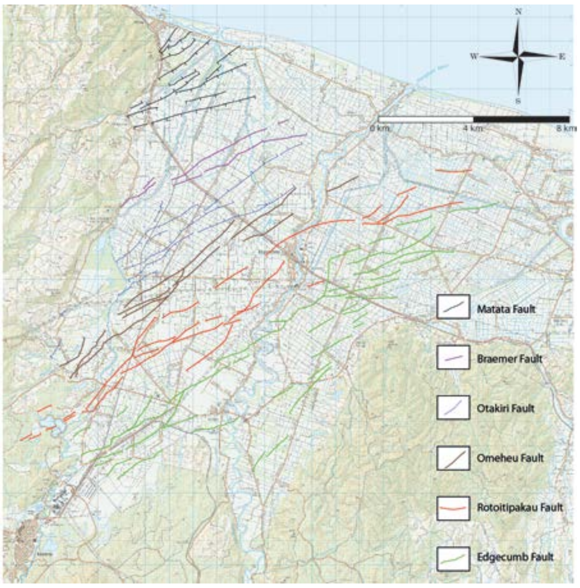

Figure 2: Map of Whakatane Graben with faults found by LiDAR. After Begg (2010)

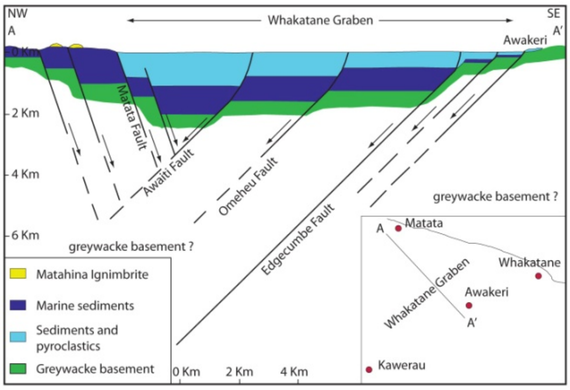

Figure 3: Model for the WG (after Cole, 1990)

3. MATATA FAULT BLOCK (MFB)

Stratigraphy within the MFB consists of terrestrial and marine deposits, which can be sub-divided and dated by tephras. The stratigraphy provides evidence of the complex history of the Taupo Rift and WG development. When correlated with the New Zealand sea level curve, it is possible to infer subsidence and uplift of the MFB over time. In detail, greywacke gravels sourced from Ikawhenau Range between Lake Matahina and Murupapa (N. Mortimer, pers. Comm. 2012) are exposed at stream level in the Awatarariki stream and are offset by several normal faults. These gravels must have been deposited prior to uplift along the western WG. The stratigraphic section at this location includes the 61 ka Rotoiti Ignimbrite, but it is missing the 320 Ka old Matahina Ignimbrite, which is generally present in the sequence of the MFB (Fig. 5). Hence, we infer a horst structure within the MFB that was uplifted before or while the Matahina Ignimbrite was emplaced, creating favourable conditions for erosion of the Matahina ignimbrite before emplacement of the Rotoiti Ignimbrite. Similar horst structures, but with less precise age control, have been documented from offshore seismic reflection data sets by Lamarche et al., (2006) and Davey et al., (1995) (Fig. 10).

Within the MFB fault orientations and dip directions delineate a complex fault zone that has evolved from east to west as a series of horsts and grabens. Most faults dip to the east and throw on discrete structures appears to increase from east to west towards the western side of the Rangitaiki Plains (Matata). In addition to exposures of major faults, numerous synthetic and antithetic conjugate faults can be observed in stream sections (Fig. 1). These data allow inference of the principal compressive stress directions at the time of their formation. Also shown is the moment tensor inferred for the 1987 Edgecumbe earthquake, which differs from the stress field inferred for the MFB based on the orientation of conjugate faults (Fig. 4).

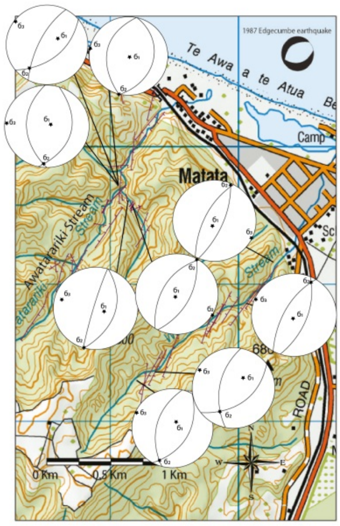

Figure 4: Matata Fault block with lower hemisphere stereonets

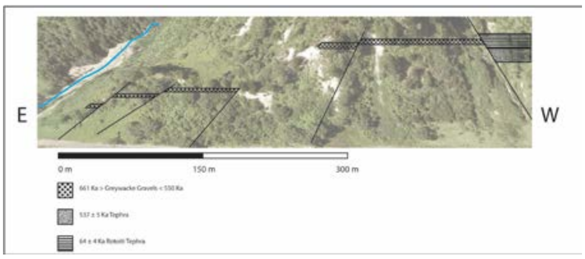

Figure 5: Oblique view of Matata Fault Block

4. MAKETU BEACH

At Maketu (Fig. 1), sedimentation patterns in Pleistocene sediments and subsequent fault structures imply that there was an older and broader WG prior to ~370 ka, after which was a major eastwards shift of the WG to its present position. New structural data supports the notion of an eastward migration in the locus of rifting, and assists with the correlation of onshore and offshore structural features. Exposed on the western side of the peninsula are two faults (Fig. 6), one of these terminates upwards at an unconformity. The second fault cuts the entire stratigraphy exposed at this location. We infer two stages of tectonism from these field relations but unfortunately we are unable to establish timing of activity. On the eastern side of the peninsula (Fig. 7), a normal fault displaces the Newdicks Member but not the Hamilton Ash and Rotoiti/Rotoehu volcaniclastics. The age control for fault movement is based on 320 ka Matahina lithic clasts identified within the Newdicks Member, yielding an age of post-Matahina fault movement and pre-Rotoiti/Rotoehu deposition (see stratigraphy in Fig. 8). These faults on either side of the Maketu peninsula bound a horst (see Fig. 1, showing the orientation of faults in a map and a stereonet lower hemisphere view). The NE strike of the major faults exposed is similar to the strike of en echelon fault segments inferred in the offshore region and also within the WG as defined from analysis of LiDAR imagery.

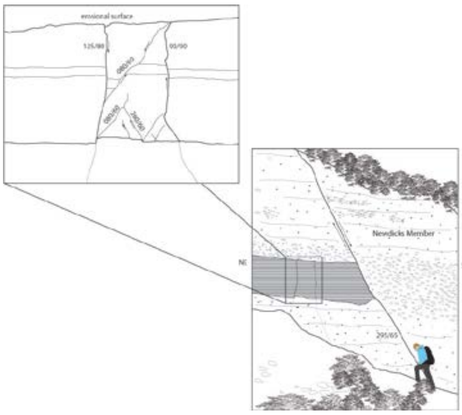

Figure 6: Outcrop situation on the western side of the Maketu Peninsula. Measured in Dip-direction, Dip.

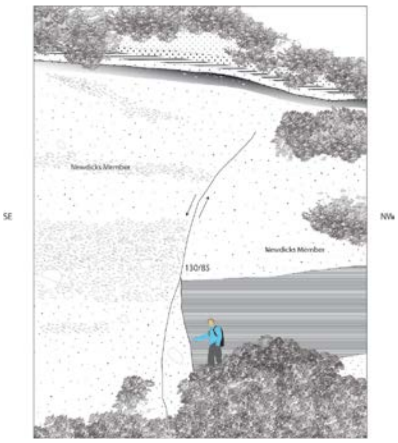

Figure 7: Outcrop situation on the eastern side of the Maketu Peninsula. Measured in Dip-direction, Dip.

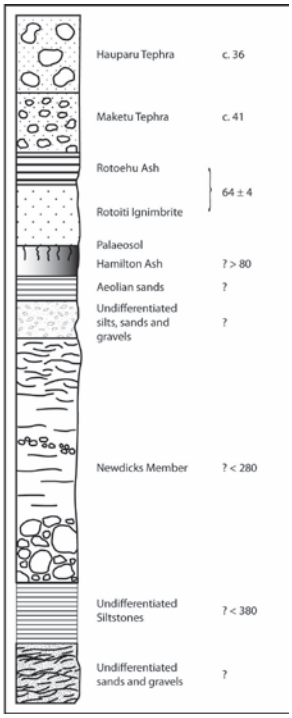

Figure 8: Stratigraphy of the outcrops of the Maketu Peninsula (after Wehrmann, 2000)

5. OTAMARAKAU GRAVITY PROFILE

In the area of Otamarakau, between Maketu and Matata (Fig. 1), greywacke basement is exposed and utilized for aggregate. This greywacke outcrop is unusual in that it is completely isolated from other exposures of greywacke. We undertook a high resolution gravity survey to help constrain the geometry of this block. Two 10 km-long gravity lines comprising ~50 stations per line, were acquired and synthesised with a regional suite of gravity data from GNS Science, to investigate the tectonic context of the Otamarakau greywacke block. Initial interpretations of the processed data indicate 6 faults over the outcropping basement (Fig. 9). These faults are laterally coincident with the greywacke outcrops that were mapped by Leonard et al. (2010); they are lying directly on the topographic highs that are built of greywacke basement. Onshore and offshore the same spacing of faulting can be observed. In both settings horst and graben structures are seen and faults are trending in similar directions. We suggest that the faults inferred from the gravity study are laterally coincident with the faults mapped in the offshore region by Lamarche (2006), which presumably root in greywacke basement.

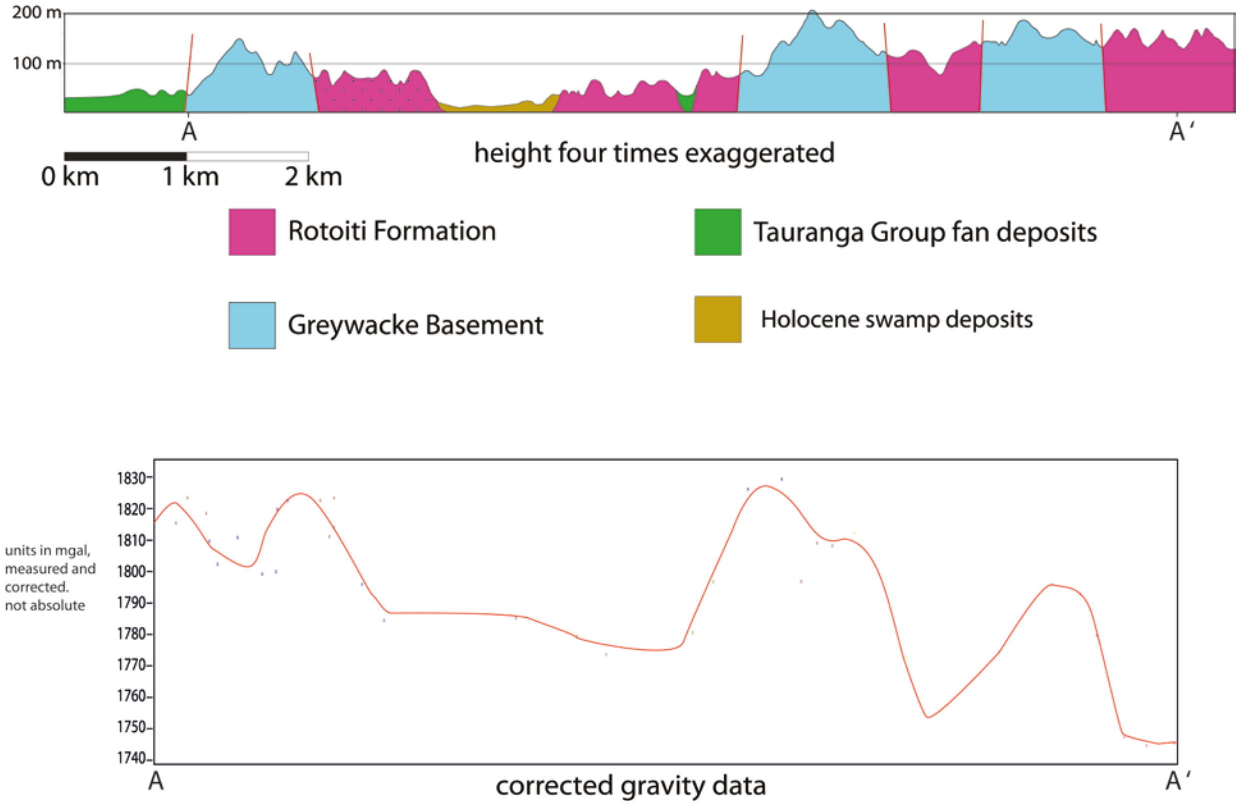

Figure 9: Profile of Otamarakau area with the interpreted faults and corrected gravity data

6. SEIMIC OFFSHORE DATA BY LAMARCHE (2006)

The active offshore WG comprises 15 major fault zones as described by Lamarche et al. (2006) (Fig. 10). As in the onshore section of the WG, the extensional strain of the eastern shoulder of the system appears localized on the offshore White Island Fault (WIF) (Lamarche et al., 2006). On the western shoulder extension is not just localized on one fault zone, but is distributed across several fault zones (Lamarche et al., 2006).

Two features characteristic of the fault architecture interpreted using offshore seismic reflection lines are similar to those found in the MFB. Lamarche (2006) describes an enchelon pattern of faulting in map view; fault geometry reduces in complexity with increasing depth; and faults root into basement rocks.

In Figure 10 the complex fault distribution over the recent offshore WG can be seen. Offshore faults do not following a strict strike, but can also be curved at some locations. The authors of this paper see this as a clue that the old basement structure influences the recent fault distribution.

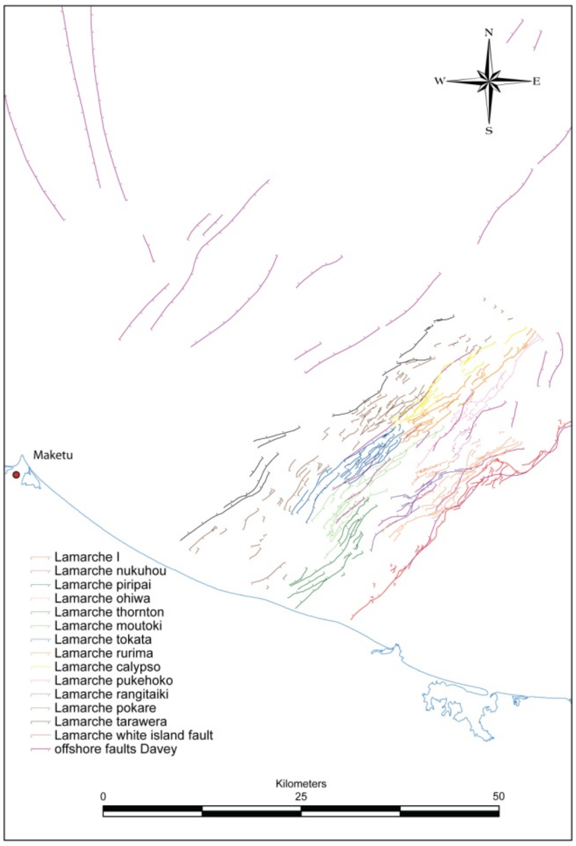

Figure 10: Offshore faults found by Lamarche et al. (2006) and Davey et al. (1995)

8. DISCUSSION

As must be clear, it is not easy to compare offshore and onshore structures since the sedimentation pattern is completely different. Nevertheless it is obvious that in both environments we are seeing the same kind of structural development of the WG. The output of sediment through rivers also controls the sedimentation on the ocean floor to a degree that is not clear, because there is always an unknown extent of currents and air driven sediment (volcanic ash). As a result of a flare up in volcanism within the TVZ, output rates of the silicic system have changed highly in the last million years. Thus, it is to be assumed that sediment rates in the northern part of the TVZ (WG) as fed through the proto and recent versions of the Rangitaiki River are also not constant. Furthermore as shown before, the eastern shoulder of the graben was not at its current position before 370 ka. Offshore seismics, gravity data and fieldwork have shown that the graben development is a highly complicated process, which involves en echelon faulting, shifting of fault activity, several fault generations in one area and development of small scale horst and graben blocks. In consequence, the landscape itself changes highly through time. These changes in topography also mean that different areas are eroded while others have high amounts of sedimentation. To a great extent sedimentation through rivers and floodplains is controlled by horsts and grabens since these form topographic highs and lows.

9. CONCLUSION

The development of the WG is consistent with the Wilson et al. (1995) model of the TVZ, whereby the modern TVZ shifted to the western shoulder of the WG, near Matata. The eastern fault observed in Maketu does not cut through the Rotoiti/Rotoehu deposition, so was inactive at least the last 60 ka. Faults show variation in strike along their length. Probably these variations are controlled by old basement structures that are favourably, but not optimally, oriented for reactivation in the current tectonic regime. The outcropping basement at Otamarakau indicates a substantial fault movement in this area. Its morphology is similar to the recent shoulder to the WG with small scale horst and graben structures. The same horst and graben structures as onshore can also be observed offshore. Furthermore Lamarche (2006) found the same kind of complex enchelon faulting as can be observed in the MFB and which we assume can also be found around Maketu and in Otamarakau. All this could be a sign of a former western shoulder of the WG, which shifted at 370 ka to its current position.

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