Offshore faulting and earthquake sources, West Coast, South Island: Stage 2

MBIE Envirolink West Coast Regional Council Advice: 1237-WCRC114

Prepared for West Coast Regional Council

June 2013

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NIWA Client Report No:	WLG2013-32
Report date:	June 2013
NIWA Project:	ELF13213

Caption for image: View looking northwards along the steep coastline representing the eroded Kongahu Fault scarp, North of Westport [Francesca Ghisetti, TerraGeoLogica]

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Executive summary

The West Coast Regional Council (WCRC) recognised that its major coastal towns and many small coastal communities could be at risk from potential earthquakes on offshore faults and tsunamis. Until now however, there have been no attempts to characterise active faulting and potential earthquake sources off the Westland coast.

In December 2011 the WCRC secured an Envirolink Medium Advice Grant from the Ministry of Science and Innovation (MSI) to commission NIWA to undertake a geophysical, geological and bathymetric data compilation as part of the first stage (Stage 1) of marine earthquake hazard assessment in the region. Stage 1 was completed in June 2012. In August 2012, a second Envirolink Medium Advice Grant was awarded by the Ministry of Business, Innovation, and Employment (MBIE) to undertake the second stage (Stage 2) of the project. This report presents the results of Stage 2, involving the identification of marine active faults and their characterisation as potential earthquake sources. To undertake this work we used extensive marine seismic reflection profiles, together with exploration well and seafloor bathymetry data.

We confirm that active marine faults, lying approximately parallel to the coast, within 30 km from shore, underlie the seafloor encompassing much of the WCRC jurisdiction. Off northern Westland, over the 320 km distance between Hokitika and Cape Farewell, 10 earthquake fault sources are recognised. These include five segments of the Cape Foulwind Fault, the Kahurangi and Kongahu faults, and the newly named Farewell, Elizabeth, and Razorback faults. These faults are old normal faults, mainly dipping east, which have been reactivated as reverse faults in the present compressional tectonic environment. The faults range in length from about 10-120 km, and are interpreted to be capable of generating earthquakes with large magnitudes ranging from M_w 6.4 to 7.8. Best estimates of earthquake source parameters indicate recurrence intervals for individual fault sources ranging from about 7500 years to 30,000 years. Large uncertainties in fault slip rate are reflected by the large range of potential earthquake recurrence intervals.

No active marine faulting is recognised in current datasets within the 170 km long region off the central Westland coast, between Hokitika and Paringa. However, off South Westland and northern Fiordland, an additional three major coast-parallel earthquake fault sources are recognised within 15-30 km from shore. These include the Milford Basin (Madagascar) and Barn thrust faults, and the newly-named Jackson Fault. They appear to be capable of generating earthquakes of magnitude M_w 7.2 to 7.6. Best estimates of earthquake source parameters indicate recurrence intervals for these southern individual fault sources ranging from about 6000 years to 27,000 years. The Alpine Fault, which extends offshore at Milford Sound, is not discussed in this report.

Considering the results of this work, we recommend that: (1) a revision of probabilistic seismic hazard assessment in the West Coast region be undertaken, (2) an evaluation of potential tsunami generation and inundation be undertaken, and (3) additional high-resolution marine geophysical data are acquired, together with refined fault source characterisation in order to reduce uncertainties in earthquake source magnitudes and recurrence intervals.

1 Background

Previous geophysical and geological research studies of the West Coast, South Island, demonstrated that several large historical earthquakes in this region were associated with a system of reverse faults, lying NW of the Alpine Fault (e.g., Berryman, 1980; Nathan et al., 1986; Anderson et al., 1993, 1994). These structures include reverse-reactivated Late Cretaceous to Eocene (c. 100-40 Ma) extensional faults (Bishop, 1992; Bishop and Buchanan, 1995; Ghisetti and Sibson, 2006; Sibson and Ghisetti, 2010), together with younger thrust faults that have formed in response to the compressional tectonic regime active during the late Cenozoic (<15 Ma) to present day. A recent update of the New Zealand National Seismic Hazard Model (Stirling et al., 2012) does not include any active marine fault earthquake sources off the West Coast, north of Fiordland (Fig. 1-1). Similarly, no marine active faults are recognised offshore Westland, in recent compilations of New Zealand active faulting (Litchfield et al., submitted). Previous work, however, by Van der Linden and Norris (1974), Sibson and Ghisetti (2010), and more recent unpublished work by Ghisetti et al. (in preparation) has highlighted the potential activity of several large offshore reverse and thrust faults in the northern part of the region. If determined to be active, these faults represent potential earthquake and tsunami hazards to Westland coastal townships.

Whilst the Alpine Fault is a well-recognised seismic hazard (Stirling et al., 2012), Westland has three major coastal towns and many small coastal communities at risk from potential marine earthquakes and tsunamis. A 2005 review of tsunami hazard and risk concluded that the West Coast is at low risk from far-field (e.g., trans-Pacific) and mid-field (regional source) tsunamis, but there is more uncertainty in the risk from possible near-field/locally generated events due to large local earthquakes (Berryman, 2005). Since the formation of the Regional Natural Hazards Management Group in 2005, the West Coast Regional Council (WCRC) compiled evidence for past near-field tsunami and their effects on the West Coast, and concluded that research is required into the level of tsunami risk from local fault and landslide sources.

A subsequent list of required actions developed by WCRC included Task 4: "*Have research done on offshore faults (activity status, recurrence period, seismic potential, recent/Holocene deformation) and offshore canyons (bathymetry, evidence of landsliding, correlations with large earthquakes etc*)". In 2011, the National Institute of Water & Atmospheric Research (NIWA) advised WCRC that Task 4 would be large, and that the work should be tackled in stages. Two stages were planned to identify and characterise active marine faulting and potential earthquake sources. Stage 1, completed in June 2012 as an Envirolink project, involved a significant technical data review and GIS compilation (Barnes et al. 2012). This work was critical to the present study, Stage 2, involving the identification of marine active faults and their characterisation as potential earthquake sources. This second stage of the project has been co-supported by significant internal core funding from NIWA.

In this report, we summarise the scope of both Stages 1 and 2, and the type and distribution of data used in Stage 2 of this project (Barnes et al. 2012). We outline the interpretation and fault mapping methods undertaken in Stage 2, and describe the major active marine faults and their estimated Late Quaternary slip rates. Finally we present an interpretation of potential marine earthquake sources. This report is complemented by ArcGIS shapefiles of Quaternary age faulting and earthquake fault sources, provided electronically to WCRC.

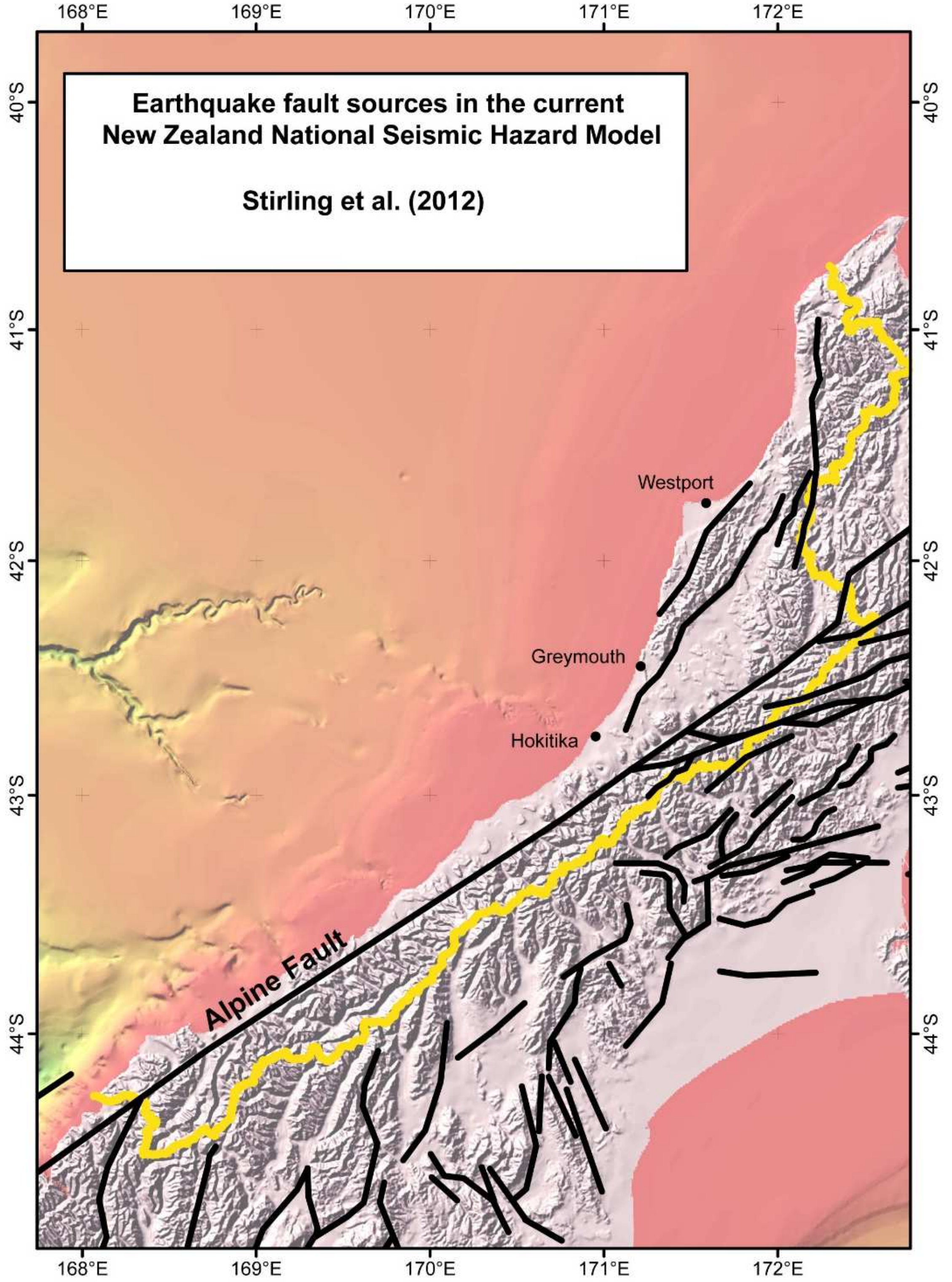

Figure 1-1: Known earthquake sources in the West Coast, South Island region. 2012 update of the National Seismic Hazard Model fault sources (Stirling et al., 2012). Bold yellow line on land bounds the area of the West Coast Regional Council jurisdiction.

1.1 Scope of Work: Stages 1 and 2

In December 2011 the WCRC secured an Envirolink Medium Advice Grant from the Ministry of Science and Innovation (MSI), to commission NIWA to undertake Stage 1.

In collaboration with Francesca Ghisetti (TerraGeoLogica), in June 2012 the tasks reported as part of Stage 1 included the following (Barnes et al. 2012):

- Acquiring hard and electronic copies of open file oil company and mining company seismic reflection data from the West Coast, from New Zealand Petroleum and Minerals (NZP&M) (Ministry of Economic Development, MED) and other data-holding agencies;
- Seeking recently reprocessed versions of vintage seismic data from private companies that we understand might be available for this work;
- Sourcing archived high-resolution seismic data from NIWA archives. These would include any available copies of boomer seismic, 12 kHz and 3.5 kHz sub-bottom profiles;
- Producing copies of multichannel seismic data recently acquired by NIWA;
- Integrating all relevant background bathymetry data, including NIWA regional contours and relevant multibeam bathymetry data;
- Acquiring existing interpretations of marine oil company seismic sections from previous studies; and
- Build working maps in ArcGIS, incorporating seismic navigation, bathymetry and well location data.

In August 2012, a second Envirolink Medium Advice Grant was awarded by the Ministry of Business, Innovation, and Employment (MBIE) to undertake the second stage (Stage 2) of the project. As part of Stage 2, we build on published results (e.g., Ghisetti and Sibson, 2006; Sibson and Ghisetti, 2010) and recent unpublished work by Ghisetti et al. (in preparation), who developed fault maps and balanced geological sections of the entire onshore and offshore foreland basins NW of the Alpine Fault, using integrated multichannel seismic reflection interpretations, well data, and onshore geological field outcrop data. Ghisetti et al. (in preparation) demonstrate widespread late Cenozoic (<15 Ma) compressional tectonic inversion of the Late Cretaceous-Eocene rift basins, and a general westward propagation of the compressionally reactivated faults and associated uplift during the last 15 Myr. The tectonic shortening is being accommodated by reverse and thrust faults, and associated fault-propagation folds.

In Stage 2 of this study, we focus on the major reverse faults of the regional deformation front, which lies offshore in northern and southern Westland regions. In available multichannel and high-resolution seismic reflection profiles, we identify all Late Cenozoic and Quaternary age contractional faulting and folding off the Westland coast, and map fault locations in ArcGIS.

Using available high-resolution sub-bottom seismic profiles in NIWA archives (e.g., Van der Linden and Norris, 1974) and reported line interpretations of data collected by mineral exploration companies (Alpine Geophysical Associates, 1968), we interpret the Late Quaternary sedimentary sequences and sea-level change surfaces in the vicinity of the active faults. In particular, identification of the post-last glacial marine transgressive surface provides a marker for interpretation of maximum potential fault activity rates since 20 ka. Using these data, we interpret the potential marine earthquake fault sources and characterise their relevant earthquake source parameters following the methods of Stirling et al. (2012).

2 Seismic Reflection and Bathymetric Data Used in this Study

Barnes et al. (2012) describe and illustrate the type and distribution of data available for this study, and we present a brief summary here. A list of industry and academic research multichannel seismic reflection data and technical reports used in this study is presented in Table 2-1.

There is a substantial amount of seismic reflection data, mainly of 1970s and 1980s vintage, for the offshore Westland region (e.g., Norris, 1978; Thrasher and Cahill, 1991; Bishop, 1992; King and Thrasher, 1996; Sircombe and Kamp, 1998; Breeze and Browne, 1999; Sibson and Ghisetti, 2010). The oil industry data are widely distributed, and are tied to offshore exploration boreholes. These include Mikonui 1 (Kidd et al., 1981), Haku 1 (Haematite Petroleum, 1970), Kongahu 1 (Wiltshire, 1984), Toropuihi 1 (Amoco NZ Exploration Co, 1987), and Cook 1 (Van Oyen and Branger, 1970) (Fig. 2-1) (see onshore well compilation by Breeze and Browne, 1999). Much of the 1970s and 1980s oil company seismic reflection data are of low fold by modern industry standards (i.e., they were collected with relatively short seismic streamers). The data include original and reprocessed sections, most in two-way travel-time, some in depth.

Of the many oil company surveys in the region, notable datasets are those acquired by Cultus Pacific (1981; NZ CK-81 lines), Esso Exploration and Production NZ (1969-1970; EZC, EZF lines), Diamond Shamrock Exploration Oil (1982a, 1982b; DS2, DS3 lines), Seahawk Oil International (1981; SH81 lines), NZ Petroleum Corporation (Anderson, 1985; 1970-1972, 1974; NZPET71/72 lines), Petrocorp (GECO NZ, 1984; PO59 lines), and Shell Petroleum Mining (2001; ST lines). Seismic reprocessing of selected lines include work reported by Anderson (1985) (DS3, PO59, 200- lines), Grande Energy (2008, 2010) (ST and 72M lines), and Widespread Energy (Geosphere, 2009; EZC, EZF, SH81, and DS3 lines). A substantial amount of the older data lodged by petroleum companies is available only as image files (tiffs), whilst some data are available in SegY digital format.

In unpublished recent work, Ghisetti et al. (in preparation) built an electronic 3D interpretation and structural analysis project using specialised software, and correlated regional stratigraphic reflectors between profiles. For the present active faulting Stage 2 project, all of the relevant seismic sections were plotted at NIWA as hard copies for interpretation of faulting and folding.

Table 2-1: Summary of seismic reflection surveys in the offshore West Coast region.

Survey	Year	Company	Relevant PR no.
Greymouth M	1966	Shell Internationale Petroleum	548
EZC	1968	Esso	401 791
EZD	1968	Esso Exploration and Production (NZ) Inc.	400
FS	1968	Aquitaine	506
EZF	1969	Esso	401
PPL711_hz	1970	Hematite Petroleum (NZ) Ltd	555
PS	1969	NZ Aquitaine Petroleum	511
NZPET70	1970	NZ Petroleum Exploration Co. Ltd	523
NZPET71	1970	NZ Petroleum Exploration Co. Ltd	523
CS	1971	NZ Aquitaine Petroleum	509 508
Howe 1971	1971	Howe Offshore Petroleum Ltd	133
Magellan Westland 1971	1971	Magellan Petroleum NZ Ltd	575
Petrel-PR642	1971	Shell Internationale Petroleum	642
NZPET72	1972	NZ Petroleum Co. Ltd	523
EL PASO	1973	El Paso Natural Gas Co	623
NZ	1973	Australian Gulf Oil Co	614 2599
NZPET74	1974	NZ Petroleum Exploration Co. Ltd	629
S74	1974	NZ Superior Development	641
WM	1979	Shell BP Todd Oil Services Ltd	627
80E	1980	Shell BP Todd Oil Services Ltd	881
CK81	1981	Cultus Pacific	884
HZT82C	1981	BHP NZ Ltd	901
SH81	1981	Seahawk Oil International	855
DS2-82	1982	Diamond Shamrock	997
DS3-82	1982	Diamond Shamrock	1124 1191 1192
W83	1983	Whitestone New Zealand Ltd	950
P059-84	1984	Petrocorp	1194 3998
S18-84	1984	NZOG	1210 1128
W84 (F Lines)	1984	Whitestone New Zealand Ltd	1064
W85	1985	Whitestone New Zealand Ltd	1357
S18-86	1986	NZOG	1172
W87-Farewell	1987	Whitestone New Zealand Ltd	1503
Sight	1996	GNS	
Haast 2001	2001	Shell Petroleum	2661 3877 4006 4167
TAN0712	2007	NIWA	

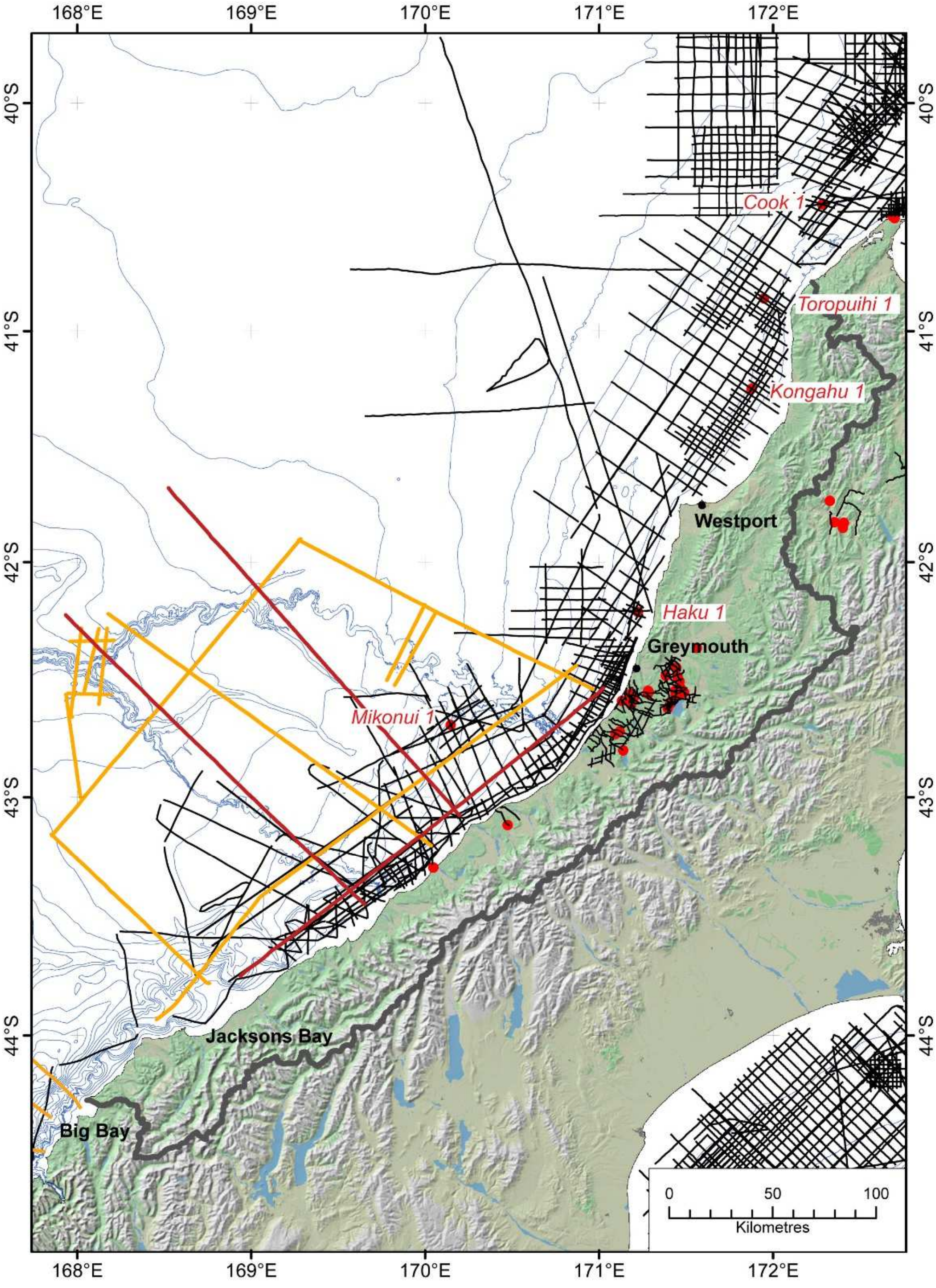

Figure 2-1: Compilation of available multichannel seismic reflection and borehole data. Black lines, MED open file oil industry data; Orange lines, NIWA RV *Tangaroa* data; Red lines, RV *Maurice Ewing* SIGHT data. Red dots, oil exploration wells (only offshore wells are named). Bathymetry contours from NIWA database, shown at 50 m intervals between 0-250 m and 250 m intervals in water depths >250 m. Bold grey line on land bounds the area of West Coast Regional Council jurisdiction.

In addition to multichannel airgun seismic data, a mixture of sparse shallow-penetration, high-resolution seismic reflection profiles were also available (Fig. 2-2). These include single-channel airgun data, boomer, and 3.5 kHz sub-bottom profiles acquired by NIWA and its predecessor, New Zealand Oceanographic Institute, DSIR. The 3.5 kHz sub-bottom profiles typically image Late Quaternary sediments up to c. 50 m beneath the seafloor. Mineral exploration companies also collected seismic data near shore, along much of the length of the West Coast. The earliest survey was undertaken by CRA (Alpine Geophysical Associates, 1968), using a sparker seismic source. The actual seismic sections were never lodged by CRA with NZP&M; however, line drawing interpretations of the sections produced by CRA geologists and by Dr Robin Falconer (previously DSIR) are available as image files on-line via NZP&M (MR2017), and have been reinterpreted as part of this study. These data are of particular relevance for mapping and analysis of the Cape Foulwind Fault. More recent, high-resolution seismic reflection sections collected by Seafield Resources Ltd for mineral exploration have not been lodged with NZP&M and were unavailable to this study.

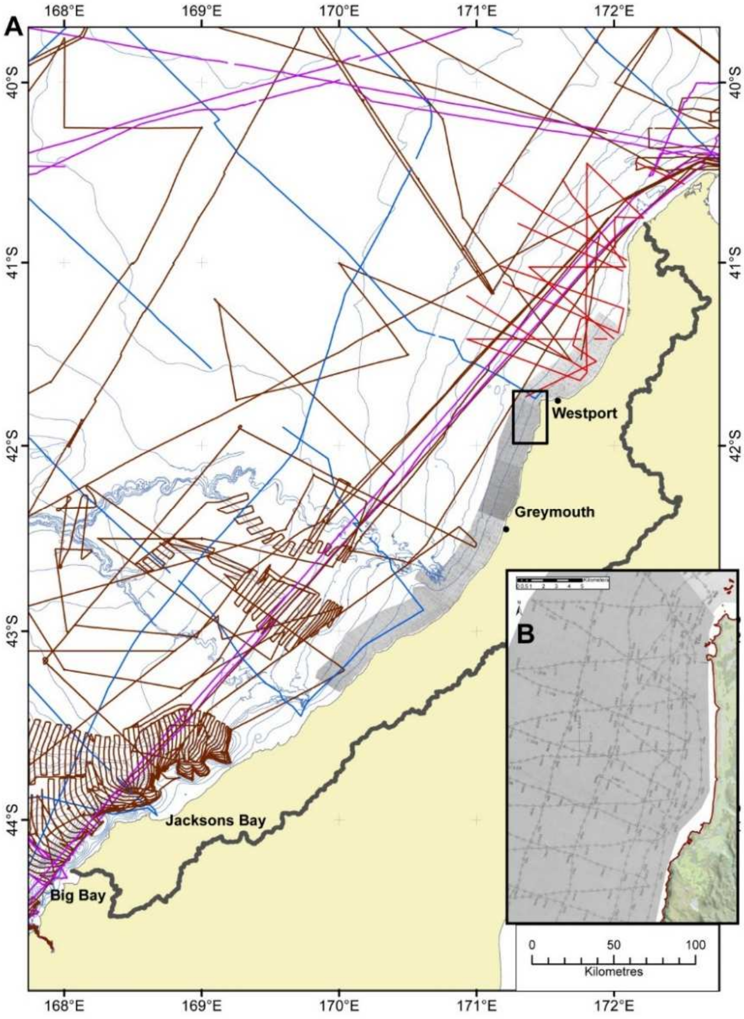

Figure 2-2: Compilation of available offshore shallow-penetration (<150 m) high-resolution seismic reflection and sub-bottom profiler data. A. Regional map coverage. Brown, magenta and blue lines, 12 kHz and 3.5 kHz data. Red lines are boomer profiles (Van der Linden and Norris, 1974). Grey shaded area along the coast is the region in which CRA Exploration Ltd acquired sparker seismic profiles at a line spacing of about 3 km (Alpine Geophysical Associates, 1968). Bathymetry contours from NIWA database, shown at 50 m intervals between 0-250 m and 250 m intervals in water depths >250 m. Bold grey line on land bounds the area of West Coast Regional Council jurisdiction. B. Enlargement to illustrate density of the >50 CRA profiles.

3 Seismic Stratigraphy

The seismic sections image basement widely, typically at 1-2 km depth, and Late Cretaceous half-graben rift basins are visible, including the Takutai Graben (e.g., Bishop, 1992). These basins have been important exploration targets in some petroleum surveys. The condensed Paleogene Cobden Limestone is recognisable regionally as a very high-amplitude reflection at the base of the Miocene section. The Neogene and Quaternary stratigraphy above the Cobden Limestone reflects the onset of Alpine uplift, with substantial clinoform progradational development and channelized sequences visible, particularly above a regional middle Miocene (~15 Ma) unconformity. Ghisetti (unpublished data) correlated a number of regional seismic reflections and tied these to borehole and outcrop data, including basement, top Cretaceous, top Oligocene, and up to three events in the Miocene and Pliocene, with inferred ages of 10 ± 3 Ma, 5 ± 2 Ma, and 2± 1 Ma, respectively. These regional markers were useful for identifying the major late Cenozoic faults and fault-related folds in the multichannel seismic sections (e.g., Ghisetti and Sibson, 2006; Sibson and Ghisetti, 2010).

To assess Late Quaternary fault activity rates, we interpreted the Late Quaternary sedimentary sequences and specific sea-level change surfaces in the vicinity of active faults, using the high-resolution sub-bottom seismic profiles and/or re-interpreted line tracings of data collected by mineral exploration companies (Alpine Geophysical Associates, 1968). In regions of high offshore sedimentation, such as West Coast, major glacio-eustatic changes in sea-level, of up to ±120 m, have a profound effect on the location of sediment depocentres (Fig. 3-1), as well as the development of erosion surfaces resulting from the migration across the continental shelf or coastal plain of near-shoreline wave abrasion (Fig. 3-2). We identified:

- the area of the glacial lowstand maximum shoreline at approximately 120 m below sea level (bsl) and the shelf-break (190-200 m bsl) last-glacial (~20 ka) sedimentary depocenter characterised by prograding clinoforms in seismic data. On Figs. 3-1 and 3-2, this region of maximum glacial sedimentation is represented as the “lowstand systems tract” (LST).

- the post-last glacial marine transgressive surface (TRS2/1), which varies in age (i.e., diachronous, ~20-7 ka). This surface underlies the “transgressive systems tract” (TST) beneath the middle to outer continental shelf, and the “highstand systems tract” (HST) beneath the inner shelf (Fig. 3-2). Beneath the middle to inner shelf, this surface is an easily recognisable erosion surface, which formed in very shallow water (<10 m) as a result of wave abrasion during rising sealevel since sea-level lowstand associated with the last glaciation. On many continental shelves, the TRS2/1 erosion surface is commonly planar, as a result of complete wave planation. However, in some cases where substantial shelf geomorphology exists, particularly in association with exposed competent -units resistant to erosion, the TRS2/1 surface may not be planar and may partially preserve last-glacial geomorphology beneath it. In this study, the shape and deformation of the TRS2/1 constrains the maximum slip rates on the Late Quaternary faults.

- the TST as the body of sediment that was deposited on the shelf in the wake of rising sea level.

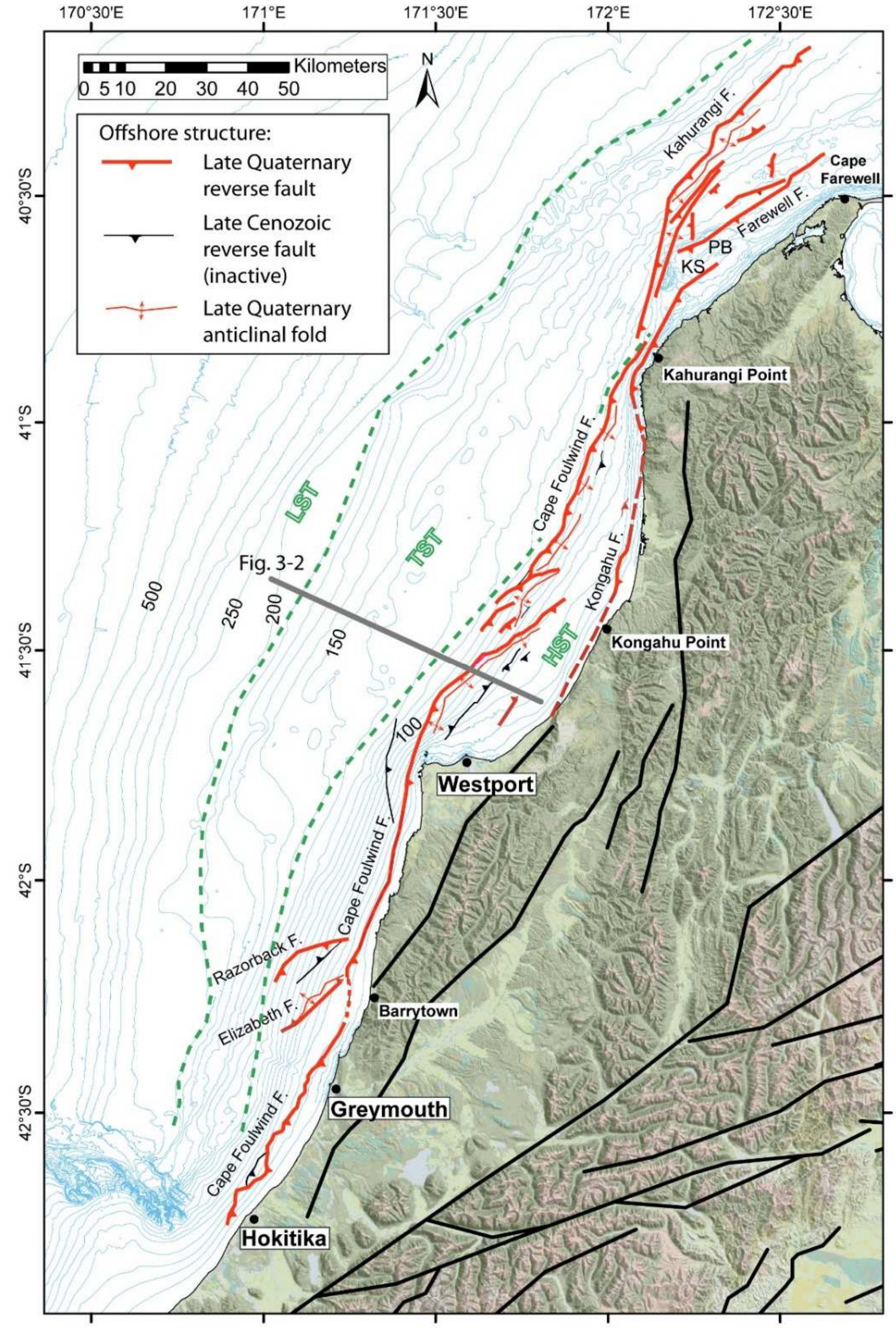

Figure 3-1: Active marine faults identified in this study in the north Westland region. Red lines are active faults, thin black lines offshore are late Cenozoic reverse structures, not interpreted as currently active. Bathymetric contours (m bsl) are from the NIWA bathymetric database, with the contour interval at 50 m on the slope beyond 200 m water depth, and 10 m inside 200 m water depth. Abbreviations include HST, highstand systems tract; TST, transgressive systems tract; and LST, lowstand systems tract (see text for details). KS, Kahurangi Shoals. PB, Paturau Bank. Thick black lines onshore are active faults interpreted as earthquake sources in the current national seismic hazard model (Stirling et al., 2012).

- the mainly Holocene HST as the lens-shaped sedimentary body with maximum thickness typically in water depth of about 50 m on the inner shelf (Figs. 3-1 and 3-2).

Collectively, the TST and HST represent the post-last glacial sequence (<20 ka). Between Greymouth and Cape Foulwind, this combined sequence reaches 100 m in thickness.

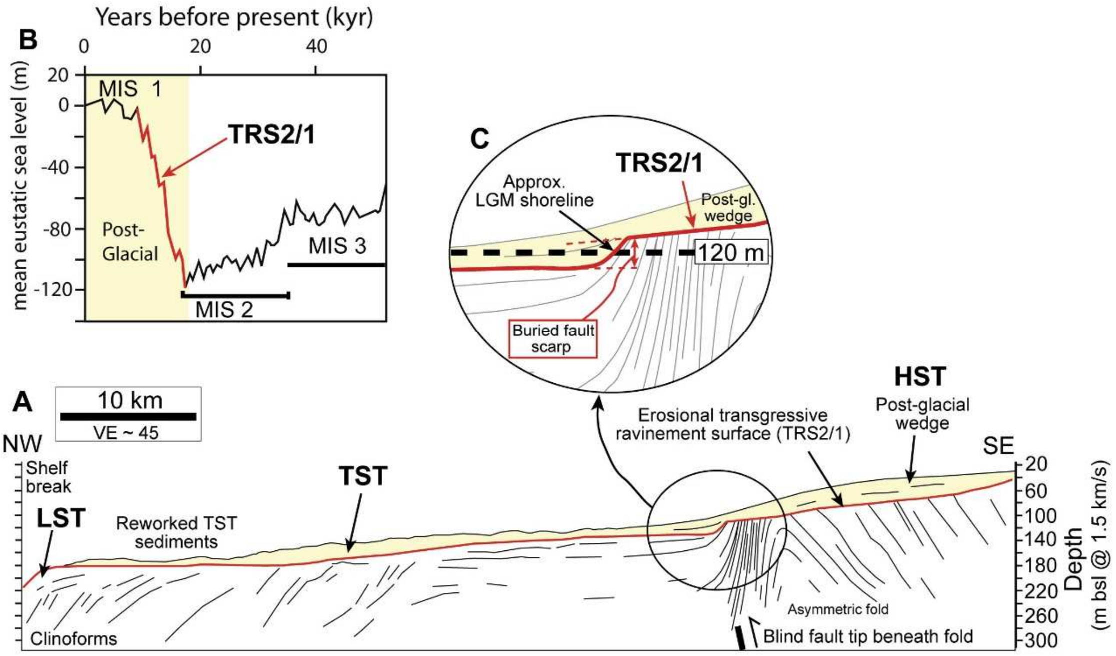

Figure 3-2: Line drawing of the last sea-level cycle sequence across the Cape Foulwind Fault on the continental shelf immediately north of Westport. A. Drawing based closely on our interpretation of high-resolution boomer seismic profiles in the vicinity of the profile location shown in Fig. 3-1. See text for explanation of abbreviations and deformation by the Cape Foulwind Fault. B. Correlation of deposits and TRS2/1 surface to major glacioeustatic sea-level change (e.g., Pillans et al., 1998) and marine oxygen isotope stages (MIS) (Imbrie et al., 1984). C. Enlargement of buried fault scarp, in this case positioned close to the approximate location of the last-glacial maximum (LGM) shoreline, showing method of footwall and hanging wall surface projections used to estimate scarp vertical relief on the boomer and sparker profiles.

4 Offshore Late Quaternary faulting

In Stage 2 of this project, all late Cenozoic faults were interpreted on each individual seismic profile, and the upper tip of the faults was mapped in ArcGIS. In this region, the fault tips are commonly blind, typically lying a few hundred meters to >1 km beneath the seafloor. Above the fault tips, strata are deformed into fault-propagation folds, forming local anticlinal structures. Faulting was correlated along strike between profiles to produce the interpreted fault maps (Fig. 3-1). Because most of the major faults dip to the east, the upper tip lines lie west of the position of the fault at basement depth. The initial fault mapping was undertaken using only the multichannel seismic profiles. Details of the fault location and associated anticlinal folding at shallow levels were then revised and fine-tuned using the relatively shallow penetration sparker, boomer and 3.5 kHz source data. We mapped faults extending

60-70 km to the north and south of the WCRC jurisdiction, to ensure that all local marine earthquake sources relevant to WCRC are fully accounted for.

Six major Late Quaternary faults are mapped offshore north of Hokitika. These include the Cape Foulwind, Kongahu, and Kahurangi faults (Rattenbury et al., 1998; Nathan et al., 2002), which have been targets for extensive oil exploration activities in the region (e.g., Esso Exploration and Production NZ, 1968; 1969-1970; NZ Aquitaine Petroleum, 1971; Cultus Pacific, 1981; Diamond Shamrock Exploration Oil, 1982a, 1982b; Seahawk Oil International, 1981; GECO NZ, 1984; Thrasher and Cahill, 1991; King and Thrasher, 1996; Geosphere, 2009). Collectively the Quaternary deformation zone comprising the active faults extends for 320 km parallel to the strike of the coast, and typically lies within 3-25 km from shore. No Late Quaternary faulting is recognised in current datasets within a 170 km long region off the central Westland coast, between Hokitika and Paringa. Off South Westland and northern Fiordland, three major coast-parallel Late Quaternary faults, including the Milford Basin thrust (Barnes et al., 2002), are recognised within 15-30 km from shore. The Alpine Fault extends offshore at Milford Sound in northern Fiordland (Barnes et al., 2005; Barnes, 2009) and is not discussed in this report.

4.1 Cape Foulwind Fault

The Cape Foulwind Fault is a segmented reverse fault zone extending along the inner shelf for 240 km between Hokitika and Kahurangi Point (Fig. 3-1). The fault has an average strike of 030°, dips to the east, and its upper tip is generally blind, lying within the Miocene-Pliocene sequence, typically 300-700 m beneath the seafloor. At Cape Foulwind and immediately south of it the fault breaches through basement units that are uplifted close to the surface in the fault hanging wall Preserved Cretaceous syn-rift units in the fault hanging wall demonstrate that the fault is a compressionally-reactivated normal fault with a dip of about 50° in the upper crust (Ghisetti et al, in preparation). The fault comprises several discrete Late Quaternary geometric segments, likely inherited from the original Late Cretaceous to Paleogene en echelon rift structures.

The southern section of the fault between Hokitika and Cape Foulwind lies close to the coast, about 3-6 km from shore, in 20-40 m water depth. Off Barrytown, there is a change in strike, where the fault bends across an inferred step-over about 5 km in width. Between Barrytown and Cape Foulwind the total vertical displacement on the fault exceeds 3 km. There, the fault is responsible for uplift and exposure of Cretaceous and Paleogene sequences at the coast, and it strongly controls the shape of the coastline (Nathan et al. 2002). Immediately North of Cape Foulwind the fault strikes more northeasterly (052°), and terminates at a major 10 km-wide, step-over off Kongahu Point. The major fault segments across this left step-over overlap by 20 km, and within the step-over region there are at least two discrete fault traces <20 km in length. The northern section of the fault lies in about 110 m water depth, and extends from the step-over, about 20 km off Kongahu Point, to Kahurangi Point. Off Kahurangi Point, the fault converges with the northern end of the Kongahu Fault and the southern end of the Kahurangi Fault (Fig. 3-1).

The Miocene to Late Quaternary units above the fault are folded, as a result of faulting at depth and propagation of shortening up dip during a prolonged period of displacement. High-resolution seismic profiles and line tracing interpretations of data available for this study demonstrate that the west-facing forelimb of the anticline forms an eroded scarp now buried beneath post-glacial sediment. The TRS2/1 erosion surface (20-7 ka) is not planar, but has relief across the fault scarp of up to ~40 m. We measured the height of the buried scarp on the TRS2/1 erosion surface on many profiles along the strike of the fault (Fig. 4-1a). If the TRS2/1 surface had formed as an entirely planar surface, all of the relief now observed on it would represent post-glacial vertical deformation on the fault at a rate of about 0.5-1.5 mm/yr (Fig. 4-1b). This is the maximum possible vertical displacement/separation rate on the fault. However, we consider it highly likely that much of the buried scarp relief on the TRS2/1 surface is paleo-geomorphic relief representing longer-term fault displacement and erosional resistance of uplifted strata on the hanging wall of the fault (SE side). Much of the relief on the fault scarp was probably not removed by erosion during the last marine transgression. Furthermore, the highest scarp height, on the southern section of the fault between Barrytown and Kongahu Point (~80-160 km from the southern end of the fault), occurs where the base of the buried scarp is close to the position of the LGM shoreline, at about 120 m bsl (Fig. 4-1a). This raises the possibility that along this section of the fault, wave abrasion at the last-glacial maximum shoreline enhanced the relief on the scarp, and that the TST accumulated preferentially against the scarp during the early stages of the marine transgression.

Although existing data do not provide conclusive evidence that the post-glacial sequence above the TRS2/1 surface is deformed, we infer that a proportion of the observed scarp relief actually results from post-glacial faulting, and folding of this surface. We, therefore, assign preferred post-glacial slip rates of up to 0.25 mm/yr, minimum slip rates of 0.05 mm/yr, and maximum slip rates of up to 1.3 mm/yr.

4.2 Kahurangi Fault

The Kahurangi Fault lies in 90-150 m water depths, and extends for about 85 km from Kahurangi Point to about 35 km NNW of Cape Farewell (Fig. 3-1). The southern 35 km of the fault has a strike of 015°, whereas the northern 50 km section strikes 043°. The fault dips to the east at about 50°, and as evidenced by seismic and borehole data, is a compressionally reactivated normal fault that bounded a half-graben rift basin in the Cretaceous. The Cretaceous and Paleogene syn- and post-rift sequence has locally been largely inverted, with the total contractional structural elevation, including fault displacement and folding exceeding 2 km. A prominent hanging wall anticline has been breached by a second major imbricate splay fault, which approaches the seafloor up to 5 km east of the major trace.

Due to greatly reduced Holocene mud supply to the shelf north of Kahurangi Point, compared to the inner shelf further south, there is no significant HST mud wedge developed over the northern shelf. The seafloor appears to be underlain by reworked transgressive (TST) sediments with bedforms and erosional scours over a wide (>40 km) terrace (Fig. 3-1). Whilst high-resolution seismic profiles in this region (single-channel airgun and 3.5 kHz sub-bottom profiles) image the anticlinal fold developed in what may be last-glacial age sediments, it is not certain whether the youngest TST is faulted or folded. Because the fault has a very similar structural and morphological expression to that of the Cape Foulwind Fault along strike, we infer similar slip rates, in the order of 0.2 ± 0.1 mm/yr.

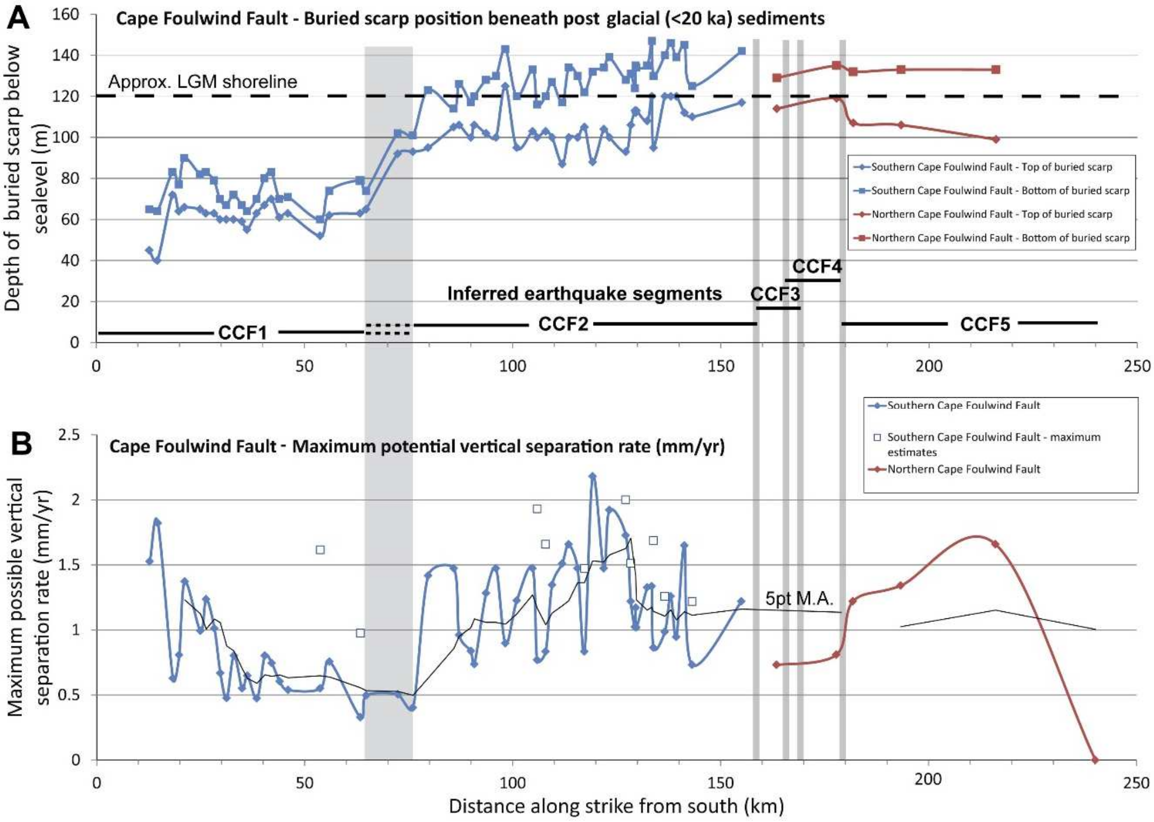

Figure 4-1: Maximum post-glacial (<20 ka) displacement and vertical displacement rates along the Cape Foulwind Fault. A. Distance along fault strike versus depth (m bsl) to the top and base of the Cape Foulwind Fault scarp, expressed as relief on the TRS2/1 surface, buried beneath the post last-glacial sequence (TST and HST). B. The highest vertical separation rates on the Cape Foulwind Fault result from the unlikely assumption that the TRS2/1 surface was completely planar when it formed and has since been folded by post-glacial deformation. 5pt M.A., 5 point moving average.

4.3 Kongahu Fault

The Kongahu Fault lies close to the coast north of Westport, strikes variably between 025º and 165º, and controls the shape of the steep coastline along the length of Karamea Bight (see cover photo of this report) (Fig. 3-1). The fault is imaged in seismic data north of Kongahu Point and around the cape at Kahurangi Point, and part of the fault zone locally comes ashore at the coast between these areas (Ghisetti, unpublished data). The fault is interpreted to extend for about 120 km from 25 km south of Kongahu Point, to about 25 km north of Kahurangi Point. Unpublished geological sections developed by Ghisetti demonstrate that the fault is a compressionally-reactivated normal fault that bounded the western flank of a Late Cretaceous graben. The total basin inversion exceeds 2.3 km of vertical deformation.

The Kongahu Fault appears to be the offshore extension, or is at least along the same structural alignment, of the Buller Fault, which lies onshore 10 km SW of Westport (Nathan et al., 2002). We have no Late Quaternary constraints on its slip rate, but infer it is in the order of 0.3 (-0.1, + 0.2) mm/yr.

4.4 Farewell Fault (unofficial new name)

The Farewell Fault (unofficially named from Cape Farewell) lies beneath the inner shelf in about 80 m water depth, about 10 km west of Cape Farewell (Fig. 3-1). The fault dips to the east, strikes 055º, and is mapped for a length of about 45 km. The southern section of the fault appears to be associated with a bathymetric escarpment on the shelf along the northern edge of Paturau Bank. Available data cannot prove that the fault is an inherited, reactivated normal fault. However, it is interesting to note that the Farewell fault is sub-parallel (but oppositely dipping) to the onshore, W-dipping Wakamarama fault. Original normal faulting along both faults is consistent with the location of the Late Cretaceous Pakawau rift basin (Nathan et al., 1986), which is presently uplifted in the Wakamarama Ranges as a result of compressional inversion. As with the Kahurangi Fault, there is not a significant HST sediment wedge developed across the fault trace, and the Late Quaternary slip rate is unconstrained. For the purpose of this project, we assign a conservatively low slip rate of 0.1 (-0.05, + 0.1) mm/yr.

4.5 Elizabeth Fault (unofficial new name)

The Elizabeth Fault (unofficially named from Point Elizabeth) lies beneath the inner shelf 10 km west of Barrytown, in about 30-90 m water depth (Fig. 3-1). The fault is reverse, about 19 km long, strikes 050º, and is one of the few offshore faults that dip to the NW. The Elizabeth Fault lies 5-25 km north of the NW-SE-striking Cretaceous Takutai half-graben (Bishop, 1992), and its northeastern end approaches to within a few kilometres of the prominent bend in the Cape Foulwind Fault, NW of Barrytown. Compared to the large displacement (2-3 km) Cape Foulwind, Kahurangi and Kongahu faults, the Elizabeth Fault has a comparatively minor total reverse offset of the Oligocene sequence of about 80-90 m.

The fault appears to be active as evidenced by a fault-related fold that affects the late Neogene and Quaternary stratigraphy. In sparker seismic data collected by Alpine Geophysical Associates (1968), the fault-related anticline is observed in Late Quaternary sediments immediately beneath the TRS2/1 erosion surface. The erosion surface across the fold appears to be planar and unfaulted. There is, therefore, no evidence for any fault displacement during the post-last glacial (<20 ka) interval. We infer a very low slip rate in the order of 0.05 mm/yr.

4.6 Razorback Fault (unofficial new name)

The Razorback Fault (unofficially named from Razorback Point) lies beneath the shelf NW of Barrytown, in about 40-120 m water depth (Fig. 3-1). The fault is reverse, about 22 km long, and strikes 050º, approximately parallel to the Elizabeth Fault. The Razorback Fault dips to the SE, thus bounding an uplifted block between these two faults. Razorback Fault has a total reverse displacement of 80-90 m on the Oligocene sequence.

Two sparker seismic profiles clearly reveal a significant buried scarp associated with the fault-propagation fold above the Razorback Fault, resembling profiles from the Cape Foulwind Fault. The TRS2/1 surface has relief of 20-35 m on these lines, indicating potentially significant post-glacial activity on the fault. Similar to the Cape Foulwind Fault scarp NW of Westport, the buried Razorback Fault scarp lies at about 120-140 m bsl, indicating that the LGM shoreline has potentially enhanced this feature by shore-face wave abrasion at about 20 ka. We suspect that much of the buried scarp relief on the TRS2/1 surface is paleo-geomorphic structural relief, enhanced by LGM shoreline erosion. Considering there is a broad seafloor ramp with >10 m of bathymetric elevation along these strike seismic sections, some post-glacial folding is likely. We infer a best estimate slip rate of 0.2 (-0.15, +0.8) mm/yr.

4.7 Jackson Fault (unofficial new name)

Jackson Fault (unofficially named from Jackson Bay) is inferred to cut across the head tributaries of Moeraki Canyon, which approach to within 1.5 km of the coast west of Paringa (Fig. 4-2). The fault is observed in only two multichannel seismic sections, but appears to have a prominent bathymetric scarp cutting across the canyon tributaries. The fault strikes 040°, is about 40 km long and dips NW. The northern section of the fault lies at about 500 m slope depths between the canyon tributaries, whereas an associated fold at its southern end is imaged beneath the outer shelf off Jackson Bay. The geomorphic evidence suggests that the fault is active, but its slip rate is not constrained. We infer a conservatively low rate of 0.1 (-0.05, +0.1) mm/yr.

The Jackson Fault lies west of the now inactive, Late Cenozoic age, South Westland Fault Zone (SWFZ), which lies within 5 km offshore and crosses the coast at several places (Fig. 4-2) (Nathan et al., 1986; Cox et al., 2007, Rattenbury et al., 2010). We mapped another inactive reverse structure beneath the inner shelf north of Paringa (Fig. 4-2), which is also likely a component of the SWFZ.

4.8 Barn Fault

The Barn Fault has been inferred in a recent update of New Zealand active faulting as the northern extension of the Milford Basin (Madagascar) thrust (Litchfield et al., submitted). Whilst there are insufficient seismic data to map this fault in the sub-surface in detail, as part of Stage 2 of this project we have reconsidered multibeam data in the region, and have reinterpreted the location of the fault. The fault is here interpreted to extend for about 55 km from offshore of Big Bay to the tributary canyons of the Milford Basin immediately off Jackson Bay (Fig. 4-2). We infer that the fault does not connect with the Jackson Fault, and place the northern tip of the fault in the southern of the two major tributary canyons. The slip rate on the fault is inferred to be 0.5 (-0.4, +0.5) mm/yr (Litchfield et al., submitted).

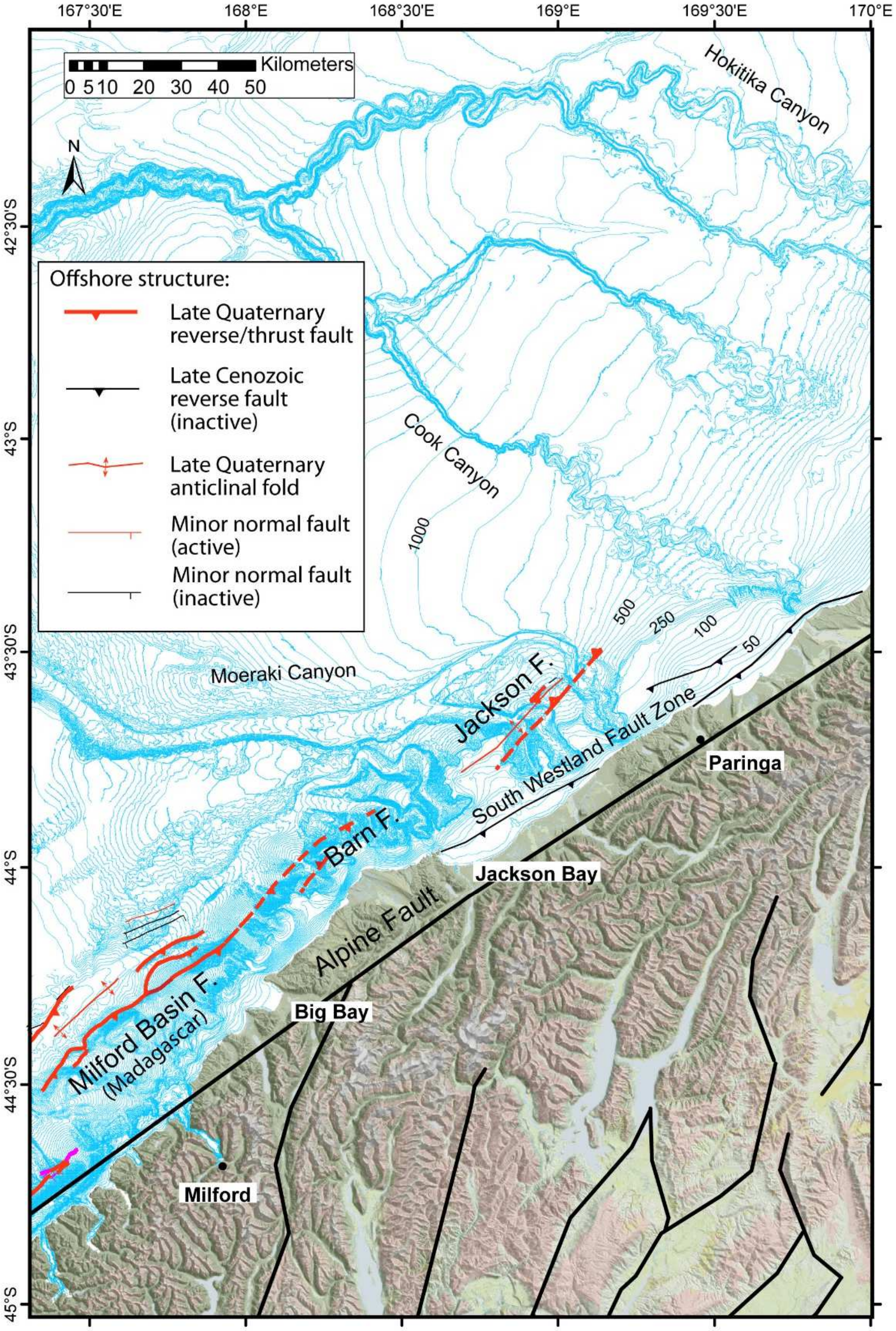

Figure 4-2: Active marine reverse faults (thick red lines, triangles in the hanging wall; dashed where inferred) and related hanging wall anticlinal folds identified in this study in the south Westland region. Bathymetric contours (m bsl) are from the NIWA bathymetric database, with contour interval at 50 m on the slope beyond 200 m water depth, and 10 m inside 200 m water depth. Thick black lines onshore are active faults interpreted as earthquake sources in the current national seismic hazard model (Stirling et al., 2012).

4.9 Milford Basin (Madagascar) thrust

The Milford Basin (Madagascar) thrust extends for about 65 km along the landward edge of Milford Basin, coinciding with a bathymetric scarp on the slope, and has been imaged in multichannel seismic data (Barnes et al., 2002). The fault lies 25-30 km west of the Alpine Fault, and dips to the east. The fault was inferred to have a slip rate of 3 ± 2 mm/yr by Stirling et al. (2012). Here we adopt a more recent, reduced estimate of the slip rate of 0.75 (-0.25, +0.4) mm/yr by Litchfield et al. (submitted), who refer to this structure as the Madagascar Fault.

5 Earthquake Fault Sources

All faults identified in this study are part of the same system of N-S to NE trending, moderately to steeply-dipping faults that comprise the sources of large historical earthquakes (e.g. 1929 **M**7.8 Buller earthquake, 1968 **M**7.1 Inangahua earthquake, 1962 **M**6 Westport earthquakes, cf. Stirling et al., 2012). All these faults are capable of being activated (rupturing) with reverse mechanisms in the present stress field (Anderson et al., 1993; Townend et al., 2012), though each individual structure may possess long recurrence intervals. In this regional context, and considering that all faults mapped on Figs. 3-1 and 4-2 are identified at or near the seabed, it is highly likely that they have progressively grown during large-magnitude, ground-rupturing earthquakes (Stirling et al., 2002, 2012). On Figures 5-1 and 5-2, and in Table 5-1, we have interpreted 13 potential earthquake sources offshore of Westland and northern Fiordland. Minor faults in the vicinity of the major traces on Figs. 3-1 and 4-2 are inferred to be secondary ground ruptures associated with coseismic displacements on the major faults. Whilst the interpretations are not the only potential earthquake scenarios, for example composite ruptures of more than one fault segment are possible during a single major earthquake, we consider them likely and indicative of the earthquake hazard posed by these structures. Ten of the earthquake sources occur in the northern region and pose a seismic hazard to the coastal townships including Hokitika, Greymouth and Westport.

Most of the earthquake fault sources lie entirely offshore. An exception is the Kongahu Fault, which appears to continue southward onshore bounding the Paparoa Range front, including the Lower Buller Fault (Nathan et al., 2002; Stirling et al., 2012; Litchfield et al. submitted; Ghisettiet al., in preparation). Although it is entirely feasible that an earthquake rupture on the Kongahu Fault could propagate onshore, we consider the offshore Kongahu Fault as a separate earthquake source with a rupture length potentially reaching 119 km.

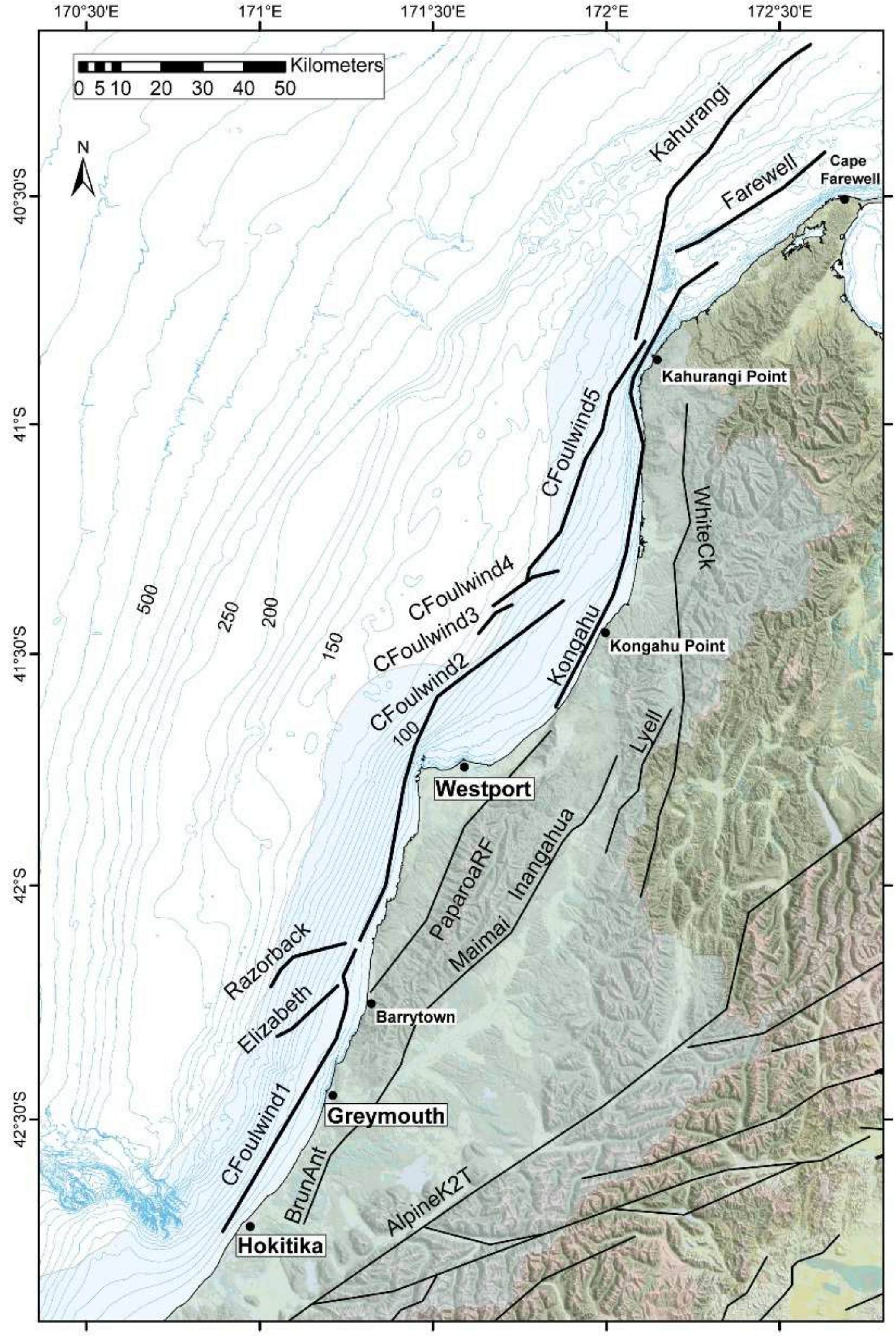

Figure 5-1: Earthquake fault sources, offshore North Westland. Black lines represent individual earthquake fault sources interpreted from the fault structures shown in Fig. 3-1, and consideration of displacement data and slip rate estimates (Table 5-1). The offshore earthquake source parameters are presented in Table 5-1. Black lines and labels onshore are earthquake fault sources with respective source labels in the current national seismic hazard model of Stirling et al. (2012).

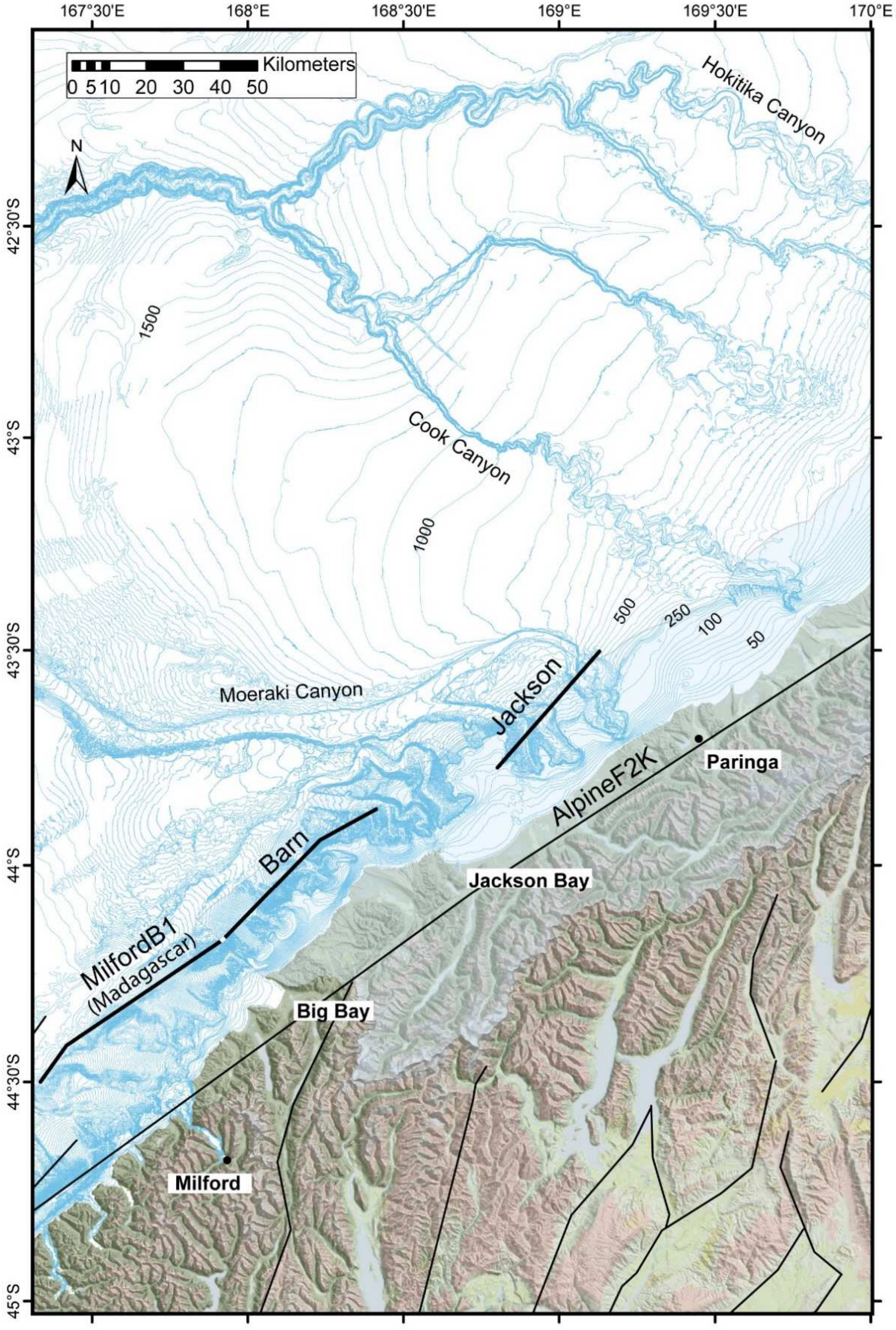

Figure 5-2: Earthquake fault sources, offshore South Westland. Black lines represent individual earthquake fault sources interpreted from the fault structures shown in Fig. 4-2. The offshore earthquake source parameters are presented in Table 5-1. Black lines and labels onshore are earthquake fault sources with respective source labels in the current national seismic hazard model of Stirling et al. (2012).

Table 5-1: Earthquake source parameters, offshore Westland, defined using the method of Stirling et al. (2012).

Fault source name	Type	Type Index	Length (km)	Dip (°)	Dip dir (°)	Depth (km)	Top (km)	SR Min. (mm/yr)	SR (mm/yr)	SR Max. (mm/yr)	Mw Min.	Mw	Mw Max.	SED (m)	RI min. (yrs)	RI (yrs)	RI max. (yrs)
Kahurangi	rv	3	87	50	125	15	0.5	0.10	0.20	0.30	7.5	7.6	7.8	6.1	18162	30270	66590
Farewell	rv	3	44	50	145	15	0.5	0.05	0.10	0.20	7.1	7.2	7.4	3.0	13690	30420	66930
Kongahu	rv	3	119	50	115	15	0.5	0.20	0.30	0.50	7.7	7.8	7.9	8.3	14980	27730	45760
C.Foulwind5	rv	3	65	50	120	15	0.5	0.05	0.25	1.30	7.3	7.5	7.6	4.5	3150	18170	99950
C.Foulwind4	rv	3	18	50	115	15	0.5	0.05	0.15	1.00	6.6	6.7	6.8	1.2	1120	8300	27380
C.Foulwind3	rv	3	11	50	115	15	0.5	0.05	0.10	0.50	6.3	6.4	6.6	0.8	1360	7570	16640
C.Foulwind2	rv	3	100	50	115	15	0.5	0.05	0.25	1.30	7.6	7.7	7.8	7.0	4810	27810	152960
C.Foulwind1	rv	3	77	50	115	15	0.5	0.05	0.20	1.00	7.4	7.6	7.7	5.4	4860	26990	118740
Razorback	rv	3	22	50	150	15	0.5	0.05	0.20	1.00	6.7	6.8	7.0	1.5	1360	7560	33250
Elizabeth	rv	3	19	50	135	15	0.5	0.05	0.05	0.05	6.6	6.7	6.9	1.3	23570	26190	28810
Jackson	rv	3	40	50	310	15	0.5	0.05	0.10	0.20	7.0	7.2	7.3	2.8	12560	27910	61410
Barn	rv	3	56	50	140	15	0.0	0.10	0.50	1.00	7.2	7.4	7.5	3.9	3510	7800	42900
MilfordB1 (Madagascar)	rv	3	63	25	140	15	0.0	0.50	0.75	1.15	7.4	7.6	7.8	4.4	3430	5850	9650

Type: rv= reverse fault

Type Index: fault source empirical earthquake magnitude code for New Zealand crustal faults, Equation 3 in Stirling et al. (2012).

Length, Dip and Dip direction are average values calculated from mapped fault traces. Fault depth is set to an average value of 15 km, consistent with average focal depth of the largest earthquakes.

Top: depth to top of blind fault tip.

SR: best estimate of the mean Late Quaternary slip rate.

Mw: Minimum (Min.) and maximum (Max.) values for Moment magnitude are calculated considering length and depth uncertainties of 10%, and dip uncertainties of 10°, for all fault sources.

SED: single-event displacement, calculated from Equation 5 in Stirling et al. (2012).

RI: recurrence interval, calculated from Equation 4 in Stirling et al. (2012).

The Cape Foulwind Fault is composed of distinct segments (Fig. 3-1), and rupture of the entire 240 km length of the fault in one single event appears unlikely. We characterise five potentially discrete earthquake segments, ranging in length from 11 km to 100 km (Fig. 5-1). It is possible that the entire southern geometric section of the fault could rupture in a single event, but we suspect a segment boundary occurs somewhere in the 10 km region north of Barrytown, where the fault bends strongly across a likely basement step-over, and converges with the Elizabeth and Razorback faults. The 10 km wide step-over in the Cape Foulwind Fault, west of Kongahu Point, is a region of segmentation complexity. We infer that segments 3 and 4 of the fault could potentially rupture on their own, although composite scenarios and sequential triggering are possible.

The Kahurangi Fault is considered a separate earthquake source, distinct from the Cape Foulwind Fault and the Kongahu Fault. The Kahurangi (length (L) 87 km) and Farewell (L 4 km) faults are the two most likely earthquake sources west of Cape Farewell. Off Barrytown, both the Elizabeth (L 19 km) and Razorback (L 22 km) faults are potential earthquake sources (Fig. 5-1). In the South Westland region, the Jackson, Barn, and Milford Basin (Madagascar) faults are each considered separate earthquake sources, although it is entirely feasible that the latter two faults could rupture together (Fig. 5-2).

Following the method of Stirling et al. (2012), we develop formula-derived estimates for the moment magnitude (M_w), single-event (coseismic) displacement (SED), and recurrence interval (RI) for the inferred earthquake sources (Table 5-1). These estimates derived from empirical relationships are considered only as indicative of the earthquake potential of the faults, particularly considering there are no marine records of actual paleo-earthquakes. The results account for uncertainties in fault length, depth, dip, area, and slip rate.

Considering the best estimates of the fault parameters(Table 5-1), the results indicate potential reverse faulting earthquakes with magnitudes ranging from M_w 6.4 to 7.8, with recurrence intervals ranging from about 7500 years to 30,000 years. The contributing uncertainties in the various fault parameters produce uncertainties in magnitude estimates for given sources of ± 0.1-0.2, whilst the large uncertainties in slip rate determine a large range of potential single-event displacements and recurrence intervals.

6 Recommendations

1. A revision of probabilistic seismic hazard assessment (e.g., Stirling et al., 2012) in the West Coast region is required in light of the new earthquake fault sources identified in this study.

2. An evaluation of potential tsunami generation, inundation and landslide triggering associated with the mapped reverse fault sources is required to assess tsunami risk in the region.

3. Large uncertainties in fault parameterisation can make a significant difference to probabilistic seismic hazard methodologies (Bradley et al., 2012). In order to greatly reduce the uncertainties in earthquake source magnitudes and recurrence intervals, it is recommended that additional high-resolution marine geophysical data in the offshore Westland region are acquired, and that the fault source characterisation undertaken in this study is refined.

7 Acknowledgements

Philip Barnes is grateful to Dr Scott Nodder (NIWA) for fruitful discussions concerning the interpretation of stratigraphy, fault slip rate and earthquake source characterisation, and for reviewing a draft version of this report. Kevin Mackay and Arne Palletin (NIWA) assisted with ArcGIS issues. Prof. Richard Sibson contributed to unpublished work with Francesca Ghisetti, and helped shape interpretations of regional faulting and active tectonics.

This work was funded jointly by two MBIE Envirolink Medium Advice Grants in 2011 (1052-WCRC103) and 2012 (1237-WCRC114), and by NIWA core funding.

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Appendix A ArcGIS Data

ArcGIS shapefiles of offshore Westland fault data and interpreted earthquake sources have been provided in electronic format to WCRC in association with this report.

The data are provided in:

Projection: Mercator

False_Easting: 0.000000

False_Northing: 0.000000

Central_Meridian: 100.000000ºE

Standard_Parallel_1: 41.000000ºS

Datum: WGS84