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Characterising the Seismic Potential of Compressional Inversion Structures, NW South Island

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LAYMAN'S ABSTRACT

The NW South Island west of the Alpine Fault is a region where steep inherited extensional faults of Late Cretaceous–Eocene age (90 – 40 Ma) trending predominantly NNE-SSW have, since c. 15 Ma, been reactivated to varying extents as reverse-slip faults during WNW-ESE compression – a style of tectonics known as *compressional inversion*. Over the past century these inversion structures have given rise to a series of $6 < \mathbf{M} < 7.8$ damaging earthquakes involving predominantly reverse slip on basin-bounding fault systems. Because inversion faults inclined at >45° to the maximum compression are poorly oriented for reshear, they are often in competition with new-forming thrust faults inclined at c. 30° to the maximum compression and well-oriented for reshear. Seismic hazard from inversion fault structures is difficult to assess because of their structural complexity, the reversal of slip-sense across the structures with time, their progressive structural adaptation, and their concealment by young sedimentary cover along basin margins.

This project has employed a range of approaches to understanding and assessing the seismic hazard from inversion structures: (i) analysing the sedimentary record within the fault-bounded basins to define the migration and changing levels of activity on the inversion fault systems; (ii) combining data from oil-industry marine seismic profiling with onshore geological and geomorphological analyses; (iii) comparing compressional inversion fault systems in the NW South Island with those in NE Honshu, Japan, where basin-bounding inversion structures have given rise to several $6 < \mathbf{M} < 7$ earthquakes over the past decade; and (iv) investigating the factors governing the competition between reverse-slip reactivation of the steep inherited faults (that are poorly oriented for reshear) and the development of new low-angle thrusts that are favourably oriented for reactivation in compressional stress regime.

Key findings from this study are:

1) Categorisation of the structural characteristics of inversion fault systems at different stages of their evolution.
2) The demonstration that integration of offshore seismic profiling with onshore data is a powerful tool for the analysis of inversion structures.
3) Aftershock patterns following inversion earthquakes in NE Honshu reveal competition between reshear of steep inherited faults and formation of new low-dipping thrusts.
4) Seismological/electrical anomalies indicating fluid overpressuring in the lower seismogenic crust of NE Honshu (critical to the reactivation of poorly oriented faults) suggest that comparable geophysical anomalies may occur in the NW South Island.
5) As inversion structures evolve, down-dip segmentation of steep inversion faults by new-forming thrust faults becomes likely unless high fluid overpressures are maintained.
6) Recognition of a Late Neogene concentration of activity around the reverse-fault systems bounding the Wakamarama-Paparoa structural high (a reverse-fault 'pop-up').
7) Identification of intense Pliocene-Holocene? deformation localised along the coast-bounding Cape Foulwind Fault with important seismic hazard implications for the coastal towns of Westport, Greymouth, and Hokitika.
8) Recognition of possible Holocene fault activity along the Wakamarama range-front.
9) Initiation of a proposal for a collaborative microearthquake network centred in the Murchison Basin area involving seismological researchers from DPRI in Kyoto and Tohoku Universities in Japan together with NZ researchers.

TECHNICAL ABSTRACT

The NW South Island west of the Alpine Fault is an area of ongoing *compressional inversion* where a set of steep former normal faults trending predominantly NNE-SSW inherited from Late Cretaceous–Eocene crustal extension have, since the mid-Miocene, been reactivated to varying extents in a WNW-ESE shortening regime. Over the past century these inversion structures have given rise to a series of 6 < **M** < 7.8 damaging earthquakes resulting predominantly from reverse slip on basin-bounding fault systems. Seismic hazard from inversion fault structures is difficult to assess because of their structural complexity, the reversal of slip-sense across the structures with time, their progressive structural adaptation, and their concealment by young sedimentary cover along basin margins.

This project has employed a multifaceted approach to understanding and assessing the seismic hazard from inversion structures, employing: (i) tectonostratigraphic basin analyses to define the migration and changing level of activity on the inversion fault systems; (ii) combining structural-stratigraphic data from oil-industry marine seismic profiling with onshore geological and morphotectonic analyses; (iii) comparing compressional inversion fault systems in the NW South Island with those in NE Honshu, Japan, where basin-bounding inversion structures have given rise to several well-studied 6 < **M** < 7 earthquakes over the past decade; and (iv) investigating, in terms of frictional fault mechanics, the factors governing the competition between reverse-slip reactivation of the steep inherited faults (that are poorly oriented for reshear) and the development of new low-angle thrusts that are favourably oriented for reactivation in the compressional stress regime.

Key findings from this study are:

1) Categorisation of the structural characteristics of inversion fault systems at different stages of their evolution.
2) The demonstration that integration of offshore seismic profiling with onshore data is a powerful tool for the analysis of inversion structures.
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4) Seismological/electrical anomalies indicating fluid overpressuring in the lower seismogenic crust of NE Honshu (critical to the reactivation of poorly oriented faults) suggest that comparable geophysical anomalies may occur in the NW South Island.
5) As inversion structures evolve, down-dip segmentation of steep inversion faults by new-forming thrust faults becomes likely unless high fluid overpressures are maintained.
6) Recognition of a Late Neogene concentration of activity around the reverse-fault systems bounding the Wakamarama-Paparoa structural high (a reverse-fault ‘pop-up’).
7) Identification of intense Pliocene-Holocene deformation localised along the coast-bounding Cape Foulwind Fault with important seismic hazard implications for the coastal towns of Westport, Greymouth, and Hokitika.
8) Recognition of possible Holocene fault activity along the Wakamarama range-front.
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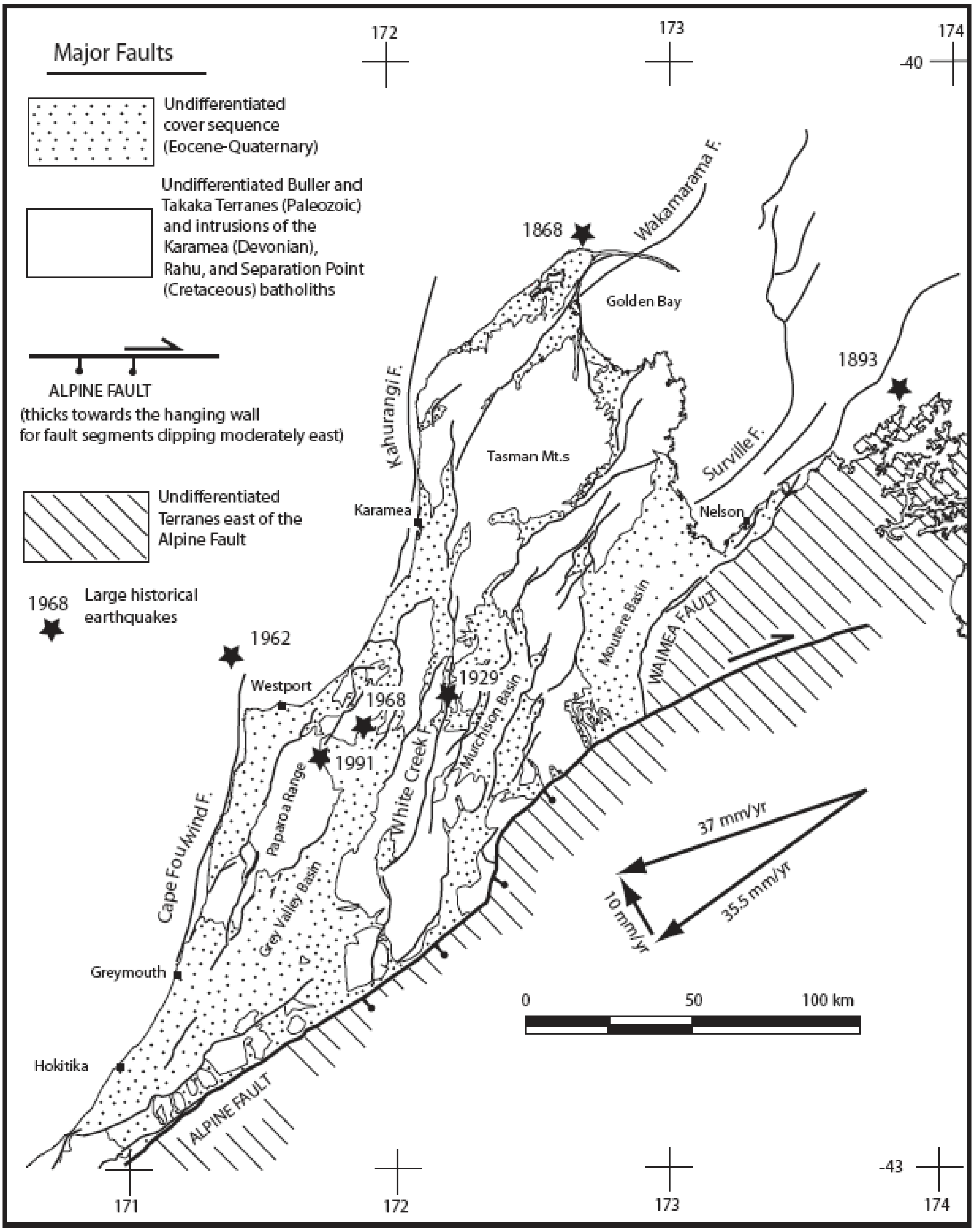

<u>Fig. 1</u> – Area of active compressional inversion in the NW South Island.

1. INTRODUCTION

The region northwest of the Alpine Fault in the northern South Island, embracing the NW Nelson and Buller districts and extending as far south as Hokitika (**Fig. 1**), is an area of active compressional inversion with a predominant NNE-SSW tectonic grain oblique to the NE-SW Alpine Fault (Wellman, 1948; Bishop & Buchanan, 1995; Ghisetti & Sibson, 2006). Within this area, extensional normal faults inherited from Late Cretaceous – Eocene rifting have, since the mid-Miocene, undergone reverse-slip (± strike-slip) reactivation in a WNW-ESE shortening regime in competition with new-forming thrust faults. Exploration for hydrocarbons in the South Taranaki and West Coast Basins provides data showing that similar deformation extends over a larger offshore area, with many faults of regional significance whose seismic potential is poorly understood.

In the broader tectonic context, the region forms part of a Miocene-Pleistocene *retroarc foreland basin system* encompassing the Taranaki Basin and the northern South Island west of the Alpine Fault (Holt & Stern, 1994). However, the tectonic style is in distinct contrast to the systematic migration of deformation expected for a 'typical' foreland fold and thrust belt (Naylor & Sinclair, 2008). Flexure of the Australian lithosphere in front of the orogenic load of the Southern Alps is not accommodated by regular and gentle eastward bending of a basement monocline but is strongly perturbed by reactivation of basement-penetrating pre-existing faults, with large reverse offsets leading to differential uplift across the foreland region.

Strong damaging earthquakes attributable to ongoing compressional inversion have occurred within this region in an upper crustal seismogenic zone extending to ~20 km depth. These include the 1868 **M**~7-7.5 Farewell Spit earthquake, the 1893 **M**~6.9 Nelson earthquake, the 1929 **M**7.8 Murchison earthquake, the 1968 **M**7.1 Inangahua earthquake, the 1962 **M**~6 Westport earthquakes, and the 1991 **M**~6 Hawk's Crag earthquakes (e.g. Anderson *et al*., 1993; Anderson *et al.,* 1994; Doser *et al*., 1999). In the Buller region, focal mechanisms for the 1962 Westport, 1968 Inangahua, and 1991 Hawk's Crag earthquakes are consistent with near-pure reverse slip on the NNE-SSW faults under compressional stress trajectories oriented WNW-ESE (Balfour *et al*., 2006). This is also consistent with the component of sinistral strike-slip observed on the more northerly trending White Creek Fault during the 1929 earthquake, and evidence of dextral shearing along more easterly trending structures such as the Karamea Fault.

Upper crustal seismicity is particularly intense in a swathe extending NNE from Greymouth to Golden Bay in NW Nelson. It is notable that the northwestward bound of upper crustal seismicity largely coincides with the western coastline of the region, while lying 20-50 km northwest of the steep seismically defined boundary to the subducting slab below (Anderson & Webb, 1994). Pronounced escarpments occur along the trace of onshore inversion structures such as the Wakamarama Fault and there is evidence offshore of relatively young deformation associated with the Cape Foulwind Fault. However, because of their uncertain status these features are omitted from one recent compilation of active fault structures used to estimate seismic hazard (Stirling *et al*., 2002) whilst being included in another (Stafford *et al*., 2008).

Assessing hazard from inversion structures is made difficult by: (i) their structural complexity - monoclinal folds associated with a mixture of inherited and new-formed reverse fault segments (**Fig. 2**); (ii) the finite displacement across the structures which may be low or contrary to that expected in the prevailing stress field, giving a misleading impression of inactivity; (iii) concealment of structurally complex assemblages by young sedimentary cover along basin margins; (iv) competition between the reactivation of unfavourably oriented inherited faults and the development of new structures optimally oriented within the prevailing stress regime, and;

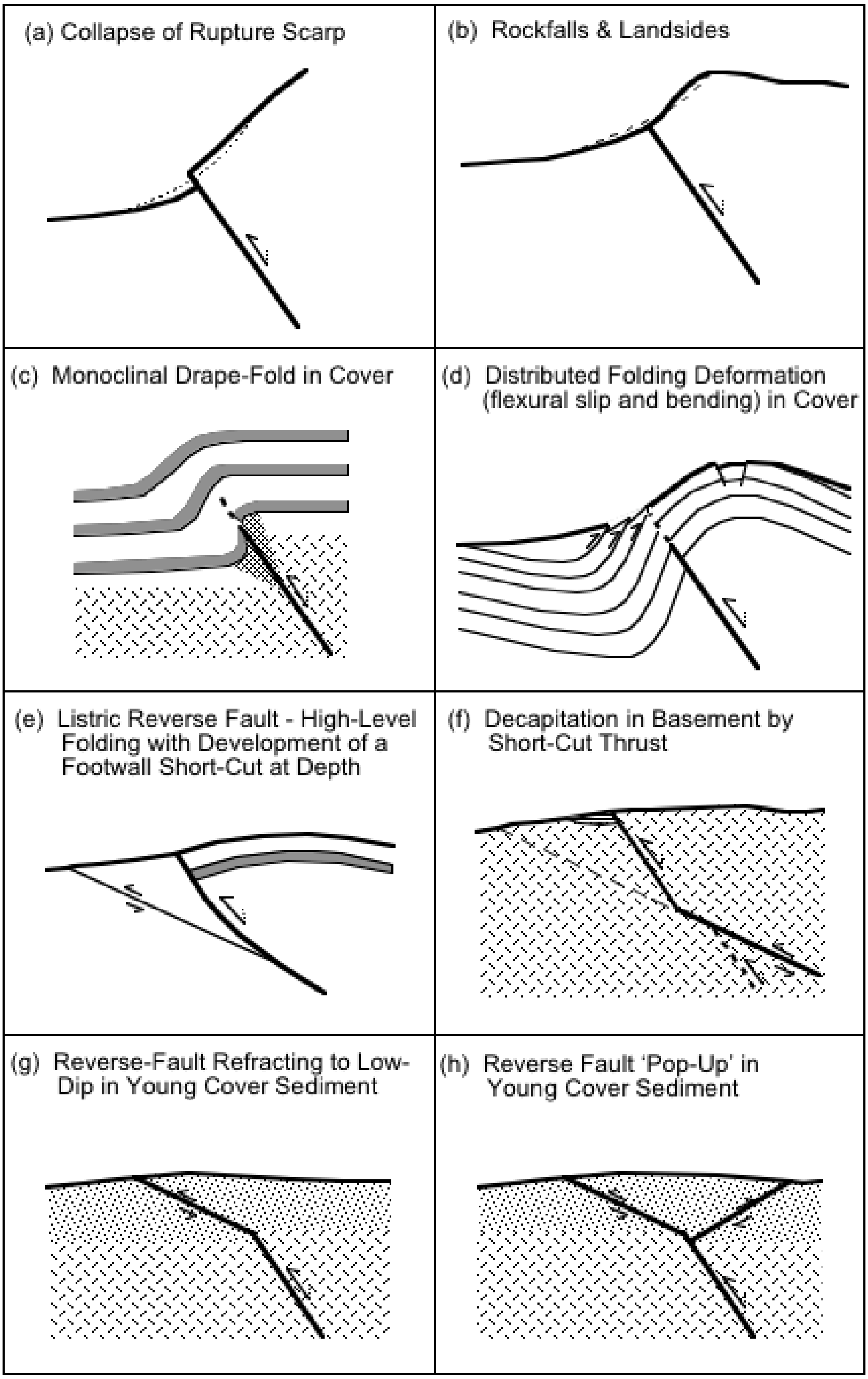

Fig. 2 – Possible complexities in the surface expression of steep reverse faults arising from compressional inversion.

(v) low time-averaged slip-rates (< 1 mm/yr) and long recurrence intervals. On the other hand, the combined structural-stratigraphic characteristics of inversion structures (**Fig. 3**) have been well characterised by both onshore and marine seismic reflection profiling because of their importance as oil-gas reservoirs (Cooper & Williams, 1989; Buchanan & Buchanan, 1995).

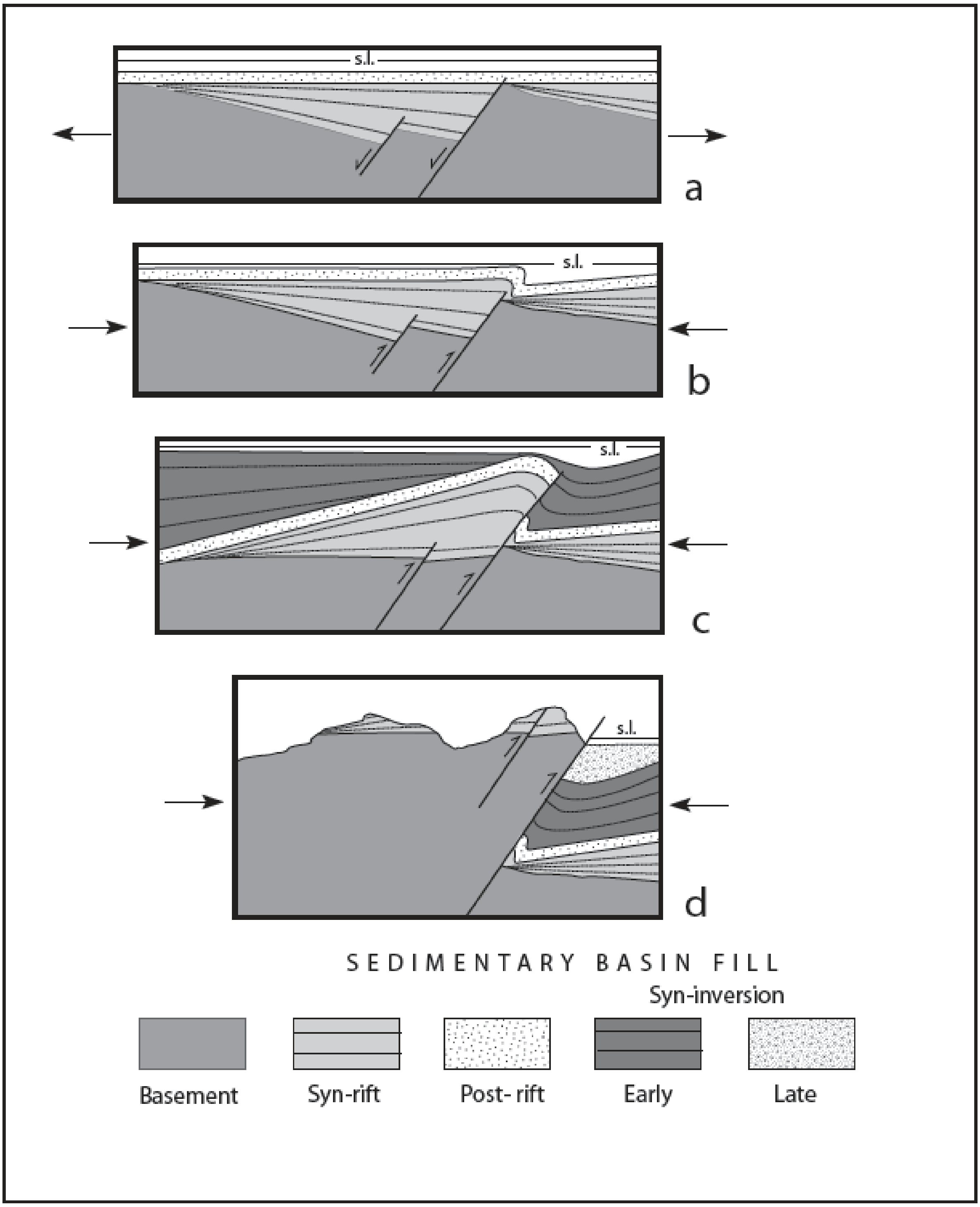

Fig. 3 – Diagnostic structural-stratigraphic signatures of compressional inversion at various stages of shortening (b, c, d) following initial extension (a).

On the basis of frictional mechanics, it has been argued that steep reverse faults require fluid overpressuring in the focal region (Sibson, 1990). Nucleation of ruptures on such faults may thus depend on the accumulation of fluid overpressure as well as tectonic stress. On these grounds, one would expect an active inversion province such as the Buller-Nelson region, which overlies the subducting and presumably dehydrating Pacific plate, to be an area of fluid activity in the mid-crust and lower seismogenic zone (10-15 km). Evidence that this may indeed be the case comes from a recent MT transect (Wannamaker *et al*. 2009), which defines a zone of high electrical conductivity attributed to infiltration of hydrothermal fluids extending from the subduction interface at c. 80 km depth in the mantle to the mid-crust below the Murchison Basin.

NE Honshu, Japan, is a magmatic arc under arc-orthogonal compression that has been undergoing compressional inversion over the past 3.5 Ma following early to mid-Miocene (25 – 13 Ma) rifting associated with the opening of the Japan Sea (Sato & Amano, 1991). Over the past few years several strong earthquakes ($6 < \mathbf{M} < 7$) have occurred within the upper crust of NE Honshu on faults with the stratigraphic/structural characteristics of compressional inversion, involving close-to-pure reverse dip-slip on steep faults (dips > 45°) along the margins of Miocene extensional basins. The active seismotectonics of NE Honshu invite comparison with the active compressional inversion province in the NW South Island.

By a combination of onshore and offshore structural-stratigraphic analyses in the NW South Island, by comparative studies of active compressional inversion faults in NE Honshu, Japan, and through consideration of the mechanics of frictional reactivation, this project has sought to develop empirical geomorphologic, stratigraphic and structural criteria for assessing the seismic hazard from compressional inversion structures. Two Principal Investigators – Dr R. H. Sibson (RHS) and Dr F.C. Ghisetti (FCG) - have been involved with the different components of the research programme as indicated below.

2. PROJECT COMPONENTS

2.1 Tectonostratigraphic Studies of Inversion Structures (FCG)

Overviews of onshore geology are given in two recent QMAP sheets for the Nelson and Greymouth areas (Rattenbury *et al.*, 1998; Nathan *et al.*, 2002). The inversion history of the region is also discussed in Nathan *et al.* (1986), Bishop & Buchanan (1995), and Ghisetti & Sibson (2006).

Tectonostratigraphic analyses of existing geological data available in the published maps, bulletins and reports on the region and in unpublished borehole logs, and public domain seismic surveys were conducted with the goals of: (1) identifying loci of localised shortening associated with persistent reactivation of reverse faults; (2) recognising styles of deformation in the cover sequences diagnostic of active faulting within the basement; (3) inferring relationships between faulting at seismogenic depth (5-15 km), fault-controlled sedimentation, and morphotectonic evolution within the *compressional inversion orogen* of the NW South Island; and, (4) identifying fault structures most likely capable of producing damaging earthquakes in the current seismotectonic regime. These were tied to two periods of fieldwork in the NW Nelson and Buller - Grey Valley areas by FCG and RHS over the periods May 20-27, 2008 and April 17 – 24, 2009. FCG also had previous experience remapping parts of the Murchison Basin area in connection with another project. During fieldwork attention was focused on the Wakamarama Fault in NW Nelson and the Inangahua-Maimai-Kumara Fault system in the Buller-Grey Valley area. Despite the limited road access, rugged topography, and extensive cover of rainforest, this reconnaissance fieldwork

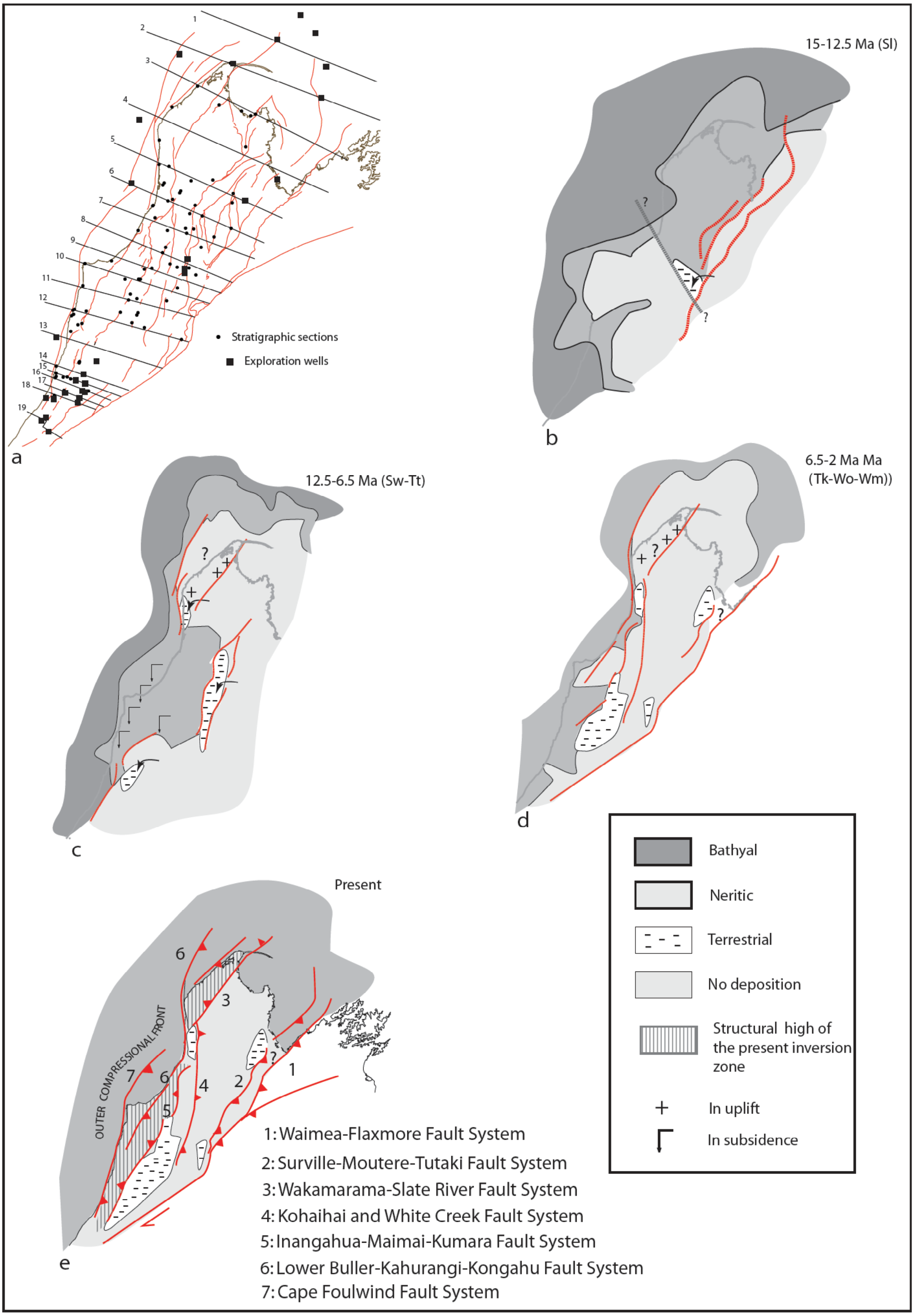

Fig. 4 – Paleotectonic reconstruction of progressive evolution of sedimentary domains in the *compressional inversion orogen*: (a) location of stratigraphic transects used for the analysis; (b-d) evolutionary stages since the mid-Miocene; (e) present setting showing the major faults within the *compressional inversion orogen*.

proved extremely helpful in defining the structural and morphotectonic characteristics of the active range-fronts.

Migration and deformation of the basins within the *compressional inversion orogen* (from offshore Nelson to Hokitika) were analysed by compiling 19 tectono-stratigraphic transects extending from the Waimea-Alpine Fault margin to the offshore, sub-orthogonal to the NNE-SSW tectonic trend (**Fig. 4a**). For each transect, available biostratigraphic data from exposed sections (Nathan, 1973; Wellman *et al*., 1973; Nathan *et al*., 1986; King *et al*., 1999) and exploration wells (data base from http://www.crownminerals.govt.nz) were employed to define differential mobility (in terms of subsidence, uplift and erosion), and the time evolution of sedimentary basins over the last 15 Ma. Analysis of these transects, coupled to the interpretation of offshore seismic lines and to the structural setting onshore, made it possible to define the location, shifting-with-time, and deformation of domains with distinct sedimentary infills (**Fig. 4b-e**), and the activity of the faults that controlled progressive incorporation of basins into the thrust belt.

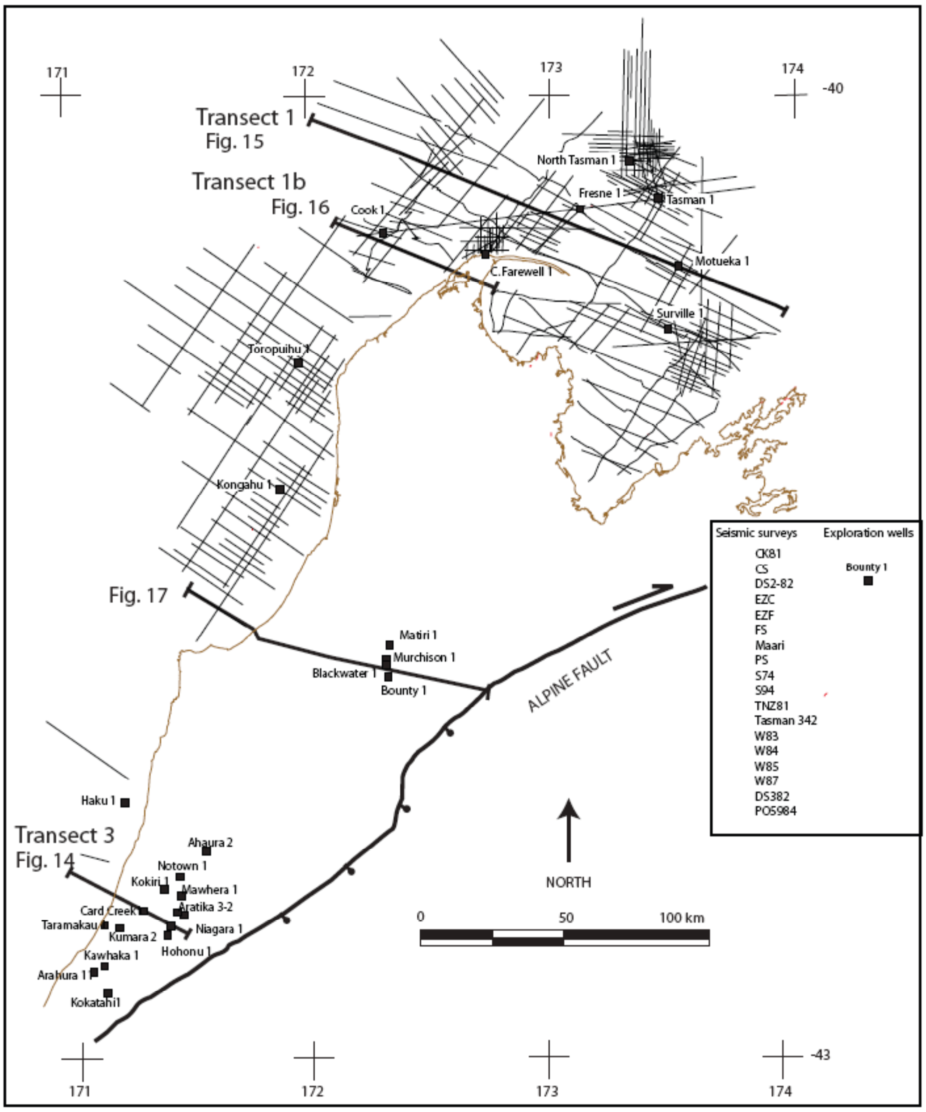

Fig. 5 – Map of public domains seismic lines and borehole logs (http://www.crownminerals.govt.nz) used for the analysis. Locations of regional cross-sections are also indicated.

2.2 Combined Offshore/Onshore Analysis of Inversion Structures (FCG)

Numerous public-domain seismic surveys are available for the Nelson and West Coast offshore areas (**Fig. 5**). They are all of 'vintage' quality; and are not available in digital format. Although their resolution is low by the standards of modern petroleum exploration, they nonetheless provide valuable information on the tectonic setting and compressional deformation offshore, with more continuous syn-inversion sequences preserved. In particular, the stratal continuity traceable offshore allows recognition of subtle fold structures and unconformities related to episodes of fault activity.

2.3 Recent Inversion Earthquakes in NE Honshu (RHS)

The original proposal requested funds for RHS to travel to Japan for comparative studies of the compressional inversion earthquakes that have occurred there in recent years. An additional attraction was the availability in Japan of dense high-quality geophysical data relating to physical conditions in areas of rupture nucleation within the crust. In the event, RHS was fortunate enough to be awarded a Short-Term Fellowship from the Japanese Society for the Promotion of Science (JSPS) that allowed him to spend 5 weeks (Oct. 9 – Nov. 13, 2008) based at Hiroshima University under the generous sponsorship of Professor Toshihiko Shimamoto.

The goals of RHS's visit to Japan were: (1) to investigate, through field visits in the company of Japanese geologists, the geological and topographical expression of the active compressional inversion structures in NE Honshu for comparison with similar systems in New Zealand; (2) to assess seismological controls on the structural geometry of fault systems responsible for recent compressional inversion earthquakes in Honshu; (3) to assess published geophysical (seismological, geodetic, and electrical) data-sets defining physical conditions (temperature, fluid-pressure, etc.) in the lower half of the seismogenic zone where the larger ruptures mostly nucleate; and, (5) to discuss with Japanese researchers a number of problems RHS has previously worked on in connection with upper crustal earthquakes, such as temperature controls on the depth of the seismogenic zone, the thickness of the seismic slip zone during individual rupture events, and the role of fluid overpressure in rupture nucleation.

2.4 Mechanics of Reverse Faulting (RHS)

In intact crust under horizontal compression with the vertical stress $\sigma_v = \sigma_3$, the expectation from classical brittle failure theory (Anderson, 1905; 1951) is that shortening will largely occur on thrust faults forming with dips of c. 30° towards the horizontal maximum compressive stress. The effect of predominantly subhorizontal layering anisotropy is to lower the overall dip of thrust systems still further. However, continental crust may also contain inherited structures liable to reactivation under compression. Not uncommonly, the situation arises where formerly rifted crust containing sets of steep (dip > 45°) normal faults is subsequently shortened and these inherited faults undergo reverse-slip (± strike-slip) reactivation during *compressional inversion*. This gives rise to a 'thick-skinned' style of compressional tectonics with strong involvement of basement.

Figure 6a is an updated global compilation of the dip distribution for reverse-fault earthquake ruptures in the upper crust where the rupture plane is positively discriminated and the slip vector rakes within ±30° of the dip direction (Sibson, 2009). Three groups are apparent. The dominant peak in the dip distribution at 30±5° likely equates to thrust faults either forming or reactivating at the optimal orientation for frictional reshear under horizontal maximum compressive stress, σ_1. An optimal dip orientation of 30° for a thrust fault corresponds to a frictional coefficient μ_s = 0.6 (at the lower end of Byerlee's (1978) range for rock friction) with an expected corresponding 'lock-up' dip of 60° (Sibson, 1985). The subordinate peak at 50±5° is probably largely attributable to compressional inversion of inherited normal faults. The lowest peak at 10±5° is dominated by thrust ruptures in foreland fold-thrust belts where the effects of layering anisotropy are pronounced. Lack of any reverse-slip ruptures with dips > 60° is consistent with expectations for reverse-fault reactivation with μ_s = 0.6.

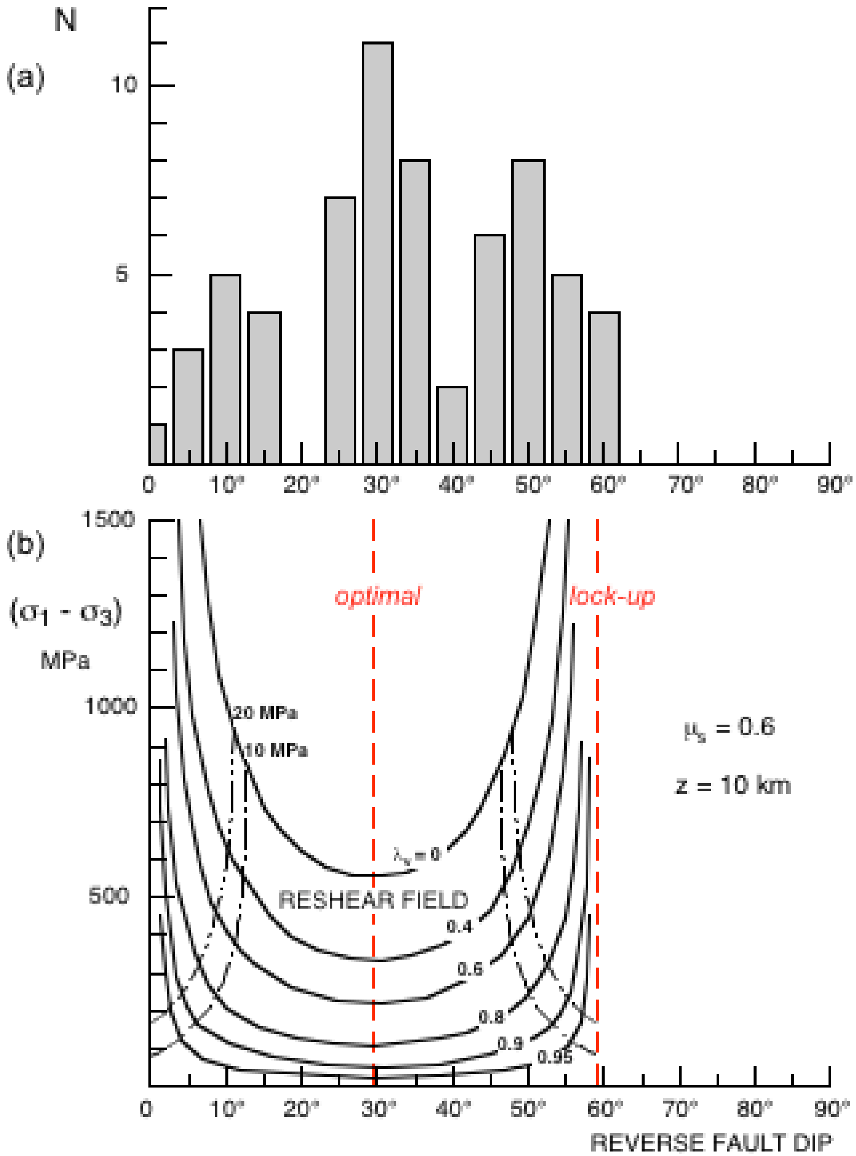

Fig. 6 – (a) Integrated global dip distribution for 64 reverse fault ruptures; (b) Reactivation plot of differential stress vs. dip angle for a cohesionless reverse fault with μ_s = 0.6 at 10 km depth for different values of the pore-fluid factor, λ_v (crustal density, ρ = 2650 kg/m^3), Shear strengths of intact rock with T = 10 and 20 MPa calculated on the assumption of μ_i = 0.75 and a cohesive strength, C = 2T, for varying λ_v (from Sibson, 2009).

In many areas undergoing compressional inversion it is apparent from structural field studies and from seismotectonic analyses that competition arises between reverse-slip reactivation of steep inherited faults and the development of new thrust faults that are optimally oriented in the prevailing compressional stress field. Eventually, activity on the lower-dipping faults, which are also more efficient at accommodating shortening, may supplant that on the steeper structures. This competition may lead to subsurface segmentation which complicates identification of potentially seismogenic structures from surface analyses alone (**Fig. 2f**). It is important therefore to attempt to understand the factors affecting the balance between reverse-slip on steep and shallow-dipping faults in different tectonic settings, and the progressive transition from one form of faulting to the other.

2.5 Establishing a Murchison Basin Seismic Network (RHS)

During his time in Japan, RHS presented the case for involvement of overpressured fluids in the lower seismogenic zone of the Murchison Basin region, both in terms of frictional reactivation mechanics and in the light of the high-conductivity zone revealed by the MT transect of Wannamaker *et al.* (2009), drawing analogies with the area of active compressional inversion in NE Honshu which also overlies a dehydrating subducting slab.

Professors Yoshihisa Iio (DPRI, Kyoto University) and Tomomi Okada (Tohoku University, Sendai) both have long-standing research interests in the involvement of fluids in seismogenesis. They expressed interest in establishing a research microearthquake network in the vicinity of the Murchison Basin and have access to low-power microearthquake recording systems which they are unable to deploy in the northern Honshu winter because of snow. They intend to submit a research proposal to fund an extensive microearthquake recording network (perhaps eventually < 60 instruments) deployed not only in the area of the Murchison Basin (where easy road access is available both north and south of the Buller River), but throughout the Marlborough strike-slip fault system as well.

3. RESULTS

3.1 Tectonostratigraphic Basin Analysis (FCG)

FCG's tectonostratigraphic analyses show a strong control of inherited paleogeography and basement discontinuities on the initial (15-12.5 Ma) configuration of segmented subsiding basins (**Fig. 4b**), followed by irregular westward and southward migration of subsiding basins and of deformed basins from 12.5 to 2 Ma (**Fig. 4c, d**). Segmentation of the foredeep is characterised by re-entrants and salients of depocentral zones, controlled by compressional reactivation of discontinuous fault segments in different positions.

The tectono-stratigraphic evolution and progressive disruption of the Westland foreland basin system records the interference on the progressive westward migration of shortening in the retro-wedge caused by reactivation of basement faults. The major fault systems bounding deformed clastic wedges are – from east to west – (1) the Waimea-Flaxmore Fault; (2) a composite fault system joining the Surville Fault in the offshore to subsurface faults in the Moutere depression and the Tutaki Fault at the east margin of the Murchison Basin; (3) the Wakamarama-Slate River Fault; (4) the Kohaihai and White Creek Faults; (5) the Inangahua-Maimai-Kumara Fault system; (6) the Lower Buller-Kongahu-Kahurangi fault system; and, (7) the Cape Foulwind Fault (**Fig. 4e**).

These faults comprise: (i) segments with demonstrated Holocene activity (e.g. the White Creek, Inangahua-Maimai and Waimea Faults), capable of generating large earthquakes; (ii) segments inherited from the Late Cretaceous rifting (e.g. the Wakamarama, Inangahua-

Maimai, Kahurangi, and Cape Foulwind Faults), and, (iii) segments that interconnect pre-existing faults along structural trends favourably oriented for reactivation. These structures are located in both the internal and external zones of the *compressional inversion orogen*, consistent with no systematic outward propagation and younging of faults, in a tectonic setting dominated by reactivation of pre-existing structures rather than by creation of new faults rupturing across undeformed basement.

Late Pliocene to Quaternary deformation of the foredeep basins is localised along a strongly uplifted reverse-fault 'pop-up' of basement bounded by E- and W-dipping steep reverse faults that can be followed from the Cape Farewell-Karamea area to the Cape Foulwind-Hokitika area (**Fig. 4e**). Emergence of this Wakamarama-Paparoa structural high has governed the westward shifting of the Pliocene foredeep and controls the present coastline; it also defines the outer front of the *compressional inversion orogen* relative to the less deformed foreland basin in the offshore.

3.2 Offshore/Onshore Morphotectonic Analyses of Inversion Structures (FCG & RHS)

The previous analyses show that persistent fault reactivation accompanying the most recent stages of compressional inversion was concentrated towards the west coast associated with fault systems for which there is no clear surface marker of Holocene reactivation (e.g. the Wakamarama Fault) and/or faults that elude both field and marine geology investigation as a consequence of their position close inshore along the coastline (e.g. the Kahurangi and Cape Foulwind Faults). Note that while there is evidence from the 1929 earthquake for a component of left-slip along the more northerly-trending White Creek Fault, and for dextral slip along the more NE-trending Karamea Fault, no evidence has been found onshore for significant strike-slip on the dominant NNE-trending fault structures which appear to be predominantly reverse dip-slip.

Interpretation of selected depth-converted TWT seismic lines tied to available exploration wells (**Fig. 7**) shows:

1. En echelon geometry of the inherited Kahurangi Fault system, that controlled the western margin of a graben infilled with Late Cretaceous terrestrial syn-rift deposits (Pakawau Group). The eastern margin of the same graben was controlled by the faults of the Wakamarama Fault system. The seismic lines show the progressive increase of compressional reactivation from north to south along the E-dipping offshore Kahurangi Fault (**Fig. 8**), marked by the onlap and flexure of the Late Miocene Blue Bottom sequence above the growth anticline in the fault hangingwall, and by the increasing amount of reverse fault throw in the basement-cover interface (from normal to null to reverse separation) (see also **Fig. 16**).

2. Associated with increasing shortening is a change in structural style, with low-angle frontal splays and footwall shortcut thrusts propagating ahead of the steep Kahurangi-Kongahu reverse fault (an inverted normal fault), with associated folding of the Miocene-Pliocene deposits and slumping within the upper Blue Bottom sequence. The splays abut another steeply W-dipping fault (part of the Wakamarama system?) in the basement (**Fig. 7**), only moderately reactivated in compression.

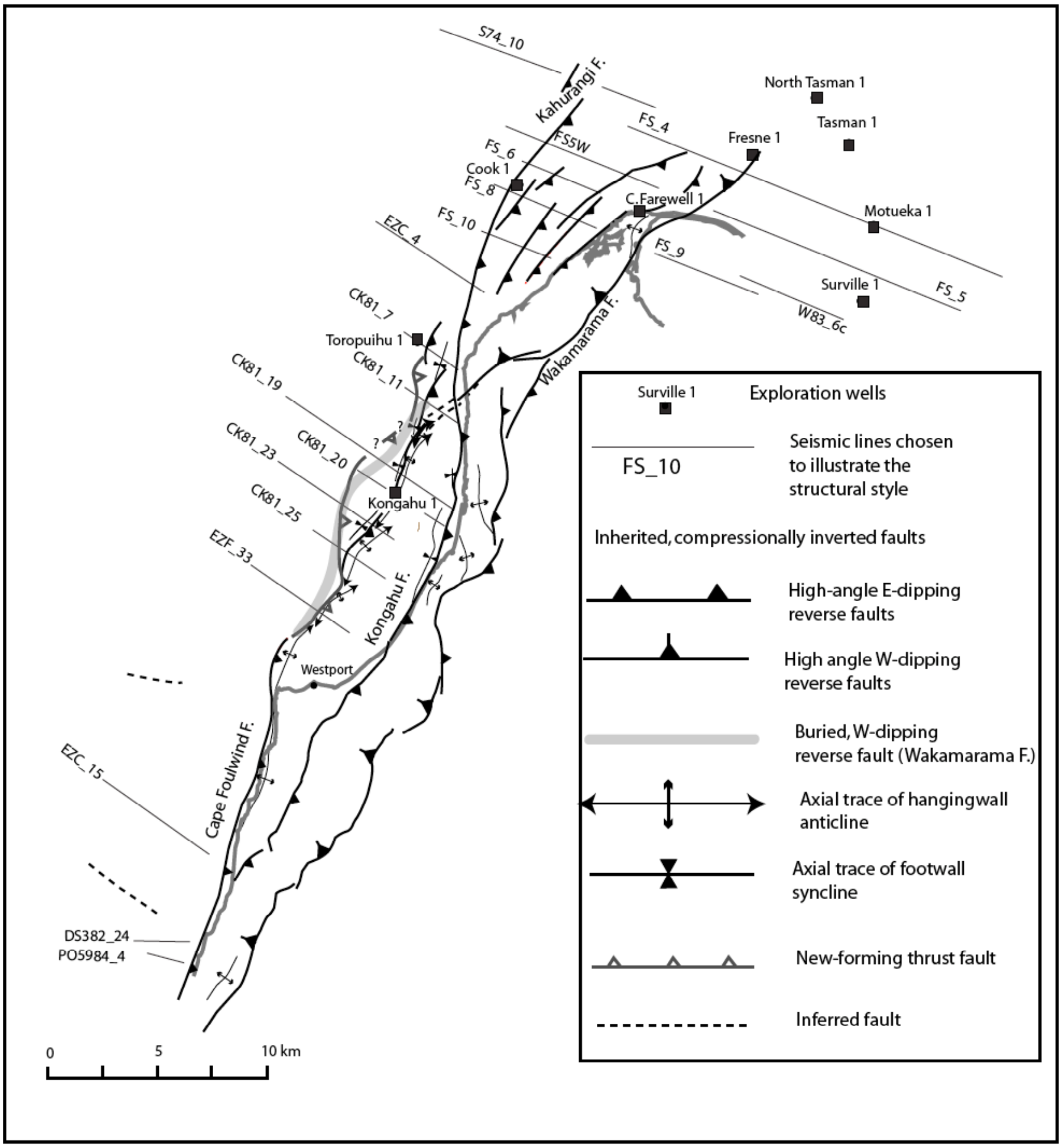

Fig. 7 – Map of fault systems associated with the coastal structural high (see text for discussion).

3. Development of a Pliocene-Pleistocene unconformity resulting from wave-cut truncation of growing anticlines in the hanging wall of the inverted normal faults. This unconformity is tilted and folded in the hanging wall of the Wakamarama Fault, providing the youngest marker of deformation for this structure. The TWT map of this unconformity provides a regional marker for the extent of compressional inversion in the offshore area (**Fig. 9**).

4. Strong deformation along the Cape Foulwind Fault, exemplified by folding of the Miocene-Pliocene clastic wedge in the hangingwall of a blind splay that propagates west of the steep reactivated normal fault (**Fig. 10**). The Late Miocene Blue Bottom sequence shows a marked thickening towards the fault, providing evidence for post-Blue Bottom compressional reactivation. On the other hand, the fold is truncated by a wave-cut erosional unconformity that likely correlates with marine terraces displaced, tilted and uplifted along the Punakaiki coast (Suggate, 1992) in the immediate hangingwall of the Cape Foulwind Fault.

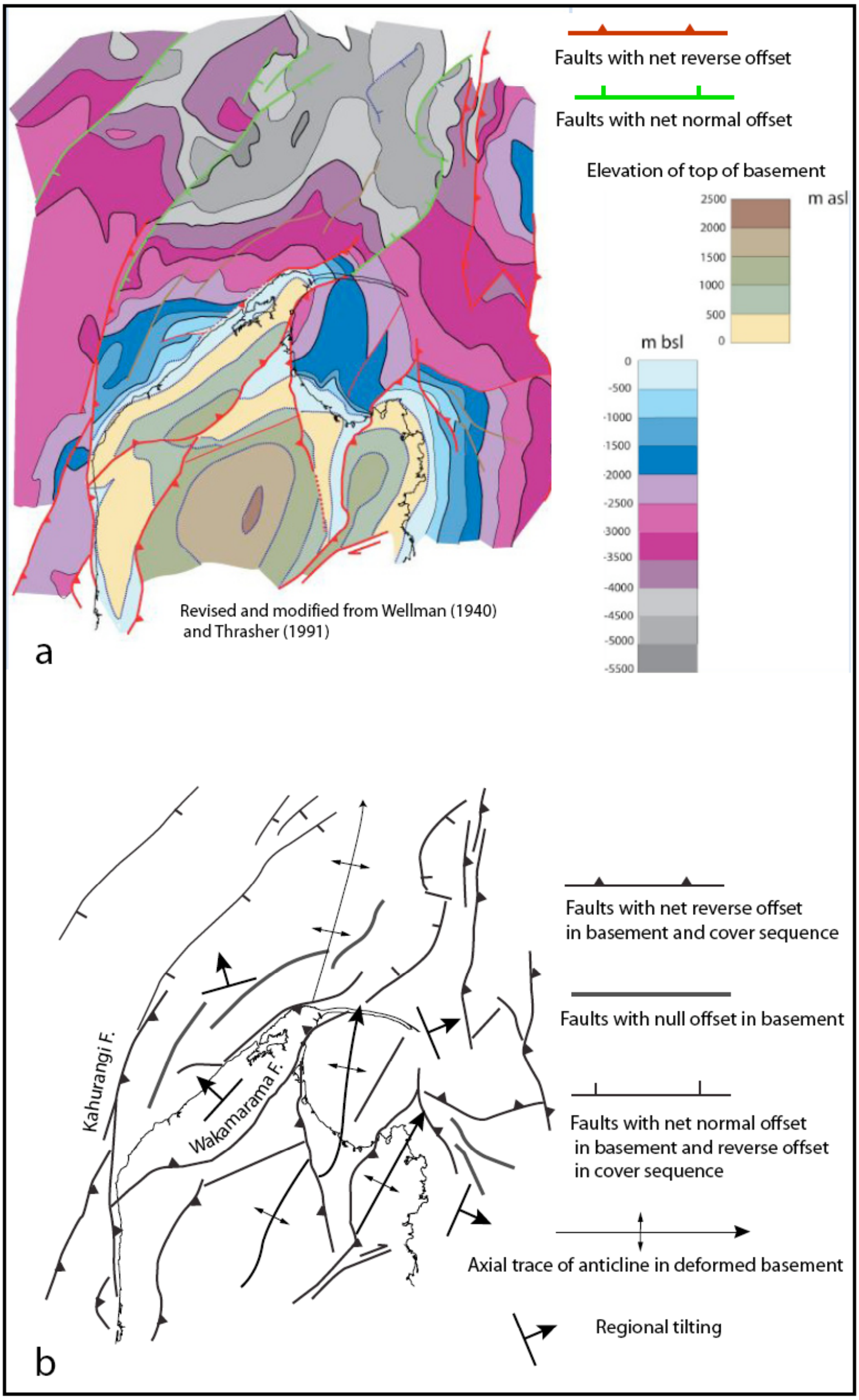

Fig. 8 – Structural controls on basement relief resulting from compressional inversion: (a) contours on top of basement from offshore seismic lines tied to the contours of the *'Ototaran Peneplain'* described by Wellman (1940); (b) major basement structures derived from (a).

Onshore field-based studies focused on two major systems involving reactivation of W-dipping inverted normal faults – the Wakamarama Fault system, and the Inangahua-Maimai-Kumara Fault system.

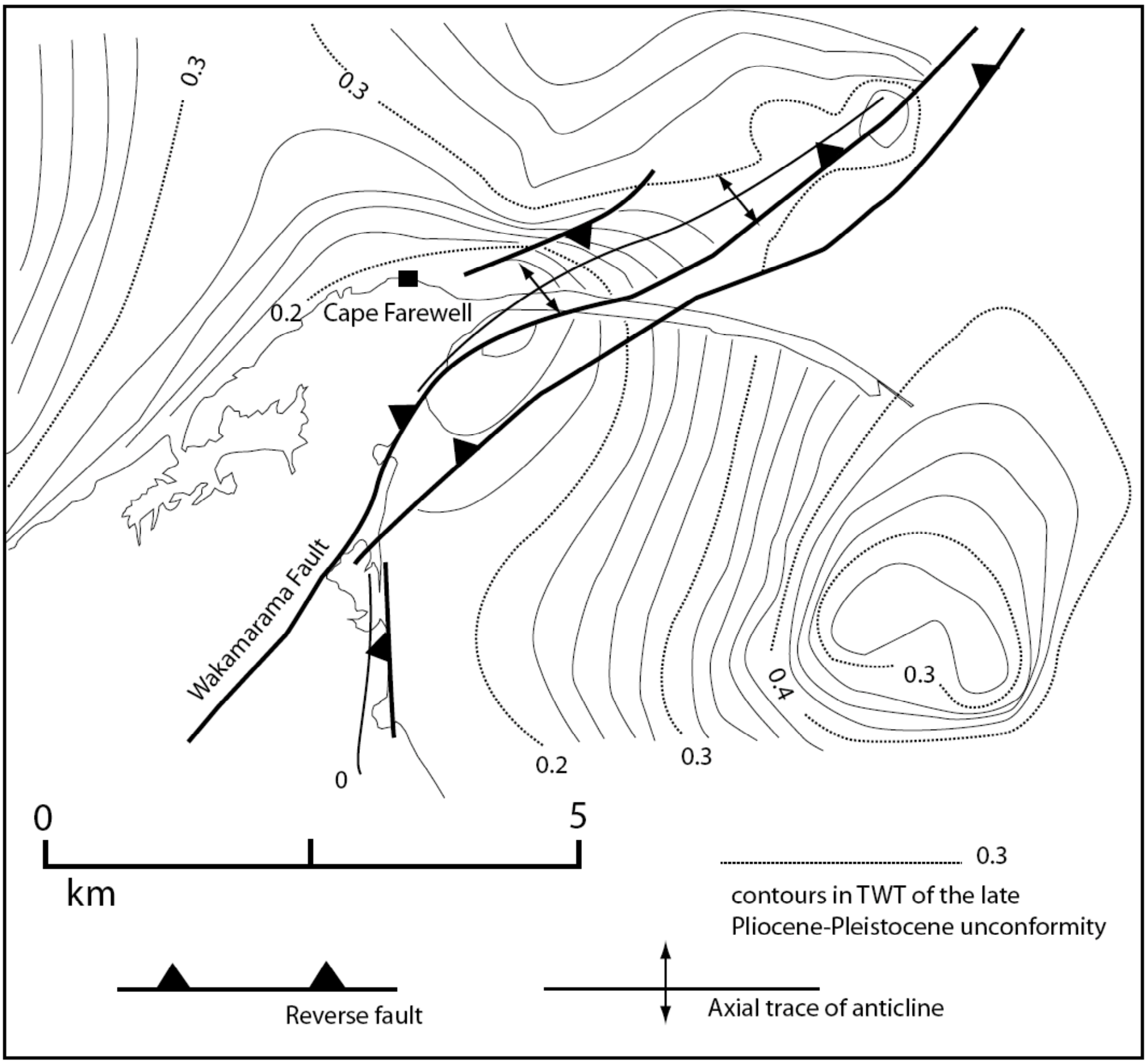

Fig. 9 – Structural contours in TWT of the Late Pliocene – Pleistocene unconformity that truncates compressional inversion structures around Cape Farewell.

Wakamarama Fault System

The Wakamarama Fault is an inherited, W-dipping Late Cretaceous normal fault that controlled sedimentation of the Pakawau Group and has undergone compressional inversion since the mid-late Miocene (**Fig. 11**). Isoseismals centred just north of Farewell Spit and evidence of ground cracking around Puponga suggest that the 1868 Cape Farewell earthquake (**M** 7.0-7.5) may have occurred on the Wakamarama Fault (Downes, 1995).

Deformation imposed by the fault is imaged by contour maps of the top of the seismic basement (**Fig. 8**), that shows complete reversal of the original normal throw along the fault

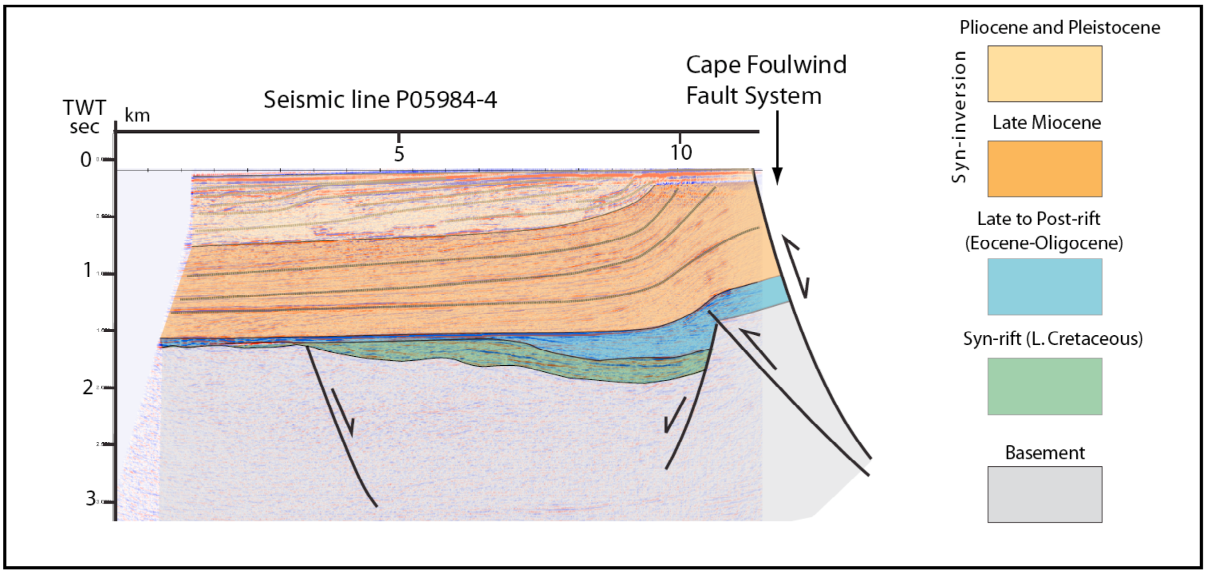

Fig. 10 – Interpretation of seismic line P05984-4 illustrating stratigraphy and structure in the footwall of the Cape Foulwind Fault system.

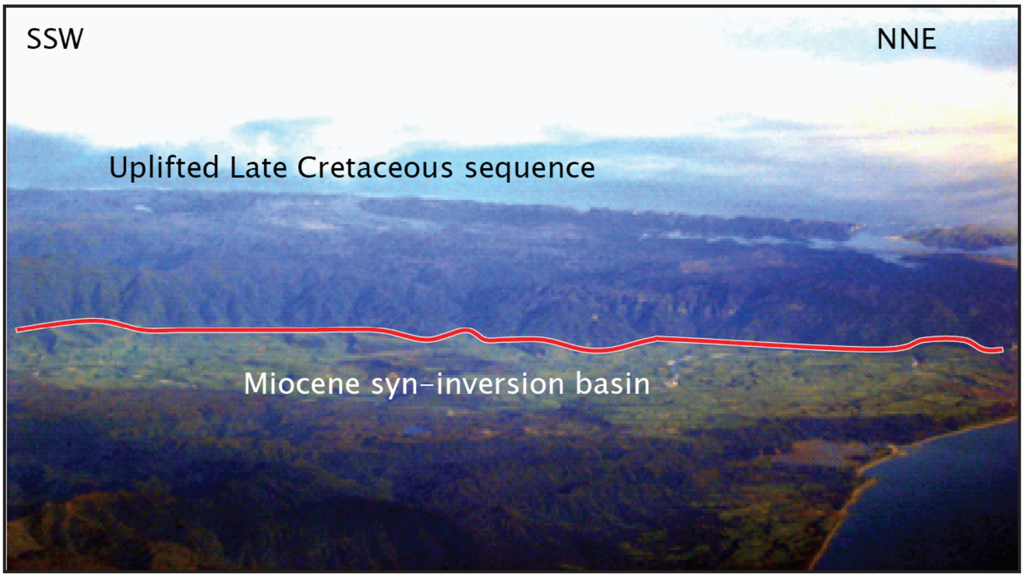

Fig. 11 – Aerial view to the west of the Wakamarama Fault escarpment.

segment that is emergent onshore, with a null point for top-basement displacement in the near offshore. This geometry is consistent with increased compressional inversion from north to south, as also occurs along the opposite-facing Kahurangi Fault. The contour map of the top of basement shows that the fault likely continues along the Slate Range-Heaphy River Fault rather than connecting through to the E-dipping segment that is mapped as part of the Wakamarama Fault in the Nelson Q-Map. Several offshore seismic lines show that large components of reverse-slip were accommodated along the Wakamarama Fault, which was clearly the master fault controlling the eastern margin of the Late Cretaceous graben, though other sub-parallel faults have been mildly reactivated in compression. One of these is an E-dipping fault located along the rectilinear coastline west of Cape Farewell.

Another important marker of recent deformation is the offshore erosional unconformity of probable late Pliocene-Pleistocene age (**Fig. 9**), that is at present located at around 200 m depth offshore. The smooth unconformity surface seems consistent with an origin by wave-cut erosion at sea-level. This unconformity truncates tilted and folded beds deformed by localised compressional inversion, and dies out laterally where the strata are undeformed. The unconformity thus marks a diachronous interval of erosion, whose duration and lateral extent were controlled by compressional fault reactivation that occurred after deposition of the Upper Blue Bottom Group (Pliocene). The amount of section removed from below the unconformity depends on the amount of uplift, emergence and erosion in the hangingwall of the compressional structures. Estimates are of ~3000 m (±860 m) at Fresne 1, and an average of 1350 m in the south Taranaki Basin based on porosity-depth curves in wells (Armstrong *et al*. 1998). According to the stratigraphic sections published by King *et al*. (1999) along a transect tied to the wells Surville 1, Tasman 1, North Tasman 1 and Maui 1,2,3 the sediments immediately above the unconformity become progressively younger southward, with ages of c. 6.5 Ma at Maui and <1.63 Ma at Surville 1. Onshore, an intra-Pliocene unconformity has been recognised in the Moutere depression, with discordant superposition of the Moutere gravels above the Glenhope beds. In the well Tapawera 1, the Moutere gravels are dated Late Pliocene-Early Pleistocene. In the Aorere Valley (footwall block of the Wakamarama Fault) the unconformity mapped by Bishop (1971) is overlain by a terrace sequence of Pleistocene to Holocene age.

Contours of the unconformity (mapped in TWT) reconstructed from the analysed seismic lines show that this surface is folded into a gentle anticline whose axial trace parallels the Wakamarama Fault (**Fig. 9**), the largest offshore uplift occurring at Cape Farewell and northeast of it. As the youngest available regional marker, this unconformity constrains the most recent episode of compressional inversion along the Wakamarama Fault.

Onshore, despite a prominent escapment, there is only minor evidence for episodes of Quaternary and/or Holocene reactivation along the Wakamarama Fault. Air photo reconnaissance mapping of major morphotectonic features (using satellite photos, LINZ orthophotos tied to Google Map, and air-photos stored at the GNS Library in Wellington) show the fault to be segmented. Fault segment boundaries control the position, linearity and westward retreat of the divide, with re-organisation and capture of the drainage in the uplifting hangingwall block. However, there is strong dissection and/or retreat and collapse of the fault scarp. Along steeper portions of the escarpment, any surface rupture traces would likely be obliterated by rock-falls and landsliding (cf. **Fig. 2f**). Another distinctive morphotectonic feature is the westward tilting of the *'Ototaran Peneplain*' (Wellman, 1940) that erodes the basement in the footwall of the fault (**Fig. 8a**). Westward components of tilt are also indicated by dissected terraces of the Aorere River alluvial plain.

At Pakawau Inlet (Davis Farm property) a prominent scarp that apparently causes offset of a river terrace by several metres (**Fig. 12**) provides possible evidence for surface rupture along a splay of the fault. Further studies (trenching?) are needed, however, to establish the nature of the scarp (erosional vs. tectonic), its connection with the main Wakamarama Fault, and its age. River sections at Walsh Creek and Eliot Creek cross the fault trace. Along the river banks a number of small-scale cataclastic fault zones are exposed in the hangingwall basement, as well as pervasive cleavage and kinking in the Tarakohe mudstones and siltstones (Blue Bottom Group), but the principal fault contact is not exposed. At Walsh Creek (E2463622/N6040568) a river terrace overlying Tarakohe mudstones is offset ~ 5 m by a 120/60 SE slip surface (**Fig. 13**) that has the appearance of a normal fault but could possibly be a slope instability associated with the morphological scarp.

Fig. 12 – NNE-SSW trending escarpment west of Pakawau Inlet on Davis farm property. Origin of the scarp and its relationship to the Wakamarama Fault remain uncertain (see text).

Fig. 13 – Apparent fault offset with normal separation of terrace gravels overlying Tarakohe mudstones at Walsh Creek (see text for details).

South of Walsh Creek the Wakamarama Fault joins the Slate Range-Heaphy River Faults. With this geometry the southern end of the Wakamarama Fault is truncated in the hangingwall of the offshore E-dipping Kahurangi Fault. The Wakamarama fault segment decapitated in the footwall is possibly recognisable in a number of offshore seismic lines, beneath the low-angle footwall shortcut thrusts of the Kahurangi Fault (**Fig. 7**).

Inangahua-Maimai-Kumara Fault System

The W-dipping Maimai-Kumara Fault is the southward extension of the Inangahua Fault, both associated with displacement of Pliocene and Quaternary markers, and – in the case of the Inangahua Fault – the **M**7.1 earthquake of 1968 for which a combination of focal mechanism and geodetic analyses suggests close to pure reverse-slip on a fault dipping c. 50°NW at the hypocentral depth of 15±5 km (Anderson *et al.*, 1994).

The Maimai Fault has a striking morphological signature, controlling the boundary between the strongly uplifted Paparoa Range in the hangingwall and the Grey River Valley Basin in the footwall (Suggate & Waight, 1999). The position of the Paparoa coal measure in the hangingwall of the fault, everted in a 'harpoon-head' anticline described by Wellman (1948) and the high rank of the exhumed coal measures (Suggate & Boudou, 1993) show the Maimai-Kumara structure to be a classic example of a compressionally reactivated inherited normal fault system. The fault system is mapped as discontinuous along the front of the Paparoa Range (**Fig. 1**), partly because of masking alluvial cover and partly because of the interpreted stratigraphic continuity along the flank connecting the Paparoa Anticline to the Grey Valley Syncline.

Evidence for intense footwall deformation with folding and overturning of gravels of the Old Man Group (2.5-1.6 Ma) near Blackball has been described by Nicol & Nathan (2001). 200-300 ky terraces old are also folded and faulted. The fault surface is exposed at E2406920/N5903392, where subvertical gravels of the Old Man Group are truncated by overlying cataclastic basement rocks along a 170°/50° SW plane.

Together, these structural characteristics define a strongly inverted fault system, with complete eversion of the syn-rift graben infill, finite reverse displacement of the basement-cover interface, and accommodation of cover sequence shortening by layer-parallel flexural-slip folding. The thick clastic sequence hosted in the hangingwall of the reverse fault, and deposited during the Late Miocene-Pliocene stages of compressional inversion masks the geometry of faulting in the basement, but vertical deflection of the bedding is a clear indication of buried basement reverse-slip faulting (**Fig. 2c, d**).

The Maimai-Kumara Fault thus provides a good example of the hidden seismic hazard posed by inverted normal faults that control folding of the cover sequence without the master fault breaking through to the surface (**Fig. 14**). In the case of an inverted normal fault, the tip of the original inherited fault cannot be at a stratigraphic horizon younger than the top of the syn-rift sequence. Thereafter, any further upward growth of the fault requires upward propagation of a new fault surface. Basement offset consequent on seismic rupture at seismogenic depths is transferred to the surface by bedding-parallel slip before eventual break-through of the upward-propagating reverse fault. The newly-propagating fault may not follow the steep trajectory of the inherited fault, and new footwall shortcut thrusts (**Fig. 2e**) may develop that are favourably oriented in the compressional stress field. This is particularly true in the case of the Maimai-Kumara fault system where the inverted normal fault is very close to the surface. New thrust faults are expected to propagate at low angles to bedding in the Grey

Valley Syncline. Further shortening may lead to decapitation of the inherited normal fault by thrust faults (**Fig. 14**).

In conclusion, the Inangahua-Maimai-Kumara and Wakamarama Fault systems are geometrically similar W-dipping faults with strong morphotectonic signatures and are likely to be strands of the same original normal fault system bounding Late Cretaceous terrestrial grabens. Evidence of Quaternary-Holocene reactivation is only clear, however, along the Inangahua-Maimai-Kumara Fault system.

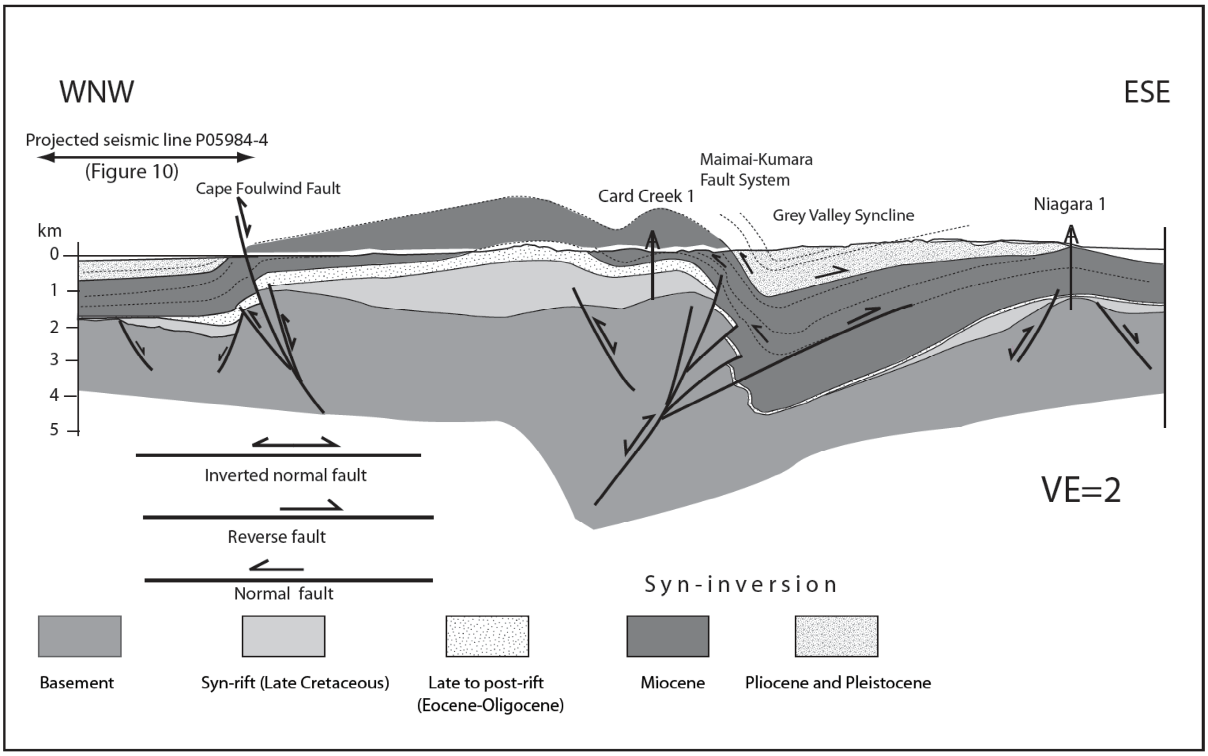

Fig. 14 – Regional Transect 3 across the Cape Foulwind and Maimai-Kumara Fault systems (see Fig. 5 for location of section).

3.3 Regional Cross-Sections (FCG)

Connections between offshore and onshore data and surface to subsurface deformation have been addressed by constructing regional transects that illustrate the geometry of the major structures, the relationships between basement and cover sequences, and the distribution of fault-controlled basins. Retrodeforming these transects allows us to understand the progressive evolution of the fault systems to the present seismotectonic regime where they may be capable of generating moderate to large earthquakes. Regional transects (**Figs. 14, 15, 16, 17**) have been constructed along directions near-orthogonal to the major N-S to NNE-SSW faults, across areas allowing integration between surface and sub-surface information (in terms of exploration wells and seismic lines), and across the major faults with the greatest potential for seismic activity (**Fig. 5**).

TRANSECT 1 (WNW-ESE - offshore west of Cape Farewell across the Kahurangi, Wakamarama and Surville Faults to the footwall of the Waimea Fault): This transect (**Fig. 15**) is entirely based on interpretation of seismic lines, tied to exploration wells. It allows the best interpretation of fault-controlled sedimentation and deformation arising from

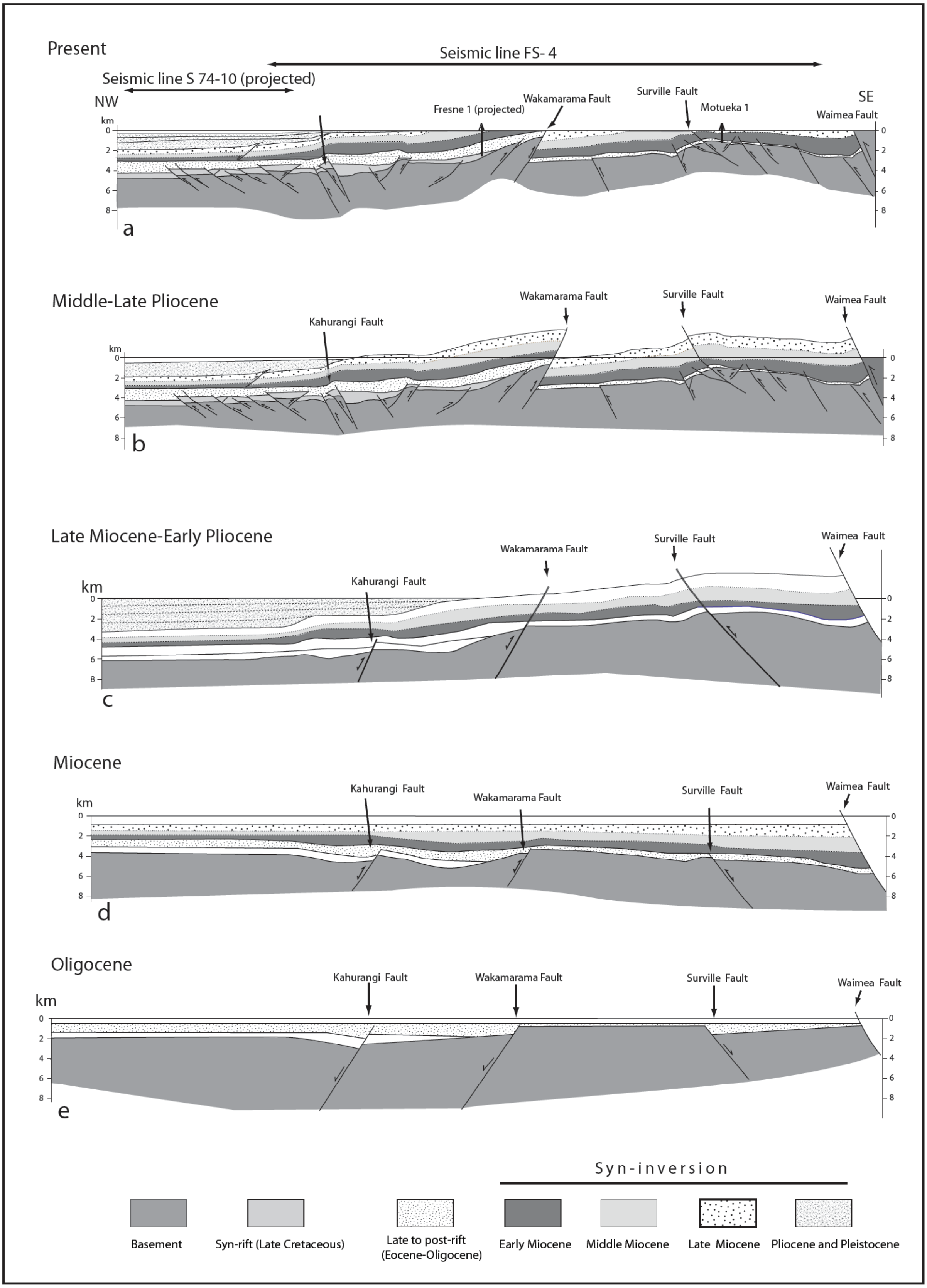

Fig. 15 – Regional Transect 1 with progressive restoration back to the Oligocene employing Lithotect software (Geo-Logic Systems) (see Fig. 5 for location of section and text for discussion).

compressional reactivation because of the well-preserved sedimentary sequence, and relatively minor erosion during a short period of emergence in the Late Pliocene. Restoration back to the Oligocene (i.e. during the post-rift stages and before the onset of compressional inversion), and in the subsequent Early and Middle Miocene stages illustrates progressive development of a continuous clastic wedge, moderately affected by incipient, localised compressional reactivation (**Fig. 15, a-e**). A large component of shortening and uplift in the Late Miocene-Early Pliocene led to fault-controlled shifting of depocentres, followed by localised compressional inversion of the Wakamarama and Kahurangi faults in the Middle-Late Pliocene (**Fig. 15c**). Reactivation of the Wakamarama Fault which accommodated most of the vertical displacement and shortening along the transect controlled the paleoposition of the Middle Pliocene coastline and adjacent emergent areas (i.e. the areas that were eroded beneath the Late Pliocene-Pleistocene unconformity – **Fig. 15b**), though Pleistocene activity was unable to keep pace with the rates of sea-level rise (eustatic?) and erosion that resulted in the drowning of previously uplifted anticlinal folds. A subparallel transect (**Fig. 16**) illustrates the geometry of the Wakamarama Fault across the emergent onshore area south of Cape Farewell, showing the folding and tilting of the Late Pliocene-Pleistocene unconformity (cf. **Fig. 9**) caused by the latest reactivation as demonstrated by available geological markers.

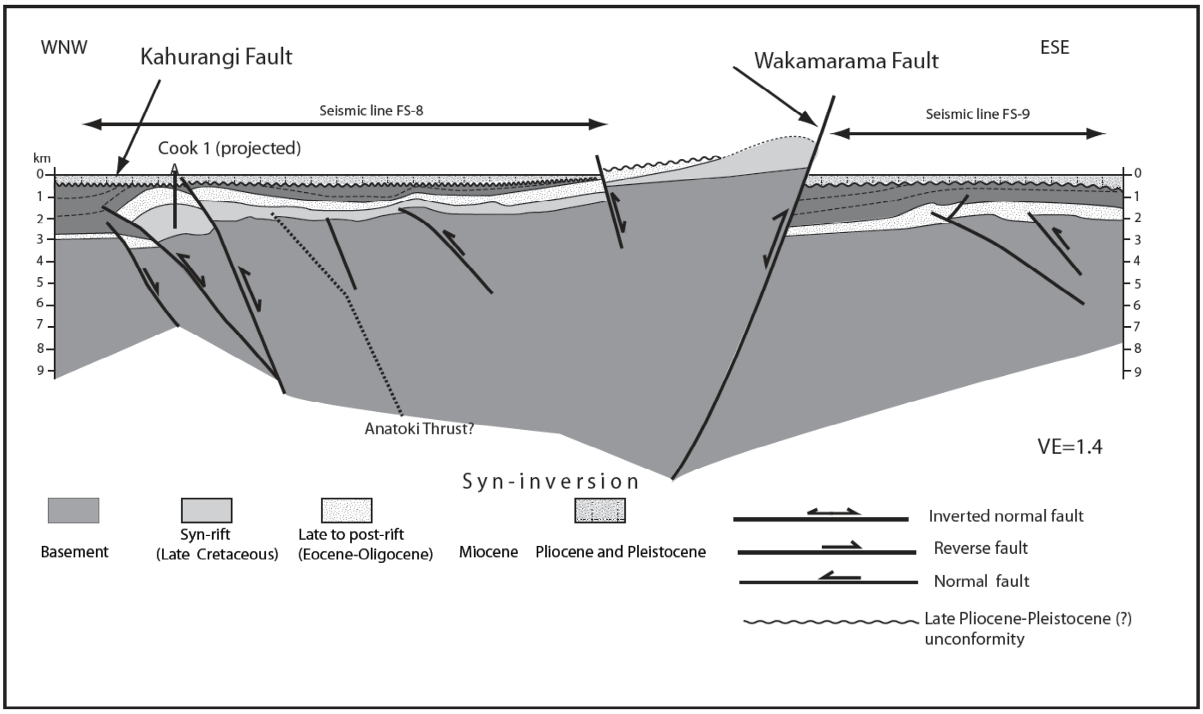

Fig. 16 – Regional Transect 1b (see Fig. 5 for location of section and text for discussion).

TRANSECT 2 (composite NW-SE and WNW-ESE section from offshore Cape Foulwind across the Inangahua and White Creek Faults and the Murchison Basin into the Alpine Fault footwall): This transect crosses the region of the *compressional inversion orogen* characterised by the largest shortening of the Oligocene marker unit (**Fig. 17**), and depicts the structural setting of the Inanagahua and White Creek Faults responsible for the largest earthquakes of the past century (Ghisetti & Sibson, 2006). It utilises offshore seismic lines (cf. Bishop & Buchanan, 1995) plus available seismics and exploration wells in the Murchison area. However, the combination of low resolution seismics across a region characterised by sub-vertical strata and poor stratigraphic penetration by wells places only limited constraints on the sub-surface geology. The eastern part of the transect also coincides with the MT transect of Wannamaker *et al*. (2009) that is consistent with upwelling hydrothermal fluids from the underlying subduction interface through a fault network below the Murchison Basin west of the Alpine Fault.

Large components of basement uplift are evident in the vicinity of the White Creek, Lyell and Inangahua Faults, where systems of steep E- and W-dipping faults separate remnants of the Miocene-Pliocene foredeep preserved in the Murchison Basin, from the Pliocene-Pleistocene to Present foredeep offshore to the west where it is deformed by compressional reactivation of the Cape Foulwind Fault.

Structural interpretation of this transect (**Fig. 17**) suggests that new low-angle thrust faults (favourably oriented in the present tectonic regime) are propagating to truncate and decapitate steep inherited faults which by themselves are not capable of accommodating the large amount of shortening accumulated since the Late Miocene (Ghisetti & Sibson, 2006). This is characteristic of the uplifted, emergent region of the *Compressional Inversion Orogen* where the Oligocene marker is shortened by nearly 40%. In contrast, deformation along the offshore Cape Foulwind Fault represents only mild compressional inversion with 'harpoon-head' folding of the everted syntectonic wedge. However, a large reverse throw and substantial footwall deformation are associated with the Cape Foulwind Fault defining the Westland coastline for nearly 100 km south of Cape Foulwind (**Figs. 10, 14 & 17**). Together with evidence for substantial coastal deformation and Holocene uplift at <0.5 mm/yr (Suggate, 1992) it is apparent that this inversion structure directly flanking the coast represents a significant source of seismic hazard to the towns of Westport, Greymouth, and Hokitika.

TRANSECT 3 (composite WNW-ESE transect from offshore west of Punakaiki across the Cape Foulwind and Maimai-Kumara Faults and Grey Valley Syncline into the footwall of the Alpine Fault): This transect (**Fig. 14**) illustrates a stage of compressional inversion intermediate between those shown by Transects 1 and 2. The syntectonic clastic wedge is deformed, uplifted and eroded in the everted region of the Paparoa Range with deformation strongly localised along reverse-reactivated faults of the original syn-rift sequence. The Maimai-Kumara Fault is the most important active structure crossed by this transect with deformation partly accommodated by propagation within the folded cover sequence of layer-parallel faults perhaps seismically capable in themselves. The coast-parallel southern segment of the Cape Foulwind Fault is another significant structure probably associated with splaying of new footwall shortcuts abutting a transverse graben mapped offshore.

3.4 Recent Compressional Inversion Earthquakes in NE Honshu (RHS)

During his 5-week visit to Japan RHS was able to visit the epicentral areas of the 2003 **M**6.4 Northern Miyagi earthquake, the 2004 **M**6.6 Mid-Niigata Prefecture earthquake, the 2007 **M**6.6 Niigataken Chuetsu-Oki earthquake, and the 2008 **M**6.9 Iwate-Miyag-Nairiku earthquake. During the visit RHS also presented talks at Hiroshima University (3); Kyoto University and also DPRI (Disaster Prevention Research Institute), Kyoto; Niigata University; Kochi Institute for Core Sample Research; the Earthquake Research Institute of Tokyo University; and Tohoku University, Sendai (2), and also contributed to graduate workshops.

The visit allowed RHS to complete documentation of nine rupture sequences on reverse faults in NE Honshu (**Table 1**). Structural analysis from high-resolution aftershock studies revealed

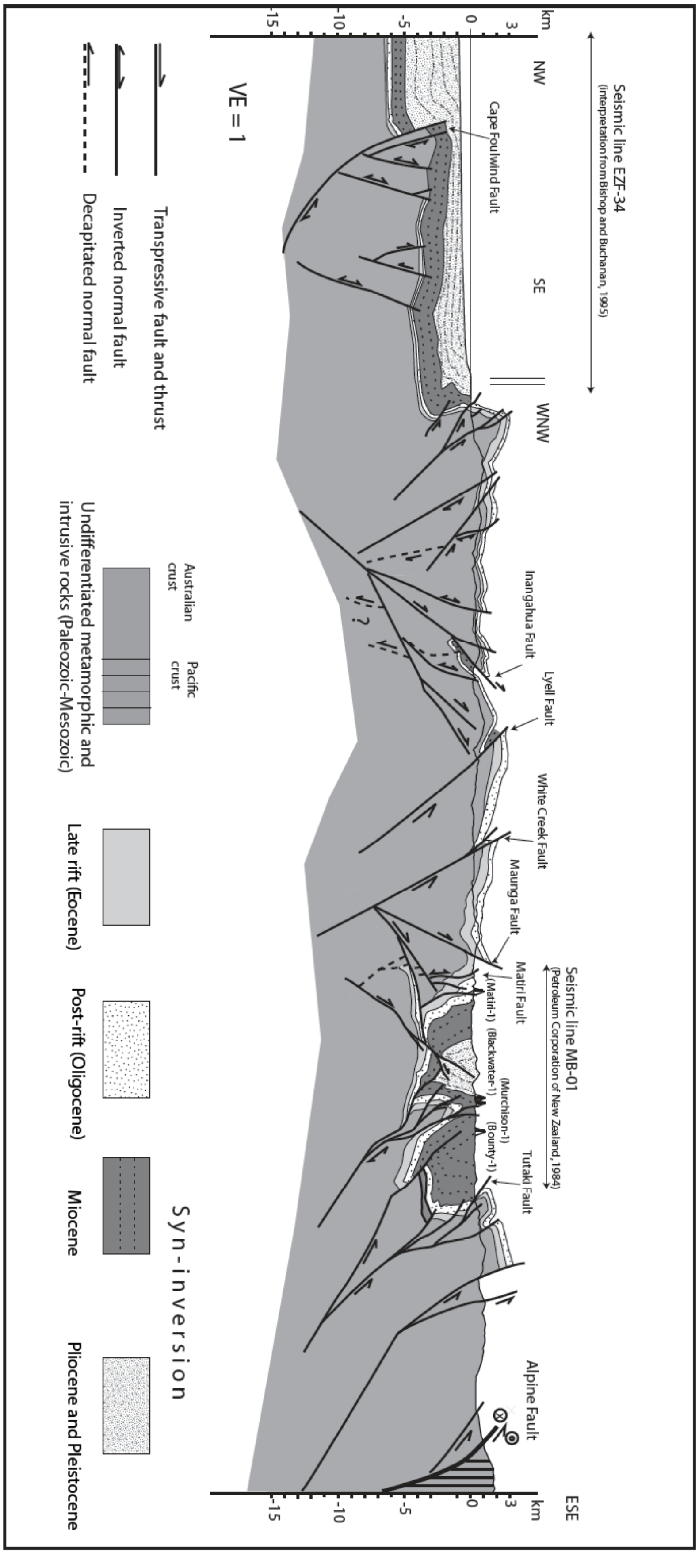

Fig. 17 – Regional Transect 2 (see Fig. 5 for location of section and text for discussion).

Date	M_w	Earthquake	Focal Depth	Mainshock Strike / Dip	Rake (dev.)	Fault Structure	Hangingwall / Footwall	References
06/13/2008	6.9	Iwate-Miyagi Nairiku	5 km?	205°/ 40° NW?	98° (+8°)			Okada et al. 2008; Harvard Global CMT
07/16/2007	6.6	Niigataken Chuetsu-oki	14 km	049°/42°SE or 219°/ 49°NW **45±5° assigned** (+ ~25°SE)	101° (+11°) 80° (-10°)	Conjugate ruptures?	Neogene fold-thrust belt	Mori 2008; NIED; Kato et al. 2008b
03/25/2007	6.7	Noto-Hanto	9 km	055°/ 60 SE	117° (+27°)	F14, 15, 16	Neogene / basement	Kato et al., 2008a; Sakai et al., 2008
10/23/2004 + 7 mins. +38 mins. 10/27/2004	6.6 (5.9) (6.3) (5.9)	Mid-Niigata Prefecture Sequence	12 km (6.5 km) (13.5 km) (12.5 km)	216°/ 53°NW (020°/ 34° SE) (216°/ 55°NW) (039°/29° SE)	93° (+3°) 73° (-17°) 94° (+4°) 73° (-17°)	Muikamachi Fault	>5 km Neogene basin / basement	Hikema & Koketsu 2005; Kato et al. 2006; Okada et al. 2006
07/26/2003	6.4	Northern Miyagi	7 km	230°/ 50° NW	?	Sue Fault	>2 km Neogene basin / basement	Kato et al., 2004; 2006 Umino et al., 2003; Okada et al. 2003; 2007
02/07/1993	6.4	Off Noto Peninsula	14 km	215°/ 48° SE (or 004°/46°NW)	68° (-22°)	?	?	Ito et al., 1994
06/16/1964	7.5	Niigata	<25 km	189°/ 56° W (009°/ 34°E?)	0° ?	?	Offshore fold-thrust belt	Abe, 1975 Satake & Abe, 1983 Morita & Mori, 2005
04/30/1962	6.5	Northern Miyagi	4-12 km	~170°/ 45-50° W	?	Sue Fault	>2 km Neogene basin / basement	Kato et al., 2006
01/17/1896	7.2	Riku-u	?	~005°/~30°E	?	Senya Fault	Mioc. marine sed. & volc. / U. Pleistocene	Sato et al., 2002

Table 1 – Structural characteristics of compressional inversion earthquake ruptures in NE Honshu (for data sources - see Sibson, 2009).

Earthquake	Low P-wave velocity	Low S-wave velocity	Vp/Vs Poisson's Ratio Anomaly	Bright-Spot Reflectors	High Electrical Conductivity	References
06/13/2008 M_w6.9 Iwate-Miyagi Nairiku	√ (lsz, mc)	√ (lsz, mc)	√ (mc)	√ (lsz, mc)	√ (lsz, mc)	Ichiki et al. 1999 Nakajima et al. 2001 Mitsuhata et al. 2002
07/16/2007 M_w6.6 Niigataken Chuetsu-oki	√ (lsz, lc)	√ (lsz, lc)	√ (lsz, lc)	-	-	Xia et al. 2008
03/25/2007 M_w6.7 Noto-Hanto	√ (fz, lsz)	√ (fz, lsz)	√ (fz, lsz)	-	√ (fz, lsz.mc)	Kato et al. 2008 Yoshimura et al. 2008
10/23/2004 M_w6.6 Mid-Niigata Prefecture	√ (lsz, mc, lc)	√ (lsz, mc,lc)	√ (lsz, mc, lc)	√ (lsz, mc, lc)	√ (lc)	Matsumoto et al. 2005 Okada et al. 2006 Uyeshima et al. 2005 Xia et al. 2008
07/26/2003 M_w6.4 Northern Miyagi	√ (lsz, mc)	√ (lsz, mc)	√ (lfz, sz, mc)	-	√ (lsz, mc)	Okada et al. 2007 Satoh et al. 2005
02/07/1993 M_w6.4 Off Noto Pen.	-	-	-	-	-	
06/16/1964 M_w7.5 Niigata	-	-	-	-	-	
04/30/1962 M_w6.5 Northern Miyagi	√ (lsz)	√ (lsz, mc)	√ (mc)	√ (lsz, mc)	√ (lsz, mc)	Asano et al. 2004 Mitsuhata et al. 2001 Nakajima et al. 2001
01/17/1896 Mw7.2 Riku-u	√ (fz,lsz, mc)	√ (fz,lsz, mc)	√ (fz, mc)	√ (lsz, mc)	√ (lsz, mc)	Asano et al. 1999 Matsubara et al. 2004 Ogawa et al. 2001 Sato et al. 2002

Table 2 – Geophysical anomalies associated with compressional inversion earthquakes in NE Honshu (for data sources - see Sibson, 2009).

competition between reverse-slip reshear on the steep inherited faults (generally, 45° < δ < 60°) and thrusting on comparatively low-angle faults (δ ~ 30±5°). A range of geophysical evidence (local bright-spot reflectors, low-velocity zones, anomalous *Vp/Vs* ratios, high electrical conductivities) also point to the involvement of overpressured pore-fluids in the lower seismogenic zone (**Table 2**) as a critical factor effecting reactivation of steep reverse faults in accordance with expectations from frictional fault mechanics. Results are summarised in Sibson (2009: *Tectonophysics* 473, 404-416).

Other impressions and observations from the visit include: (i) general similarities in structural and sedimentation style between the Murchison Basin in the Buller district, the Niigata Basin of NE Honshu, and also the Ventura Basin of California, all of which have comparable histories of compressional inversion; (ii) the poor topographic expression of some inversion faults still capable of generating substantial **M** > 6 earthquakes; (iii) the fact that the facing of reverse-slip on inversion faults may be contrary to that implied by regional topographic trends; (iv) the role of folding and bedding-plane slip distributing deformation in the cover sequence above buried steep reverse faults in the basement; (v) the evidence from preservation of Miocene sedimentary basins kilometres deep on the hangingwalls of the reverse faults that, despite the high level of seismic activity, compressional inversion in Honshu is generally less advanced than in the Buller-Nelson region; and (vi) evidence from contrasting mainshock rupture dips and from well-analysed aftershock sequences for continuing competition between the reverse reactivation of poorly oriented steep inherited faults and the formation of presumably younger, optimally oriented 'Andersonian' thrusts dipping at c. 30° (**Fig. 18**).

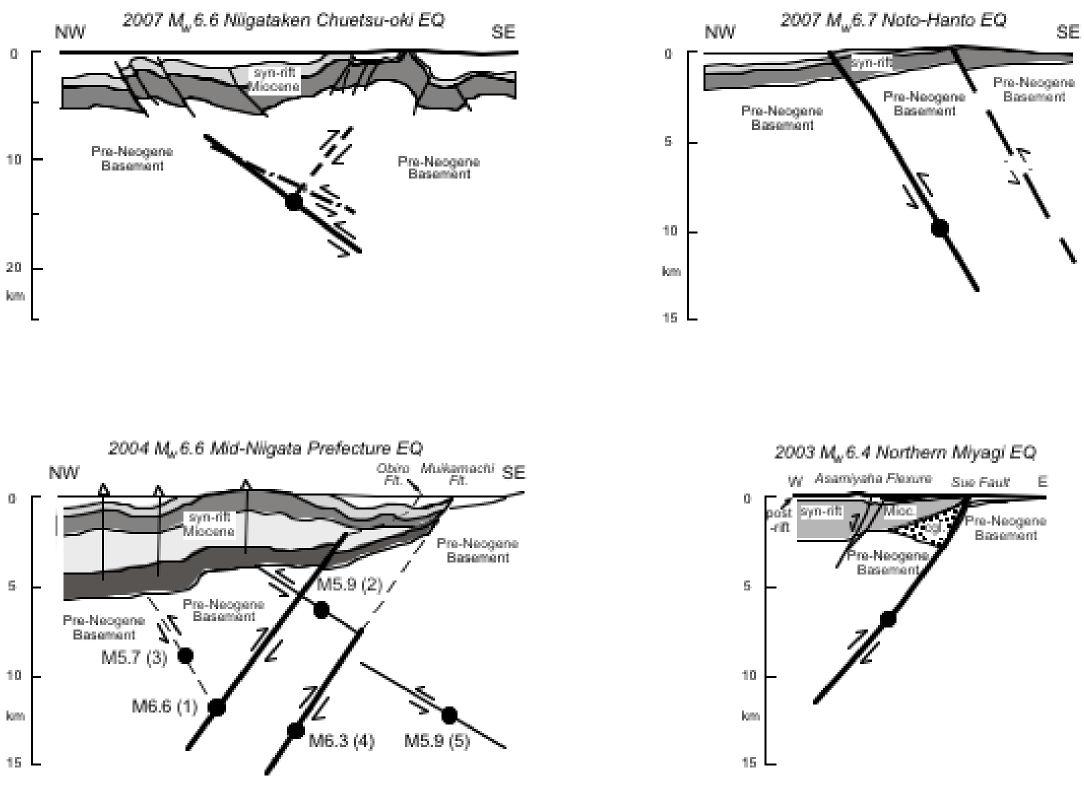

Fig. 18 – Rupture planes of recent compressional inversion earthquake sequences in NE Honshu determined from focal mechanisms and high resolution aftershock studies. Note the competition between steep and shallow-dipping reverse faults and the preservation of former extensional basins on the hangingwalls of the steep faults.

3.5 Mechanics of Reverse Faults (RHS)

The condition for frictional reactivation of an existing fault under shear stress, τ, and normal stress, σ_n, in crust with pore-fluid pressure, P_f, is approximated by *Amontons Law*:

$$\tau = c + \mu_s\sigma_n' = c + \mu_s(\sigma_n - P_f) \qquad (1)$$

where c is the cohesion on the fault and the coefficient of static friction generally lies in the range $0.6 < \mu_s < 0.85$ (Byerlee, 1978). This expression can be rewritten in terms of the principal compressive stresses ($\sigma_1 > \sigma_2 > \sigma_3$). For faults containing the σ_2 axis with poles lying in the σ_1/σ_3 plane, oriented at a reactivation angle θ_r to σ_1, equation 1 becomes:

$$(\sigma_1 - \sigma_3) = [(\tan\theta_r + \cot\theta_r)/(1 - \mu_s\tan\theta_r)]\,[c + \mu_s\sigma_v'] \qquad (2)$$

(Sibson, 2009). At a depth, z, in crust with average density, ρ, the effective vertical stress is:

$$\sigma_v' = (\sigma_v - P_f) = \rho g z(1 - \lambda_v) \qquad (3)$$

where g is gravitational acceleration and the pore-fluid factor, $\lambda_v = P_f/\sigma_v$. For reverse faulting in an *'Andersonian'* compressional regime the reactivation angle corresponds to the fault dip, δ. These relationships allow the differential stress needed for reverse-slip reactivation at a particular depth to be plotted as a function of fault dip for particular values of c and μ_s, and varying λ_v.

Figure 6b is a plot of the differential stress required for reshear of reverse faults with zero cohesion and $\mu_s = 0.6$ against fault dip at a typical seismogenic nucleation depth of 10 km, for various values of λ_v (Sibson, 2009). Optimal reactivation occurs at $\delta \sim 30°$ and frictional lock-up at $\delta \sim 60°$. The dash-dot lines represent estimates of the failure strength of intact rock with tensile strengths T = 10 and 20 MPa calculated from a composite Griffith-Coulomb failure envelope. It is apparent from the plot that reshear of the existing faults with $\delta > 45°$ in preference to shear failure of intact rock requires fluid overpressuring with $\lambda_v >> 0.4$.

Brittle failure mode plots of differential stress ($\sigma_1 - \sigma_3$) versus effective vertical stress, $\sigma_v' = (\sigma_v - P_f)$ for pure dip-slip settings may also be employed to illustrate the competition between frictional reactivation of existing faults at different orientations and brittle shear failure of intact rock (Sibson, 2000). To illustrate this, consider the 'generic' case illustrated in **Figure 19** where a cover sequence of cohesionless sediments overlies basement rock containing an inherited steeply-dipping fault, the whole being subjected to horizontal compressive stress. The basement assemblage is assumed to be made up of uniform rock of moderate competence (tensile strength, T = 10 MPa; coefficient of internal friction, $\mu_i = 0.75$) and the fault to have zero cohesion and a 'Byerlee' friction coefficient, $\mu_s = 0.6$. Pore-fluid pressure is assumed to be hydrostatic ($\lambda_v = P_f/\sigma_v \sim 0.4$).

First, within previously undeformed cover sediments, a new thrust fault is likely to develop as an up-dip continuation of the buried basement fault but at a characteristic 'Andersonian' dip of c. 30° (**Fig. 2g, h**) Such a situation is often replicated in analogue modelling experiments of compressional inversion (McClay & Buchanan, 1992). Within the basement, the existing fault continues to reactivate at lower stress levels than those required for shear failure of the intact basement rock until its dip exceeds about 45°. However, for a 50° dipping fault (corresponding to the dip estimated seismologically for the 1968 Inangahua earthquake (Anderson *et al.*, 1994)), there is a critical transition depth above which it requires less differential stress to reactivate the steeply dipping fault, but below which shear failure of intact rock occurs at lower levels of differential stress.

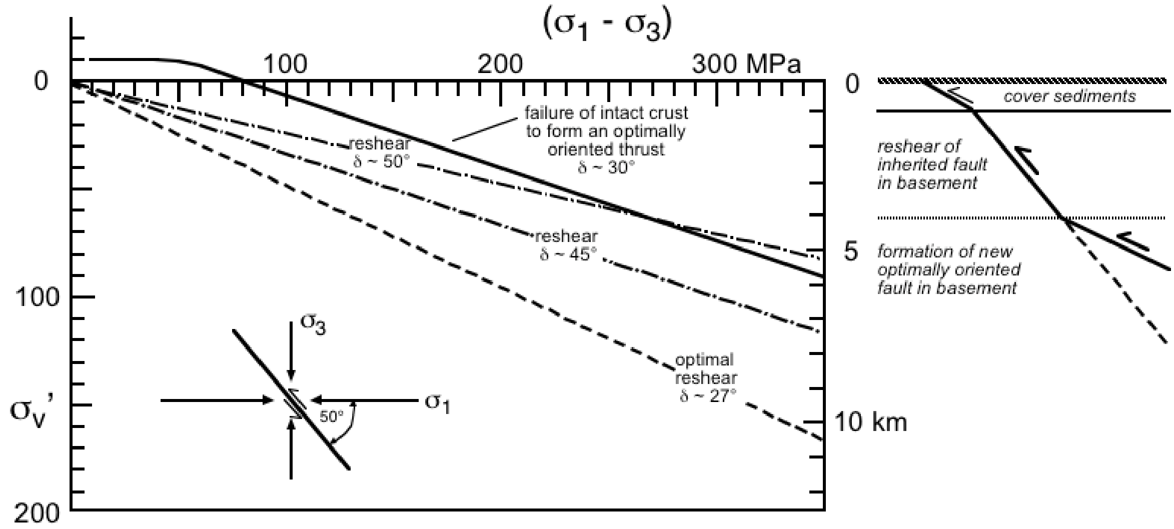

Fig. 19 – Failure mode plot illustrating the stress requirements for failure of intact crust of moderate competence (T = 10 MPa; $\mu_i = 0.75$) versus those required for the reshear of cohesionless reverse faults with $\mu_s = 0.6$ dipping at various angles under hydrostatic fluid-pressure conditions ($\lambda_v = 0.4$). Inset on the right show how reshear of the basement fault at high levels is supplanted by the formation of a new low-angle thrust fault at depth.

Elevated pore-fluid pressure ($\lambda_v = P_f/\sigma_v > 0.4$) will deepen the transition from reactivation of the 50° dipping plane to shear failure of intact rock. Adding cohesive strength to the fault makes the transition to shear failure of intact rock occur at shallower depth. Nonetheless, there is a general expectation that steeply-dipping reverse faults may be supplanted by shallow-dipping thrust faults over a range of depths depending on varying material properties of the crust and physical conditions. The upshot of all this is the likelihood, in areas of compressional inversion such as the NW South Island where reverse-dip-slip faulting is predominant, that reverse-slip faults may be complexly segmented at depth, and that the near-surface dip of a reverse fault in basement may not reflect the orientation of the active structure at depth.

3.6 Murchison Basin Seismic Network (RHS)

A initial trial deployment of microearthquake recording systems in the Murchison Basin area took place from Nov. 3-10, 2009, following an initial visit to GNS coincident with the southern North Island subduction workshop organised by Dr Stuart Henrys. Personnel included Professor Yoshihisa Iio and Drs Yukitoshi Fukahata and Shiro Ohmi (DPSRI, Kyoto University) plus Professor Tomomi Okada (Tohoku University, Sendai), together with Dr John Townend (VUW) and RHS. Two instruments were installed; one on Mt Ella Station (Mr Rick Monk) at the south end of the Tutaki Valley in a disused quarry of Permian Wooded Peak limestone/marble (S 41° 59.487'; E 172° 30.813'; 416 m a.s.l.); the other on Matiri Heights farm (Mr Darcy Grooby) on a 4 m thick steeply inclined sandstone unit of the Mangles formation (S 41° 43.838'; E 172° 20.419'; 227 m a.s.l.).

Current plans are for the instruments to be serviced and data downloaded in late March, 2010. A research proposal to establish a full network will be submitted to funding agencies in Japan in late 2010.

4. FINDINGS

Original objectives of this research programme included:

(1) Developing empirical geomorphologic, stratigraphic, and structural criteria for assessing seismic hazard from compressional inversion structures in the NW South Island.

(2) Comparing NZ compressional inversion structural assemblages with those responsible for recent strong (6 < **M** < 7) reverse fault ruptures attributable to ongoing compressional inversion in Japan.

(3) Developing frictional reactivation criteria assessing relative reactivation potential of differently oriented fault structures in a specified tectonic stress field.

(4) Identifying the most earthquake capable inversion structures in the region for hazard assessment.

(5) Integration of the empirical and mechanical-analytical approaches.

We believe that significant progress has been made in all these areas. First, we have demonstrated that the sedimentary record within fault-bounded basins provide a long-term record of fault activity throughout the inversion province and may be used to study the evolution and migration of faulting activity over time. Whilst not having the specific time-focus needed for quantitative seismic hazard this technique does illuminate the structures maintaining longer-term activity. Much has also been learnt by merging offshore marine seismic profiles with onshore geological mapping. The offshore profiles record subtle features (low-amplitude folds and unconformities) reflecting episodes of fault activity that in many cases would be difficult or impossible to recognize by onshore mapping alone. Using these techniques we have been able to categorise four progressive stages of compressional inversion in the Nelson – Buller – Grey Valley region (**Fig. 20**).

(a) Incipient Compressional Inversion is characterised by a fault that maintains the original normal separation in the top-of-basement and a flexural monocline in the cover sequence, with dip opposite to that of the buried fault (**Fig. 20a**).

(b) Moderate Compressional Inversion is still characterised by normal separation in the top-of-basement, but the hanging wall fold is well developed in a 'harpoon-head' anticline of short wavelength with an axial surface dipping sub-parallel to the dip of the fault. The anticline is not associated with well-developed adjoining synclines (**Fig. 20b**).

(c) ***Strong Compressional Inversion*** is characterised by the attainment of null or reverse displacement in the top-of-basement. However, the inherited normal fault generally does not propagate across the overlying syn-inversion sequence that accommodates shortening by folding (i.e. the fault is suitable for reactivation, but it is not suitably oriented for growth by upsection propagation). The hangingwall anticline and frontal footwall syncline are well developed. Inversion is recorded by differential thickening of the syn-inversion sequence, with depocentre in the footwall syncline and reduced sequence in the hangingwall anticline. Growth folding is recorded by progradation of clinoforms in the syn-inversion sequence (**Fig. 20c**). The whole set of sub-parallel, inherited normal faults is suitable for reactivation, but the strongest components of inversion appear to characterise the master faults that initially possessed the largest normal throw. These faults have the most continuous and well-developed surfaces that can successfully accommodate the reversal of displacement.

(d) Advanced Compressional Inversion is characterised by the development of low-angle footwall thrust faults that produce the largest shortening in the basement and in the cover

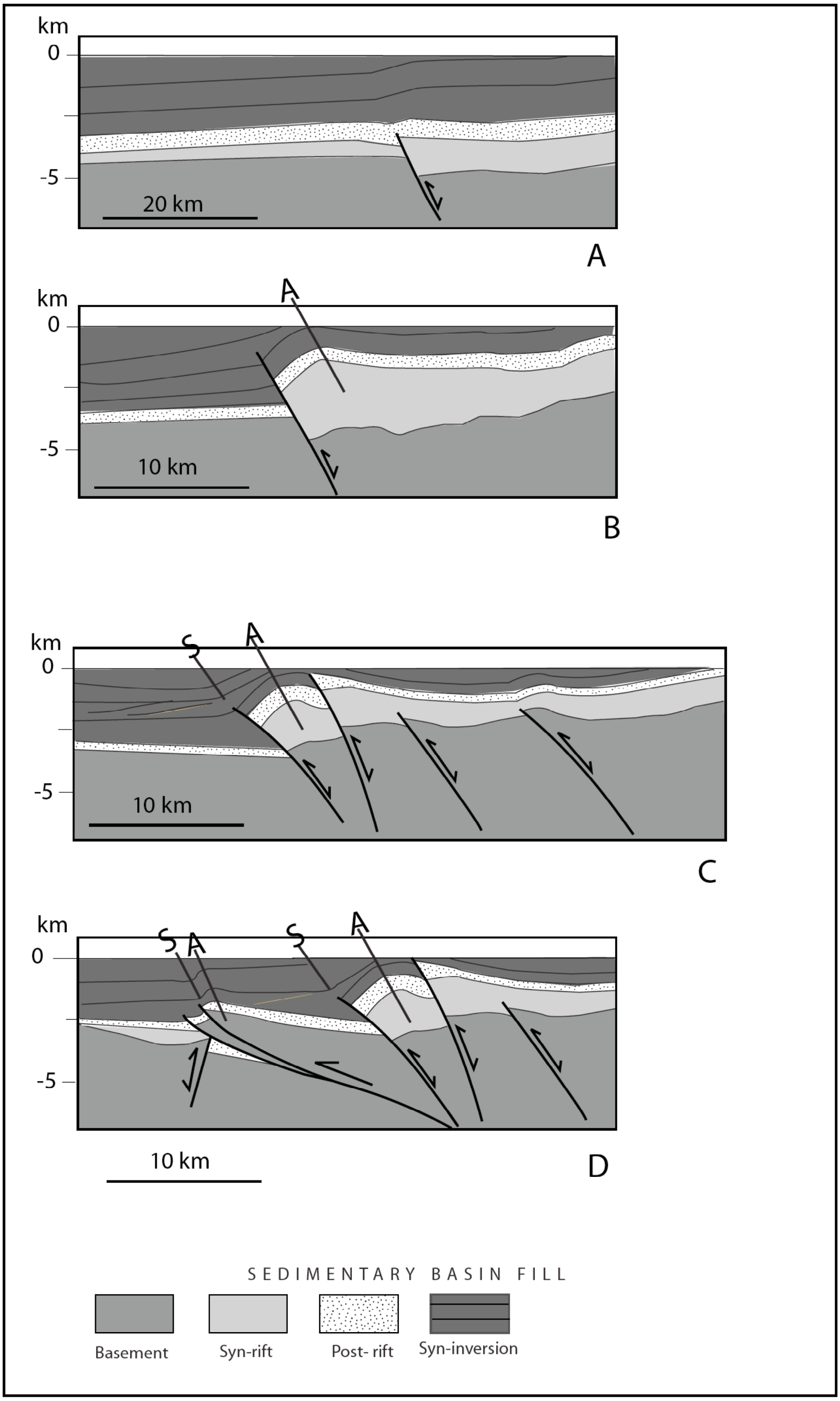

Fig. 20 – Four recognisable stages of compressional inversion in the Nelson – Buller – Grey Valley region (A = anticline; S = syncline).

sequence (**Fig. 20d**). Growth folding with short wavelength anticlines is recorded by syn-sedimentary instabilities in the syn-inversion sequence. These footwall shortcut thrusts are generally blind, but propagate as well-oriented faults in the compressional stress field.

Time spent in Japan by RHS was extremely rewarding. Many similarities in structural and sedimentological style were noted between NE Honshu inversion structures and those in the NW South Island. Not least was the evidence (within aftershock patterns of recent strong inversion earthquakes) for active competition between reverse-slip reshear of the inherited steep faults and development of new 'Andersonian' thrusts. However, despite the high present level of earthquake activity, the degree of inversion is in many cases not so advanced as in the NW South Island, with reverse-fault structures often having only subdued expression along the margins of former extensional basins (< 6 km deep) preserved on their hangingwalls. Cataloguing the wide variety of electrical and seismological anomalies employed to infer the presence of overpressured fluids in the mid-crust also proved invaluable as a guide to future geophysical investigations that may eventually be carried out in the NW South Island. Additionally, contacts established during this visit have led to the proposal (and initial deployment) of a collaborative microearthquake investigation of the Murchison Basin area.

With respect to inferences from our field structural studies that steep reverse faulting at the surface gives way with depth to thrusting on low-dipping planes (Ghisetti & Sibson, 1986), the application of brittle failure mode plots has allowed new insights into factors governing the competition between reactivation of steep inherited faults and the formation of new 'well-oriented' thrusts in areas of compressional inversion. This competition may initially lead to composite reverse faults made up of variably dipping segments, perhaps less likely to generate large ruptures. However, it is clear that unless near-lithostatic fluid overpressures can be maintained in advanced stages of compressional inversion, low-dipping thrusting at depth is likely to supplant activity on steeply dipping reverse faults. In this regard, it may be significant that the active inversion structures in many cases lie close to major terrane boundaries in the basement (Mortimer, 2004) which potentially provide access pathways for deep-sourced fluids. The possibility must also be considered that low-angle thrust structures in the region (e.g. Tutaki Thrust) are also capable of generating large earthquakes. Note, however, that recent activity on such structures is less easy to recognise because of their sinuous outcrop trace and the tendency for scarp collapse.

While Neogene fault activity is distributed over a large domain, there appears to be a concentration of activity around the reverse-fault systems that bound the Wakamarama-Paparoa structural high. In particular, evidence for intense Pliocene-Holocene? deformation localised along the coast-bounding Cape Foulwind Fault has important implications for seismic hazard in the coastal towns of Westport, Greymouth, and Hokitika.

5. RECOMMENDATIONS

In the broad tectonic context, the emergent landmass of the South Island represents an active *compressional inversion orogen* flanking the Pacific-Australia plate boundary defined by the Alpine fault system (Norris *et al.*, 1976). Much of the distributed seismicity away from the main plate boundary fault system is thus likely related to ongoing compressional inversion. For example, Holocene reverse-slip on the Ostler Fault in the McKenzie Basin also appears to result from compressional inversion (Ghisetti *et al.*, 2007). It is also clear that combining structural-stratigraphic data from marine seismic reflection profiling with onshore geology has special application to hazard appraisal along other compressional inversion coastlines such as the East Otago coastline defined by the trend of the Akatore - Titri fault system from Nugget Point south of Dunedin northeastward to Oamaru (site of the 1974 **M**~5 Dunedin earthquake and the two **M**~6 Oamaru earthquakes of 1876).

Our research has defined the regional framework of active compressional inversion in the NW South Island and recognised a concentration of inversion fault activity along the flanks of the Wakamarama–Paparoa structural high, but has not reached the stage of being able to provide quantitative hazard estimates for individual fault structures. To advance this work further we make the following specific recommendations.

- Research should be focused on the prominent Wakamarama and Cape Foulwind Faults as representative inversion structures, with the goal of defining their Quaternary (and in particular their Holocene) activity more fully.
- Historic marine seismic lines (generally not of high resolution by today's standards) could be reprocessed with information from new lines incorporated into the data-set as and when they become available.
- A programme of near-shore marine seismic reflection lines across the Cape Foulwind Fault should be targeted to examine young deformation along the fault that potentially could be correlated to the Quaternary record of coastal uplift and deformation (Suggate, 1992).
- Detailed remapping of the Wakamarama Fault onshore coupled with trench exploration of the putative scarp in Pakawau Inlet (Davis Farm property) should be combined with morphotectonic analyses aimed at defining along-strike segmentation.
- Targeted geophysical investigation (seismological, electrical) investigating physical conditions in the lower seismogenic zone (10-20 km depth) of the Buller-NW Nelson region, aimed especially at defining the presence or absence of overpressured pore-fluids. This will, in fact, be a major focus of the proposed Japan – New Zealand seismological network centred around the Murchison Basin.

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Sibson, R.H. 2008a (abstract): Rupturing in fluid-overpressured crust – recent compressional inversion earthquakes in Japan and their lessons for New Zealand. Geosciences '08, Wellington, Nov. 24-26, 2008.

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