Geosciences 2014

Annual Conference of the Geoscience Society of New Zealand

Field Trip 6

28th November 2014

LATE NEOGENE NORMAL FAULT ARCHITECTURE AND TECTONIC HISTORY ALONG THE NORTH TARANAKI COAST.

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Cover photo: Faulted 'Elephant' stack in the Tongaporutu River coastal section.
Photograph from GNS Science.

Bibliographic reference:

Nicol, A. (2014). Late Neogene normal fault architecture and tectonic history along the north Taranaki coast. In: Holt, K.A. (compiler). Field Trip Guide Volume, GeoSciences 2014 Conference, 24th – 27th November 2014, Pukekura Raceway and Function Centre, New Plymouth, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 139B. pp 19 – 38.

Health, safety and weather

The coastal cliffs, Tongaporutu River and the encroaching sea present a number of hazards that you should be aware of during this trip. The cliffs can be unstable and portions may collapse or shed debris without warning. Caution should be exercised when examining rocks at the base of the cliffs. Hard hats will be provided. In addition, wave, river, and tidal conditions can be dangerous. **Participants must heed and observe the warnings and time limitations imposed at certain stops by the trip leader.**

The fieldtrip leader will conduct a brief safety briefing before we visit our first outcrop.

The weather in November should be stable and warm (18-24^{o} C), although participants should be prepared for cold, warm, wet, and/or dry conditions. A sunhat, suncream, sunglasses, and insect repellent are essential. A waterproof raincoat, warm hat and warm clothing (layers) are advised. **Please don't under-estimate the climatic variations that are possible.**

A good level of fitness and mobility is required; there may be some hill walking, clambering over rocks and moderate beach walks (< 1 km). Running shoes or lightweight boots are adequate footwear; some participants may wish to use sturdy walking sandals for the beach.

There may be some wading in the sea (if conditions are suitable). It is recommended that a change of pants and socks (and perhaps shoes) be carried.

Participants should carry any personal medications, including those for allergic reactions (e.g. insect stings, pollen), with them at all times.

Introduction

We will visit coastal exposures of normal faults within the Late Miocene Mount Messenger Formation near Tongaporutu River, north Taranaki (e.g., Fig. 1). The coastal cliffs are spectacular examples of faulted deepwater turbidites. The coastal exposures visited during this fieldtrip offer many geological insights including;

- architecture and depositional processes of deepwater basin floor to slope depositional facies of the Mount Messenger Formation turbidite sequence,
- outcrop-scale geometries and deformation processes of normal faults and fault zones,
- outcrop analogues of producing oil and gas reservoir units in the nearby fields of the Taranaki Peninsula (e.g., Kaimiro, Ngatoro and Cheal fields).
- the stratotype for the New Zealand Late Miocene Tongaporutuan Stage (7.2-11 Ma, New Zealand Geological Timescale v. 2012/1).

We will focus on the faulting with some attention also given to gravitational slump folding within the Mount Messenger Formation. The coastal outcrops offer near-complete exposure of small (displacements < 35 m) faults from which it is possible to examine fault geometries and fault-zone architecture. Today we will discuss the development of the faults and fault zones, their regional tectonic setting (including the set of circumstances that lead to them being at sea level) and the potential impact of faults on fluid flow.

We will visit up to three coastal sections in the Tongaporutu River area (referred to here as, Tongaporutu River, Rapanui Stream and Jamroll Bay, Fig. 2). The key objectives of the field trip are to:

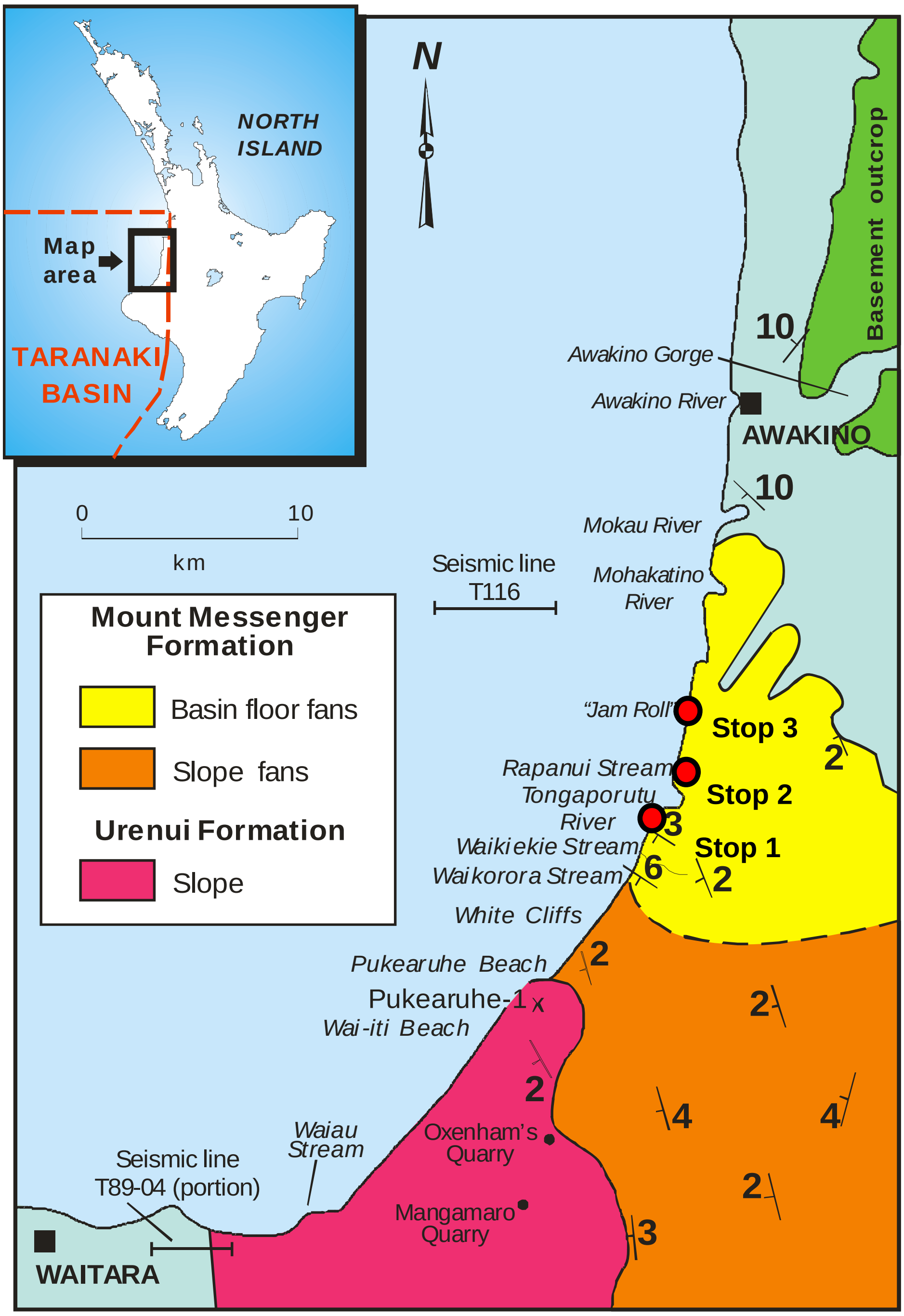
1) Examine and discuss the Late Miocene and younger tectonic history of the north Taranaki region,
2) The gain an impression of what normal faults look like in three dimensions and how rapidly their geometries can change along strike,
3) Consider the processes that result in the generation of fault rock in weakly lithified bedded rocks (e.g., shale smear and cataclasis),
4) Discuss the growth and evolution of fault zones,
5) Examine and discuss the origins of slump folding within the Mount Messenger Formation.

Figure 1. View south across Tongaporutu River mouth along the coastal section at stop 1. The photograph shows the Three sisters (prior to the smallest stack collapsing); the Whitecliffs in the middle distance and Mount Taranaki in the far distance. Photograph from GNS Science.

Tectonic Setting

The Taranaki Basin has had a complex tectonic and depositional history, with multiple episodes of rifting and contraction (King and Thrasher 1992, 1996; Giba et al., 2010). The tectonic evolution of the northern Taranaki Basin is dominated by three phases of deformation; 1) Late Cretaceous to Paleocene (~85-55 Ma) rifting and extension, 2) Late Eocene to Early Miocene contraction (mainly manifest as displacement on the Taranaki Fault) and, 3) Late Miocene to Pliocene (~12-2 Ma) rifting and extension (King and Thrasher, 1996; Stagpoole and Nicol, 2008; Giba et al., 2010). The palinspastic reconstruction of an approximately west-east cross-section shows the basin evolution from the Late Cretaceous (Fig. 3). The focus of this field trip is on the faults that formed during the Late Miocene and younger phase of rifting and extension.

Figure 2. Geological map of the north Taranaki coast showing the locations of the three sections that



will be visited during this field trip. Diagram from GNS Science.

The Mount Messenger Formation dips south at 2-6º in the region of the field trip (Fig. 2). The coastal exposures are located above basement rocks of the Jurassic Murihiku Supergroup, which are thrust over the pre-Oligocene section along the Taranaki Fault (Fig. 3). With subsequent subsidence, and an influx of clastic sediment from eroding hinterlands to the east and south, Miocene strata onlap the basement high produced by Early Miocene thrusting. Deep-water sediments of the Mount Messenger Formation were probably uplifted ~1 km during the Plio-Pleistocene associated with exhumation of the central and western North Island (Pulford and Stern 2004; Seebeck et al., 2014).

About 1-1.5 km of sedimentary rocks were eroded from above the Mt Messenger Formation in the area of the fieldtrip.

The normal faults exposed in the north Taranaki coastal section occur along the eastern margin of the northern graben (King and Thrasher, 1996)(Fig. 4). These faults form part of a rift system that at the latitude of Tongaporutu River is about 100 km wide and has been mapped for 350 km along the Taranaki Basin in a north-south direction (Giba et al., 2010). The rift faults progressively young to the south, commencing movement at 10-12 Ma west of Auckland and 3-4 Ma south of New Plymouth. In the field trip area they are thought to have mainly formed between 2 and 6 Ma. Late Miocene and younger rifting may have formed in association with rollback and steepening of the underlying subducting Pacific Plate (e.g., King and Thrasher, 1996; Giba et al., 2010, 2013; Seebeck et al., 2014). The faults accrued slip at shallow depths (<2 km) and low confining pressures (e.g., <40 MPa), displacing weakly lithified Late Miocene (~9-11.5 Ma) deep-water turbidites of the Mount Messenger Formation. There is no evidence that faults in the Mount Messenger coastal section displace the overlying Rapanui marine terrace which has an inferred age of 125 kyr. Therefore, the faults do not appear to have been active in the Late Quaternary.

Mount Messenger Formation

The Mount Messenger Formation is exposed on the coast north of New Plymouth and in many petroleum exploration wells throughout the northern Taranaki Basin. The coastal cliffs provide an excellent (in some place three dimensional), nearly continuous exposure through a normal-faulted, diachronous, progradational, 3rd-order deep-water clastic depositional system of Late Miocene (Tongaporutuan) age (~9-11.5 Ma; Crundwell, 2004). The locality is recognised as one of the best outcrop analogues world-wide for examining the stratal architecture of deep-water successions (e.g., King et al. 1993, 1994, 2007, 2011; Browne et al., 1996, 2000, 2005, 2007a, 2007b; King and Thrasher 1996; King and Browne, 2001; Browne and Slatt, 2002; Arnot et al., 2007a, 2007b).

The 30 km outcrop transect cuts obliquely through the ≥1500 m thick depositional succession. The Mount Messenger Formation comprises basin floor to base-of-slope strata deposited in deepwater at bathyal water depths (i.e. 200-1500 m below sea level, ~1000 m in the area of the field trip). The Mount Messenger interval consists of several fining-upward, heterolithic, 4th-order cycles, but is generally sand-dominated overall. The coastline exposure is an important analogue for laterally equivalent reservoir intervals in the nearby subsurface. The Mount Messenger Formation is producing oil and gas in onshore Taranaki Peninsula and remains an exploration reservoir target.

The wave-washed and generally clean cliff faces allow detailed examination of depositional facies and faults which provide insights into the geological processes. Particular attention will be given to the faults, their spatial variability, the generation of fault rock by cataclasis and shale smear processes, the architecture of fault zones and their potential impact on fluid flow. The architecture and permeability of fault zones has implications for petroleum exploration and production in deep-water turbidites.

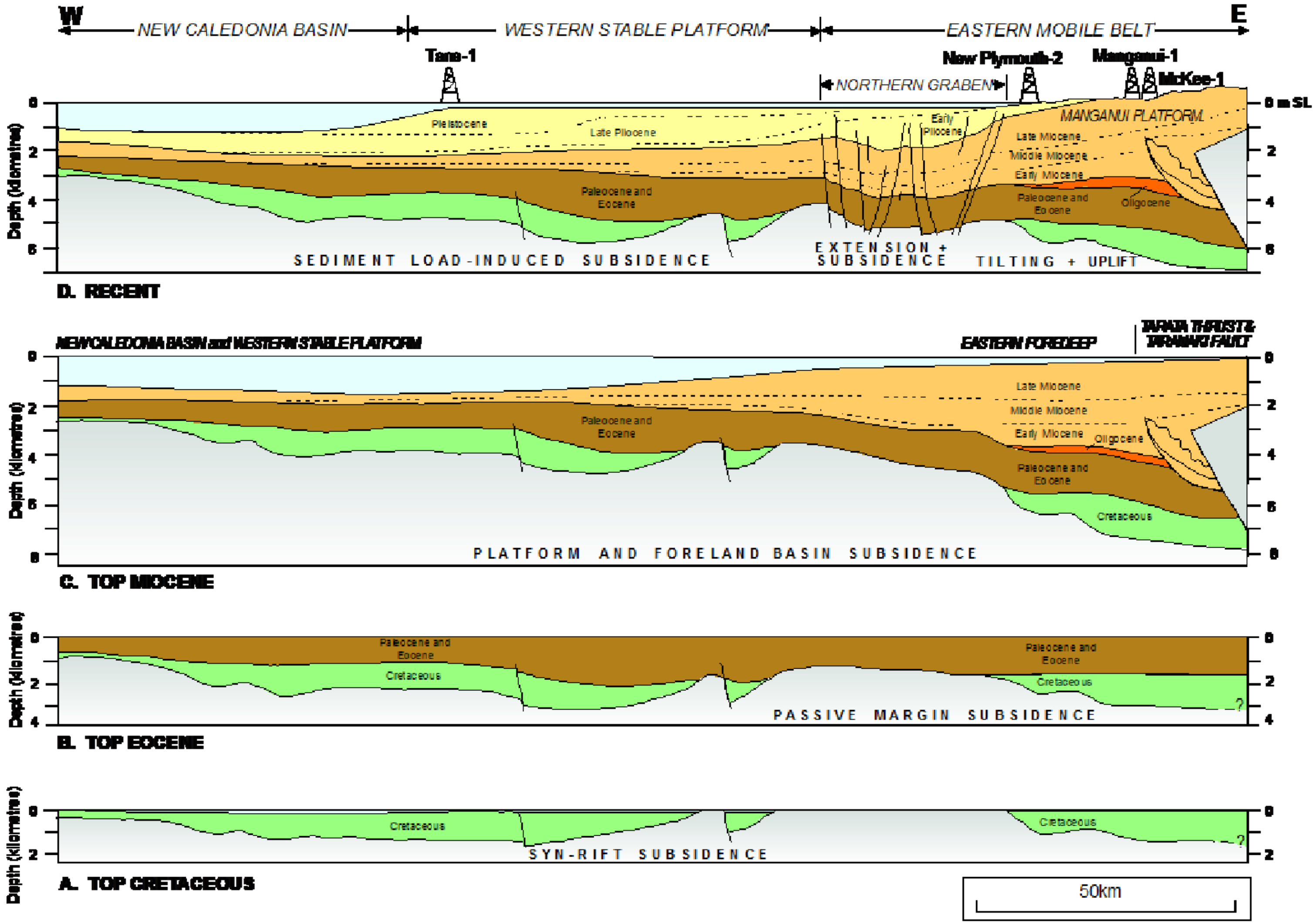


Figure 3. Northern Taranaki Basin cross-sections showing basin evolution from the Late Cretaceous (from King and Thrasher, 1996). See Fig. 4a for Restored Section location.

Normal faults

Small normal faults (0.001 to 70 m vertical displacement) are exposed in the coastal cliffs of Mount Messenger Formation (Fig. 4). The coastal cliffs examined during this field trip provide mainly cross-sectional exposures of normal faults along which faults can be traced up to 200 metres (mostly <30 m). In places, for example, immediately south of Tongaporutu River, the same faults intersect the irregular coastal cliff at several locations, offering a three-dimensional perspective of a fault system (we will look at these faults during the field trip).

Normal faults within the Mount Messenger Formation are post-depositional and mainly strike 005º and 045º, each set comprising two fault dip directions to define a quadrimodal population of fault orientations (Childs et al., 2005, 2007). Measurements of fault slip direction mainly indicate dip-slip normal movement with approximately northwest-southeast extension. Faults zones are well exposed in the cliffs and display many of the attributes common to normal faults elsewhere. These include; fault segmentation and relays, conjugate faults, cataclastic deformation bands, shale smear, slip surfaces and fault gouge (Childs et al., 2005, 2007; Nicol et al, 2013). These fault-attributes together with the spatial variability of fault-zone structure and fault system geometries will be examined.

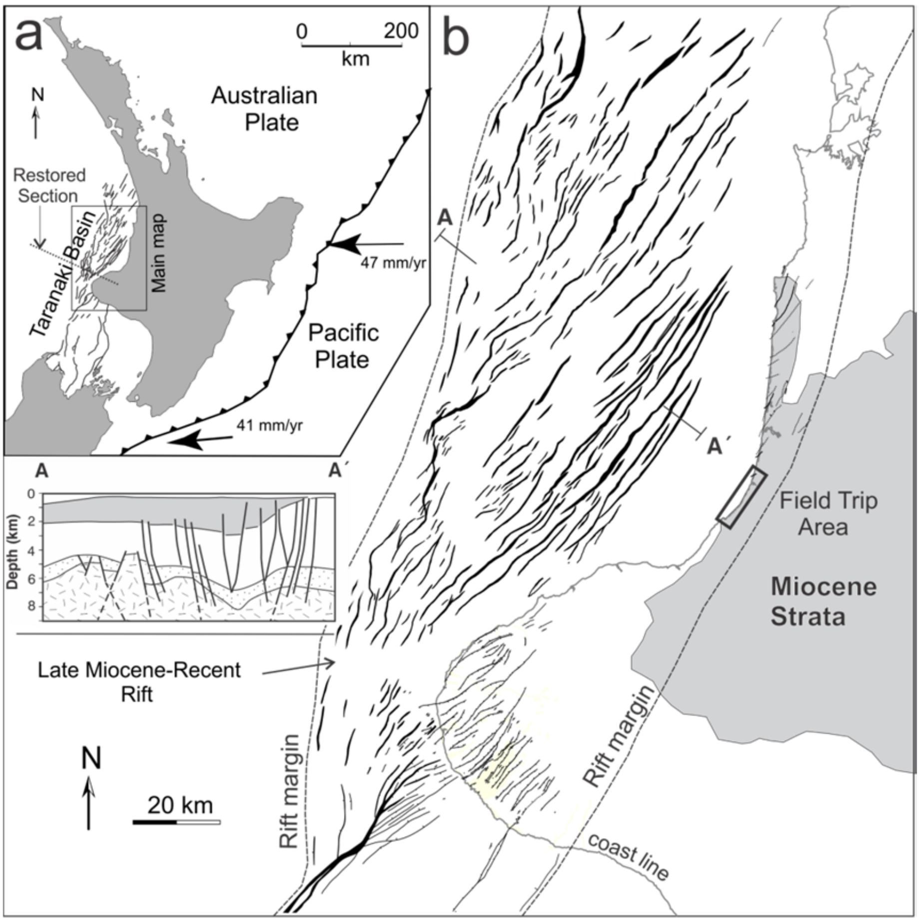


Figure 4. a) Location of the Taranaki Basin relative to subduction of the Pacific Plate east of the North Island of New Zealand. b) Map of the northern Taranaki Basin showing the distribution of Late Miocene and younger normal faults with displacements ≥~50 m. The locations of this field trip and of the restored section in Fig. 3 are shown. Fault map modified from Giba et al. (2010).

Stop 1 Tongaporutu River Coastal section

This cliff section begins at Tongaporutu River, and extends south along the beach for several kilometres. From the river we will walk up-section through thick-bedded sandstones, thinly inter-bedded sandstone and siltstones, and up into a capping siltstone. Both the beach and the river mouth sections are intensely faulted. We shall spend several hours looking at, and discussing, the faults in the Tongaporutu section. Careful examination of the faults reveals the following conclusions which are listed below.

Figure 5. Multiple small faults (displacements <6 m) exposed in a 20 m high cliff (often referred to as the "keystone exposure"). The largest fault on the left side of the exposure can be observed in three additional cliff faces further south and we shall trace it along the coastal outcrop. The photograph was taken in about 2003 (Childs et al., 2005) and comparison to the present cliff highlights the high rates of coastal erosion and the role that 'weak' faults and fractures have in focusing this erosion.

Key conclusions from the Tongaporutu section

1) **Fault and fault zone geometries.** The geometries of faults and fault zones can vary dramatically along strike and up dip over short distances. Many faults intersect nearby faults and are segmented. Few faults display the widely accepted damage zone fault core model (Fig. 6a). The thickness of fault rock and fault zones on individual faults vary by more than an

order of magnitude over distances of up to 20 m (Figs 6-8). The widest fault zones typically occur at irregularities on the fault surface (e.g., steps, bends segment boundaries).

2) **Fault rock formation.** Fault rock is generated by both cataclasis (tectonic crushing of sand grains) of sandstone beds and smear of shale (Figs 9-11). Cataclasis is much more important for the development of fault rock than assumed by methods for estimating the amount of clay rich fault rock (Fig. 11). For the purposes of estimating the permeability of faults we need to reassess whether presently favoured methods are appropriate (e.g., Fig. 11). These variations in fault rock thickness together with reductions in permeability of up to six orders of magnitude (~0.0008 to 800 to mD) arising from cataclasis have the potential to impact fluid flow and should be accounted for when assigning properties to faults in fluid flow models.
3) **Fault growth.** Cataclastic deformation bands indicate that these small faults developed progressively in a series of discrete events (e.g., small earthquakes). Cross-cutting faults suggest that larger faults accrued displacement in more events than smaller faults. Single event displacements also increased with fault size, as has been widely observed for historical earthquakes.
4) **Faults and coastal erosion.** The coast line has numerous stacks and caves. The evolution of coastal morphology from embayments to caves to stacks is strongly influenced by faulting. The stacks are bound by faults, while the caves are universally developed along faults. Faults and fractures represent zones of weakness that are more easily eroded than the surrounding undeformed host rock.

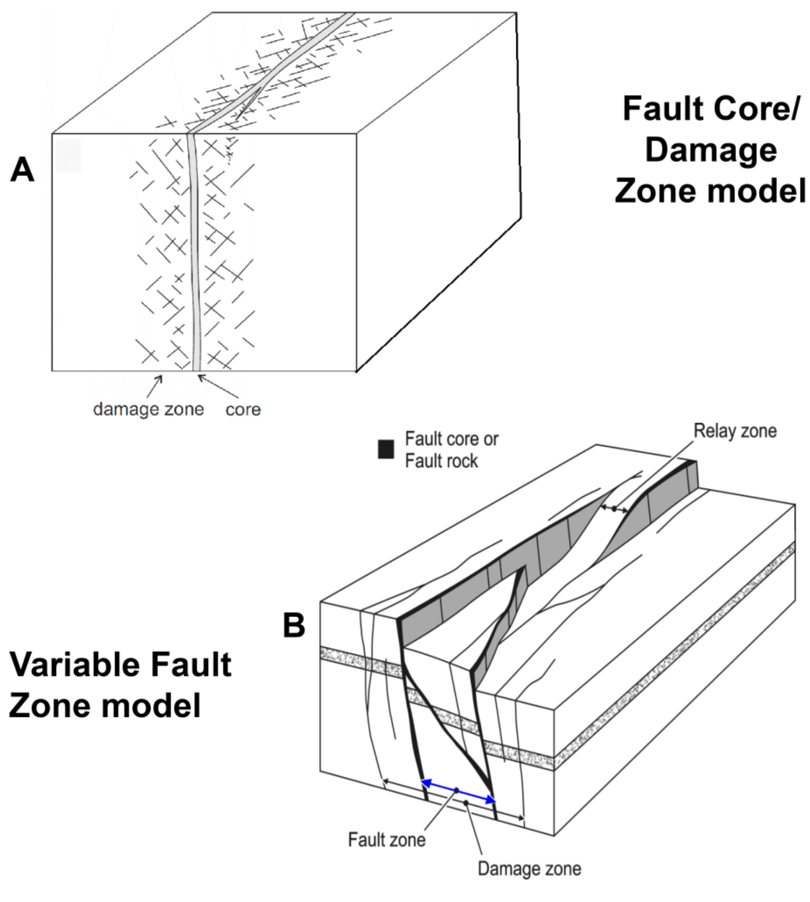


Figure 6. Schematic diagrams illustrating fault zone architecture and terminology (A – Faulkner et al., 2010; B - Childs et al., 2009).

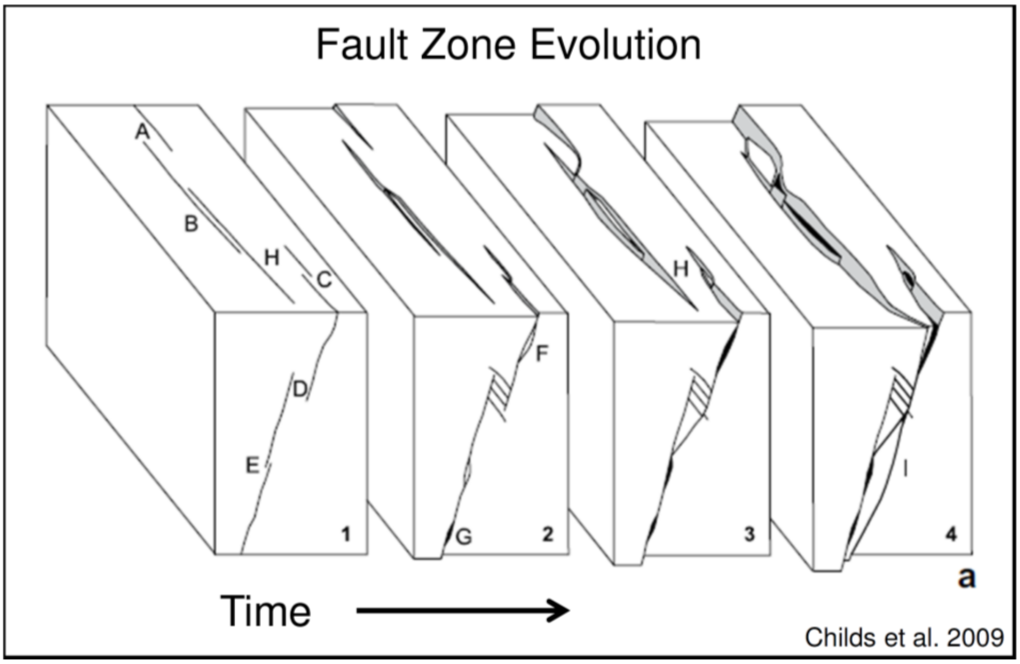


Figure 7. Block diagram illustrating the evolution of a fault array with increasing displacement at times 1 to 4. Individual fault irregularities, either asperities or segment boundaries are labelled A to I. Figure modified from Childs et al. (2009).

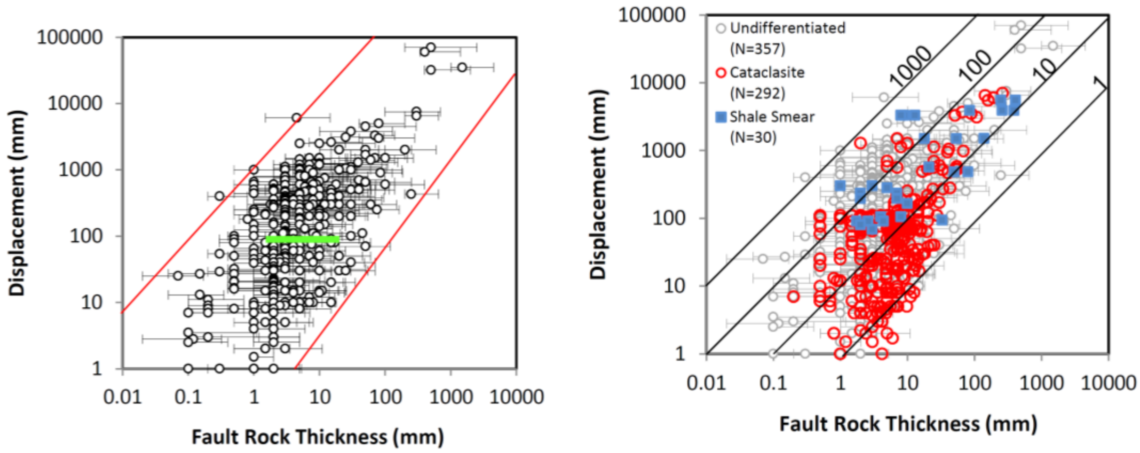


Figure 8. Plots of displacement vs fault-rock thickness for faults from the northern Taranaki coastal sections. Symbols represent the average fault rock thickness for each fault within the lower 5-10 m of cliff. Bars associated with each black (upper graph) and grey (lower graph) symbol indicate the range of fault-rock thickness. Red lines in the upper graph define the approximate limits of the data cloud. 1-1000 lines on the lower graph indicate contours of the ratio of displacement to fault rock thickness. A key conclusion from the plots is that fault-rock thickness varies significantly on individual faults and for different faults with the same displacement.

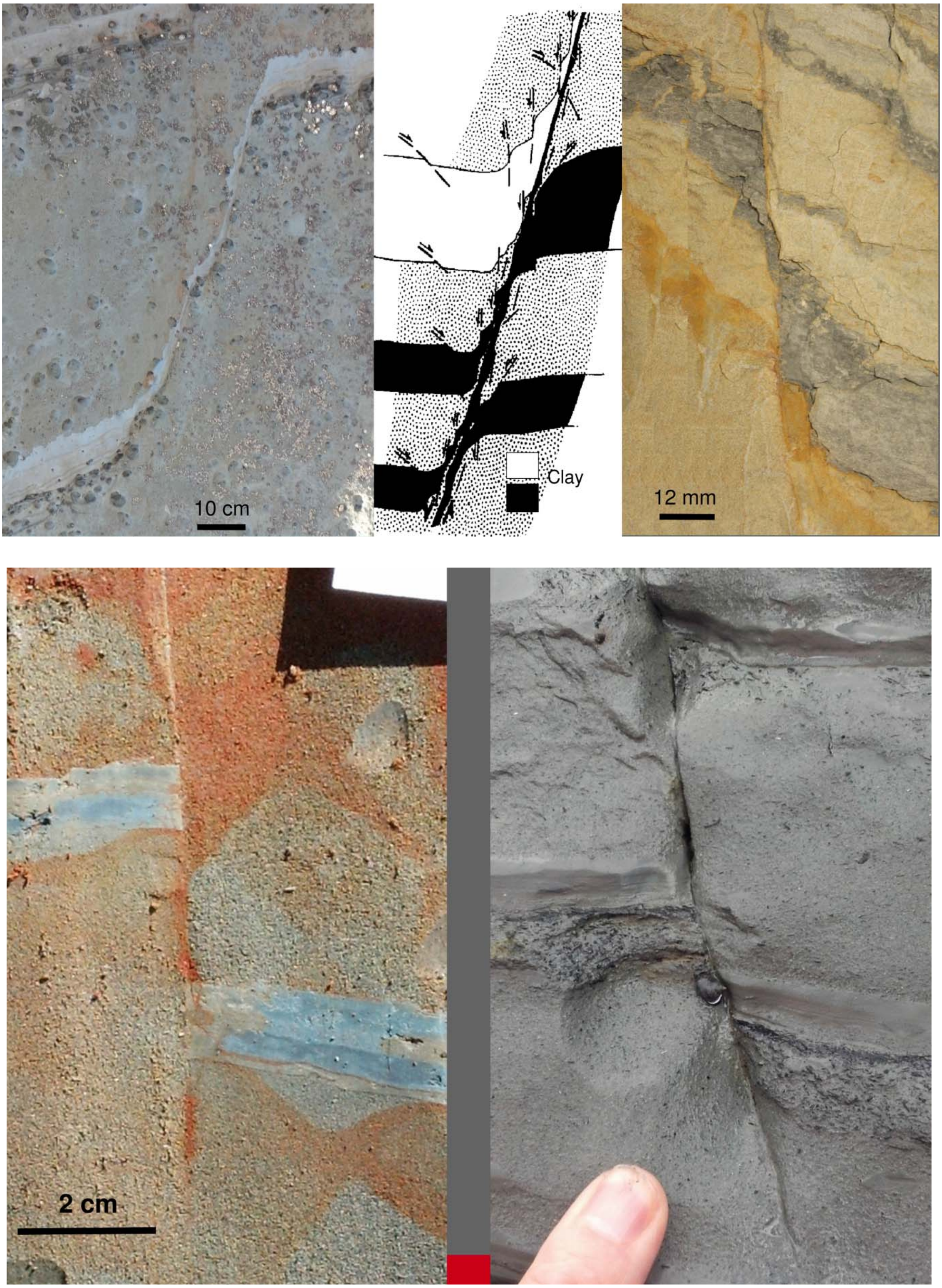


Figure 9. Outcrop examples of normal faults that comprise fault rock generated by shale smear (top row) and cataclasis (i.e. non shale smear; bottom row). Top left example is from the Mount Messenger Formation to the north of Tongaporutu River. Top centre diagram is modified from Yielding et al. (1997). Both examples of non shale smear are from the Tongaporutu River coastal outcrop.

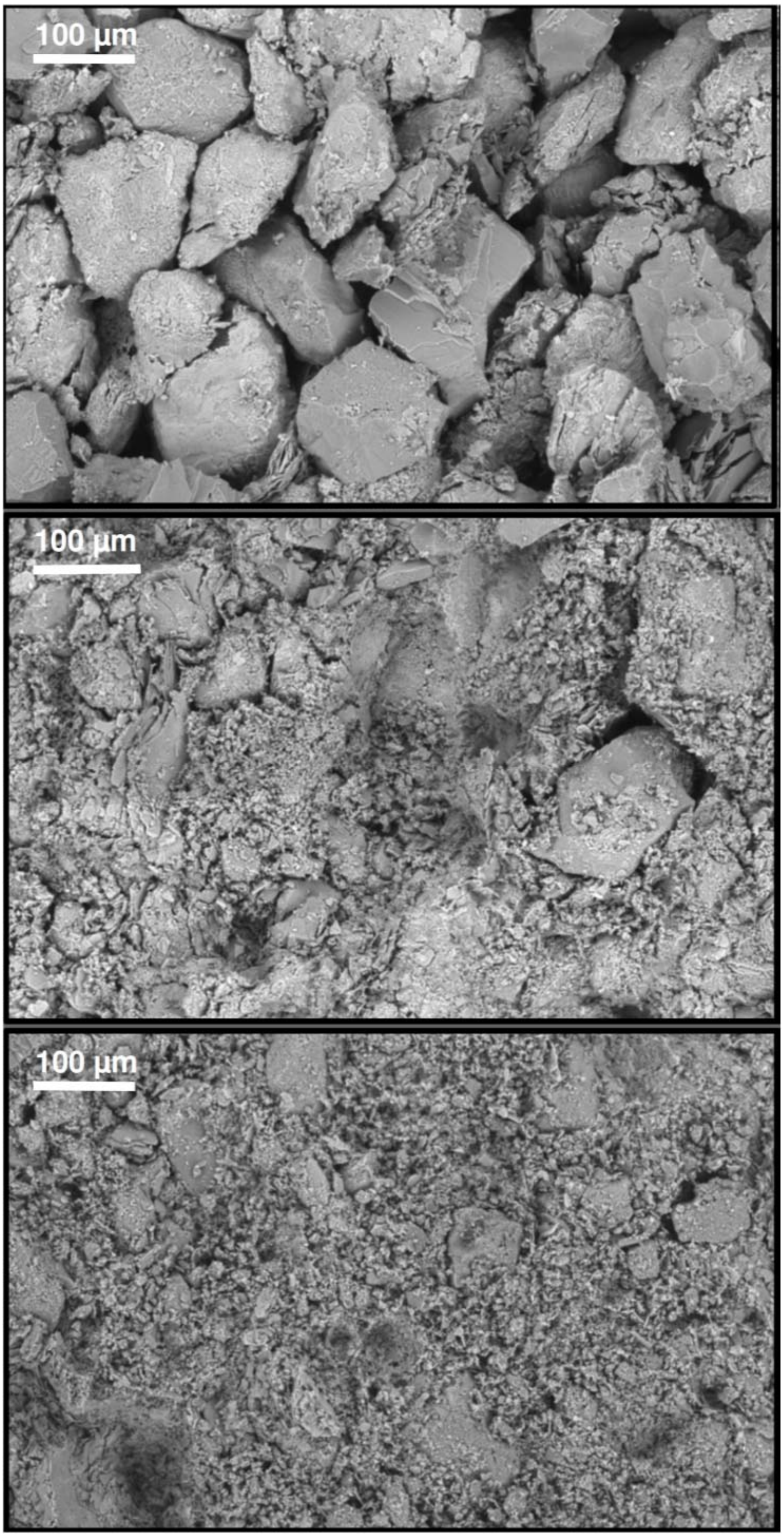


Figure 10. SEM images of unfaulted (top image) and faulted (middle and lower images) sandstone from the Mount Messenger Formation in the Tongaporutu River coastal section. The middle image is from a faulted sandstone with 1 mm of displacement and the bottom image a fault zone in a sandstone after 65 mm of fault displacement. Note the rapid initial destruction of the sandstone grains after ~1 mm of displacement.

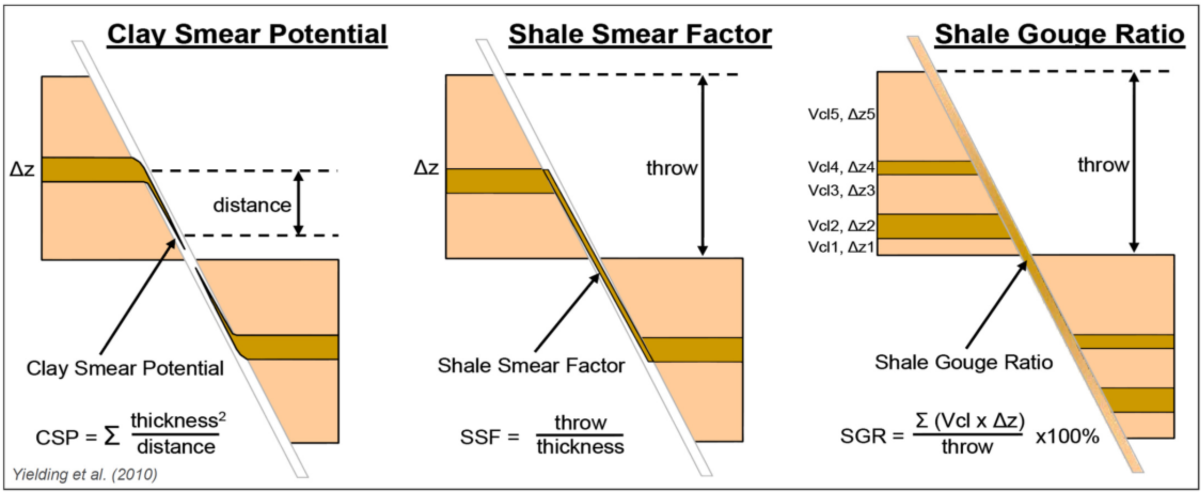


Figure 11. Schematic cross sections showing the three main methods for describing the amount of low permeability clay/mudstone within fault zones. Each of the methods implicitly or explicitly assumes that fault rock is formed by smear of mudstone beds into the fault zone. Diagram from Yielding et al. (2010).

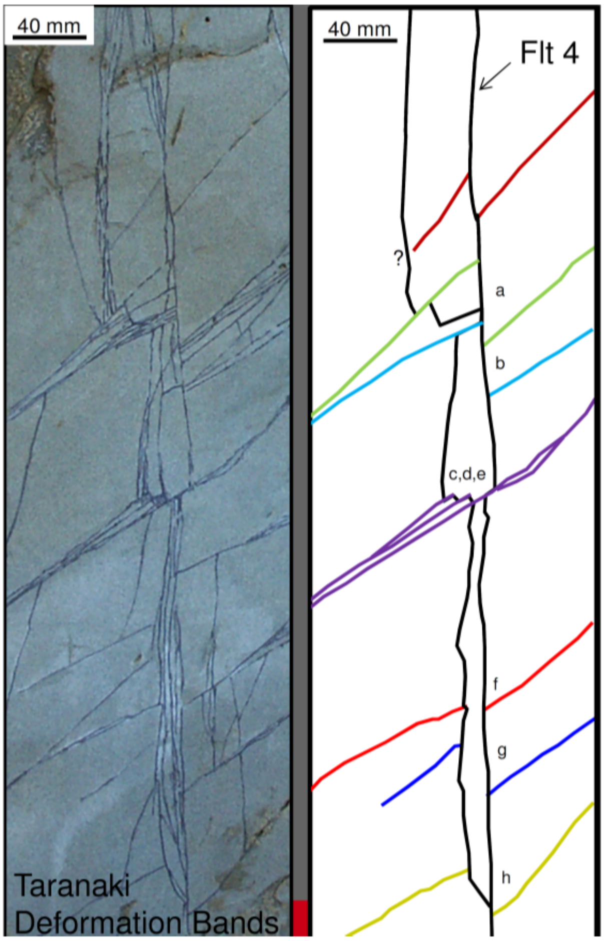


Figure 12. Cross-cutting deformation bands at Tongaporutu River, north coast of Taranaki. Left shows outcrop of deformation bands (which unfortunately has long since been eroded). Right shows interpretation of outcrop where fault 4 (black lines) displaces seven deformation bands (each represented by a different colour and labelled a-h) by different amounts (see Fig. 13). The variable displacements of the cross-cutting deformation bands (bands a-h) suggest that these bands formed at different times and that fault 4 accrued its total displacement in a series of small (≤5-15 mm) increments. These increments are inferred to be small earthquakes.

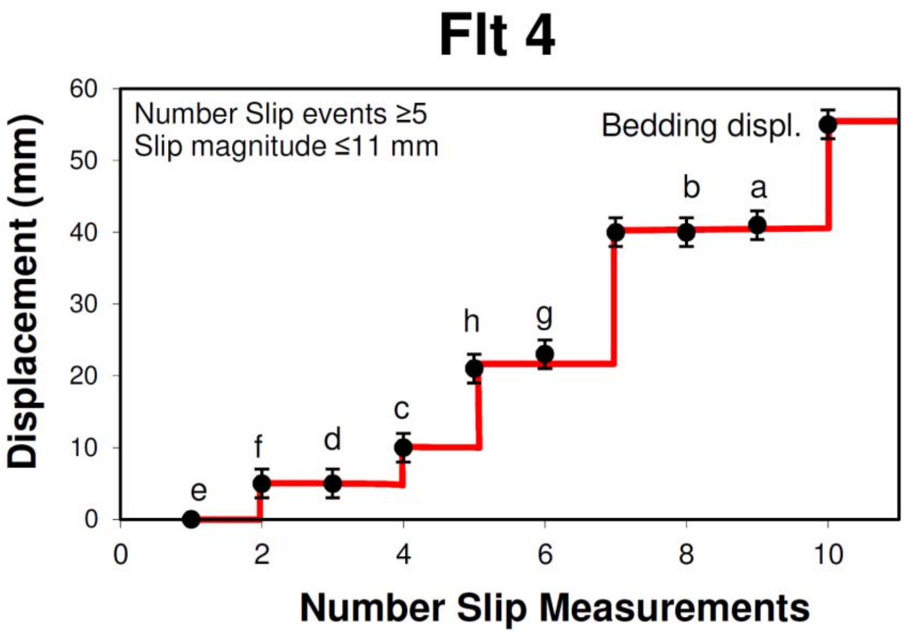


Figure 13. Displacements of cross-cutting faults a-h by fault 4 (see Fig. 12). Red line shows inferred displacement accumulation model based on the available data; vertical parts of the red line represent slip increments. The interpreted number of slip events is a minimum and the slip during these increments a maximum (i.e. we may be missing slip events on fault 4 that accrued over time intervals when no cross-cutting faults formed).

Stop 2 Rapanui Stream

Rapanui Stream, 2 km to the north of the Tongaporutu River outcrops, exposes a large fault (Fig. 14) and a mass transport deposit (MTD) comprising large blocks of sandstone floating as rafts within slumped siltstone. Of the larger faults exposed in the coastal cliffs the most accessible crops out at the northern end of the beach (Fig. 14). The fault has a vertical displacement of 30-40 m and is large enough that it would probably be resolved by seismic reflection lines. This exposure illustrates the key elements of fault zones and supports many of our observations at Tongaporutu River. We will examine the architecture of the fault zone and the distribution of silt/clay dominated fault rock within the zone. Consideration will be given to the origin of fine-grained fault rock and the implications of this low permeability material for fluid flow across the fault. We will also consider the importance of scale for the observation and interpretation of fault-zone structure.

Figure 14. Photographs illustrating the range of fault rocks developed within a 30-40 m displacement normal fault at Rapanui Stream. The ~3 m wide fault zone dips to the right in (a). There are four main slip surfaces which are shown in detail in (b), (c), (d) and (g). The fault zone contains large lens of sandstone bounded by slip surfaces containing fault rock. (f) is a hand specimen of fault rock showing the layered nature of the fault rock. Photographs from Childs et al. (2007).

The MTD outcropping at the southern end of the beach is common along the coastal section (if we have time we will also visit the 'Jamroll' locality at Stop 3). These MTDs formed in deep water while the sediments were mostly unlithified (i.e. in many cases they were soft enough to fold without extensive fracturing). They are generally inferred to have formed in the toe regions of large gravitation failures of saturated marine sediments within a few 10s of metres of the sea bed. Based on the seaward vergence of the slump folds the paleoslope direction in the Miocene appears to have been similar to that observed today.

Figure 15. Mass transport deposit folded siltstones (grey) with rafted blocks of sandstone, overlain by thick-bedded sandstones (brown), lower bathyal basin floor fan, Mount Messenger formation, Rapanui Stream (photograph from Peter King).

Stop 3 Jamroll Bay

At 'Jamroll' Bay spectacular complex folded and slumped strata are exposed and are the focus of this stop (Fig. 16). Folded and convoluted beds of well-bedded siltstone and thick-bedded massive medium-grained sandstone occur in variously deformed masses. Sandstone beds were pre-compacted, and remained relatively intact during deformation. Based on broad stratigraphic position, a basin floor setting is inferred. Mudstones contain common tuff layers.

Figure 16. Folded and slumped siltstones and sandstones (mass transport deposit), Jamroll Bay, Mount Messenger Formation (Photograph from Greg Browne).

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