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Field Trip 9

28th – 30th November 2013

Cretaceous–Paleogene Stratigraphy of North-Eastern South Island:

North Canterbury, Kaikoura, South-Eastern Marlborough

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Cover photo: Muzzle Group rocks exposed in Mead Stream, photo Kyle Bland

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F***igure 1.*** *The Paleogene sequence in the mid-Waipara River valley, looking east from Laidmore Rd View with uppermost Eocene-Oligocene Amuri Limestone in foreground and forming the ridge line, underlain by softer lithologies of Eocene Ashley Mudstone and Paleocene Waipara Greensand. The peak in the distance, North Dean, is upper Lower Miocene limestone and calcareous siltstone of the Mt Brown Formation.* Photo R. Funnell

Health and Safety

This field trip requires a moderate level of fitness and some experience in stream crossings is desirable. Participants need to be prepared for a wide range of conditions: from cool temperate to warm subtropical. Bring sunhat, sunblock, insect repellent, parka or rain coat, warm base or middle layer, and hiking boots or sturdy footwear, and safety glasses if you plan to hammer rocks. Each day will entail multiple stream crossings, so be prepared to have wet footwear and bring a change of footwear for the end of each day. All attempts to keep your feet dry will ultimately prove fruitless, so don't be tempted by boulder hopping. Seals are likely to be prolific on the coastal part of Day 3. Keep 5 m away from them and avoid stepping between seals and the sea. Follow the instructions of your field trip leaders.

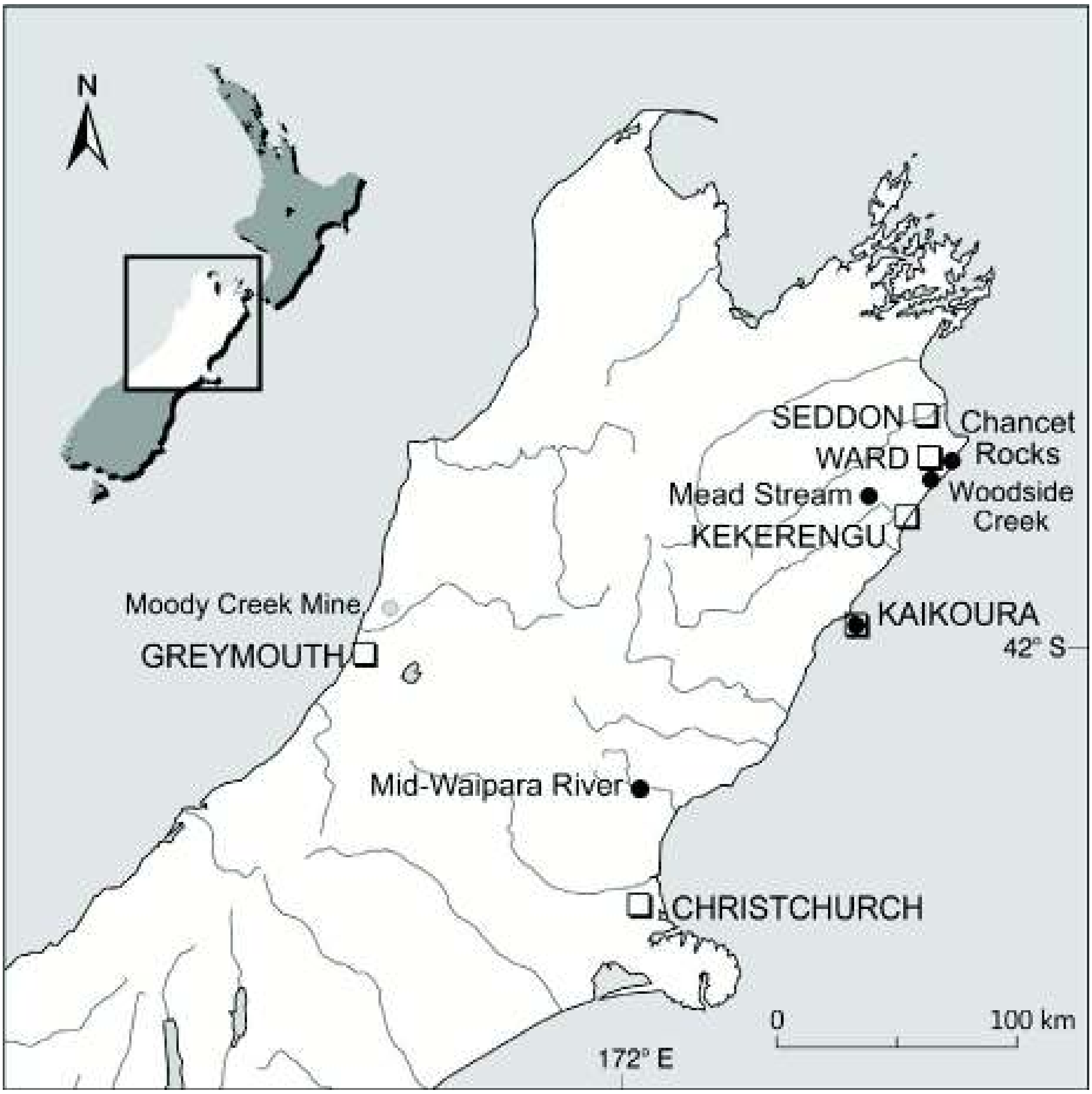

Figure 2. *General route map for Field Trip 1. Filled circles = main stops.*

FIELD TRIP 1: SCHEDULE

Day 1: Thursday 28 November (Mid-Waipara River, Kaikoura)

08.00 – 08.15	Depart from university campus
08.15 – 09.15	Travel to Mid-Waipara River, via Amberley
09.15 – 10.30	STOP 1A: K/Pg boundary
10.30 – 13.00	STOP 1B: Paleocene-Eocene succession (lunch)
13.00 – 15.00	Travel to Kaikoura
15.00 – 15.45	Check in to Kaikoura Field Station
16.00 – 17.00	STOP 2A: Kaikoura Wharf section, K/Pg to Eocene
17.15 – 18.30	STOP 2B: Kaikoura South Coast, Eocene-Miocene
19.00 – 21.00	Dinner, Kaikoura

NOTES: Christchurch to Waipara = 1 hr; Waipara to Kaikoura = 2 hrs; Low tide = 19.35

Day 2: Friday 29 November (Mead Stream)

07.00 – 08.00	Breakfast (Kaikoura)
08.15 – 09.00	Travel to Kekerengu
09.15 – 10.30	Travel to Coverham
10.30 – 11.45	STOP 3: Ouse Gorge, mid-Cretaceous
12.00 – 16.30	STOP 4: Mead Stream, Cretaceous-Eocene section, E/O boundary, Miocene, Clarence Fault (lunch)
18.00 – 20.00	BBQ Dinner, Kekerengu
20.00 – 21.00	Return to Kaikoura Field Station

NOTES: Kaikoura to Kekerengu = 45 mins; Kekerengu to Mead Stream = 1.5 hrs; Mead Stream – Kaikoura = 2.5 hrs; Low tide = 7.53; 20.19

Day 3: Saturday 30 November (Chancet Rocks, Woodside Creek)

06.30 – 07.15	Breakfast (Kaikoura)
07.30 – 08.30	Travel to Ward
08.45 – 09.30	STOP 5A: Chancet Rocks, K/Pg boundary, Paleocene paramoudra
09.30 – 10.30	STOP 5B: Chancet ammonite beach / walk to Ward Beach
10.45 – 11.45	Morning Tea, Chancet Station
12.00 – 14.00	STOP 6: Woodside Creek, K/Pg boundary (lunch)
14.30 – 16.00	STOP 7: Yealands Estate, late lunch, wine-tasting
16.00	Vans depart for Blenheim, Picton, Christchurch (ETA 20.00)

Notes: Ward to Christchurch = 4 hrs; Low tide: 08.42

EMERGENCY NUMBERS

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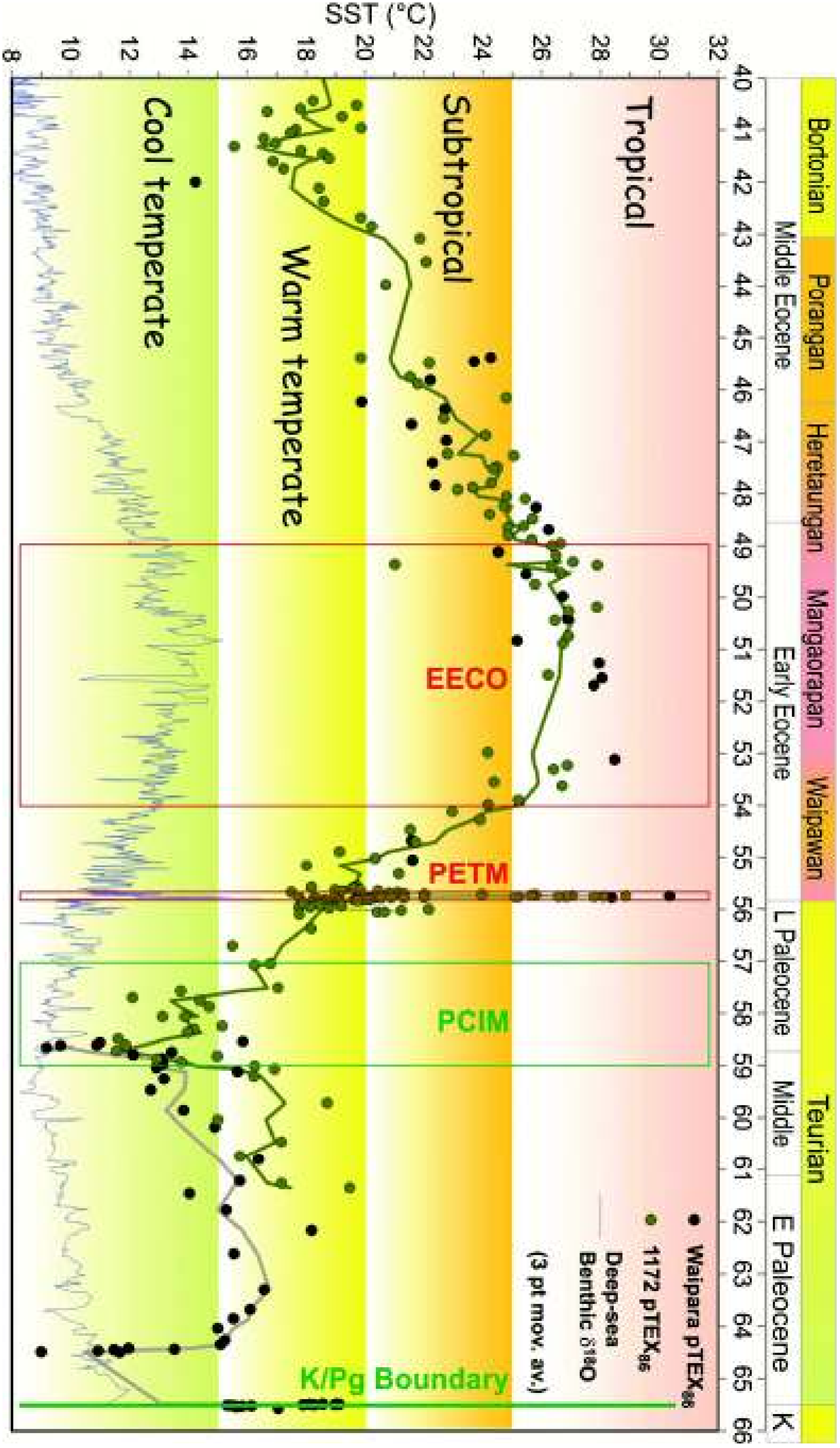


Figure 3. *Sea surface temperatures (SST) for the early Paleogene based on a paleo-calibration of the* TEX_{86} *proxy* ($pTEX_{86}$ *- Hollis et al. 2012) recovered from sediment samples at Mid-Waipara River and ODP Site 1172 (East Tasman Plateau).*

SYNOPSIS

New Zealand is well endowed with Upper Cretaceous and Paleogene sedimentary records. Sandwiched between prolonged episodes of active tectonism and uplift, sedimentary sequences from 80 to 25 Ma were deposited during a phase of thermal relaxation, passive margin subsidence, in a wide variety of sedimentary settings within basins marginal to the gradually foundering New Zealand landmass.

This field trip is an introduction to the Upper Cretaceous and Paleogene stratigraphy of the north-eastern South Island (**Fig. 2**), with a focus on records of major climatic and biotic events in the early Paleogene (**Fig. 3**). The trip takes in rock records from two sedimentary basins: the Canterbury and East Coast Basins. Respectively, these allow us to compare and contrast shallow to deep marine siliciclastic and pelagic sedimentation at a middle-latitude, passive continental margin. The trip starts with a visit to the neritic to upper bathyal glauconite-rich mid-Waipara section, north Canterbury, which typifies shelf sedimentation in the Canterbury Basin from Late Cretaceous to Late Eocene times. We then travel north to examine the terrigenous sediment-starved pelagic succession in Kaikoura and eastern Marlborough.

The trip's itinerary includes records of the mid-Cretaceous initiation in passive margin sedimentation in the East Coast Basin, the Cretaceous/Paleogene (K/Pg) boundary at five sites (mid-Waipara River, Mead Stream, Chancet Rocks, Chancet Quarry and Woodside Creek), the Paleocene Carbon Isotope Maximum (PCIM) or correlated unconformity at three sites (mid-Waipara, Kaikoura, Mead), the Paleocene/Eocene Thermal Maximum (PETM) at two sites (mid-Waipara, Mead), the Early Eocene Climatic Optimum (EECO) at three sites (mid-Waipara, Kaikoura, Mead) and the Marshall Unconformity at two sites (Kaikoura, Mead). Mead Stream may also include the Middle Eocene Climatic Optimum (MECO). For background reading into these events and local records, see: Hollis (2003a, b), Hollis et al. (Hollis et al. 2005a), Norris et al. (2013), Zachos et al. (2008), Zeebe (2013).

DAY 1 (Thursday, 28 November): mid-Waipara River and Kaikoura

Introduction

Today we first head north from Christchurch, across the Canterbury Plains, to the Waipara River valley. After visiting the mid-Waipara section, we travel north to Kaikoura and visit two coastal sections. We approach the mid-Waipara section from the lower part at the Laidmore Road ford. We first walk upstream to the K/Pg boundary exposure and then double back to visit the Paleocene-Lower Eocene section (**Figs. 4, 5**).

The middle reaches of the Waipara River (**Fig. 4**) have long been of interest to geologists because the banks expose a near complete record of neritic to upper bathyal sedimentation from Late Cretaceous to Middle Eocene. The river's sinuosity, the low angle of dip and lateral facies variation complicate correlation between outcrops but we estimate a total stratigraphic thickness of ~210 m from the K/Pg boundary to the base of the Eocene-Oligocene Amuri Limestone (**Fig. 5**). The section we will examine includes the K/Pg boundary (Conway Formation), Paleocene greensand (Waipara Greensand), including an organic-rich interval correlated with the Tartan Formation (= Waipawa Formation), and calcareous mudstone (Ashley Mudstone) that may include the PETM at the base and is correlated with the EECO in the lower part of the section exposed in the river bed. Details of stratigraphy and GNS sampling campaigns are provided by Morgans et al. (2005).

In recent years, the section has been the focus of a series of paleoclimate studies. Relatively weak induration and low thermal maturity mean that the sediments yield well-preserved microfossils and organic biomarkers. Integrated studies of temperature proxies – oxygen isotopes and Mg/Ca ratios from foraminifera and TEX_{86} from archaeol lipids – have yielded a remarkable climate history for Canterbury Basin (Hollis et al. 2009; 2012; Creech et al. 2010) that parallels a TEX_{86} record for the SW Tasman Sea (Bijl et al. 2009).

TEX_{86} is an organic biomarker that is used as a proxy for sea surface temperature. It was first developed in 2002 (Schouten et al. 2002) and has been applied widely in subsequent years although debate continues over the calibration of TEX_{86} values to absolute temperature (see Schouten et al. 2013; Taylor et al. 2013). Hollis et al. (2012) introduced a simplistic alternative to modern calibrations. They calibrated TEX_{86} to the best available SST estimates derived from other proxies in Paleogene sections and in this way developed a paleo-calibration ($pTEX_{86}$) that generally yields temperatures that are cooler than the two standard modern calibrations recommended for SSTs above 15°C, i.e. $1/TEX_{86}$ (Liu et al. 2009) and $TEX_{86}H$ (Kim et al. 2010). Hollis et al. (2012) also argue that TEX_{86}-derived SSTs are likely to have a summer bias in middle and high latitudes. TEX_{86} stands for the TetraEther indeX of tetraethers consisting of 86 carbon atoms and is a ratio of various types of isoprenoid glycerol dibiphytanyl glycerol tetraethers (or GDGTs). GDGTs are common in marine sediments and are the remnants of membranes lipid from various types of Archaea (bacteria-like microbes). Schouten et al. (2002) discovered that there was a clear relationship between a ratio of GDGTs and SST and the proxy developed from there. The proxy has particular utility in New Zealand Paleogene sections where fossils with well-preserved carbonate are scarce.

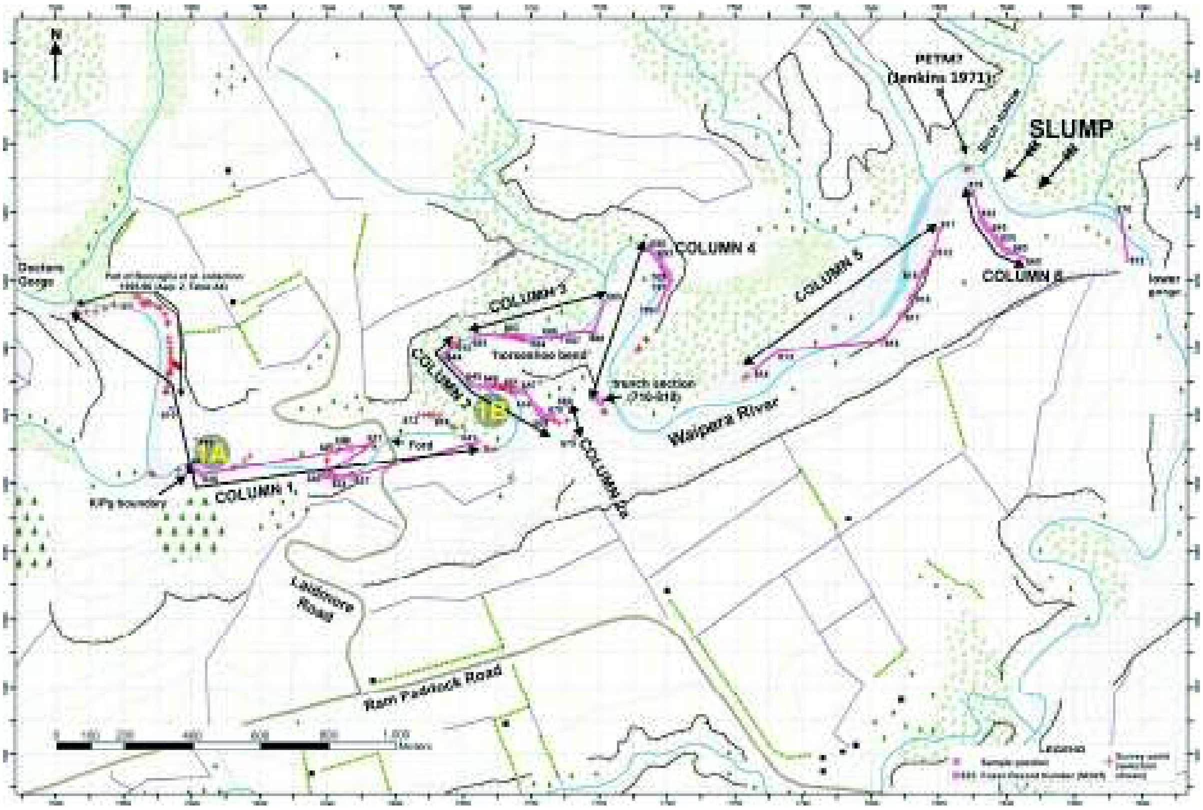


__Figure 4.__ Map of Mid-Waipara River, showing location of measured stratigraphic columns (from Morgans et al. 2005) and Stops 1A and 1B.

STOP 1A. Mid-Waipara Section: K/Pg Boundary

We walk upstream through the Loburn Formation. At 4 m below the base of the Loburn Formation in Column 1 (NZMS 260 grid ref. M34/7605 9402), we find the K/Pg boundary within the Conway Formation. The boundary is a poorly defined, somewhat irregular 1-2 cm thick iron-stained band, separating slightly calcareous Cretaceous siltstone from noncalcareous, glauconite-rich Paleocene sandstone (**Fig. 5**). Despite its unspectacular appearance (**Fig. 6**), this K/Pg boundary has several important features (**Fig. 7**). Planktic foram and calcareous nannofossil extinctions are well-defined. In fact planktic forams are extremely sparse within the overlying 30+ m. This section includes the only New Zealand record of the early Paleocene index species *Antarcticella pauciloculata* – initially thought to be a planktic species but ascribed to a benthic habitat by Liu et al. (1998). The boundary layer is enriched in iridium (albeit only 50 x crustal average at 0.49 ng/g – Brooks et al. 1986). The boundary also contains a muted fern spike, which was reported by Vajda et al. (2001; see also Vajda & Raine 2003) along with the much more clearly defined fern spike in the terrestrial Moody Creek Mine section, north of Greymouth (**Fig. 2**).

The fern spike has been interpreted as an indication of global destruction of forests as a consequence of the K/Pg asteroid impact – either due to global conflagration or "impact winter" (see Hollis 2003b – handout). At Moody Creek Mine, we see a clear record of disappearance of the mixed forest pollen record at the K/Pg boundary followed by a succession of ferns that is consistent with re-colonisation of bare ground (**Fig. 8**). The interval dominated by tree ferns suggests warm climatic conditions whereas the increase in *Phyllocladites mawsonii* (= Huon Pine) suggests cooling.

The same vegetation succession is seen at mid-Waipara except that bioturbation has blurred the signal (**Fig. 7**). Here we also see an initial spike in ground ferns at the K/Pg boundary prior to an increase in tree ferns. This is followed by a major expansion in gymnosperms (conifers) with *Phyllocladites mawsonii* making up a significant component. New TEX_{86} analyses (Hollis et al. 2012; Taylor et al. in prep.) seem to confirm that the tree fern spike is associated with warming and the increase in conifers is linked to significant cooling. The $pTEX_{86}$ calibration indicates that SST initially warmed by 3-4°C across the boundary (from 15-16° to 18-19°C) before cooling to below 10°C. This is extraordinarily cold for the "greenhouse" world of the Paleocene (equivalent to modern day winter SST off the Canterbury coast). We suspect the Paleocene recovery interval may be truncated by an unconformity ~20 cm above the boundary but overall this pattern of climate shift is consistent with the record from SE Marlborough (Hollis 2003a; Hollis et al. 2003a, b).

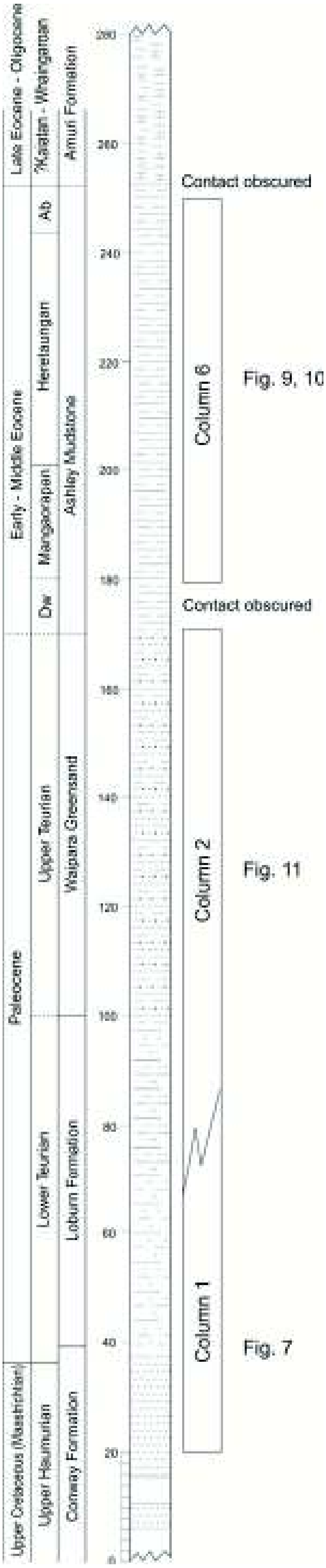


Figure 5. *Stratigraphy of the mid-Waipara composite section (from Morgans et al. 2005*

Initial cooling due to the impact winter probably only lasted a few years at most and so is not recorded in the rock record here. What tends to be more widely recorded is a post-impact warming, which may be related to the release of CO_2 as a consequence of the asteroid impacting carbonate-rich target rock and also the global shut-down in photosynthesis (Pope et al. 1997; Brinkhuis et al. 1998). We speculate that the greenhouse climate may have ended once plant communities recovered and photosynthetic drawdown of CO_2 increased. This may explain the prolonged interval of cool conditions, although cooling seems more pronounced in New Zealand than in other regions. It is possible that mild global cooling was accentuated in the South Pacific due to accompanying changes in ocean circulation. Certainly, this interval of cool conditions is linked to an increase in biosiliceous sediments in SE Marlborough., which is interpreted as evidence for intensification of coastal upwelling (Hollis 2003a).

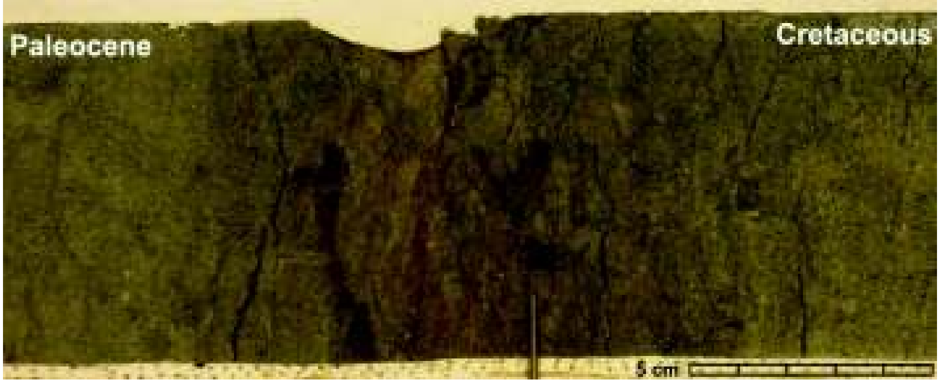


Figure 6. *A polished slab of the boundary reveals that the irregular nature of the boundary and the muted biological and chemical signals of the boundary event are due to intense bioturbation.*

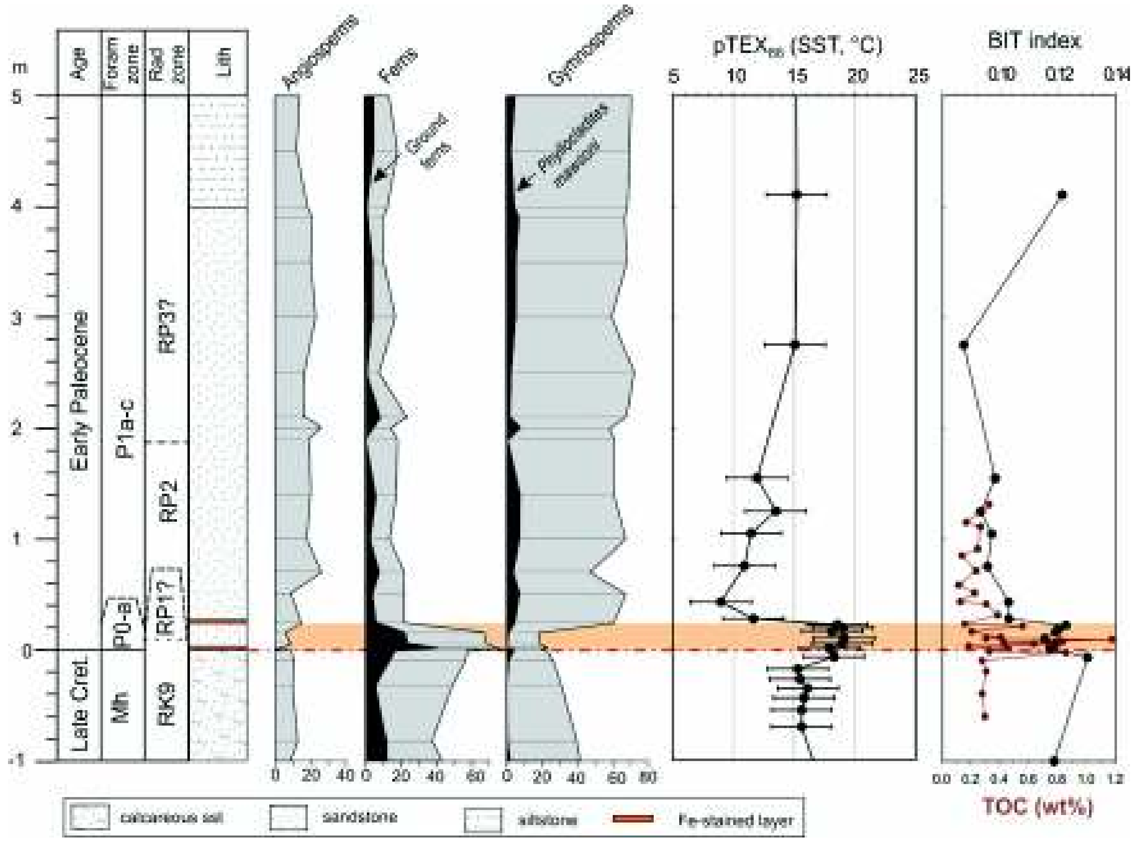


Figure 7. *Stratigraphy, palynomorphs and geochemical variation across the K/Pg boundary at mid-Waipara River (after Hollis and Strong 2003; Vajda and Raine 2003; Hollis et al. 2012; Taylor et al. in prep.). The BIT index is a guide to terrigenous input and indicates that this input decreases as temperature cools.*

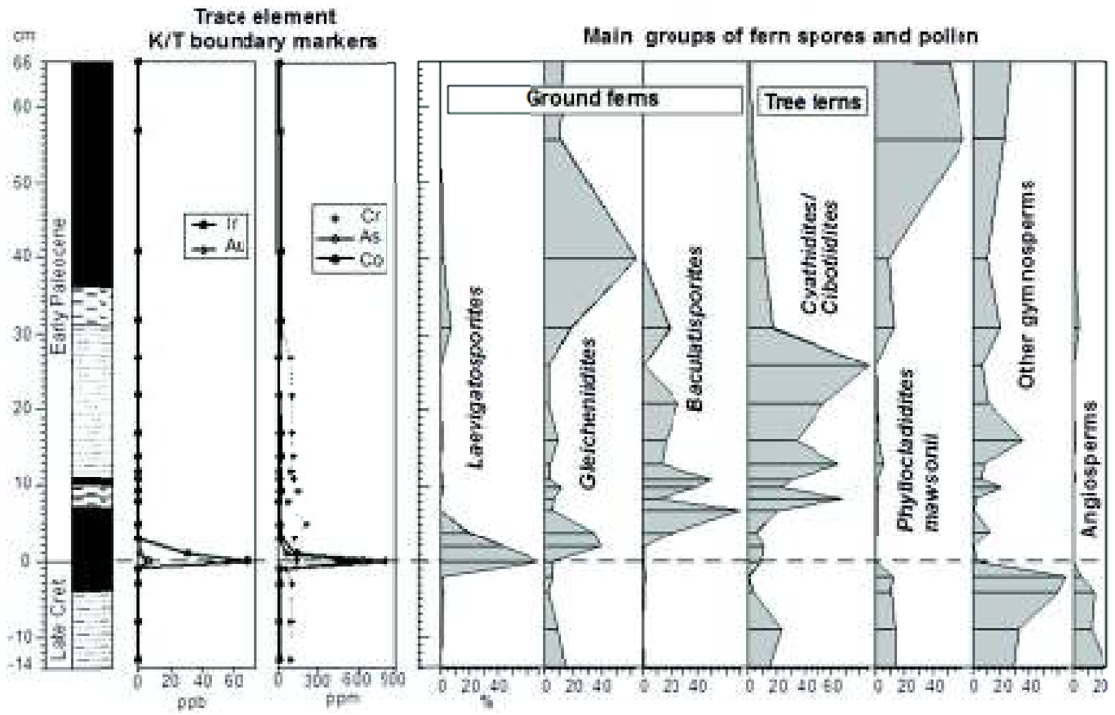


Figure 8. *Iridium and other elemental anomalies and the plant succession across the K/Pg boundary at Moody Creek Mine, West Coast (from Vajda et al, 2001).*

STOP 1B. Mid-Waipara section: Paleocene Waipara Greensand

At this stop we view the upper part of the Waipara Greensand exposed in Column 2 (NZMS grid ref. M34/7706 9420) and debate whether the calcareous mudstone at the top of the section is in place, and therefore possibly the PETM, or a displaced block of Ashley Mudstone.

Before we consider this section in detail, let's consider what is further upstream and not able to be visited on this trip, namely the Ashley Mudstone section in Column 6. We are not missing much because it is a very unspectacular exposure of calcareous mudstone . However, it has a remarkable story to tell. The Lower Eocene Ashley Mudstone that is well-exposed in the river bed contains the Mangaorapan-Heretaungan stage boundary, as defined by the first appearance of a benthic foram – *Elphidium hampdenense*, which is ~49.5 Ma. Higher in the section, there appears to be an unconformity as the uppermost Ashley is upper Middle Eocene (Bortonian). Early collections indicate that the Paleocene-Eocene boundary was exposed at the base of the section on the northern bank (Birch Hollow), but this part of the section is now obscured by a large slump. All we can say is that the lowest samples in Column 6 from the stream bed are Waipawan (lower Eocene, 56 to 53.4 Ma).

A multidisciplinary study of the section has been undertaken to test the hypothesis that the Mangaorapan-Heretaungan boundary is a mild cooling event that marks the termination of the Early Eocene Climatic Optimum (EECO). Correlation is based on foraminifera, calcareous nannofossils, radiolarians and dinocysts (**Fig. 9**). Environmental changes were inferred from sedimentology, palynomorph assemblages and organic geochemistry. Sea temperature changes were inferred from oxygen isotopes and Mg/Ca ratios of single foram specimens and by TEX_{86} analyses (Hollis et al. 2009). The results show that there is certainly slight cooling in the lower Heretaungan but the most remarkable finding is the degree to which sea temperatures warmed during the EECO – all three proxies record tropical temperatures ~30°C for surface waters and ~20°C at the sea floor (**Fig. 10**). The values have been lowered slightly following a review of the proxies (Hollis et al. 2012; see **Fig. 3**) but continue to point to near tropical conditions in the Early Eocene in Canterbury, results that are in line with studies from the SE Tasman Sea and Antarctic margin (Bijl et al. 2009; Pross et al. 2012).

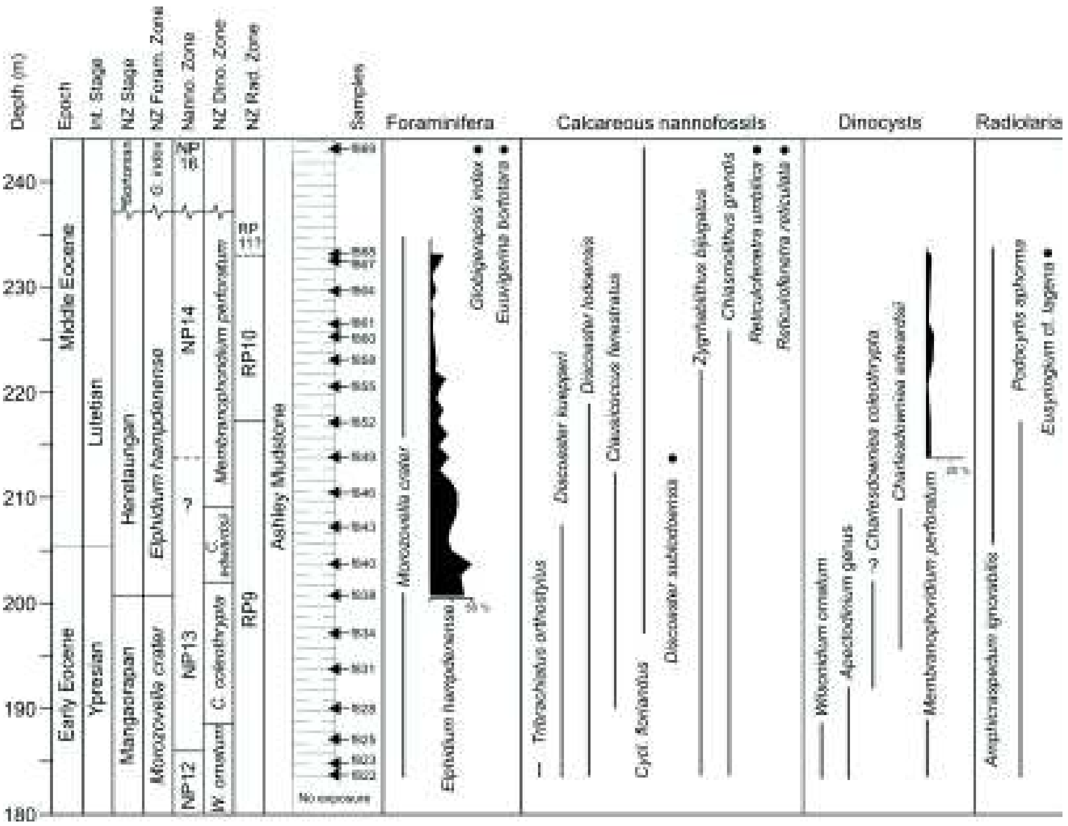


Figure 9. *Stratigraphy of Ashley Mudstone, mid-Waipara River (Column 6) (from Hollis et al. 2009).*

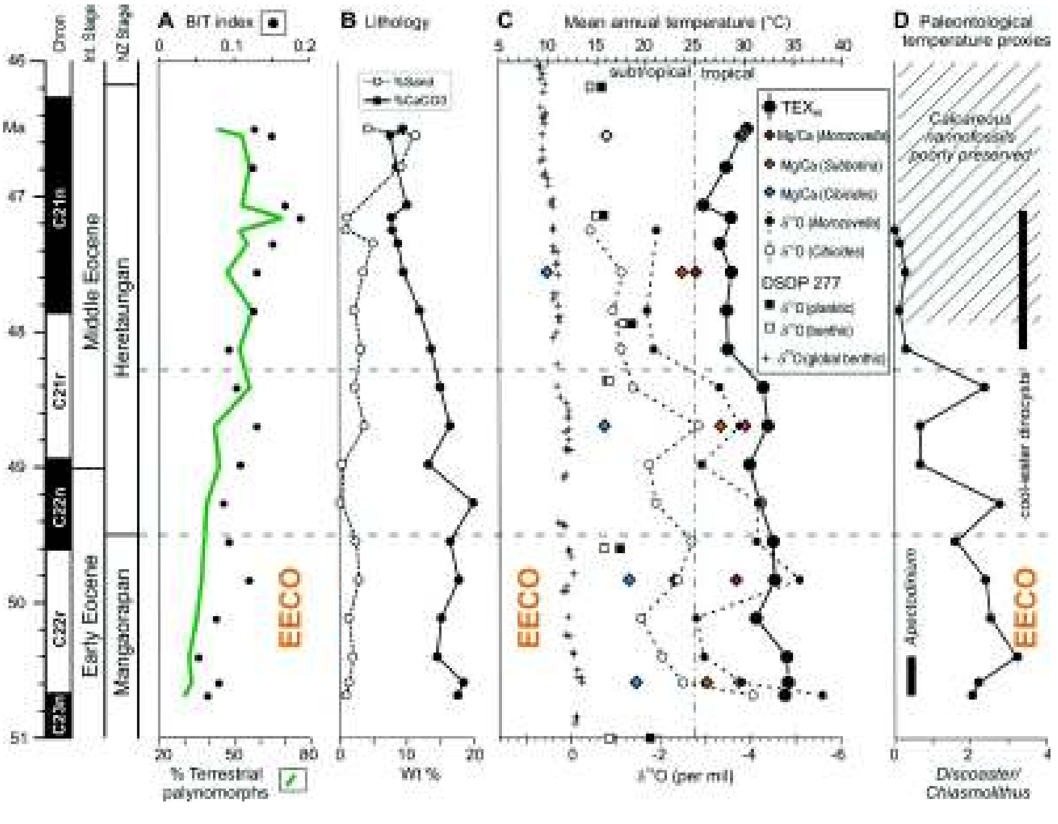


Figure 10. *Environmental and sea temperature changes through Ashley Mudstone, mid-Waipara River (from Hollis et al. 2009).*

In the context of the Ashley Mudstone record, the upper Waipara Greensand is similarly remarkable (**Fig. 11**). TEX_{86} results indicate a striking contrast to the tropical temperatures recorded in the Ashley Mudstone. Through most of this section, SSTs hover around 20°C but they fall to 17°C in an organic-rich, ^{12}C-depleted interval at the top of the formation. These geochemical characteristics, along with enrichment in C30 steranes, typify a widespread unit in the Late Paleocene of New Zealand – the Waipawa or Tartan Formation, which often has 4-10% TOC and is a known source rock for oil. Schiøler et al. (2010) have shown that this formation was deposited during regression, probably linked to a eustatic fall in sea level at the Selandian-Thanetian boundary (~59 Ma). In contrast to previous studies, which report an abundance of marine organic matter in the unit, Schiøler et al. (2010) contend that the organic content is primarily terrestrial, dominated by phytoclasts. Significant cooling linked to a global fall in sea level suggests growth of continental ice sheets at this time. This cooling event appears to be linked to the onset of the Paleocene Carbon Isotope Maximum (PCIM), an interval from 59-56 Ma in which $\delta^{13}C$ in deep sea carbonate (perhaps also terrestrial carbon) reaches peak values for the entire Cenozoic. The link between the cooling event and the PCIM, however, is still a matter of debate.

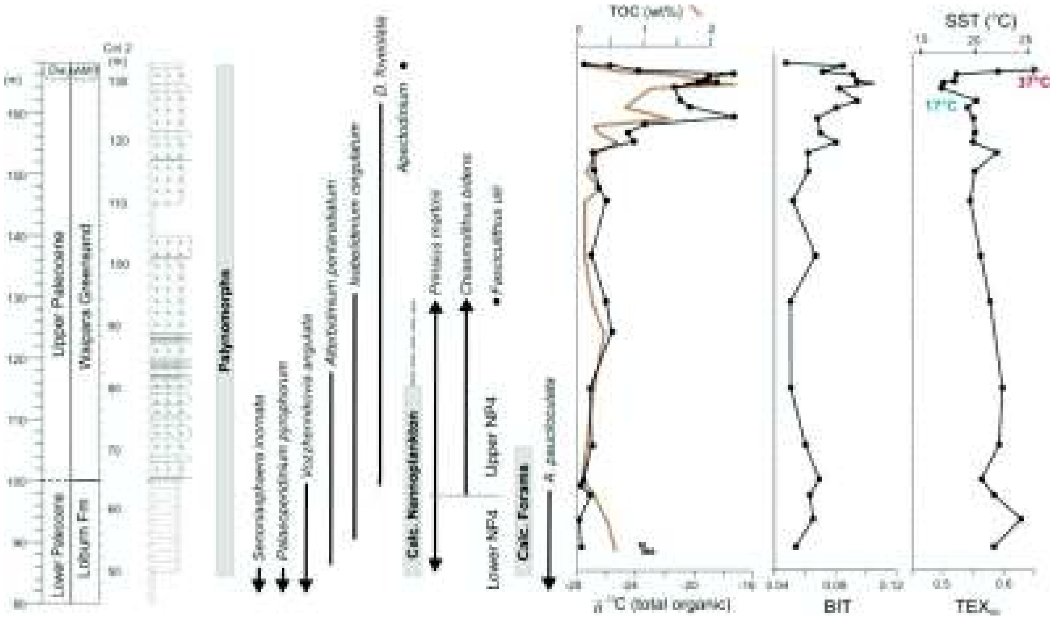


Figure 11. *Stratigraphy and environmental variation in upper Loburn Formation and Waipara Greensand, mid-Waipara River (Column 2).*

One further point of interest in the Waipara Greensand is the common occurrence of the problematic macrofossil now referred to *Waiparaconus zelandicum* (Withers, 1951), which we expect to see at Stop 1B. This bizarre organism forms curved, tusk-like, elongate tubes up to about 15 cm long, comprised of massive, thick overlapping calcite cones (**Fig. 12**). It was first recorded from the Waipara Greensand in the Waipara Gorge by Sir Julius von Haast (1871). To cut a long story short, this fossil has been interpreted variously as a barnacle (a view championed by the famous German palaeontologist Adolf Seilacher [Seilacher and Seilacher-Drexler 1986]), an annelid worm and, most recently, as a pennatulacean octocoral (Buckeridge et al. in press). *Waiparaconus* is apparently restricted to Upper Cretaceous to Eocene strata of the Southern Hemisphere, with records from New Zealand, New Caledonia, Western Australia, and Antarctica (Buckeridge et al. in press).

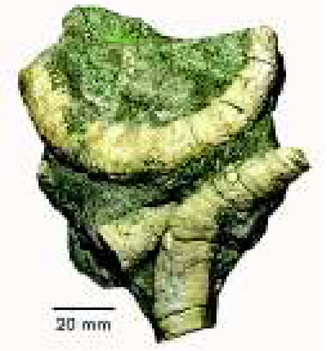


Figure 12. Waiparaconus zelandicum *(Withers, 1951) from the Waipara Greensand, Waipara.*

Kaikoura and SE Marlborough

This part of the excursion showcases the spectacular Upper Cretaceous to Eocene passive margin, fining-upwards succession of Kaikoura and SE Marlborough (**Fig. 12, 13**). We will examine how pre-existing topography, local tectonics, global climate change and extreme events are reflected in the local stratigraphy. At Woodside Creek, Mead Stream and Chancet Rocks we will view the best on-land Southern Hemisphere records of the K/Pg boundary in marine sediments and review local evidence for asteroid impact, mass extinction, collapse of the ocean ecosystem and long-term climate change in the context of almost complete survival of Cretaceous radiolarians.

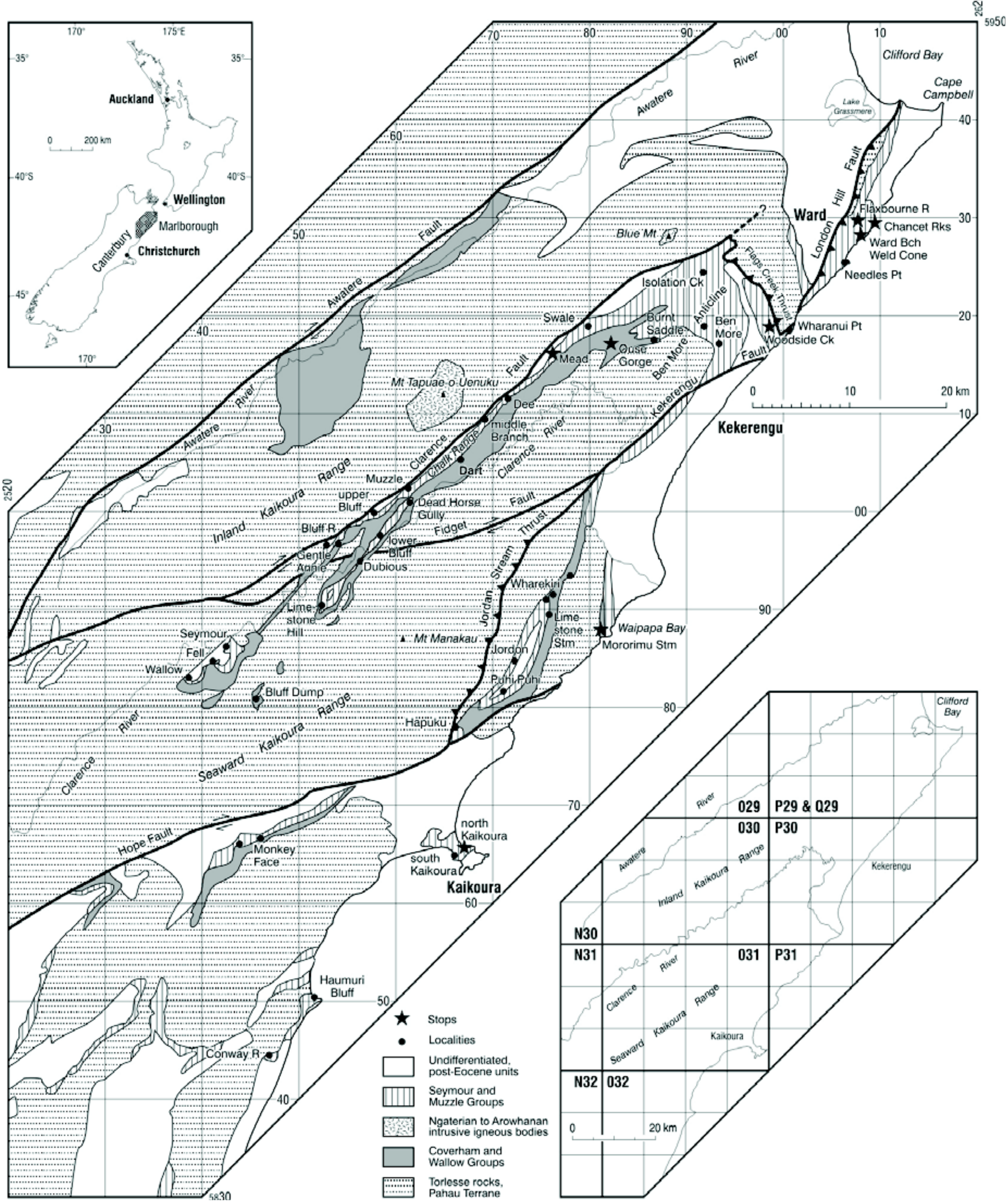


Figure 13 *Simplified geological map for eastern Marlborough and northern Canterbury showing field trip stops and other key localities for Cretaceous-Paleogene stratigraphy (after Crampton et al. 2003).*

At Mead Stream, a 650 m thick section through various pelagic facies of the Muzzle Group is a window into the evolution of the South Pacific Ocean from latest Cretaceous to Middle Eocene times: from chert-rich episodes of cooling in the Cretaceous and Early Paleocene to marl-rich episodes of extreme global warming in the early and middle Eocene, including a well-delineated record of the Paleocene-Eocene Thermal Maximum (PETM). At Mead Stream we will also view the Great Marlborough Conglomerate and the Clarence Fault, evidence of active tectonics in Miocene-Recent times.

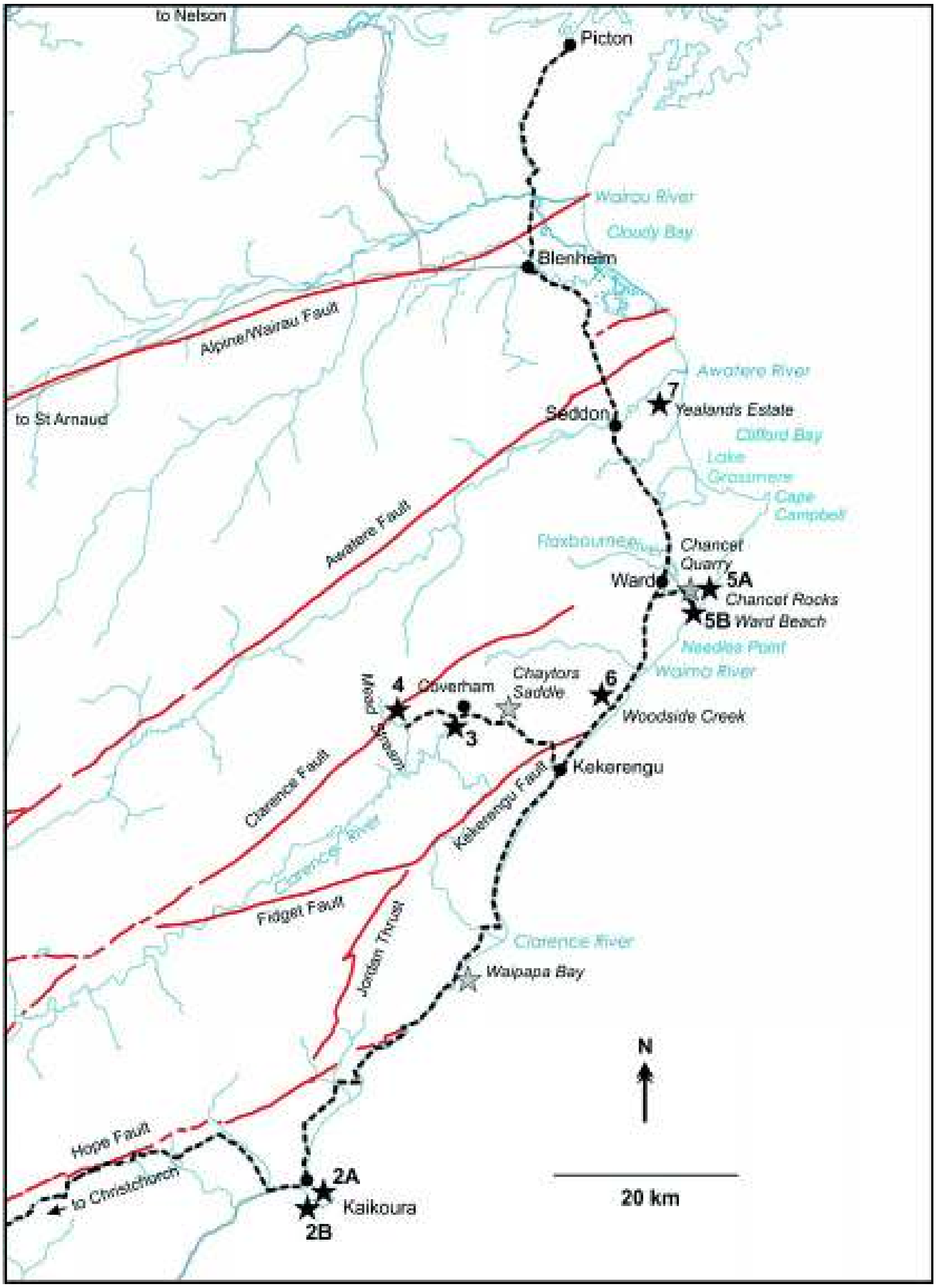


Figure 14. *Route map for Days 2 and 3, Kaikoura and Marlborough. Black stars = stops, grey stars = points of interest.*

We begin this part of the trip by examining correlative shallower facies of the Mead Stream succession at Kaikoura, in a micritic limestone succession of Late Cretaceous to early Miocene age, with major unconformities at the K/Pg, Middle/Late Paleocene and Eocene/Oligocene boundaries.

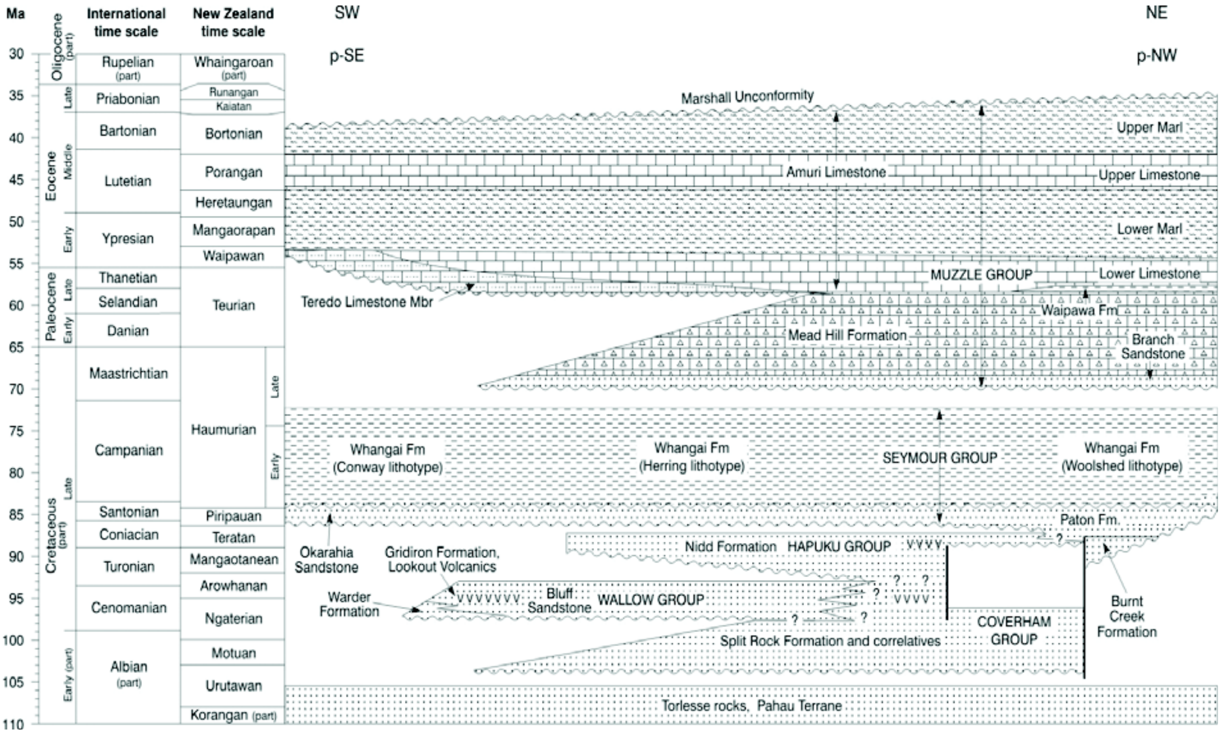


Figure 15. *Chronostratigraphy of Cretaceous and lower Paleogene sedimentary strata in SE Marlborough (after Crampton et al. 2003).*

Mesozoic siliciclastic sedimentary rocks

Mid-Cretaceous strata in SE Marlborough rest with angular unconformity on an indurated and highly deformed basement of the Early Cretaceous Torlesse composite terrane (Pahau terrane). This regional angular unconformity is the stratigraphic expression of a fundamental change in tectonic regime from compressional to extensional. Post-Torlesse extension resulted in block faulting and the local formation of half-grabens (**Fig. 15**).

The infilling mid-Cretaceous strata are represented over most of SE Marlborough by the Split Rock Formation of the Coverham Group. The formation is typically composed of one or more upward-fining units containing mass-flow conglomerate at the base, passing upwards through turbidites or other sediment gravity flow deposits into massive or laminated mudstone. Cenomanian time saw regional uplift, tilting and erosion of the Split Rock Formation, and deposition of nonmarine and shallow marine conglomerate, sandstone and mudstone accompanied by the widespread intrusion of dikes and extrusion of alkaline intraplate basalt, above a widespread unconformity. Deposition of these early Late Cretaceous sediments represents the onset of a period of slow subsidence interrupted by episodic relative sea level changes, represented by marginal and shallow marine sediments that onlapped pre-existing, paleo-NE-SW trending, faulted troughs and swells on the eastern edge of a large embayment in the paleo-Pacific continental margin (Crampton et al. 2003).

SE Marlborough is inferred to have experienced about 100° of clockwise, post-Oligocene, vertical-axis rotation (Townsend 2001). The mid-Cretaceous, NE-SW trending structures mentioned are, therefore, approximately *orthogonal* to the modern day NE-SW trend of the Clarence valley (Crampton et al. 2003) (**Fig. 16**).

A minor break in sedimentation occurs in the latest Cenomanian-Turonian condensed sequence of dominantly shallow marine clastic sediments (Hapuku Group; Nidd Fm in Coverham) overlying an erosion surface. There is no angular discordance at the basal contact, but there is a shallowing of facies across the erosion surface. The break is inferred to reflect a drop in relative sea level, superimposed on continuing regional subsidence. Recent carbon isotope analyses have demonstrated that the Cenomanian/Turonian boundary is preserved in the Nidd Formation at Coverham (Hasegawa et al. 2013). This boundary corresponds in many parts of the world to a major episode of black shale deposition, Oceanic Anoxic Event 2, a significant positive carbon isotope excursion, and perhaps a second-tier mass extinction event. In New Zealand, the boundary lies within an interval that is conspicuously barren of macrofossils but preserves evidence of enhanced sea-floor oxygenation; the significance of these observations remains unknown (Hasegawa et al. 2013). Based on these findings, the Cenomanian/Turonian boundary is now correlated with the uppermost Arowhanan New Zealand stage.

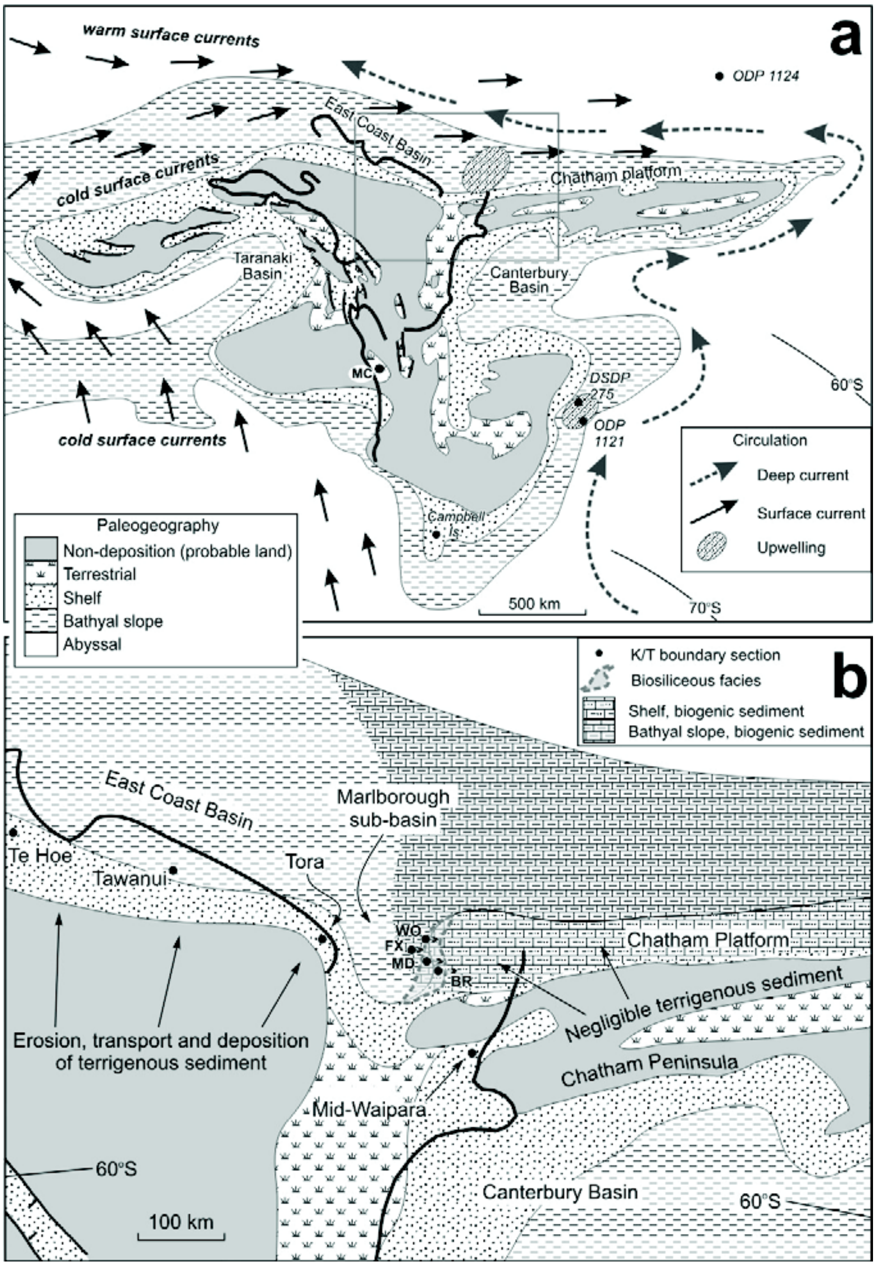


Figure 16. *Palinspastic reconstructions for the (a) New Zealand region and (b) central New Zealand for latest Cretaceous times (65 Ma). From Hollis (2003; after Crampton et al. 2003), with base map modified from King et al. (1999) and orientation and paleolatitude based on Sutherland et al. (2001).*

A further change in deposition occurred in the Coniacian. In the western part of the basin it is represented by an erosion surface, whereas in the east the break is represented by a rapid facies transition. A shallowing of facies occurs across the erosion surface: from outer shelf mudstones and slightly glauconitic sandstones to marginal marine or shallow marine sandstone, commonly highly glauconitic (Paton Sandstone). A relative sea level fall is again inferred, after which regional transgression resumed, resulting in deposition of dark grey or black jarositic and carbonaceous sandy to siliceous mudstone.

Under the broad definition adopted here, this unit and all other mudstone-dominated lithotypes (e.g. Herring and Woolshed formations) that overlie the Paton Formation or correlative sandstone facies and are unconformably overlain by Muzzle Group strata, are assigned to the Whangai Formation (Moore 1988). The Paton and Whangai Formations constitute the Seymour Group. The Whangai Formation is generally conformable on the Paton Formation, but detailed dinoflagellate biostratigraphy and quantitative biostratigraphic analysis indicate that the contact is a disconformity throughout Marlborough (Schiøler et al. 2002, Crampton et al. 2006).

The Seymour Group transgression is much more widespread and significant than earlier relative sea level rises. With initial deposition of the Paton and Whangai formations, the early Haumurian (84 Ma) marks the onset of a phase of fining upwards sedimentation, with some brief and notable interruptions, that continued into the Oligocene and reflects increased regional subsidence across a passive margin (Ballance 1993; Crampton et al. 2003).

The general deepening trend within the Whangai Formation was interrupted in latest Haumurian times in the southwest of the area by an erosion surface overlain by the shallow marine Branch Sandstone (basal Muzzle Group), a massive, moderately well-sorted, intensely-burrowed, fine-grained sandstone. This drop in relative sea level may have been related to tectonic events affecting parts of the South Island at about this time. Branch Sandstone is overlain conformably but sharply by siliceous biomicrites of the Mead Hill Formation. To the northeast, the Branch Sandstone is absent, and the Whangai Formation passes abruptly up into the Mead Hill Formation, which extends into the Paleocene (**Fig 15**).

A contrast in stratigraphy and depositional environment occurs in the coastal block lying east of the transpressional London Hill Fault, where the mainly fine-grained Whangai Formation is interbedded with thick bodies of mass-flow sandstones and turbidites. This block has an uncertain tectonic relationship to the remainder of Kaikoura-Marlborough (Crampton et al. 2003) and may be allochthonous.

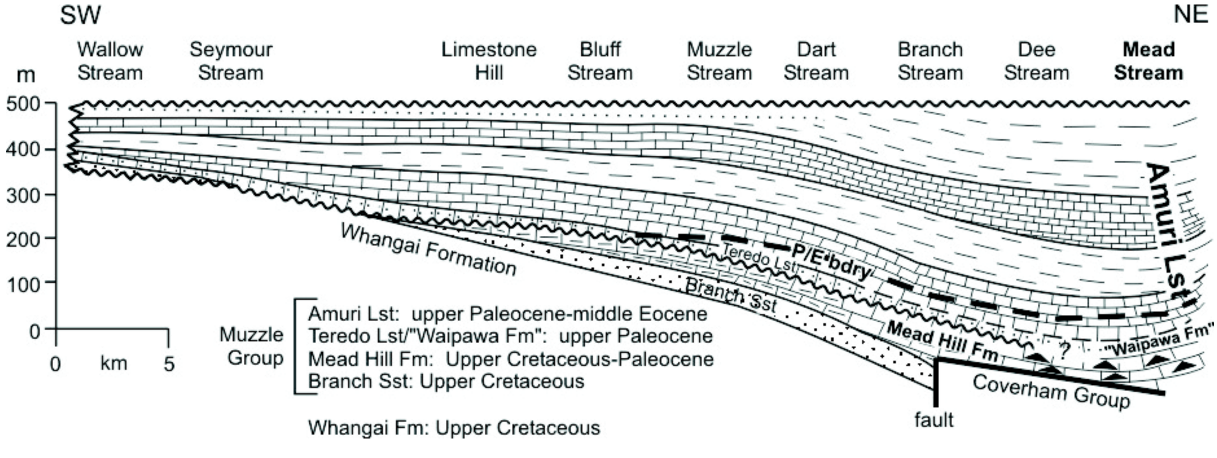


Figure 17. *Lithofacies trends within Muzzle Group strata in the Clarence valley (from Hollis et al. 2005a; after Reay 1993).*

Latest Cretaceous and Paleogene pelagic sediments

Foraminifera indicate a deepening trend, with increasingly oceanic conditions, from mid-shelf near the base of the Mead Hill Formation, to upper to middle bathyal (slope) depths throughout eastern Marlborough by the end of the Cretaceous (Strong et al. 1995). The catastrophic effects of the K/Pg boundary asteroid impact (Hollis 2003a, b), especially mass extinction of calcareous plankton (Strong 2000) and local deforestation (Vajda et al. 2001; Vajda & Raine 2003), complicate interpretation of the dramatic lithofacies changes that occur across the K/Pg boundary in Marlborough.

Increases in benthic foraminifera relative to planktics, siliceous microfossils relative to calcareous microfossils, diatoms relative to radiolarians, and biogenic silica and clay relative to carbonate are explained by a combination of factors (Hollis 2003a):

- mass extinction of calcareous nannoplankton and planktic foraminifera and associated reduction in carbonate accumulation rate (Strong 2000);
- almost complete survival of diatoms and radiolarians, resulting in sustained or increased biogenic silica accumulation (Harwood 1988; Hollis 1996);
- significant earliest Paleocene cooling and/or enhanced upwelling as evident from a c. 1 million year diatom bloom (Hollis et al. 1995, 2003a, b);
- a probable fall in relative sea-level as evident from basal Paleocene hiatuses and increases in terrigenous clay and terrestrial palynomorphs (Hollis 2003a, Hollis et al. 2003b).

The Paleocene portion of the Mead Hill Formation is present only in NE Marlborough (including Mead Stream, where it has its maximum preserved thickness), as it is truncated by a regional low-angle unconformity cutting across successively older formations to the south and southwest (Strong & Beggs 1990; Reay 1993; Hollis et al. 2005b: **Fig. 17**). Paleocene Mead Hill Formation is highly siliceous (massive chert at Mead Stream, bedded porcellanite at Woodside Creek and Flaxbourne River) at the base, but becomes moderately calcareous (thin-bedded biomicrites with chert ribbons at Mead Stream, thick bedded biomicrite with chert nodules at Woodside Creek) in the mid-Paleocene (63-60 Ma). The upper Paleocene (60-59 Ma) top of the formation is a moderately siliceous interval that is only seen in the northern Clarence valley (Dee, Branch, Mead and Swale Streams). At Mead Stream it is overlain by 2.6 m of dark grey siliceous mudstone, which is correlated with the Waipawa Formation based on its lithology and distinctive geochemical signature (Killops et al. 2000; Hollis et al. 2005a). The basal contact is sharp and possibly erosional. Overlying Waipawa Formation at Mead Stream and Mead Hill Formation in sections to the south are the basal lithofacies of the Amuri Limestone. In NE Marlborough the basal unit is the late Paleocene-early Eocene dm-bedded siliceous limestone (Lower Limestone lithotype). Further south the basal unit is the Teredo Limestone Member, a condensed unit of highly bioturbated calcareous greensand, which is also of late Paleocene-early Eocene age and is overlain either by Lower Limestone or Lower Marl lithotypes.

Throughout eastern Marlborough and Kaikoura, Amuri Limestone appears to have been deposited at mid- to lower bathyal depths in a terrigenous sediment-starved setting similar to the modern Chatham Rise or Hikurangi Plateau. The alternation between marl and limestone deposition operates on three scales:

- two long-term cycles from Lower Limestone to Lower Marl and Upper Limestone to Upper Marl
- several distinctive marl-rich intervals, the most thoroughly studied of which is the Dee Marl that corresponds to the PETM
- alternating beds of limestone and marl within the Lower and Upper Marl lithotypes

All three scales appear to be modulated by climatic influences with the marl-rich intervals corresponding to warm climatic episodes characterised by reduced pelagic productivity and increased terrigenous supply through enhanced precipitation, weathering and terrestrial erosion (Hollis et al. 2005a, b). The Lower and Upper Marl lithotypes are correlated to the Early and Middle Eocene Climatic Optima (EECO and MECO at 52-50 and ~40 Ma, respectively – Zachos et al. 2001; Bohaty and Zachos 2003). In contrast, the Waipawa Formation, Teredo Limestone and basal Lower

Limestone were deposited during a late Paleocene episode of relatively cool climatic conditions that is associated with high biological productivity in many oceanic regions (Hollis 2002; Hollis et al. 2005a) and is referred to as the Paleocene Carbon Isotope Maximum (PCIM). The Upper Limestone was also deposited during a time of relatively cool climatic conditions between the EECO and MECO, which is correlated with a widespread Porangan (early middle Eocene) unconformity in other New Zealand basins.

The Amuri Limestone is a distinctive East Coast biomicrite that extends from SE Wairarapa to Marlborough (Field et al. 1997), Canterbury and into the Great South Basin and Campbell Plateau. It has its most complete development in the Coverham-Mead Stream area of Marlborough, where it is 400 m thick. Here its middle Eocene (Bortonian) top is truncated by an Early Miocene unconformity, and the Late Eocene and entire Oligocene is missing, suggesting that it may have originally been much thicker. The base of the formation is diachronous. It is oldest in the Mead Stream area, and youngs steadily to the south and southwest to become restricted to the Oligocene in central and southern Canterbury.

A regionally extensive late Eocene-early Miocene (late Waitakian) unconformity truncates older rocks in Marlborough. The unconformity is overlain by up to 100 m of Waitakian limestone and calcareous sandstone (Weka Pass Stone and Whales Back Limestone), deposited in outer shelf and bathyal settings. These in turn are overlain by bathyal, blue-grey calcareous sandy siltstone (Waima Formation) of Otaian to Lillburnian (Early to Middle Miocene) age. The Waima Formation forms the background sediment into which the Great Marlborough Conglomerate (GMC) was deposited. The GMC comprises channelised cohesive debris flow deposits of mainly late Early Miocene (Altonian) age that crop out in many parts of southern Marlborough. These deposits, which consist mainly of Torlesse clasts, mark the first regionally significant uplift of greywacke fault blocks in New Zealand and the onset of the Kaikoura Orogeny.

Kaikoura

At Kaikoura we get our first opportunity to examine the Muzzle Group micritic limestones that will be central feature of the next 2 days (**Fig. 18**). We compare and contrast unconformities at the Eocene/Oligocene and Cretaceous/Paleocene boundaries and examine a limestone-marl succession that contains the EECO.

Once a sleepy town with a falling population, Kaikoura is now a bustling tourist destination thanks to "whale-watching". The nutrient-rich waters of the Kaikoura canyon, located a few hundred metres offshore, attract regular numbers of sperm whales throughout the year and a far greater number of whale-watchers. The peninsula comprises an Upper Cretaceous to Miocene sandstone-mudstone-micritic limestone succession folded around NE-trending fold axes. We will examine the SW-dipping sequence in the vicinity of localities 1 and 2 on **Fig. 18.**

STOP 2A: Kaikoura North Coast Shore Platform

The section exposed on the shore platform between the Canterbury University field station and the eastern side of the wharf comprises Upper Cretaceous Whangai Formation (the local name is Herring Formation), a macrofossil-bearing sandy limestone facies of the Mead Hill Formation, and an Amuri Limestone succession with spectacular bioturbation in the basal Teredo Limestone Member. The Whangai Formation contains huge spheroidal or lenticular dolomitic concretions, up to 3 m in diameter. They may be massive, concentrically zoned (**Fig. 19**) or with bedding preserved. In the upper 4-5 m of Whangai Formation, sediments are very disrupted and several of the concretions have phosphatised and bored outer margins (**Fig. 20**), which indicate that they have been exhumed and rolled on the seafloor – possibly in a high energy shallow marine setting. The implication here is that the concretions formed soon after deposition and then were exhumed by uplift or sea-floor erosion, colonised by shallow-marine rock borers and then transported into a deeper marine setting by slumping (Browne 1985; Browne et al. 2005).

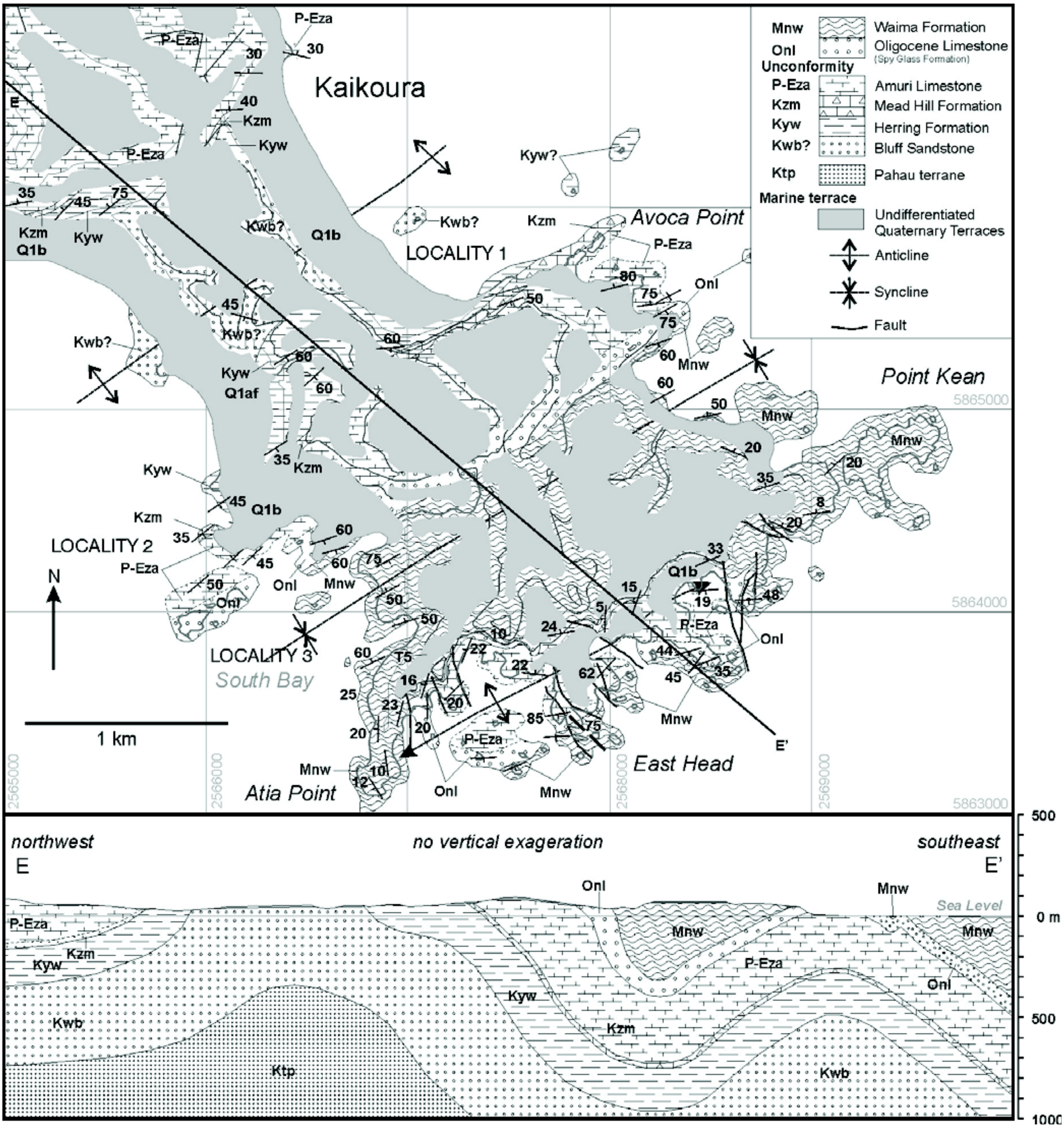


Figure 18. *Geological map and cross-section of Kaikoura Peninsula (from Browne et al. 2005; modified from Rattenbury et al. 2006).*

__Figure 19.__ Large dolomitic concretion with concentric banding and a light grey siliceous core. Scale bar is 50 cm long (from Browne et al. 2005).

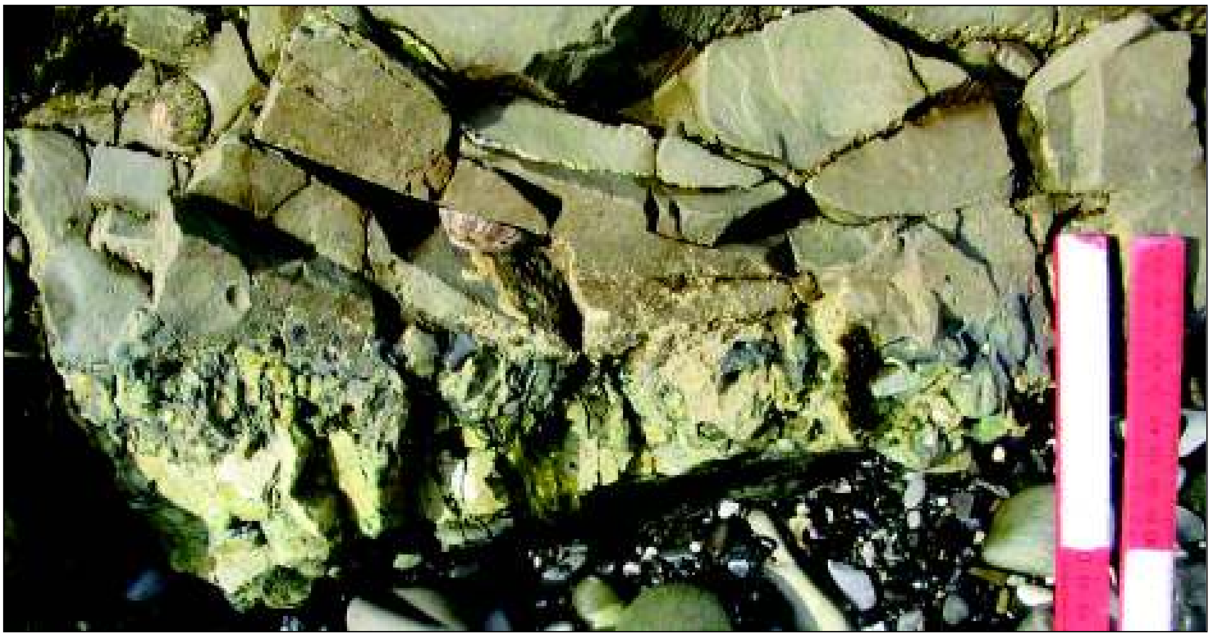


__Figure 20.__ Phosphatised and bored outer margin of dolomitic concretion. White band on ruler = 10 cm (from Browne et al. 2005).

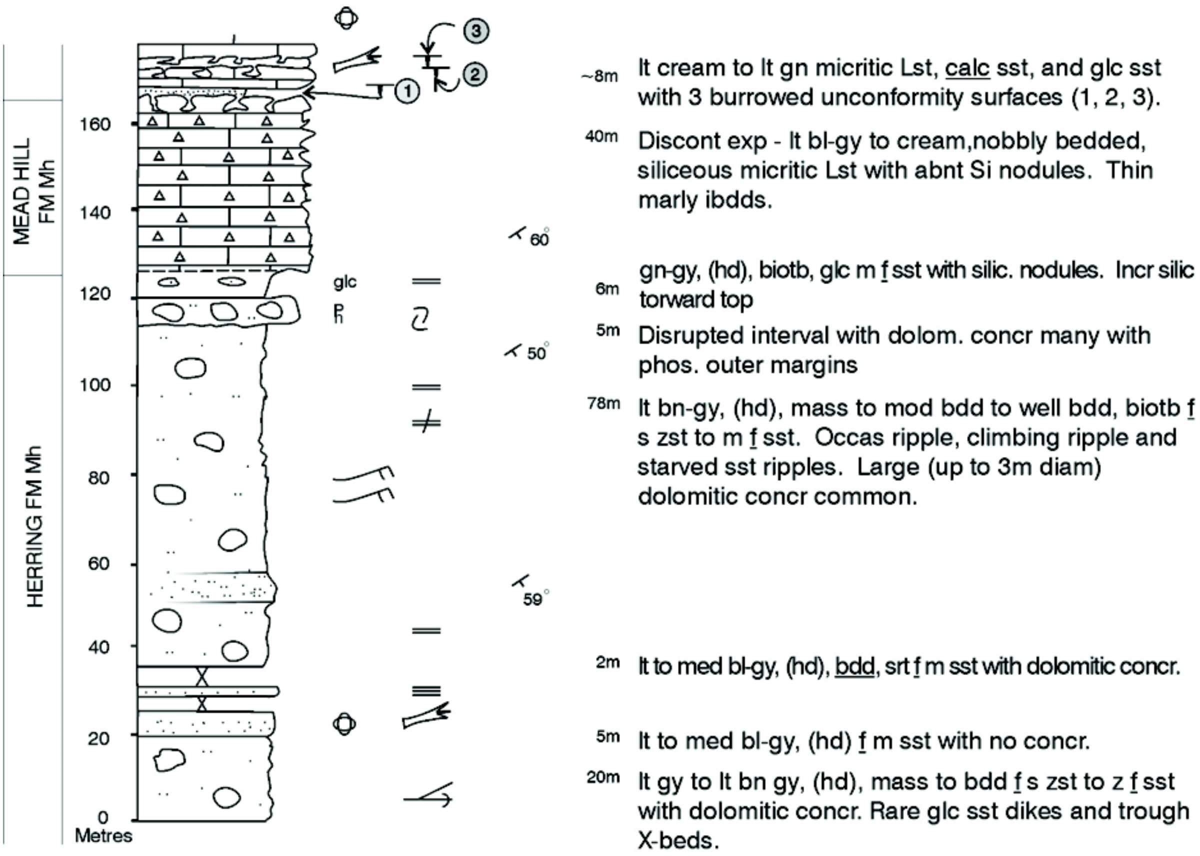


Figure 21. *Stratigraphic section on shore platform, north side of Kaikoura Peninsula (from Browne et al. 2005).*

The overlying interval is rich in glauconite and passes gradationally into the Mead Hill Formation. This formation differs from that seen to the north in eastern Marlborough in several respects: it is rich in glauconite, at least in the lower part; it is sandy throughout; apparent chert nodules (as recorded in **Fig. 21**) are in fact micritic limestone; and several intervals contain macrofossils, including brachiopods, bivalves and echinoid spines. These features imply significantly shallower depositional conditions than in the northern Clarence valley or northeastern Marlborough. The unit still has knobbly bedding, which is typical of Mead Hill Fm throughout the region.

To view the truncated top of the Mead Hill Formation, we cross the road and walk to the eastern side of the wharf, past the hotel and fish factory. A least three heavily burrowed unconformities can be seen in the Mead Hill Formation–Teredo Limestone succession here (**Fig. 21**). Preliminary foraminiferal ages indicate that the Teredo Limestone is Paleocene at the base and Early Eocene (Waipawan) near the top (P. Strong pers. obs.).

The highly condensed or truncated K/Pg boundary succession in these Kaikoura sections is also seen in Clarence valley sections south of Mead Stream (Hollis et al. 2005b) and suggests that a significant fall in sea level or intensification of bottom current flows occurred in Paleocene times. Both are consistent with the cool-water upwelling regime evident in the Marlborough Paleocene sections to the north (Hollis 2003a, Hollis et al. 2005a). Similar evidence for Paleocene cool-water flows with or without sea-level fall is found on the Chatham Islands to the east (Hollis 1995), and Campbell Plateau to the southeast (Hollis 2002).

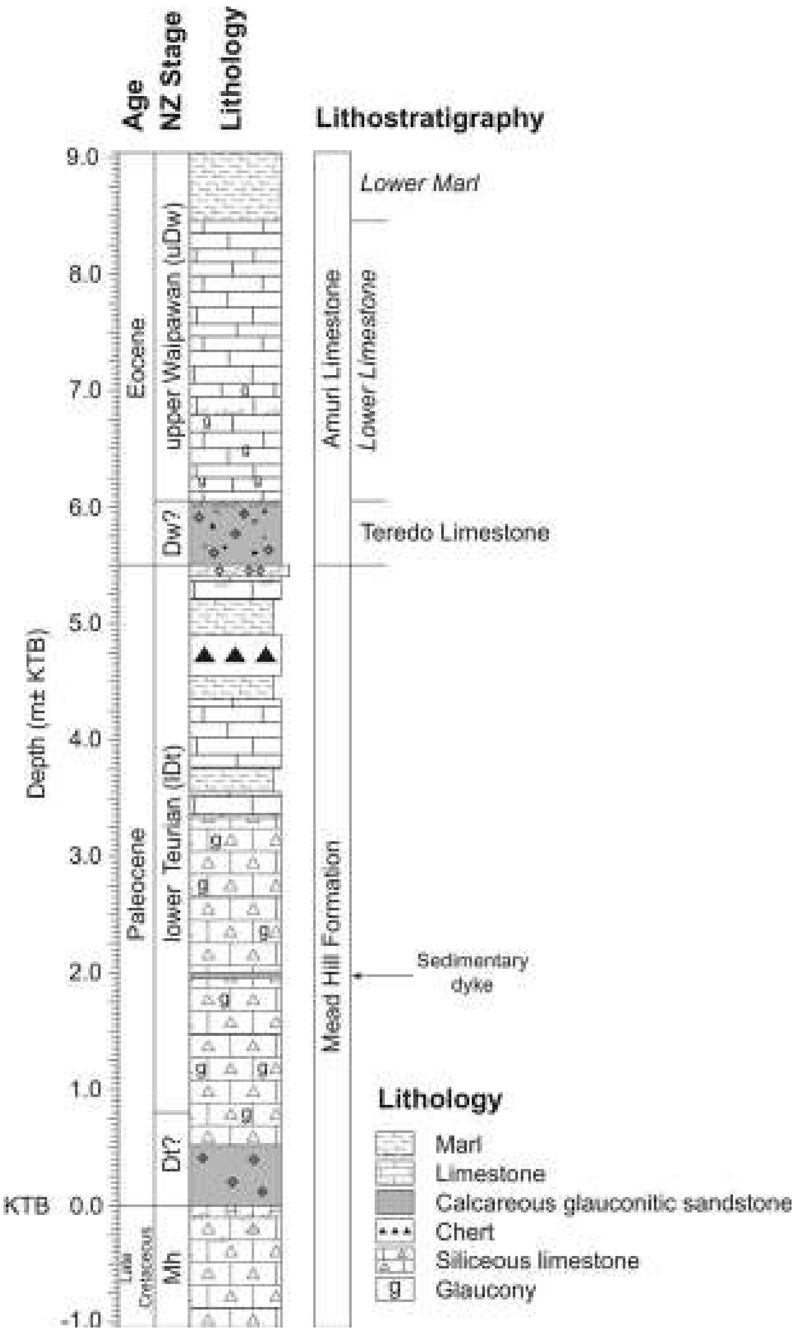


Fig. 22. Stratigraphic section through two unconformities separating Upper Cretaceous, Paleocene and Eocene strata, Kaikoura Wharf section (from Andrew 2010).

Kaikoura Field Station ("Kaikoura Lab" section)

The Kaikoura "lab" section is exposed in a gully behind the University of Canterbury field station (**Fig. 24**). Cretaceous Mead Hill Formation is disconformably overlain by 7 m of Teredo Limestone, which is overlain by 30+ m of Amuri Limestone. Foram biostratigraphy indicates a Waipawan to Mangaorapan (Early Eocene) age for the Amuri succession. The Teredo Limestone is overlain by Lower Marl, which is capped by the cliff-forming Upper Limestone. In contrast to the middle Clarence valley sections at Muzzle and Bluff Stream (Hollis et al. 2005b), Lower Limestone is missing or very condensed in this section.

STOP 2B: Kaikoura south coast: Marshall Unconformity

The focus of this stop is the Eocene–Miocene section (**Fig. 22**). Here we have our first chance on this trip to view the Marshall Unconformity: an erosional episode centred in the early Oligocene that is found throughout the SW Pacific and is thought to mark initiation of Antarctic-sourced deep-water flow in response to Antarctic glaciation (Carter et al. 2004). Consider how this erosional record differs from the Paleocene unconformity at the base of the Teredo Limestone that we will see at the next stop. Here the Marshall Unconformity separates Middle Eocene Amuri Limestone and early Miocene Spy Glass Formation. A layer of chert nodules is seen in the lower part of the Spy Glass Formation, which is overlain by a thick fining-upward succession of Early to early Middle Miocene sandstone and siltstone (Waima Formation). While the oceanographic interpretation of the Marshall Unconformity has dominated the literature, this locality shows that the unconformity is clearly angular, truncating the uppermost bed of Amuri Limestone. This suggests that tectonics may have some role to play in the development of this widespread event (see Sutherland et al. 2010).

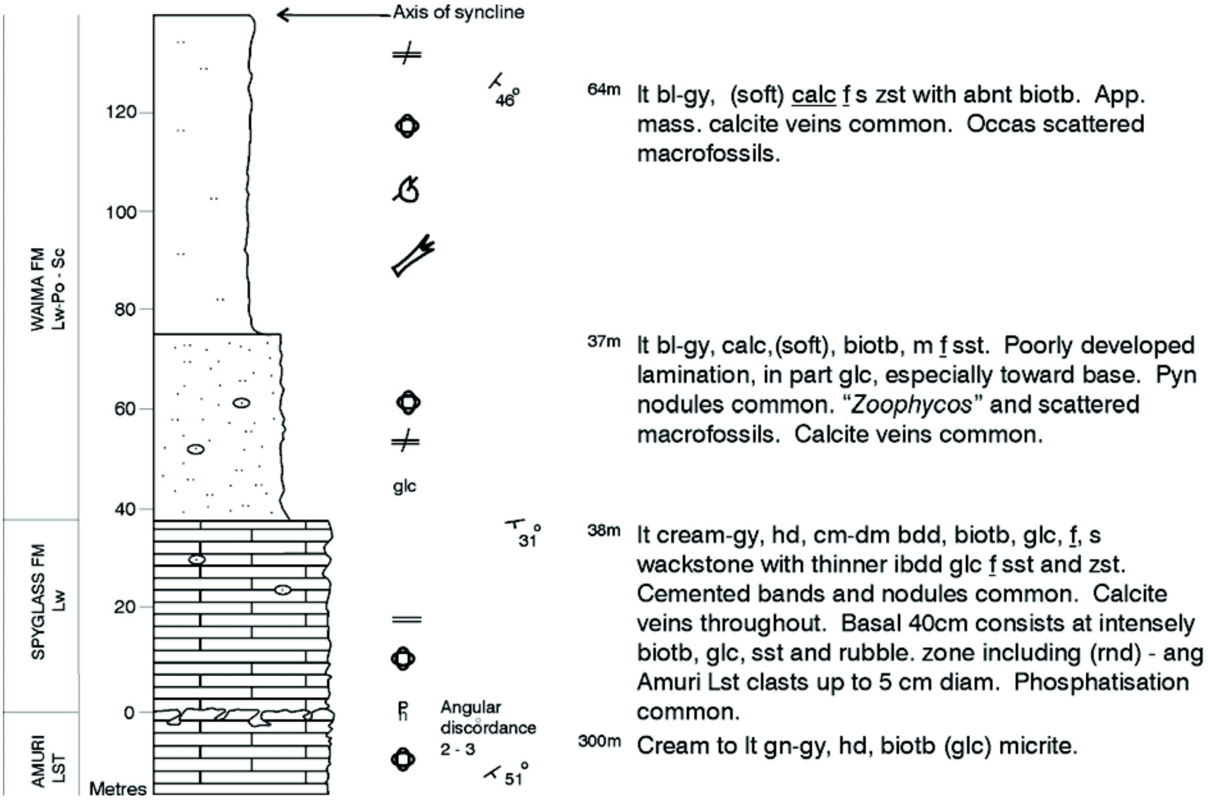


***Figure 23.** Stratigraphic section of Eocene to Miocene rocks on south side of Kaikoura Peninsula (from Browne et al. 2005).*

At South Bay the Amuri limestone is a micritic limestone (**Fig. 24**) with sparse glauconite and rare chert. Fossil content is dominated by planktic forams in a mud matrix. The unconformity between the Amuri and Spyglass reflects a break in deposition as well as probable erosion and spans approximately 7 Myrs or Late Eocene to Mid-Oligocene (Rattenbury et al 2006). The upper Amuri is intensely burrowed and bored, indicating the development of a hardground surface (**Fig. 25**). The base of the Spyglass Formation has pebbles and cobbles of Amuri Limestone that are variously glauconitised. In outcrop some large fragments appear glauconitised but slabbed specimens show many larger Amuri clasts have only a veneer of glauconite, where others, often the smaller clasts, are quite heavily glauconitised. This variation in glauconitisation indicates that although this surface is relatively long-lived, clasts of Amuri were being derived from erosion of this surface right up to the time of deposition of the Spyglass.

The Spyglass Formation has similar components to the Amuri Limestone; planktic foraminifera, micrite, glauconite and chert but in distinctly different proportions. Texturally the Spyglass is a wackestone to packestone composed of abundant planktic foraminifera with sparse mud. This fits the model of increased deep water currents following the inception of the DWBC (Carter et al. 2004) – a continued supply of planktic forams to the seafloor, but with the inception of deep-water currents the mud that dominates the Amuri Limestone is not able to accummulate. Glauconite occurs throughout and discrete horizons are conspicuous, but probably reflect both depositional processes (periodic winnowing leaving a lag of heavy minerals) and concentration by pressure dissolution during diagenesis.

Figure 24 *– The steeply east-dipping Amuri Limestone and Spyglass Formation in South Bay. The Marshall Unconformity is well exposed in the prominent under-hang, and note the angular nature of the unconformity.*

Figure 25 *– Detail of the Marshall Unconformity – showing Spyglass filled burrows and borings and prominent glauconitised pebble horizon, and chert nodules in the lower Spyglass.*

Day 2 (Friday 29 November): Mead Stream & Ouse Gorge

The drive to the Mead Stream section takes about 2 hours and passes through some dramatic scenery and geology. After leaving Kaikoura, we travel north along the coast to the mouth of the Kekerengu River. We pass spectacular coastal exposures of Pahau Terrane greywacke, a popular haunt for NZ fur seals.

In the railway cutting at Waipapa Bay, there is a condensed section through the upper Whangai Formation, Branch Sandstone and basal Mead Hill Formation (**Fig. 26**). Morris (1987) logged a full Muzzle Group succession from Branch Sandstone to Upper Marl in this area but so far the shore platform has only yielded Late Paleocene radiolarian ages, which are indicative of Paleocene Mead Hill Formation. Siliceous biomicrites on the shore platform were assumed to be younger Amuri Limestone by Morris (1987).

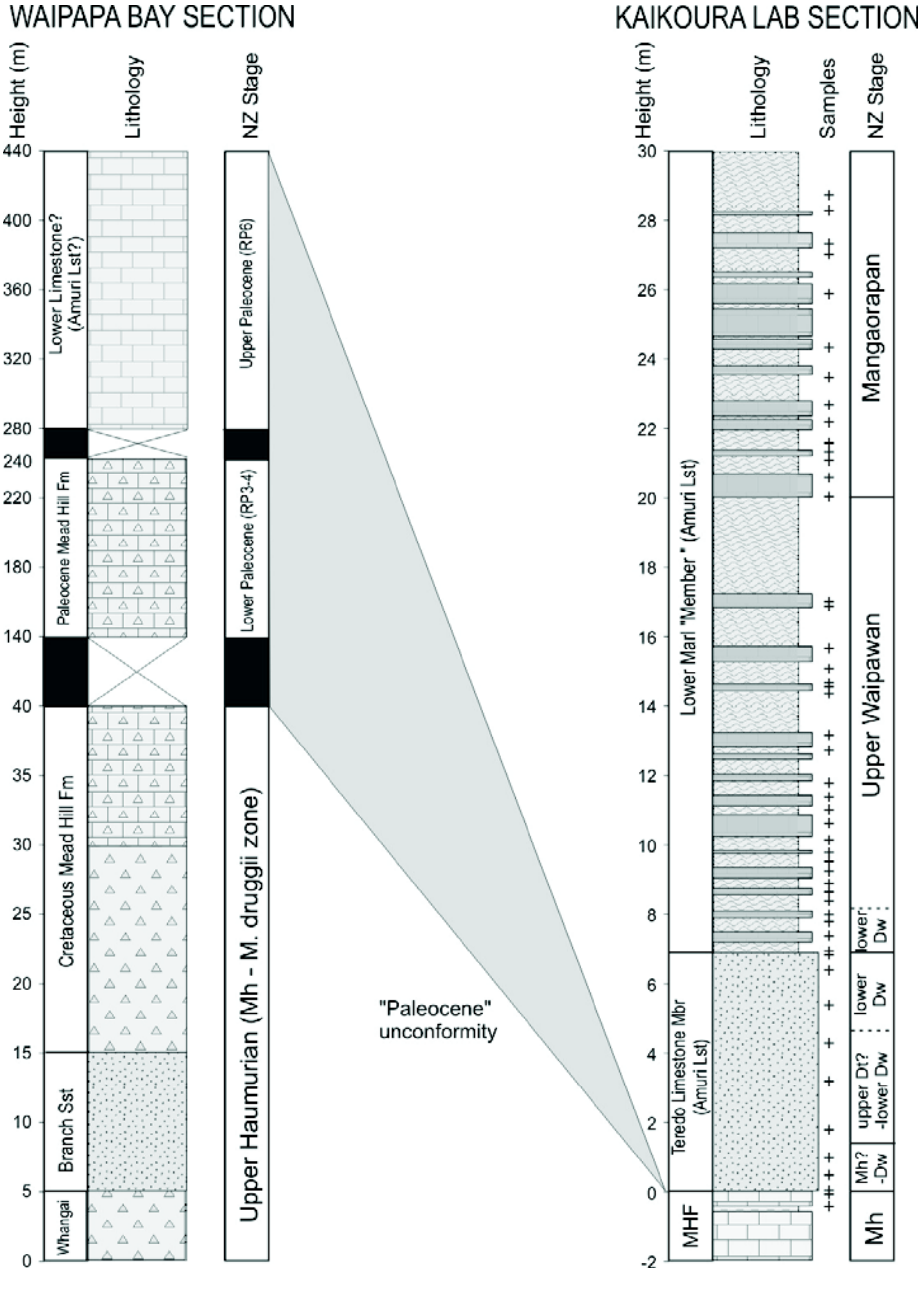


Figure 26. Stratigraphy of Waipapa Bay and Kaikoura "lab" sections. Age control is based on preliminary radiolarian, dinoflagellate, planktic foram and nannofossil biostratigraphy.

At Kekerengu our route leaves State Highway 1 and turns inland, heading up the Kekerengu River valley. Approximately 3 km from the coast we cross the Kekerengu Fault, an active strike-slip fault with perhaps 5-15 km of total Neogene dextral displacement (Crampton et al. 2003). A short distance further on our route leaves the river and climbs the southern side of the valley. From this point onwards we are on private land of Bluff Station, formerly one of New Zealand's largest freehold stations and still a formidably large property. The farm road ascends the northern end of the Sawtooth Range, the continuation of the Seaward Kaikoura Range north of the Clarence River gorge. We cross Chaytors Saddle at 700 m. *En route* the road passes through indurated, occasionally photogenically-deformed flysch, sandstone and polymict pebble conglomerate beds up to 50 m thick, all included within the Pahau Terrane. Below, in the Kekerengu valley, these strata contain Early Cretaceous inoceramid macrofossils.

Figure 27. *View from the crest of the Chalk Range, west of Coverham, looking SW into Clarence valley. Mt Tapuae-o-Uenuku is the high point on the Inland Kaikoura Range to the right. The Chalk Range is a strike ridge of Late Cretaceous-Eocene limestone that runs immediately east of the Clarence Fault. The low country in the centre of the view is mid- to Late Cretaceous mud-dominated strata. Photo J. Crampton.*

Chaytors Saddle

At Chaytors Saddle there are spectacular views eastwards over the Coverham area and south along the Clarence valley. The foreground comprises generally NW-dipping, stratigraphically complex mid- to Late Cretaceous rocks. These strata unconformably overlie Pahau Terrane rocks that form the Seaward and Inland Kaikoura Ranges bounding the Clarence valley. Extending up the valley, on its western side, is a conspicuous white-coloured range, the Chalk Range, which is a fault-bounded strike ridge of latest Cretaceous and Paleogene chert and limestone (**Fig. 27**). Several dramatic and sometimes physically challenging gorges cut through this range: Mead Stream being the most salubrious. Immediately west of the Chalk Range is the Clarence Fault that bounds the high country of the Inland Kaikoura Range. Mount Tapuae-o-Uenuku dominates the range at a height of 2885 m (and rising).

From Chaytors Saddle the road descends into Burnt Stream and the Clarence River catchment. Burnt Stream is the type section for the Late Cretaceous Burnt Creek Formation that rests unconformably on Pahau Terrane rocks (Crampton & Laird 1997). The road fords Wharf Stream and immediately crosses the Ouse Fault that separates Burnt Creek Formation from Late Cretaceous Whangai Formation. The Ouse Fault is well exposed in the road cut and is inferred to have been a mid-Cretaceous normal fault that was reactivated as a reverse fault in the Miocene (Crampton & Laird 1997). From Wharf Stream the road crosses a low ridge and descends to Coverham homestead, sometimes home to musterers of Bluff Station.

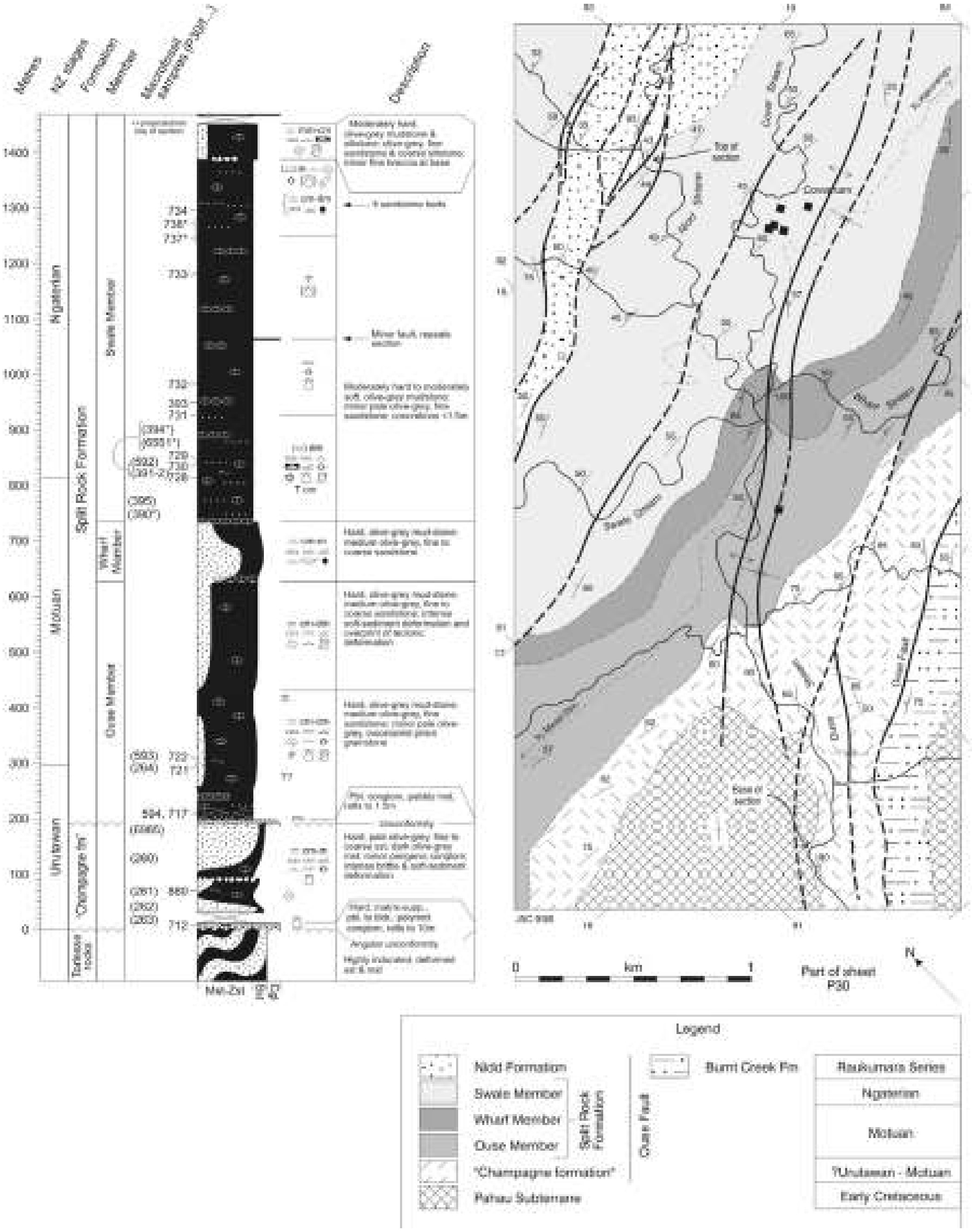


Figure 28. *Measured section and geological map for mid-Cretaceous strata exposed in Ouse Gorge and Nidd Stream (after Crampton et al. 1998).*

Stop 3: Top of Ouse Gorge

At the top of the Ouse Stream gorge in Coverham, we will examine part of the mid-Cretaceous basal "cover" sequence. The Ouse Gorge-Nidd Stream section at Coverham is one of the classic stratigraphic locales in New Zealand that has been key to the development of Cretaceous biostratigraphy and interpretations of Cretaceous geological history in this country (McKay 1886; Woods 1917; Thomson 1919; Wellman 1955; Hall 1963, 1964; Gair 1967; Henderson 1973; Ritchie 1986). Because of stratigraphic and structural complexity, interpretations of the succession and geology have varied widely. The unconformity at the base of the Split Rock Formation has been at the centre of controversies surrounding the reality, nature and expression of a regional mid-Cretaceous unconformity that supposedly resulted from peneplanation following the Rangitata Orogeny. Thus, for example, Wellman (1959: p. 131) stated that "… deposition may have been substantially continuous over parts of New Zealand from the Jurassic until the Cretaceous.". In contrast, Gair (1967: p. ii) concluded that "… the Rangitata Orogeny and subsequent peneplanation were New Zealand-wide in extent …".

Until the work of Ritchie and Bradshaw (1985) and Ritchie (1986), the boundary between Torlesse rocks (i.e., Pahau Terrane) and "cover" sequences in the Coverham area was generally placed at the base of the Ouse Member, lowest member of the Split Rock Formation (e.g., Gair 1967). Some authors, however, had noted the presence of pebble-cobble conglomerates further down the Ouse Stream and had speculated on their significance (e.g., Thomson 1919). In an important contribution, Ritchie (1986) clarified many of the stratigraphic and structural relationships in the Coverham area and recognised that there was another unconformity-bounded cover unit, the Champagne Member, which underlies the Ouse Member. Ritchie (1986) regarded this unit as a member of Split Rock Formation. Subsequently, it has been elevated to "Champagne formation" (informal) by Crampton and Laird (1997) and Crampton et al. (2004). Importantly, this unit is lithologically and structurally very similar to older Pahau Terrane rocks, but it has a map distribution that parallels the Split Rock Formation and cuts across form-lines in the underlying Pahau Terrane, although an angular unconformity is not demonstrable in many outcrops.

During this field trip we will examine upper parts of the Champagne formation and lowest parts of the Split Rock Formation at the top of the Ouse Gorge (**Fig. 28**). Unfortunately the basal contact of the Champagne formation is not well exposed in the upper gorge but crops out about 1 km downstream and is well exposed some 2 km along strike and downstream. The basal part of the formation comprises polymict, pebble to cobble conglomerate at least 10 m thick. This is overlain by c. 170 m or more of highly deformed, centimetre to metre interbedded sandstone and mudstone. The lower part is mudstone-dominated; the upper part is sandstone-dominated. Deformation includes both pervasive(?) soft-sediment deformation (**Fig. 29**) and brittle, tectonic deformation related to Neogene folding and, possibly, Cretaceous faulting on the Ouse Fault (**Fig. 28**).

***Figure 29**. Soft-sediment deformation within "Champagne formation" in Ouse Gorge. Bedding strikes away from the viewer. Hammer handle 50 cm long.*

Champagne formation is inferred to represent the deposits of large slumps or debris flows, and other gravity flow processes, into a mid-Cretaceous fault-bounded basin. As such, it may be a lateral equivalent of similar, widely distributed, mélange-like formations such as Gentle Annie Formation in Wairarapa-southern Hawkes Bay (Crampton 1989) and the Oponae Mélange in the Raukumara Ranges (Feary 1979). Macrofossils and microfossils collected from Champagne formation indicate an Urutawan age (Crampton et al. 2004).

Unconformably overlying Champagne formation is the Ouse Member of the Split Rock Formation of Suggate (1958). This member is dominated by silty mudstone and subordinate, centimetre to decimetre-bedded sandstone, and it is affected by intense soft-sediment and tectonic deformation. The base of the member comprises 8 m of conglomerate and pebbly mudstone overlain by a spectacular, 20 m thick inoceramid bivalve shellbed dominated by *Mytiloides ipuanus* (Wellman, 1959). The base of the Motuan Stage, defined by the lowest occurrence of the small bivalve *Aucellina euglypha* (Woods, 1917), is about 100 m above the *M. ipuanus* shellbed.

At this outcrop we will have 30-40 minutes to:

- discuss the Torlesse-like nature of the Champagne formation and try to convince ourselves that it is indeed *not* Torlesse;
- consider some of the multifarious interpretations of mid-Cretaceous stratigraphy of the Coverham area in the context of understanding New Zealand-wide geological history;
- ruminate in the footsteps of pioneering New Zealand geologists – McKay, Hector, Thomson and Wellman.

Figure 30. *Muzzle Group strata exposed on the southern face of the Mead Stream gorge.* Photo: C. Hollis

Stop 4: Mead Stream

Mead Stream is one of New Zealand's finest geological marvels! It offers a near complete record of bathyal pelagic sedimentation from Late Cretaceous to Middle Eocene times: a 40 million year record that includes the Cretaceous/Tertiary mass extinction, one the three largest biological catastrophes in Earth history, as well as one of the best known ancient analogues for extreme global warming, the Paleocene-Eocene thermal maximum (PETM).

Capping this record is a major erosional event associated with the opening of the Tasmanian/ Antarctic Gateway and intensification of southern-sourced currents. The resumption of sedimentation in the Miocene heralds the onset of the Kaikoura Orogeny, with deposition of the 260 m thick Great Marlborough Conglomerate – a spectacular record of submarine avalanches and debris flows resulting from the rapid uplift and erosion of inland fault blocks. The unit is truncated by the active Clarence Fault – one of the principal elements of the Marlborough fault system with a current right-lateral slip rate of 5 mm/yr (Nicol & Van Dissen 2002).

The drive down into Mead Stream gorge offers stunning views of the Muzzle Group succession from the sharp (probably faulted) contact with underlying Split Rock Formation to the recessive bands that represent the Lower and Upper Marl lithotypes of the Amuri Limestone (**Fig. 30)**. The massive chert that overlies the K/Pg boundary forms a distinct dark band in the nearest face. We leave the vehicles on the northern (true left) side of the stream bed and proceed upstream, past Split Rock Formation outcrops, before crossing the stream, climbing over a small hill, and entering the main (southernmost) Mead Stream gorge.

Mead Hill Formation: the K/Pg Boundary

Strong et al. (1995) presented a general biostratigraphic and paleoenvironmental overview of the Late Cretaceous to middle Eocene Muzzle Group sequence, which has been followed by detailed studies of the K/Pg and Paleocene/Eocene boundary intervals (Hollis et al. 2003b, 2005a). The Neogene succession was described by Browne (1995).

The logged section starts at the faulted base of Mead Hill Formation against mid-Cretaceous Split Rock Formation. The abundance of dolomite nodules and foraminiferal evidence for relatively shallow water depths indicate we are close to the base of the Mead Hill Formation. Dolomite seems to have formed in Mead Hill Formation when there was a slightly higher terrigenous content than typical, as is found near the base of the formation and just above the K/Pg boundary, suggesting that the magnesium is derived from alteration of clay minerals. Above this level, about 150 m of dm-bedded siliceous limestone, with lenticular chert nodules, is typical Cretaceous Mead Hill Formation, made more photogenic by the Marlborough rock daisies (*Pachystegia insignis*).

The K/Pg boundary (**Fig. 31**) is a sharp planar contact separating pale siliceous limestone from a 2.5 m interval of dolomitised chert and porcellanite, overlain by 18 m of m-bedded black chert. These two Paleocene units represent 1-2 million years of radiolarian-diatom ooze deposition following the K/Pg boundary, prior to a relatively rapid return to more typical Mead Hill Formation sediments in the overlying ribbon cherts.

Stratigraphic completeness?

An intriguing feature of Marlborough K/Pg boundary sections is that although all of them have a thin boundary clay or zone enriched in iridium and associated indications of the K/Pg asteroid impact, only Chancet Quarry (Flaxbourne River) has biostratigraphic evidence for completeness, i.e. it is the only section in which all earliest Paleocene foraminiferal zones have been identified (Strong 2000). Because the basal Paleocene is too hard to yield forams, completeness has yet to be established for Chancet Rocks and Wharanui Point sections. But both Needles and Woodside sections are biostratigraphically incomplete because basal Paleocene sediments contain foraminifera that only appear 100,000 years after the K/Pg boundary. For Woodside Creek this implies that the boundary clay is not primary fallout but redeposited, a feature that is difficult to reconcile with the high iridium anomaly, abundant "soot", the presence of so-called fullerenes (Hollis et al. 2003a) and the impact "rain drops" evident on the top Cretaceous bedding plane.

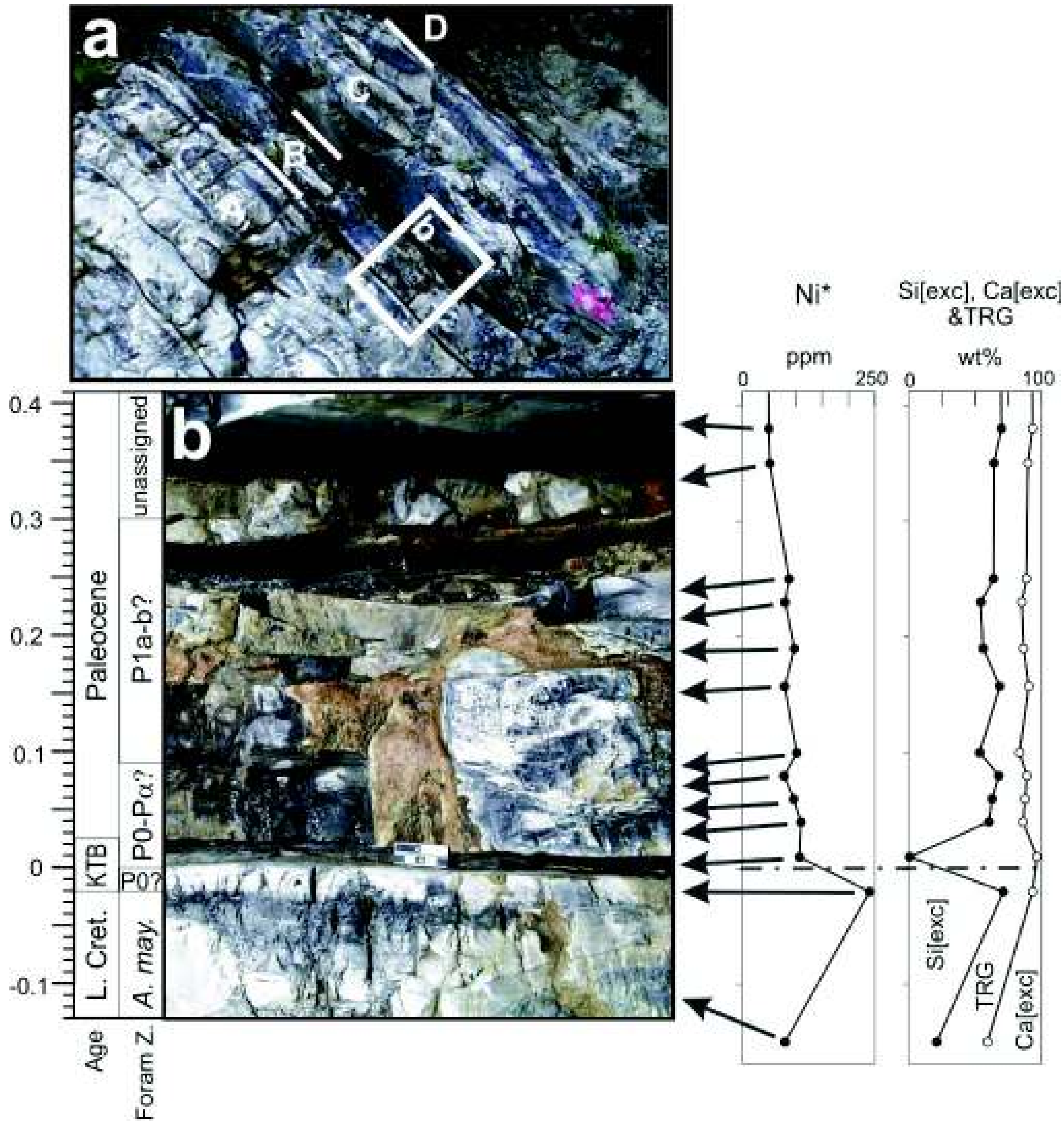


Figure 31. The K/Pg boundary at Mead Stream showing a nickel anomaly and earliest Paleocene forams in the top of the uppermost Cretaceous limestone (from Hollis et al. 2003b). Photos B. Field.

Even more curious, the boundary clay at Mead Stream is a normal clay that has no geochemical anomalies at all (**Fig. 31**). Instead, earliest Paleocene forams (*Guembelitira cretacea* Zone) and the geochemical anomaly reside in small burrow fills in the top Cretaceous limestone (Hollis et al. 2003b). A similar K/Pg boundary record has been described from deep sea sediments on the Shatsky Rise, North Pacific (Bralower et al. 2002). The conclusion to draw from this is that despite the superficial similarities, events at the K/Pg boundary affected each section slightly differently: steady deposition at Flaxbourne River, initial deposition then erosion at Mead Stream, and deposition at Woodside Creek followed by erosion and redeposition of fallout material.

The Paleocene Carbon Isotope Maximum

The Mead Hill Formation is overlain by what we now identify as the Waipawa Formation (**Fig. 32**) – the same organic-rich mudstone that is the primary hydrocarbon source rock in eastern North Island (Hollis et al. 2005a). Here, the unit is more siliceous and better bedded than typical Waipawa Formation but it still bears the unique $\delta^{13}C$ and biomarker signature of the formation (Killops et al. 2000).

Note that there is a second 20 cm thick "Waipawa pulse" 4.8 m above the main unit, this "two-pulse" feature is also observed at many Waipawa sections in North Island.

Figure 32. *The Waipawa Formation at Mead Stream is a thin bedded organic-rich siliceous mudstone separating the Mead Hill and Amuri Limestone formations.* Photo M. Dow.

Amuri Limestone: turning up the heat

Deposition of the overlying Amuri Limestone marks a transition into a warmer world. Chert is infrequent and diatoms absent from the siliceous assemblages. The first "greenhouse event" in this interval is 20 m above the base of the Lower Limestone – a 20 cm thick marl bed that contains the first occurrences of warm-water radiolarians and a small negative carbon isotope excursion (**Fig. 33**).

These phenomena would not stand out if they weren't seen again on a much grander scale at the mouth of the next gorge. Here we find a 2.4 m thick recessed marly unit, dubbed the Dee Marl (**Fig. 34**), which marks the base of the Eocene.

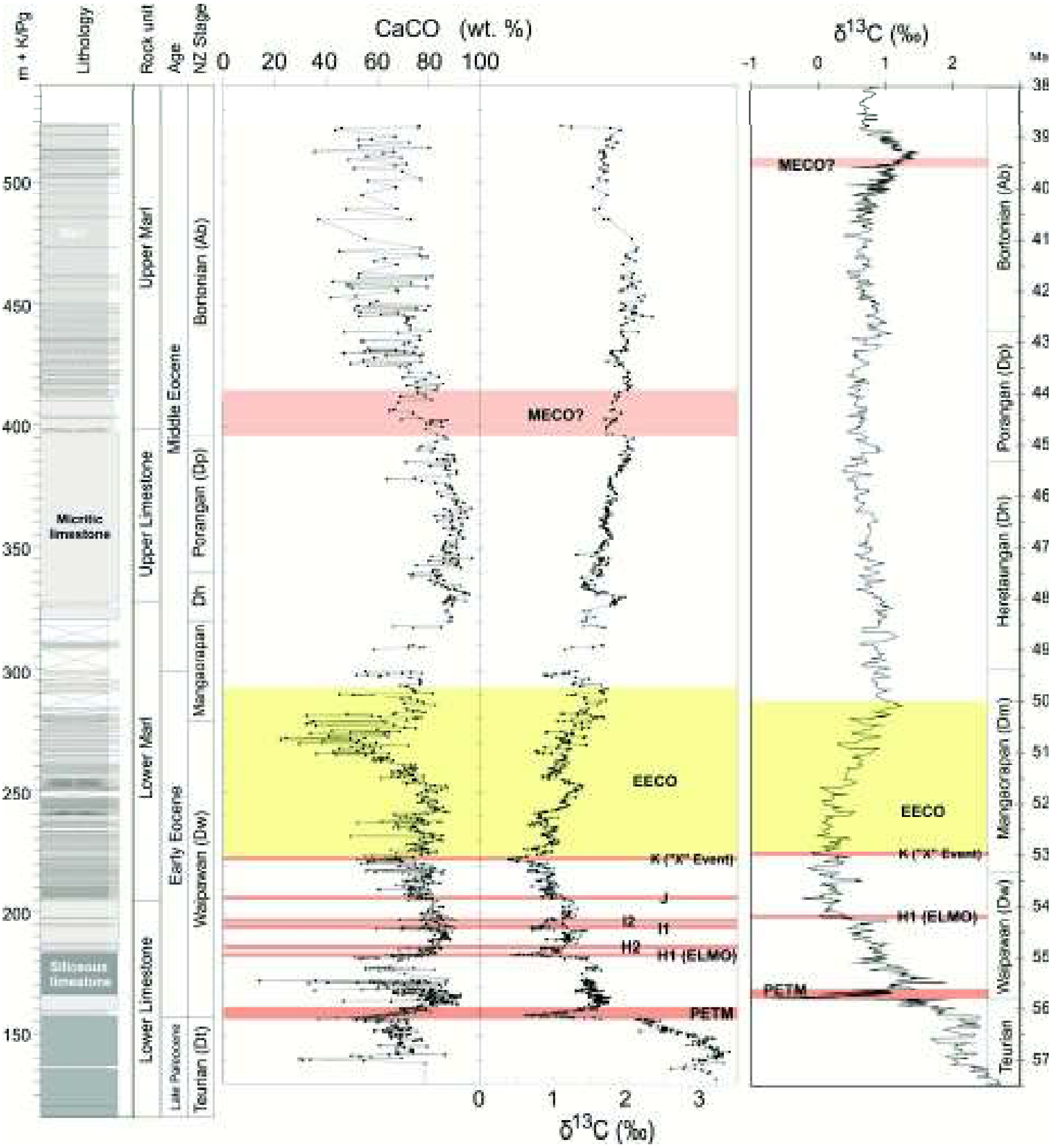


Figure 33. *Trends in carbonate content and carbon isotopes (bulk carbonate) from Late Paleocene to Middle Eocene at Mead Stream (Slotnick et al. 2013), showing a succession of caron isotope excursions (CIEs) and hyperthermal events, including the Paleocene thermal maximum (PETM) and the Early and (possible) Middle Eocene Climatic Optima (EECO, MECO). Panel on right is the global deep-sea benthic foraminiferal d13C compilation of Cramer et al. (2009); 5 point moving average, GTS2004 timescale (Gradstein et al. 2004).*

The Dee Marl is characterised by a negative carbon isotope excursion (CIE) of 1‰, short-lived occurrences of warm-water forams, radiolarians and nannofossils (**Fig. 35**), and a sudden cessation in bioturbation. These features identify the Paleocene-Eocene thermal maximum (PETM), a 100-200 thousand year event of pronounce global warming.

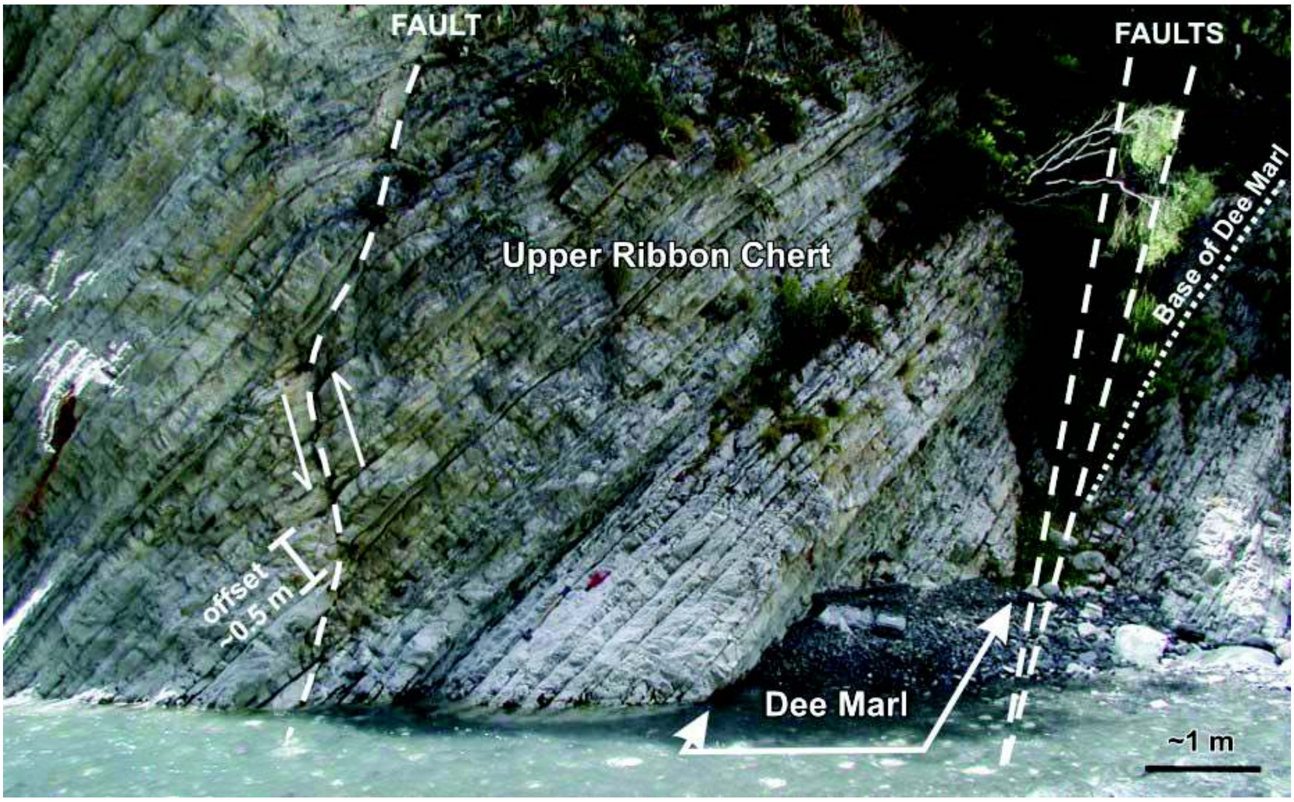
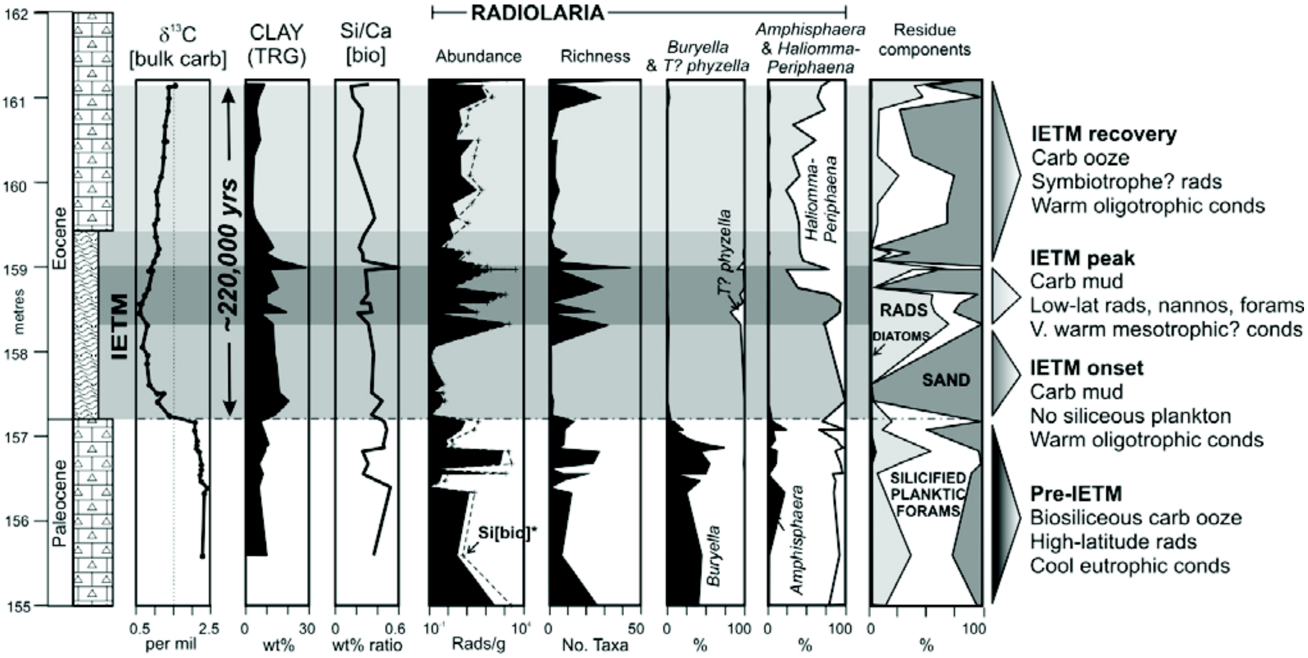


Figure 34. *The Dee Marl at Mead Stream, representing the main phase of the Paleocene-Eocene Thermal Maximum (PETM). Photo B. Field.*



* Si[bio] = diatoms + radiolarians + sponge spicules + silicified foram tests

Figure 35. *Siliceous plankton response to the PETM at Mead Stream. Biosiliceous productivity plummets at the onset of the PETM (labelled IETM, I = Initial) but only during its peak is there fossil evidence for extreme warmth (after Hollis 2006).*

The PETM is thought to have been triggered by deep ocean currents warming sufficiently to melt a submarine store of frozen methane, or gas hydrate. This massive oceanic burp is modelled to have injected 2000 gigatonnes of carbon into the atmosphere (2 x 10^{18} g), which caused further greenhouse warming of 4-9°C (Dickens 1999, 2011; Zachos et al. 2001, 2003, 2008). How Earth systems recovered from this event is still a matter of considerable debate and intense interest as we barrel along into another super-greenhouse world (see Norris et al. 2013; Zeebe 2013).
Ongoing studies of this section have identified a further CIEs that have been correlated with a succession of short-lived episodes of global warming, termed hyperthermals, that lead into the prolonged episode of global warmth, the Early Eocene Climatic Optimum (**Fig. 29**). There is some evidence for these hyperthermals being orbitally paced (Cramer et al. 2003) although it is also possible that the pacing relates to the recharge interval for gas hydrate reservoirs (Dickens 2011).

The PETM has been tracked as far south as Muzzle Stream in Clarence valley (Hancock et al. 2003; Hollis et al. 2005b) and in all sections it occurs as a recessive marly unit sandwiched between biomicrites. One of the first global records of the event was in a mudstone section at Tawanui, southern Hawke's Bay (Kaiho et al. 1996; Crouch et al. 2003). These New Zealand records reveal that the event had an intriguing effect on marine ecosystems. A bloom in the dinoflagellate genus *Apectodinium* at Tawanui (Crouch et al. 2003) indicates that neritic plankton thrived in response to an injection of nutrients from land and the warming of shelf seas. In contrast, reduced biogenic sediment accumulation, especially biogenic silica, in the Amuri Limestone sections indicates that oceanic productivity declined – probably due to changes in oceanic circulation: the expansion of warm oligotrophic waters at the expense of the cool eutrophic system that had maintained biosiliceous productivity through the Late Cretaceous and Paleocene.

The base of the Dee Marl is laminated and carbonate lean and shows a remarkable cessation in bioturbation. This implies dysoxic conditions that may have resulted from the PETM methane burp (Nicolo et al. 2010); it is suggested that much of the methane oxidised near the sea floor and was released from the oceans as CO_2. Oxidation and CO2 release are also implicated in ocean acidification during the initial phase of the PETM (Zachos et al. 2005). Within the PETM, radiolarian abundance fluctuates widely and there are unusual blooms of thick-walled spumellarians (**Fig. 35**). Several warm-water species are restricted to this interval at Mead Stream (Hollis 2006). Above the PETM at Mead Stream, a narrow gorge of siliceous limestone with chert ribbons represents the last macroscopic evidence of biogenic silica in the section.

Upstream of the narrow gorge, the uppermost Lower Limestone contains two pairs of recessive marly limestones, each associated with negative carbon isotope excursions (the H1, H2, I1 and I2 events identified by Nicolo et al. 2007) (**Fig. 33**). The Lower Limestone grades into a marl-rich interval called the Lower Marl, which is of late Waipawan to late Mangaorapan age. The top of the Lower Marl is now well dated by foraminifera (Slotnick et al. 2012). The unit is correlated with the EECO, although as with hyperthermals H1 to I2, further paleontological and geochemical studies are required to established that the lithological changes correspond with climatic warming in this rock sequence.

Lower Marl consists of ~120 marl beds alternating with packets of limestone beds that tend to thin upwards. With an age range of ~4.5 million years, that suggests a Milankovitch-scale cyclicity close to 40,000 years, and there are plans to test this in detail. The overlying Upper Limestone and Upper Marl are Middle Eocene age (Heretaungan to Bortonian) and have yet to be studied in detail. Radiolarian and foraminiferal preservation through the upper part of this interval is good to very good (Strong et al. 1995), so there is a good chance of testing our contention that this unit includes the Middle Eocene Climatic Optimum (MECO) (Bijl et al. 2010; Bohaty & Zachos 2003; Bohaty et al. 2009).

Beyond the Amuri: unconformities, uplift and earthquakes

Resting unconformably on the Upper Marl is the earliest Miocene (Waitakian) Weka Pass Stone, a well-bedded calcarenite (**Fig. 36**). The unconformity surface has conspicuous *Thallasinoides* burrows and corresponds to the Marshall Unconformity (Browne 1995; Carter et al. 2004).

Disconformably overlying this is another carbonate unit, the Early Miocene Whales Back Limestone, also resting on a burrowed surface. This unit, rich in *Zoophycos,* passes gradationally upwards into siltstone and lesser very fine sandstone of the Waima Formation, an extensive clastic unit that occurs throughout NE parts of the South Island. At its base, the Waima Formation is Waitakian or Otaian and the bulk of the formation is probably Altonian (late Early Miocene). The Waima Formation forms the background sediment into which the Great Marlborough Conglomerate (GMC) was deposited. This spectacular unit marks the first regionally significant uplift of greywacke fault blocks in the Marlborough region associated with the start of the Kaikoura Orogeny (Browne 1995).
At Mead Stream, the transition from pelagic limestone and siltstone to conglomerate is dramatic. The conglomerate is over 260 m thick, and comprises a series of debris-flow beds, each up to 20 m thick. Individual units of GMC are lenticular over long strike distances and these lenticular bodies sit within the Waima Formation. Clast size varies from granule to boulder and some megaclasts are 30 x 100 m in size (Prebble 1980). Most clasts are well-rounded and derived from Torlesse rocks. At Mead Stream, clasts in the upper few tens of metres are dominated by pale limestones from the underlying Late Cretaceous-Paleogene succession.

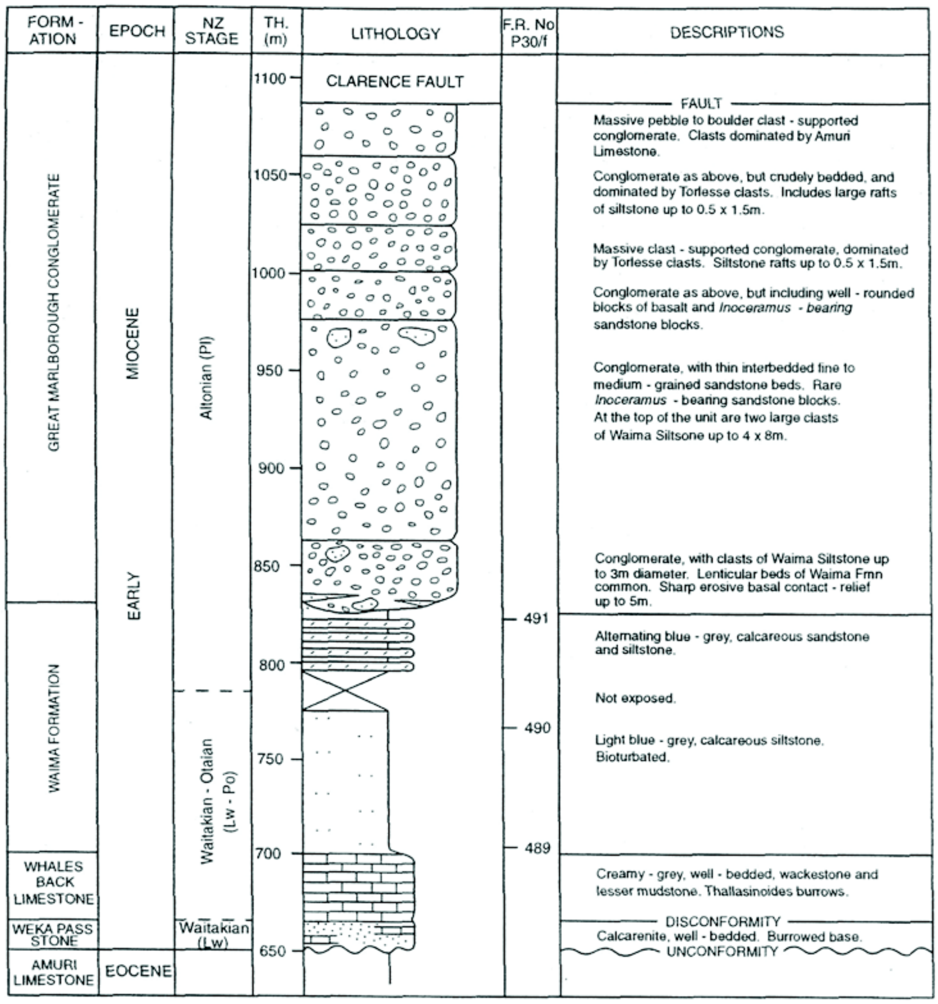


Figure 36. *Measured section for Neogene portion of the Mead Stream section. From Crampton et al. (1998). Based on unpublished column by G. Browne.*

The Clarence Fault

The GMC is truncated against the Clarence Fault (**Fig. 37**) – one of the principal elements of the Marlborough fault system. In Clarence valley, the fault runs along the foot of the Inland Kaikoura Range and forms a prominent active trace with current right-lateral strike slip rates of c. 5 mm/yr (Nicol & Van Dissen 2002). At Mead Stream, four subzones are recognised within Torlesse rocks in the 100 m thick fault zone: (i) 1-3 m of gouge immediately adjacent to the GMC; (ii) 8-10 m of intensely sheared material; (iii) c. 15 m of sheared material with discernible, discontinuous or attenuated dikes, and (iv) 60-80 m of sheared rock with undeformed or faulted dikes.

Outcrop mapping of the fault zone in Clarence valley and other lines of evidence, indicate that the Clarence Fault has been active for 100 million years, with three episodes of discernible displacement: (a) mid-Cretaceous (c. 100 Ma) normal displacement associated with igneous intrusion and crustal extension; (b) early Miocene (c. 22 Ma) fault reactivation and inversion, and (c) rejuvenated reverse displacement in Plio-Pleistocene times.

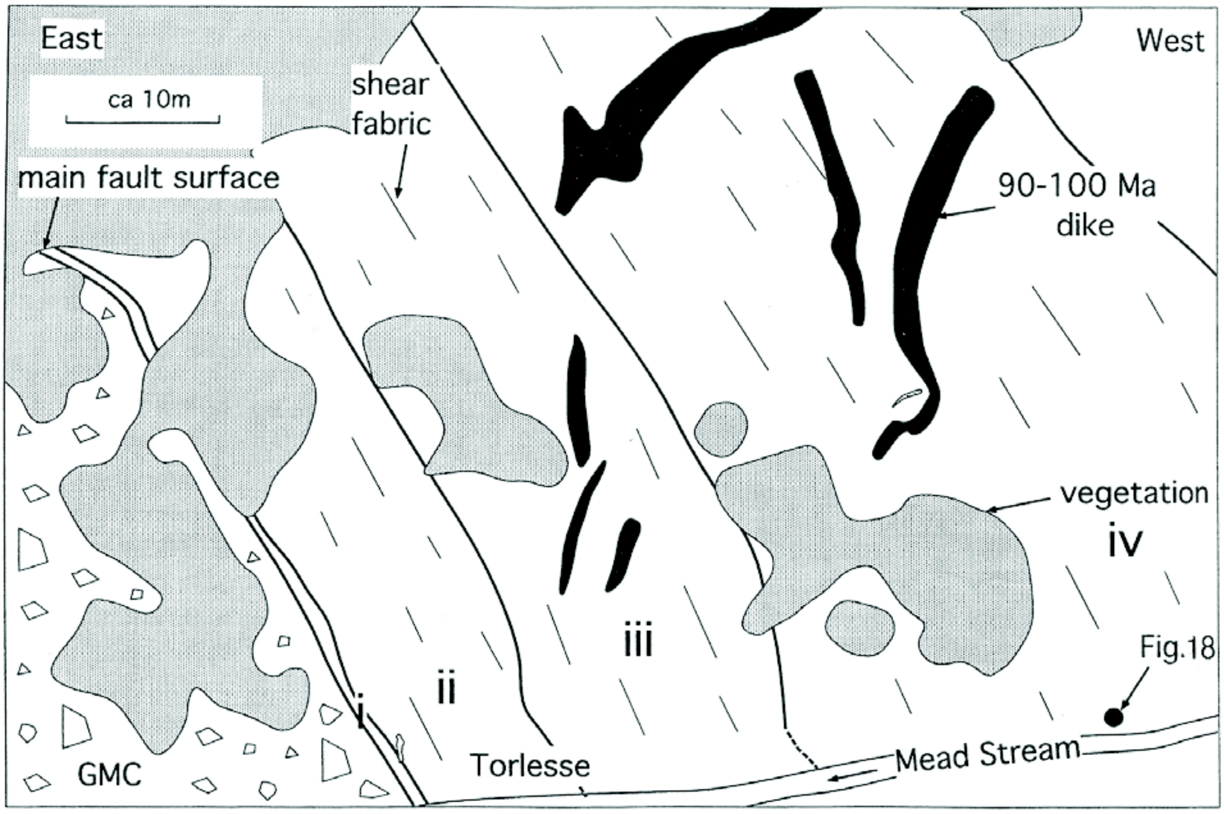


Figure 37. *Line drawing of the Clarence Fault zone on the southern, true right, bank of Mead Stream (from Crampton et al. 1998).*

Day 3 (Saturday 30 November) Chancet Rocks and Woodside Creek

The Cretaceous/Paleogene (K/Pg) boundary in coastal sections of SE Marlborough

Five K/Pg boundary sections are known within a 15 km stretch of coastline between Woodside Creek and Wharanui Point in the south and Chancet Rocks in the north (**Fig. 13**) (Strong 1977, 1984, 1885, 2000; Strong et al. 1987, 1988; Hollis et al. 2003a). The K/Pg boundary interval is within siliceous biomicrites of the Mead Hill Formation. The coastal sections consist of a similar succession of pelagic lithofacies: Late Cretaceous pale siliceous biomicrite (10-60 m thick), becoming less siliceous in the upper 5-10 m; earliest Paleocene dark grey, clay-rich, calcareous porcellanite (0.2-2 m), with a thin iridium-rich "boundary" clay at the base; pale calcareous porcellanite (10-16 m), becoming less siliceous in the upper part; white to pinkish biomicrite (25 m+). The porcellanite in these sections has previously been labelled "siliceous limestone" based on field assessment but geochemical analyses indicate a silica content of >50%. The Mead and Branch Stream sections have a similar but even more siliceous succession including a massive chert unit in the basal Paleocene.

The K/Pg boundary is well defined in all of these sections. It is placed at a distinct lithologic change that separates thick-bedded limestone, containing typical Late Cretaceous foraminiferal faunas, from thin-bedded porcellanite containing Early Paleocene foraminifera and dwarfed Cretaceous “survivors”. Dinoflagellate and radiolarian biostratigraphy support lithologic and foraminiferal evidence for the boundary location. Although radiolarians survive the K/Pg extinction event, all Marlborough sections show a marked change in faunal composition across the boundary: Cretaceous assemblages are dominated by nassellarians but early Paleocene assemblages are dominated by spheroidal spumellarians.

The K/Pg boundary is also marked by a thin clay layer that is enriched in iridium and other siderophiles (nickel, chromium, copper). The Woodside Creek boundary clay contains the highest iridium concentration in the Southern Hemisphere and one of the highest in the world (70 ng/g). It has been reported to contain abundant "soot" particles (Wolbach et al. 1988) and fullerenes (Heymann et al. 1994), large carbon molecules thought to form only during combustion, which have been cited as evidence for global firestorms following the K/Pg asteroid impact. Palynological evidence for the destruction of New Zealand forest supports this hypothesis (Vajda et al. 2001; Vajda & Raine 2003). Soot has also been reported from the Chancet K/Pg boundary and fullerenes have been identified in the Flaxbourne boundary clay. Impact-shocked mineral grains have been reported from the boundary clay at Woodside Creek and Chancet Rocks (Bohor et al. 1987) although their identification has been questioned (Izett 1990).

Flaxbourne River (Chancet Quarry)

Flaxbourne River has been a very useful epithet for an important K/Pg boundary section (Strong et al. 1987; Strong 2000; Hollis et al. 2003a) within a working quarry. The name has allowed landowner Herb Thompson to vet and guide numerous visitors who have followed the access instructions in publications on the section. In contrast, those who have ignored those instructions have spent frustrating hours or days wandering up and down the outcrop-lean Flaxbourne River. For participants on this excursion, we trust you to observe the standard protocols in the future: the Flaxbourne River K/Pg boundary section (**Fig. 38**) is in a working limestone quarry on Chancet Station - if you want to visit, contact Herb to arrange access (03-575 6885).

All exposures in Chancet quarry are Mead Hill Formation; Whangai Formation is poorly exposed at the quarry boundary. In general, Mead Hill Formation dips and youngs to the northwest although it is moderately to highly deformed. Fortunately, the K/Pg boundary interval itself is relatively free of deformation in the higher parts of the quarry that are not currently being worked. As at Woodside Creek, the K/Pg boundary rests on a thick uppermost Cretaceous limestone bed.

Figure 38. *The K/Pg boundary at Flaxbourne River (Chancet Quarry).* Photo C. Hollis.

In contrast to Woodside Creek, the basal Paleocene consists of a distinctive 0.5 m thick interval of thin-bedded, clay-rich porcellanite with thin mudstone interbeds. Detailed studies of this interval (Strong 2000; Hollis et al. 2003a) show it to record the abrupt collapse of a Cretaceous pelagic ecosystem dominated by calcareous plankton and progressive expansion of an early Paleocene ecosystem dominated by siliceous plankton (diatoms and radiolarians). Latest Cretaceous planktic foraminifera, represented by large *Globigerinelloides, Heterohelix, Abathomphalus* and *globotruncanids* are replaced by diminutive specimens of *Hedbergella, Guembelitria, Chiloguembelina* and *Eoglobigerina.*

Although it looks like limestone, the overlying 5 m of rock is clay-rich porcellanite with an average silica content of 75% and a carbonate content <10%. It records a million year diatom bloom suggestive of an extremely prolonged "impact winter" (**Fig. 39)**. In Northern Hemisphere K/Pg records, post-impact recovery is relatively rapid with calcareous microfossils returning to Cretaceous levels of abundance in less than 100 kyrs. The "impact winter" that was probably the main cause of mass extinctions is thought to have been very brief, lasting a few years at most, and is thought to have been followed by a much longer greenhouse event, which was caused by the vaporisation of limestone and evaporite target rocks at impact site that led to a mass injection of CO_2 into the atmosphere.

There is some evidence for this impact winter-greenhouse scenario in the fine-scale pattern of microfossil recovery in the few centimetres above the boundary in Chancet quarry (Hollis 2003a; Hollis et al. 2003a). However, the dominant signal is progressive and extreme long-term cooling: delaying recovery of calcareous plankton for at least one million years; promoting the recovery and expansion of a distinctive high-latitude radiolarian assemblage; and causing a diatom bloom by intensifying coastal upwelling of cool, southern-sourced deep waters (Hollis et al. 1995, 2003a; Hollis 1996, 2003).
This may be a little hard to visualise in the moderately weathered and somewhat deformed quarry exposure. So, think back to the Paleocene chert unit at Mead Stream. The Mead chert and the Flaxbourne porcellanite span the same time interval (radiolarian zones RP1 to RP3, 65-63 Ma).

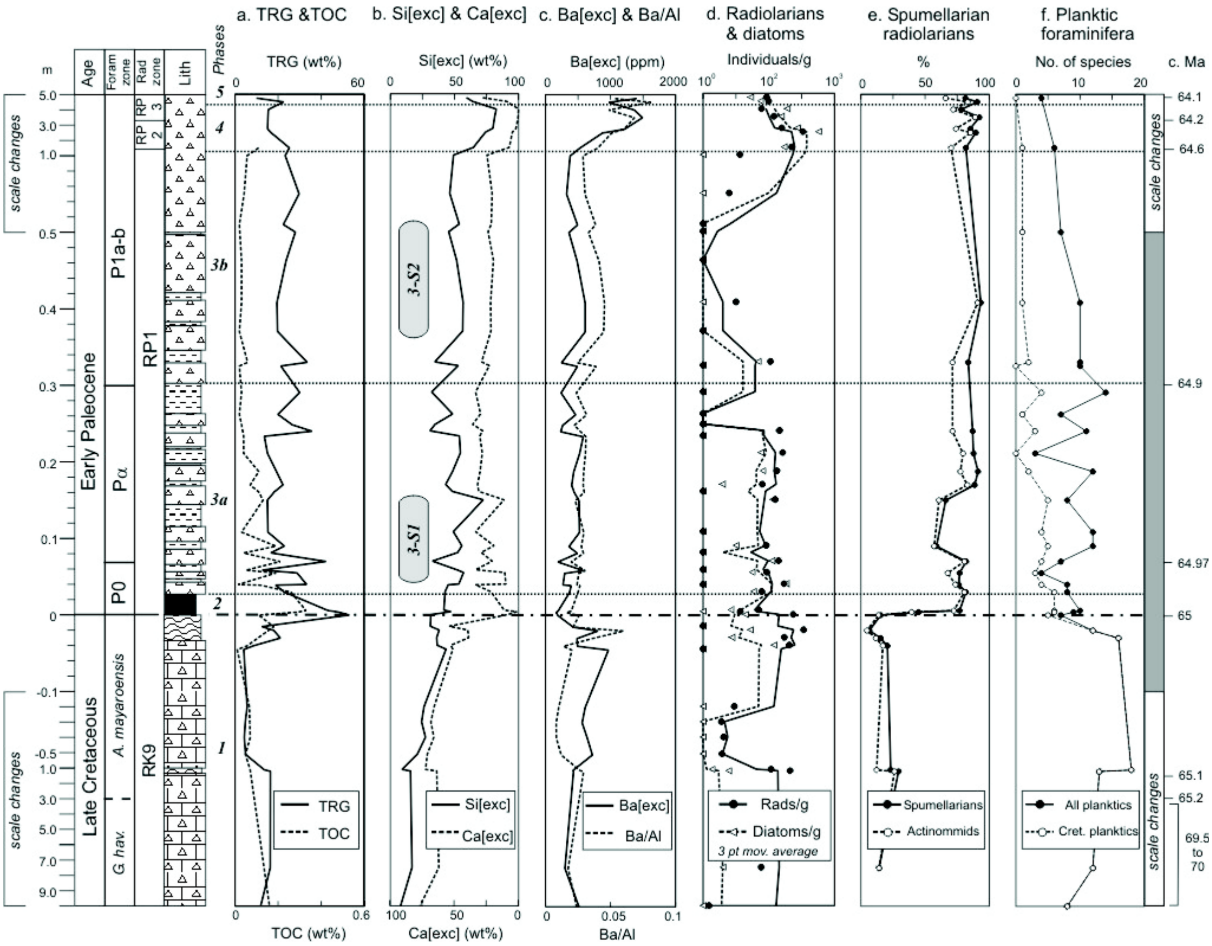


Figure 39. *Variation in geochemical and paleontological environmental proxies through the K/Pg boundary transition at Flaxbourne River (from Hollis et al. 2003a).*

Above the 5 m-thick porcellanite at Chancet quarry, the section becomes very disturbed and apparently faulted as an entire radiolarian zone (RP4, 63-61 Ma) is missing between this unit and the next coherent rock package, which is late Paleocene (RP5) Mead Hill Formation. Behind the quarry, a series of limestone bluffs are surrounded by pinkish marly limestone of Late Paleocene age that closely resembles the eastern North Island Wanstead Formation.

STOP 5: Chancet Rocks K/Pg Boundary and Paleocene Paramoudra

The Chancet Rocks K/Pg boundary section (Strong 1984) is similar to that at Flaxbourne River in most respects. The radiolarian assemblages in particular are almost identical and suggest a deeper bathyal setting than the upper bathyal environment inferred for the Woodside Creek section (Hollis 1996, 1997). The pink limestone on the shore platform contains the famous “sponge fossils” that are now interpreted as *Paramoudra* or networks of the trace fossil *Thalassinoides* that have become distorted by growth of chert nodules. The K/Pg boundary outcrops at two other coastal localities between Chancet Rocks and Kekerengu: Needles Point (Strong 1985), which can be seen from Chancet Rocks, and Wharanui Point (Strong et al. 1988; Hollis 1997), a rock stack just south of the mouth of Woodside Creek.

Chancet Rocks is a Scientific Reserve, so no hammering please!!

Figure 40. *An ammonite from Mead Hill Formation collected from boulder beach NE of Chancet Rocks.* Photo P. Strong.

North of Chancet Rocks, a boulder beach has been the surprising source of ammonites (**Fig. 40**), which appear to be eroding from the cliff of Mead Hill Formation behind the beach. This is surprising because there have been no other reports of macrofossils from Mead Hill Formation anywhere else in Marlborough. It is possible that they derive from a single exceptional horizon restricted to this location, although we have yet to locate such a horizon in outcrop.

Cretaceous sequence at Ward Beach

Ward Beach is a popular haunt for rock hounds. The smooth limestone pebbles, often with artistically placed *Zoophycos* traces or chert nodules, are increasingly sought after for rock gardens, decorations and jewellery.

Over most of NE Marlborough, as noted earlier, the Haumurian sedimentary rocks consist of a lower portion, comprising the fine-grained clastic Whangai Formation, which passes upwards abruptly or with rapid transition into the siliceous biomicrites of the Mead Hill Formation, which occupies the upper portion. The Whangai Formation typically comprises a monotonous succession of massive or finely-laminated dark silty or very fine sandy mudstone, in some instances with thin sandy layers, commonly reaching a thickness of ~200 m, and locally (Woodside Creek) up to 700 m. In the hills and coastal area east of Ward, however, the lateral correlatives of the Whangai Formation are represented by massive sandstone bodies, thick turbidite units, and conglomerates, which, with interspersed finer-grained units, are significant enough to have been given separate formal stratigraphic names (Mirza and Butt Formations: Price 1974; Lensen *in* Suggate et al. 1978). The coarser units are inferred to occupy channels eroded into the background fine-grained sediments. Locally the Whangai Formation is slump-folded.

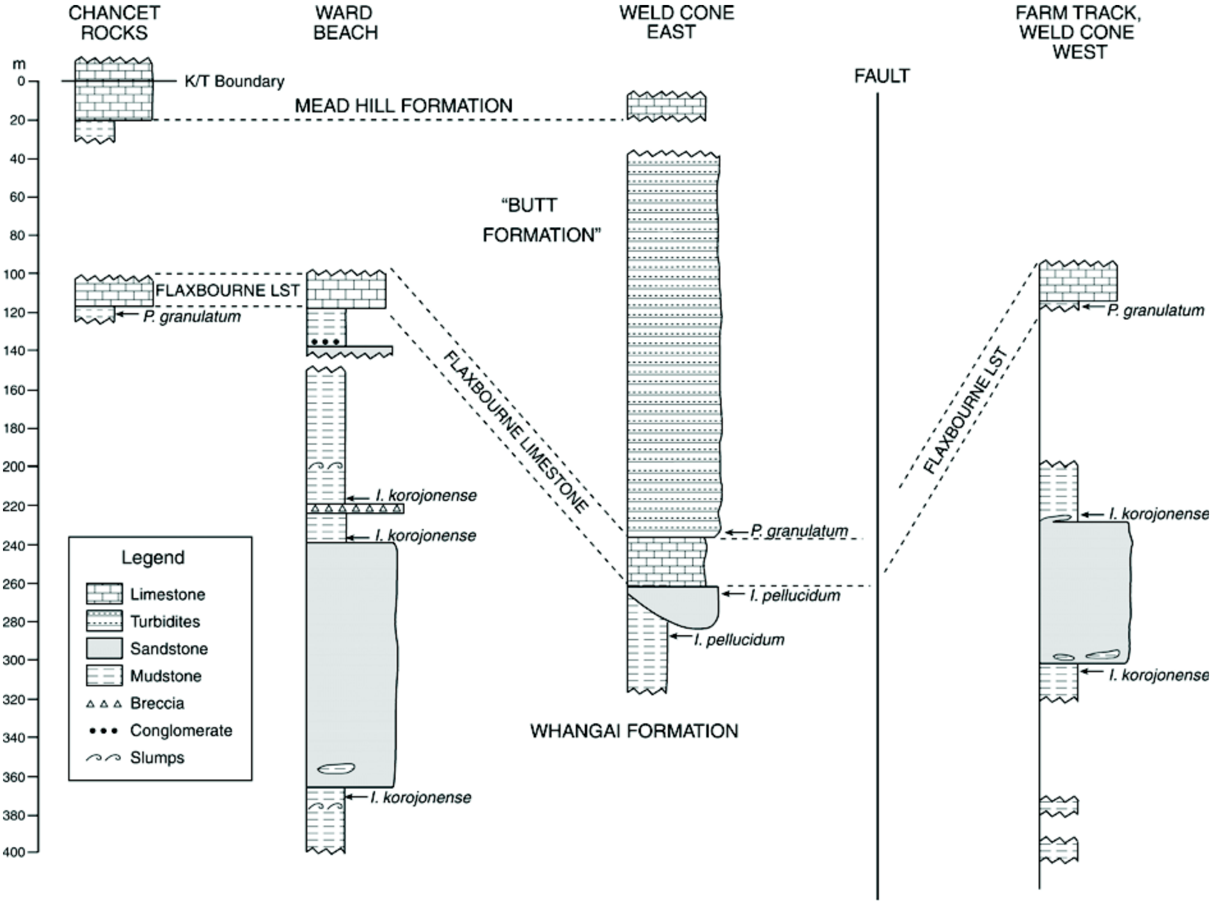


Figure 40. *Measured sections for the Late Cretaceous portion of the Ward coastal block (from Hollis et al. 2005c)*

The Ward Beach section (**Fig. 41)** lies between Flaxbourne River and Chancet Rocks, and forms the western limb of an anticline. A 120 m thick body of well-sorted fine sandstone occupies most of the lower half of the section, which is of mid-Campanian (*Isabelidinium korojonense* dinoflagellate zone) age. The lower and upper contacts of the sandstone body with the surrounding Whangai Formation are sharp. Large rounded inclusions, and a raft of 2 m thick laminated dark mudstone identical to the underlying Whangai Formation, are incorporated in the basal 15 m, suggesting erosion and incorporation into a sandy debris flow. The bulk of the sandstone unit is apparently massive, although well-washed surfaces locally show traces of large-scale cross-bedding or parallel lamination.

The remainder of the succession is made up largely of Whangai Formation, with scattered intervals of matrix-supported intra-basinal breccia and conglomerate, or graded sandstone beds up to 5 m thick, interpreted to represent debris flows, slumps and turbidites, and occupying shallow channels. Soft sediment slumping occurs at several horizons. The fine-grained succession passes upwards with rapid transition into the Flaxbourne Limestone, a >20 m thick siliceous biomicrite of early Maastrichtian (*Palaeocystodinium granulatum* subzone) age. Sills and dikes of glauconitic sandstone mark the lower few metres of the formation. The remainder of the succession up to the Mead Hill Formation and the K/Pg boundary is not exposed in this section. We will not have time to cross to the south side of the Flaxbourne River mouth, where better exposures of the upper part of the succession occur.

STOP 6: Woodside Creek

In the past, no visit to Woodside Creek was complete without stopping off at the Benmore Station homestead to say hello to Margaret Parsons, admire her garden and scan the impressive who's who of geology in her visitors' book. As the owners of Benmore Station, Margaret and husband David witnessed the rise to fame of the Woodside Creek gorge since initial location of the K/Pg boundary (Strong 1977) and discovery of the iridium anomaly (Alvarez et al. 1980). But Margaret has passed away, husband David has moved to Blenheim, and the station is now managed by nephew Jock Clouston. The gorge is also a mecca for botanists, being the home of many local indigenous plants and specimen trees. From the homestead, the lower gorge is a 5 minute drive or 15 minute walk up the creek, past some patchy outcrops of Eocene mudstone, the Woodside Formation.

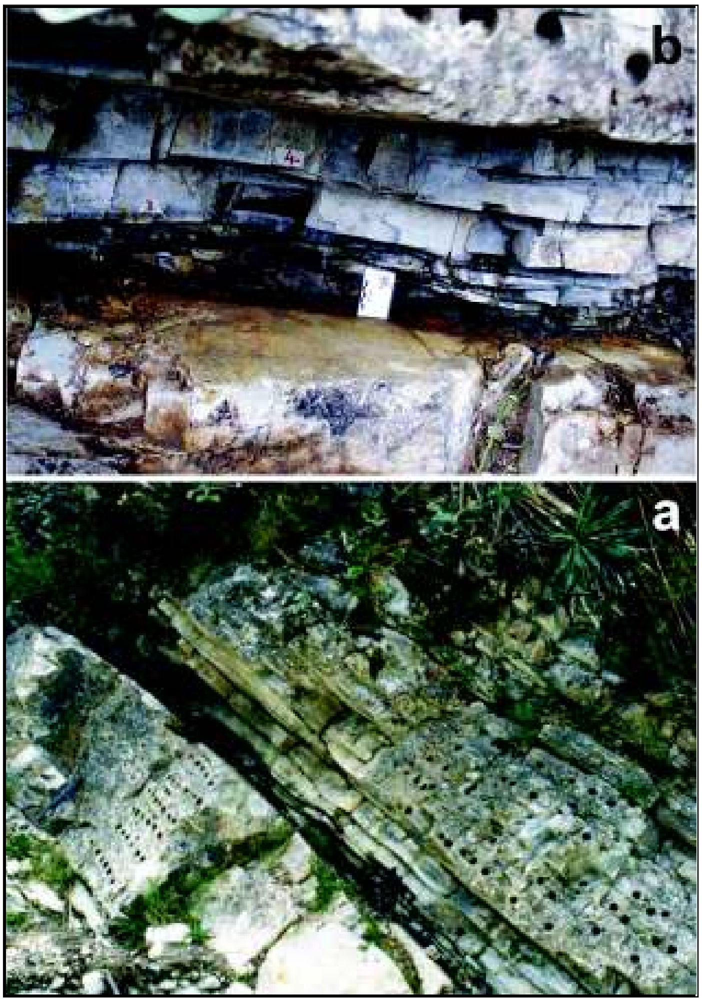


Figure 42. *The K/Pg boundary at Woodside Creek.* Photo a C. Hollis, Photo b B. Field.

The gorge **section youngs to the north, so we enter fr**om the Paleocene end. The dip-slope on the eastern side is where rock was excavated for St Oswald's Church at Wharanui and other local landmarks. The K/Pg boundary is exposed on both banks about 50 m into the gorge (**Fig. 42**). Thanks to Dale Russell it is the most easily recognised K/Pg boundary in the world. Beds on the true left bank are pock-marked with his drillholes, which he made in the 1970s as part of an unsuccessful paleomagnetic experiment. He also supplied the Alvarez team with the sample that produced the iridium anomaly, which ultimately led to a scale of excavation that exceeds that of the famous European sections at Gubbio and Stevens Klint.

Things to observe at the K/Pg boundary:

- Change in bedding style and carbonate content across the boundary
- Laminated nature of basal Paleocene sediments
- Intensely weathered nature of the boundary clay

<u>No hammering close to the boundary please!</u>

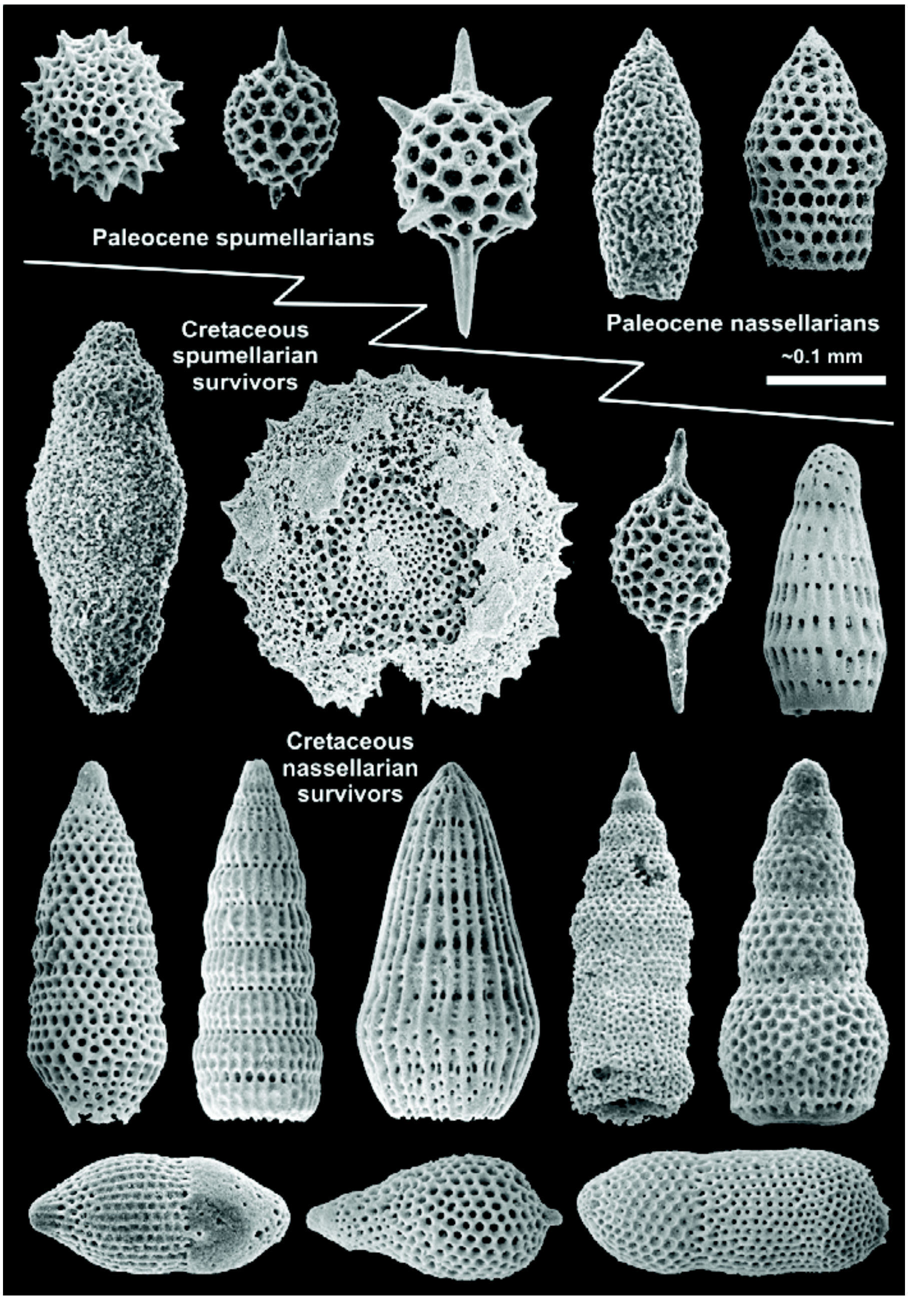


Figure 43. *Some radiolarians from Woodside Creek: Cretaceous survivors and Paleocene arrivals (images from Hollis 1997).*

Upstream you can examine the transition from the Mead Hill Formation to the underlying Whangai Formation, which in this area is predominantly massive siltstone, locally moderately siliceous, with rare sandstone beds and common large concretions. This lithotype has been mapped as Woolshed Formation and closely resembles the eastern North Island Rakauroa Member of the Whangai Formation.

Downstream you can examine the progressive increase in bed thickness and carbonate content in Paleocene Mead Hill Formation. These beds contain abundant well-preserved radiolarians (**Fig. 43**) and form the stratotype for four of seven Paleocene radiolarian biozones; these four zones have so far only been identified in southern high latitudes (Hollis 1993, 2002) although similar successions are known from the boreal Paleogene and Japan. Radiolarian biostratigraphy has shown that the succession above the K/Pg boundary is earliest to early Late Paleocene age (Zones RP1 to RP5). A stratigraphic contact with overlying Lower Eocene (Waipawan?) mudstone and volcanics of the Woodside Formation has not been observed, nor has Amuri Limestone been identified in the coastal area between Woodside Creek and Cape Campbell. Similar radiolarian successions in the Chancet Rocks and Flaxbourne River sections (Hollis 1997) indicate that all Cenozoic limestone in the Ward area is Paleocene Mead Hill Formation.

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