50th Kaikoura05

The Organising Committee extends a warm welcome to all delegates and visitors to Kaikoura, where it all began 50 years ago.

Please note that all information in this publication was correct at the time of going to print. However, due to factors beyond our immediate control, such as weather, road conditions and permission for land access, some unexpected late changes in field trip routes and itineraries may be required.

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Geological Society of New Zealand

50th Annual Conference

28 November to 1 December 2005
Kaikoura Memorial Hall and Takahanga Marae
Kaikoura

Field Trip Guides

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Field Trip Guides – Contents

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MID-CONFERENCE FIELD TRIPS

POST-CONFERENCE FIELD TRIPS

Field Trip 1

CRETACEOUS-PALEOGENE STRATIGRAPHY OF EASTERN MARLBOROUGH: OPENING A SOUTH PACIFIC WINDOW ON A GREENHOUSE EARTH

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OVERVIEW

This excursion will showcase the spectacular Late Cretaceous to middle Eocene passive margin, fining-upwards succession of eastern Marlborough (**Fig. 1**). We will examine how pre-existing topography, local tectonics, global climate change and extreme events are reflected in the local stratigraphy. At Ward Beach and surrounding areas we will view slumps, mass flow deposits and channelling within the Late Cretaceous siliciclastic Whangai Formation. At Woodside Creek, Flaxbourne River and Chancet Rocks we will view the best on-land Southern Hemisphere records of the K/T boundary and review local evidence for asteroid impact, mass extinction, collapse of the ocean ecosystem and long-term climate change. At Mead Stream, a 650 m thick section through various pelagic facies of the Mead Hill Formation 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 mid-Eocene, including a well-delineated record of the Initial Eocene Thermal Maximum. We will also examine Cretaceous fossiliferous strata in Coverham area, the Great Marlborough Conglomerate and the Clarence Fault (Mead Stream), the Late Cretaceous transition from siliciclastic to pelagic deposition (Waipapa Bay) and correlative, more proximal facies of the Mead Stream succession at Kaikoura.

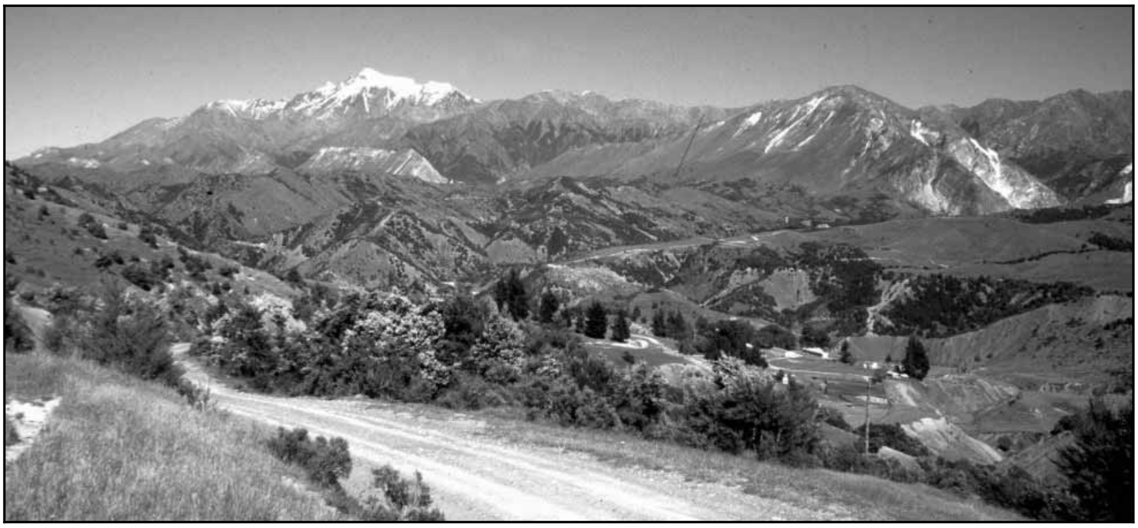

Figure 1. View from road into Coverham, northern Clarence valley, with Mt Tapuae-o-Uenuku rising behind Muzzle Group limestones of the Chalk Range. The peak to the right is Mead Hill and the Mead Stream gorge is directly below the right flank of Tapuae-o-Uenuku.

ITINERARY (Fig. 2)

Day 1: Saturday 26th November

Meet at Picton ferry terminal at midday and travel directly to Ward. Visit Woodside Creek, Flaxbourne River and Chancet Rocks K/T boundary sections in afternoon (low tide 7 pm).

Day 2: Sunday 27th November

Travel to Mead Stream section via Kekerengu and Coverham (Bluff Station). En route, examine Cretaceous succession in Ouse Gorge. At Mead Stream, examine Split Rock Group, Late Cretaceous-Paleocene Mead Hill Formation, K/T boundary, Waipawa Formation, Paleocene-Eocene Amuri Limestone, Initial Eocene Thermal Maximum, Early Eocene

Climatic Optimum, Eocene/Miocene unconformity, Great Marlborough Conglomerate, Clarence Fault. Dinner at Kekerengu Store with public talks on local geology (James, Chris, Russ Van Dissen).

Day 3: Monday 28th November
Ward Beach-Weld Cone sections. Travel to Kaikoura with brief stops at Waipapa Bay and Kaikoura lab section (as time allows). Arriving at Kaikoura at 4.30 pm.

Be prepared for fording streams and getting your feet wet at Mead Stream & probably Woodside Creek

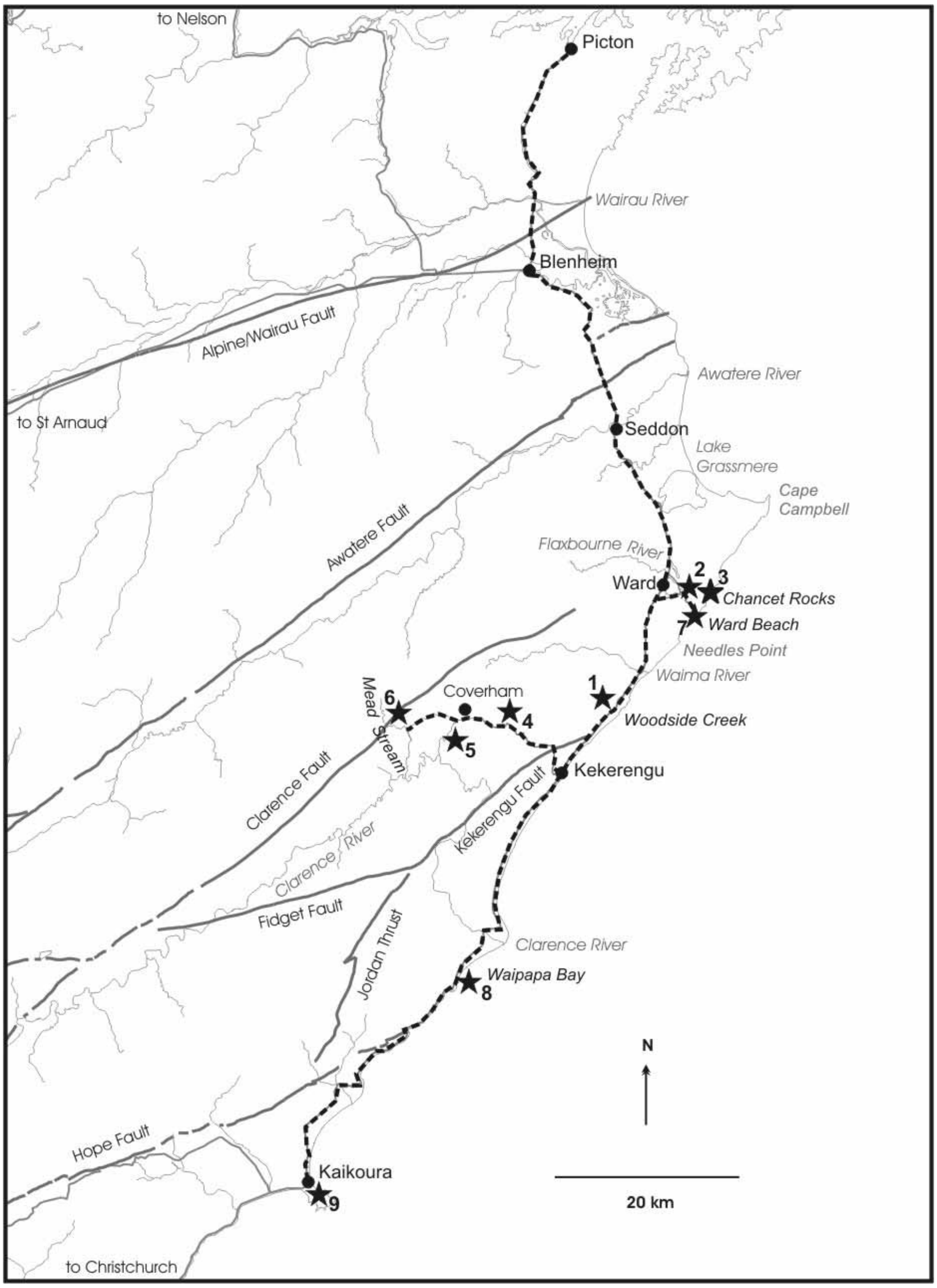

Figure 2: Route map for Field Trip 1 (supplied by D. Townsend).

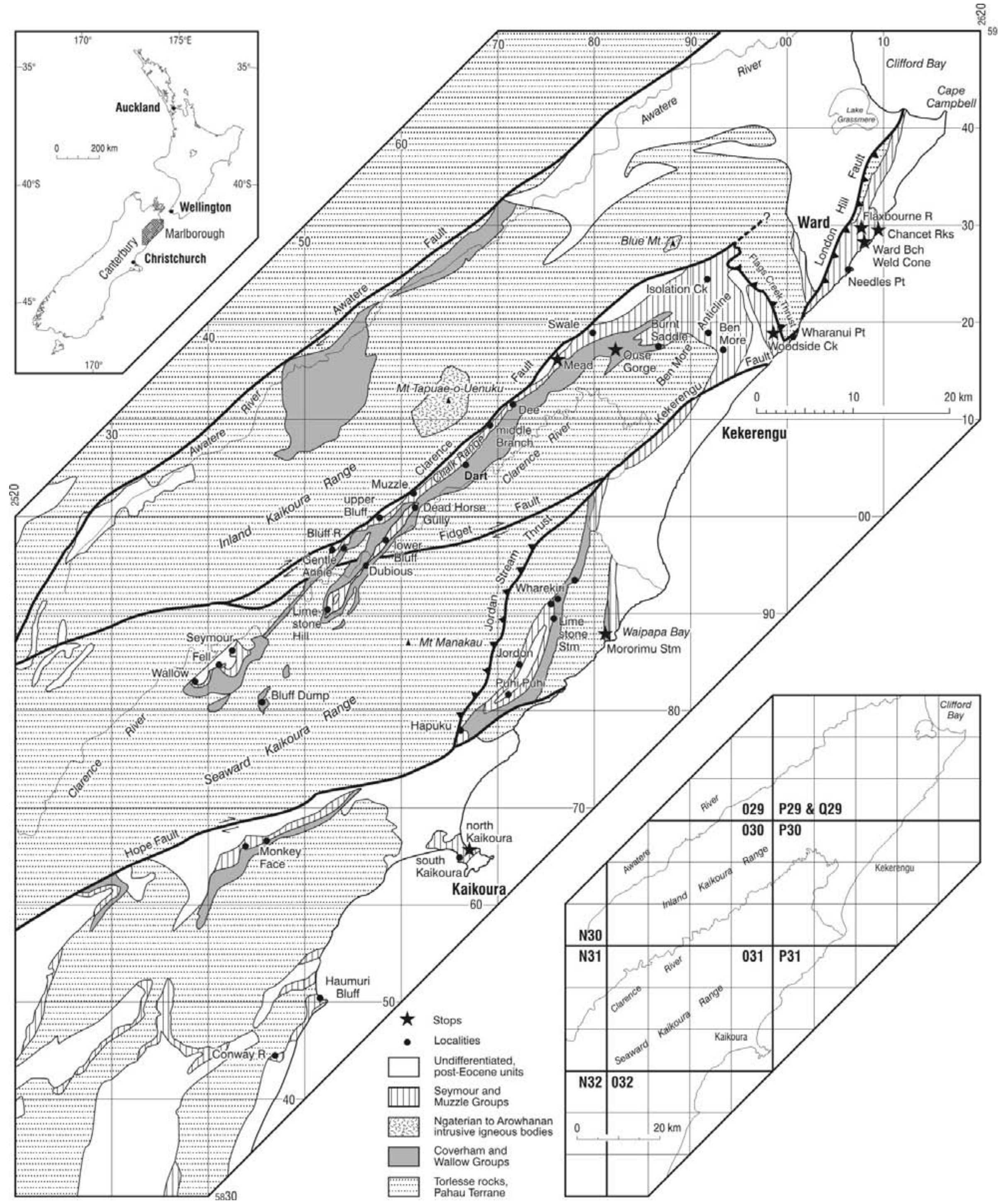

Figure 3: Simplified geological map for eastern Marlborough and northern Canterbury showing field trip stops and other key localities for Cretaceous-Paleogene stratigraphy (after Crampton et al. 2003).

GEOLOGICAL SETTING

Cretaceous siliciclastic sediments

Mid-Cretaceous strata in Marlborough rest with angular unconformity on an indurated and highly deformed basement of the Early Cretaceous Torlesse composite terrane (Pahau terrane) (**Fig. 4**). 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. The infilling mid-Cretaceous strata are represented over most of Marlborough by the Motuan-early Ngaterian Split Rock Formation of the Coverham Group (the age relationship between NZ and international stages is shown in **Fig. 4**). The Split Rock 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. In some instances, other unconformity-bound units, such as the Urutawan-Motuan "Champagne Formation" exposed in Ouse Stream are interposed between the Split Rock Formation and the basement.

Later Ngaterian time saw regional uplift, tilting and erosion of the Split Rock Formation, and deposition of non-marine and shallow marine conglomerate, sandstone and mudstone accompanied by the widespread intrusion of dikes and extrusion of alkaline intraplate basalt, above a widespread unconformity. K/Ar dates on trachybasalt flows from the Clarence Valley range between 93 and 98 Ma (Reay 1993); a recent Ar/Ar date from the lowest basalt flow in Seymour Stream yielded an age of 96 Ma (Crampton et al. 2004a). Rb/Sr isochron ages from an associated plutonic complex (Tapuaenuku Plutonic Complex) yielded a mean age of 96 Ma (Baker & Seward 1996). These volcanic and sedimentary deposits, which form the Wallow Group, are faulted out of the section we will be examining.

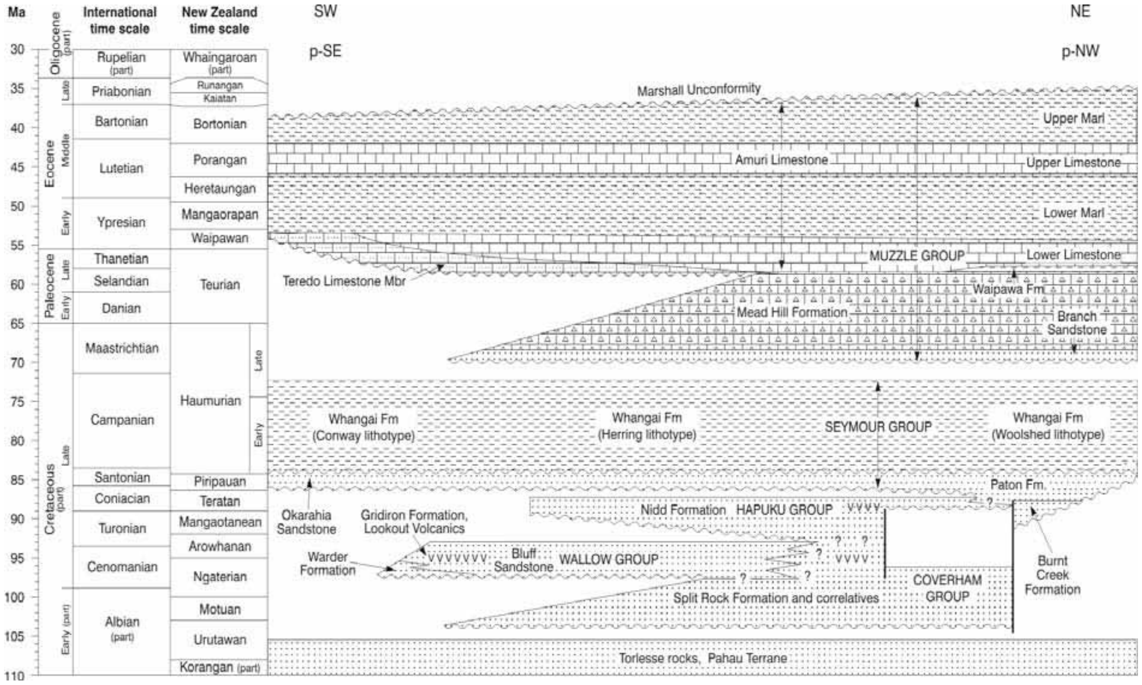

Figure 4: Chronostratigraphy of Cretaceous and lower Paleogene sedimentary strata in eastern Marlborough (after Crampton et al. 2003).

The deposition of Wallow Group represents the onset of a period of slow subsidence interrupted by episodic relative sea level changes, which persisted into the late Cretaceous. This period, from late Ngaterian to Early Haumurian, saw the deposition of dominantly 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 (Laird 1992; Crampton et al. 2003; see also **Fig. 5**). Note that all of southeastern Marlborough has apparently experienced about 100° of clockwise, post-Oligocene, vertical-axis rotation (Vickery & Lamb 1995; 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). Herein, compass bearings that refer to the pre-rotation geography are prefixed with the word "paleo".

A further minor break in sedimentation occurs at the late Ngaterian-early Arowhanan boundary with an Arowhanan to Teratan condensed sequence of non-marine to shallow marine clastic sediments (Hapuku Group) 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 (Laird et al. 1994). In the Coverham area, the Hapuku Group is represented by the Nidd Formation.

A further change in deposition occurred in late Teratan times. 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. Again 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 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 1988a). The Paton and Whangai Formations constitute the Seymour Group. The Whangai Formation is generally conformable on the Paton Formation, but detailed dinoflagellate biostratigraphy indicates that the contact is a disconformity throughout Marlborough (Schiøler et al. 2002; Crampton et al. unpublished data).

The transgression associated with the Seymour Group 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 beginning of a long 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). Globally, the interval from 84 Ma to mid-Paleocene times (c. 60 Ma) is characterised by falling sea level and cooling temperature (Huber et al. 1997; Clark & Jenkyns 1999).

The Cretaceous stratigraphy outlined above is typical of Marlborough with the exception of a small area lying east of Coverham and in the upper part of the Kekerengu River valley. This area lies east of the Ouse Fault (**Fig. 3**), which is inferred to have been an active normal fault in mid-Cretaceous times (Ritchie & Bradshaw 1985; Ritchie 1986; Crampton & Laird 1997). In contrast to the stratigraphy west of the fault, the oldest strata resting unconformably on Torlesse rocks are of Mangaotanean to Teratan age, and form part of the Burnt Creek Formation. In contrast to its age equivalents to the west, which belong to the non-marine to shallow marine Hapuku Group, the Burnt Creek Formation comprises a fining upward succession of mass flow conglomerate, turbidites and siltstone deposited in an outer neritic to upper bathyal environment (Crampton & Laird 1997). Active faulting is likely to have ceased by the end of Raukumara times, although some tectonic activity may have persisted as late as Early Haumurian times, indicated by a deeper water facies and substantially greater thickness of the Paton Formation east of the Ouse Fault and isopach patterns in the Seymour Group (Crampton et al. 2003). However, by Late Haumurian times, uniform depositional conditions prevailed on both sides of the Ouse Fault and there is no evidence for tectonic activity.

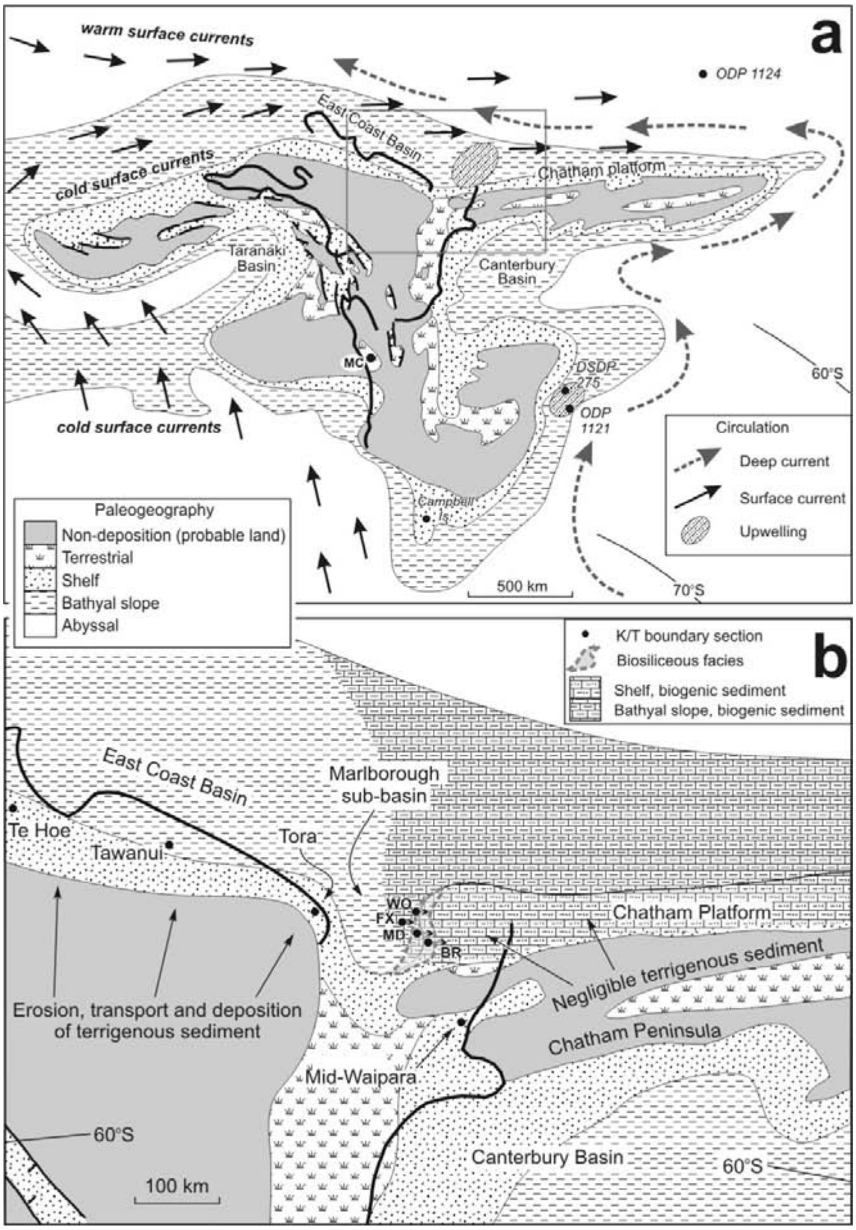

Figure 5: Palinspastic reconstructions for the (a) New Zealand region and (b) central New Zealand for latest Cretaceous times (65 Ma). From Hollis (2003; after Crampton et al. 2003), with base map modified from King et al. (1999) and orientation and paleolatitude based on Sutherland et al. (2001).

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 (Laird 1994). 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. 6**).

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 (see under **Day 3**). This block has an uncertain tectonic relationship to the remainder of Marlborough (Crampton et al. 2003) and may be allochthonous (Laird 2005).

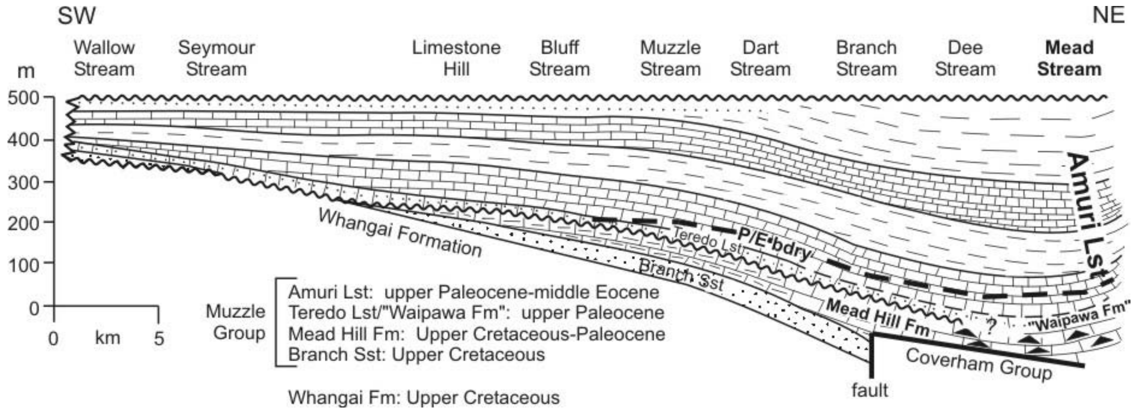

Figure 6: Lithofacies trends within Muzzle Group strata in the Clarence valley (from Hollis et al. 2005a; after Reay 1993)

Latest Cretaceous and Paleogene pelagic sediments

Foraminifera indicate a deepening trend, with increasingly oceanic conditions, from mid- or inner shelf near the base of the Mead Hill Formation, to bathyal depths throughout eastern Marlborough by the end of the Cretaceous (Strong et al. 1995). The catastrophic effects of the K/T boundary asteroid impact (Hollis 2003a), especially mass extinction of calcareous plankton (Smit & Romein 1985; Zachos et al. 1989) and local deforestation (Vajda et al. 2001; Vajda & Raine 2003), complicate interpretation of the dramatic lithofacies changes that occur across the K/T 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, b):

- 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 2003b, 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. 6**). 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 contact is sharp but apparently conformable (Hollis et al. 2005a). 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 Initial Eocene (or Paleocene-Eocene) Thermal Maximum (IETM)
- 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 42-40 Ma, respectively – Zachos et al. 2001; Bohaty and Zachos 2003). In contrast, the Waipawa Formation, Teredo Formation 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 (Cook et al. 1999). 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 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 Altonian age that crop out in many parts of southern Marlborough (Lewis et al., 1980). 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.

DAY 1: K/T BOUNDARY SECTIONS OF NE MARLBOROUGH

The foci of the afternoon's excursion are the most well known, the most demonstrably complete and the most seal-infested Cretaceous-Tertiary (K/T) boundary sections in New Zealand: Woodside Creek, Flaxbourne River and Chancet Rocks, respectively.

Blenheim to Ward

Our route south of Blenheim takes us across postglacial sediments which have aggraded over the latest glacial outwash deposits because of rising sea level. At the end of the plains, the route crosses hills composed mainly of late Miocene to Pliocene conglomerate, sandstone and siltstone deposited in fluvial-lacustrine and alluvial fan, shoreface, shelf and bathyal settings, before dropping into the Awatere Valley. This valley is controlled by the NE-trending Awatere Fault, a major member of the dextral strike-slip fault system initiated in the Miocene. Considerable earth movement occurred along the Awatere Fault during the Wellington earthquake of 1848 (M = 7.1), and great rents occurred along the surface trace. It forms the NW boundary of the Inland Kaikoura Range, which rises to a height of 2885 m in Mt Tapuae-o-Uenuku - the highest point outside the Southern Alps. According to Maori legend, this mountain was formed from one of the crew of the waka *Araiteuru*, newly arrived from Hawaiki, who swam ashore as they sailed down the east coast of the South Island. According to geological legend, Mount Tapuae-o-Uenuku comprises a mid-Cretaceous layered intrusion of pyroxenites, gabbros and more felsic rocks derived from contaminated ocean island basalt magma (Baker et al. 1994). Origins from things oceanic seems to be a common element of both legends. Further up the valley, a thick succession of basaltic lavas occurs (Lookout Volcanics, the extrusive equivalents of the plutonic complex).

The route crosses the Awatere River via a "double-decker" road/rail bridge and heads south to pass Lake Grassmere, a natural shallow marine embayment stop-banked by man to produce New Zealand's only extensive solar salt works. This part of Marlborough receives New Zealand's highest sunshine hours. Most of the products of the works are used by the New Zealand freezing industry for treatment of hides and skins.

The K/T boundary in eastern Marlborough

Five Cretaceous/Tertiary (K/T) 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. 2, 3**; Strong 1977, 1984, 1885, 2000; Strong et al. 1987, 1988; Hollis et al. 2003a). Two inland sections have also been described from Mead and Branch Streams (Strong et al. 1995; Hollis et al. 2003b). The K/T 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/T 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 either Early Paleocene foraminifera or dwarfed Cretaceous “survivors”. Dinoflagellate and radiolarian biostratigraphy support lithologic and foraminiferal evidence for the boundary location. Although radiolarians survive the K/T extinction event, all Marlborough sections show remarkable change in faunal composition across the boundary: Cretaceous assemblages are dominated by nassellarians (pointy or bullet-shaped forms) but early Paleocene assemblages are dominated by spheroidal spumellarians (**Fig. 7**).

The K/T 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 also contains 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/T 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/T 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).

<u>STOP 1</u>. Woodside Creek

In the past, no visit to Woodside Creek was complete without stopping off at the Benmore homestead to say hello to Margaret Parsons, admire her garden and scan the impressive who’s who of geology in her visitors’ book. Margaret and David Parsons, the retired owners of Benmore Station (who have recently moved into Blenheim), witnessed the rise to fame of the Woodside Creek gorge since initial location of the K/T boundary (Strong 1977) and discovery of the iridium anomaly (Alvarez et al. 1980). 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 poorly described Eocene mudstone, the Woodside Formation. The gorge section youngs to the north, so we enter from 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/T boundary is exposed on both banks about 50 m into the gorge (**Fig. 8**). Thanks to Dale Russell it is the most easily recognised K/T 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.

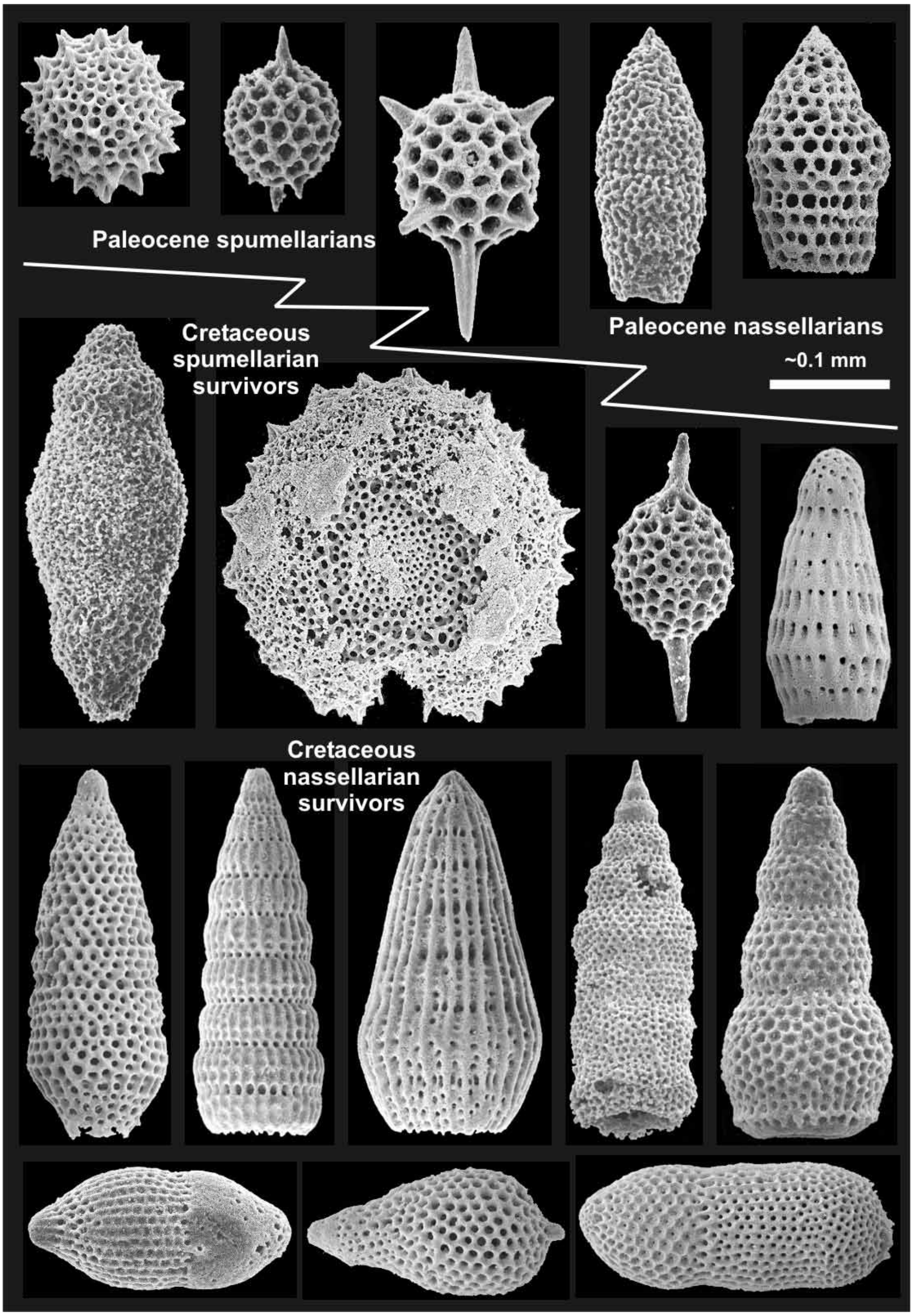

Figure 7: Some radiolarians from Woodside Creek: Cretaceous survivors and Paleocene arrivals. Images from Hollis (1997)

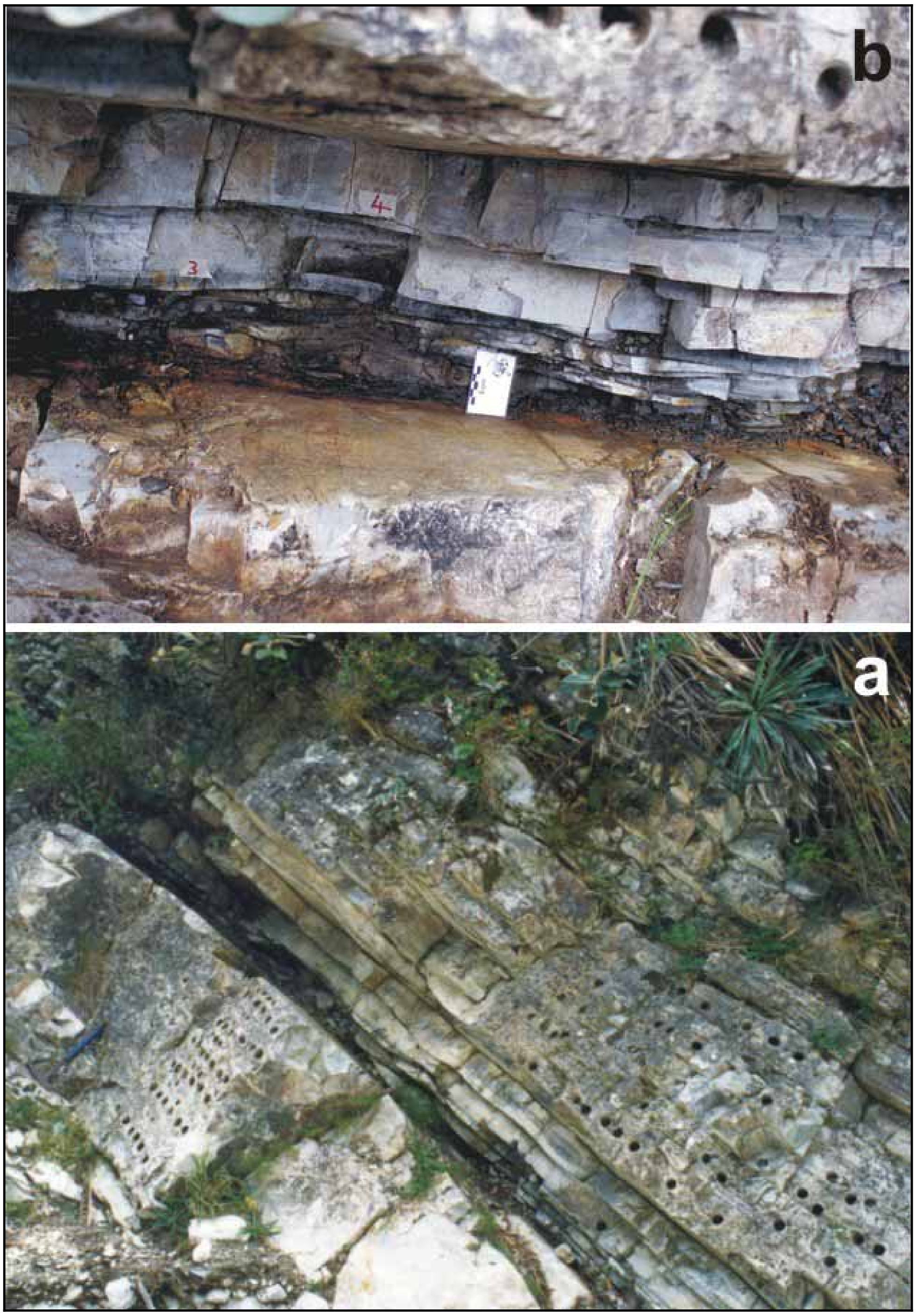

Figure 8. The K/T boundary at Woodside Creek. *Photo a C. Hollis, Photo b B. Field*

Things to observe at the K/T boundary:

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

It's suffered enough don't you think: so no hammering please!

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. Note the dolomitised nodular siliceous beds near the top of the unit. 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 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 (Kozlova 1999). Radiolarian biostratigraphy has shown that the succession above the K/T boundary is earliest to early late Paleocene age (radiolarian zones RP1 to RP5), supporting correlation with the Mead Hill Formation. A stratigraphic contact with overlying Eocene (Mangaorapan-Heretaungan) 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 indicate that all the Cenozoic limestone in the Ward area is Paleocene Mead Hill Formation (Hollis 1997).

STOP 2. Flaxbourne River (Chancet Quarry)

Flaxbourne River has been a very useful epithet for an important K/T 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/T boundary section (**Fig. 9**) is in a working limestone quarry on Chancet Station. If you want to visit it again, contact Herb to arrange access (03-575 6885).

Chancet quarry consists entirely of Mead Hill Formation. In general it dips and youngs to the northwest although it is moderately to highly deformed. Fortunately, the K/T boundary is relatively free of deformation in the higher parts of the quarry that are not currently being worked. As at Woodside Creek, the K/T boundary rests on a thick uppermost Cretaceous limestone bed. 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 2003b; Hollis et al. 2003a; Su et al. 2003) 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 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. 10)**. In Northern Hemisphere K/T boundary records, post-impact recovery is relatively rapid with calcareous microfossils returning to Cretaceous levels of abundance in less than 100,000 years. 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. The impact winter 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.

Figure 9. The K/T boundary at Flaxbourne River (Chancet Quarry). *Photo C. Hollis*

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 2003b; 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, read through this again tomorrow when you are standing in front of the 20 m thick basal 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).

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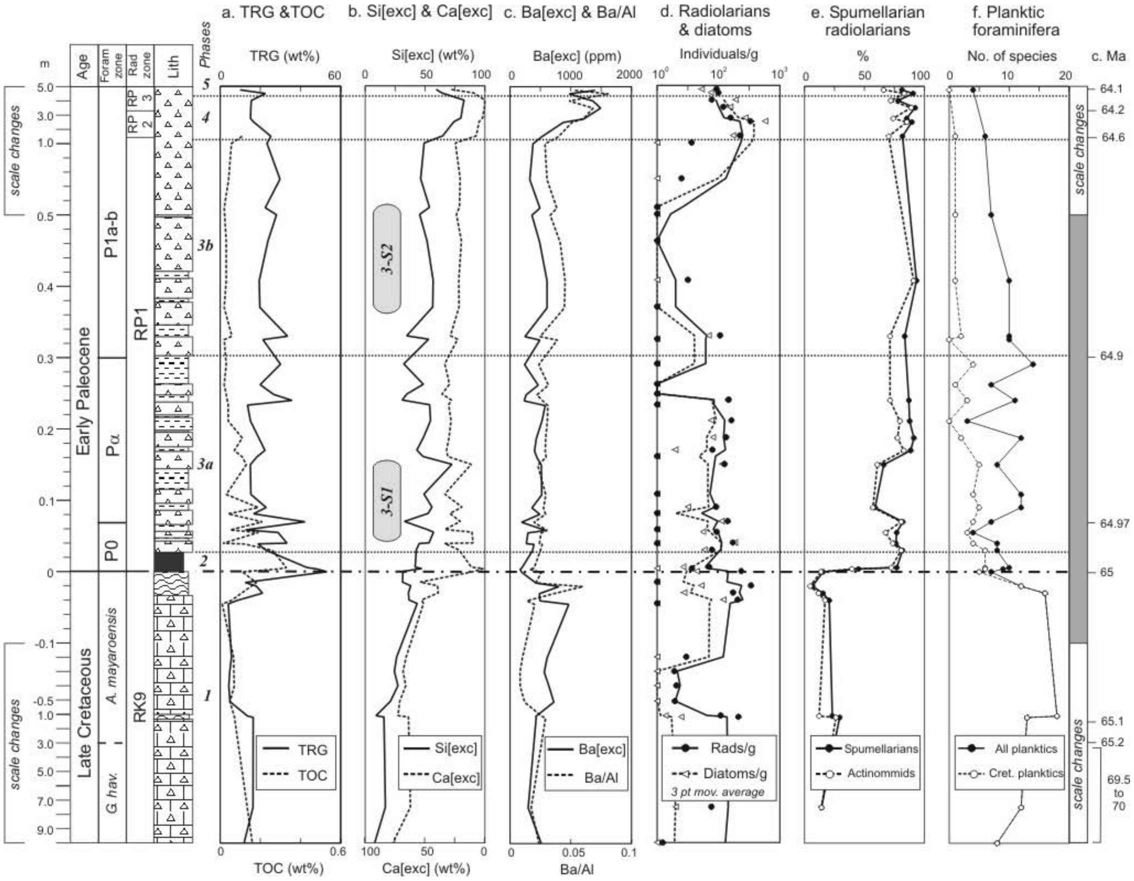

Figure 10. Variation in geochemical and paleontological environmental proxies through the K/T boundary transition at Flaxbourne River (from Hollis 2003b).

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 that closely resembles the eastern North Island Wanstead Formation or the Kandahar Formation of Tora (Field et al. 1997). Initial foraminiferal and radiolarian age determinations indicate a late Paleocene age.

STOP 3. Chancet Rocks

The Chancet Rocks K/T boundary section (Strong 1984) is similar to 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). Consider in what way it differs from the quarry section and if these differences can be explained by marine vs. terrestrial outcrop weathering, deformation within the boundary zone, and a more complete upper Paleocene succession. 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.

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

The K/T 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.

Stratigraphic completeness?

An intriguing feature of Marlborough K/T boundary sections is that although all of them have a thin boundary clay or zone enriched in iridium and associated indications of the K/T asteroid impact, only 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/T 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" and the presence of fullerenes (Hollis et al. 2003a).

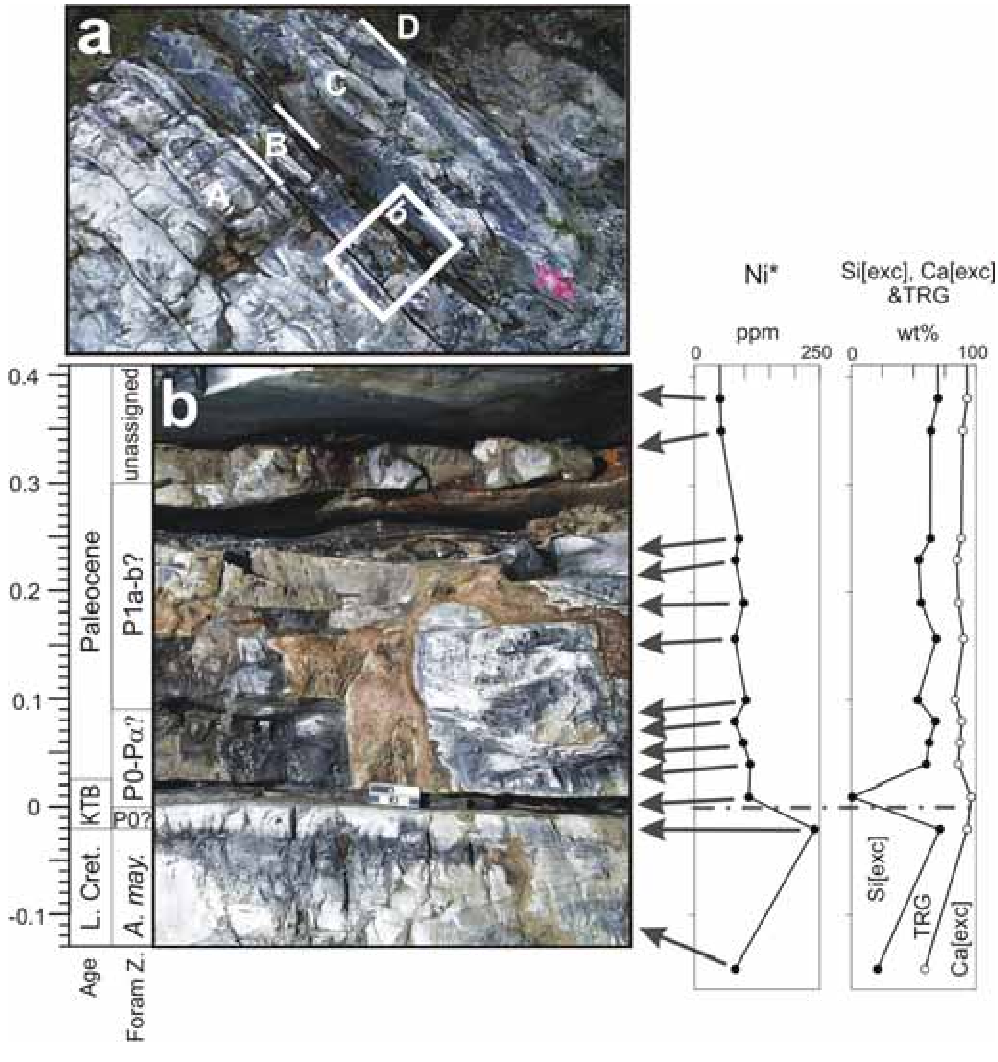

Figure 11. The K/T boundary at Mead Stream showing a nickel anomaly and earliest Paleocene forams in the top of the uppermost Cretaceous limestone (from Hollis et al. 2003b). *Photos B. Field*

Even more curious, the boundary clay at Mead Stream is a normal clay that has no geochemical anomalies at all (**Fig. 11**). 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/T 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/T boundary affected each section slightly differently: steady deposition at Flaxbourne River, initial deposition then erosion at Mead Stream, and erosion or non-deposition at Woodside Creek followed by redeposition of fallout material.

DAY 2: OUSE GORGE-NIDD STREAM & MEAD STREAM

The drive in

The drive to the Mead Stream section takes about one hour and passes through some dramatic scenery and geology. After leaving Ward, we travel south along the coast to the mouth of the Kekerengu River, approximately 20 km. Along the way we pass deformed Late Jurassic to Pliocene rocks, similar to those we will examine during the day. Where the road starts hugging the coastline about 6 km south of Woodside Creek, you'll notice soft unstable gunge to your right. This is Blue Slip or other smaller exposures of smectitic marl within Amuri Limestone that have a tendency to slide and block the road in periods of heavy rain.

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 Urutawan-Motuan (Early Cretaceous) inoceramid macrofossils.

<u>STOP 4</u>. 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. 12**). 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 Mangaotanean to Teratan (Late Cretaceous) Burnt Creek Formation that rests unconformably on Pahau Terrane rocks (Crampton & Laird 1997). Time permitting, we will stop at a fossiliferous outcrop of Burnt Creek Formation on the return trip. 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).

Northwest of the Ouse Fault the Cretaceous succession changes dramatically; it is these strata that are exposed in the Ouse Gorge-Nidd Stream section (**Fig. 13**). From Wharf Stream the road crosses a low ridge and descends to Coverham homestead, sometimes home to musterers of Bluff Station and the occasional very large pig. A short drive further on takes us close to the top of the Ouse Gorge and from there we walk a short distance into the gorge.

Figure 12. 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.*

STOP 5. Ouse Gorge

The Ouse Gorge-Nidd Stream section at Coverham is one of the classic stratigraphic locales in New Zealand and the area has been central 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 the stratigraphic and structural complexity, interpretations of the succession and geology have varied widely. During the present field trip we will have time only for a brief stop to view the unconformity at the base of the Split Rock Formation. This unconformity 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, "…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…".

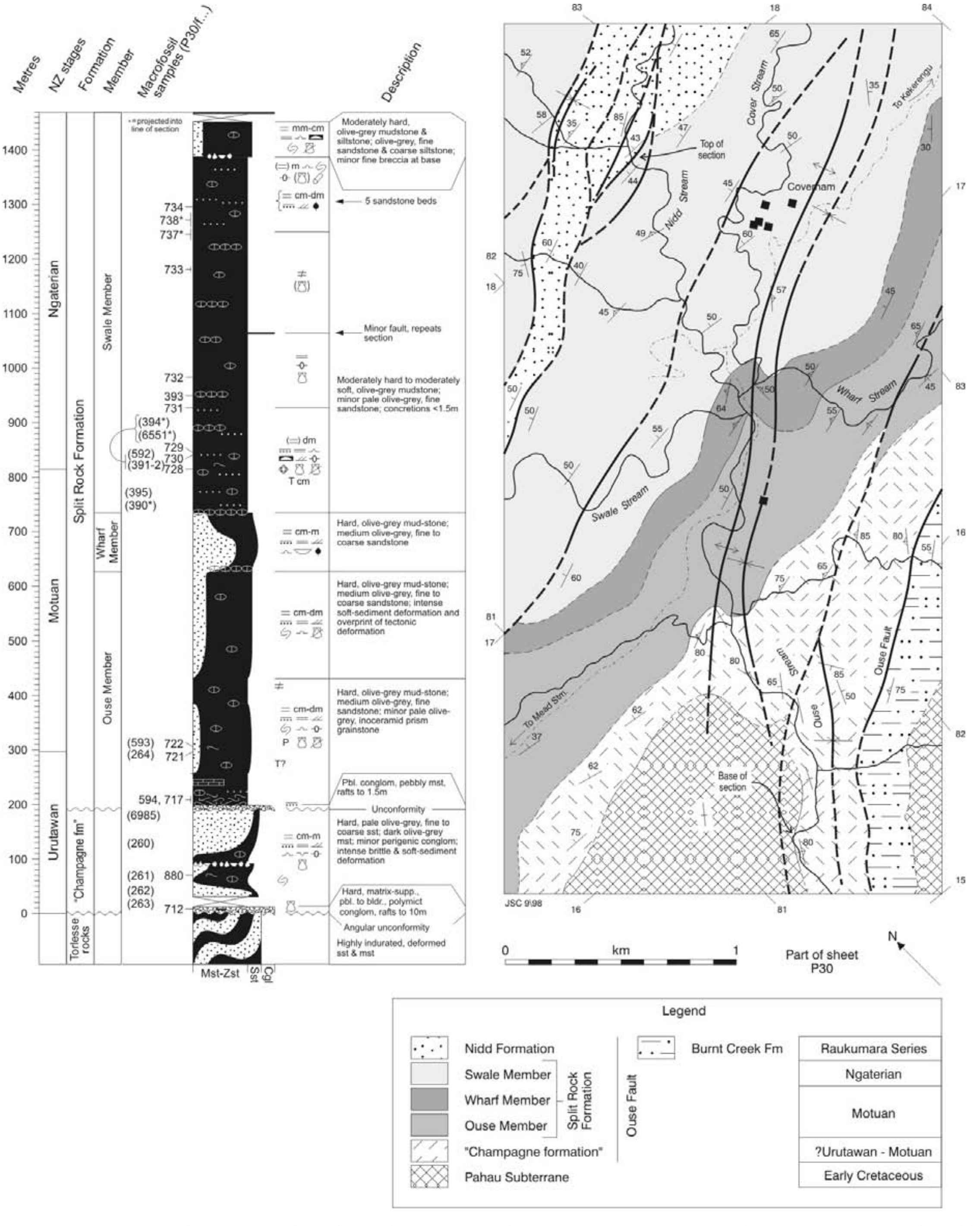

Figure 13. Measured section and geological map for mid-Cretaceous strata exposed in Ouse Gorge and Nidd Stream (after Crampton et al. 1998).

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. 13**). 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 soft-sediment deformation and brittle, tectonic deformation. Macrofossils and microfossils collected from Champagne formation indicate an Urutawan age (Crampton et al. 2004a).

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*. The base of the Motuan Stage, defined by the lowest occurrence of the small bivalve *Aucellina euglypha*, 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.

STOP 6. Mead Stream

Mead Stream is one of New Zealand's finest geological marvels! It offers a near complete record of bathyal pelagic sedimentation from Upper 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 (the other two being the Permian/Triassic mass extinction and the current anthropogenic extinction), as well as one of the best known ancient analogues for extreme global warming: the Initial Eocene Thermal Maximum (IETM, 55 Ma). 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 record of spectacular 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. 14**). The massive chert that overlies the K/T 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.

Figure 14. Muzzle Group strata exposed on the southern face of the Mead Stream gorge. *Photo: C. Hollis*

Take care fording the stream & keep your boots on – we will be crossing back and forth all day

Mead Hill Formation: ice in the greenhouse?

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/T and Paleocene/Eocene boundary intervals (Hollis et al. 2003, 2005). The Neogene succession was described by Browne (1995).

The logged section (**Fig. 15**) 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 form in Mead Hill Formation where there is a slightly higher terrigenous content than typical, as is found near the base of the formation and just above the

K/T 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 profuse growth of Marlborough rock daisies.

The K/T boundary (**Fig. 10**) is a sharp planar contact separating pale siliceous limestone from a 2.5 m interval of dolomitised chert and porcellanite, which is 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/T boundary impact prior to a relatively rapid return to more typical Mead Hill Formation sediments in the overlying ribbon cherts. Think back to the Woodside Creek and Flaxbourne River sections and consider what this means in terms of how New Zealand oceans were affected by the K/T boundary event.

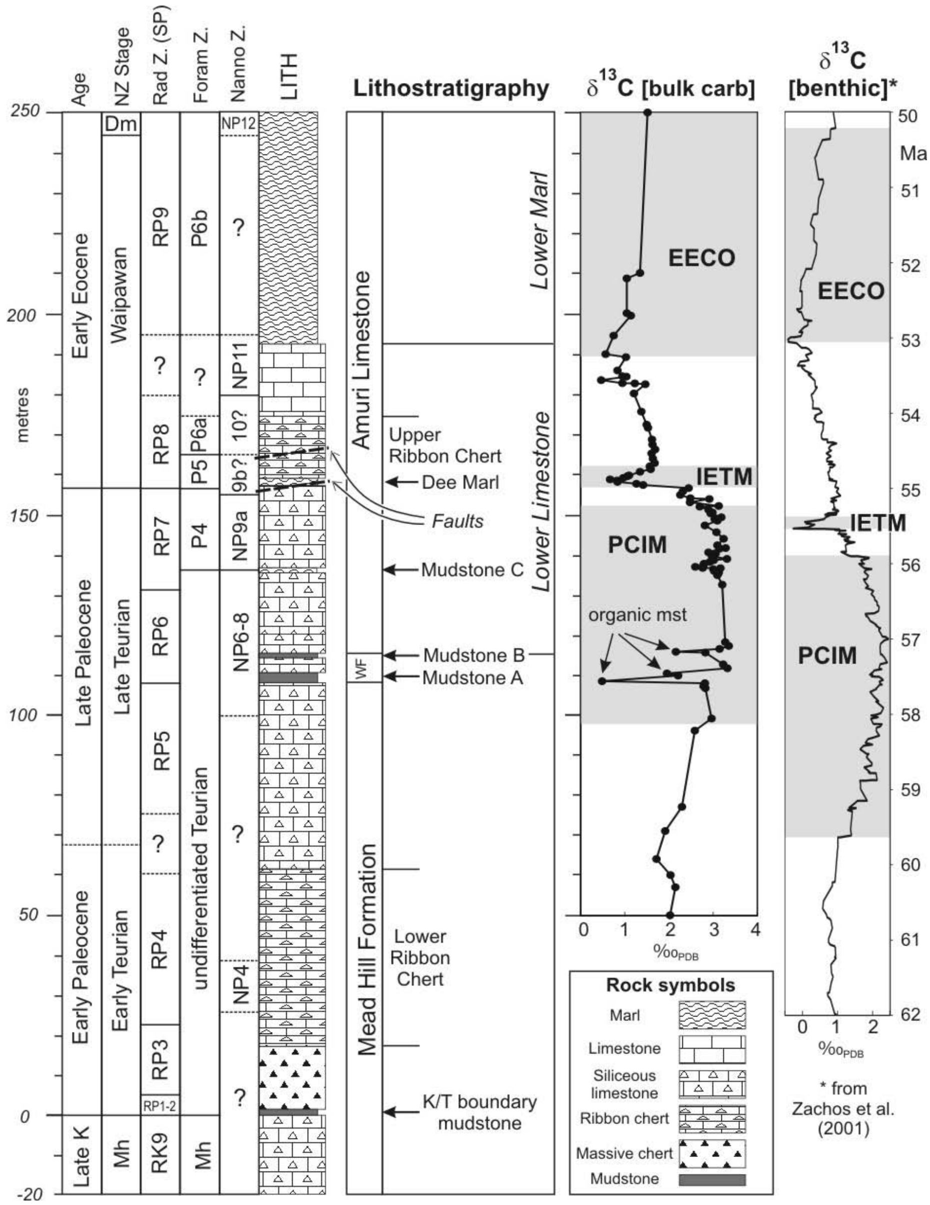

Figure 15. Lithostratigraphy, biostratigraphy and carbon isotope stratigraphy of latest Cretaceous-early Eocene Muzzle Group strata at Mead Stream (from Hollis et al. 2005a).

The Mead Hill Formation is overlain by what we now identify as the Waipawa Formation (Hollis et al. 2005a) – the same organic-rich mudstone that is the primary hydrocarbon source rock in eastern North Island and a known source of oil in north Taranaki Basin (Killops et al. 1994). Here, the unit is more siliceous, better bedded, and slightly lower in organic content 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.

Amuri Limestone: turning up the heat

The Amuri Limestone succession from Lower to Upper Limestone is the "South Pacific window into a greenhouse Earth" referred to in the title of this excursion. Does this window seem a little opaque to you? 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 some warm-water radiolarians and a small negative $\delta^{13}C$ excursion (**Fig. 15**), phenomena that 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. 16**), which marks the base of the Eocene (which now is known to equal the Teurian/Waipawan boundary). It is characterised by a negative $\delta^{13}C$ excursion of 1‰, the short-lived occurrences of warm-water forams, radiolarians and nannofossils (**Fig. 17**), and a sudden cessation in bioturbation. These features identify the IETM, a 100-200 thousand year event 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 (2×10^{18} g), which caused further greenhouse warming of 4-9°C (Dickens 1999; Zachos et al. 2001, 2003). 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.

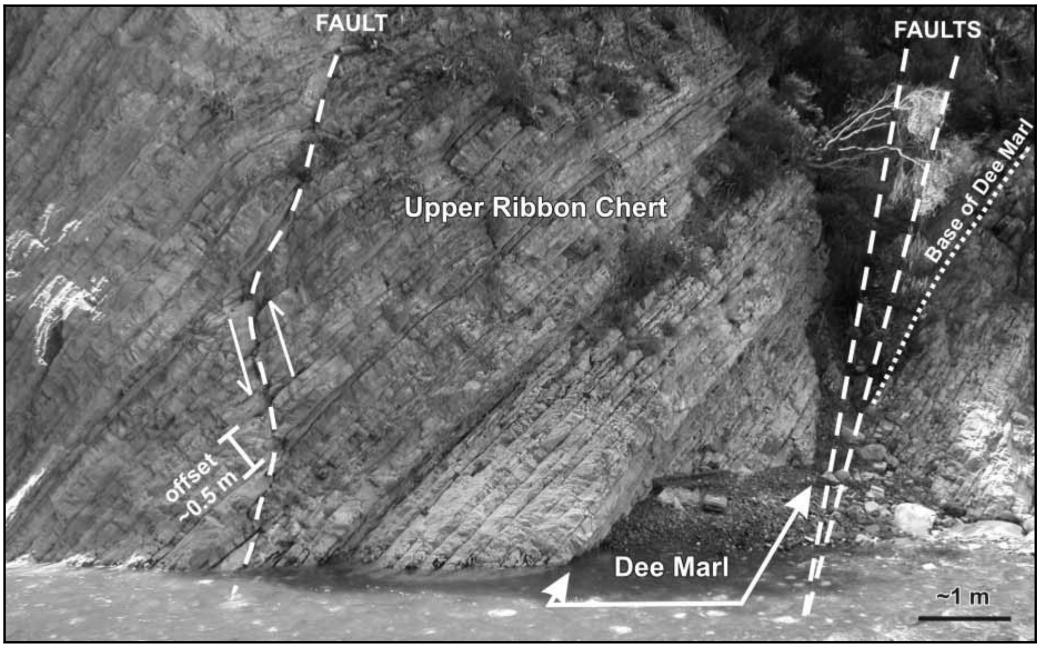

Figure 16. The Dee Marl at Mead Stream, representing the main phase of the Initial Eocene Thermal Maximum (IETM). *Photo B. Field*

The IETM 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 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 message: for temperate NZ waters global warming means red tides and less fish!

The base of the Dee Marl appears to be laminated and carbonate lean. This may signal acidification of the oceans and shoaling of the carbonate compensation depth in response to oxidation of methane (Zachos et al. 2005). Above the IETM at Mead Stream, we observe a period of recovery in the form of the gorge itself that consists of siliceous limestone with chert ribbons – the last macroscopic evidence of biogenic silica in the section. Coming out of the gorge we transition into an IETM-like event on a much broader and more subdued scale. Lower Limestone grades into Lower Marl, which is correlated with the Early Eocene Climatic Optimum (EECO) - a 3 million year episode of global warming (Zachos et al. 2001). Although the lower and middle portions of the Lower Marl are firmly dated as Waipawan and Mangaorapan, the age of the uppermost part of the unit is unclear. To date, the Heretaungan Stage has not been identified at Mead Stream, nor at any of the sections nearby.

Two things to consider here:

- Another short-lived IETM-like event called the ELMO has recently been identified in South Atlantic deep sea cores just below the onset of the EECO at about 53.5 Ma (Lourens et al. 2005). Can you see it at Mead Stream? Is there more than one?
- Lower Marl consists of c.120 marl beds alternating with packets of limestone beds that tend to thin upwards. The late Waipawan-Mangaorapan unit could represent anything from 2 to 5 million years. That's Milankovitch-scale isn't it?

The overlying Upper Limestone and Upper Marl are middle Eocene age (Porangan to Bortonian) and have yet to be studied in detail. Microfossil preservation through the upper part of this interval is quite good (Strong et al. 1995) so there is a good chance of testing our contention that this unit corresponds with the Middle Eocene Climatic Optimum (MECO) (Bohaty & Zachos 2003).

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. 18**). The unconformity surface has conspicuous *Thallasinoides* burrows and corresponds to the Marshall Unconformity (Browne 1995). Disconformably overlying this is another carbonate unit, the Early Miocene Whales Back Limestone, which also rests on a burrowed surface. This unit, which is rife with *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.

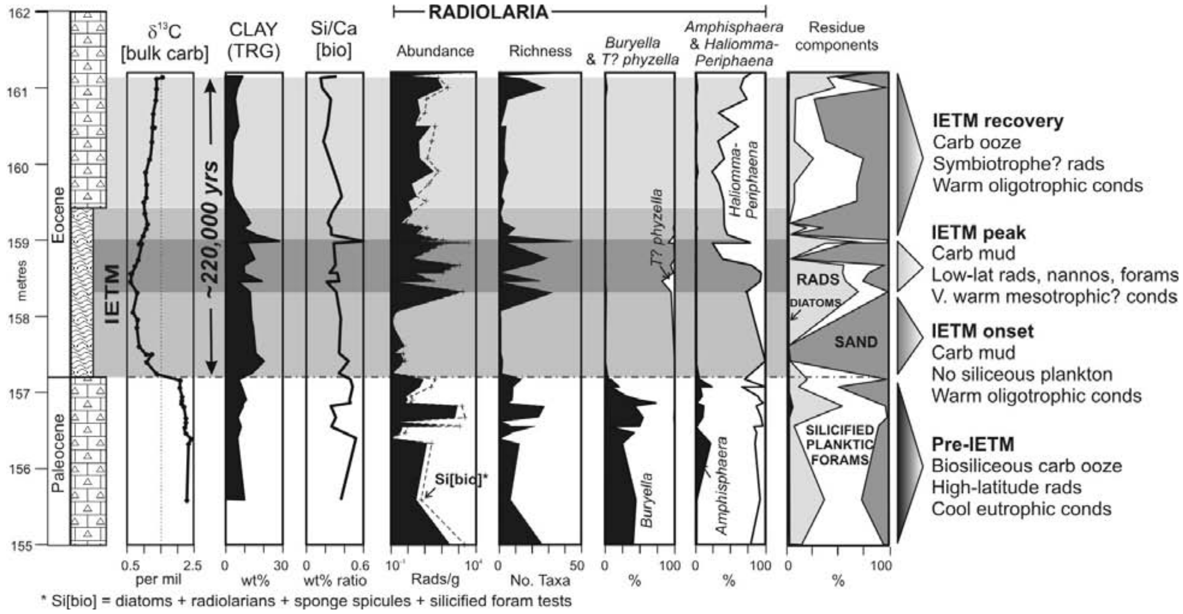

Figure 17. Siliceous plankton response to IETM at Mead Stream. Biosiliceous productivity plummets at the onset of the IETM but only during its peak is there fossil evidence for extreme warmth (from Hollis et al. 2004).

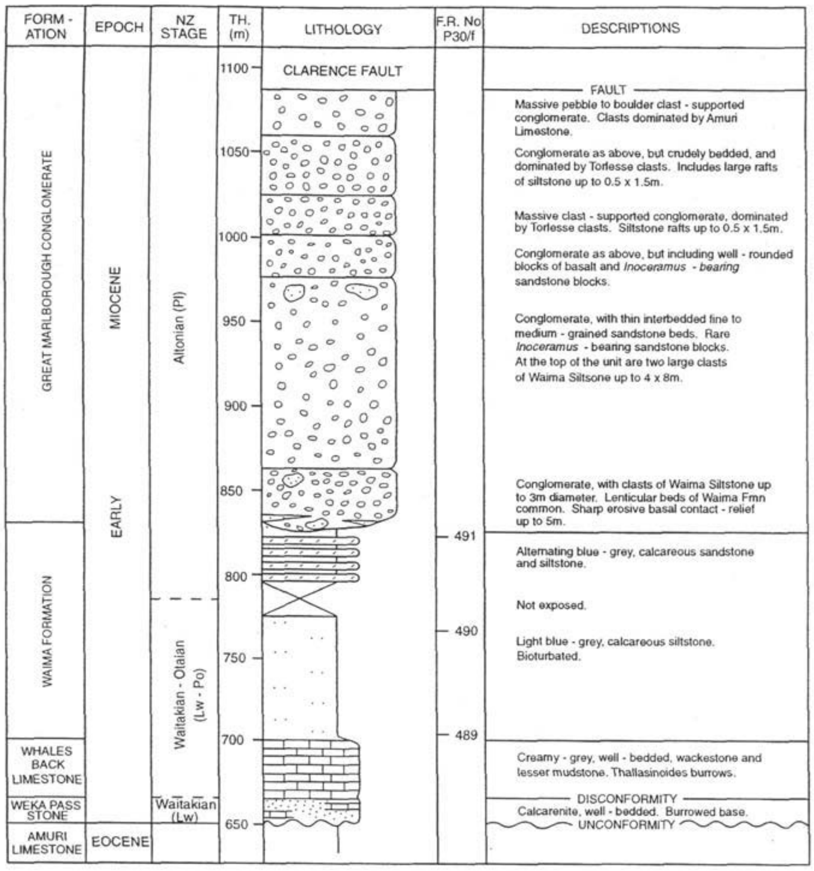

Figure 18. Measured section for Neogene portion of the Mead Stream section. From Crampton et al. (1998). Based on unpublished column by G. Browne.

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 (Lewis and Laird 1980). 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 diameter (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.

The Clarence Fault

The GMC is truncated against the Clarence Fault (**Fig. 19**). This fault is one of the principal elements of the Marlborough fault system. In Clarence valley it runs along the foot of the Inland Kaikoura Range, forming 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 yrs, 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.

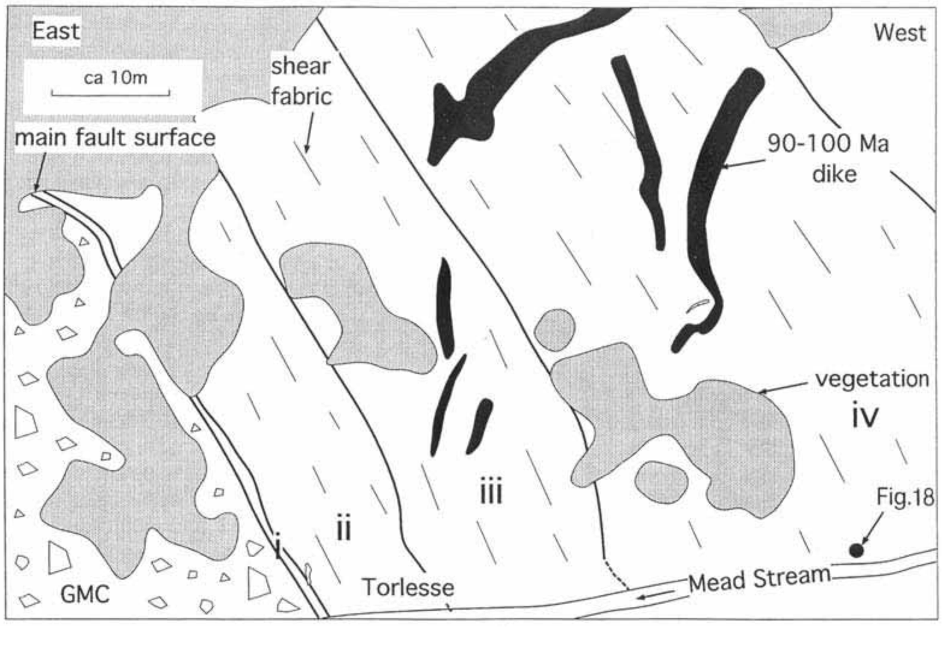

Figure 19. Line drawing of the Clarence Fault zone on the southern, true right, bank of Mead Stream (from Crampton et al. 1998).

DAY 3: WARD BEACH TO KAIKOURA

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.

STOP 7. The Haumurian succession at Ward Beach and Weld Cone

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.

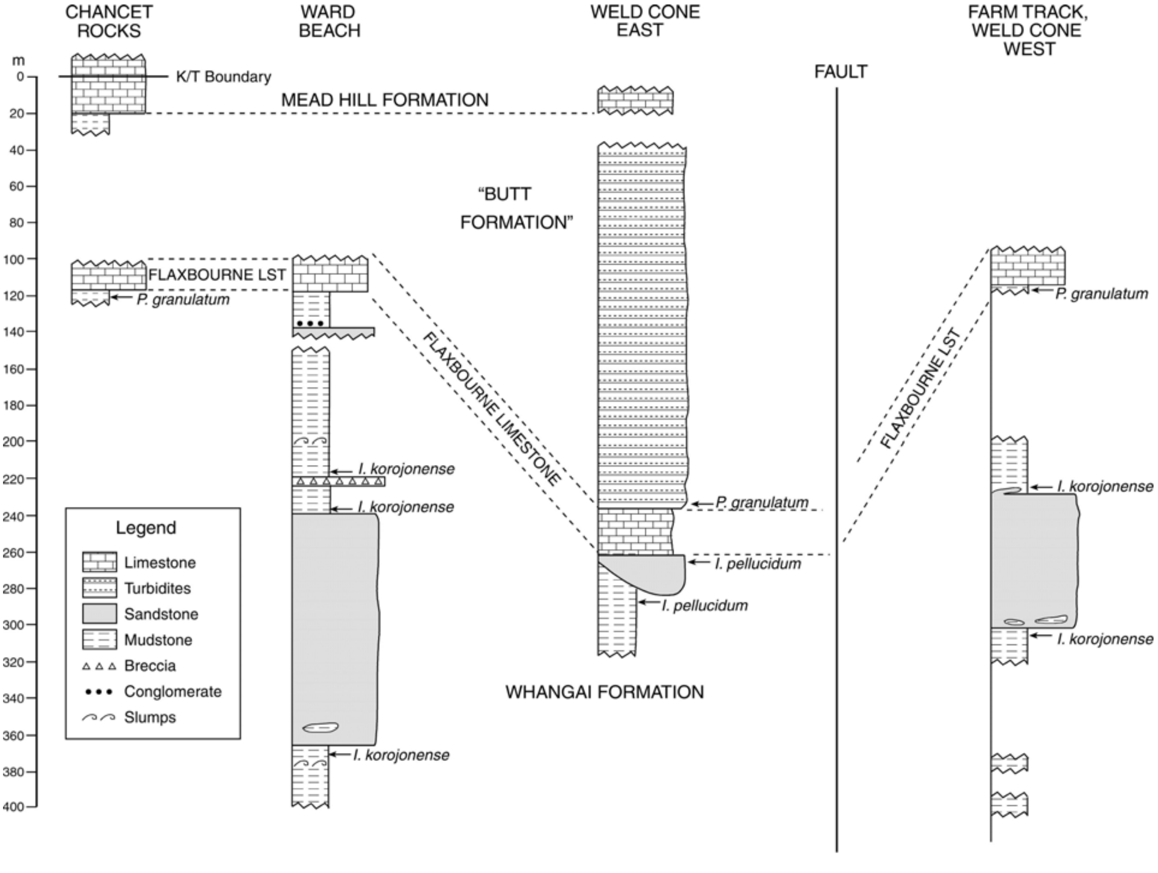

Figure 20. Measured sections for the Late Cretaceous portion of the Ward coastal block.

The Ward Beach section (**Fig. 20**) 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 late Early Haumurian (*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 Late Haumurian (*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/T boundary is not exposed in this section.

We will cross to the south side of the Flaxbourne River mouth, where better exposures of the upper part of the succession occur. Here, on the shore platform, we will see zones of soft sediment slumping within the upper part of the Whangai Formation, channel-fill sandstone bodies, some with water-escape structures (sheet structures) suggesting deposition from suspension flows, and pebbly mudstones. A 1 m thick pebbly mudstone beneath the Flaxbourne Limestone contains mainly rounded clasts, up to 80 cm, of chert, basalt and sandstone. Along the track at the base of Weld Cone we will view a stream section consisting of channel-fill, massive, well-sorted fine sandstone bodies up to 20 m thick underlying 25 m thick Flaxbourne Limestone, and a >220 m thick unit of turbidite sandstone between the Flaxbourne Limestone and Mead Hill Formation. Rare grooves and flute casts on the base of sandstone beds indicate current flow towards the ESE. The contact between the Flaxbourne Limestone and the turbidites is sharp. The upper 10 cm of the limestone contains small horizontal burrows, which may indicate that a hiatus followed limestone deposition. The turbidite unit also appears 11 km to the southeast at Wharanui, where it is >200 m thick, and underlies the Mead Hill Formation. However, the equivalent interval between the Flaxbourne Limestone and Mead Hill Formation at Chancet Rocks to the north is poorly exposed. The turbidites are of Late Haumurian age (*P.granulatum* subzone) at the base.

The thick sandstone unit underlying the Flaxbourne Limestone in the East Weld Cone area appears to be the infill of a significant but restricted channel system, which is not seen in the Ward Beach section. It has eroded substantially into the underlying Whangai Formation, as indicated by the significantly older age of the underlying strata (Fig.20). The extensive turbidite unit above the Flaxbourne Limestone at the same locality may also record infill of a depression remaining after deposition of the limestone as a drape, or a laterally-migrating turbidite fan, or both. Discussion is welcomed. The thick sandstone bodies present in the Early Haumurian part of the section are also inferred to be channel-fill deposits.

Palynomorphs in the clastic Haumurian sediments are dominated by wood debris and common spores and pollen, suggesting proximity to land. The microflora suggests an initial setting in a relatively shallow marine environment (Schiøler, pers. comm.), but supporting evidence from shallow-water sedimentary structures is lacking, and it is evident that much of the material has been transported and redeposited in deeper water. Microfossils from the overlying Mead Hill Formation indicate an upper mid-bathyal setting (Hollis et al., 2003b). The underlying horizons of debris flows, turbidites, channels and slump deposits are compatible with a slope or shelf edge environment.

As noted earlier, with the exception of scattered sandstone beds in the otherwise fine-grained Woodside Creek succession, the coarse-grained channel-fill deposits do not occur in equivalent successions to the west of the London Hill Fault. This latter feature appears to be the western boundary of a system of Neogene transpressive faults intersecting the Ward coastal area, and is inferred to have undergone a limited amount of dextral strike-slip movement (amounting to a few km), as well as overthrusting, during the Neogene (Audru 1996; Townsend & Little 1998). This seems unlikely to account for the marked difference in sedimentary facies and inferred depositional setting across the London Hill Fault. There are, however, similarities between the Haumurian Ward coastal succession and the succession at Tora in SE Wairarapa (Laird et al. 2003), where similar channels, slumps and coarse clastic deposits also occur in the upper part of the sequence. Beds of micritic limestone interspersed within clastic beds close to the K/T boundary there may correlate to the Flaxbourne Limestone. The Late Cretaceous succession at Tora represents the southernmost segment in the North Island of the partly allochthonous Eastern Sub-belt (Moore 1988b), and it is possible that the Sub-belt extended further south to include the Ward coastal area, with the London Hill Fault marking the tectonic boundary of a well-travelled block (Laird 2005).

Figure 21. View of the east face of Weld Cone, displaying latest Cretaceous stratigraphic units. The Flaxbourne Limestone occupies the middle portion, with a thick turbidite unit overlying towards the top left-hand corner. Channel-fill sandstone underlies the limestone (bottom right of centre), and fine-grained Herring Formation is exposed to the bottom right of the photo. *Photo M. Laird*

If time permits, we will drive up Weld Cone on a private track to the repeater station to obtain a bird's eye view of the upper part of the succession (**Fig. 21**). On the way we will pass a well-exposed 80 m thick sandstone body in the Whangai Formation, also with large rafts of Whangai Formation in its basal portion, and occupying a similar horizon to the late early Haumurian body we saw earlier in the Ward Beach section. It occurs in a separate fault slice from Ward Beach, and it is uncertain whether the bodies are linked, or occupy separate channels.

The drive south

The drive south from Kekerengu takes us past spectacular coastal exposures of Pahau Terrane greywacke. If you haven't had enough of seals by now, there are a few good seal-watching spots to the south, as well as a nice 10-15 min return scenic walk to a waterfall.

STOP 8. Waipapa Bay

In the railway cutting at Waipapa Bay, we will examine a condensed section through the upper Whangai Formation, Branch Sandstone and basal Mead Hill Formation. Note similarities between cherty intervals either side of the Branch Sandstone. Morris (1987) has 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 (C. Hollis, pers. obs.), which are indicative of Paleocene Mead Hill Formation. Siliceous biomicrites on the shore platform were assumed to be Amuri Limestone by Morris (1987).

Kaikoura Field Station section

If we get to Kaikoura early, we can visit a shallower correlative of the Mead Stream section exposed in a gully behind the University of Canterbury field station. In this section, 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 age for the Amuri succession, which suggests that it is primarily Lower Marl, probably capped with 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.

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