

# CRETACEOUS STRATIGRAPHY AND EVOLUTION OF THE MARLBOROUGH SEGMENT OF THE EAST COAST REGION

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## Abstract

Mid to Late Cretaceous strata in Marlborough rest with marked unconformity on an indurated and highly deformed "basement" of Early Cretaceous Torlesse sediments. This regional angular unconformity, of late Albian age, is the stratigraphic expression of a fundamental change in tectonic regime from compressional to extensional. Post-Torlesse extension resulted in half graben formation late in the Albian, mild uplift and tilting in early Cenomanian times, and probable thermal subsidence from the Campanian onwards.

Late Albian to Coniacian strata overlying the late Albian regional unconformity are represented in the west and south of the region by three lithostratigraphical units (Coverham Group, Wallow Group and Hapuku Formation) bounded by unconformities and correlative conformities. In the northeast, the age-equivalent Burnt Creek Formation which is in fault contact with the remainder of the region and has contrasting lithology, represents continuous sedimentation from the unconformity on Torlesse. These units are inferred to have been deposited in a north-northeast to northeast trending basin closing to the south, the Burnt Creek Formation representing part of the eastern margin of the basin which has been tectonically telescoped against the western margin.

Campanian events began with a relative drop in sea level, followed by major transgression induced by regional tectonic subsidence, which caused continued deepening throughout the remainder of the Cretaceous.

The Campanian-Maastrichtian Seymour Group, which blankets the entire region, was also partly controlled by local structure, occupying a basin oriented NE-SW and opening to the NE.

## Introduction

Marlborough forms the southern extension of the East Coast Region, bounded to the north and west by the Wairau/Alpine Fault, and to the south by the Hope Fault (Fig. 1). Like the rest of the region, it has suffered considerable Neogene deformation. Dextral strike-slip movement on the major Marlborough faults (Hope, Clarence, and Awatere; Fig. 2), probable block rotation, and large-scale thrusting has caused disruption of elements of the series of original Cretaceous basins which occupied the region. Not only has deformation rendered uncertain the original relationships of the basin segments to each other, but substantial Neogene uplift and erosion has meant that remaining outcrops are widely dispersed and mainly restricted to strips exposed on the lower flanks of the Inland and Seaward Kaikoura Ranges.

Although the Cretaceous rocks of specific areas have been studied by geologists in the past, e.g., the Clarence Valley (Thomson, 1919; Wellman, 1955; Suggate, 1958; Hall, 1963; Ritchie and Bradshaw, 1985; Reay, in prep.), the Awatere Valley (Challis, 1966; Lewis and Laird, 1986), and some localities south of the Hope Fault (Warren and Speden, 1978; Crampton, 1988), regional syntheses have been few. A text on the general geology of the region accompanied a 1:250 000 geological map of Marlborough (Lensen, 1962); and a section on the Cretaceous geology of Marlborough was included in *Geology of New Zealand* (Lensen, 1978).

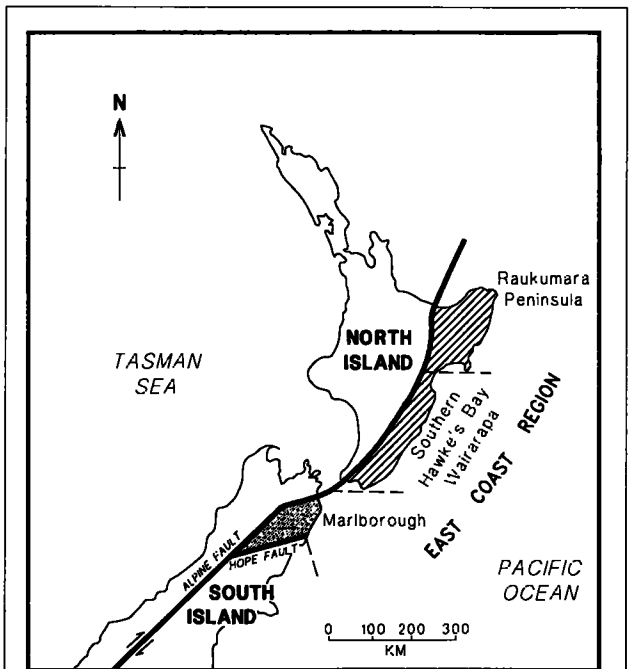


Figure 1: Map showing the location of the Marlborough sub-region (stippled) within the East Coast Region of the Sedimentary Basin Studies sub-Programme.



### Torlesse Supergroup

The oldest succession consists of Torlesse rocks, which constitute the "basement" of the region. The strata, which consist dominantly of indurated sandstones and mudstones, but include conglomerates, rare cherts, volcanics (including tuffs), and limestones, are highly deformed. Lithofacies are highly variable, including conglomerate units sometimes tens of metres thick, metre-bedded sandstones in thick successions, thick sheared mudstone units, and alternating sandstone and mudstone. Shelly fossils are rare, but their occurrence and the presence of dinoflagellates suggest that the environment of deposition was dominantly marine.

The age of the succession (almost entirely based on dinoflagellates and palynomorphs) is latest Jurassic to Early Cretaceous, ranging up to as young as Motuan\* (late Albian).

It had been previously inferred (Lensen, 1962; Lensen 1978) that the Torlesse rocks in Marlborough passed upwards conformably, at least over much of the region, into younger strata. However, it is now clear that the Torlesse Supergroup is separated from younger units by a major region-wide angular unconformity. This unconformity is considered to represent the stratigraphic expression of the end of the Early Cretaceous Rangitata Orogeny II (Bradshaw *et al.*, 1981), during which the Torlesse rocks were deformed and uplifted. This culminating event and subsequent erosion must have taken place over a limited time interval (less than 5 my), since Motuan rocks of the Coverham Group unaffected by the Orogeny overlie partly Motuan Torlesse rocks unconformably.

### Coverham Group

The Coverham Group, which overlies Torlesse rocks with marked unconformity, occupies fault-controlled basins which accumulated in excess of 2000 m of deposits of mainly sediment gravity flow origin.

The period of Motuan-early Ngaterian block faulting associated with the Group formed part of the widespread tectonism which produced grabens and half grabens over much of the South Island and western North Island (Laird, 1981). The unusual characteristic of the Marlborough basins is that they were infilled entirely by marine sediments, in contrast to all the other South Island infills, which are either entirely non-marine, or, in a few instances, paralic.

In the central Clarence Valley the Coverham Group is represented by the Split Rock Formation (Suggate, 1958). The formation was traced by Reay (1987) as far as Mead Stream in the lower Clarence Valley. The use of the name was extended by Ritchie (1986) to include strata of similar age and appearance in the Coverham area (Ouse Stream), where he recognised four members: Champagne, Ouse, Wharfe Sandstone, and Swale Siltstone.

In the upper Awatere Valley the Gladstone and Winterton Formations of Challis (1966) are included in the Coverham Group. These formations were later refined and expanded by Montague (1981), who recognised the Totara, Gladstone, and Lower and Upper Winterton Formations. In the middle Awatere Valley and southeast of the Hope Fault, unnamed correlative strata are also included in the Coverham Group.

At all exposures the Coverham Group rests unconformably on Torlesse Supergroup rocks, in some instances with angular discordance of up to 90°. Formations

\* New Zealand stage names are used throughout the text. See the left side of Figure 3 for correlation with International stages.

making up the Group are characteristically composed of one or more upwards-fining units containing conglomerate at the base, and passing upwards through alternating fine to very-fine grained sandstone to laminated mudstone.

The basal deposits are variable but in almost all cases coarse-grained. At the type locality of the Split Rock Formation in the middle Clarence Valley (Bluff Dump Hill\*\* section, Figure 2) the basal 26 m is occupied by metre-bedded clast and matrix-supported conglomerate and pebbly mudstone containing scattered shelly fossils overlying channelled Torlesse Supergroup. The conglomerate includes subrounded boulders of Torlesse sandstone up to 80 cm in diameter, and rare rafts of bedded sandstone up to 4.7 m long parallel to bedding. This facies is typical of most of the basal deposits throughout the region, and is interpreted as being the result of submarine debris flows.

Two notable exceptions are the Penk Stream section (Awatere Valley) and a local occurrence in Wharekiri Stream, where boulders in a muddy matrix occupy deep channels eroded into the unconformity on Torlesse rocks. The more striking example is in Penk Stream, a tributary of the Awatere River, where an almost complete and well-exposed succession from Torlesse through Motuan and early Ngaterian strata occurs (Lewis and Laird, 1986). Immediately overlying the unconformity is an olistostrome 240 m thick consisting of a massive, muddy, matrix-supported conglomerate containing both well-rounded pebbles and randomly oriented blocks (some in excess of 20 m) of bedded conglomerates, sandstones and mudstones. At the base, large rafts of slumped sandstone occur. There are scattered occurrences of the bivalves *Inoceramus* or *Aucellina euglypha*: a few belemnites (*Dimetobelus superstes*) occur loose in the matrix. Absence of any kind of stratification throughout the entire olistostrome suggests emplacement in one continuous event. This, together with the channelled nature of the base, suggests that the olistostrome may represent the fill of a submarine canyon.

Above the olistostrome is a further conglomeratic unit some 60 m thick which is mainly clast-supported and has a sandy matrix; weak stratification can be seen and clasts have a preferred fabric. These strata are inferred to have been deposited by a series of non-cohesive debris flows.

The coarse-grained deposits fine upwards through several metres of alternating conglomerate and parallel to cross-bedded fine-grained sandstone/mudstone successions into a 350 m thick unit of interbedded fine-grained graded sandstones and thinner mudstones, with rare granule conglomerates, interpreted as turbidites. Abruptly but conformably overlying the alternating sequence is at least 150 m of mudstone containing sparse calcareous concretions. Rare *Inoceramus* specimens indicate a Ngaterian age for the mudstone and upper few metres of the underlying alternating sequence. Marine macro-fossils occur throughout the succession.

The Penk River succession above the olistostrome is reflected by the majority of the Coverham Group strata elsewhere, particularly in the west of the region. In the east, notably in Wharekiri Stream and Mororimu Stream, instead of alternating sandstones and mudstones, mudstone-dominated successions containing scattered thin debris flow deposits, pebbly mudstones, and thin slump packets dominate.

\*\* All key section localities are shown on Figure 2.

Dramatic differences however occur in sections in the middle Awatere Valley adjacent to Penk River. In the Hodder River, 10 km to the southwest of Penk River, mudstone dominates the succession, with subordinate sandstone and only rare conglomerate. Slumping and sandstone dikes are common, suggesting downslope movement after deposition. A contrasting section occurs midway between the Hodder and Penk exposures, outcrops consisting of interbedded sandy conglomerates and thick sandstones, often infilling shallow channels and scours. The strata here and in the Hodder River pass upwards into mud-dominated deposits with scattered, thin graded sandstone and conglomerates also of Motuan age.

These rapid changes of lithofacies throughout this relatively small region are best explained by syndimentary faulting; at least one post-Motuan, pre-late Ngaterian fault has been recognised in outcrop (Lewis and Laird, 1986). Thus sedimentation is likely to have occurred in a series of closely-spaced half-grabens (maximum separation 5 km) bounded by growth faults.

Evidence of deposition of the Coverham Group in half-grabens is found in other Marlborough successions. In the upper Awatere Valley, Motuan strata in excess of 2000 m occur locally. In the valley of the Winterton River three fining upwards sequences of Motuan strata, separated by slightly discordant erosion surfaces, occur in succession. This sequential arrangement is just what would be expected if a succession of tectonic movements occurred along a fault scarp bounding a half graben (see Surlyk, 1984). A similar situation is represented at the type locality of the Split Rock Formation, where two fining-upward units occur in succession.

Paleodepth and paleoenvironment for much of the succession is uncertain, mainly because of the resedimented nature of the deposits. However, if the assumption is made that the 250 m thick Penk olistostrome was emplaced in one depositional episode, bathyal or greater depths were reached at least locally. In the nearby Cam River/Awatere River section, common ripple marks and some probable wave-induced ripples suggest deposition above at least storm wave base.

In only one instance, in a drillhole at Hapuku River (12 km north of Kaikoura) have what are interpreted to be shallow marine deposits been recognised (Laird, 1982). To the south of this locality, no Motuan rocks are known and a basin margin is inferred. The position of the western margin is entirely unknown, due to lack of exposure.

Plots of thickness distribution of the Coverham Group follow no discernable pattern, a fact mainly attributable to deposition in local small basins, but also to stripping of these sediments in the west during intra-Ngaterian uplift and erosion. Transport direction of the sediments throughout the region was dominantly towards the northeast.

Marine macro-fossils, including *Inoceramus ipuanus-kapuus* and *Aucellina euglypha* occur commonly throughout the region, the latter indicating a Motuan age for most of the Split Rock Sequence. In Penk, Mororimu, and Wharekiri Streams *Inoceramus tawhanus* is found in the top portion of the successions, indicating that the sequence extends into the Ngaterian.

### Wallow Group

Tectonic activity, which waned during the late Motuan, was reactivated in Ngaterian times, resulting in uplift, tilting and

erosion of the Motuan sediments in the west. Deposition of marine and non-marine conglomerates, sandstones, and mudstones of late Ngaterian and, locally of Arowhanan age, accompanied by the eruption of extensive alkaline basaltic lavas, heralded a new depositional cycle represented by the Wallow Group. Strata of this unit rest unconformably on older rocks in the west, but may be conformable with sediments of the Coverham Group in the east. In the west and south the succession consists dominantly of fine-grained well-sorted sandstone (Bluff Sandstone Formation - Lensen, 1978) interleaved with or overlain by basaltic lava of mildly alkaline affinities (Gridiron Volcanics Formation - Reay, in prep.)

At the base of the succession in the extreme west and southwest in the Clarence Valley and to the south, non-marine beds occur (Warder Coal Measure Formation; Lensen, 1978). The beds are (locally) up to 150 m thick and rest with up to 35° angular unconformity on the Coverham Group or Torlesse Supergroup. These pass laterally and upwards into basalts (Gridiron Volcanics Formation) and metre-bedded sandstones with marine shelly fossils (Bluff Sandstone Formation). Horizons of conglomerate occur locally in the latter, particularly in the west and southwest, and thin units of alternating sandstone and mudstone, increasing in frequency towards the northeast, are also present. The metre-bedded sandstone is typically fine to very fine grained, indistinctly parallel-laminated, with common ovoid weathered sideritic concretions up to 1 m in diameter. Pyrite nodules are locally common, and there are rare shelly and burrowed horizons. Hummocky cross-stratification has been recognised in the extreme southwest (Crampton, 1988) and southeast.

Towards the east and northeast (basinwards) units of alternating sandstone and mudstone become more common, and metre-bedded sandstones decrease in frequency. In the coastal strip north of Kaikoura, mudstone with thin graded sandstone and conglomerate beds, probably deposited by sediment gravity flow mechanisms predominates. Here there is no recognised unconformity between the Wallow and the Coverham Groups.

In the Awatere Valley basaltic lavas of the same age but with slightly different geochemistry (Lookout Volcanics Formation) from these in the Clarence Valley, rest unconformably on Bluff Sandstone or on Coverham Group strata. Dikes and sills of similar composition are included in the unit. Geochemical study (Nicol, 1977; Warner, 1990) indicates that the igneous rocks of the Awatere and Clarence Valleys were derived from different sources. The thickest exposed section of volcanics in the Awatere Valley exceeds 700 m. In the Clarence Valley flows reach a maximum cumulative thickness of 170 m in Seymour Stream, and thin to the northeast and southwest. To the northeast they disappear before reaching Muzzle Stream, although a 2 m thick flow with pillow structures (possibly unfaulted) at Coverham may be related.

In the Clarence Valley, a fluvial succession up to 170 m thick consisting mainly of interbedded basaltic conglomerate and sandstone, (Willows Formation; Reay, in prep.) is interstratified with and overlies the upper flows of the Gridiron Volcanics Formation. The formation has not been recognised beyond the Clarence Valley, where it is restricted to the southwest.

Aggregate thicknesses for the Wallow Group of up to 1100 m occur locally, but these are likely to be associated

with renewed half-graben formation during Ngaterian times. In at least one area, in the valley of Wharekiri Stream, a rapid thickness change from ca 400 m to ca 1100 m over a lateral distance of 5 km suggests penecontemporaneous fault control. In addition, the thinner sequence consists of massive or laminated mudstone, while the thick sequence is dominated by mudstones with common debris flows, slumps, and turbidites, suggesting proximity either to a slope or a penecontemporaneously active fault.

The Mt Lookout area of the upper Awatere Valley also provides evidence of tectonic activity continuing into late Ngaterian times. The Bluff Sandstone Formation, which rests unconformably on the Wallow Group here, is only patchily distributed and is preserved now only in small down-faulted blocks (Laird, 1989). Further uplift and erosion must have followed, since the Bluff Sandstone is overlain unconformably by Ngaterian basaltic lavas and thin, mainly shallow marine sandstones.

As for the Coverham Group, plots of thickness distribution for the Wallow Group follow no discernable pattern, a fact suggesting that these sediments too were deposited in part in small local fault-controlled depocentres. Erosion of the sediments following deposition has also probably affected the thickness distribution pattern.

Reasonable evidence is available on paleoshoreline and on paleoenvironment of deposition (Figure 4). In the south and west (in the upper Awatere and Clarence Valleys, and south of the Hope Fault) non-marine beds occur at or near the base of the Wallow Group suggesting an adjacent shoreline. The occurrence of brackish marine successions at Hapuku River and in the upper Awatere Valley also indicates proximity to a shoreline. There is an overall gradation eastward or northeastwards from non-marine through shallow marine thick-bedded sandstones, and then into increasingly deeper marine alternating sandstones and mudstones interbedded with thick bedded sandstones. However, there is a gap in exposure between the sandstone-dominated succession and the mudstone/turbidite dominated successions lying to the east and northeast. A submarine ramp down

which sediment gravity flows could have been initiated is likely to have existed here.

It appears from the outcrop distribution that, in the south, the Wallow basin was approximately co-terminus with the Coverham basin.

Paleocurrent evidence is sparse over much of the region. Reay (1980) records sedimentary structures indicating northeasterly, east-southeasterly, and west-southwesterly directions of transport in the Bluff Sandstone Formation of the western Clarence Valley. Crampton (1988) records a crudely bi-polar northwest-southeast paleocurrent orientation from cross-beds in the formation south of the Hope Fault, and sparse sole marks from the Bluff Sandstone Formation in Hapuku River in the east indicate orientations in the northeast-southwest quadrants.

Shelly fossils in the Bluff Sandstone Formation, including *Inoceramus tawhanus*, indicate a uniform Ngaterian age, except for localities in the extreme west of the outcrop area in Clarence Valley which include *Inoceramus rangatira*, an index fossil for the Arowhanan Stage. Total rock potassium argon dating of the Lookout Volcanic Member in Seymour Stream gave ages of  $94.62 \pm 1.30$  Ma and  $97.30 \pm 1.36$  Ma, and for a flow in Bluff Stream an age of  $97.6 \pm 1.6$  Ma (C.J. Adams, DSIR Physical Science, pers. comm.). These dates are consistent with the Ngaterian age given by the majority of the macrofossils.

A more constrained Rb-Sr isochron age of  $97.0 \pm 0.5$  Ma has been obtained from the geochemically similar Mandamus Igneous Complex, lying 80 km to the southwest of the volcanics in the Clarence Valley (Weaver and Pankhurst, in press).

#### “Hapuku Formation”

This unit has not been previously recorded, and has yet to be described and defined formally. It has so far been recognised at three localities only (Hapuku River, Wharekiri Stream, and Dubious Stream), but is probably present and previously overlooked in other sections. It overlies the Wallow Group erosively but without angular discordance.

In the Hapuku River section the basal deposits of the formation infill channels up to 30 cm deep, and are eroded into the top of the Bluff Sandstone Formation of the Wallow Group. The infill includes small pebbles of quartz and fragments of *Inoceramus* shells and belemnite guards. One kilometre to the south in Long Creek, where an equivalent section is exposed, no channels occur, and sandstone with layers of quartz grit overlie the Bluff Sandstone Formation with a burrowed upper surface. In Wharekiri Stream the contact is not well-exposed, but the basal sediments of the “Hapuku Formation” consist of metre-bedded very fine-grained sandstone with prominent *Ophiomorpha* burrows, and scattered pyrite nodules. In Dubious Stream, lava of the Gridiron Volcanics Formation is overlain erosively by thin glauconitic conglomerate containing broken prisms of *Inoceramus*, woody fragments, and large horizontal burrows (*Ophiomorpha*?).

The lithology of the bulk of the Formation varies somewhat from locality to locality, but one characteristic in common is the highly burrowed nature of the deposits. In addition to common small mm- to cm-scale burrows, large, dominantly horizontal burrows up to several decimetres long (*Ophiomorpha*?) also occur at several horizons in the Hapuku River, Wharekiri Stream, and Dubious Stream

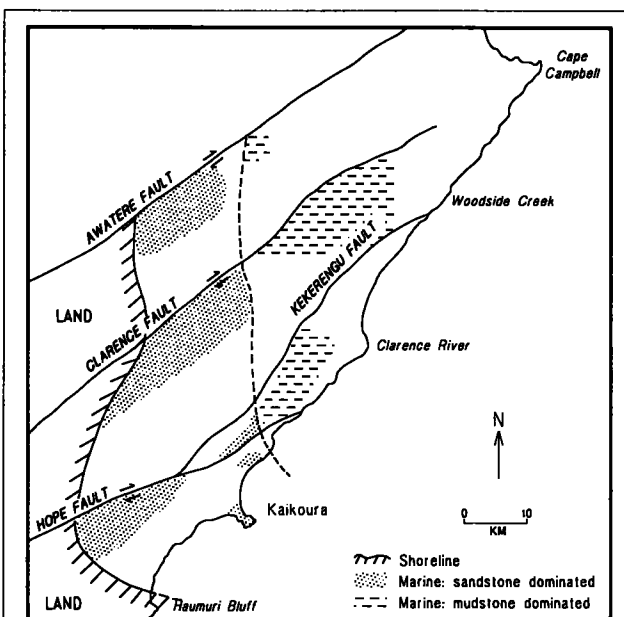


Figure 4: Inferred shoreline and generalised facies belts during early Wallow Group times (mid Ngaterian). •

sections. At Dubious Stream and at Hapuku River, the bulk of the sediments consist of indistinctly-bedded purple-brown siltstone and very fine-grained muddy sandstone. Glauconite is largely absent apart from blebs in the basal few centimetres. Shallow channels, and rare cross-bedded sandstone beds, occur in the Dubious Stream section. By contrast, glauconite is common in the Wharekiri Stream section. Bedding is more distinct, and large-scale cross-bedding occurs at several horizons.

Thickness varies from a minimum of 37 m at Hapuku River to a maximum of 98 m at Wharekiri Stream. No directions of sediment transport have been recorded. The highly-burrowed glauconitic nature of the deposits, and the presence of cross-bedding, suggests that the sequence was deposited in a shallow marine environment.

The age (almost wholly determined from dinoflagellates, and scattered guards of the belemnite *Dimetobelus superstes*) is Mangaotanean to Teratan.

### **Burnt Creek Formation**

This is a unit of Motuan to Teratan age defined by Hall (1965) in an unpublished M.Sc. thesis to include strata unconformably overlying Torlesse Supergroup rocks east of Ouse Stream. They were considered to be sufficiently different in lithology, and were also structurally separated from the adjacent and partly age-equivalent Split Rock Formation (Coverham Group) to be differentiated, and subsequent use of the formation name has been extended into the Kekerengu Valley to the east (Prebble, 1976). At the type locality of the formation the succession consists of massive basal conglomerate consisting of sub-rounded pebbles and boulders (mainly of Torlesse Supergroup lithologies) in a sandstone matrix, succeeded by alternations of thin conglomerate layers, alternating mudstone and graded-bedded sandstone, and increasingly thick mudstone units towards the top. Glauconite fragments occur in granule conglomerates at several horizons. To the east, in the Kekerengu Valley, the formation consists mainly of dark grey micaceous sandy mudstone, with interbedded layers of glauconitic sandstone or grit.

The Burnt Creek Formation was mapped by Ritchie (1986) as far south as the Clarence River near the junction with Ouse Stream, where, above a basal conglomerate, it consists mainly of several hundred metres of alternating sandstone and mudstone. Here and to the northeast it is separated from Torlesse Supergroup and from the Split Rock Formation by a major structure, the northeast-trending Ouse Fault. Ritchie and Bradshaw (1985) noted important differences in lithology across the fault: the Paton Formation (see below), which overlies the Burnt Creek Formation, is the oldest Late Cretaceous unit common to successions on both sides of the fault.

The formation is thickest in the west adjacent to the Ouse Fault, reaching a minimum of 660 m at the junction of Ouse Stream and Clarence River, and over 500 m in Latters Stream (Ritchie, 1986). Eastward, in the Kekerengu Valley, it thins to 160 m.

The common occurrence of graded bedding in the west suggests that many of the coarser-grained sediments were deposited by sediment gravity flows at moderate depths. Eastward shallowing to shelf depths may be indicated by the more frequent presence of glauconitic horizons in the Kekerengu Valley. Sparse paleocurrent indicators suggest

a direction of sediment transport towards the north-northwest (Ritchie, 1986).

The Burnt Creek Formation has an age range from Motuan to Teratan in the west, but youngs to the east and is restricted to Teratan in the Kekerengu Valley.

The Burnt Creek Formation has not been mapped south of the Clarence River. However, a condensed sedimentary unit of Ngaterian to Teratan age in Mororimu Stream may represent a southern extension. In the north branch 30 cm of muddy cone-in-cone limestone, with scattered small cubes of pyrite, rests with sharp but concordant contact on Ngaterian mudstone (possibly leached) of the Wallow Group. The limestone is overlain by 1 m of calcite-cemented conglomerate containing glauconitic blebs, small rounded granules of quartz up to 1 cm diameter and sparse shelly fossils. This is followed by 35 m of carbonaceous and glauconitic massive sandstone, overlain in turn by alternating mudstone and glauconitic sandstone beds (some graded), and thick laminated mudstones. Layers of broken shells occur at several horizons. Total thickness is 85 m.

The section differs from Burnt Creek strata described from the type area to the north in resting on the Wallow Group rather than on Torlesse Supergroup rocks. An alternative potential correlation is with the "Hapuku Formation" to the west, which also has some lithological similarities. However, this appears to be restricted in age to Mangaotanean and Teratan. Although further sampling and paleontological dating may yet change the interpretation, correlation of the Mororimu Stream section with the Burnt Creek Formation is considered to best fit the present data.

### **Seymour Group**

Piripauan times ushered in major transgression throughout the whole of Marlborough, resulting in deposition of a blanket of glauconitic sandstone and jarositic mudstone and fine-grained sandstone - the Seymour Group (Reay, in prep.). It is composed of three formations, the Paton and Herring Formations (Webb, 1971), and the Claverley Sandstone (Warren and Speden, 1978).

The Paton Formation consists dominantly of glauconitic fine to medium-grained sandstone. It rests apparently conformably on the Burnt Creek Formation in the east, but is in erosional contact with older units to the west of the Ouse Fault. Basal scours up to one or two metres deep are locally eroded into the underlying strata, e.g., Dubious Stream, lower Hapuku River, and infilled with pebbly or gritty coarse to medium-grained sandstone. In the upstream part of the syncline exposed in Hapuku River, large burrows (*Ophiomorpha?*) infilled with glauconitic sandstone extend from the base of the Paton Formation for several centimetres into the top of the underlying "Hapuku Formation". In its type area, in the upper Kekerengu Valley, the Paton Formation appears to pass conformably downwards into the Burnt Creek Formation. However, in the Mororimu Stream section, the contact is concordant but sharp. It overlies a 20 cm-thick possibly weathered zone of red-brown mudstone. The basal few centimetres above the contact consists of mudstone with scattered pebbles of Torlesse sandstone, blebs of glauconite, and rounded clasts up to 1 cm diameter of pale-coloured phosphatic or calcareous nodules. A hiatus between the two units seems probable. A characteristic everywhere of the Paton Formation is its strongly burrowed character, including large *Ophiomorpha*.

The Paton Formation has been recognised throughout most of Marlborough, the main exceptions being outcrops in the Clarence Valley west of The Fell, and south of the Kaikoura Peninsula. Although it is recognised in a drillhole at South Bay, Kaikoura, and also in the succession at Monkey Face to the west, it is not present at Haumuri Bluff and localities further south. Chronostratigraphically it correlates with the Piripauan Okarahia Sandstone, which overlies Torlesse Supergroup rocks unconformably at Haumuri Bluff (Warren and Speden, 1978). However, this lacks glauconite and includes many shallow water marine features such as cross stratification and richly fossiliferous shelly layers. Part of the succession is likely to be non-marine (Warren and Speden, 1978), indicating the proximity of a paleo-shoreline.

Isopachs (Figure 5) show a consistent and steady thickening of the formation towards the northeast, from zero in the vicinity of Haumuri Bluff, to a maximum of 107 m in Benmore Stream in the northeast. The latter thickness shows a sudden increase from the 26 m at Burnt Saddle, 6 km to the west. This may represent rapid thickening basinwards across a shelf/slope break, or possibly the effects of tectonic telescoping by Neogene thrust faults.

Burrows, including *Ophiomorpha*, are extremely common, sometimes in such abundance that beds are mottled throughout without trace of original sedimentary structures. A shallow marine, probably inner shelf, environment is inferred. Paleocurrent data is too sparse to be useful, but the isopach interpretation coupled with facies changes in the extreme south, suggest a basin oriented towards the present northeast, with a southern shoreline in the vicinity of Haumuri Bluff.

The age of the Paton Formation is mainly Piripauan, but may reach into the Haumurian in the southwest.

The Herring Formation follows the Paton Formation everywhere, with sharp, but conformable contact. It and its correlatives are the most widespread of the Marlborough Cretaceous units, being present in all unfaulted sections, and extending to the south from Haumuri Bluff into the Canterbury

region as the time-equivalent Conway Siltstone (Warren and Speden, 1978). Correlatives in the Marlborough region include the Woolshed Shale (MacPherson, 1948), the Butt and Mirza Formations (Webb, 1971), and the Whangai Formation (Prebble, 1976). The dominant lithology is dark grey or black jarositic and carbonaceous sandy mudstone, with rare interbeds of well-sorted very fine-grained sandstone. Dikes of similar well-sorted sandstone are locally common. In Bluff River, 14 m of deformed chert form the base of the formation, but this lithology is not seen elsewhere. Burrowing occurs at many horizons, but is not as ubiquitous as in the Paton Formation. The formation is characterised by jarositic efflorescence, and by the presence of large scattered dolomitic concretions up to 5 m in diameter (Browne, 1985). In the northeast, the lithology changes rapidly in content, from massive mudstone with only rare thin sandstone beds near the top in the Whernside and upper Benmore Stream sections, to similar mudstones with intercalated thick beds of sandstone in the Woodside Creek section only 5 km to the east. Some sandstone beds are massive and up to 5 m thick, but commonly they are decimetre-bedded and show parallel lamination. Grading occurs in some instances. Some thicker sandstone beds, particularly in the lower part of the section, apparently infill small channels. One slumped bed was noted. Pyrite occurs at some horizons. In the coastal area to the northeast of Woodside Creek sandstone dominates, and a thin limestone unit is present near the top of the formation.

Isopachs on the Herring Formation (Figure 6), like those drawn on the conformably underlying Paton Formation, show a relatively consistent and steady thickening of the formation towards the northeast. Thicknesses vary from a minimum of about 10 m in the middle of the region to 700+ in the northeast. An abrupt increase in thickness, from approximately 220 m in the upper Benmore Stream and Whernside sections to over 700 m in Woodside Creek, occurs in the same area where the sudden change in thickness of the underlying Paton Formation also takes place. Although it is possible for such changes to take place over a short distance, e.g., at a shelf/slope break, it is also possible that

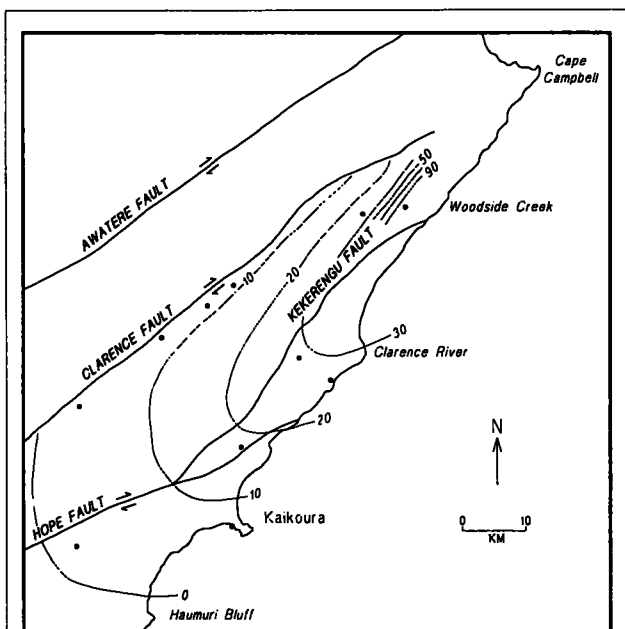


Figure 5. Isopachs on Paton Formation (Piripauan). Contours at 10 m intervals (20 m in the northeast).

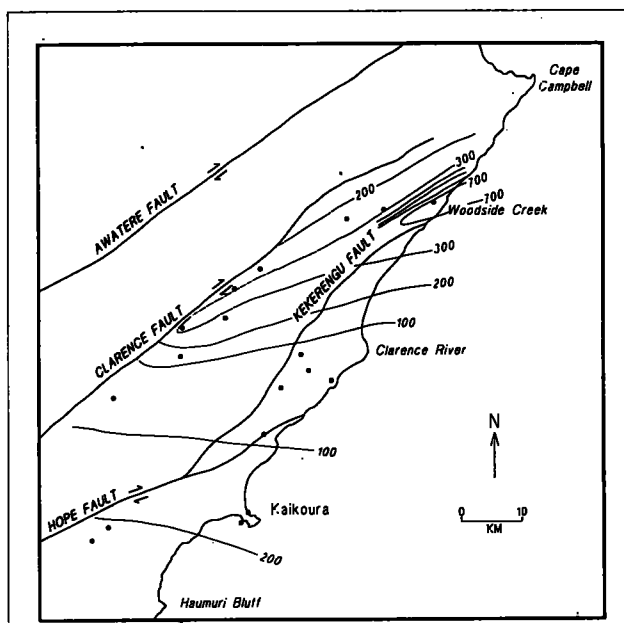


Figure 6. Isopachs on the Herring Formation (Haumurian). Contours at 100 m intervals (200 m in the northeast).

crustal shortening of perhaps several tens of kilometres has taken place across Neogene faults such as the Flags Creek Thrust (Waters, 1988).

The bulk of the Herring Formation was probably formed in a shallow marine, poorly oxygenated, reducing environment. The presence of sandstone-filled shallow channels and a slump horizon in the Woodside Creek succession suggests that the sediments here, and possibly those further to the northeast, were deposited in a slope environment. Paleocurrent data is too sparse to be useful, but the isopach map suggests the presence of a narrow, northeast-trending basin along the present site of the present Clarence Valley and out to the coast near Woodside Creek. The similarity of the isopach plot to that of the underlying Paton Formation suggests that the effects of erosion of the top of the Herring Formation in the west has not significantly affected the plot. As noted earlier, the Herring Formation and marine correlatives extend far beyond the borders of Marlborough, so a paleoshoreline cannot be determined. Oil seeps, attributed to the Herring Formation as source (R A Cook, pers. comm.), occur in the northeast where the formation is thickest, suggesting that here the sediments have reached sufficient maturity for oil generation.

The Claverley Sandstone is a pale yellow-brown and grey, poorly sorted, silty very fine-grained sandstone which conformably overlies the Herring Formation in the Haumuri Bluff area. It is composed dominantly of subrounded to angular grains of quartz, although glauconite is present throughout, mostly making up 5-10% of the rock, and locally reaching 30%. Reworking by burrowing organisms is extensive. Thickness is variable, with a maximum of 43 m south of Haumuri Bluff.

The poorly-sorted nature of the deposits, combined with extensive reworking by burrowing organisms, suggests shallow marine deposition under low-energy conditions. Warren and Speden (1978) speculated that most of the terrigenous detritus originated from settling through water of wind-blown material. The age of the Claverley Sandstone is restricted to the Haumurian.

### **Latest Cretaceous Units**

The study of these units was outside the scope of the present research, but they have been examined in some sections, and are here briefly discussed for completeness.

Two units have been recognised: the Branch Sandstone (Reay and Strong, in press) and the Mead Hill Formation (Webb, 1971). The Branch Sandstone is usually a massive fine-grained sandstone which disconformably overlies the Herring Formation south of the Hope Fault and in the Clarence Valley as far northeast as Branch Stream. Further east it is absent. Sedimentary structures are rare, probably due to its intensely burrowed nature. In Wharekiri Stream, it has a sharp base covered with prominent horizontal burrows. Here, and in Bluff Stream, a thin matrix-supported pebble conglomerate forms the basal few centimetres. At Branch Stream the upper part of the formation is highly carbonaceous. The thickness varies between 50 cm and about 75 m, but no pattern can be distinguished. The almost ubiquitous burrowing and the well-sorted nature of the sandstone suggests a shallow marine shelf environment, periodically swept by strong currents. The Branch Sandstone is Haumurian in age.

The Mead Hill Formation consists of chert-rich micritic limestone forming the basal unit of the Amuri Limestone. It rests conformably on Branch Sandstone in the west, and conformably on Herring Formation from Wherside to the northeast. Thickness is normally several tens of metres. The lack of clastic sediments compared with the underlying formations suggests a quiet environment more remote from land and/or in deeper water. This is confirmed by foraminiferal studies, which suggest paleoenvironments throughout the formation deepening from inner-to-mid shelf to bathyal depths (Strong *et al.*, 1991). Age of the lower part of the formation is late Haumurian, but it extends up into the Tertiary.

## **Tectonic Events**

At least three tectonic events can be recognised in the early and mid Cretaceous of Marlborough, and a further period of general subsidence in the Late Cretaceous.

### **Early Cretaceous Tectonism**

The most significant event affecting the Marlborough region in the Early Cretaceous was the Rangitata II Orogeny (Bradshaw *et al.*, 1981), which resulted in deformation and uplift of the Torlesse rocks. This is attributed to the culmination of a period of convergent margin tectonics brought about by collision and subduction of the Phoenix/Pacific Ridge along the active margin lying to the east of New Zealand (Bradshaw, 1989). In Marlborough the Orogeny apparently did not reach its peak until early Motuan times, as in some localities Torlesse rocks containing Motuan fossils have been folded and eroded. The main stratigraphic feature of the Orogeny is a striking angular unconformity separating Torlesse strata from younger rocks.

### **Mid-Late Motuan Tectonism**

Following a period of tectonic quiescence, during which erosion of the uplifted Torlesse rocks occurred, a period of block faulting resulting in the widespread formation of half grabens began in mid or late Motuan times. Sporadic vigorous uplift along faults bounding the half grabens, as well as rapid subsidence of the basins, is indicated by the presence in the infill of olistostromes, debris flows, and other sediment gravity flow deposits, as well as repetitive fining-upwards units, of the Coverham Group. Activity continued until early Ngaterian times.

The period of half graben formation in Marlborough represents a period of crustal extension which occurred over most of the New Zealand region at this time. The Pacific margin extensional tectonics, at least, are considered by Bradshaw (1989) to reflect passive subsidence, the result of the thermal decline of underlying Cretaceous lithosphere. However, the half grabens may represent crustal rifting that presaged the opening of the Tasman Sea and Southern Ocean (Laird, 1981).

### **Ngaterian Tectonism**

A further, less significant tectonic event occurred in Ngaterian times prior to deposition of the Wallow Group, resulting in the tilting of parts of the Coverham Group by up to 30° in the west, while leaving strata in the east unaffected. This may, however, represent the continuation of uplift along faults bounding the Motuan-early Ngaterian half grabens.

A more significant event is represented by the widespread intrusion of dikes accompanied by major outpourings of alkaline basalts in the Awatere and Clarence Valleys. Geochemical study of the basalts shows that they contain no subduction-related signature, and they are consistent with intraplate volcanism (Warner, 1990). In the Mt Lookout area of the upper Awatere Valley a period of normal faulting immediately prior to deposition of the Lookout Volcanic Formation is indicated by the presence of isolated unfaulted remnants of Bluff Sandstone Formation below lavas (Laird, 1989), and there is also evidence that locally in the Clarence Valley half graben formation continued, as noted earlier. The geochemistry of the somewhat younger intermediate to silicic Mount Somers volcanics of the Canterbury region to the southwest of Marlborough is also consistent with intraplate extension (Barley, 1987).

This period of tectonism may relate to extensional events accompanying sea floor spreading between Australia and Antarctica at  $95 \pm 5$  Ma (Veevers, 1986) or 98 Ma (Lowry and Longley, 1991).

### Late Cretaceous Subsidence

There was apparent tectonic quiescence in the Marlborough region in post Ngaterian times until a major transgression of the sea in the Piripauan, resulting in deposition of the Seymour Sequence and subsequent units. Transgression and deepening continued until early Oligocene times, and is attributed to thermal subsidence accompanying the drift of New Zealand away from Australia-Antarctica at about 84 Ma.

### Movement on the Ouse Fault

To explain the contrasting stratigraphy on either side of the Ouse Fault prior to the Paton Formation, it seems necessary to invoke movement on this and associated faults. Ritchie and Bradshaw (1985) speculated that the lithological differences were brought about by one of several means. One possibility was that the blocks have not greatly changed in position, but differing patterns of subsidence and sediment supply operated on either side of the fault. An alternative hypothesis was that the eastern and western blocks were originally kilometres apart and were brought together by strike-slip or thrust faulting prior to deposition of the Paton Formation. A third alternative, preferred here, is that post-Cretaceous, probably Neogene, reverse faulting, juxtaposed the two blocks. Both Paton and Herring Formations have characteristics and lithofacies associations which are similar to correlative units throughout the whole East Coast Deformed Belt, and displacement of strata by many tens of kilometres might not be readily recognisable.

## Sequences and Relative Sea Level Changes

Of the five post-Torlesse Supergroup unconformity-bounded units discussed under the stratigraphic section, at least three are related to the effects of change in relative sea level; the remaining two are likely to have resulted from tectonic processes.

Deposition of the Coverham Group is considered to have been essentially tectonically controlled, as indicated by evidence of deposition in small half grabens and for semi-continuous vigorous uplift along basin margin faults.

Sedimentation in the older part at least of the Burnt Creek Formation in its type area is also likely to have been tectonically controlled. This is suggested partly by the common sediment gravity flow deposits, and by the rapidly eastward-younging age of the base of the unit accompanied by eastward thinning and shallowing. These features suggest a series of controlling faults downthrown to the west. In the upper Kekerengu Valley, where the succession is thinner and entirely of Teratan age, the dominant control may be sea level change, but there is insufficient evidence from which to draw conclusions. The succession in Mororimu Stream (tentatively included as part of the Burnt Creek Formation) differs in that relative to outcrops to the north it is a condensed sequence, only 85 m of section representing the 3+ New Zealand stages from Ngaterian to Teratan, whereas to the west the Ngaterian alone reaches a local thickness of 1100 m. Glauconite is also common. The Mororimu Stream succession may therefore represent the condensed section element of a Transgressive Systems Tract.

The Wallow Group almost certainly represents the results of sea level change. The basal unconformity represents a type 1 sequence boundary which has been subaerially exposed, at least in the west. Westward onlap of the overlying sequence has occurred. The sediments, in particular the sandstone-dominated suite in the west, are inferred to represent portions of the Transgressive and Highstand Systems Tracts. A succession of upward-thickening mudstone/sandstone cycles in Hapuku River probably represents a progradational parasequence tract within a Highstand Systems Tract. Three sea level falls and subsequent rises during the Ngaterian (95-100 Ma) are represented on the coastal onlap cycle chart of Haq *et al.* (1987). However, the major sea level fall at the UZA-1/UZA-2 boundary at 98 Ma is the most likely tie for the sequence boundary, as it not only represents the largest fall, but it conforms best to the sparse radiometric age data available from the Lookout Volcanic Member. It also fits extremely well with the  $97.0 \pm 0.5$  Ma Rb-Sr isochron age for the correlative Mandamus Igneous Complex (Weaver and Pankhurst, in press).

The unconformity below the Hapuku Formation almost certainly also represents a sequence boundary, although the limited outcrop makes it difficult to determine the type. It is a condensed sequence occupying much of two New Zealand stages and most of the exposure may represent the condensed section element of a Transgressive Systems Tract. Representatives of the Highstand Systems Tract may have been removed by subsequent erosion. The major sea level fall at the UZA-2/UZA-3 boundary at 90 Ma represents the most likely candidate for the sequence boundary tie.

The unconformity at the base of the Seymour Group is inferred to represent a type 1 sequence boundary. Although the Piripauan deposits consist mainly of glauconitic sandstone, they pass into non-marine sediments near the base in the south of the area near Haumuri Bluff (Warren and Speden, 1977). The whole sequence, which deepens upwards, represents a Transgressive Systems Tract, the Paton Formation probably representing a condensed section. On the Haq *et al.* (1987) curve there are moderate drops in sea level at 83 Ma and 85 Ma, either of which could be associated with the basal unconformity. However, as noted above, tectonic-associated subsidence is likely to have played the major role in the subsequent transgression, although this may have been enhanced by eustatic sea level rise.

## Basin Evolution and Paleogeography

For much of the Cretaceous, the area that is now the East Coast region occupied a site on the Pacific margin of Gondwana. During the Permian to Early Cretaceous, rocks of the Torlesse Supergroup were accreted to this margin along a westerly or southwesterly-dipping subduction zone (Bradshaw *et al.*, 1981; Bradshaw, 1989).

In the mid Cretaceous convergence ceased, at least in the southern part of the New Zealand microcontinent, and was followed by crustal extension associated initially with rifting, and then with drifting of New Zealand from Australia and Antarctica (Laird, 1981). The inferred cause of this change in tectonic regime was the oblique subduction of the spreading ridge between the Pacific and Phoenix Plates (Bradshaw, 1989). In southern and western New Zealand the onset of extension was marked by the formation of rift basins (Laird, 1981). In the northern portion of the East Coast region, however, there is strong evidence to suggest that convergence and subduction continued into the Late Cretaceous (Spörli and Ballance, 1989).

The mid and Late Cretaceous of Marlborough, although it has grossly similar stratigraphy to that of the North Island segment of the East Coast region, appears to have close relationships in deformational style, particularly in the mid Cretaceous, to that shown by successions in southern and western New Zealand. As in these areas, basin development in Marlborough was dominated by extensional tectonics.

Block faulting resulting in the widespread formation of half grabens began in late Motuan times and lasted until the early Ngaterian. Infill was entirely marine and dominated by sediment gravity flow deposits, indicating ongoing tectonic activity. Because of this general uniformity in sediment type, the shape of the basin and the paleogeography of the Coverham Group is hard to determine. Only in the south, where a drillhole at Hapuku River penetrated Motuan strata of shallow marine aspect and where Motuan strata are absent further south, can a possible basin margin be inferred. Indications of deposition towards the centre of the basin may be given by the thick mudstone-dominated successions at Wharekiri Stream, Mororimu Stream, and Coverham. In these localities also, no break is detectable between Coverham and Wallow Groups which can be a further indicator of remoteness from the basin margin. A further clue is given by

paleocurrent directions derived from sole marks associated with sediment gravity flows, which are also likely to be paleoslope indicators. In the Awatere Valley paleocurrent indicators are uniformly towards the northeast or east, suggesting a northwesterly or northerly-directed basin margin. At Coverham, the direction is both to the north-northeast and to the southwest. At Mororimu Stream the direction is towards the northwest, suggesting a northeasterly-directed basin margin. A basin with a north or north-northeast axis and closing to the south near Kaikoura is inferred.

A relative fall in sea level in early Ngaterian times (at about 98 Ma) caused emergence and subaerial erosion of parts of the Coverham Group. A succeeding sea level rise resulted in transgression and the deposition of mainly shallow marine sands, and in the west and south, fluvial deposits. Renewed tectonic activity resulted in outpourings of basaltic lava in the west, and rejuvenation of some pre-existing faults. At the time of maximum transgression the Wallow basin probably extended beyond the limits of the Coverham basin, both to the west and the south. A basin with a north-northeast to northeast axis and closing to the south near Haumuri Bluff is inferred from generalised paleoshoreline data (Figure 4), and from an increase in mudstone/sandstone ratios to the northeast.

A further relative fall in sea level at about 90 Ma resulted in the erosion of the Wallow Group sediments, and the subsequent sea level rise resulted in the deposition of poorly-sorted, highly-bioturbated, shallow marine, moderately glauconitic, muddy sands of the Hapuku Formation. Data is too sparse to determine basin configuration.

The Burnt Creek Formation has previously presented somewhat of an enigma. The basal few hundred metres are the same age as, and superficially resemble the Coverham Group, where faulted against it, consist of a similar basal conglomerate and overlying alternating sandstones and mudstones. The adjacent Coverham Group, however, is much finer grained, is differentiated into several lithological units, and lacks the glauconitic and pebbly horizons which occur sporadically throughout the Burnt Creek succession. The latter formation also passes upwards and eastwards into younger mudstone lithologies and then into Paton Sandstone without perceptible break, in contrast to units lying west of

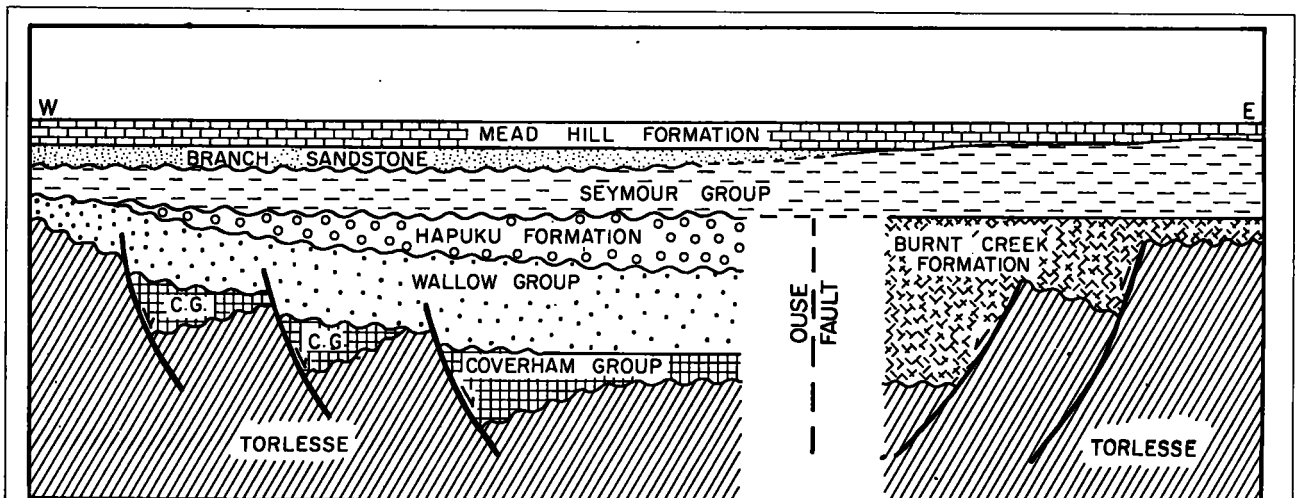


Figure 7. Oblique section across Marlborough showing basin framework and relationship of Cretaceous sedimentary units. Vertical scale arbitrary.

the Ouse Fault. As noted previously, it is evident that movement on the Ouse and associated faults has juxtaposed two blocks of similar age but contrasting stratigraphy and depositional history.

The rapid younging, shallowing, and thinning of the Burnt Creek Formation to the east is consistent with increasing proximity to a basin margin, probably fault controlled, lying to the east. This inference is supported by sparse paleocurrents with a mode directed towards the northwest. The Burnt Creek Formation therefore was deposited on the eastern flank of a basin which persisted from Motuan until Teratan times, and whose western flank, against which the Burnt Creek Formation has been tectonically juxtaposed, is represented by the successive deposits of the Coverham, Wallow, and Hapuku successions (Figure 7). Part of the central portion of the basin is probably missing because of

tectonic telescoping, remnants persisting only in Wharekiri and Mororimu Streams and Coverham. The northwesterly-directed paleocurrent (paleoslope) directions confirm the northeasterly orientation of the eastern basin margin indicated by the Coverham Group in Mororimu Stream.

A relative drop in sea level at about 83-85 Ma preceded a major regional transgression in Piriapuan times induced by thermal subsidence associated with sea floor spreading between New Zealand and Australia and Antarctica. This transgression caused continued deepening throughout the remainder of the Cretaceous. Deposition of the Seymour Group was structurally controlled, and infilled a basin oriented northeast-southwest. Development of a shelf/slope break may be indicated by a rapid thickening of sediments and significant facies changes in the northeast of the region.

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