# Revision of the Piripauan and Haumurian local stages and correlation of the Santonian–Maastrichtian (Late Cretaceous) in New Zealand

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**Abstract**    The uppermost Cretaceous in New Zealand is represented by the local Mata Series, composed of the Piripauan and overlying Haumurian Stages. The existing definitions and subdivision of these stages, and the type section at Haumuri Bluff, southeastern Marlborough, are wholly inadequate. To address these problems, three key sections in southeastern Marlborough have been studied in detail: a tributary of Ben More Stream, the headwaters of Kekerengu River, and a railway cutting at the mouth of Conway River. All three sections have yielded rich

palynomorph assemblages and the first two contain inoceramid bivalves and foraminiferal faunas. In addition, magnetostratigraphic data have been obtained from the Ben More Stream section.

We propose to revise the Piripauan and Haumurian Stages from new boundary stratotypes in the Ben More Stream section. The Piripauan is defined at the lowest occurrence of the inoceramid *I. pacificus*. The base of the Haumurian Stage is defined at the lowest occurrence of the dinoflagellate *Nelsoniella aceras*. In addition, we propose to subdivide the Haumurian into formal Lower and Upper substages; the base of the Upper Haumurian is defined at the lowest occurrence of the dinoflagellate *Isabelidinium pellucidum* in a boundary stratotype in the Conway River railway cutting. These boundary criteria can be correlated widely within New Zealand across a broad range of marine facies. The Piripauan contains two inoceramid and three dinoflagellate zones. The Haumurian contains six dinoflagellate zones and five subzones. Based on biostratigraphic and magnetostratigraphic data, the Piripauan/Haumurian boundary is correlated with the C34-C33 magnetochron boundary and with the middle–upper Santonian boundary. The Piripauan and Haumurian Stages thus have durations of c. 1.7 and 19.5 m.y., respectively.

In terms of content, these revisions largely preserve the stages as used previously in New Zealand and require no significant changes to existing geological maps.

## INTRODUCTION

New Zealand stratigraphers and paleontologists employ a system of local series and stages to subdivide Mesozoic and Cenozoic strata. This local time-scale has been modified from the schemes proposed originally by Finlay & Marwick (1940), Marwick (1951), and Wellman (1959). There has been lengthy debate on the relative merits of using a local time-scale, based on local strata and fossils, versus the international time-scale, based largely on European stratotypes and fossils (e.g., Hornibrook 1965; Carter 1974). The New Zealand time-scale was first erected because of faunal endemism and the consequent difficulties of correlation with the international stages. For much of the Mesozoic and Cenozoic, the New Zealand stages continue to have a local utility that cannot be matched by the international units (but see Carter & Naish 1998). This utility is measured both in terms of precision and stability of concept. The present state of knowledge does not favour wholesale adoption of the international time-scale in New

Zealand, although this continues to be a long-term goal of stratigraphers and paleontologists.

There remain a number of conspicuous problems with some parts of the New Zealand time-scale. Foremost amongst these are the definition and subdivision of the uppermost two Cretaceous stages, the Piripauan and Haumurian, which together comprise the Mata Series. The purpose of this paper is to revise these two stages and, for the first time, to propose a lower boundary stratotype for each. Correlations with the international time-scale are advanced using new biostratigraphic and magneto-stratigraphic data.

The work presented here is complementary to a refined subdivision of the Haumurian Stage based on dinoflagellate biozones (Roncaglia & Schiøler 1997; Roncaglia et al. 1999). Detailed taxonomic studies of key fossil groups are published elsewhere (Crampton 1996; Schiøler & Wilson 1998; Roncaglia et al. 1999). In recent related studies, other New Zealand Upper Cretaceous stages have been emended by Crampton (1996) and the biostratigraphy of uppermost Haumurian to middle Eocene strata has been described by Strong et al. (1995). All this work comprises part of the Time-scale Programme of the Institute of Geological & Nuclear Sciences that seeks to review, refine, and revise the entire New Zealand time-scale.

In the text, detailed locality descriptions are accompanied by eight-figure abbreviated grid references based on the New Zealand map grid. These are given in the following format: "P30/12349876", where "P30" refers to the NZMS 260 series 1:50 000 map sheet number, "1234" refers to the eastings, and "9876" refers to the northings. All sites at which macrofossils have been collected or observed, or that have been sampled for microfossils, are registered in the New Zealand Fossil Record File (FRF). FRF numbers appear in the following format: "P30/f123", where "P30" refers to the map sheet number (as above) and "f123" refers to a unique locality number within that sheet. The relevant FRF files are housed in the Department of Earth Sciences, University of Canterbury, Christchurch. All fossil collections are housed at the Institute of Geological & Nuclear Sciences, Lower Hutt. Different types of biostratigraphic zones used herein follow the definitions of Salvador (1994) and are in accord with current international practice.

## EXISTING STATUS OF THE MATA SERIES AND ITS STAGES

### History of the Mata Series and its stages

The local Mata Series was introduced by Finlay & Marwick (1947). They recognised three constituent stages, in ascending order, the Piripauan (Thomson 1917), Teurian (Finlay & Marwick 1947), and Wangaloan (Morgan 1918). The Piripauan and Teurian were correlated with the "Senonian" of the European time-scale and the Wangaloan was correlated with the Danian (Fig. 1).

Hornibrook & Harrington (1957) recommended suppression of the Wangaloan Stage on the grounds that it was equivalent to some part of the Teurian Stage and/or overlying Dannevirke Series. Wellman's (1959) milestone subdivision of the Cretaceous recognised three stages in the Mata Series, the Piripauan, his new Haumurian, and the Teurian. These he correlated with the European Campanian, Maastrichtian, and Danian, respectively. The Teurian

subsequently has been excluded from the Mata Series following removal of the Danian from the Cretaceous (Fig. 1) (Hornibrook 1962).

Since 1962, the subdivision and content of the Mata Series have not changed. Stage correlations, however, have been modified, the Piripauan Stage being correlated with progressively older parts of the European time-scale and the Haumurian increasing in relative duration (Fig. 1) (e.g., Stevens 1981; Edwards et al. 1988).

Previous biozonal subdivisions of the Mata Series are summarised in Fig. 2. These zonal schemes are not integrated and correlations between them are approximate.

### Present definitions and status of the Piripauan and Haumurian Stages

The Piripauan and Haumurian Stages were defined from a type section at Haumuri Bluff on the coast of southeastern Marlborough, some 22 km south of Kaikoura, in the northeastern part of the South Island (Fig. 3). Selection of this stratotype followed comparatively intense early exploration and discussion of the locality by several pioneering New Zealand geologists (e.g., Hector 1868, 1874, 1878; Haast 1871; McKay 1877a,b, 1886; for a full discussion of early work see Warren & Speden 1978). The Piripauan Stage, as emended by Wellman (1959), was defined as those strata containing *Inoceramus pacificus* Woods and *I. australis* Woods. The Haumurian Stage was rather loosely defined to be those beds with the "Haumurian fauna", in particular "*I. matotorus*" Wellman and *Ostrea lapillicola* Marwick.

The rich and diverse macrofossil faunas from Haumuri Bluff have been listed by Warren & Speden (1978, and references therein). Recently, Roncaglia et al. (1999) have described the abundant dinoflagellate assemblages from this section. In contrast, and despite repeated sampling, foraminifera are rare and poorly preserved at Haumuri Bluff (Webb 1971; Warren & Speden 1978).

The geology of Haumuri Bluff and environs has been mapped and described in detail by Warren & Speden (1978). They identified a number of problems with the Mata Series stratotype.

(1) The base of the section is a major angular unconformity which may postdate the incoming of the index fauna elsewhere in New Zealand.

(2) The fossil fauna within the type Piripauan is strongly facies controlled and is not typical of coeval faunas from other parts of New Zealand.

(3) The base of the Haumurian Stage occurs in facies representing a very restricted depositional environment and, as with point 2 above, this makes correlations away from the type section difficult and suspect.

(4) The upper limit of the Haumurian remains undefined in the type section.

(5) The lithological unit that comprises much of the Haumurian is largely devoid of calcareous faunas, making correlation difficult.

In addition to these problems, recent studies have identified other difficulties with the existing definition of the Haumurian Stage.

(6) One of the two key index fossils for recognition of the Haumurian Stage, "*Inoceramus matotorus*" Wellman, cannot be diagnosed and specimens so identified are
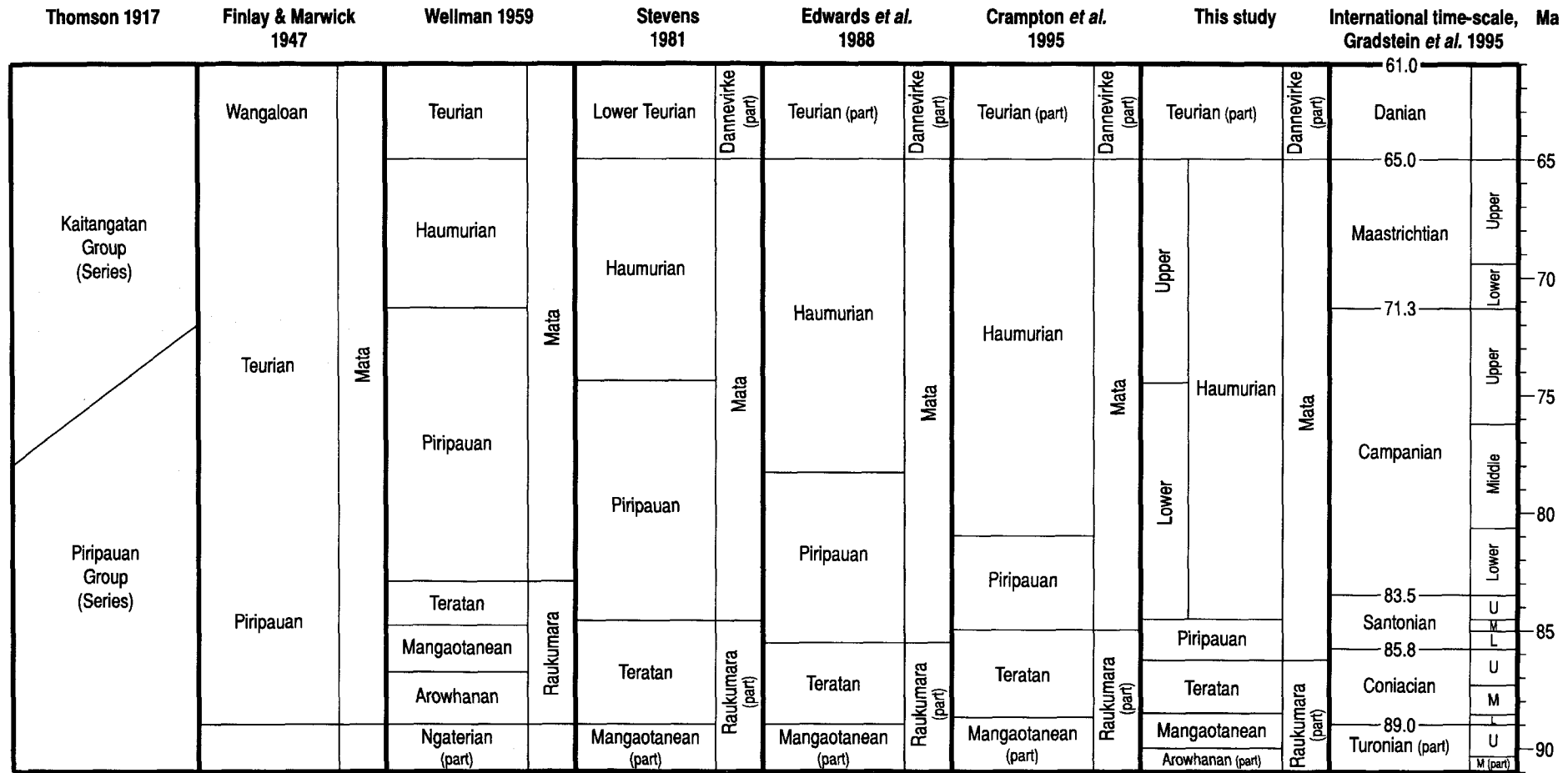
| Thomson 1917 | Finlay & Marwick 1947 | Wellman 1959 | Stevens 1981 | Edwards *et al.* 1988 | Crampton *et al.* 1995 | This study | International time-scale, Ma Gradstein *et al.* 1995 |
|---|---|---|---|---|---|---|---|
| | Wangaloan | Teurian | Lower Teurian | Teurian (part) | Teurian (part) | Teurian (part) | 61.0 Danian |
| Kaitangatan Group (Series) | | Haumurian | Haumurian | Haumurian | Haumurian | Upper Haumurian | 65.0 Maastrichtian (Upper / Lower) 71.3 |
| | Teurian | Piripauan | Piripauan | Piripauan | | Lower | Campanian (Upper / Middle / Lower) |
| Piripauan Group (Series) | | Teratan | | | Piripauan | Piripauan | 83.5 Santonian (U/M/L) 85.8 |
| | Piripauan | Mangaotanean | Teratan | Teratan | Teratan | Teratan | Coniacian (U/M) |
| | | Arowhanan | | | | Mangaotanean | 89.0 |
| | | Ngaterian (part) | Mangaotanean (part) | Mangaotanean (part) | Mangaotanean (part) | Arowhanan (part) | Turonian (part) (M part) |

Mata / Raukumara / Dannevirke (part) labels span the respective columns.

**Fig. 1** Summary key stages in the development of the Mata Series and its stages. All correlations and subdivisions have been recast to the international time-scale of Gradstein et al. (1995).
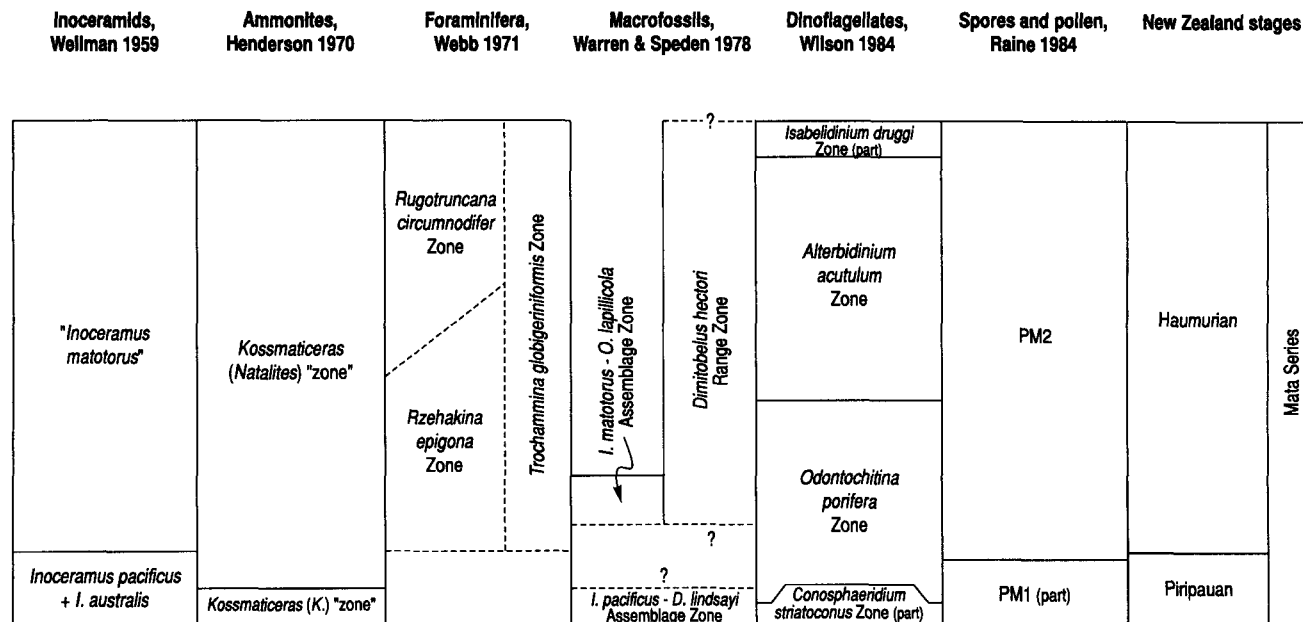
| Inoceramids, Wellman 1959 | Ammonites, Henderson 1970 | Foraminifera, Webb 1971 | Macrofossils, Warren & Speden 1978 | Dinoflagellates, Wilson 1984 | Spores and pollen, Raine 1984 | New Zealand stages |
|---|---|---|---|---|---|---|
| "Inoceramus matotorus" | Kossmaticeras (Natalites) "zone" | *Rugotruncana circumnodifer* Zone / *Trochammina globigeriniformis* Zone / *Rzehakina epigona* Zone | *I. matotorus - O. lapillicola* Assemblage Zone / *Dimitobelus hectori* Range Zone | *Isabelidinium druggi* Zone (part) / *Alterbidinium acutulum* Zone / *Odontochitina porifera* Zone | PM2 / Haumurian | Mata Series |
| Inoceramus pacificus + I. australis | Kossmaticeras (K.) "zone" | | I. pacificus - D. lindsayi Assemblage Zone | *Conosphaeridium striatoconus* Zone (part) | PM1 (part) / Piripauan | |

Fig. 2 Summary of existing biostratigraphic zonal subdivisions of the Mata Series. These zonations are not integrated and therefore correlations are approximate. All schemes have been recast to the time-scale proposed herein. See text for further discussion.

almost certainly polytaxic (Crampton 1996, pp. 53–54). The taxonomy of the other key index species, *Ostrea lapillicola* Marwick, is poorly known.

(7) The boundary between the Piripauan and Haumurian Stages in the type section is a disconformity and at least two dinoflagellate zones are missing (Roncaglia & Schiøler 1997; Roncaglia et al. 1999).

A more general problem pertains to the majority of New Zealand stages. Most were originally defined as one or more biozones tied to a type section and, hence, are essentially biostratigraphic rather than chronostratigraphic (Carter 1974; Warren & Speden 1978). These definitions are not in accord with accepted current practice that requires stage *boundaries* to be established by reference to a *point in time* represented by a "golden spike" within a stratotype (Salvador 1994). As noted by Crampton (1996), the emphasis has been on units of correlation rather than unambiguous definition of time planes.

Given the diversity and scale of these problems, it is clear that existing definitions of the Piripauan and Haumurian Stages are entirely inadequate, a conclusion noted previously by Warren & Speden (1978).

## LOCALITIES

Sections through Mata Series strata that are well exposed, fossiliferous, and lacking obvious unconformities are not well represented in New Zealand. In part, this is because the base of the Mata Series corresponds approximately to the age of a major transgression that is marked, in most places, by a regional unconformity separating Piripauan strata from older Cretaceous rocks or basement. This transgression is inferred to have resulted from passive thermal subsidence following the rifting of New Zealand from Gondwanaland during the Late Cretaceous (e.g., Bradshaw 1989). The unconformity generally is absent only

in the far east of the North Island, in relatively coarse grained and poorly fossiliferous strata that were deposited in comparatively deep water (Mazengarb 1993; Crampton 1997). In addition, however, there are near-continuous sections through the Mata Series in the northeastern part of the South Island, in southeastern Marlborough. These strata represent relatively proximal facies deposited close to the southern margin of a major system of Cretaceous basins that occupied the east coast region (Field & Uruski et al. 1997). Previous reconnaissance has suggested that these sections might furnish the best prospects for detailed biostratigraphic studies of the Piripauan and Haumurian Stages, and hence the present study was restricted largely to two areas in southeastern Marlborough. The sections are close to the existing type locality of the Mata Series at Haumuri Bluff (Fig. 3, 4).

The northern area occupies the hinge region of a large, structurally complex, north-plunging anticline that crops out in the coastal hills northeast of the Clarence valley and the Seaward Kaikoura Range, southeastern Marlborough (Fig. 3) (Lensen 1962). The Cretaceous stratigraphy of southeastern Marlborough is characterised by marked lateral changes in facies and thickness and the lithostratigraphy remains poorly understood (e.g., Laird 1992). Lithostratigraphic nomenclature used here follows Crampton & Laird (1997) and references therein. Within the study area, Upper Cretaceous strata comprise, in ascending order, the Burnt Creek, Paton, and Herring Formations. A section along a tributary of Ben More Stream and a second in the upper reaches of Kekerengu River were selected for measurement. Both lie within NZMS 260 series 1:50 000 map sheet P30 (Clarence) and are described below.

The southern area occupies part of a narrow, east-dipping strip of Upper Cretaceous–Eocene rocks that crop out adjacent to the coast between Haumuri Bluff in the north and the Conway River mouth in the south, southeastern Marlborough (Fig. 4) (Warren 1995). Stratigraphic
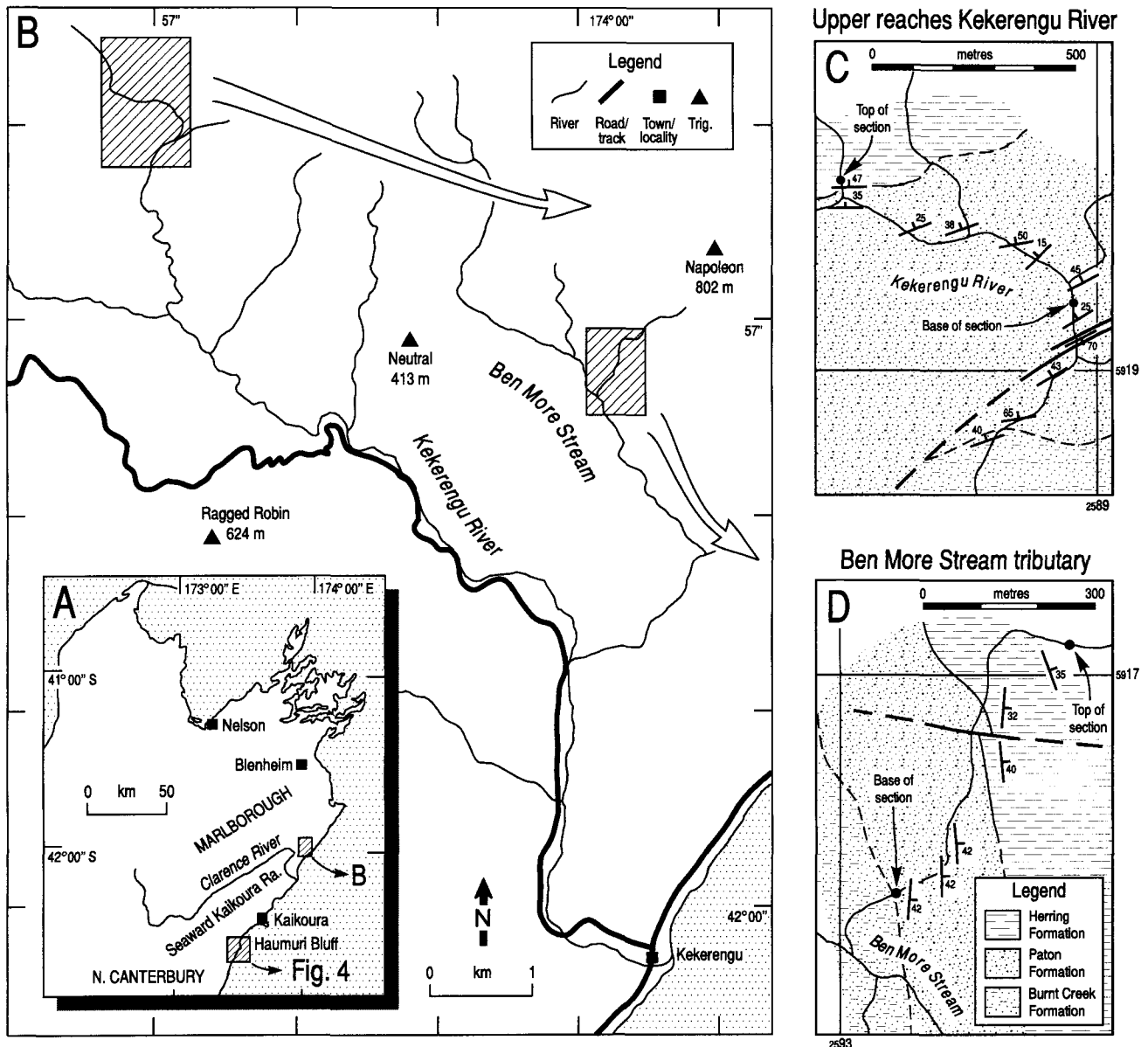
**Fig. 3** **A**, Northern part of the South Island, New Zealand, naming key places mentioned in the text. Areas shown in more detail are shaded. **B**, Locality map for the Ben More Stream and Kekerengu River sections, southeastern Marlborough. **C**, Simplified geological map of the Kekerengu River section and environs (after Crampton & Laird 1997). **D**, Simplified geological map of the Ben More Stream section and environs.

nomenclature follows Browne & Field (1985). Upper Cretaceous units unconformably overlie Pahau Subterrane basement and comprise, in ascending order, the Okarahia Sandstone and the Conway and Claverley Formations. The studied section, described below, crops out in a railway cutting on the northern bank of the Conway River and lies within NZMS 260 series map sheet O32. This section occupies a somewhat higher stratigraphic interval than the Ben More Stream and Kekerengu River localities, although there is some overlap, and it is one of a number of sections described in detail by Roncaglia & Schiøler (1997) and Roncaglia et al. (1999).

**Ben More Stream tributary**

Ben More Stream is a major tributary of the Kekerengu River that drains the coastal ranges immediately north of the Clarence valley, southeastern Marlborough (Fig. 3). The

section studied, henceforth referred to as the "BMS section", extends up a small, south-flowing tributary of Ben More Stream for c. 400 m from its mouth (grid ref. P30/93091662–93381703, Fig. 3). Access is over private property, via four-wheel-drive farm track from Matiawa Station, Kekerengu.

The measured section exposes the Paton and overlying Herring Formations. Burnt Creek Formation is inferred to underlie the lowest part of the stream but is not exposed. Paton Formation is at least 170 m thick and is composed largely of rather uniform, poorly to well-bedded, olive grey, fine to very fine grained muddy sandstone and lesser sandy mudstone. The sandstone is glauconic in places, in particular in the upper parts, and is burrowed throughout. Conspicuous "red" and "green" sandstone beds occur in the middle part and near the top of the formation. Herring Formation overlies Paton Formation with a sharp contact at 168.5 m above the base of the section. This contact is offset and repeated by a
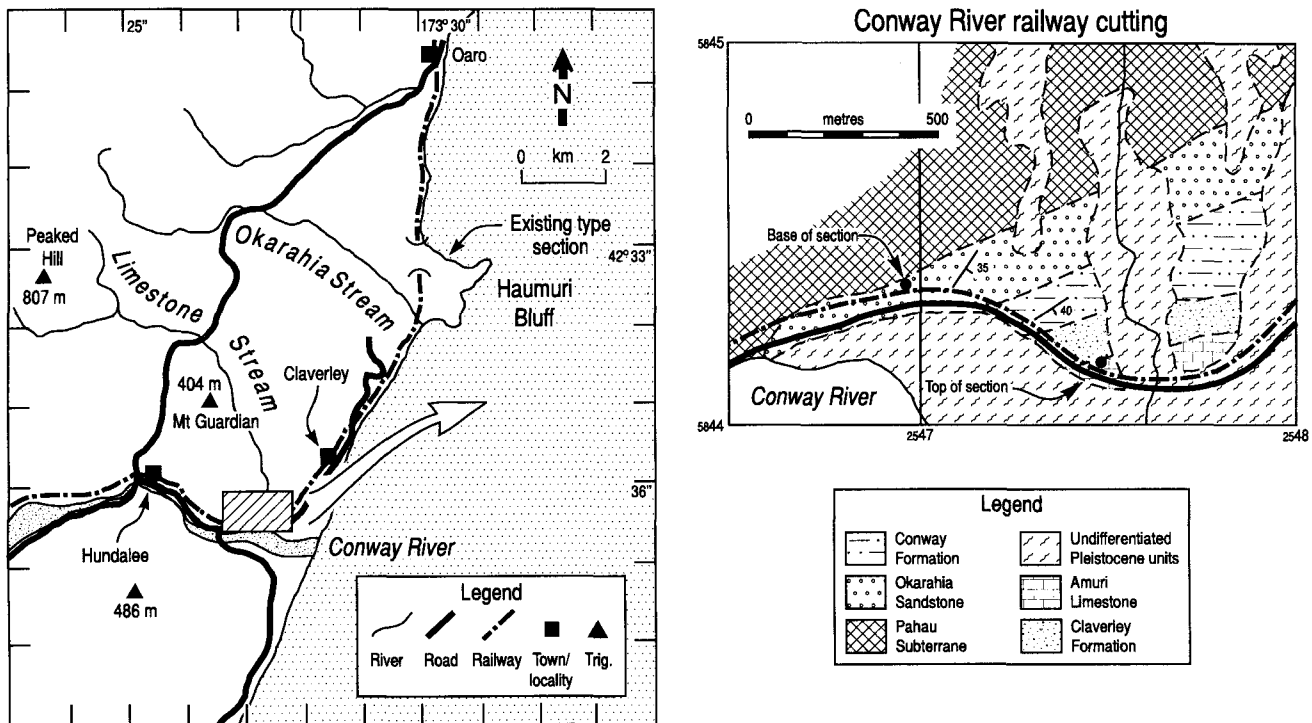
**Fig. 4**   Locality map of the Haumuri Bluff and Conway River mouth region, southeastern Marlborough, and simplified geological map of the Conway River railway cutting section (after Warren 1995). The existing type section of the Mata Series at Haumuri Bluff is marked.

minor, east–west-trending fault with a throw of c. 10 m. Herring Formation is 200–300 m thick, although only the lowest 100 m were logged. It comprises poorly to well-bedded, highly indurated, splintery, dark grey, siliceous, micaceous mudstone that weathers pale grey with distinctive, rusty-orange surfaces. Glauconic fine sandstone beds and pyrite nodules occur near the base.

**Upper reaches of Kekerengu River**

The "KR section" is in a northern tributary in the headwaters of the Kekerengu River (grid ref. P30/88951918–88371947, Fig. 3), c. 5 km ENE of the BMS section. The base of the section is 80 m north of a fault and extends for c. 700 m upstream of this point. Access is over private property via four-wheel-drive farm track and foot from Remuera Station. A geological map of the locality and of regions to the west is given in Crampton & Laird (1997).

The stratigraphic succession resembles that in the BMS section, except that the Paton Formation is >300 m thick. Exposures in the stream are affected by several small faults with offsets of a few metres. The base of the Herring Formation is not exposed, and only a few metres of this unit were logged.

**Conway River railway cutting**

The "CR section" extends along 500 m of railway cutting c. 1 km west of the Conway River mouth (grid ref. O32/ 46964436–47464414, Fig. 4). Access is from the Hundalee–Claverley road that parallels the railway line. A geological map of the area is given in Warren (1995).

Okarahia Sandstone is inferred to rest unconformably on indurated, deformed, Upper Jurassic or Lower Cretaceous sandstone and mudstone of the Pahau Subterrane, although the contact is not exposed. This contact is, however, well-exposed at Haumuri Bluff, 6.5 km to the NNE (Roncaglia & Schiøler 1997). The Okarahia Sandstone is c. 80 m thick and comprises moderately weathered, yellow grey, fine to medium grained sandstone. In places the sandstone is slightly glauconic. The contact with overlying Conway Formation is not exposed. The Conway Formation is c. 126 m thick and is formed of weathered, medium grey, slightly glauconic, sandy siltstone to silty, very fine grained sandstone. This, in turn, is overlain by 40 m of sandstone and mudstone of the Claverley Formation.

**RESULTS**

Stratigraphic logs through the Paton and Herring Formations in the BMS and KR sections are shown in Fig. 5 and 6. These sections were sampled for macrofossils, foraminifera, and palynomorphs. In addition, the BMS section was sampled for paleomagnetic analysis. A number of samples were examined for nannofossils but were barren. The CR section (Fig. 7) was sampled for palynomorphs only. Biostratigraphic and magnetostratigraphic results are discussed below.

**Inoceramid bivalves**

Macrofossils are abundant at restricted levels in Paton Formation and, locally, in the lower part of Herring Formation (Fig. 5, 6). Fossil assemblages are dominated by inoceramid bivalves; belemnites have been observed at a few places. The taxonomy and biostratigraphy of Mata Series inoceramids have been revised recently by Crampton (1996),
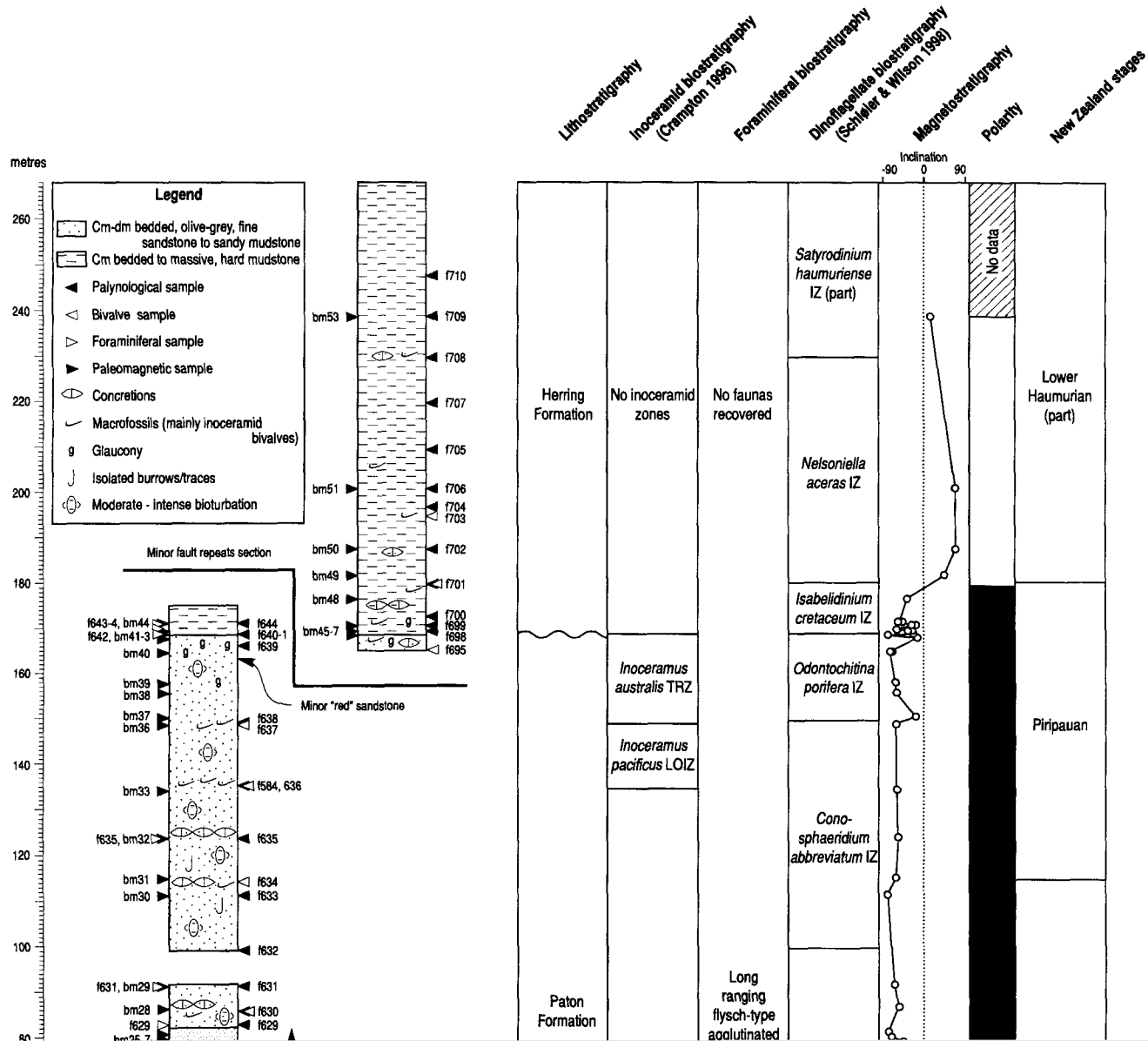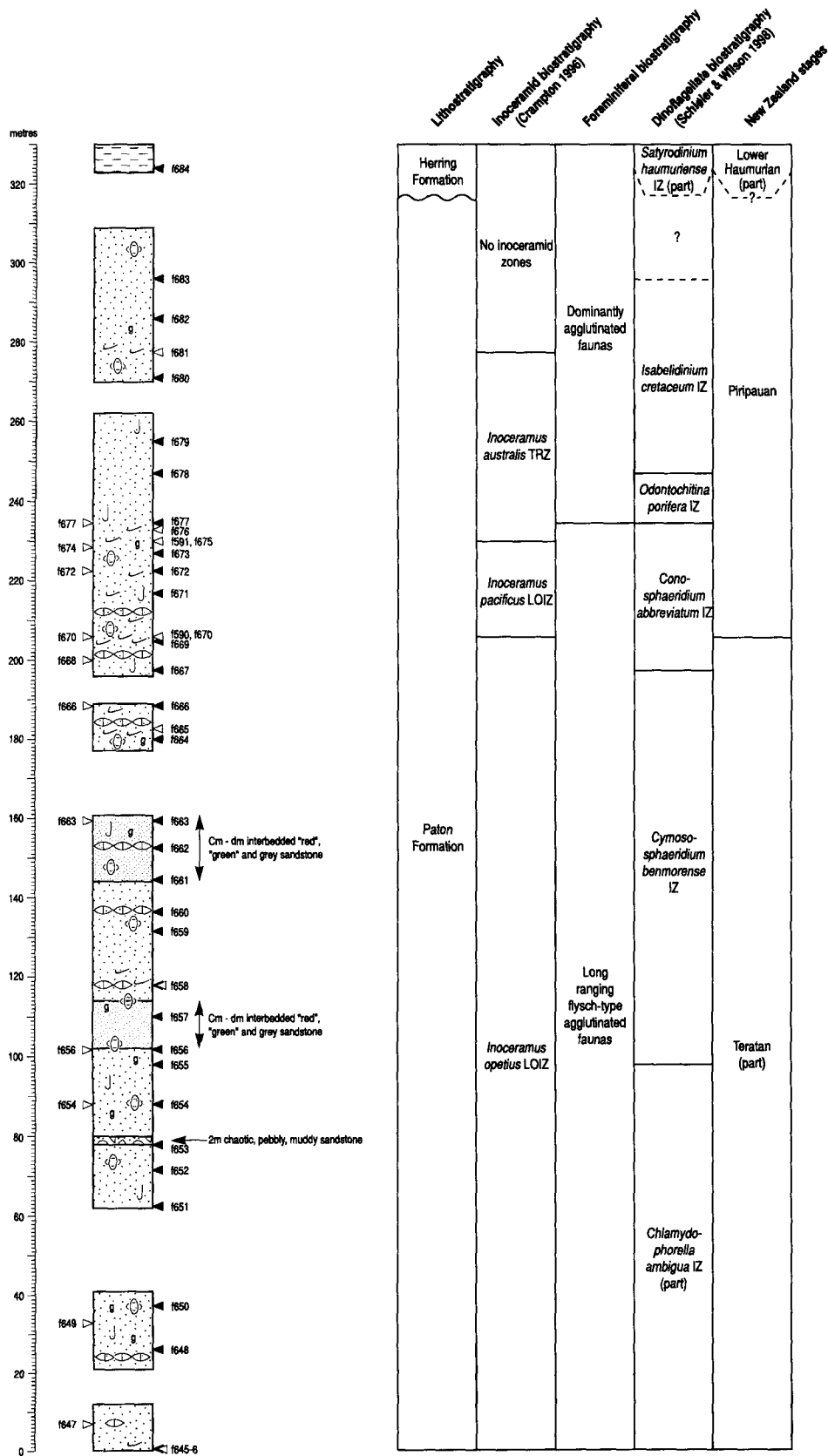
**Fig. 6**  Log of the section in the upper reaches of Kekerengu River, showing sample horizons and summarising biostratigraphic results. All fossil localities are registered in the Fossil Record File for map sheet P30, housed in the Department of Earth Sciences in the University of Canterbury, Christchurch. Legend as for Fig. 5.

who erected a series of inoceramid biozones and documented the ranges of these bivalves in the BMS and KR sections (his fig. 21 and 22).

Paton Formation is subdivided into three inoceramid zones. The positions of zonal boundaries are summarised in

Table 1. The lowest strata in each section contain *Inoceramus* cf. *opetius*. *Inoceramus*? *madagascariensis* has been collected at the very base of the KR section. These rocks are assigned to the *I. opetius* Lowest-occurrence Interval Zone (LOIZ) (Crampton 1996). Above this, the *I. pacificus*
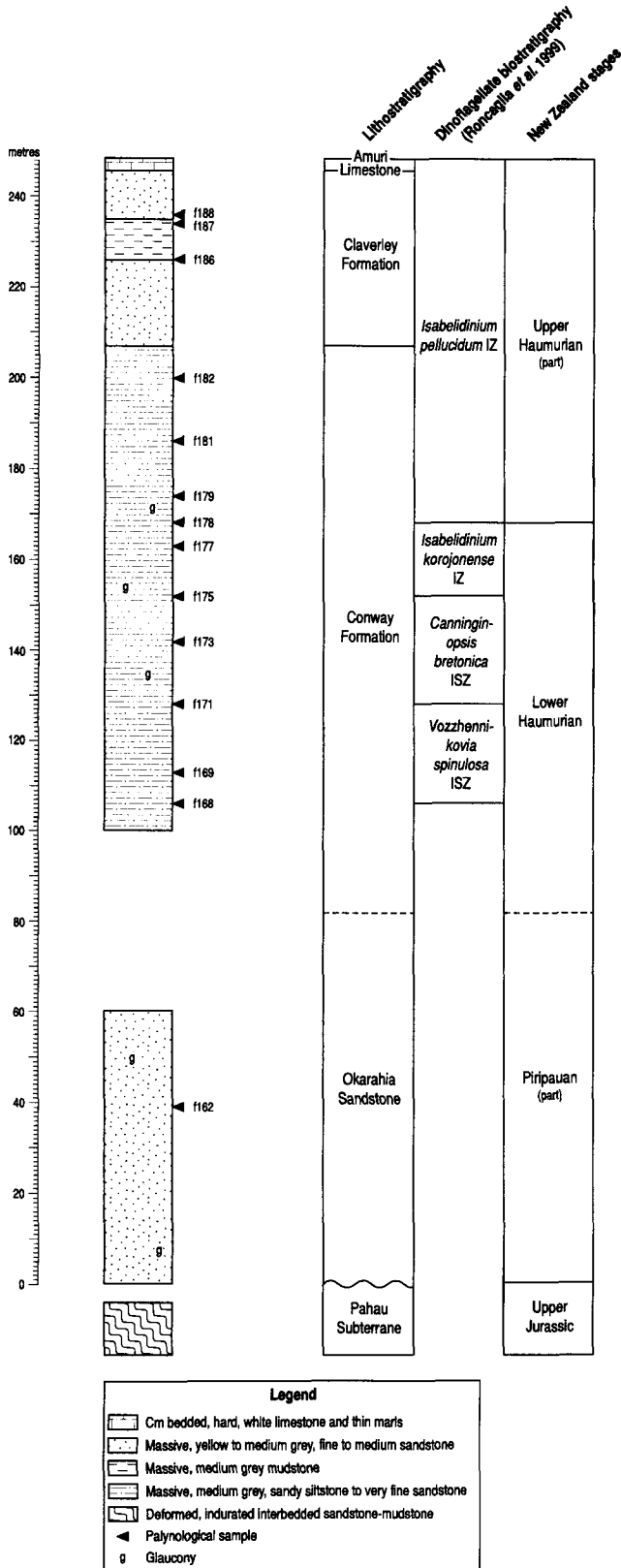
LOIZ (Crampton 1996) includes a single species, *I. pacificus* (Fig. 8). Two subspecies have been recognised, *I. pacificus pacificus* and *I. pacificus nanakius*, but these cannot be used to further subdivide the interval (Crampton 1996). The uppermost inoceramid zone is the *I. australis* Taxon-range Zone (Crampton 1996) and, again, contains a single species, *I. australis* (Fig. 8). The top of this zone lies at the top of, or within the upper part of, the Paton Formation.

In the BMS section, the lowest 60 m of Herring Formation contains abundant, poorly preserved bivalves. These have a prismatic, weakly inflated, smooth or lamellose shell and are distinct from any of the afore-mentioned species. Similar occurrences from elsewhere in New Zealand previously have been assigned to the taxon "*Inoceramus matotorus*". As noted above, the taxonomy and biostratigraphy of material identified as "*I. matotorus*" are too confused to allow its use as a biostratigraphic index. Consequently, strata overlying the *australis* Zone cannot be subdivided on the basis of inoceramids.

## Foraminifera

Twelve samples from the BMS section and 11 from the KR section (Fig. 5, 6) were examined for foraminifera. In general, foraminiferal faunas are comparatively poor and consist almost entirely of low-diversity assemblages of siliceous, agglutinated taxa. Most faunas were recovered from the lower part of the Paton Formation; the Herring Formation was sampled in the BMS section only and yielded no foraminifera. Overall, the BMS section is somewhat more fossiliferous than the KR section.

The lower part of Paton Formation contains sparse to moderately abundant assemblages, diversity and abundance increasing upsection. Samples from the lowest 91 m of the BMS section and the lowest 210 m of the KR section (eight samples each) include *Glomospira charoides*, *Ammodiscus cretaceus*, *Thalmannammina subturbinata*, *Karreriella conversa*, *Haplophragmoides suborbicularis*, and *H. walteri*. All these taxa have stratigraphic ranges that are either long or unknown. Sample P30/f631, from the BMS section, also contains rare, poorly preserved calcareous forms that possibly include *Marginulinopsis curvisepta*, a species apparently restricted to the Teratan and Piripauan Stages (Hornibrook et al. 1989). The upper parts of Paton Formation are barren to sparsely fossiliferous or lack age-diagnostic taxa. The highest sample in the KR section, P30/f677, contains a few poorly preserved calcareous benthic taxa, including small specimens of *Gyroidinoides globosus* that are typical of upper Raukumara Series and lower Mata Series strata (Hornibrook et al. 1989).

Foraminiferal assemblages from Paton Formation suggest a stressed, bathyal environment of deposition and minimum water depths of c. 400 m (Hayward 1986).

Previously collected samples from Mata Series strata that crop out in Ben More Stream, c. 1 km below the logged section, are more productive. These strata, however, are poorly exposed and are faulted. Assemblages from Paton Formation (P30/f7612, f7613) include *Marginulinopsis curvisepta*, *Tritaxia capitosa*, *Gavelinella complanata*, and *Rugoglobigerina pilula*. Samples from the overlying Herring Formation contain abundant siliceous agglutinated foraminifera, lagenids of undetermined biostratigraphic significance, and *Rugoglobigerina* cf. *rugosa*. These samples suggest that foraminifera are, locally, more abundant in the



**Fig. 7** Log of the Conway River railway cutting section, showing sample horizons and summarising biostratigraphic results. All fossil localities are registered in the Fossil Record File for map sheet O32, housed in the Department of Earth Sciences, University of Canterbury, Christchurch.
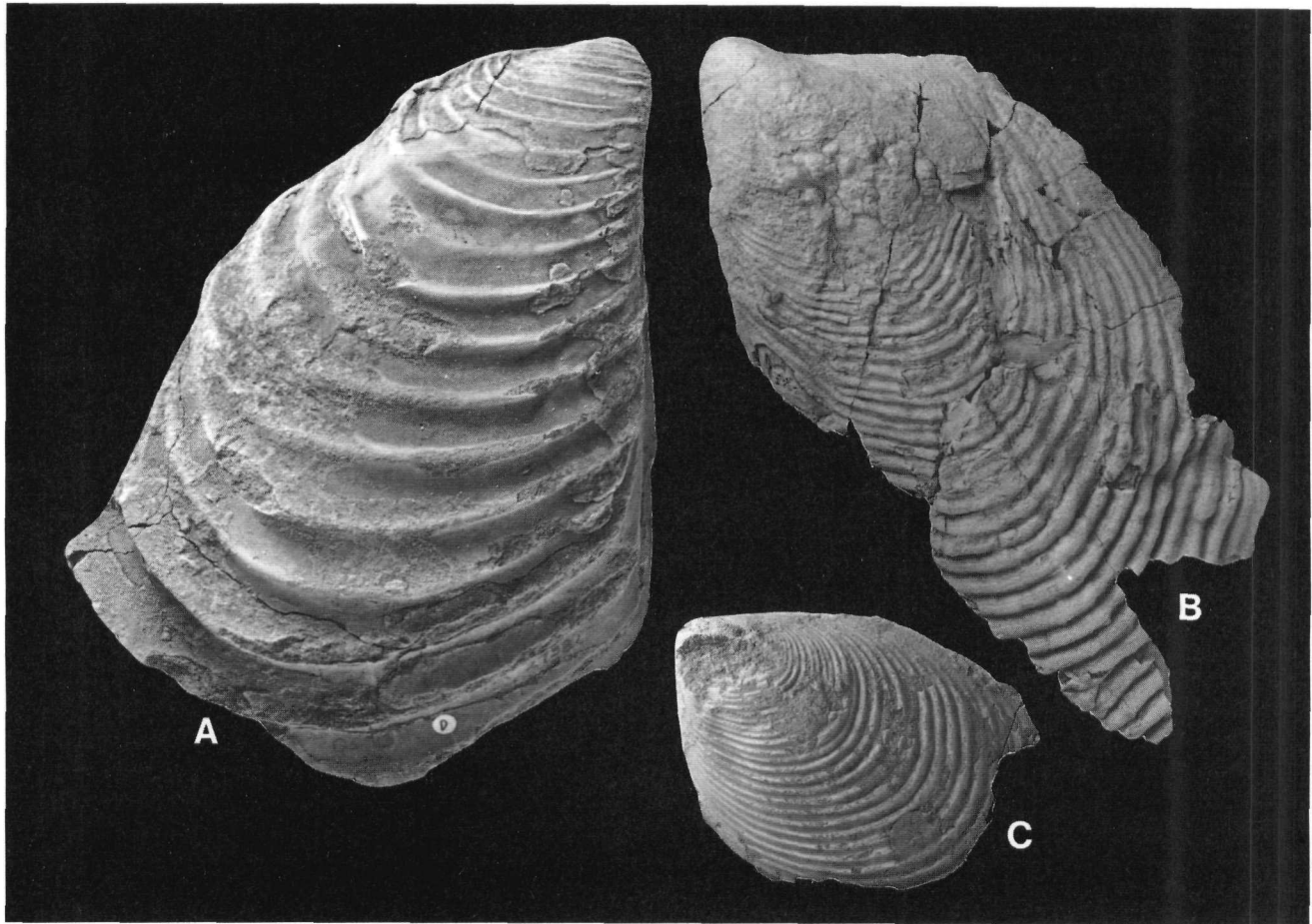
**Fig. 8**  Piripauan (uppermost Coniacian to middle Santonian) inoceramid bivalves from the northeastern part of the South Island, New Zealand. All specimens ×0.66 and whitened with ammonium chloride. Specimens prefixed "IGNS" are housed at the IGNS, Lower Hutt. The specimen prefixed "BMNH" is housed at the Natural History Museum, London. **A**, *Inoceramus australis* Woods (lectotype). IGNS TM2738, GS13, O32/f8025, Haumuri Bluff. Right valve, internal mould with patches of shell preserved. **B**, *Inoceramus pacificus nanakius* Crampton (holotype). IGNS TM7974, GS15053, P30/f584, Ben More Stream section. Left valve, prismatic shell preserved. **C**, *Inoceramus pacificus pacificus* Woods. BMNH LL9789, O32/f- (not registered), Haumuri Bluff. Left valve, internal mould.

Paton and Herring Formations and that future re-sampling in these or nearby sections may be worthwhile.

### Dinoflagellates

Seventy-eight samples were processed for dinoflagellates, 37 from the BMS section, 27 from the KR section, and 14 from the CR section (Fig. 5–7). These have yielded rich dinoflagellate assemblages. The taxonomy and biostratigraphy of the floras have been described in detail by Roncaglia & Schiøler (1997), Schiøler & Wilson (1998), and Roncaglia et al. (1999). These authors have emended the existing zonation and erected a number of new dinoflagellate zones.

More than 70 dinoflagellate taxa have been identified; key species are illustrated in Fig. 9. Seven dinoflagellate biozones have been recognised in the BMS section, six in the KR section, and four in the CR section. The positions of zonal boundaries are summarised in Tables 1 and 2. In

**Table 1**  Heights of biozone bases in the Ben More Stream and Kekerengu River sections.

| | Biozone | Ben More Stream tributary | Upper reaches Kekerengu River |
|---|---|---|---|
| Inoceramid biozones | *Inoceramus opetius* Lowest-occurrence interval zone (LOIZ) | below base of section | below base of section |
| | *I. pacificus* LOIZ | 135.0 m | 206.0 m |
| | *I. australis* Taxon-range Zone | 148.5 m, top = 168.5 m | 230.0 m |
| Dinoflagellate biozones | *Chlamydophorella ambigua* Interval Zone (IZ) | below base of section | below base of section |
| | *Cymososphaeridium benmorense* IZ | 42.5 m | 98.0 m |
| | *Conosphaeridium abbreviatum* IZ | 98.5 m | 197.5 m |
| | *Odontochitina porifera* IZ | 149.0 m | 234.7 m |
| | *Isabelidinium cretaceum* IZ | 168.7 m | 247.0 m |
| | *Nelsoniella aceras* IZ | 179.5 m | Not recognised |
| | *Satyrodinium haumuriense* IZ | 229.5 m | 324.0 m |

ascending order, the dinoflagellate zones are: *Chlamy-dophorella ambigua* Interval Zone (IZ) (Schiøler & Wilson 1998), *Cymososphaeridium benmorense* IZ (Schiøler & Wilson 1998), *Conosphaeridium abbreviatum* IZ (Schiøler & Wilson 1998), *Odontochitina porifera* IZ (Helby et al. 1987), *Isabelidinium cretaceum* IZ (Evans 1971), *Nelsoniella aceras* IZ (Evans 1971), *Satyrodinium haumuriense* IZ (Marshall 1990), *Vozzhennikovia spinulosa* Interval Subzone (ISZ) (Roncaglia & Schiøler 1997), *Canninginopsis bretonica* ISZ (Roncaglia & Schiøler 1997), *Isabelidinium korojonense* IZ (Roncaglia et al. 1999), and *I. pellucidum* IZ (Roncaglia & Schiøler 1997).

Palynofacies analysis suggests that Paton Formation in the BMS and KR sections was deposited under oxic conditions in a nearshore environment and probably in proximity to a river mouth (Schiøler & Wilson 1998). These conclusions are somewhat at variance with interpretations from foraminifera (see above). Equivalent data from Herring Formation indicate deposition at inner to mid-shelf depths under poorly oxygenated bottom conditions. In the CR section, a single palynomorph assemblage from the Okarahia Sandstone suggests deposition in a marginal marine environment. Samples from the Conway and Claverley Formations apparently record fully marine conditions, coastal progradation, and shallowing upsection, and again, a nearby source of terrestrial debris (Roncaglia & Schiøler 1997).

Biostratigraphic data from dinoflagellates indicate that the Paton-Herring formational contact is a diachronous paraconformity (Schiøler & Wilson 1998; unpubl. data). In the BMS section the paraconformity lies between, and probably eliminates some part of, the *Odontochitina porifera* and overlying *Isabelidinium cretaceum* Zones (Fig. 5). In the KR section the paraconformity is not exposed but is younger, lying above the base of the *I. cretaceum* Zone (Fig. 6). Based on comparisons of zone thicknesses between the two closely spaced sections, it is inferred that some (or most) of the *N. aceras* Zone, and possibly minor parts of the adjacent two zones, are missing at the Paton-Herring formational contact in the KR section.

## Magnetostratigraphy

Samples for paleomagnetic analysis were collected from a total of 55 horizons, BM1–55, in the BMS section. Samples BM1–42 are from Paton Formation; samples BM43, 44, and 46–55 are from Herring Formation. Samples BM27, 40, and 45 are from red sandstone units within Paton Formation. Whereas Paton Formation was drilled *in situ*, due to the hardness of the mudstone, Herring Formation was sampled as oriented blocks that were drilled in the laboratory. Two or three specimens were cut from most samples. All specimens were stored in magnetically shielded containers before and between analyses.

Paleomagnetic measurements were carried out using an ScT cryogenic magnetometer, capable of measuring magnetic moments down to $10^{-11}$ A.m$^2$, and thermal demagnetisation equipment housed at Victoria University of Wellington. During initial analysis (TM), one specimen from each of 28 sites was subjected to stepwise thermal demagnetisation at temperatures of 200, 250, and 300°C. Alternating field demagnetisation was also carried out on a smaller number of specimens, but proved less efficient at isolating the characteristic component of magnetisation: these results are not discussed further. During subsequent follow-up work (GT), a further 30 specimens were progressively demagnetised either to 620°C, or until their magnetisation was too weak to measure, or until changes to the magnetic mineralogy became evident. Such mineralogical changes were detected by measuring the magnetic susceptibility of each specimen after each heating step and monitoring for changes that might indicate formation of a new magnetic phase (usually through oxidation). The average susceptibility of samples from Paton Formation is c. $150 \times 10^{-6}$ SI, red sandstone units within Paton Formation have an average of $300 \times 10^{-6}$ SI, and samples from Herring Formation have an average of c. $75 \times 10^{-6}$ SI. The red sandstones and many of the siltier samples showed no change in susceptibility after heating to 620°C. In contrast, some muddier specimens displayed significant increases in susceptibility following heating, and these changes were typically accompanied by a reddening in colour. (For example, in BM12 the susceptibility doubled to $300 \times 10^{-6}$ SI at 350°C, and in BM47 the susceptibility tripled to $300 \times 10^{-6}$ SI at 270°C and continued to rise with further heating.)

The dataset described below comprises both the initial and follow-up measurements. Results are summarised in Table 3. The mean intensity of natural remanent magnetisation (NRM) in most samples from the Paton Formation is $(0.67 \pm 0.45) \times 10^{-3}$ A.m$^{-1}$. The red sandstones, however, are over an order of magnitude stronger in signal, with intensities averaging $(12.2 \pm 2.4) \times 10^{-3}$ A.m$^{-1}$. The mean NRM of the Herring Formation samples is somewhat lower at $(0.24 \pm 0.20) \times 10^{-3}$ A.m$^{-1}$.

Demagnetisation data of some typical specimens are plotted in Fig. 10. Almost all specimens are affected by a recent thermoviscous component of magnetisation (TVRM) carried by grains with the lowest blocking temperatures. The component of magnetisation removed below 200°C averages $D = 359.6°$, $I = -71.4°$, $\alpha$-95 $= 6.8°$, in present-day co-ordinates. This is close to, but slightly steeper than, both the axial geocentric dipole field for the site ($D = 0, I = -61°$) and the present-day magnetic field direction ($D = 24°$, $I = -67°$). The difference is probably due to the removal of a small part of the underlying magnetisation along with the TVRM.

The BMS section lies within the Marlborough Fault System, a zone of dextral transpression that links subduction along the Hikurangi margin to the north with strike-slip movement on the Alpine Fault to the south. Locally, the beds

Table 2  Heights of biozone bases in the Conway River railway cutting section.

| | Biozone | Height |
|---|---|---|
| Dinoflagellate biozones | *Vozzhennikovia spinulosa* Interval Subzone (ISZ) | below base of section |
| | *Canninginopsis bretonica* ISZ | 128.0 m |
| | *Isabelidinium korojonense* Interval Zone (IZ) | 152.0 m |
| | *I. pellucidum* IZ | 168.0 m |
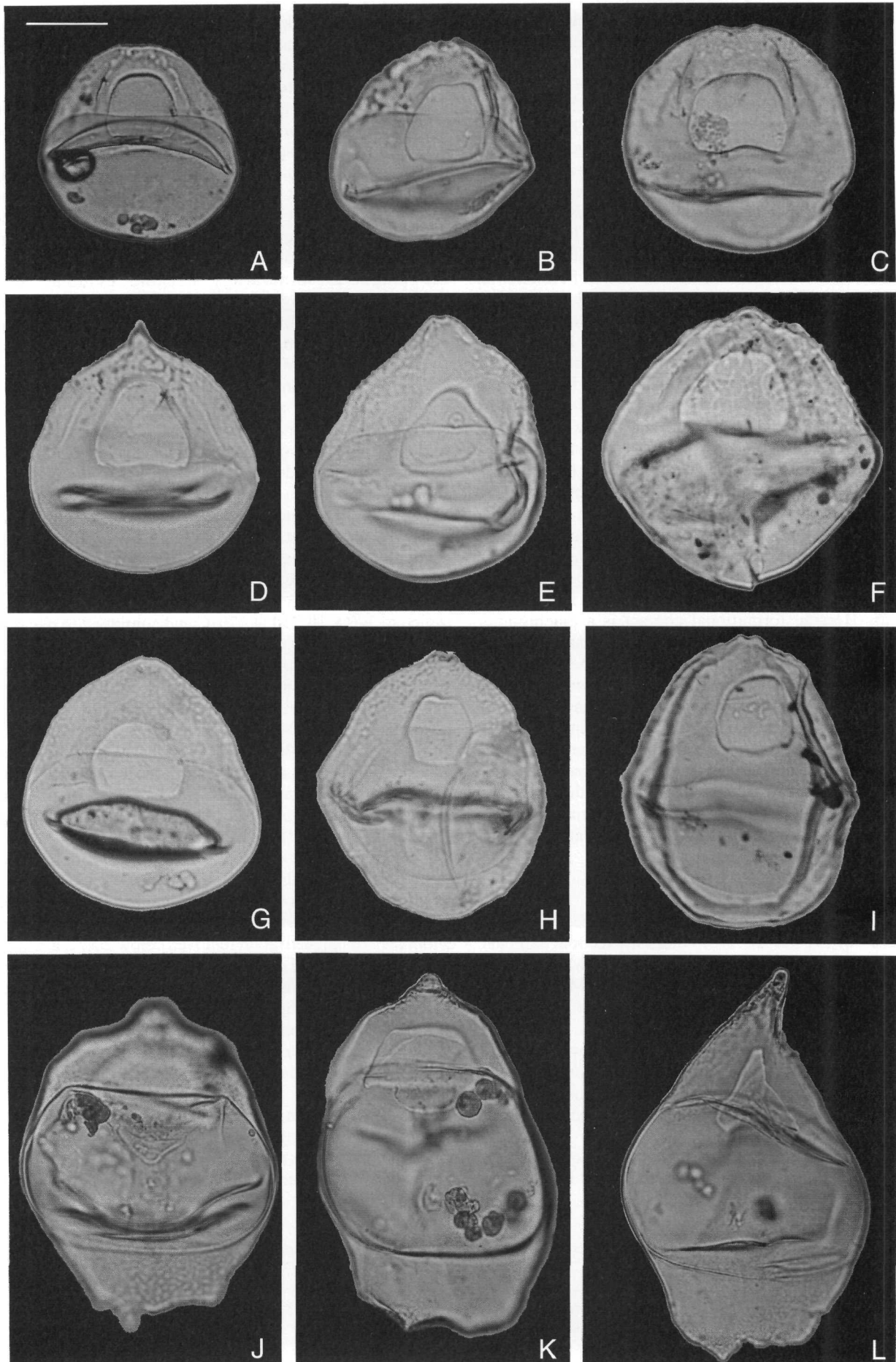
dip by c. 40° to the east, the exact dip and strike varying by c. 20° within the interval sampled. Thus, a substantial bedding correction must be made to the measured magnetisation directions to restore them to a pre-deformation "stratigraphic" reference frame. The data of Fig. 10 are shown in this stratigraphic reference frame.

Figure 10A shows a normally magnetised specimen from site BM44 within the Paton Formation. After removal of the TVRM, a single characteristic component of magnetisation (ChRM) is isolated and this is interpreted as the primary magnetisation. The blocking temperature spectrum extends up to c. 450°C. Figure 10B illustrates a reversely magnetised specimen from site BM50 within the Herring Formation. The blocking temperature spectrum is similar to that of BM44, with almost all the magnetisation removed by 450°C. By contrast, a red sandstone specimen from BM27 within the Paton Formation, shown in Fig. 10C, has grains with blocking temperatures exceeding 620°C and a much stronger single-component magnetisation, with an extremely stable direction.

Demagnetisation data for each specimen were examined using Enkin's paleomagnetic analysis programs. Characteristic components of magnetisation were identified and their directions estimated using principal component analysis (PCA) for 50 of the sites. With the exception of the redbeds (see below), these directions are interpreted as primary components of magnetisation, of depositional or post-depositional detrital origin, carried by very low concentrations of ferrimagnetic minerals, probably titanomagnetite originating from a source in the Torlesse greywackes. The magnetisation of the redbeds is, however, carried by a mineral with a blocking temperature spectrum that extends well above the Curie temperature of magnetite (580°C) and with high coercivities. This mineral is almost certainly haematite. Since the saturation magnetisation of haematite is three orders of magnitude less than those of magnetite and titanomagnetite, its concentration must be high in order to produce the observed high intensity of NRM. These features, as well as the extremely stable and tightly clustered directions of the characteristic magnetisation, argue that it is not of detrital origin, but was probably acquired during post-depositional chemical changes. The timing of such changes, and of magnetisation in redbeds, is in general a controversial subject (e.g., Butler 1992, ch. 8).

The ChRM directions of each sample horizon are listed in Table 3, together with NRM intensities, and are shown in

stratigraphic form in Fig. 5. The most significant feature of the data is the transition from normal to reversed polarity that occurs in the lower part of the Herring Formation, between horizons BM48 and 49. With the exceptions of BM14, 19, and 20, all sample horizons below BM49 have negative inclinations and are interpreted as recording normal polarity. Biostratigraphic results strongly suggest that the change from normal to reversed polarity represents the C34n–C33r transition, corresponding to the end of the 34 m.y. long Cretaceous normal superchron (correlations discussed below).

The mean ChRM direction of all normal horizons, except the redbeds, is ($D$ = 295.8°, $I$ = –74.7°, $\alpha$-95 = 14.8°, $N$ = 41 horizons), whereas that of the redbeds is ($D$ = 93.3°, $I$ = –76.2°, $\alpha$-95 = 8.1°, $N$ = 4 horizons) (Fig. 11). The steep negative inclinations are consistent with the high paleolatitude of this part of the Pacific plate during the Cretaceous (Smith et al. 1994). This result also supports the contention that the redbeds were magnetised fairly soon after deposition, before drift to a significantly lower paleolatitude occurred. The scatter observed in the normal directions, particularly in the lower part of the Paton Formation ($\theta$-63 = 45°), is, however, much higher than would be expected from paleomagnetic secular variation alone (c. 20°). It is probable that the simple stratigraphic correction described above does not fully allow for the complex tectonics of the region (e.g., Vickery & Lamb 1995).

There is a suggestion that the normal directions are straddled around a great circle in the ENE–WSW plane, with the mean direction from the upper Paton Formation samples having a westerly declination and those from the redbeds an easterly declination. The strike of these directions is roughly perpendicular to the trend of the Marlborough Fault System and the tectonic trend of the country as a whole.

Finally, positive inclinations observed at horizons BM14, 19, and 20, and in particular the latter, may reflect instability of the geomagnetic field and short periods of reversed polarity before the C33n–C34r reversal. Their reliability needs to be confirmed by further sampling. A number of other workers, however, have noted similar reversals in the upper part of C34n: Verosub et al. (1989) have recorded one such event from sections in the Sacramento Valley, California; Toshimitshu & Kikawa (1997) reported two reversals in a section in northwestern Hokkaido, Japan; and Montgomery et al. (1998) recorded six reversals from sections in southern England.

◄ **Fig. 9** Upper Cretaceous dinoflagellates from New Zealand sections and the Danish Gassum-1 well. All to the same scale. Scale bar in (A) = 30 μm. Specimens prefixed "IGNS" are kept at the IGNS, Lower Hutt; those prefixed "GEUS" are kept at the Geological Survey of Denmark and Greenland, Copenhagen. **A**, *Nelsoniella aceras* Cookson & Eisenack. Sample P30/f705, IGNS SM4550, Ben More Stream section. Dorsal surface in low focus. **B**, *Nelsoniella aceras* Cookson & Eisenack. Sample P30/f705, GEUS SM74, Ben More Stream section. Sectional focus, dorsal surface up. **C**, *Nelsoniella aceras* Cookson & Eisenack. Sample P30/f708, GEUS SM75, Ben More Stream section. Dorsal surface in high focus. Endocyst missing. **D**, *Nelsoniella tuberculata* Cookson & Eisenack. Sample P30/f709, IGNS SM4551, Ben More Stream section. Dorsal surface in low focus. **E**, *Nelsoniella* cf. *tuberculata* Cookson & Eisenack. Gassum-1 well, 755.47 m, GEUS SM2. Sectional focus, dorsal surface up. **F**, *Nelsoniella* cf. *semireticulata* Cookson & Eisenack. Sample O32/f217, GEUS SM10, Haumuri Bluff. Ventral surface in low focus. **G**, *Nelsoniella* cf. *tuberculata* Cookson & Eisenack. Gassum-1 well, 755.47 m, GEUS SM7. Sectional focus, ventral surface up. **H**, *Eucladinium madurense* (Cookson & Eisenack) Stover & Evitt. Sample P30/f701, IGNS SM4549, Ben More Stream section. Dorsal surface in low focus. **I**, *Eucladinium kaikourense* Schiøler & Wilson. Sample P30/f701, IGNS SM4544, Ben More Stream section. Sectional focus, ventral surface up. **J**, *Isabelidinium pellucidum* (Deflandre & Cookson) Lentin & Williams. Sample M34/f380, IGNS SM4698a, Mid-Waipara section. Sectional focus, dorsal surface up. **K**, *Isabelidinium pellucidum* (Deflandre & Cookson) Lentin & Williams. Sample M34/f380, IGNS SM4698b, Mid-Waipara section. Sectional focus, dorsal surface up. **L**, *Isabelidinium pellucidum* (Deflandre & Cookson) Lentin & Williams. Sample M34/f380, IGNS SM4699, Mid-Waipara section. Sectional focus, dorsal surface up. Apical area damaged.

## REVISION OF THE PIRIPAUAN STAGE

LOWER BOUNDARY STRATOTYPE: Paton Formation in the Ben More Stream tributary section, southeastern Marlborough, New Zealand (Fig. 3, 5).

DEFINITION: It is proposed that the base of the Piripauan Stage correspond to the lower boundary of the *Inoceramus pacificus* Lowest-occurrence Interval Zone in the stratotype, 135.0 m above the base of the section at fossil locality P30/ f636 (grid ref. P30/9323 1680). This locality is c. 350 m in a straight line above the stream mouth and stratigraphically 53 m above the top of a conspicuous, 11.5 m thick interval of "red", "green", and grey sandstone beds.

DISCUSSION: Wellman (1959) defined the Piripauan Stage as those beds containing *I. pacificus* and *I. australis* in the type section at Haumuri Bluff. Recent work has demonstrated that these two taxa do not have coincident biostratigraphic ranges and that the lowest occurrence of *I. pacificus* precedes that of *I. australis* (Crampton 1996, fig. 26). The proposed **boundary** stratotype at Ben More Stream replaces the existing **interval** stratotype at Haumuri Bluff that now becomes a reference section for part of the stage. The upper limit of the Piripauan Stage is placed at the lower boundary of the overlying Haumurian Stage, defined in the same boundary type section (see below).

The lowest occurrence of the inoceramid *I. pacificus* is considered to be an ideal marker for the base of the Piripauan Stage within New Zealand for three reasons.

(1) *Inoceramus pacificus* is widespread and abundant in marine Cretaceous strata and occurs in most marine formations and sections of appropriate age (Crampton 1996). The species apparently had rather broad habitat tolerances. It occurs in shallow marine, nearshore sandstone facies such as the Maungataniwha Sandstone in northern Hawke's Bay (Crampton & Moore 1990) and the Okarahia Sandstone at Haumuri Bluff (Warren & Speden 1978). It is abundant in probable shelf mudstone facies of the Karekare Formation on Raukumara Peninsula (Crampton 1996, fig. 12, 15). It has been recorded widely from turbidite facies that were deposited at outer shelf or bathyal depths, such as the Tikihore Formation on Raukumara Peninsula and the Glenburn Formation in Wairarapa (Crampton 1996, fig. 7, 10, 16, 18).

(2) *Inoceramus pacificus* can be readily identified from fairly complete specimens or from modest-sized collections (Fig. 8). This species is distinctive within its biostratigraphic context and can often be recognised in the field. *Inoceramus pacificus* is, however, difficult to identify from incomplete, fragmentary material. In particular, it is most likely to be confused with the Mangaotanean–Teratan (Turonian–Coniacian) *I. spedeni*. Unlike this older species, *I. pacificus* is equivalve and has a simple ligament area morphology. Differences between these and other similar taxa are summarised in Crampton (1996, p. 64, table 1).

(3) In practice, the revised definition for the base of the Piripauan Stage is close to Wellman's (1959) concept, and the changes proposed herein will have little impact on the composition of Piripauan strata as currently recognised in New Zealand.

## Correlations within New Zealand

MACROFOSSILS: As discussed above, *Inoceramus pacificus* can be correlated widely within New Zealand Upper Cretaceous strata. The only other Piripauan inoceramid, *I. australis*, has a similarly broad distribution and is easily identified in even poorly preserved material (Crampton 1996). The *I. australis* Taxon-range Zone corresponds to the upper part of the Piripauan Stage. In the boundary stratotype, the lowest occurrence of *I. australis* is 13.5 m above the base of the *I. pacificus* Zone.

Other macrofossil groups are uncommon in the Upper Cretaceous of New Zealand and consequently have limited potential in local correlation. Ammonites, although abundant at a few sites, are lacking at most Piripauan localities. Henderson (1970) did erect an informal, ammonite zonation for the Mata Series (Fig. 2) and he noted that his "zones" were not sufficiently widespread or well known to warrant formal definition. The lowest of his two units, the ?lower Piripauan *Kossmaticeras* (*K.*) "zone", was based entirely on material from Haumuri Bluff; subsequently, Warren & Speden (1978, p. 40) have questioned the biostratigraphic basis for this "zone". The belemnite *Dimitobelus lindsayi* may be restricted largely to the Piripauan Stage and clearly has some potential for correlation. It is abundant at Haumuri Bluff and, although nowhere common, has been found at scattered localities throughout the east coast region of New Zealand (Stevens 1965 and unpubl. data). In the BMS section, the only belemnite collected was derived from uppermost Teratan strata at locality P30/f634B, is poorly preserved, and is tentatively identified as *D. lindsayi*? Other molluscs are abundant locally in shallow-marine facies, and certain groups, such as the trigoniid bivalves, may have some largely untested biostratigraphic utility (e.g., Fleming 1987).

FORAMINIFERA: The record of Piripauan foraminifera is scanty and a search of the Fossil Record database identified only 24 Piripauan faunas that had been recognised prior to the current work. Piripauan ages were assigned to these collections on the basis of associated *I. pacificus* and/or *I. australis* or from their occurrence in well-dated rocks. A number of these earlier collections have been re-diagnosed as Haumurian during this study. Most Piripauan foraminiferal localities are in Northland, Raukumara Peninsula, and Marlborough. No significant foraminiferal faunas have been recovered from the shallow-water facies at Haumuri Bluff (Webb 1971; Warren & Speden 1978).

Examination of all Piripauan foraminiferal assemblage slides reveals that about one-half of the recovered faunas are siliceous, flysch-type agglutinated assemblages (*sensu* Gradstein & Berggren 1981) with low to moderate diversity. These are similar to the bulk of material recovered from the BMS and KR sections. The remaining assemblages contain common to dominant calcareous benthic and planktic foraminifera. Calcareous assemblages include *Tritaxia capitosa*, *Gavelinella complanata*, *Marginulinopsis curvisepta*, and *Rugoglobigerina pilula*. The total assemblage appears to be uniquely Piripauan, although individual taxa range higher and lower. In overall aspect, Piripauan faunas resemble those of the underlying Raukumara Series more closely than those of the overlying Haumurian Stage.

NANNOFOSSILS: Samples examined during the present study were barren of nannofossils and this group remains largely unknown in Mata Series strata of New Zealand. A single nannofossiliferous sample from Piripauan rocks on Raukumara Peninsula is discussed below.

DINOFLAGELLATES: A recent study of dinoflagellate cysts from the BMS and KR sections has shown that the base of the Piripauan Stage lies above the base of the *Cono-*

*sphaeridium abbreviatum* Zone and that the top of the stage as redefined here coincides with the top of the *Isabelidinium cretaceum* Zone (Schiøler & Wilson 1998). The stage includes the upper ranges of the following key taxa: *Conosphaeridium abbreviatum*, *C. striatoconus*, *Cymososphaeridium benmorense*; and the lower ranges of *Odontochitina* and *Isabelidinium cretaceum*. The base of the overlying Haumurian Stage is marked by the first appearance of *Nelsoniella aceras* (see below). The dinoflagellate

Table 3 Characteristic directions of magnetisation, after stratigraphic correction, and NRM intensity for horizons of the Ben More Stream section. Inclinations are plotted on Fig. 5 and directions are plotted on Fig. 11.

| Sample, BM... (stratigraphic order) | Formation | Height in section (m) | Characteristic declination (degrees) | Characteristic inclination (degrees) | NRM intensity (mA/m) |
|---|---|---|---|---|---|
| 1 | Paton | 3.5 | 215.6 | −50.6 | 0.460 |
| 2 | Paton | 6.5 | 85.1 | −53.1 | 0.311 |
| 4 | Paton | 8.7 | 135.2 | −70.9 | 0.525 |
| 5 | Paton | 10.3 | 315.4 | −11.9 | 0.560 |
| 6 | Paton | 14.2 | 270.3 | −20.6 | 0.410 |
| 7 | Paton | 18.8 | 288.8 | −37.2 | 0.373 |
| 8 | Paton | 19.0 | 209.8 | −78.1 | 0.704 |
| 9 | Paton | 19.1 | 140.9 | −38.2 | 0.348 |
| 10 | Paton | 22.6 | 274.6 | −23.1 | 0.690 |
| 11 | Paton | 29.3 | 65.8 | −8.5 | 0.371 |
| 12 | Paton | 36.5 | 118 | −5.8 | 0.201 |
| 13 | Paton | 43.7 | 108.6 | −68.3 | 0.428 |
| 14 | Paton | 49.9 | 134.1 | 10.7 | 0.182 |
| 15 | Paton | 53.3 | 156.8 | −41.0 | 0.490 |
| 17 | Paton | 55.9 | 313.6 | −67.8 | 0.640 |
| 18 | Paton | 57.9 | 329.6 | −33.0 | 0.483 |
| 19 | Paton | 61.7 | 351.3 | 6.3 | 0.168 |
| 20 | Paton | 62.0 | 228.6 | 19.5 | 0.490 |
| 21 | Paton | 64.8 | 23.1 | −33.3 | 0.744 |
| 22 | Paton | 69.8 | 21.4 | −45.6 | 0.503 |
| 23 | Paton | 70.3 | 124.2 | −71.0 | 0.380 |
| 24 | Paton | 76.0 | 208.6 | −83.1 | 2.460 |
| 25 | Paton | 78.5 | 143.3 | −46.5 | 0.380 |
| 26 | Paton | 79.0 | 59.2 | −70.5 | 1.200 |
| 27 | Paton (redbed) | 80.0 | 94.9 | −77.0 | 15.000 |
| 28 | Paton | 86.0 | 148.4 | −56.7 | 0.980 |
| 29 | Paton | 91.0 | 59 | −64.0 | 1.200 |
| 30 | Paton | 111.0 | 50.1 | −81.5 | 1.170 |
| 31 | Paton | 114.5 | 236.2 | −60.2 | 0.730 |
| 32 | Paton | 123.6 | 225.6 | −56.4 | 1.060 |
| 33 | Paton | 134.0 | 328.8 | −59.2 | 0.557 |
| 36 | Paton | 148.5 | 358.6 | −61.1 | 0.503 |
| 37 | Paton | 150.0 | 253.7 | −18.6 | 0.444 |
| 38 | Paton | 155.2 | 64 | −61.3 | 1.600 |
| 39 | Paton | 157.5 | 241.8 | −63.2 | 1.000 |
| 40 | Paton (redbed) | 164.2 | 92.3 | −69.5 | 11.300 |
| 40 | Paton (redbed) | 164.2 | 70.4 | −74.9 | 13.000 |
| 41 | Paton | 167.7 | 296.6 | −15.4 | 0.954 |
| 45 | Paton (redbed) | 168.0 | 130.5 | −80.4 | 9.300 |
| 42 | Paton | 168.4 | 275.2 | −24.7 | 0.350 |
| 46 | Herring | 168.7 | 280.9 | −36.1 | 0.101 |
| 46 | Herring | 168.7 | 307 | −26.5 | 0.140 |
| 43 | Herring | 169.2 | 298 | −61.3 | 0.290 |
| 47 | Herring | 170.0 | 328.2 | −28.6 | 0.164 |
| 47 | Herring | 170.0 | 259.2 | −18.6 | 0.230 |
| 44 | Herring | 171.0 | 340.3 | −57.0 | 0.297 |
| 44 | Herring | 171.0 | 329 | −47.8 | 0.260 |
| 48 | Herring | 175.9 | 267 | −37.1 | 0.250 |
| 49 | Herring | 181.3 | 128 | 44.0 | 0.086 |
| 50 | Herring | 186.8 | 227.8 | 69.8 | 0.100 |
| 51 | Herring | 200.3 | 239.1 | 68.3 | 0.130 |
| 53 | Herring | 238.3 | 175.8 | 11.1 | 0.830 |

A  **BM44  171.0 m**  Stratigraphic coordinates
NRM, T130, T180, T230, T270, T350, T400, T450
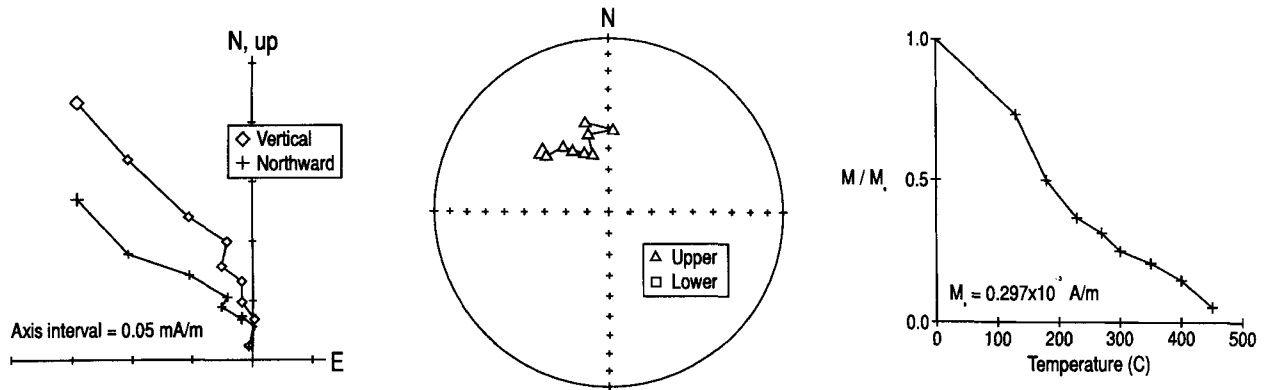


B  **BM50  187.5 m**  Stratigraphic coordinates
NRM, T250, T300, T350, T380, T400
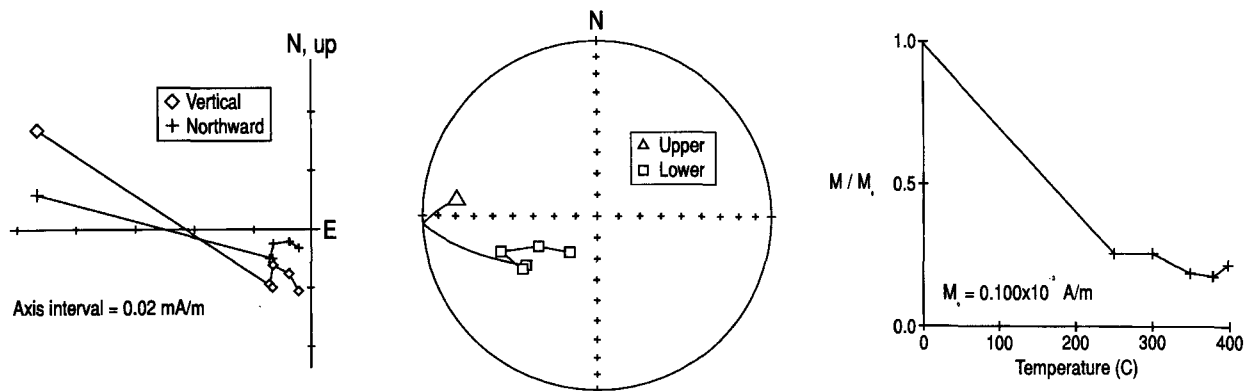


C  **BM27  80.0 m**  Stratigraphic coordinates
NRM, T200, T250, T260, T300, T350, T380, T400, T450, T530, T620
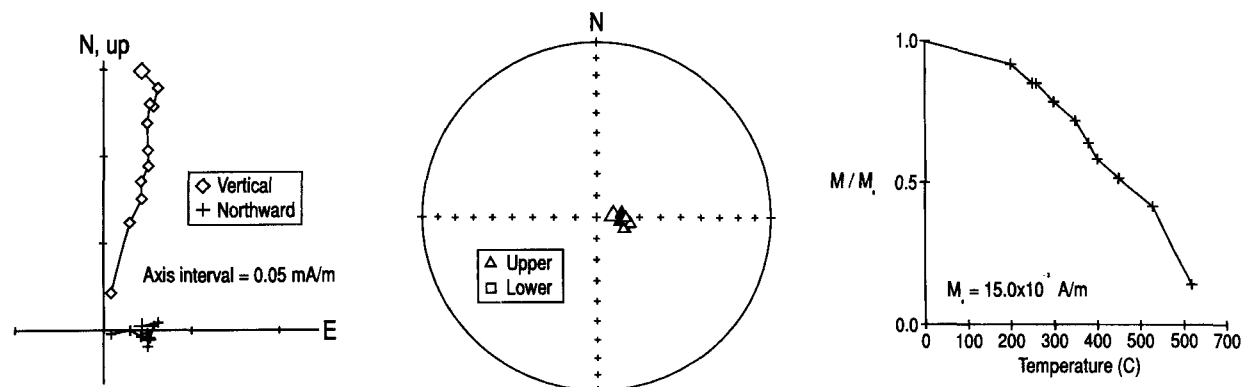


**Fig. 10**  Thermal demagnetisation data for typical specimens from the Ben More Stream section. BM44 is a normally magnetised specimen from Paton Formation; BM50 is a reversely magnetised specimen from Herring Formation; and BM27 is from a normally magnetised red sandstone ("redbed") within Paton Formation. Left-hand plots are vector component diagrams showing the vertical and northward components plotted against the eastward component. The middle diagrams are stereographic projections of the directions of the remanence vectors; directions in the upper hemisphere correspond to negative inclinations, those in the lower hemisphere correspond to positive inclinations. The right-hand diagrams show the decay of remanent intensity with each demagnetisation step. Stratigraphic corrections have been applied to all magnetisation vectors.
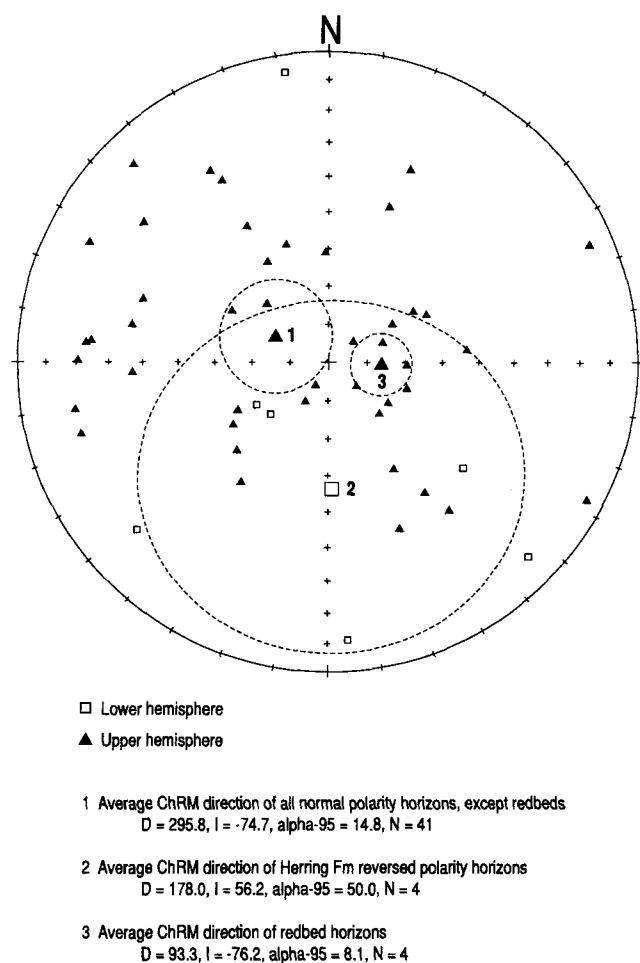
**Fig. 11** Directions of characteristic remanent magnetisation for all samples studied here. Mean values and α-95 ellipses shown for three subsets of the data. Stratigraphic corrections have been applied to all magnetisation vectors. See text for discussion. Data presented in Table 3.

succession reveals the presence of an unconformity between the type Piripauan and Haumurian Stages at Haumuri Bluff (Roncaglia & Schiøler 1997; Roncaglia et al. 1999).

Few detailed studies have been published on Piripauan dinoflagellate biostratigraphy in other parts of New Zealand. Several assemblages of undifferentiated Piripauan to early Haumurian age have been reported from other parts of the east coast and from Northland (Wilson 1982, 1984). An obvious area for further detailed study is "Te Rata stream", Raukumara Peninsula, the type locality for *Conosphaeridium abbreviatum* in strata overlying the type Teratan.

## REVISION OF THE HAUMURIAN STAGE

LOWER BOUNDARY STRATOTYPE: Herring Formation in the Ben More Stream tributary section, southeastern Marlborough, New Zealand (Fig. 3, 5).

DEFINITION: It is proposed that the base of the Haumurian Stage correspond to the lower boundary of the *Nelsoniella aceras* Interval Zone in the stratotype, 179.5 m above the base of the section at fossil locality P30/f701 (grid ref. P30/93271705). This locality is in a farm track cutting c. 10 m

east of a ford through the stream and 7 m stratigraphically above the level of the stream bed.

DISCUSSION: Studies over the last 20 years have demonstrated that Wellman's (1959) definition of the Haumurian Stage is unworkable. The proposed revision places the lower boundary at the lowest occurrence of the dinoflagellate *Nelsoniella aceras* in the boundary stratotype. As for the Piripauan Stage, the proposed **boundary** stratotype at Ben More Stream replaces the existing **interval** stratotype at Haumuri Bluff that now becomes a reference section for part of the stage. The upper limit of the Haumurian Stage is defined at the lower boundary of the overlying Teurian Stage in the Waipara River, North Canterbury (Hoskins 1982, fig. 2; Strong 1984). The base of the Teurian Stage marks the Cretaceous/Paleogene boundary in New Zealand.

The lowest occurrence of *Nelsoniella aceras* represents an ideal marker for the base of the Haumurian Stage for the following reasons.

(1) The lowest occurrence of *Nelsoniella aceras* corresponds to the first appearance of this genus in the New Zealand succession. The genus apparently is restricted to the Haumurian Stage and, globally, it is probably nowhere younger than early Maastrichtian (see below).

(2) The genus *Nelsoniella* has been recorded from many localities in northern and eastern parts of the North Island and in northeastern parts of the South Island. In addition, it has been identified in several wells on the west coast of the North Island (unpubl. data). It occurs in nearshore to deep-water marine facies. For example, *Nelsoniella* has been identified in shallow-water sandstones of the Tarapuhi Grit at Haumuri Bluff and in the Broken River Formation in North Canterbury (Roncaglia & Schiøler 1997; Roncaglia et al. 1999). It is widespread in mudstone facies that were deposited between shelf and bathyal depths, such as Whangai Formation in the North Island and the correlative Herring and Conway Formations in the northeastern South Island (Roncaglia & Schiøler 1997; unpubl. data). It has been recorded from turbidite facies that were probably deposited at outer shelf or bathyal depths, such as Tapuwaeroa Formation on Raukumara Peninsula and Glenburn Formation in Wairarapa (unpubl. data).

(3) The only other dinoflagellates with superficial resemblance to species of *Nelsoniella* are members of the genus *Eucladinium*. Species of *Eucladinium*, however, can be easily distinguished from species of *Nelsoniella* by the presence of a hypocoel in the former, whereas species of *Nelsoniella* are epicavate.

(4) At Haumuri Bluff, *N. aceras* is present from the base of the Haumurian Stage *sensu* Wellman (1959) and it is absent from underlying Piripauan strata (Roncaglia & Schiøler 1997; Roncaglia et al. 1999). In the proposed boundary stratotype, the lowest occurrence of *N. aceras* is c. 11 m above the base of the Herring Formation and the lowest occurrence of indeterminate bivalve fossils formerly assigned to "*Inoceramus matotorus*" (Fig. 5). The Haumurian Stage as emended here is thus little different in content from the Haumurian Stage as originally defined by Wellman. As with the Piripauan Stage, the proposed revisions will have minimal impact on the composition of Haumurian strata as currently

recognised in New Zealand. This is of considerable practical benefit to the wider geological community.

(5) *Nelsoniella* can be correlated internationally and it is distributed widely in Australia, Antarctica, and ODP/DSDP wells in the Southern Ocean. In all these regions it is of late Santonian to early Maastrichtian age (e.g., Cookson & Eisenack 1960, 1982; Davey 1978; Helby et al. 1987; Askin 1988; Marshall 1990; papers in Duane et al. 1992; Mao & Mohr 1992; Riding et al. 1992; Pirrie et al. 1997; Mohr & Mao 1997). In Australia, the age range of *N. aceras* is late Santonian to early Campanian (Helby et al. 1987; Ingram & Morgan 1988; McMinn 1988). In addition to these records, the genus occurs in the Campanian of Hungary (Siegl-Farkas 1997, pl. 6, fig. 4), in the upper Campanian of northwestern Germany (Smelror et al. 1995; Smelror & Riegraf 1996), in the lower Campanian of Denmark (Fig. 9E, G) (Schiøler unpubl. data, age from D. Jutson pers. comm. 1997), and in the upper Campanian to lowermost Maastrichtian of Israel (Hoek et al. 1996).

(6) The lowest occurrence of *N. aceras* in the BMS section is, within sample resolution, coincident with a paleomagnetic reversal. Correlations of this reversal are discussed below.

## Lower and Upper Haumurian Substages

Revised correlations of the Piripauan and Haumurian Stages with the international time-scale (see below) suggest that the Haumurian represents a relatively long interval of time of c. 19.5 m.y. (Fig. 12). In comparison, the Piripauan represents only c. 1.7 m.y. Consequently, it is expedient to subdivide the Haumurian Stage into formal Upper and Lower substages. The base of the Lower Haumurian Substage is, by definition, coincident with the base of the Haumurian Stage and is not discussed further. The top of the Lower Haumurian corresponds to the base of the overlying Upper Haumurian Substage, defined below.

LOWER BOUNDARY STRATOTYPE OF THE UPPER HAUMURIAN SUBSTAGE: Conway Formation in the Conway River railway cutting section, southeastern Marlborough, New Zealand (Fig. 4, 7).

DEFINITION OF THE UPPER HAUMURIAN SUBSTAGE: The base of the Upper Haumurian Substage corresponds to the lower boundary of the *Isabelidinium pellucidum* Interval Zone in the stratotype, 168 m above the base of the section at fossil locality O32/f178 (grid ref. O32/47314434). This locality is in the railway cutting on the northern side of the railway line, c. 3 km ESE of Hundalee.

DISCUSSION: The *Isabelidinium pellucidum* Interval Zone was established by Roncaglia & Schiøler (1997) on the basis of a study of Late Cretaceous dinoflagellate assemblages from southeastern Marlborough and northern Canterbury. They observed that the lowest occurrences of *Isabelidinium pellucidum* and *I. korojonense* were concurrent in the Haumuri Bluff and CR sections. From this they inferred that the base of the *I. pellucidum* Zone, as defined at Haumuri Bluff, coincided with the base of the Australian *I. korojonense* Range Zone of Helby et al. (1987). Subsequently, more detailed study of the key Haumuri Bluff and CR sections (Roncaglia et al. 1999) has demonstrated

that the lowest occurrence of *I. korojonense* is below that of *I. pellucidum* in both sections (e.g., Fig. 7).
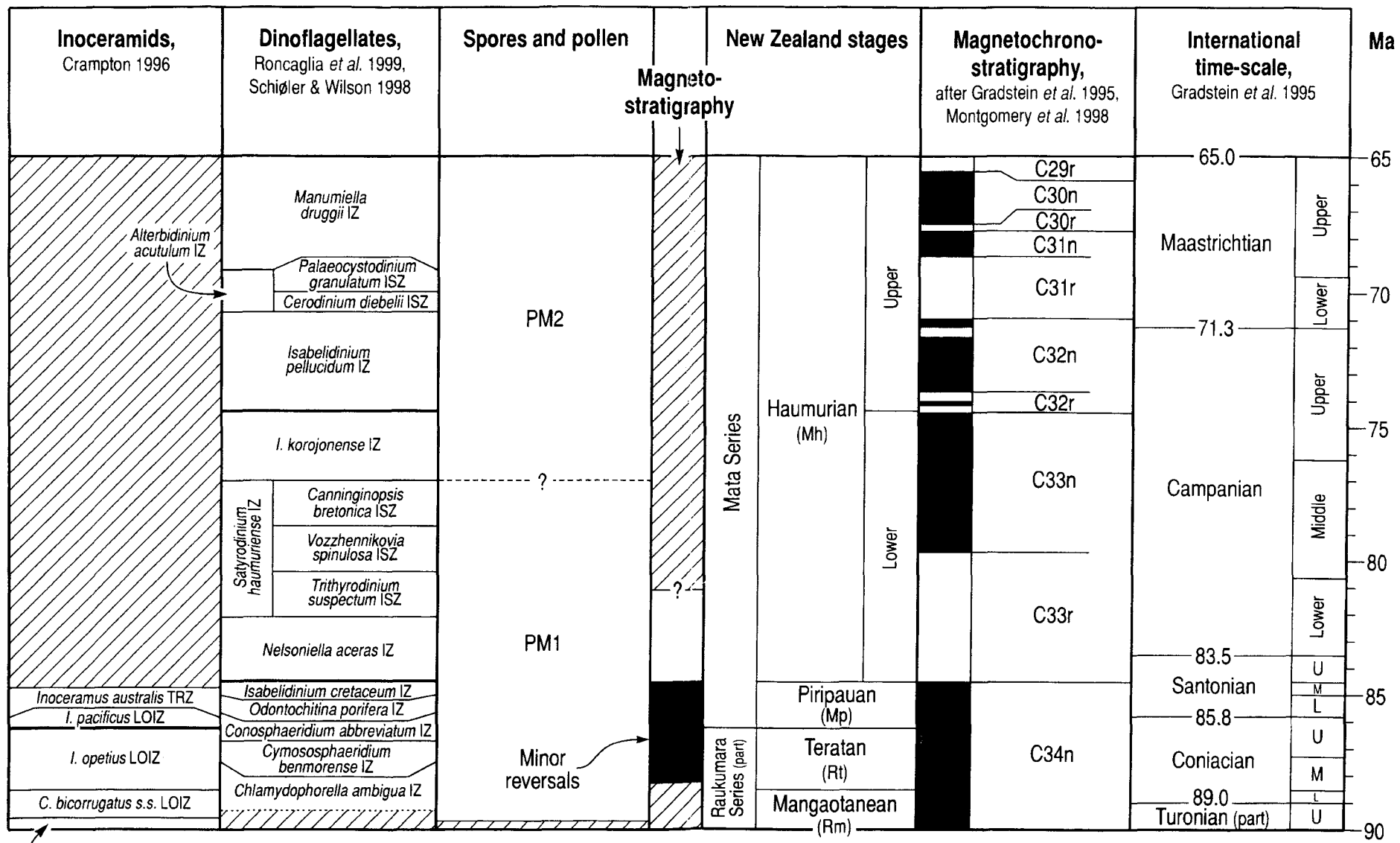
The base of the *I. pellucidum* Zone is not exposed in the BMS section and, hence, it has not been possible to define the base of the Haumurian Stage and the base of the Upper Haumurian from the single stratotype.

The lowest occurrence of *Isabelidinium pellucidum* is chosen herein as the marker for the Lower–Upper Haumurian boundary for the following reasons.

(1) In New Zealand, *I. pellucidum* is recorded from different localities in the northeastern part of the South Island and it is abundant to common in the stage stratotype at Haumuri Bluff (Wilson 1983; Roncaglia & Schiøler 1997; Roncaglia et al. 1999). It also occurs in northern Hawke's Bay, Raukumara Peninsula, and Northland (unpubl. data). In addition, *I. pellucidum* has been recorded from offshore exploration wells in the Taranaki Basin, west of the North Island, and in the Great South Basin, southwest of the South Island (unpubl. data).

(2) *Isabelidinium pellucidum* is distinctive and can be readily identified in even relatively poorly preserved material.

(3) *Isabelidinium pellucidum* occurs in a range of facies that were deposited within coastal swamps to open marine environments.

(4) On a geochronological time-scale, the lowest occurrence of *I. pellucidum* divides the Haumurian Stage into two approximately equal parts (Fig. 12).

(5) *Isabelidinium pellucidum* can be correlated internationally and is distributed widely in Australia, Antarctica, in the Southern Ocean ODP/DSDP cores, and in the southern Indian Ocean. In Australia, the lowest occurrence of this species is in the middle Campanian to lower Maastrichtian (Marshall 1985; Helby et al. 1987; McMinn 1988). In the James Ross Island area, Southern Ocean, it is recorded in the upper Campanian to lowest Maastrichtian (Crame et al. 1991, 1999; Pirrie et al. 1991; Riding et al. 1992; Smith 1992; Wood & Askin 1992; Pirrie et al. 1997; Mohr & Mao 1997). On the Kerguelen Plateau, southern Indian Ocean, the lowest occurrence of *I. pellucidum* is in the lower Maastrichtian (Mao & Mohr 1992).

## Correlations within New Zealand

MACROFOSSILS: The key index macrofossils for the Haumurian Stage that were identified by Wellman (1959), the bivalves "*Inoceramus matotorus*" and *Ostrea lapillicola*, cannot be used reliably for correlation within New Zealand. Stevens (1965) inferred that the belemnite *Dimitobelus hectori* is restricted to the Haumurian Stage. This conclusion is supported by its presence at Haumuri Bluff and Waipara River in strata shown to be Haumurian by Roncaglia & Schiøler (1997). *Dimitobelus hectori*, although nowhere abundant, is widespread from Northland to Otago in a range of sedimentary facies and is probably valuable in correlation. A relatively large number of inferred Haumurian ammonites have been described by Henderson (1970), who erected an informal zonation for the Mata Series (Fig. 2 and see discussion above). The majority of these are known from few localities in areas of poorly correlated stratigraphy, extreme structural complexity, or restricted facies. Ammonites are extremely rare in most Upper Cretaceous sections in New Zealand, a fact that renders them of limited

| Inoceramids, Crampton 1996 | Dinoflagellates, Roncaglia et al. 1999, Schiøler & Wilson 1998 | Spores and pollen | Magneto-stratigraphy | New Zealand stages | Magnetochrono-stratigraphy, after Gradstein et al. 1995, Montgomery et al. 1998 | International time-scale, Gradstein et al. 1995 | Ma |
|---|---|---|---|---|---|---|---|

Biostratigraphic correlation chart. Key zones and stages:

**Inoceramids:** Inoceramus australis TRZ, I. pacificus LOIZ, I. opetius LOIZ, C. bicorrugatus s.s. LOIZ, C. bicorrugatus matamuus LOIZ

**Dinoflagellates:** Alterbidinium acutulum IZ, Manumiella druggii IZ, Palaeocystodinium granulatum ISZ, Cerodinium diebelii ISZ, Isabelidinium pellucidum IZ, I. korojonense IZ, Satyrodinium haumuriense IZ (Canninginopsis bretonica ISZ, Vozzhennikovia spinulosa ISZ, Trithyrodinium suspectum ISZ), Nelsoniella aceras IZ, Isabelidinium cretaceum IZ, Odontochitina porifera IZ, Conosphaeridium abbreviatum IZ, Cymososphaeridium benmorense IZ, Chlamydophorella ambigua IZ

**Spores and pollen:** PM2, PM1, Minor reversals

**New Zealand stages (Mata Series, Raukumara Series part):** Haumurian (Mh) Upper/Lower, Piripauan (Mp), Teratan (Rt), Mangaotanean (Rm)

**Magnetochronostratigraphy:** C29r, C30n, C30r, C31n, C31r, C32n, C32r, C33n, C33r, C34n

**International time-scale:** Maastrichtian (Upper, Lower 71.3), Campanian (Upper, Middle, Lower 83.5), Santonian (U/M/L 85.8), Coniacian (U/M/L 89.0), Turonian (part) (U), 65.0, 90

**Legend**
IZ = Interval Zone
ISZ = Interval Subzone
LOIZ = Lowest-occurrence Interval Zone
TRZ = Taxon-range Zone
— = Key biostratigraphic datum
▨ = No data

Fig. 12 Summary correlation of integrated biostratigraphy, magnetostratigraphy, and New Zealand chronostratigraphy with the international magnetochronostratigraphic scale and time-scale. See text for discussion of correlations.

value in local correlation. Other macrofossil groups are generally absent except at a few localities within very shallow marine facies, such as at Haumuri Bluff and in northern Hawke's Bay (Warren & Speden 1978; Crampton & Moore 1990).

FORAMINIFERA: No foraminifera were recovered from Haumurian strata in the studied sections. In contrast to the Piripauan Stage, however, Haumurian foraminiferal assemblages are abundant and diverse at many localities in New Zealand. Webb (1971) subdivided the Haumurian into three biostratigraphic units on the basis of foraminifera (Fig. 2). These three units are essentially biofacies. The lower two units, the *Rzehakina epigona* and *Trochammina globigeriniformis* Zones, contain facies-controlled assemblages that are, in part at least, laterally equivalent. The *R. epigona* Zone comprises flysch-type siliceous agglutinated foraminiferal assemblages, whereas the *T. globigeriniformis* contains mainly coarsely agglutinated taxa characteristic of inner shelf to paralic paleoenvironments. The third unit, the *Rugotruncana circumnodifer* Zone, includes both agglutinated and calcareous benthic foraminifera and common to abundant planktic taxa typical of normal marine environments. In addition to Webb's zones, at least some of Huber's (1992) southern high latitude planktic zones can be identified locally in suitable facies in New Zealand, although these have not been formally integrated into the local subdivision.

Although biostratigraphic ranges for key foraminifera cannot be integrated precisely at the sections described here, reasonable correlations are possible at a few localities in northern Canterbury and southeastern Marlborough. In the middle Waipara River section in northern Canterbury, Webb's (1971) zones can be correlated with the recent dinoflagellate subdivision of Roncaglia & Schiøler (1997) and Roncaglia et al. (1999). At this site, the foraminiferal *T. globigeriniformis* Zone probably correlates with the *Manumiella druggii* dinoflagellate zone of the upper part of the Haumurian Stage. In the middle reaches of Ben More Stream, c. 1 km downstream of the tributary studied here, the *R. epigona* Zone in the Herring Formation (Woolshed Formation of Webb 1971, p. 807) is likely to be no lower than the uppermost Piripauan *I. cretaceum* Zone (herein). In the Mead Stream section, central Clarence valley, Marlborough, uppermost Haumurian foraminiferal, dinoflagellate, and radiolarian biozones have been integrated by Strong et al. (1995).

These data indicate that Webb's (1971) three "zones" correlate largely with the Haumurian Stage as defined herein, although the *R. epigona* Zone may well extend down into the uppermost Piripauan. The downward extent of the zones cannot be determined with confidence because of the paucity of Piripauan foraminiferal assemblages. In addition, the biostratigraphic distributions of individual taxa remain poorly known, although the ranges of a number of uppermost Haumurian forms have been documented recently by Strong et al. (1995). On present knowledge, key taxa for identifying the Haumurian Stage include *Dorothia elongata*, *D. biformis*, and *Gaudryina healyi*, all of which are considered to range through the entire stage (Hornibrook et al. 1989).

NANNOFOSSILS: As for the Piripauan Stage, nannofossils were not recovered during the present study and they remain largely unknown in the New Zealand Mata Series.

DINOFLAGELLATES: *Nelsoniella aceras* occurs widely throughout New Zealand. A total of six dinoflagellate zones and five subzones have been recognised in the Haumurian (Fig. 12) (Wilson 1984; Roncaglia & Schiøler 1997; Schiøler & Wilson 1998; Roncaglia et al. 1999). The zones are, in ascending order: *Nelsoniella aceras* Interval Zone; *Satyrodinium haumuriense* IZ, divided into *Trithyrodinium suspectum*, *Vozzhennikovia spinulosa*, and *Canninginopsis bretonica* Interval Subzones; *Isabelidinium korojonense* IZ; *I. pellucidum* IZ; *Alterbidinium acutulum* IZ, divided into the *Cerodinium diebelii* ISZ and *Palaeocystodinium granulatum* ISZ; and *Manumiella druggii* IZ. Although these zones have been established through detailed study of key sections in southern Marlborough and northern Canterbury, most of the zone index fossils have been reported widely from throughout New Zealand (Wilson 1982; and unpubl. reports).

SPORES AND POLLEN: In a miospore zonation of Cretaceous–Paleogene strata occurring on the west coast of South Island, Raine (1984) defined two Late Cretaceous zones, successively PM1 and PM2, within his *Phyllocladidites mawsonii* Assemblage (or superzone). The zonation has been used subsequently elsewhere in New Zealand in regional geological and basin studies work. The lower boundary of PM1 is pre-Mata in age, but that of PM2, which is defined by the first appearance of *Tricolporites lilliei*, appears to lie within the Haumurian Stage as now redefined. The upper boundary of PM2 coincides with the first appearance of the succeeding zone index, *Tricolpites secarius*, and correlates closely with the Cretaceous/Cenozoic boundary. *T. lilliei* occurs widely in Late Cretaceous marine and nonmarine strata in the New Zealand region (e.g., Couper 1960; Raine 1984) and has been used as a proxy Haumurian index in miospore dating (e.g., Raine et al. 1993).

*Tricolporites lilliei* occurred widely in high southern latitudes in the Campanian–Maastrichtian, being present also in Australia (Stover & Evans 1973; Helby et al. 1988) and in the Antarctic Peninsula (Dettmann & Thomson 1987; Askin 1988). In eastern Australia, according to Helby et al. (1987), its first appearance approximates that of *Isabelidinium korojonense*, or is slightly above (Marshall 1990). Miospores have not yet been examined from the Conway River or Haumuri Bluff sections, but *T. lilliei* occurs in basal Broken River Formation in the Waipara River South Branch section (locality S68/f753; Couper 1960), within the *I. pellucidum* Zone. Another important section is Kaiwhata Stream, Wairarapa, where *T. lilliei* occurs at locality T27/ f328 in association with a basal *I. korojonense* Zone dinoflagellate assemblage including *I. korojonense*, *Satyrodinium haumuriense*, and *Odontochitina* spp. About 80 m lower in the section, at locality T27/f333, a rich miospore assemblage of typical upper PM1 zone aspect lacks *T. lilliei*; associated dinoflagellates *S. haumuriense* and *Nelsoniella aceras* indicate lower–middle *S. haumuriense* Zone. Other New Zealand data are also in agreement with those from Australia, and the lowest occurrence of *T. lilliei* is provisionally placed at the base of the *I. korojonense* Zone.

## CORRELATIONS WITH THE INTERNATIONAL TIME-SCALE

The endemic nature of many New Zealand Cretaceous fossil groups has in the past hampered correlations with the

international time-scale. The present study revises previous international correlations substantially (Fig. 1, 12). The Piripauan Stage is correlated with the uppermost Coniacian and lower–middle Santonian; the Haumurian Stage is correlated with the upper Santonian, Campanian, and Maastrichtian (Fig. 12). The Piripauan/Haumurian boundary is provisionally placed at the middle/upper Santonian boundary. The Lower/Upper Haumurian boundary is placed within the upper Campanian. These revisions are based on several lines of evidence, discussed below in ascending stratigraphic order.

(1) The inoceramids *Inoceramus*? *madagascariensis* and *I. opetius* occur in the Teratan Stage and have inferred middle Coniacian and early–middle Coniacian correlations, respectively (Crampton 1996).

(2) A single, poorly preserved, low abundance nannofossil assemblage from the *I. australis* Zone in the Mangaotane Stream section on Raukumara Peninsula (sample X16/f88, see Crampton 1996, fig. 12), includes *Kamptnerius magnificus*, *Thiesteinia ecclesiastica*, and, questionably, *Reinhardtites anthophorus*. This assemblage indicates a Turonian–Santonian correlation and, if the identification of *R. anthophorus* is correct, an earliest Santonian age (J. Burnett, University College London, pers. comm. 1994).

(3) The dinoflagellate *Conosphaeridium striatoconum* ranges up into the *C. abbreviatum* Interval Zone in the studied sections (Schiøler & Wilson 1998). This zone spans the Teratan/Piripauan Stage boundary. Based on nannofossils and foraminiferal data in Australia, Helby et al. (1987) correlated the upper limit of *C. striatoconum* with the lowest Santonian (see also synthesis in Young & Laurie 1996).

(4) The dinoflagellate *Odontochitina porifera* occupies the middle Piripauan in the studied sections and is early–middle Santonian, according to nannofossil and foraminiferal correlations in Australia (Helby et al. 1987; Young & Laurie 1996).

(5) The ammonite subgenus *Kossmaticeras* (*Kossmaticeras*) occurs in the Haumuri Bluff section and is likely to be of Santonian age (Henderson 1970).

(6) The dinoflagellate genus *Nelsoniella*, used herein to define the base of the Haumurian, is probably restricted to the upper Santonian to Campanian interval, although it may possibly extend into the lower Maastrichtian.

(7) Magnetostratigraphic data from the BMS section indicate a change from normal to reversed polarity at, or very close to, the base of the revised Haumurian Stage (Fig. 5). Based on other evidence discussed above, this reversal is correlated with the C34–C33 magnetochron boundary (Fig. 12). Correlations of this boundary to the international time-scale remain somewhat problematic and are discussed below.

(8) Based on Sr isotopic correlations to the global standard $^{87}Sr/^{86}Sr$ reference curve, Crame et al. (1999) inferred that the *Gunnarites antarcticus* ammonite faunal assemblage of the Antarctic Peninsula region is of earliest Maastrichtian age. The associated dinoflagellate flora contains the taxa *Cerodinium diebelii*, *Isabelidinium korojonense*, *Odontochitina porifera*, and *I. pellucidum* (Pirrie et al. 1997), and correlates with the *I. pellucidum* Zone in New Zealand. This suggests, therefore, that the *I. pellucidum* Zone correlates, in part, with the lowest Maastrichtian.

(9) The upper Maastrichtian index planktic foraminifer, *Abathomphalus mayaroensis*, is well represented in Upper Haumurian strata in New Zealand (e.g., Hornibrook et al. 1989; Strong et al. 1995).

(10) By definition, the top of the Haumurian Stage is placed at the base of the overlying Teurian Stage that is correlated with the Cretaceous/Paleogene boundary. This correlation is well established from faunal and geochemical data at a number of boundary sections in Marlborough (e.g., Strong et al. 1995 and references therein).

## Global correlation of the Santonian/Campanian boundary and the magnetochronostratigraphic scale

The definition of the Santonian/Campanian boundary is currently under revision as part of an overall revision of the international Cretaceous stages (Birkelund et al. 1984; Hancock & Gale 1996). To date, no consensus has been achieved regarding a suitable boundary definition or stratotype. The boundary is likely to be established using crinoids, ammonites, belemnites, foraminifera, or nannofossils in a section in southern England or Texas (Hancock & Gale 1996). None of the key taxa under consideration have been recorded in New Zealand sections; consequently, correlations are indirect and are based on the taxa listed above and on magnetostratigraphic data.

Correlation of the magnetochronostratigraphic scale to the international time-scale remains controversial. In part, this problem results from the use of different biostratigraphic markers to define the boundary in Europe and North America, and the likelihood that these markers are of different ages (Kennedy et al. 1997). Opinions on the correlation of the C34–C33 boundary are divided between three schools of thought:

(1) the C34–C33 magnetochron boundary is at or close to the Santonian/Campanian boundary (Hambach & Krumsiek 1991; Ogg 1995; Gradstein et al. 1995; Opdyke & Channell 1996);

(2) the C34–C33 boundary is significantly younger than the age of the Santonian/Campanian boundary (Lillegraven 1991; Cande & Kent 1992, 1995; Barchi et al. 1996; Toshimitsu & Kikawa 1997);

(3) the C34–C33 boundary is significantly older than the age of the Santonian/Campanian boundary (Leahy & Lerbekmo 1995; Gale et al. 1995; Hancock & Gale 1996; Montgomery et al. 1998).

Resolution of this problem requires, first, establishment of the Santonian/Campanian boundary criterion in a type section and, secondly, studies to establish either the magnetostratigraphic sequence in this section or robust correlations to sections with known magnetostratigraphic sequences.

Correlations established here (Fig. 12) are based on the recent and thorough work of Montgomery et al. (1998): the C34–C33 boundary is placed close to the top of the middle Santonian. These authors, however, assumed an absolute age of 83.5 Ma for the C34–C33 boundary, whereas this radiometric date was derived from a bentonite in the Western Interior of North America that is more correctly tied to the biostratigraphic definition of the Santonian/Campanian

boundary (Obradovich 1993). Hence, in Fig. 12, we retain an age of 83.5 Ma for the Santonian/Campanian boundary (cf. Montgomery et al. 1998). Other correlations shown in Fig. 12 are based on the synthetic international time-scale of Gradstein et al. (1995).

Future revision of the correlations between the magnetochronostratigraphic scale and the international time-scale may require adjustment of the correlations given here between the New Zealand time-scale and the international time-scale. These adjustments, however, are likely to be minor.

## SUMMARY

1. The uppermost Cretaceous in New Zealand is represented by the local Mata Series and its stages, the Piripauan and overlying Haumurian. The existing stratotype for the Mata Series is at Haumuri Bluff, southeastern Marlborough. This stratotype, and the stage definitions, are wholly inadequate.

2. Two new sections through the lower part of the Mata Series have been examined in detail. These sections are in a tributary of Ben More Stream and in the headwaters of the Kekerengu River, southeastern Marlborough. They span parts of the Paton and overlying Herring Formations. Both sections have yielded inoceramid bivalve faunas and rich palynomorph floras. Foraminiferal assemblages are of low diversity, and nannofossils were not recovered. Magnetostratigraphic data were obtained from the BMS section. A third section, through the middle part of the Mata Series, has been studied as part of a complementary study (Roncaglia & Schiøler 1997; Roncaglia et al. 1999) and is reported here. This section is in a railway cutting adjacent to the Conway River, southeastern Marlborough, and has yielded rich palynomorph floras.

3. New and existing inoceramid and dinoflagellate biozonations have been integrated for the entire Mata Series. The Piripauan is subdivided into two inoceramid zones and three dinoflagellate zones. The Haumurian is subdivided into 11 dinoflagellate zones and subzones. These zonations represent a three-fold increase in biostratigraphic resolution for this interval of time. We envisage that these zonations, in particular the dinoflagellate scheme, will have considerable utility elsewhere in southern high paleolatitudes.

4. A single paleomagnetic polarity reversal has been identified. This occurs at the base of the *Nelsoniella aceras* dinoflagellate zone.

5. Definitions of the Piripauan and Haumurian Stages are revised herein from proposed new boundary stratotype sections in the tributary of Ben More Stream. The base of the Piripauan Stage is defined at the lowest occurrence of the inoceramid *I. pacificus*. The base of the Haumurian Stage is defined at the lowest occurrence of the dinoflagellate genus *Nelsoniella* and the species *N. aceras*. The Haumurian Stage is divided into Lower and Upper substages; the base of the Upper Haumurian is defined from a proposed new boundary stratotype in the Conway River railway cutting at the lowest occurrence of the dinoflagellate *Isabelidinium pellucidum*. These lower boundary criteria can be correlated widely within New Zealand across a broad range of marine facies.

6. In terms of content, these revisions will have little impact on the recognition of Piripauan and Haumurian strata elsewhere in New Zealand. Existing geological maps of these stages remain essentially correct.

7. Using biostratigraphic and magnetostratigraphic criteria, we correlate the Piripauan Stage with the uppermost Coniacian to middle Santonian, and the Haumurian Stage with the upper Santonian–Maastrichtian. The Piripauan/Haumurian boundary correlates with the middle/upper Santonian boundary. Possible future changes to international magnetochronostratigraphic correlations may necessitate minor revision of the Piripauan/Haumurian Stage boundary correlation. The top of the Haumurian Stage correlates exactly with the Cretaceous/Cenozoic boundary. Using these results, the Piripauan and Haumurian Stages have durations of c. 1.7 and 19.5 m.y., respectively.

## ACKNOWLEDGMENTS

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