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A coherent middle Pliocene magnetostratigraphy, Wanganui Basin, New Zealand

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Abstract We document magnetostratigraphies for three river sections (Turakina, Rangitikei, Wanganui) in Wanganui Basin and interpret them as corresponding to the Upper Gilbert, the Gauss and lower Matuyama Chrons of the Geomagnetic Polarity Timescale, in agreement with foraminiferal biostratigraphic datums. The Gauss-Gilbert transition (3.58 Ma) is located in both the Turakina and Wanganui River sections, while the Gauss-Matuyama transition (2.58 Ma) is located in all three sections, as are the lower and upper boundaries of the Mammoth (3.33–3.22 Ma) and Kaena (3.11–3.04 Ma) Subchrons. Our interpretations are based in part on the re-analysis of existing datasets and in part on the acquisition and analysis of new data, particularly for the Wanganui River section. The palaeomagnetic dates of these six horizons provide the only numerical age control for a thick (up to 2000 m) mudstone succession (Tangahoe Mudstone) that accumulated chiefly in upper bathyal and outer neritic palaeoenvironments. In the Wanganui River section the mean sediment accumulation rate is estimated to have been about 1.8 m/k.y., in the Turakina section it was about 1.5 m/k.y., and in the Rangitikei section, the mean rate from the beginning of the Mammoth Subchron to the Hautawa Shellbed was about 1.1 m/k.y. The high rates may be associated with the progradation of slope clinoforms northward through the basin. This new palaeomagnetic timescale allows revised correlations to be made between cyclothems in the Rangitikei River section and the global Oxygen Isotope Stages (OIS) as represented in Ocean Drilling Program (ODP) Site 846. The 16 depositional sequences between the end of the Mammoth Subchron and the Gauss-Matuyama Boundary are correlated with OIS MG2 to 100. The cyclothems average 39 k.y. in duration in our age model, which is close to the 41 k.y. duration of the orbital obliquity cycles. We support the arguments advanced recently in defence of the need for local New Zealand stages as a means of classifying New Zealand sedimentary successions, and strongly oppose the proposal to move stage boundaries to selected geomagnetic polarity transitions. The primary magnetisation of New Zealand mudstone

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is frequently overprinted with secondary components of diagenetic origin, and hence it is often difficult to obtain reliable magnetostratigraphic records. We suggest specific approaches, analytical methods, and criteria to help ensure robustness and coherency in the palaeomagnetic identification of chron boundaries in typical New Zealand Cenozoic mudstone successions.

Keywords palaeomagnetism; magnetostratigraphy; geomagnetic polarity timescale; Wanganui Basin; middle Pliocene; sequence stratigraphy; oxygen isotope stages

INTRODUCTION

Wanganui Basin has been shown to contain a late Pliocene through late Pleistocene (upper Mangapanian-Castlecliffian) cyclothemic shelf succession, which is well exposed in the coastal section north-west of Wanganui City and in the main north-east to south-west oriented river valleys farther to the east (Fig. 1) (e.g., Fleming 1953; Beu & Edwards 1984; Kamp & Turner 1990; Turner & Kamp 1990; Abbott & Carter 1994; Pillans et al. 1994; Naish & Kamp 1995, 1997; Kamp & McIntyre 1998; McIntyre & Kamp 1998). Recent work has shown that there is also an underlying late Miocene through early Pliocene (upper Tongaporutuan-lower Opoitian) cyclothemic shelf succession, which is exposed extensively in northern parts of Wanganui Basin (Kamp et al. 1999, 2002, 2004; Vonk et al. 2002; Hendy & Kamp 2004; Vonk & Kamp 2004). A thick mudstone unit (Tangahoe Mudstone) that accumulated at upper bathyal depths in a continental slope environment separates the two shelf successions. The identification of Vail-type sequences (Vail et al. 1991) in the shelfal parts of the basin record has been significant for various reasons, amongst them their possible origin as the local expression of eustatic (global) sea level oscillations. In attempts to substantiate this, researchers have been driven to correlate the Wanganui sequences with the oxygen isotope records of deep-sea sediment cores.

The application of palaeomagnetic techniques to Wanganui Basin strata, in combination with biostratigraphy, have proved to be, and remain, the critical means of dating the sedimentary successions, potentially enabling the sequences to be individually correlated with Oxygen Isotope Stages (OIS), and thereby achieving a fine-scale and wide-ranging (global) correlation scheme for the late Neogene. The original Middle Pliocene magnetostratigraphic record for the Rangitikei River section of Seward et al. (1986) has been revised and re-interpreted by Wilson (1993), Journeaux et al. (1996), and most recently by Naish et al. (1998) and Carter & Naish (1998). A global correlation scheme and chart, involving Wanganui Basin strata ranging in age between 3.5 Ma and the Holocene, that attempts a sequence-scale correlation with the OIS, has been published by Naish et al. (1998) and Carter & Naish (1998). The middle to late Pleistocene (OIS 5–31; 5th order) cycles reproduced in those charts are regular, mirroring the 41 k.y. obliquity controlled cycles predicted by Laskar (1990) between 2.5 and 1.0 Ma, and the 100 k.y. eccentricity dominated cycles thereafter. The correlations shown for the middle to late Pliocene, however, are irregular, ranging between 80 k.y. and 160 k.y., and are difficult to reconcile with orbital forcing.

In this paper, we address the coherency of the Pliocene magnetostratigraphic datums used by Naish et al. (1998) and Carter & Naish (1998) to underpin the correlations of Mangapanian and Waipipian sequences in Wanganui Basin with the global OIS in Ocean Drilling Program (ODP) site 846 (Shackleton et al. 1995). As a result of better understanding of the secondary components of magnetisation of Wanganui Basin sediments (Turner 2001), we are able to produce new, coherent magnetostratigraphies for key sections in the basin (Rangitikei, Turakina, and Wanganui River valleys). This, amongst other uses, allows new sequence-OIS correlations to be made for the Gauss Chron for the Rangitikei River section where the depositional sequences are best expressed for this interval.

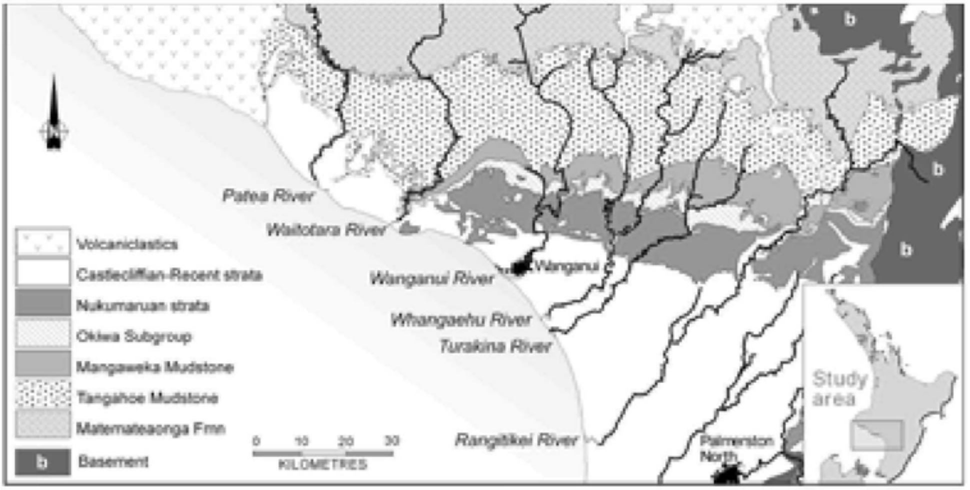


Fig. 1 Map of the Wanganui Basin, North Island, New Zealand, showing the location of the Wanganui, Turakina, and Rangitikei Rivers, which flow from the Central Volcanic Region into the Tasman Sea.

MAGNETOSTRATIGRAPHIC DATING OF WANGANUI BASIN SEDIMENTS

The use of geomagnetic polarity reversals for the age control of sedimentary sequences is not without problems. The evidence for polarity reversals of the main geomagnetic dipole, and their globally synchronous nature are well established. However, the binary nature of the polarity signal leaves room for misidentification of particular reversals. Significant time lag between a reversal and its recording could also cause problems; and the palaeomagnetic analysis of sedimentary rocks can be complicated by difficulties associated with separation of the primary or characteristic component of magnetisation from any components of later origin.

These latter issues relate to the acquisition of detrital remanent magnetisation (DRM) in sediments, and the possibility of its subsequent alteration or overprinting. Laboratory redeposition experiments (Verosub 1977) suggest that the lock-in depth, below which a post-depositional detrital remanent magnetisation becomes stable, is typically a few decimetres. Only in extremely slowly accumulating sediments is the associated time lag likely to be comparable with the c. 5000-year duration of a geomagnetic polarity reversal. In continental shelf and slope sediments such as those in Wanganui Basin, with an estimated average accumulation rate of c. 1.0–1.5 m/k.y., the time lag should be negligible.

Confident identification of the primary component of magnetisation can be difficult, however, due to the additional presence of secondary magnetisations. The siliciclastic mudstones of Wanganui Basin are extremely weakly magnetised ($10^{-3} - 10^{-5}$ Am^{-1}), and are prone to diagenetic alteration by percolating fluids. A thermo-viscous secondary component, resident in the (magnetically) less stable grains, with shortest magnetic relaxation times and lowest blocking temperatures, is almost ubiquitous, and is invariably close to the present-day field direction. It is generally easy to recognise and remove this component by progressive thermal demagnetisation. A secondary component of diagenetic or chemical origin is also common, and this appears to reside in an authigenic population of grains with blocking temperatures generally higher than those of the primary detrital grains (Turner 2001). Formation of these authigenic grains seems to involve dissolution of the primary magnetic mineral, and the growth of the high blocking temperature secondary component of magnetisation is accompanied by a reduction in the mid-blocking temperature, primary component. This primary component is often difficult to isolate during thermal demagnetisation, as thermal alteration of clay minerals in the sediments between c. 300 and 400°C often yields new magnetite that masks any remnants of the natural remanent magnetisation (NRM). The high blocking temperature component of magnetisation can often only be inferred from the failure of demagnetisation data to trend toward the origin of a vector component plot. Turner (2001) warned that conventional interpretation of palaeomagnetic progressive demagnetisation data could lead to mistaking the high T_B secondary component for the primary magnetisation, and hence assigning erroneous polarities.

In this paper, we re-examine the extensive palaeomagnetic data from the Turakina River Valley, originally acquired by McGuire (1989). Despite having a much more complete coverage and closer sampling interval than other studies, these data have never been used in magnetostratigraphic interpretations of the Wanganui Basin. McGuire (1989) admitted having difficulty separating the various components of magnetisation evident in his progressive demagnetisation data. When the possibility of a high blocking temperature secondary component of magnetisation is considered, and the mid-blocking temperature component is interpreted as the primary, a clear magnetostratigraphic record is obtained. We also present new data from the Wanganui River valley, and add some new data to the Rangitikei Valley record of Wilson (1993). We present a single coherent magnetostratigraphic interpretation of the three contemporaneous sequences, which necessitates revision of the Waipipian and Mangapanian part of all previously published chronostratigraphies for Wanganui Basin (e.g., Carter & Naish 1998; Naish et al. 1998).

GEOLOGICAL SETTING

The Wanganui Basin (Fig. 1) is a subcircular basin in south-western North Island, located south-west of the active volcanic arc (Taupo Volcanic Zone), and west of the accretionary prism that forms the leading edge of the overriding part of the Hikurangi Margin, where oceanic Pacific plate is subducting below continental crust of the Australian plate. The basin is, therefore, not a simple backarc basin, but neither is it a forearc basin; its tectonic origin is probably related to the transition along central New Zealand from ocean-continent convergence to continent-continent collision. Basement in the main depocentre of the basin reaches depths of 4000 m and all of this subsidence and associated sedimentation has occurred during the Pliocene and Pleistocene (e.g., Kamp et al. 2004). The stratigraphic succession in the basin is well exposed in north-east to south-west oriented river valleys and along coastal cliffs, where it dips 3–4° south or south-west as part of a regional monocline (Kamp et al. 2002). The succession can be subdivided into three main parts: an early Pliocene continental shelf succession (Matemateaonga Formation), an overlying middle Pliocene continental slope succession (Tangahoe Mudstone) (Hayton 1998), and an uppermost late Pliocene–Pleistocene shelf succession (Okiwa Subgroup and younger units) (Fleming 1953; McIntyre 2002).

We are concerned here with the middle to late Pliocene part of the succession, which includes the uppermost part of the Opoitian, and the Waipipian and Mangapanian Stages (Morgans et al. 1996). The studied sections in the Turakina and Wanganui River valleys in the central parts of the basin (Fig. 1) start at the base of the Tangahoe Mudstone (Fig. 2) (Kamp et al. 2004). The sampled part of the Rangitikei River section extends from part way up the Tangahoe Mudstone and into the overlying Mangaweka Mudstone and the Mangarere Formation (Naish & Kamp 1995; Journeaux et al. 1996). The Utiku Subgroup and Mangaweka Mudstone overlie the Tangahoe Mudstone in the sampled part of Turakina River section (Fig. 2) (McGuire

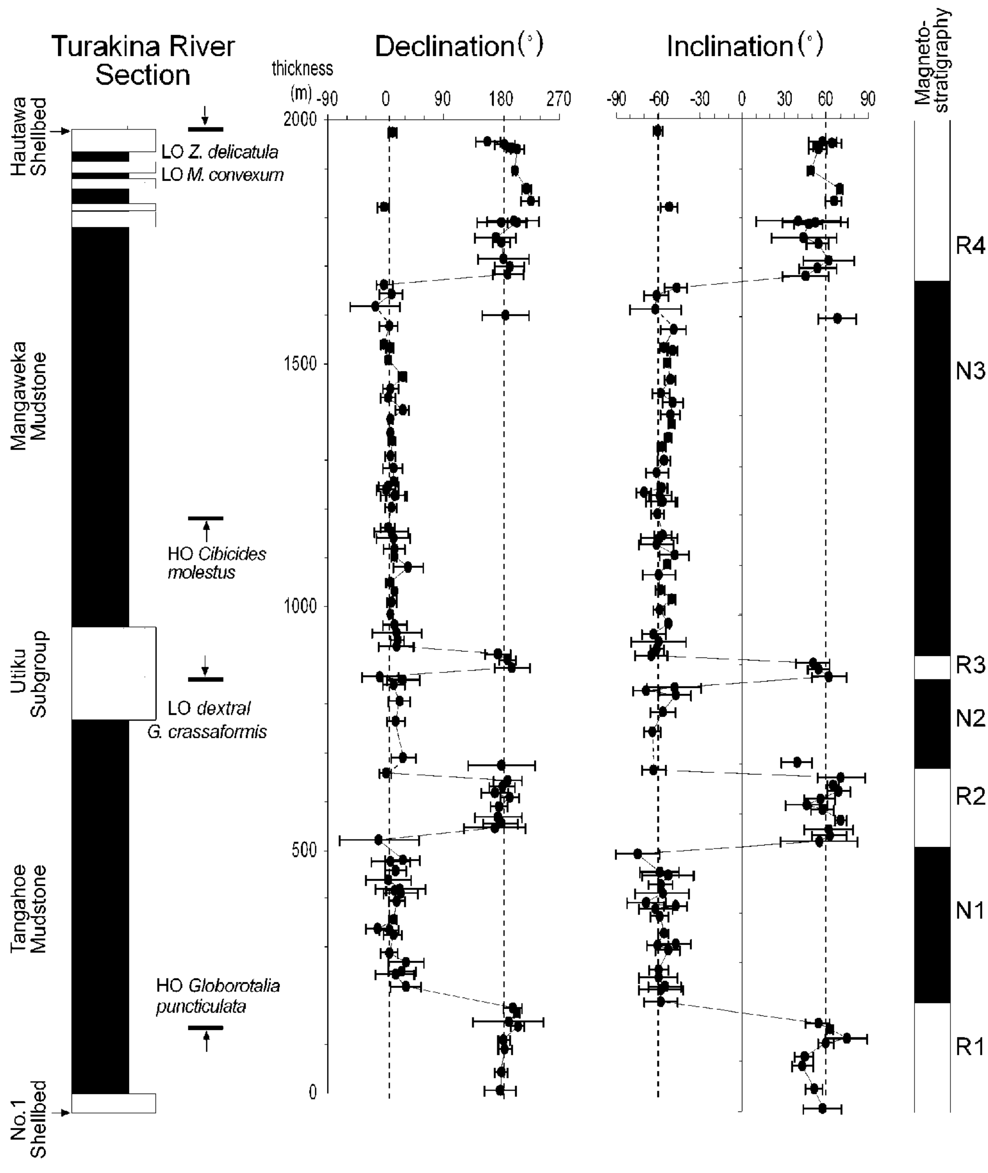


Fig. 2 Turakina River section. Biostratigraphic and lithological logs, declination and inclination of the mean characteristic component of remanence at each site, with alpha-95, and inferred magnetostratigraphy. Dashed lines show expected declination and inclination at the section for a geocentric axial dipole field allowing for drift of the Australian plate over the past 3 m.y. See Appendix for a listing of the palaeomagnetic data. Note, we use the HO (highest occurrence) and LO (lowest occurrence) notation of Cooper (2004) in defining the boundaries of taxa in this and subsequent figures.

1989). In the Wanganui River section, the Utiku Subgroup is not present, but the Tangahoe Mudstone contains five sandstone members (Jerusalem, Matahiwi, Koroniti, Ahurangi, and Atene Sandstone Members) (Hayton 1998). The Mangaweka Mudstone crops out higher in the section (McIntyre 2002).

PALAEOMAGNETIC RECORDS

Turakina River section

McGuire (1989) sampled in detail a 2000 m thick succession exposed in the banks of the Turakina River (Fig. 1) between Kaimatiri Road in the north and James Road in the south. NZMS 260 grid references of all sampling sites and site location maps for all sections are presented in the Appendix. This succession consists of 760 m of Tangahoe Mudstone, 200 m of the Utiku Subgroup, and 840 m of Mangaweka Mudstone. McGuire (1989) collected a minimum of three oriented cores from each of 98 sites, at an average stratigraphic interval of about 20 m. McGuire's uppermost site (97T) is some 1805 m stratigraphically above the "No. 1 Shellbed" and 1182 m below the Hautawa Shellbed (Fig. 2) (McIntyre 2002). Samples from sites H125–H133, collected by Wilson (1993), complete the sample sequence above the uppermost site of McGuire (1989).

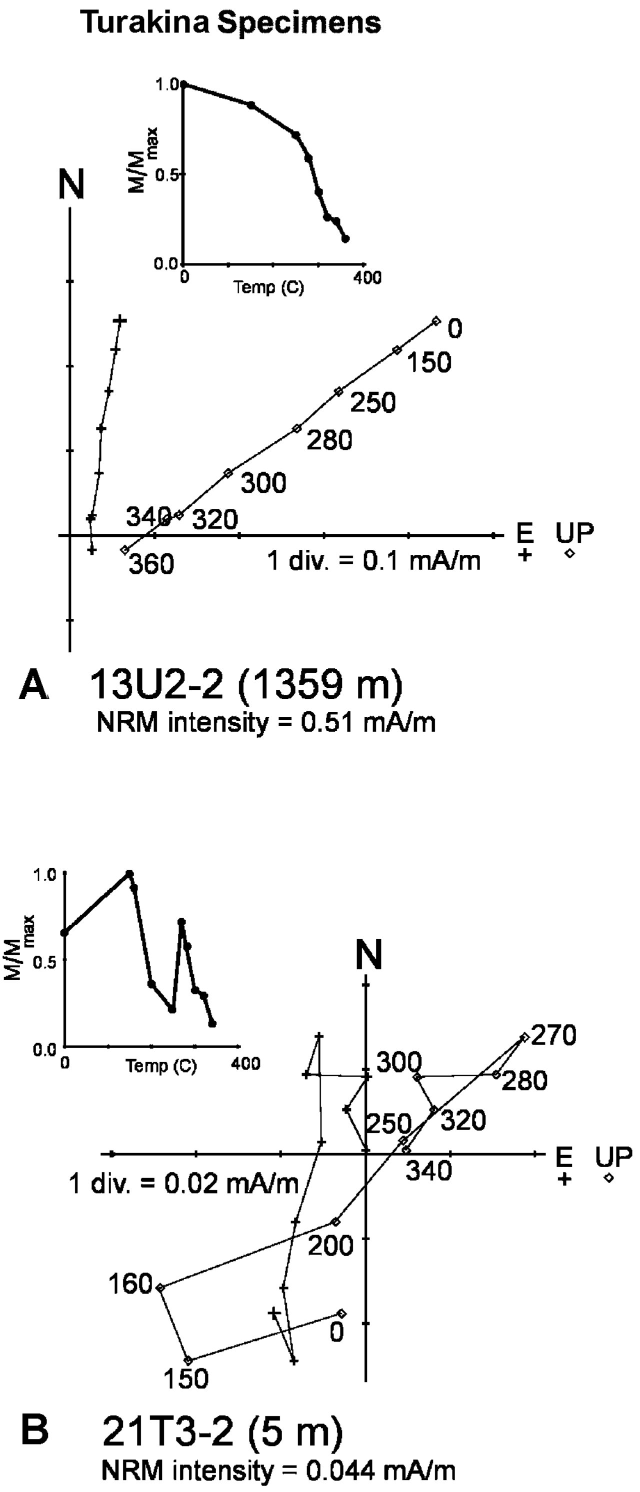
In general, at least two specimens from each sample were subjected to progressive thermal demagnetisation. Demagnetisation was halted when a change in the low-field magnetic susceptibility of a specimen indicated that thermally induced alteration to the magnetic mineralogy had occurred. This usually occurred at c. 300°C.

McGuire (1989) based his original interpretation of the demagnetisation data on the premise that the primary, detrital component of magnetisation was the highest blocking temperature component. He made significant use of great circles analysis (Halls 1976, 1978; McFadden & McElhinny 1988) to interpret data that had not reached a stable endpoint before thermal alteration occurred. The overall result of his analysis was a rather noisy, mixed polarity record that was difficult to correlate with the geomagnetic polarity timescale.

The demagnetisation data of McGuire (1989) have been completely re-interpreted in this study, based on the hypothesis that the NRM may have three components, of which the mid-blocking temperature component (c. 150–250°C) generally represents the primary magnetisation (Turner 2001). Demagnetisation data from two representative specimens are shown in Fig. 3. Specimen 13U2-2 carries a normal polarity magnetisation throughout the 360°C blocking temperature range covered. This probably represents the combination of a thermo-viscous component (ambient temperature to c. 150°C) and a stable primary component (c. 150 to >360°C). However, the fact that the demagnetisation vector does not trend to the origin of the plot indicates that there is an underlying, unresolved high blocking temperature component in this specimen, which is assumed to be of secondary origin. Specimen 21T3-2 has more complicated behaviour. From ambient temperature to 160°C, a normal polarity thermo-viscous component, close to the present day field direction, is removed. From 160 to 270°C a reversed polarity component is removed, but this is underlain by a well-resolved third component, which has normal polarity, and is held by grains with blocking temperatures above 270°C. This third component is interpreted as a secondary component carried by high stability authigenic grains. The reversed polarity component that unblocked between 160 and 270°C is taken to be the primary component, which has almost certainly lost some of its original intensity with growth of the high blocking temperature secondary component.

These two specimens are good examples of the range of observed demagnetisation behaviour. Both specimens show evidence of three components of magnetisation, but 21T3-2 is considerably more affected by the diagenetic secondary component, which is made all the more obvious as it is parallel to the low blocking temperature thermo-viscous component, while the intermediate primary magnetisation is in the opposite direction. Re-interpretation of the demagnetisation data under the assumption that the intermediate unblocking temperature component represents the primary magnetisation, results in the reversing of several of McGuire's original polarity interpretations and yields the magnetostratigraphy shown in Fig. 2.

Fig. 3 Progressive thermal demagnetisation data for representative specimens from the Turakina River section. Crosses show the horizontal component (N versus E) after each stage of demagnetisation, diamonds show the vertical N-S component (N versus upward) after each stage. Demagnetisation temperatures are indicated. Insets show the intensity of magnetisation remaining after each demagnetisation step.



The Turakina section is dominanted by normal polarity, which is consistent with the middle-Pliocene age, and clearly correlates with the normal-polarity, Gauss Chron of the geomagnetic polarity timescale (GPTS), as discussed below. The lowermost 150 m of the Tangahoe Mudstone is reversely magnetised. Two further intervals of reversed polarity occur between 540 and 675 m, in the upper part of the Tangahoe Mudstone, and between 860 and 910 m, in the upper part of the Utiku Formation. The main part of the Mangaweka Mudstone has normal polarity, with a single reversed polarity site (01U) at 1597 m, and a transition to reversed polarity between 1660 and 1685 m (sites 90T and 91T). The uppermost part of the studied section has reversed polarity, with the exception of single normal polarity sites at 1822 and 1975 m.

Rangitikei River section

The Rangitikei data presented here are mainly from the samples of Wilson (1993), (sites R135–R197) supplemented by sites sampled by McIntyre (2002, sites S140–S146) (Fig. 4 and the Appendix). The lower part of the Tangahoe Mudstone, also known as the Taihape Mudstone, is difficult to access in the Rangitikei Valley, as it crops out where the river passes through a narrow gorge. Therefore, only the uppermost 250 m of Tangahoe Mudstone was sampled. This part of the section is overlain by the Utiku Subgroup, which is much expanded here compared with the Turakina Valley, with a total thickness of about 350 m. Journeaux et al. (1996) identified four unconformity-bounded cyclothems within the Utiku Subgroup in the Rangitikei Valley. A c. 400 m thickness of the Mangaweka Mudstone lies between the Utiku Subgroup and the Mangarere Formation. On the basis of sediment textural analyses, Journeaux et al. (1996) described seven more sedimentary cycles within the Mangaweka Mudstone. They interpreted these to reflect cycling between an outer shelf environment and an upper bathyal one. The Hautawa Shellbed lies above the Mangarere Formation, in what Journeaux et al. (1996) took to be a single sedimentary cycle. The Hautawa Shellbed marks the top of the section discussed here.

Palaeomagnetic data from 52 sites, covering a total stratigraphic thickness of 1250 m, are presented in Fig. 4. The sampling interval is variable, and is particularly sparse in the coarser lithologies of the Te Rimu Sandstone and the Utiku Subgroup. There is some disagreement in the stratigraphic ordering of some sites between Wilson (1993) and Journeaux et al. (1996) and Naish et al. (1998), who report the data. This has been overcome by the sampling undertaken by McIntyre (2002), and only those sites for which there is no ambiguity have been used here.

In general the NRM of the Rangitikei sediments seems to be less affected by post-depositional diagenesis than either the Turakina or Wanganui Valley sediments. Progressive demagnetisation data for typical specimens from the Rangitikei River section are shown in Fig. 5A–C. Specimens S140A-2 and S142A-2 are typical of the majority of specimens, which carry a normal polarity thermo-viscous component underlain by a normal or a reversed polarity primary magnetisation, respectively, and only minor high blocking temperature secondary components. Specimen S146C-2 is a rare example of a specimen carrying three clearly defined components, with normal, reversed and normal polarities, respectively. The reversed polarity, intermediate blocking temperature component is interpreted as the remnant of the primary magnetisation, although it has been significantly weakened with the growth of the high blocking temperature secondary component. The site-mean palaeomagnetic directions and polarities presented in Fig. 4, and listed in the Appendix, are generally consistent with those of Wilson (1993). Most of the section records normal polarity. Reversed polarity intervals occur in the uppermost c. 120 m of the Tangahoe Mudstone, and between c. 500 and 600 m, in the upper part of the Utiku Subgroup. A single normal polarity site occurs in the middle of the lower of these two intervals, and its significance is still uncertain. The upper of

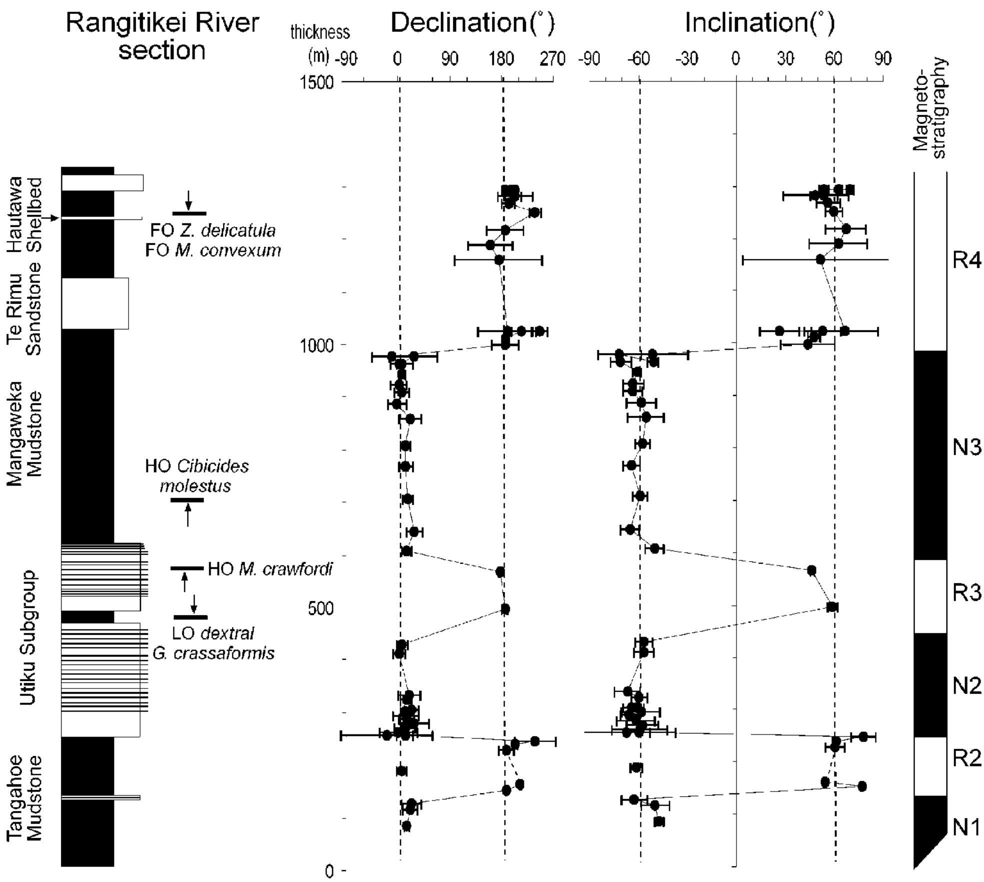


Fig. 4 Rangitikei River section. Biostratigraphic and lithological logs, declination and inclination of the mean characteristic component of remanence at each site, with alpha-95, and inferred magnetostratigraphy. Dashed lines show expected declination and inclination at the section for a geocentric axial dipole field allowing for drift of the Australian plate over the past 3 m.y. See Appendix for a listing of the palaeomagnetic data.

these two reversed polarity intervals is represented by only two sites. It is, therefore, possible that it is not a single magnetozone. The lower part of the Mangaweka Mudstone has normal polarity, with a normal to reversed polarity transition about 50 m below the Te Rimu Sandstone. The remaining, uppermost part of the section has reversed polarity.

Wanganui River section

Sample sites and palaeomagnetic results from the stratigraphically equivalent section in the Wanganui River valley are given in Fig. 6 and the Appendix. Data are shown from 30 new sites spanning a 2200 m thick interval exposed between Jerusalem and Parikino (see Appendix). The average sampling interval is greater and the overall resolution, therefore, is not as good as in either of the other sections. In the stratigraphic interval from 4100 to 4700 m, it was possible to sample fresh outcrop that shows little sign of weathering or iron staining. The NRM in this interval was relatively intense ($10^{-4} - 5 \times 10^{-3}$ Am^{-1}) and stable, and the primary

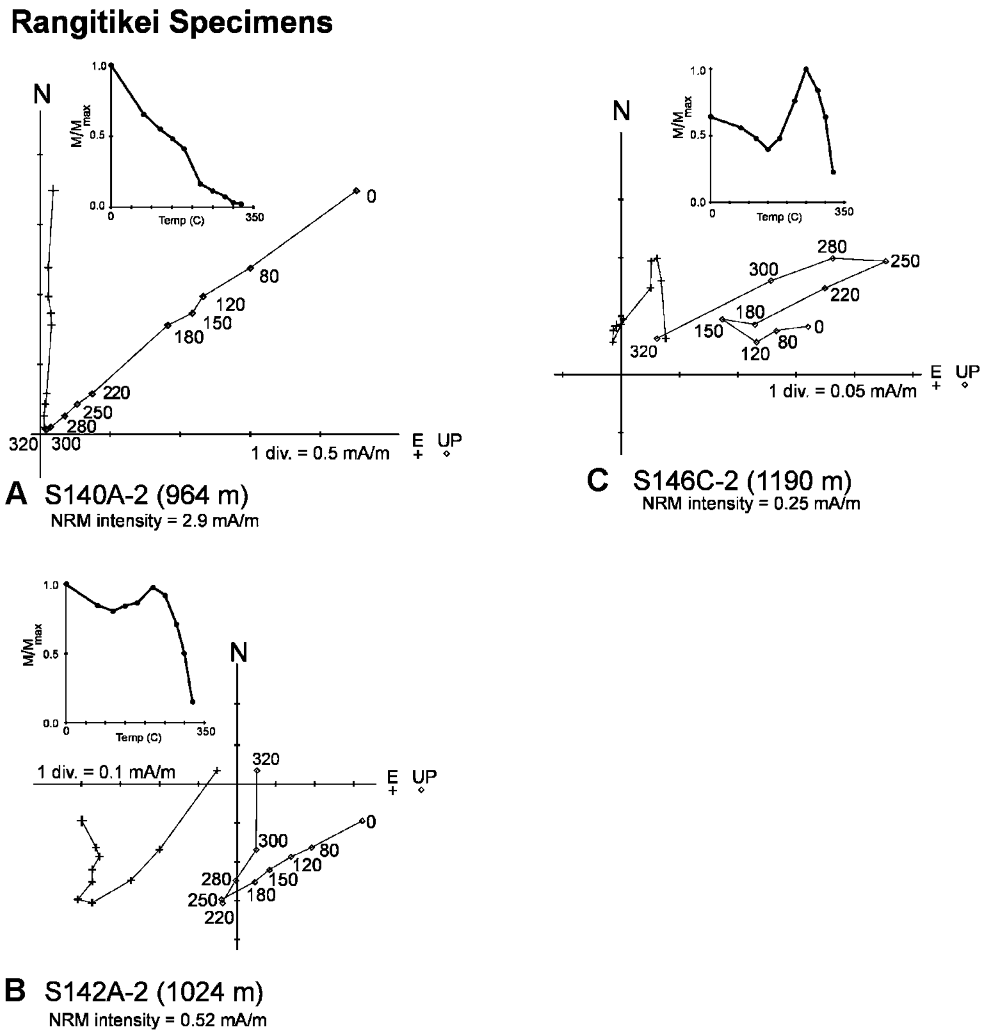


Fig. 5 Progressive thermal demagnetisation data for representative specimens from the Rangitikei River section. Crosses show the horizontal component (N versus E) after each stage of demagnetisation, diamonds show the vertical N-S component (N versus upward) after each stage. Demagnetisation temperatures are indicated. Insets show the intensity of magnetisation remaining after each demagnetisation step.

component was readily identified and determined by principal component analysis (Fig. 7A–D). However, above and below this interval, it was harder to find good unweathered exposure, and iron mobility was particularly evident in the Mangaweka Mudstone. Samples from these parts of the section were generally weaker (NRM intensities $<5 \times 10^{-4} Am^{-1}$) and frequently displayed three components of magnetisation, consistent with the dissolution of the primary remanence carrying mineral and a reduction of its contribution to the NRM. The intermediate blocking temperature component, which is interpreted as the remnant of the primary magnetisation, was sometimes difficult to isolate. At a number of sites we give only the polarity, as we could not estimate the primary direction with reasonable certainty. Despite such reservations, the

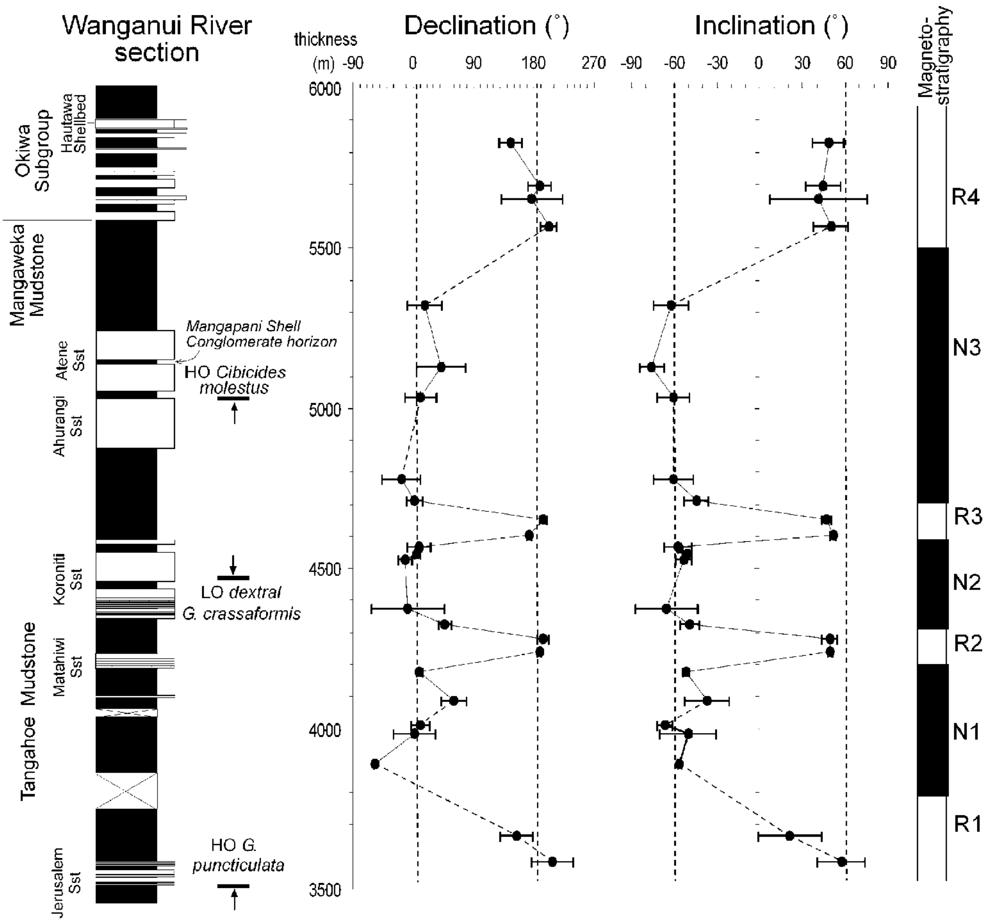


Fig. 6 Wanganui River section. Biostratigraphic and lithological logs, declination and inclination of the mean characteristic component of remanence at each site, with alpha-95, and inferred magnetostratigraphy. Dashed lines show expected declination and inclination at the section for a geocentric axial dipole field allowing for drift of the Australian plate over the past 3 m.y. See Appendix for a listing of the palaeomagnetic data.

sequence of polarity intervals obtained from the Wanganui Valley section (Fig. 6) is unmistakably similar to those from the Turakina and Rangitikei Valley sections (Fig. 2, 4).

The lowermost part of the section has reversed polarity, with a R-N transition occurring in a stratigraphic interval of over 100 m thickness covered by slumps, some 150 m above the Jerusalem Sandstone Member (Fig. 6). Two well resolved reversed intervals, each of about 100 m thickness, occur between the Matahiwi Sandstone Member and just above the top of the Koroniti Sandstone Member. A N-R transition occurs about 400 m below the Hautawa Shellbed. Data from a single site (W113) of Wilson (1993) have been re-analysed and added at 5557 m (Appendix).

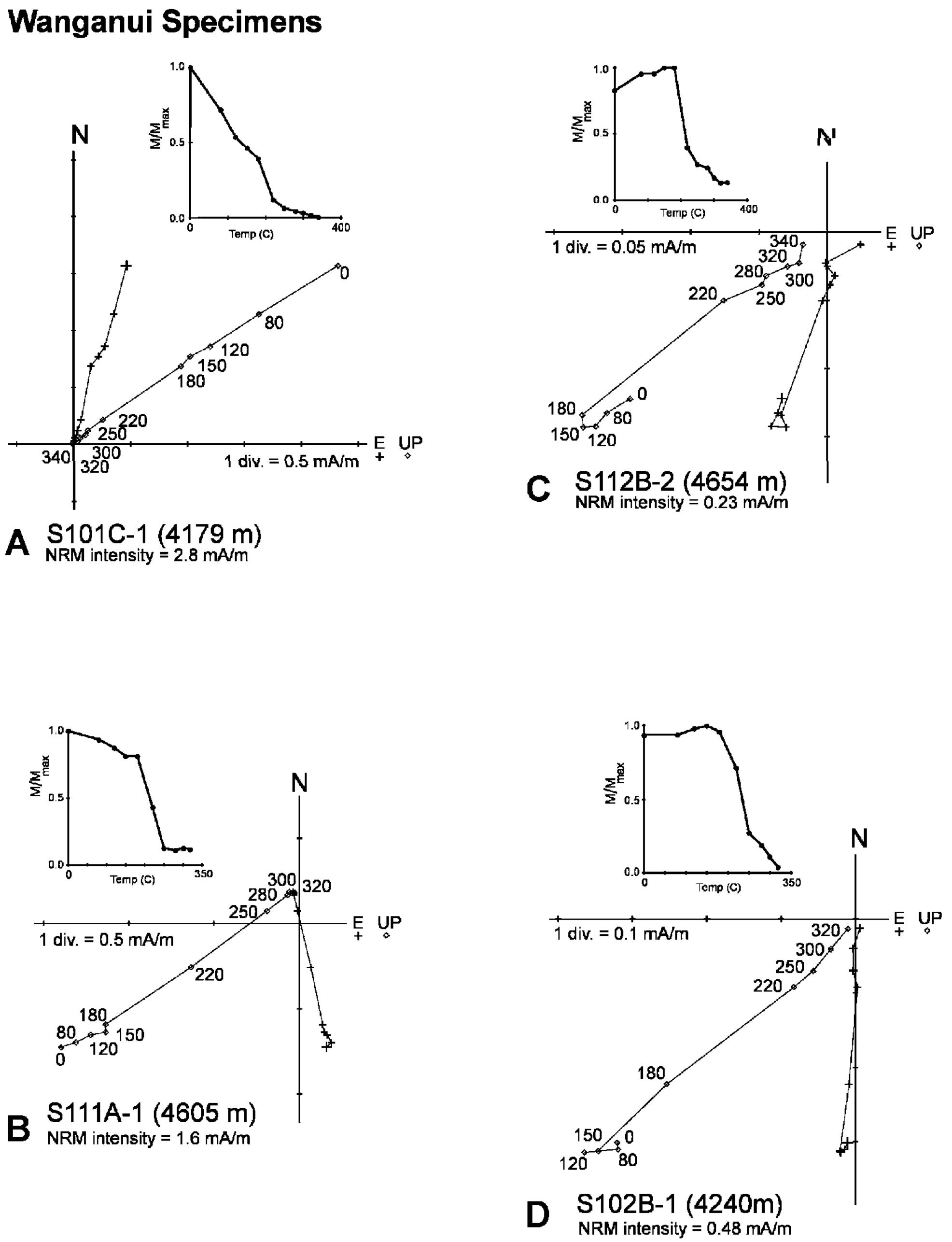


Fig. 7 Progressive thermal demagnetisation data for representative specimens from the Wanganui River section. Crosses show the horizontal component (N versus E) after each stage of demagnetisation, diamonds show the vertical N-S component (N versus upward) after each stage. Demagnetisation temperatures are indicated. Insets show the intensity of magnetisation remaining after each demagnetisation step.

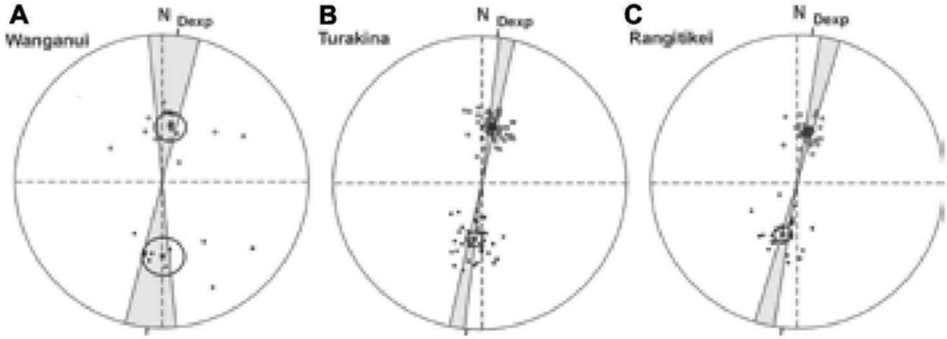


Fig. 8 Equal area projections showing the site mean directions for **A**, Wanganui; **B**, Turakina; and **C**, Rangitikei sections. Normal polarity directions are shown as grey dots, and reversed polarity directions as black dots. The mean normal and reversed polarity directions for each section are shown as grey and black stars, with corresponding cones of 95% confidence. Dexp is the expected declination for 3 Ma at each section, and the grey sectors indicate the overall mean declinations for each section with their 95% confidence limits. The declination anomaly increases from west (Wanganui) to east (Rangitikei). The data plotted here are summarised in Table 1.

Table 1 Summary of mean palaeomagnetic directions and declination anomalies for the Wanganui, Turakina, and Rangitkei River sections.

		Declination (°E)	Inclination (°)	Alpha-95 (°)	*N*
Wanganui	Mean normal direction	8.9	–59.1	8.2	16
	Mean reversed direction	178.9	47.0	11.1	10
	Overall mean direction	4.7	–54.9	6.8	26
	Expected declination	5.8	–60.8		
	Declination anomaly	–1.1 ± 10.0			
Turakina	Mean normal direction	10.9	–57.7	1.8	65
	Mean reversed direction	187.7	58.4	4.3	36
	Overall mean direction	9.7	–57.7	2.0	101
	Expected declination	5.9	–60.8		
	Declination anomaly	3.8 ± 3.0			
Rangitikei	Mean normal direction	11.3	–60.4	2.5	31
	Mean reversed direction	195.5	59.7	4.9	22
	Overall mean direction	13.0	–60.1	2.6	53
	Expected declination	5.9	–60.9		
	Declination anomaly	7.1 ± 3.9			

DISCUSSION

Section mean directions and field tests

The mean directions of all Wanganui, Turakina, and Rangitikei sites are plotted on equal area stereographic projections in Fig. 8. Corrections have been applied for bedding, which dips between 3 and 6° towards the south or south-east (strikes 045–115°). Overall mean directions and statistics are also given for each section (Table 1).

For each section, the mean normal polarity direction and the mean reversed polarity direction are antipodal at the 95% level of confidence, indicating that secondary components of magnetisation have probably been effectively removed.

Wanganui Basin lies on the Australian plate, west of the Hikurangi Margin along which the Pacific plate subducts beneath the Australian plate. Over the past 65 m.y. the Australian plate has moved steadily northwards, producing a north–south trending apparent polar wander path (Veevers & Li 1991). The 3 Ma (south) palaeomagnetic pole lies at latitude 85°S and longitude 111°E, which, assuming that the time averaged geomagnetic field approximates an axial geocentric dipole, yields expected mean palaeomagnetic directions for our Wanganui Basin locations of 5.8–5.9° declination, and –60.8 to –60.9° inclination. The overall mean directions for our sections (calculated by averaging each normal polarity direction and the inverse of each reversed polarity direction) have inclinations that are consistent with the mean directions. For the Wanganui Valley sites the declination of the mean direction is also consistent with the expected declination, although for the Turakina Valley sites, there is a small clockwise declination anomaly of 3.8 ± 3.0°, and for the Rangitikei Valley sites, there is an anomaly of 7.1 ± 3.9°. These anomalies probably reflect vertical axis rotations having a tectonic origin associated with deformation of the leading edge of the Australian plate within the Hikurangi margin.

Correlation with the Geomagnetic Polarity Timescale

Our correlation of the three middle Pliocene Wanganui Basin magnetostratigraphic records with the GPTS is shown in Fig. 9. The correlations between the sections are corroborated by the biostratigraphic datums shown in Fig. 2, 4, 6. To facilitate discussion, the reversed polarity intervals have been labelled R1–R4 from the bottom to the top on each record, and the intervening normal polarity intervals are labelled N1–N3. The highest occurrence (HO), using the boundary defining event notation of Cooper (2004) of *G. puncticulata* occurs in reversed polarity interval R1, near the base of each of the Turakina and Wanganui sections (Hayton 1998). The lowest occurrence (LO) (Cooper 2004) of dextral *G. crassaformis*, the datum used by Hornibrook (1981) and Morgans et al. (1996) to locate the base of the Mangapanian in deep water sediments, occurs within the Utiku Subgroup, near the base of reversed polarity interval R3 in the Rangitikei and Turakina sections, and in the Koroniti Sandstone, just below R3 in the Wanganui section (McIntyre 2002). In all three sections the HO of *Cibicides molestus* occurs above R3 in the long normal polarity interval N3 (Hayton 1998; Kamp et al. 1998). Finally, the LO of *Z. delicatula*, along with that of *M. convexum*, lies within the Hautawa Shellbed, in the uppermost reversed polarity interval R4, and corresponds with the base of the Nukumaruan Stage (Beu 1990; Morgans et al. 1996).

Clearly, the biostratigraphic datums are consistent with the magnetostratigraphic correlation of the three sections as proposed in Fig. 9, which can be regarded as a single coherent middle Pliocene magnetostratigraphy for the Wanganui Basin. Correlation of this magnetostratigraphy with the geomagnetic polarity reversal timescale (GPTS) provides numerical ages, enabling the middle to late Pliocene Wanganui Basin succession to be placed in the international chronostratigraphic framework.

Radiometric age estimates on tephra located stratigraphically above Hautawa Shellbed (Pillans et al. 1994; Naish et al. 1998), together with the conclusions of previous palaeomagnetic studies (Seward et al. 1986; Wilson 1993), imply that the uppermost normal to reversed polarity transition (N3–R4) correlates with the Gauss-Matuyama transition (C2An-C2r), which has an age of 2.58 Ma (Berggren et al. 1995; Cande & Kent 1995). The Gauss Chron (C2An) spans 1 m.y., and includes two reversed polarity subchrons: the Mammoth Subchron or C2An.2r (3.33–3.22 Ma), and the Kaena Subchron or C2An.1r (3.11–3.04 Ma). All previous studies (Wilson 1993; Journeaux et al. 1996; Carter & Naish 1998) have associated both the Kaena and Mammoth Subchrons with interval R3 within the Utiku Group, and have correlated the underlying R2–N2 transition with the Gilbert/Gauss (C2Ar-C2An) transition. We differ. We see

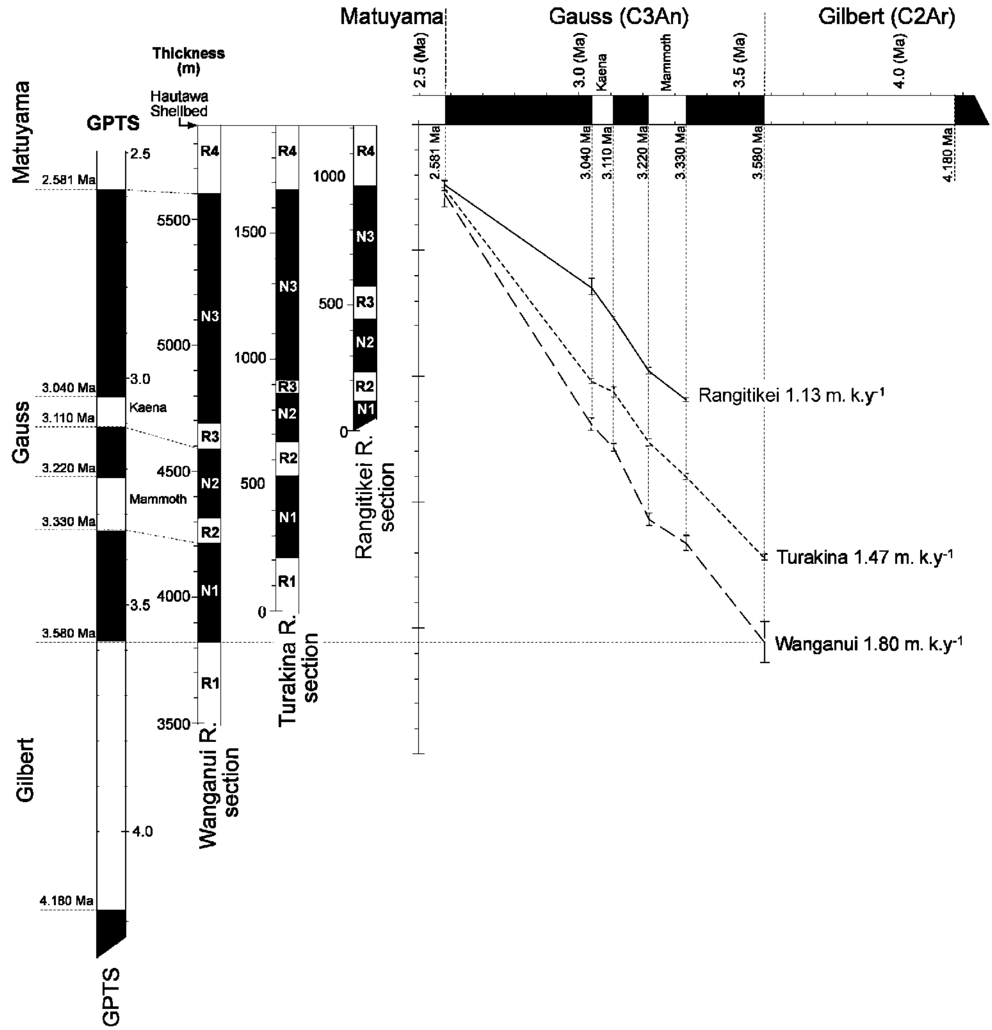


Fig. 9 Correlation of the Wanganui, Turakina, and Rangitikei River section magnetostratigraphic records to the Geomagnetic Polarity Timescale (GPTS) of Cande & Kent (1995). The magnetostratigraphies of Fig. 2, 4, 6 are aligned at the Hautawa Shellbed, and plotted on the same scales. Note, however, that the zero stratigraphic elevations are particular to each section. Correlation to the GPTS is indicated on the left, and inferred accumulation curves are shown on the right of the figure, with average accumulation rate values indicated.

no evidence of normal polarity magnetisations within interval R3, particularly in the Turakina Valley section where this interval is best resolved. Furthermore, all three records show that R2 is also a well-defined, relatively short-lived reversed polarity interval. We suggest that R2 is too short to be the uppermost reversed polarity interval of the Gilbert Chron (C2Ar), which has a duration of 0.6 m.y., and suggest that it is far more likely to represent the lower reversed polarity interval of the Gauss Chron, that is, the Mammoth Subchron. Furthermore, in both the Turakina and Wanganui River sections, where the whole of the Tangahoe Mudstone has been sampled, interval N1 spans 300–400 m, which is, therefore, more likely to represent the 0.25 m.y. long normal polarity interval at the base of the Gauss Chron than the uppermost normal polarity subchron of the Gilbert, the Cochiti Subchron, which had a duration of only

0.11 m.y. Therefore, we correlate interval N1 with the lowermost part of the Gauss Chron, and the R1–N1 transition with the Gilbert/Gauss (C2Ar-C2An) transition at 3.58 Ma, as shown in Fig. 9.

Implications for Wanganui Basin middle Pliocene chronostratigraphy

Our chronostratigraphic interpretation allows the ages of up to six chron and subchron boundaries to be transferred from the GPTS to the Wanganui Basin succession. The resulting timescale also allows the observed cyclothems to be correlated with more confidence with the global OIS scheme. It also requires significant revision of all previous middle Pliocene chronostratigraphies for the Wanganui Basin, which have been based on earlier interpretations of palaeomagnetic results from the Rangitikei River succession alone.

Our revised middle to late Pliocene integrated chronostratigraphy for the Wanganui Basin succession is shown in Fig. 10. The Rangitikei River section has become the preferred middle to late Pliocene section for correlation with the OIS, because of the recognition of four cyclic sequences in the shelfal Utiku Group, and of a further 12 sequences in the overlying Mangaweka Mudstone. The stratigraphy, sedimentology, foraminiferal palaeoecology and sequence stratigraphy of these units have been described and successively revised by Journeaux et al. (1996), Kamp et al. (1998), and McIntyre (2002), upon which much of the detail in Fig. 10 is based. The lowermost part of the Tangahoe Mudstone has never been sampled in the Rangitikei River, because of difficult access. The Turakina and Wanganui records are crucial in determining the position of the Gilbert/Gauss transition, and therefore the lowermost part of the Wanganui River magnetostratigraphy is also shown in Fig. 10.

In Fig. 10 we show the vertical stratigraphic extent of each of the cyclic sequences, labelled as M1–M18, alongside the graphic log. Based on the palaeomagnetic transitions bounding the Gauss Chron and the subchrons within it, we show a new correlation of the sequences with the OIS record, from ODP Site 846 (Shackleton et al. 1995). This correlation is substantially different from those shown in all previous publications (Journeaux et al. 1996; Carter & Naish 1998; Naish et al. 1998; Kamp et al. 1998) because of the downward redefinition of the Mammoth Subchron in our study. A prominent sandstone unit within the upper part of the Tangahoe Mudstone is correlated with the inferred sea level fall from OIS MG3 into MG2. However, the slightly younger ^{18}O-enriched stage M2 does not appear to be expressed by a coarsening in sediment texture. Stages KM6 and KM4 are correlated with the transition from Tangahoe Mudstone into Utiku Subgroup, and the four sequences (M3–M6) within the Utiku Subgroup are correlated with successive OIS KM2–G20 (Fig. 10). Three coarsening upward sequences within the lower part of the Mangaweka Mudstone (M7–M9) are correlated with G19–G18, G17–G16, and G15–G14. The main part of the Mangaweka Mudstone is made up of eight sedimentary cycles (M10–M17) characterised by coarsening and fining in sediment texture (Journeaux et al. 1996; McIntyre 2002), corresponding to OIS G13–G12, G11–G10, G9–G8, G7–G6, G5–G4, G3–G2, G1–104, and 103–102. The sharp contact between the Mangaweka Mudstone and Mangarere Formation (Naish & Kamp 1995) is associated with OIS 101–100 (Naish & Kamp 1997).

The one-to-one correlation of textural sequences in the Utiku Group and Mangaweka Mudstone with the OIS couplets (which reflect changes in ocean palaeotemperature and ice volume) through most of the Gauss Chron suggests a common driving mechanism. There are 15–16 depositional sequences in the 625 k.y. interval between the top of the Mammoth Subchron and the Gauss-Matuyama boundary, which averages 39–41 k.y. per cycle and this duration is close to the 41 k.y. periodicity of Earth's orbital obliquity (axial tilt), which is considered to determine the seasonal distribution of insolation on Earth (Laskar 1990).

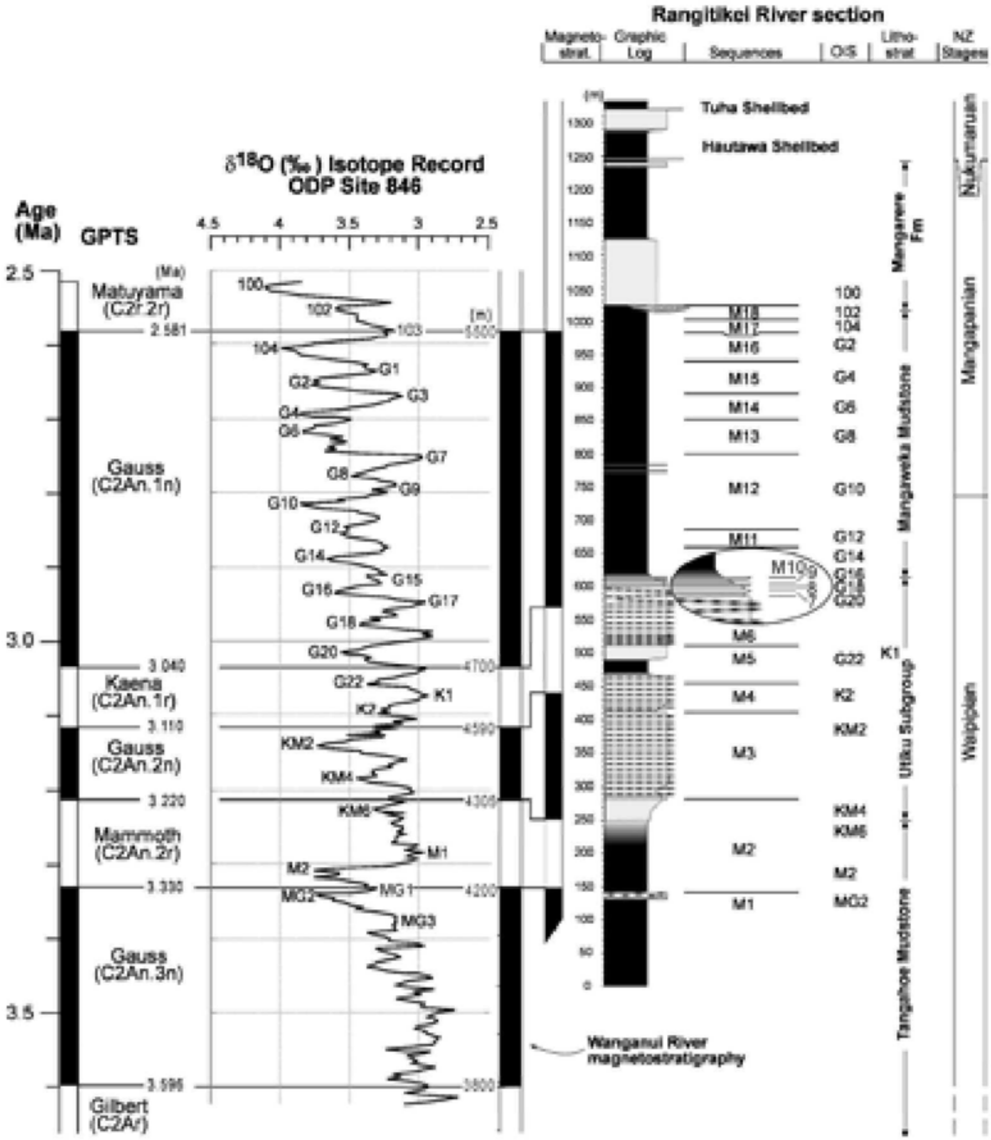


Fig. 10 Middle Pliocene chronology of the Rangitikei River and Wanganui River sections including graphic log, the stratigraphic extent of sequences and their correlation to the Oxygen Isotope Stages (OIS) for ODP Site 846 (Shackleton et al. 1995), New Zealand Stages, magnetostratigraphy and its correlation with the geomagnetic polarity timescale (Cande & Kent 1995).

The Wanganui Basin sequences are driven by sea level changes that are inferred to originate from orbitally forced climate changes. With our new chronology, sequences M3–M6, which were originally identified by Journeaux et al. (1996) in the Utiku Subgroup, have the same 41 k.y. duration as the succeeding cycles in the Mangaweka Mudstone. Previously, the Utiku cycles were thought to have a longer periodicity of c. 135 k.y., which is not one of the periodicities associated with the orbital insolation model.

Sediment accumulation rates

Geological mapping and section description of the northern parts of Wanganui Basin have shown that the thickest parts of the middle and late Pliocene succession (base of the Tangahoe Mudstone to the Hautawa Shellbed) occur between the Wanganui (2300 m) and Turakina (1840 m) River sections (Feldmeyer et al. 1943; McGuire 1989; Hayton 1998; McIntyre 2002). The basin stratigraphy thins away from the Wanganui–Turakina Valleys toward the coastal section in the west (2010 m; Kamp et al. 1999) and toward the Rangitikei section in the east (1640 m; Journeaux et al. 1996; Kamp et al. 1998). The stratigraphic thicknesses are based on the measurement of shallow south to south-westward dipping (c. 4°) successions that crop out in river valleys extending over 25–35 km across the strike of the beds. As such, they are unavoidably composited sections, and, given the southward migration of depocentres through the Pliocene and Pleistocene (Fleming 1953), we have probably overestimated the true stratigraphic thicknesses of units at particular locations.

The whole Tangahoe Mudstone and Mangaweka Mudstone succession spans a period from about 3.8 Ma (Upper Gilbert) to about 2.45 Ma (Lower Matuyama), a total of 1.35 m.y. In this part of the Wanganui River section, the mean sediment accumulation rate is estimated to have been c. 1.80 m/k.y. In the Turakina section the sediment accumulation rate was c. 1.47 m/k.y., and in the Rangitikei section, the mean rate from the base of the Mammoth Subchron to the Hautawa Shellbed was c. 1.13 m/k.y.

Sediment accumulation rates of the order of 1 m/k.y. also appear to be typical of Neogene basins in Hawke's Bay and Wairarapa (Field & Uruski 1997). These are high rates of sediment accumulation and require comparable rates of basin subsidence and sediment supply. Through the late Miocene and Pliocene the sediment was chiefly sourced from erosion of the continent-continent collision zone within the Southern Alps of South Island (Kamp et al. 1989). Sediment was transported into Wanganui Basin by northward flowing river systems. From analysis of the sedimentary successions in Wanganui and King Country Basins, it is clear that at times the rate of sediment supply exceeded the rate of basin subsidence (e.g., late Miocene-early Pliocene), and that at other times the opposite was the case (Kamp et al. 2004). The upper Opoitian–Waipipian was an interval of marked subsidence, which led to the formation of the main depocentre of Wanganui Basin, as suggested by a marked increase in palaeobathymetry from inner shelf to upper bathyal depths. This allowed the Tangahoe Mudstone to accumulate in a continental slope environment as slope sets, followed by the progradation of a shelf succession (e.g., Okiwa Subgroup and younger formations; McIntyre & Kamp 1998). The high rates of sediment accumulation through the Tangahoe Mudstone largely represent the expanded sedimentation associated with northward progradation of large scale slope clinoforms, analogous to those of the Giant Foresets Formation beneath the modern shelf and slope of Taranaki Basin (Beggs 1990; Hansen & Kamp 2004).

Implications for the definition of local Pliocene Stages

New Zealand stratigraphic stages have traditionally been defined in terms of local palaeontological content (Cooper 2004). Carter & Naish (1998), on the other hand, made a case for abandoning biostratigraphic definitions of the local Pliocene-Pleistocene stages in favour of numerical age datums based on magnetostratigraphy and correlation with the GPTS. Beu (2001) defended the need for local stages, defined by the most accessible objectively determined means. He proposed new definitions for the stage-base boundaries within the Pliocene and Pleistocene, based on visible markers at a standard section and point (SSP), with biostratigraphic proxies to aid in their location at other localities (Beu 2001; Cooper 2004).

Litho-, bio- and magnetostratigraphy all have important roles to play in the construction of a timescale, with initial stratigraphic ordering and classification being primarily based on visible and readily determined methods such as litho- and biostratigraphy, while age assignment and alignment with international timescales must rely on numerical methods such as magnetostratigraphy and isotopic age estimation, notably on tephra.

The SSP defining the base of the Nukumaruan Stage is the base of the Hautawa Shellbed in the section on Old Hautawa Road, close to the Rangitikei River section, which corresponds to the LO of *Zygochlamys delicatula* (Beu 2001; Cooper 2004). This stage boundary occurs significantly above the Gauss-Matuyama transition (Fig. 9, 10), which Carter & Naish (1998) suggested as the position of their redefined base of the Nukumaruan Stage. Upward extrapolation from the Gauss-Matuyama transition of the mean sedimentation rates for all three sections presented here would imply an age for the base of the Nukumaruan Stage of 2.30–2.44 Ma.

The base of the Mangapanian Stage is defined as the base of the Mangapani Shell Conglomerate in Mangapunipuni Stream, Waitotara Valley (Fleming 1953; Beu 2001; Cooper 2004). The Mangapani Shell Conglomerate has been physically mapped into the Wanganui Valley (Fig. 6) by McIntyre (2002), where he correlated it, based on its cyclostratigraphic position and the magnetostratigraphy presented here, with the transition from the middle of OIS G10 to the early part of G9. From the interpolated age of the middle of OIS G10 (Shackleton et al. 1995; Lourens et al. 1996), the base of the Mangapanian Stage was assigned an age of 2.8 ± 0.1 Ma by McIntyre (2002). The HO of the benthic foraminifer *C. molestus* (Collen 1972; Hornibrook et al. 1989) occurs about 90 m lower in the Wanganui River section (Hayton 1998), which correlates with OIS G12 (McIntyre 2002). In the Rangitikei River section the HO of *C. molestus* occurs at about 690 m in the base of cycle M12 of the Mangaweka Mudstone, which we follow McIntyre (2002) in correlating with OIS G10 (Fig. 10). The HO of *C. molestus* is more precisely located in the Rangitikei River section than in the Wanganui River section because of the more continuous exposure and opportunity to collect much more closely spaced fresh blue-grey mudstone samples. The Rangitikei samples from which the HO of *C. molestus* was determined were from Journeaux et al. (1996) and the location of the refined position of this datum (Fig. 4) follows the re-examination by M. P. Crundwell of the foraminiferal slides prepared by Journeaux et al. (1996), as reported in McIntyre (2002). The HO in the Rangitikei River section of the mollusc *M. crawfordi*, which, in the past, has also been used as a proxy for the base of the Mangapanian Stage, lies at a lower stratigraphic level (Fig. 4), but this is probably facies controlled due to the marked increase in bathymetry (Kamp et al. 1998) between the Utiku Group shelfal sandstone and the upper bathyal Mangaweka Mudstone.

Beu (2001) noted that a SSP for the base of the Waipipian has yet to be located in Wanganui Basin. He suggested that the stage base might be recognised by the HO of *Towaipecton ongleyi* in shallow water facies. It is unlikely, however, that neritic facies of appropriate age exist in on-land sections in Wanganui Basin because upper bathyal Tangahoe Mudstone accumulated during the late Opoitian and early Waipipian (Hayton 1998; Kamp et al. 2004). Cooper (2004) suggested an alternative definition based on the HO of the nannofossil *Reticulofenestra pseudoumbilica*. No systematic search for this datum has been undertaken in Wanganui Basin, but at ODP Site 1123 the HO of *Reticulofenestra pseudoumbilica* is closely associated with the Gilbert-Gauss transition. It is possible, given the upper bathyal facies of the Tangahoe Mudstone near the expected base of the Waipipian in Wanganui Basin, that the HO of *Reticulofenestra pseudoumbilica* may be located through further work. Location of this nannofossil in either the Turakina or Wanganui river sections in the context of the magnetostratigraphy reported here may provide a test of its synchroneity between ODP Site 1123 and Wanganui Basin.

Hoskins & McGuire (1990) placed the base of the Waipipian Stage in the Turakina River section at their site 17U (394 m), which is between fossil record sites T21f61 (387 m, Opoitian based on HO *Cibicides finlayi* Gibson) and T21f62 (401 m, Waipipian on presence of *Cibicides molestus*). According to the Cooper (2004) criterion for the definition of the base of the

Waipipian Stage, the Hoskins & McGuire (1990) placement of the boundary in the Turakina River section is about 200 m too high.

Carter & Naish (1998) placed the base of the Waipipian Stage within Taihape Mudstone in the Rangitikei River section, based on prior (Naish et al. 1998) placement of the Gauss-Gilbert boundary. We have shown here that the Gauss-Gilbert boundary is stratigraphically below the whole of the Rangitikei River section sampled for palaeomagnetic analysis (Fig. 4, 9), and, therefore, must be below the stratigraphic position assumed by Carter & Naish (1998). We anticipate that the base of the Waipipian Stage will lie near the Gilbert-Gauss transition (3.58 Ma); that is, at c. 200 m in the Turakina River section (Fig. 2), and at c. 3800 m in the Wanganui River section (Fig. 6), but demonstration of this awaits further biostratigraphic analysis.

The role of palaeomagnetism in New Zealand chronostratigraphy

Palaeomagnetism is a powerful geophysical technique, and correlation of a robust, replicated magnetostratigraphy with the GPTS is clearly an excellent and reliable way to assign numerical ages to a sedimentary succession. In this study, we establish the integrity of our magnetostratigraphy by correlation of three sequences in the Wanganui Basin, a correlation that is independently corroborated by biostratigraphic data. However, as described here and elsewhere (Roberts & Pillans 1993; Roberts & Turner 1993; Wilson & Roberts 1999; Turner 2001) the weak, multi-component nature of the NRM of Wanganui Basin and other New Zealand Miocene-Pleistocene sediments requires careful, usually time consuming, analysis and interpretation. The nature of the secondary components of magnetisation frequently carried by these sediments is still incompletely understood (Turner 2001) and often it is difficult, and sometimes impossible, to isolate and determine the direction of the primary detrital component with confidence.

We agree with Beu (2001) in his assertion that litho- and biostratigraphy provide a quicker, more reliable means of local classification. It is when the local (New Zealand) framework needs to be aligned with the international timescale that careful, reliable magnetostratigraphy provides the crucial link to the numerical ages of the GPTS.

Morgans et al. (1996) presented a Cenozoic timescale for New Zealand, in which they assigned ages from the GPTS to the local biostratigraphically defined framework. They employed reliability criteria, based on earlier work by Edwards et al. (1988) that included a letter based on the integrity of the bio-event and a numeral based on whether the chron boundary was identified directly or by extrapolation, in New Zealand or elsewhere. We suggest the need for further criteria that reflect the reliability of the palaeomagnetic identification of chron boundaries:

1. A sufficiently long interval should be sampled to include at least two, preferably three, geomagnetic polarity transitions.
2. That detailed stepwise thermal demagnetisation should be carried out to enable confident identification of the primary component of magnetisation. This may be complemented by alternating field (AF) demagnetisation, although in our experience AF demagnetisation is not usually successful in separating the various components of magnetisation.
3. That the inferred primary or characteristic component of magnetisation must be reproducible. Directions should be obtained from at least three specimens per site, and these should be sufficiently well grouped to yield a reliable polarity. In this study we have followed tradition in calculating and quoting alpha-95, the semi-angle of the cone of 95% confidence in the calculated mean (Fig. 2, 4, 6; Appendix). Technically speaking, use of this statistic is valid only if the measured directions form a representative sample of a Fisher-distributed population (Fisher 1953). The validity is questionable for small ($N \leq 6$) numbers of direction estimates (Butler 1992), and we suggest that a more direct measure of scatter, such as

the mean angular deviation from the average direction (δ), would, in future, be preferable. The calculation of δ (= $\cos^{-1}(R/N)$, where R is the length of the vector sum of unit vectors parallel to each estimated direction, and N is the number of estimates) makes no assumptions about the distribution of the dataset, but approaches the circular standard deviation, ($\theta - 63 \approx 81/\sqrt{K}$, where K is the precision parameter $\approx (N-1)/(N-R)$), for moderate to large samples of a Fisher-distributed population (Butler 1992). We suggest that δ should generally be less than 20°, or that K, the precision parameter, should be at least 16.

4. That field and structural corrections are sufficiently well determined that they do not add significant uncertainty to the palaeomagnetic directions.
5. Reversals tests and, where possible, fold tests should be applied to support the integrity and stability of the primary or characteristic magnetisation (Graham 1949; Cox & Doell 1960; McElhinny 1973; Butler 1992).
6. Ideally, that the transition or series of transitions be recorded in at least two sedimentary successions that can be independently correlated by other means, e.g., biostratigraphy, lithostratigraphy, and/or tephrochronology.

Criteria of this kind are standard in other areas of palaeomagnetism where high-resolution records are used for dating purposes, e.g., in the construction of secular variation master curves (Turner & Thompson 1980). We strongly recommend their adoption in situations where magnetostratigraphy is to be used to provide a timescale for chronostratigraphic purposes.

CONCLUSIONS

Re-analysis of palaeomagnetic data reported for the middle to late Pliocene parts of the Turakina (McGuire 1989) and Rangitikei River sections (Wilson 1993) in Wanganui Basin, together with new palaeomagnetic data for the Wanganui River section and part of the Rangitikei River section, have produced three comparable magnetostratigraphies that can be readily correlated with the GPTS using foraminiferal biostratigraphic datums. The Gauss-Gilbert transition is evident in the Turakina and Wanganui River sections, and the Gauss-Matuyama transition is documented in all three sections. The Mammoth and Kaena Subchrons have also been identified in all three sections.

Palaeomagnetic dating provides the only means at present of attributing numerical ages to a thick (up to 2000 m) siliciclastic succession that accumulated chiefly in upper bathyal and outer neritic palaeo environments. In the Wanganui section the mean accumulation rate is c. 1.3 m/k.y., in the Turakina section it is c. 1.8 m/k.y., and in the Rangitikei section, the mean rate from the base of the Mammoth Subchron to the Hautawa Shellbed is c. 1.1 m/k.y. These rates are comparable to those in forearc basins within the plate boundary zone in eastern North Island, and reflect high rates of basin subsidence and sediment flux. An additional feature is the expanded rate of sediment accumulation associated with progradation of slope clinoforms, which is inferred for the Tangahoe Mudstone during the middle Pliocene in Wanganui Basin (Kamp et al. 2004).

The new palaeomagnetic chronology developed for the middle to late Pliocene parts of the Wanganui Basin succession allows new correlations to be made between cyclothems in the Rangitikei River section and the globally representative OIS record from ODP Site 846. The 16 depositional sequences from the top of the Mammoth Subchron to just above the Gauss-Matuyama Boundary are correlated with the OIS between MG2 and 100. The cyclothems have an average duration of c. 39 k.y., which is close to the 41 k.y. duration of orbital obliquity controlled cycles in the insolation model of Laskar (1990).

We support the arguments advanced by Beu (2001) in defence of the need for local New Zealand stages, and strongly oppose the case advanced by Carter & Naish (1998) to abandon the classical criteria for their definition, and to redefine their boundaries to selected geomagnetic polarity transitions. Our re-interpretation of some of the palaeomagnetic data upon which the Carter & Naish (1998) arguments are based, and the consequent need to move the stratigraphic positions of some of the palaeomagnetic boundaries, provides a cautionary tale for their extraordinary proposal.

Palaeomagnetic analysis of late Miocene and Pliocene mudstone in Wanganui Basin and elsewhere in New Zealand can be difficult due to the weak natural magnetisation of the sediments and the common chemical/diagenetic overprinting of their primary, detrital magnetisation. We suggest specific approaches, analytical methods, and criteria to help ensure robustness and coherency in the palaeomagnetic identification of chron boundaries in typical New Zealand Cenozoic mudstone successions.

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Appendix 1 Location, stratigraphic elevation, and palaeomagnetic data for sample sites in the Rangitikei, Turakina, and Wanganui River sections, Wanganui Basin, New Zealand. Dec, = declination; Inc. = inclination.

Rangitikei River section

Site	Elevation (m)	Easting	Northing	*N*	Dec. (°)	Inc. (°)	Kappa	Alpha-95 (°)	Polarity	Reference
R197	1295.0	2740321	6143665	3	187	69.7	1045.3	2.5	R	Wilson (1993)
R195	1293.0	2742592	6144119	3	203.1	53.6	833	2.8	R	Wilson (1993)
R196	1293.0	2742806	6143878	3	197.7	63.0	1633	2	R	Wilson (1993)
R194	1283.0	2743206	6144413	3	200.6	53.7	93	8.4	R	Wilson (1993)
R193	1282.0	2743794	6144813	3	202.9	48.7	16	20	Tr	Wilson (1993)
R190	1267.0	2743153	6145214	3	192.2	56.3	137	6.9	R	Wilson (1993)
R186	1252.6	2743607	6145668	3	238.7	59.5	242	5.2	R	Wilson (1993)
R182	1218.4	2743741	6146123	3	187	67.2	42	12.5	R	Wilson (1993)
S146	1190.3	2744793	6145778	4	161.4	62.6	15	17.9	R	This paper
S145	1160.2	2744636	6146165	4	175.3	51.2	2	47.7	R	This paper
R181	1024.3	2744809	6146924	3	215.1	52.9	52	11.2	R	Wilson (1993)
S143	1024.3	2745245	6146940	4	189.9	66.5	12	20.3	R	This paper
S142	1024.3	2745355	6147041	4	245.7	26.2	34	12	R	This paper
R188	1010.9	2747695	6147592	3	187.5	47.7	477	3.7	R	Wilson (1993)
S144	998.8	2745143	6146912	4	186.3	43.7	18	16.6	R	This paper
R185	994.9	2749004	6148741	3	205.1	56.8	653333	0.1	R	Wilson (1993)
R192	978.8	2748283	6147458	3	27.5	−71.7	38	13.1	N	Wilson (1993)
S141	978.8	2745558	6147364	4	349.9	−51.4	10	22.2	N	This paper
S140	964.1	2748012	6147465	4	3	−50.9	424	3.4	N	This paper
R191	964.1	2748764	6147993	3	6.4	−70.9	150	6.6	N	Wilson (1993)
R189	944.7	2749298	6148393	3	6.8	−60.6	896	2.7	N	Wilson (1993)
R180	923.2	2748710	6149088	3	1.1	−63.2	150	6.6	N	Wilson (1993)
R179	909.9	2748256	6149596	3	6.1	−63.4	181	6	N	Wilson (1993)
R178	887.8	2748790	6150077	3	358.6	−58.3	84	8.8	N	Wilson (1993)
R177	858.3	2748443	6150531	3	21.6	−55.5	54	11	N	Wilson (1993)
R176	807.4	2749378	6150905	3	13.2	−57.7	309	4.6	N	Wilson (1993)
R174	767.3	2749458	6151359	3	13.6	−64.6	233	5.3	N	Wilson (1993)
R172	707.0	2750607	6151840	3	17.1	−58.9	323	4.5	N	Wilson (1993)
R171	644.1	2750687	6152241	3	28.1	−65.3	194	5.8	N	Wilson (1993)
R169	606.6	2750741	6153149	3	14.4	−50.2	201	5.7	N	Wilson (1993)
R167	566.5	2750661	6154164	3	177.7	46.5	10208	0.8	R	Wilson (1993)
R165	496.2	2750634	6155527	3	185.9	59.1	777	2.9	R	Wilson (1993)
R164	430.6	2751996	6155420	3	7	−56.9	224	5.4	N	Wilson (1993)
R163	411.2	2751061	6155954	3	1.6	−56.8	176	6.1	N	Wilson (1993)
R149	332.0	2763191	6162393	4	19.9	−66.9	85	7.6	N	Wilson (1993)
R162	324.1	2752103	6156355	3	14.3	−59.5	251	5.1	N	Wilson (1993)
R148	304.0	2763805	6162580	3	22.7	−64.2	208	5.6	N	Wilson (1993)
R160	302.7	2752691	6156943	3	12.6	−60.7	430	3.9	N	Wilson (1993)
R155	295.0	2752790	6157350	3	14.4	−58.3	48	11.7	N	Wilson (1993)
R157	288.7	2753653	6157023	3	15.1	−65.9	224	5.4	N	Wilson (1993)
R156	279.3	2754250	6156800	3	28.9	−61.3	48	11.7	N	Wilson (1993)
R154	271.3	2754321	6157237	3	12.7	−57.6	68	9.8	N	Wilson (1993)
R153	263.2	2756592	6156809	3	1	−59.2	23	17	N	Wilson (1993)
R152	257.2	2757126	6156916	3	341	−67.4	7	30.2	Tr	Wilson (1993)
R147	257.0	2764794	6162447	3	11.8	−60.0	123	7.3	N	Wilson (1993)
R146	247.2	2765034	6163275	3	238.1	78.0	119	7.4	R	Wilson (1993)
R145	239.8	2765275	6163729	3	203.7	61.1	1633	2	R	Wilson (1993)
R151	229.8	2757180	6157638	4	188.2	60.3	132	6.1	R	Wilson (1993)
R143	188.9	2767332	6164103	3	5.9	−61.2	408	4	N	Wilson (1993)

(continued)

Appendix 1 (*continued*)

Rangitikei River section

Site	Elevation (m)	Easting	Northing	*N*	Dec. (°)	Inc. (°)	Kappa	Alpha-95 (°)	Polarity	Reference
R142	162.8	2769149	6166294	3	212.7	54.3	13333	0.7	R	Wilson (1993)
R141	153.4	2767679	6164451	3	187.6	76.9	72593	0.3	R	Wilson (1993)
R138	127.3	2768000	6164531	3	23.8	–62.7	102	8	N	Wilson (1993)
R136	116.6	2769576	6166267	3	21.3	–49.8	88	8.6	N	Wilson (1993)
R135	85.2	2770271	6166481	3	15.5	–47.4	966	2.6	N	Wilson (1993)

Turakina River section

H133	1975.0	2723400	6148700	5	10.4	–60.3	383	3.2	N	Wilson (1993)
H132	1955.0	2723500	6148800	5	158.8	57.6	40	9.9	R	Wilson (1993)
H131	1950.0	2728320	6148520	7	185.1	64.3	64	6.6	R	Wilson (1993)
H130	1945.0	2728600	6148470	6	192.3	53.7	417	2.8	R	Wilson (1993)
H129	1940.0	2725400	6151300	4	204.9	54.2	112	6.6	R	Wilson (1993)
H128	1895.0	2725940	6151030	4	200.2	48.9	1111	2.1	R	Wilson (1993)
H127	1860.0	2725700	6151300	5	219	69.3	810	2.2	R	Wilson (1993)
H126	1833.0	2725610	6151540	4	225.4	65.6	146	5.8	R	Wilson (1993)
H125	1822.0	2725600	6151700	5	356.4	–51.9	109	6.0	N	Wilson (1993)
97T	1793.2	2723100	6151800	5	198.6	40.4	4	30.2	R	McGuire (1989)
98T	1789.9	2722600	6152200	5	180.4	52.3	7	23.5	R	McGuire (1989)
96T	1789.0	2723000	6152000	6	203.7	47.4	33	10.0	R	McGuire (1989)
95T	1759.6	2722800	6152500	6	171.1	44.1	6	23.1	R	McGuire (1989)
94T	1747.8	2723100	6152600	13	180	54.1	25	7.7	R	McGuire (1989)
93T	1714.2	2723000	6153000	8	183.1	62.3	7	18.2	R	McGuire (1989)
92T	1699.1	2723000	6153200	6	192.6	54	18	13.3	R	McGuire (1989)
91T	1684.8	2723300	6153400	6	189.7	45.2	12	16.7	R	McGuire (1989)
90T	1660.4	2723400	6153700	10	357.8	–47.2	31	8.0	N	McGuire (1989)
89T	1642.7	2723600	6153800	6	8.3	–61.6	45	8.5	N	McGuire (1989)
02U	1616.7	2723500	6154300	6	343.4	–62	10	18.2	N	McGuire (1989)
01U	1597.3	2723700	6154500	6	186.5	67.9	18	13.5	R	McGuire (1989)
82T	1576.3	2723900	6154800	11	4.6	–49.2	23	8.8	N	McGuire (1989)
81T	1537.6	2724300	6155200	12	356.8	–56	208	2.8	N	McGuire (1989)
03U	1534.3	2723800	6155400	6	6.2	–49.9	252	3.6	N	McGuire (1989)
80T	1507.4	2724000	6155800	18	4.4	–53.9	225	2.2	N	McGuire (1989)
79T	1474.6	2724000	6156200	11	25.9	–51.3	111	4.0	N	McGuire (1989)
78T	1448.5	2724300	6156500	12	7.5	–58.2	41	6.3	N	McGuire (1989)
77T	1429.2	2724300	6156800	10	4	–49.7	37	7.3	N	McGuire (1989)
76T	1404.0	2724500	6156900	11	26.2	–51.4	42	6.5	N	McGuire (1989)
71T	1386.3	2724800	6157100	8	7.3	–50.5	556	2.1	N	McGuire (1989)
13U	1358.6	2724500	6157500	8	6.7	–53.1	556	2.1	N	McGuire (1989)
69T	1340.9	2724900	6157600	9	10	–57.6	213	3.2	N	McGuire (1989)
06U	1310.6	2724700	6158200	6	6.7	–56.2	154	4.6	N	McGuire (1989)
66T	1286.3	2724400	6158700	9	11.3	–60.9	36	7.8	N	McGuire (1989)
67T	1257.7	2724400	6159200	6	12.5	–57.3	283	3.4	N	McGuire (1989)
65T	1246.7	2724800	6159400	6	3.9	–70.4	121	5.2	N	McGuire (1989)
68T	1241.7	2724600	6159300	6	0	–58.7	54	7.8	N	McGuire (1989)
64T	1229.9	2724800	6159700	6	12.8	–57.5	25	11.4	N	McGuire (1989)
63T	1229.9	2724800	6159900	6	15.5	–56.4	46	8.4	N	McGuire (1989)
87T	1204.7	2724900	6161200	22	8.2	–60.6	46	4.4	N	McGuire (1989)
86T	1161.8	2725400	6160900	6	3.1	–56.8	97	5.8	N	McGuire (1989)
62T	1155.1	2725400	6160700	6	9	–59.1	18	13.3	N	McGuire (1989)
85T	1141.7	2725600	6160800	6	11.8	–61.5	21	12.4	N	McGuire (1989)
61T	1120.6	2725400	6161200	7	13.6	–48.5	25	10.5	N	McGuire (1989)
60T	1102.1	2725400	6161400	10	13.1	–53.7	314	2.5	N	McGuire (1989)
59T	1082.0	2725400	6161800	6	34.8	–59.4	25	11.5	N	McGuire (1989)

Site	Elevation (m)	Easting	Northing	*N*	Dec. (°)	Inc. (°)	Kappa	Alpha-95 (°)	Polarity	Reference
08U	1051.7	2725600	6162100	13	6.2	−58.6	147	3.2	N	McGuire (1989)
58T	1031.5	2725500	6162400	9	13.6	−50.4	348	2.5	N	McGuire (1989)
57T	1010.5	2725500	6162800	10	9.3	−59.1	117	4.1	N	McGuire (1989)
07U	984.4	2725700	6163100	6	7.6	−53.1	2269	1.2	N	McGuire (1989)
56T	960.9	2725700	6163400	6	13.6	−63.3	45	8.5	N	McGuire (1989)
55T	945.8	2725800	6163800	9	17.6	−59.6	6	19.7	N	McGuire (1989)
54T	932.3	2725900	6163900	13	17.7	−61	58	5.1	N	McGuire (1989)
53T	917.2	2726000	6164200	10	16.2	−64.8	15	11.3	N	McGuire (1989)
52T	902.0	2726100	6164400	9	174.6	50.5	15	12.1	R	McGuire (1989)
51T	890.3	2726200	6164700	13	189.9	54.8	26	7.6	R	McGuire (1989)
50T	874.3	2726300	6164800	10	196.7	62.1	13	12.5	R	McGuire (1989)
49T	855.0	2726500	6165100	5	350.9	−48.6	11	19.2	N	McGuire (1989)
15U	848.2	2726500	6165300	8	27.3	−68.7	28	9.4	N	McGuire (1989)
48T	839.0	2726600	6165400	8	12.2	−47.9	18	11.7	N	McGuire (1989)
73T	804.5	2727300	6165700	10	21	−56.7	22	9.4	N	McGuire (1989)
10U	765.0	2727100	6166400	15	15.5	−64.4	36	6.0	N	McGuire (1989)
47T	704.0	2727800	6166400	12	192	39	14	10.7	R	McGuire (1989)
46T	689.0	2727900	6166500	8	27.5	−63.2	33	8.6	N	McGuire (1989)
45T	674.0	2728100	6166700	9	180.4	70.7	8	17.0	R?	McGuire (1989)
44T	658.0	2728200	6166900	8	0.1	64.8	170	3.8	Tr	McGuire (1989)
43T	644.0	2728700	6166800	9	189.9	69	33	8.1	R	McGuire (1989)
42T	629.0	2728800	6167000	9	181.3	55.9	18	11.0	R	McGuire (1989)
41T	619.0	2728800	6167100	10	169.3	46.1	9	15.0	R	McGuire (1989)
40T	608.0	2728900	6167300	8	192.8	57.4	37	8.1	R	McGuire (1989)
39T	588.0	2729200	6167400	6	176.4	70.7	161	4.5	R	McGuire (1989)
02T	568.0	2729100	6167900	7	175.3	61.9	9	17.4	R	McGuire (1989)
01T	555.0	2729400	6168000	9	179.2	62.4	14	12.5	R	McGuire (1989)
34T	544.0	2729200	6168400	4	169.5	55.1	6	27.5	R	McGuire (1989)
37T	520.0	2729400	6168600	6	349.5	−74.9	12	16.2	N	McGuire (1989)
35T	481.0	2729800	6169100	6	26.1	−59.2	16	14.1	N	McGuire (1989)
33T	475.0	2729600	6169300	6	7.4	−53.1	10	18.5	N	McGuire (1989)
32T	458.0	2729800	6169600	6	15.4	−58.6	43	8.7	N	McGuire (1989)
30T	438.0	2730000	6169700	6	4.4	−57.1	9	19.2	N	McGuire (1989)
31T	421.0	2729900	6170100	6	22.5	−68.5	17	14.0	N	McGuire (1989)
38T	416.0	2730200	6170200	6	13.1	−47.5	46	8.4	N	McGuire (1989)
16U	410.0	2730200	6170400	8	23.9	−62.3	17	12.1	N	McGuire (1989)
17U	394.0	2730300	6170700	8	17.3	−59.2	60	6.4	N	McGuire (1989)
24T	358.0	2730400	6171400	7	11.2	−56.2	257	3.3	N	McGuire (1989)
BT	337.0	2730700	6172000	8	346.7	−47.8	19	11.5	N	McGuire (1989)
28T	335.0	2730700	6171600	7	5.3	−60.6	51	7.4	N	McGuire (1989)
19T	327.0	2730400	6172000	9	11.3	−53.3	29	8.6	N	McGuire (1989)
11T	287.0	2730600	6172700	8	5.6	−59.6	53	6.8	N	McGuire (1989)
03T	271.0	2730600	6173100	8	31.3	−60.1	13	13.9	N	McGuire (1989)
88T	252.0	2730800	6173200	10	25	−55.5	14	11.7	N	McGuire (1989)
04T	246.0	2730900	6173300	7	14.7	−58.3	11	16.1	N	McGuire (1989)
18T	220.0	2730800	6173900	10	30.9	−58.1	13	12.3	N	McGuire (1989)
16T	177.0	2731200	6174300	11	198.1	54.1	24	8.6	R	McGuire (1989)
15T	167.0	2731100	6174600	6	203.8	63	675	2.2	R	McGuire (1989)
14T	148.0	2731400	6174700	8	190.8	74.5	11	14.7	R	McGuire (1989)
13T	138.0	2731500	6174800	13	205.1	60.1	46	5.7	R	McGuire (1989)
06T	110.0	2731600	6175200	9	183.4	44.5	52	6.5	R	McGuire (1989)
07T	92.0	2731800	6175400	18	185.3	43.2	18	7.8	R	McGuire (1989)
10T	45.0	2731900	6176300	10	179.8	51.4	51	6.2	R	McGuire (1989)
21T	5.0	2732000	6176900	12	178.4	57.6	9	13.4	R	McGuire (1989)

(*continued*)

Wanganui River section

Site	Elevation (m)	Easting	Northing	*N*	Dec. (°)	Inc. (°)	Kappa	Alpha-95 (°)	Polarity	Reference
S125	5830	2693800	6154400	4	145.3	48.4	14	19	R	This paper
S124	5695	2694100	6157000	4	189.1	44.6	11	21.1	R	This paper
S123	5655	2695200	6157200	4	177.4	41	1	58.9	R	This paper
S122	5648	2695300	6157200	4					R*	This paper
W113	5557	2695960	6157720	3	211.2	50	42	12.4	R	Wilson (1993)
S121	5542	2695000	6158700	4					N*	This paper
S119	5358	2694900	6160700	4					R*	This paper
S118	5321	2695000	6160900	4	16.9	–62	11	21	N	This paper
S117	5131	2692300	6163200	4	41.5	–76	22	14.9	N	This paper
S116	5034	2693300	6164800	4	11.1	–60.9	13	19.5	N	This paper
S115	4850	2695100	6167300	4					N*	This paper
S114	4780	2695100	6168100	4	341.9	–60.3	9	23.9	N	This paper
S113	4710	2695400	6169200	3	1.7	–44.7	28	15.3	N	This paper
S112	4654	2696100	6169900	5	193.5	46.9	121	5.7	R	This paper
S111	4605	2696500	6170500	5	173.6	51.6	339	3.4	R	This paper
S108	4570	2696500	6171100	4	8.6	–57.2	18	16.6	N	This paper
S110	4563	2696500	6171400	5	8.6	–56.2	1210	1.8	N	This paper
S109	4547	2696600	6171600	4	6	–50.7	174	5.3	N	This paper
S107	4528	2696600	6172200	4	348	–53.1	48	10.1	N	This paper
S105	4377	2696500	6173100	4	352.1	–65.9	3	38	N	This paper
S104	4324	2696500	6173800	4	47.2	–49.5	39	11.2	N	This paper
S103	4280	2696300	6174400	5	193.5	48.9	41	9.8	R	This paper
S102	4240	2695800	6175700	5	188.2	48.9	500	2.8	R	This paper
S101	4179	2695600	6175800	5	9.5	–51.9	233	4.1	N	This paper
S90	4090	2694500	6176500	4	60.9	–37	7	26.5	N	This paper
S11	4075	2694100	6176800	6					N*	This paper
S89	4012	2693300	6176800	4	10.5	–66.7	57	9.3	N	This paper
S10	3984	2692800	6177000	4	1.9	–50.4	4	34.1	N	This paper
S88	3892	2692400	6177500	4	303.5	–56.2	784	2.5	N	This paper
S08	3733	2690200	6178400	6					R*	This paper
S87	3733	2690200	6178400	5					R*	This paper
S86	3664	2689400	6179400	6	154.4	20.9	2	38.5	R	This paper
S06	3585	2688700	6180200	6	208.2	57.3	4	28.8	R	This paper

*, Polarity only.

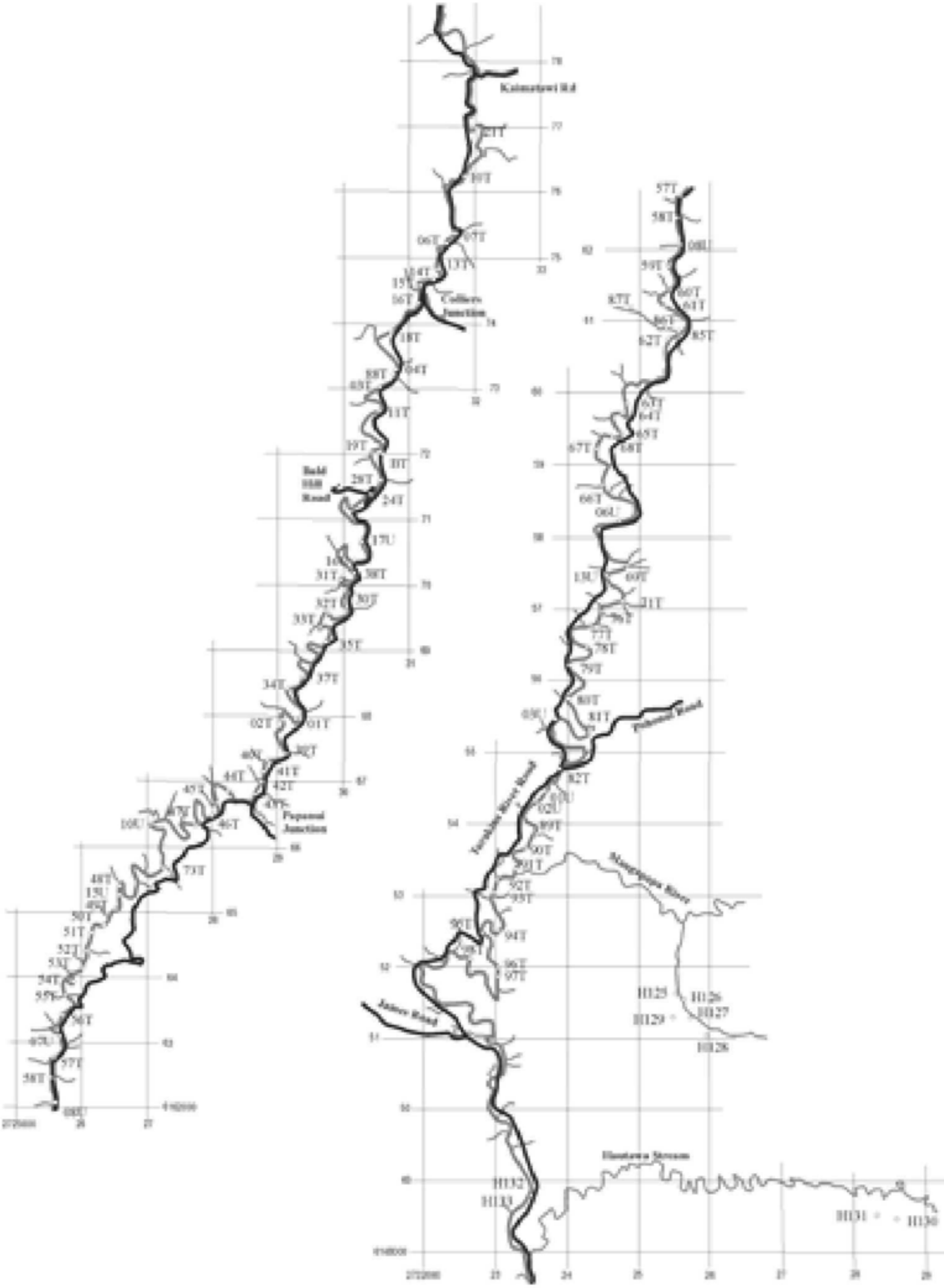

Fig. A1 Site location map, using the New Zealand map grid, for the Turakina River section showing only rivers and important roads.

Fig. A2 Site location map, using the New Zealand map grid, for the Rangitikei River section showing only rivers and important roads.

Fig. A3 Site location map, using the New Zealand map grid, for the Wanganui River section showing only rivers and important roads.