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Pliocene–Pleistocene marine cyclothems, Wanganui Basin, New Zealand: a lithostratigraphic framework

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Abstract The Rangitikei River valley between Mangaweka and Vinegar Hill and the surrounding Ohingaiti region in eastern Wanganui Basin contains a late Pliocene to early Pleistocene (c. 2.6–1.7 Ma), c. 1100 m thick, southward-dipping (4–9°), marine cyclothemic succession. Twenty sedimentary cycles occur within the succession, each of which contains coarse-grained (siliciclastic sandstone and coquina) and fine-grained (siliciclastic siltstone) units. Nineteen of the cycles are assigned to the **Rangitikei Group** (new). Six new formations are defined within the Rangitikei Group, and their distribution in the Ohingaiti region is represented in a new geologic map. The new formations are named: **Mangarere**, **Tikapu**, **Makohine**, **Orangipongo**, **Mangaonoho**, and **Vinegar Hill**. Each formation comprises one or more cyclothems and includes a previously described and named distinctive basal horizon. Discrete sandstones, siltstones, and coquinas within formations are assigned member status and correspond to systems tracts in sequence stratigraphic nomenclature. The members provide the link between the new formational lithostratigraphy and the sequence stratigraphy of the Rangitikei Group. Base of cycle coquina members accumulated during episodes of sediment starvation associated with stratigraphic condensation on an open marine shelf during sea-level transgressions. Siltstone members accumulated in mid-shelf environments (50–100 m water depth) during sea-level highstands, whereas the overlying sandstone members are ascribed to inner shelf and shoreface environments (0–50 m water depth) and accumulated during falling eustatic sea-level conditions. Repetitive changes in water depth of 50–100 m magnitude are consistent with a glacio-eustatic origin for the cyclothems, which correspond to an interval of Earth history when successive glaciations in the Northern Hemisphere are known to have occurred. Moreover, the chronology of the Rangitikei River section indicates that Rangitikei Group cyclothems accumulated during short duration, 41 ka cycles in continental ice volume attributed to the dominance of the Milankovitch obliquity orbital parameter.

The Ohingaiti region has simple postdepositional structure. The late Pliocene formations dip generally to the SSW between 4° and 9°. Discernible discordances of c. 1° between successively younger formations are attributed to synsedimentary tilting of the shelf concomitant with migration of the tectonic hingeline southward into the basin. The outcrop distribution of the Rangitikei Group is strongly influenced by this regional tilt and also by three major northeast–southwest oriented, high-angle reverse faults (Rauoterangi, Pakihikura, and Rangitikei Faults).

Keywords late Pliocene; Nukumaruan Stage; cyclothems; Wanganui Basin; glacio-eustacy; sea-level change; new stratigraphic names; Mangarere Formation; Tikapu Formation; Makohine Formation; Orangipongo Formation; Mangaonoho Formation; Vinegar Hill Formation; Rangitikei Group

INTRODUCTION

Wanganui Basin contains a thick (4 km) Pliocene–Pleistocene sedimentary fill of mainly marine strata that has accumulated in various shelf and paralic environments. The northern and eastern margins of the basin are now uplifted, and gently dipping (2–15°) marine strata are well exposed along the coastline northwest of Wanganui City and within deeply incised river valleys further to the east (Fig. 1). The Wanganui Basin succession has proved to be important in studies of global climate change because it contains an exceptionally complete on-land record of cyclothemic sedimentation in response to glacio-eustatic sea-level fluctuations (Beu & Edwards 1984; Kamp & Turner 1990; Abbott & Carter 1994). Moreover, it affords a unique opportunity to examine the relationships between on-land and offshore stratigraphic records of the Pliocene–Pleistocene. Recent published studies have concentrated on Pleistocene strata, especially those of the Nukumaruan and Castlecliffian stratotype sections exposed along the Wanganui coastline (Beu & Edwards 1984; Kamp & Turner 1990; Abbott & Carter 1994). The underlying late Pliocene succession (Mangapanian–Nukumaruan) in Wanganui Basin, which was also deposited under conditions of rapid basinal subsidence and high sedimentation rates during a period of Northern Hemisphere-driven, glacio-eustatic sea-level fluctuations, should also reveal a detailed record of sedimentary cyclicity.

Between Mangaweka and Vinegar Hill, an c. 1100 m thick, southward-dipping (4–9°), late Pliocene (c. 2.6–1.7 Ma) marine cyclothemic succession is spectacularly exposed in cliffs of the Rangitikei River (Fig. 1). We have identified 20 sedimentary cycles or cyclothems within the succession, each of which contains coarse-grained (sandstone and coquina) and fine-grained (siltstone) units. Fine-grained lithologies contain diagnostic molluscan and foraminiferal fauna that indicate deposition in predominantly mid-shelf environments (c. 50–100 m water depth), whereas coarse-grained lithologies accumulated in a range of nearshore–inner shelf environments

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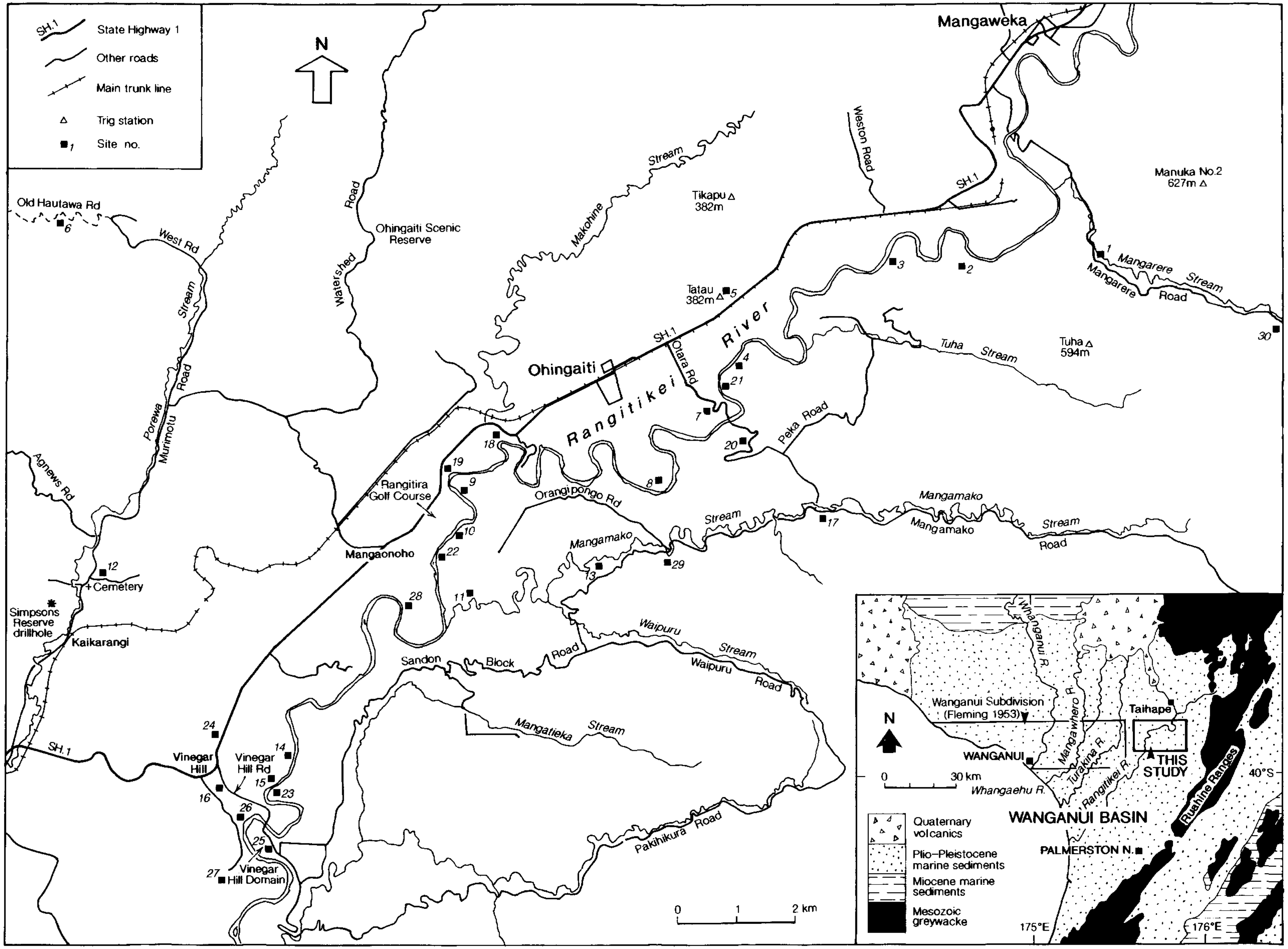


Fig. 1 Map of the Ohingaiti region showing names, physiographic features, and numbered sections referred to in the text. *Inset*: simplified geology of the southwestern North Island, showing location of study area.

(c. 0–50 m water depth). Each cyclothem is characterised by a remarkably similar lithofacies architecture, corresponds in duration to the 41 ka Milankovitch obliquity frequency, and the 20 cyclothems are correlated with oxygen isotope stages 100–58. Details of the sequence architecture, correlations with the global isotope model, and faunal characteristics are presented elsewhere (Naish & Kamp in prep. "Pliocene–Pleistocene shelf cyclothems, Wanganui Basin, New Zealand: a high-resolution facies and sequence stratigraphic analysis").

Given the remarkable exposure, the continuity of the record, and the dramatic lithologic and faunal changes between low and high relative sea-level deposits, the Rangitikei River section deserves to become a global on-land reference section recording sea-level, paleoclimatic, and environmental change. For this to be considered seriously, a detailed geologic map and formal lithostratigraphy of the region needs to be widely available. A formal (descriptive) lithostratigraphy, including a detailed description of individual cyclothems, is also essential as a framework for interpretation of the sequence stratigraphy of the sedimentary succession, which is a related part of our study of the region.

Some of the strata exposed in this area have been mapped previously by the Superior Oil Co. of N.Z. (1943) and by Te Punga (1953). Subsequent studies (e.g., Seward et al. 1986) have applied lithostratigraphic nomenclature from western Wanganui Basin (Wanganui Subdivision; Fleming 1953) to presumed correlatives exposed in the Rangitikei River valley. Although several names have been employed for late Pliocene strata in eastern Wanganui Basin, no unified scheme is currently available, and many of the existing names for units in the Rangitikei River valley are inadequately defined. Problems in lithostratigraphic nomenclature have arisen from the application of Fleming's (1953) scheme to strata in the Rangitikei River valley. Some units show dramatic changes in lithology across the basin, and the use of names derived from localities in western Wanganui Basin may be inappropriate for defining type and reference localities within the eastern part of the basin. For those cases more appropriate names are presented here. However, the revised nomenclature retains, wherever possible, historically significant pre-existing names to maintain a continuity of usage.

The present study is concerned with establishing a formal lithostratigraphic framework for the late Pliocene–early Pleistocene succession exposed in the Rangitikei River valley and the surrounding Ohingaiti region (Fig. 1). We ascribe all strata in this region, between the Mangaweka Mudstone and the Vinegar Hill Tephra, to the **Rangitikei Group** (new), and we present here a new 1:50 000 geologic map. New detailed stratigraphic logs are also presented for the Rangitikei River section, Porewa Valley section, and a 200 m deep stratigraphic drillhole sited in Simpsons Reserve (Fig. 1; New Zealand metric Topomap NZMS 260 series, grid reference T22/320417) in May 1991 by the Institute of Geological and Nuclear Sciences Ltd. We discuss the importance of applying a lithostratigraphic subdivision to high-order (6th) cyclothemic strata and comment on the problems associated with mapping cyclothems in Wanganui Basin. We explore the local and more regional implications of our proposed lithostratigraphy and make basin-wide comparisons with correlative strata in the "Wanganui Subdivision" (Fleming 1953; Fig. 1). We also comment on the late Pliocene depositional setting of eastern Wanganui Basin and discuss the origin of cyclicity preserved within the Rangitikei Group strata.

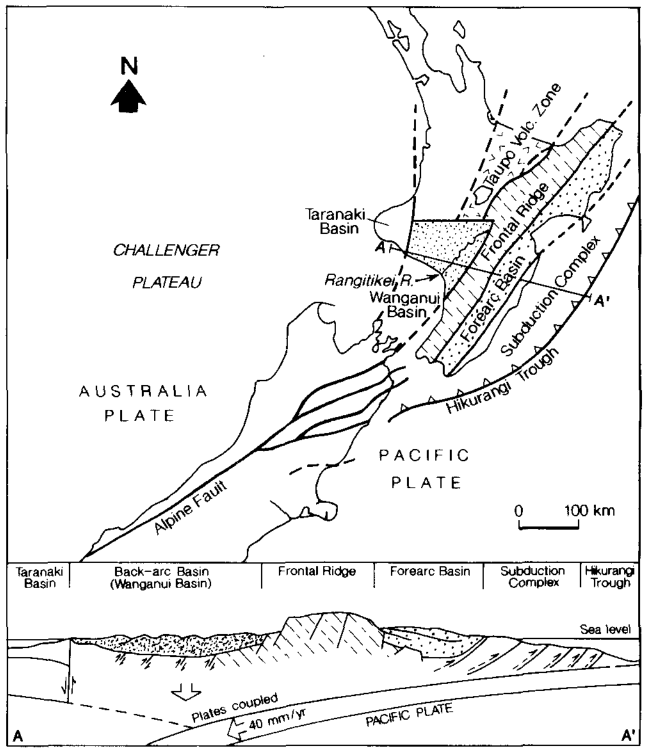


Fig. 2 The regional tectonic setting of Wanganui Basin with respect to the main structural and tectonic features of the Hikurangi margin. The schematic section across southern central North Island shows the eastern margin of Taranaki Basin, Wanganui Basin, the axial ranges, and the eastern North Island accretionary borderland.

TECTONIC SETTING

The Pliocene–Pleistocene tectonic setting of Wanganui Basin with respect to the Hikurangi margin is illustrated in Fig. 2. Wanganui Basin is broadly elliptical, located behind the accretionary borderland of the southern portion of the Hikurangi margin, and is mildly deformed by northeast–southwest-trending high-angle reverse faults. Stern & Davey (1989, 1990) argued that development of Wanganui Basin has been controlled by Pacific plate subduction processes. Pliocene–Pleistocene subsidence is attributed to an early phase of compressional downwarping driven by coupling of the overriding and subducting plates. Regional tilting of Neogene strata in Wanganui Basin is considered to be a response to southward migration of the depocentre and coeval uplift towards the north. Sediments deposited in eastern portions of the basin, and described herein, have been gently upwarped along the axial ranges at rates of 1–3 m/ka during the late Quaternary (Pillans 1986), as recorded by a series of well-developed alluvial terraces in Rangitikei Valley (Milne 1973).

STRUCTURE OF THE OHINGAITI REGION

The Rangitikei Group strata in the study area have simple postdepositional structure (Fig. 3). The succession dips generally to the SSW at between 4° and 9°; steeper dips (up to 15°) and more variable dip directions occur in the vicinity of faults (Fig. 3, 4A, B). Subtle synsedimentary deformation of tectonic origin is evidenced by discernible angular discordances of c. 1° across some unconformities.

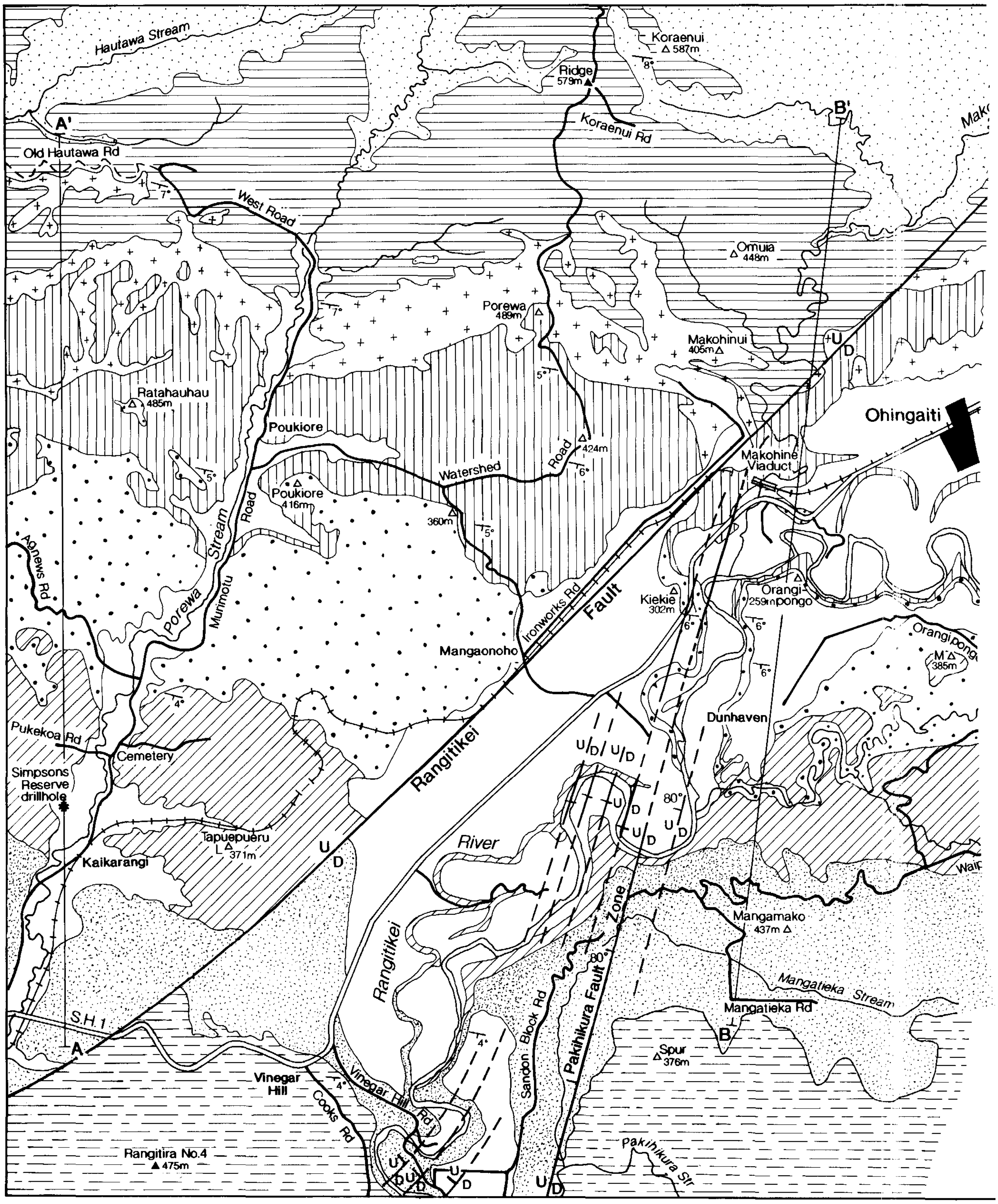


Fig. 3 Geologic map of the Ohingaiti region showing regional structure and outcrop pattern of the newly defined late Pliocene formations of the Rangitikei Group.

Figure 5G illustrates low-angle stratal discordance across the unconformity at the base of the Mangaonoho Formation (site 11, Fig. 1). A decrease in dip angle of 1° occurs between successively younger formations of the Rangitikei Group (Fig. 4A, B). We suggest synsedimentary tilting of the shelf occurred in response to flexural uplift in the north associated with progressive southward migration of the basin depocentre during the late Pliocene.

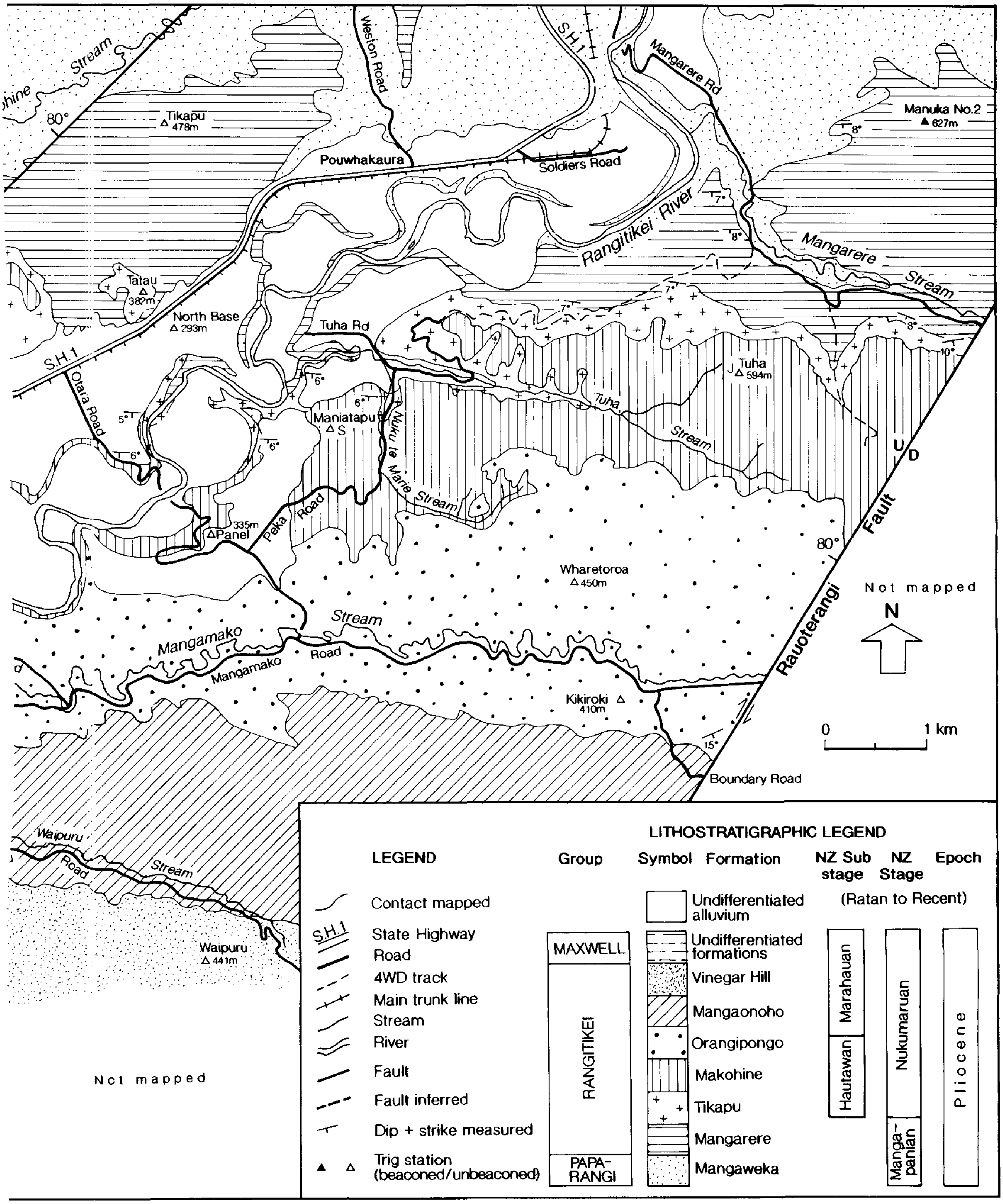


Fig. 3 (*continued*)

Two major northeast–southwest oriented faults (Rangitikei and Rauoterangi) occur in the study area. Although the fault planes are exposed in outcrop at only a few places, both faults display high angles (80°) of dip, have reverse displacement, and are upthrown to the west. Within the map area, Rauoterangi Fault is clearly exposed at site 30 (Fig. 1) on Mangarere Road, and has a throw of c. 200 m, juxtaposing Mangarere Formation siltstone against Orangipongo Formation sandstone. Structural analysis of our geologic map indicates throws of c. 100 m across the Rangitikei Fault (Fig.

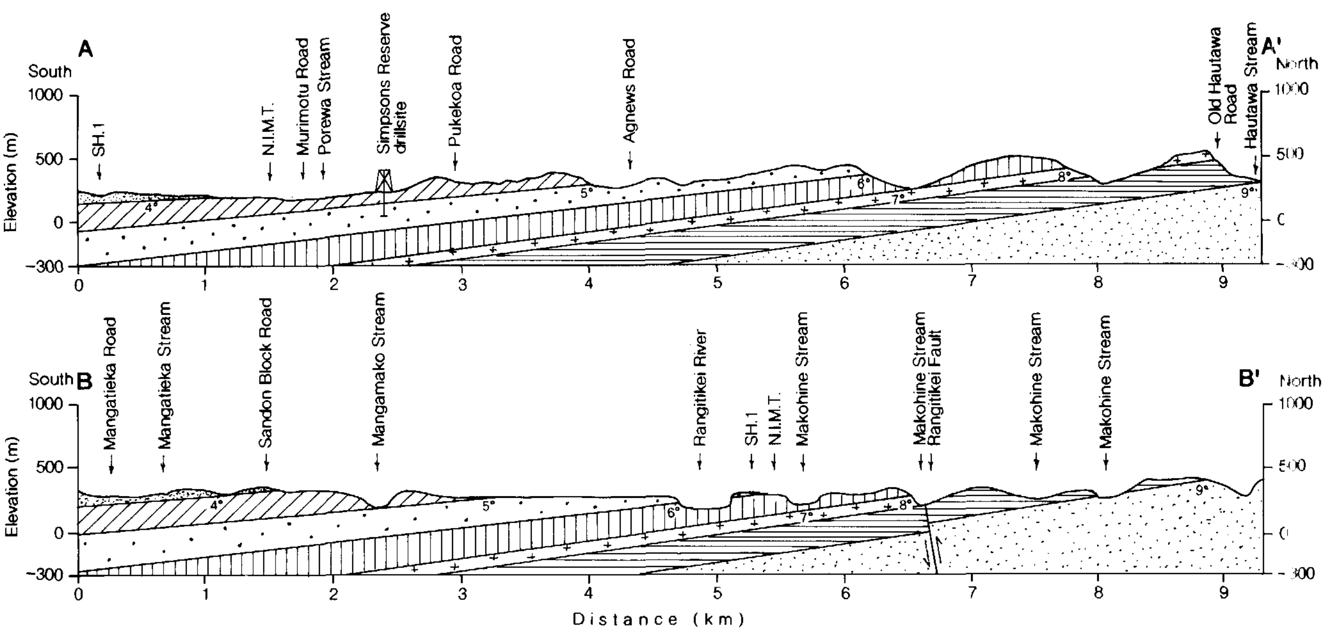


Fig. 4 Cross-sections illustrating the relatively simple postdepositional structure of the Rangitikei Group. Dips shallow in successively younger formations. **A**, Section A–A′ relates the stratigraphy of the Simpsons Reserve drillcore to the regional outcrop pattern. **B**, Section B–B′ shows the structural complexity associated with the Rangitikei Fault.

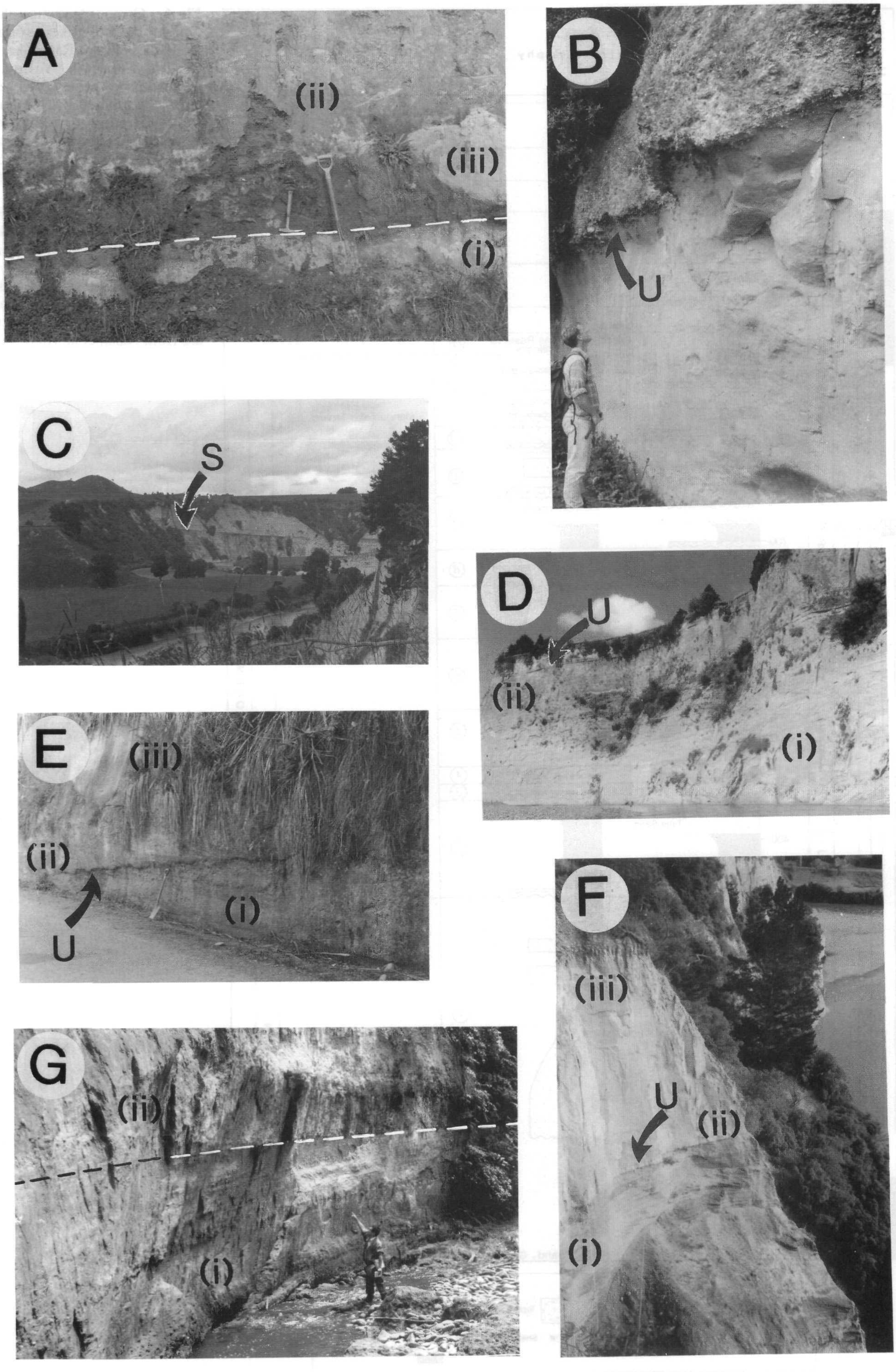
4B), which is exposed on Vinegar Hill (Superior Oil Co. of N.Z. 1943) and as a scarp east of Hunterville where it truncates the Vinegar Hill Tephra. The regional strike of strata is 100–110° but, adjacent to the Rauoterangi Fault, strikes between 60° and 90° occur (Fig. 3). This difference in attitude of strata adjacent to the faults is attributed to drag associated with limited dextral strike-slip movement along the Rauoterangi Fault. Moreover, dramatic variations in throw along both faults are also consistent with a dextral wrench fault pattern of deformation (Anderton 1981).

Between Makohine and Pakihikura Streams, a 1.5 km wide zone of en echelon high-angle (75–90°) reverse and subordinate normal faults locally complicates the outcrop distribution of the Mangaonoho and Vinegar Hill Formations. We refer to this more structurally complex region as the Pakihikura Fault Zone (Fig. 3). The faults are sympathetic to the Rangitikei Fault and their origin is probably associated with minor dextral strike-slip movement along the Rangitikei Fault. Throws on the major faults range between 10 and 30 m, with greater displacement occurring towards the north where the faults appear to bifurcate from the Rangitikei Fault. The major influence the faults have had on the outcrop pattern of the Rangitikei Group is the formation of a series of fault blocks that progressively uplift strata eastward across the Pakihikura Fault Zone. Strike-parallel differential tilting of faulted blocks causes local variations in dip of strata. Strata exposed in a 1 km long section in the east bank of the Rangitikei River opposite Rowes Road (Fig. 1) are almost flat lying. Numerous normal and reverse faults with minor displacements (< 5 m) that deform strata on a smaller scale in the Ohingaiti region have not all been mapped.

LITHOSTRATIGRAPHIC SUBDIVISION OF CYCLOTHEMIC STRATA

Fleming (1953) was the first to recognise that the Pliocene–Pleistocene succession comprised unconformity-bounded sediment wedges that thicken eastwards in the direction of the basin depocentre. He established and applied a comprehensive lithostratigraphy to strata cropping out in the Wanganui Subdivision, which has been utilised widely by others (Seward 1974; Beu & Edwards 1984; Kamp & Turner 1990; Abbott & Carter 1994; Pillans et al. 1994). In the middle Pleistocene (Castlecliffian Stage) part of the record, Fleming's

Fig. 5 Prominent unconformities and lithologies within the Rangitikei Group. **A**, Channelled base of the Mangarere Formation (T22/497480). The unconformity is highlighted (dashed line). (i) Mangaweka Formation siltstone. (ii) Channel-fill conglomerate member ($Mrcfm_1$). (iii) A clast (c. 1 m diam.) of underlying Mangaweka Formation siltstone within channel-fill member. **B**, Base of the Hautawa Shellbed exposed at the type locality (GS3096; Fleming 1953), "Old Hautawa Road" at the end of West Road (T22/325484). "U" marks the unconformity. **C**, Base of the Tikapu Formation exposed in the east bank of the Rangitikei River (T22/436456). The prominent horizon in the cliff (S) is the Hautawa Shellbed ($Tusm_1$; Fig 7B). **D**, Base of the Makohine Formation exposed in the west bank of the Rangitikei River (T22/434455). (i) Siliciclastic siltstone member $Tuzm_1$ passes gradationally upsection into (ii) Tuha Sand ($Mksm_1$), which is sharply truncated by the upper cycle bounding unconformity (U). **E**, Cycle bounding unconformity (U) within the Makohine Formation (T22/434450) truncates shoreface facies within the upper portion of the (i) Tuha Sandstone ($Mksm_1$). (ii) Coquina member $Mkcm_1$ is sharply overlain by (iii) siliciclastic siltstone member $Mkzm_1$. **F**, Burrowed cycle bounding unconformity (U) within the Orangipongo Formation sharply truncates (i) large-scale bidirectional trough cross-bedded sands within the top of the Ohingaiti Sand ($Orsm_1$) and is sharply overlain by (ii) coquina member ($Orcm_1$), which passes upsection into (iii) siliciclastic siltstone member $Orzm_1$. **G**, Unconformity (dashed line) at the base of the Mangaonoho Formation exposed in Mangamako Stream (T22/394417) truncates (i) regressive shoreline facies of the underlying Orangipongo Formation. (ii) Mangamako Shellbed ($Mhcm_1$) above unconfromity.


A
(ii)
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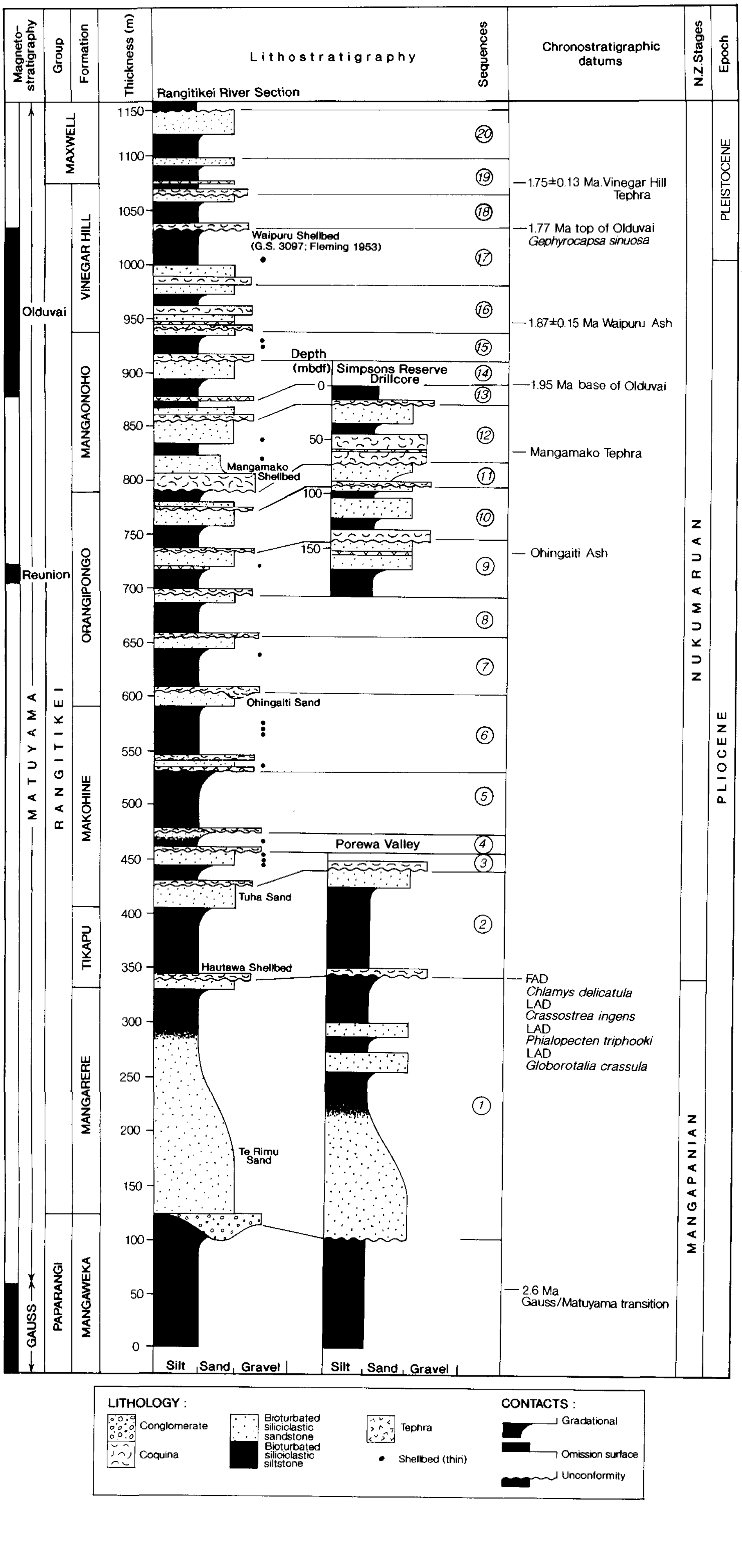


Fig. 6 Composite stratigraphic column for the Rangitikei Group. Correlations between Rangitikei River section, Porewa Valley, and Simpsons Reserve drillcore have been established on the basis of lithostratigraphy and geological mapping. Formation thicknesses and lithologies have been derived from type and reference localities for the Rangitikei River section and are illustrated in more detail in Fig. 7. Magnetostratigraphy is after Seward (1986), Wilson (1993), and Naish et al. (in press). Biostratigraphy is after Fleming (1953) and Beu & Edwards (1984). Isothermal plateau fission track ages on rhyolitic tephra are from Naish et al. (in press).

formations correspond to systems tracts in terms of sequence stratigraphic nomenclature. This is particularly evident in the Castlecliffian stratotype section (Abbott & Carter 1994). However, away from well-exposed coastline and river sections, Fleming (1953) was not able to map individual formations. This was due to: (1) paucity of outcrop in the interfluves; (2) poor surface geomorphic expression of sandstone and siltstone lithologies; (3) lateral changes in lithofacies within individual cyclothems; and (4) repetition of similar lithofacies successions from one cyclothem to another, thereby creating the potential for miscorrelation. Consequently, largely undifferentiated groups containing a few prominent horizons were mapped across the Wanganui Subdivision. In the Ohingaiti region, Superior Oil Co. of N.Z. (1943) and Te Punga (1953) adopted a similar approach, mapping distinctive horizons within broad formations or groups.

Following the recognition by recent workers that the Wanganui Basin contains an exceptional record of Milankovitch-driven cyclicity, the emphasis has changed from one of mapping lithologic units to developing integrated stratigraphies and chronologies aimed at identifying the global climatic and sea-level signatures within the sediments and their relationship to local events such as volcanic eruptions (e.g., Pillans 1983; Turner & Kamp 1990; Pillans et al. 1994). The corresponding change in approach has been to measure well-exposed sections, the correlations between sections being supported by integrated chronostratigraphies. To date, most of the published work of this kind has been undertaken within the Wanganui Subdivision part of the basin, and has been possible largely because of the lithostratigraphic framework and mapping undertaken by Fleming (1953). Our work in the Ohingaiti region is directed chiefly at documenting the global signals of climatic and sea-level change contained in the sediments, and the controls on accumulation of the succession. Applying and testing sequence stratigraphic concepts (cf. Vail 1987) is one means by which we are doing this work. However, in order to do this and adequately report the results, we have found it necessary to develop a comprehensive lithostratigraphy and geologic map as a framework to which we can relate our descriptions and interpretations.

In this paper we present a new lithostratigraphy and geologic map for the Ohingaiti region for two reasons: (1) as a basis for sequence stratigraphic analysis (as above), and (2) to relate the stratigraphy in the Ohingaiti region to that in the Wanganui Subdivision. We therefore subdivide Rangitikei Group strata into six new formations bounded by prominent mappable lithologic horizons. Each formation comprises a package of one or more cyclothems, and includes as members previously described distinctive units (Superior Oil Co. of N.Z. 1943; Te Punga 1953; Fleming 1953): Te Rimu Sand, Hautawa Shellbed, Tuha Sand, Ohingaiti Sand, Mangamako Shellbed, and Waipuru Shellbed. The formations, in ascending order, are named: **Mangarere**, **Tikapu**, **Makohine**, **Orangipongo**, **Mangaonoho**, and **Vinegar Hill**. Figures 6 and 7A–F illustrate the detailed lithostratigraphy of each formation. An important consideration when establishing the formational stratigraphy was that the formations should be mappable units. Discrete lithologic units within formations correspond to systems tracts. These units could not be mapped reliably across the Ohingaiti region and are assigned member status. Cyclothem-bounding unconformities, or sequence boundaries, truncate coarse-grained regressive shoreline facies in many places and are overlain by coarse-grained basal transgressive shellbeds. This means that sequence boundaries may lie within coarse-grained strata and may not necessarily coincide with formation boundaries, which are placed at the contacts of sandstones and siltstones in the Tikapu, Makohine, Orangipongo, and Vinegar Hill Formations. However, in the lithostratigraphy defined here, sequence boundaries coincide with member boundaries, which distinguish lithologic differences within the coarser grained units. Figure 8 illustrates the relationships between cyclothems and members within the Orangipongo Formation. It is the characteristics of the members that define the detailed sequence architecture and provide the essential link between the formational lithostratigraphy and the sequence stratigraphy of the Rangitikei Group strata. This contrasts with Fleming's (1953) subdivision of the middle Pleistocene Castlecliff section, where the formations are essentially systems tracts.

Given the large number of members that can usefully be defined within each formation of the Rangitikei Group, it has proved impractical to ascribe members a geographical name. Consequently, we have adopted an alpha-numeric nomenclatural system that assigns a code to each member. The code contains three parts: (1) the abbreviated name of the formation in which the member occurs (i.e., Vh = Vinegar Hill Formation); (2) an abbreviated lithologic term (i.e., sm = sand member); and (3) a numerical term denoting stratigraphic position of the member within the formation (i.e., $Vhsm_1$ = lowest sand member of the Vinegar Hill Formation).

LITHOSTRATIGRAPHY

RANGITIKEI GROUP (new)

HISTORY: A summary of the formational nomenclature used by previous workers to describe late Pliocene strata in eastern Wanganui Basin is given in Fig. 9. A report detailing the geology of the "Palmerston–Wanganui area" by the Superior Oil Co. N.Z. (1943) provides the earliest significant reference to the stratigraphy of the Rangitikei Valley region. "Superior" geologists based their mapping of Wanganui Basin on detailed descriptions of sections sampled in Rangitikei, Turakina, Mangawhero, and Whanganui Rivers. Strata of Pliocene age were grouped into two microfaunally defined stages, the Waitotaran and Nukumaruan Stages. The latter stage was further subdivided to include the "Lower Nukumaruan Formation" and the "Petane or Upper Nukumaruan Formation". Three prominent horizons were described within the Lower Nukumaruan Formation: the Basal Nukumaruan Sand, the Tuha Sand, and the Hautawa Reef. Overlying strata of the Petane Formation comprised faunas similar to those of the type Nukumaruan coastal section and included three key beds: the Ohingaiti Sand, the Mangamako Shellbed, and the Waipuru Fossiliferous Sand Horizon.

Te Punga (1953) renamed strata of Waitotaran age below the Basal Nukumaruan Sand as Lower Rangitikei Formation. Overlying Nukumaruan strata were assigned to the Middle Rangitikei Formation (Fig. 9).

Fleming (1953) adopted in the Wanganui Subdivision, with minor emendation, the mapping of the Superior Oil Co. of N.Z. (1943), matching the Rangitikei stratigraphy with presumed correlatives in the Wanganui Subdivision. Some of the names applied by Superior Oil Co. of N.Z. (1943) were rejected by Fleming (1953) as they confused biostratigraphic

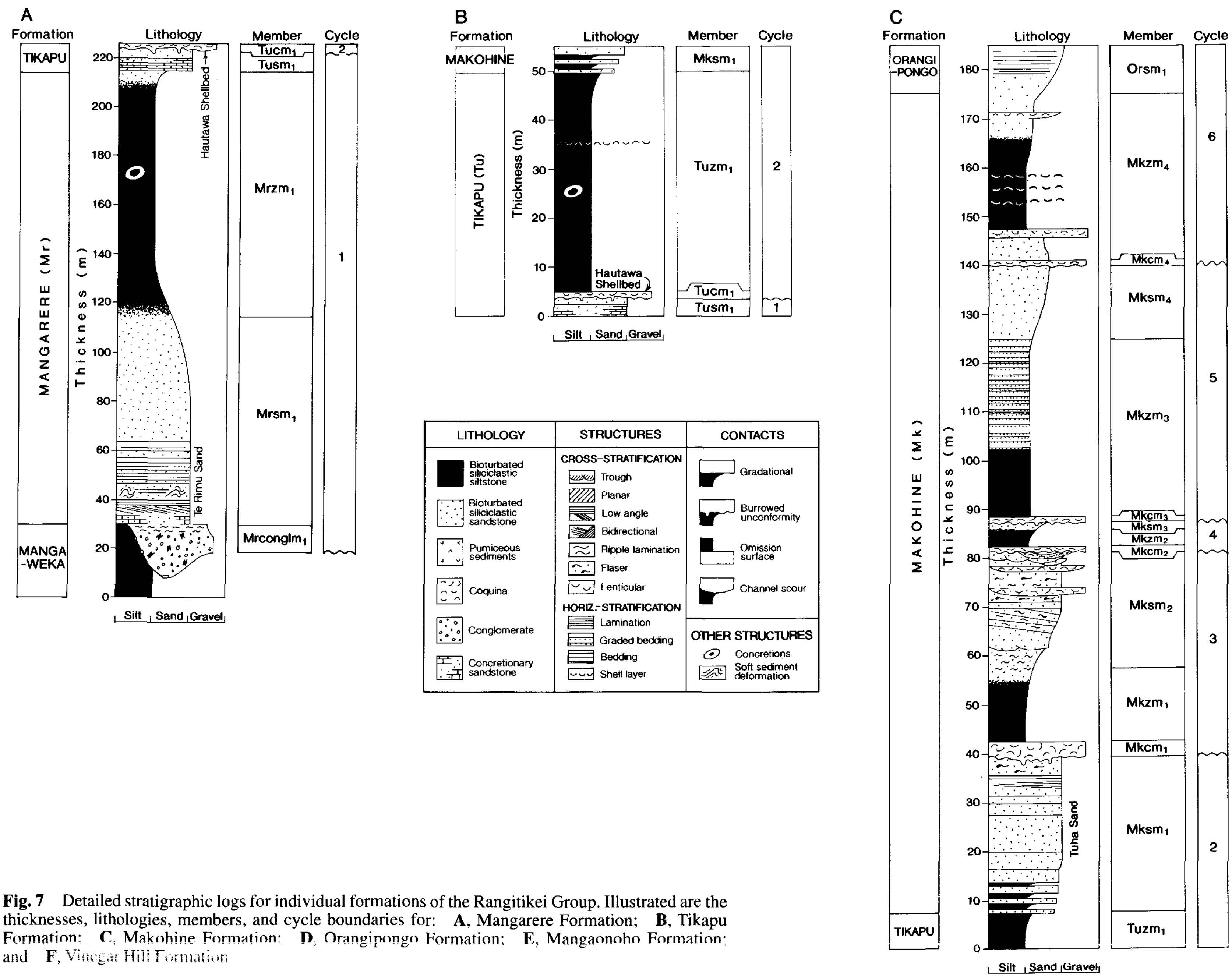
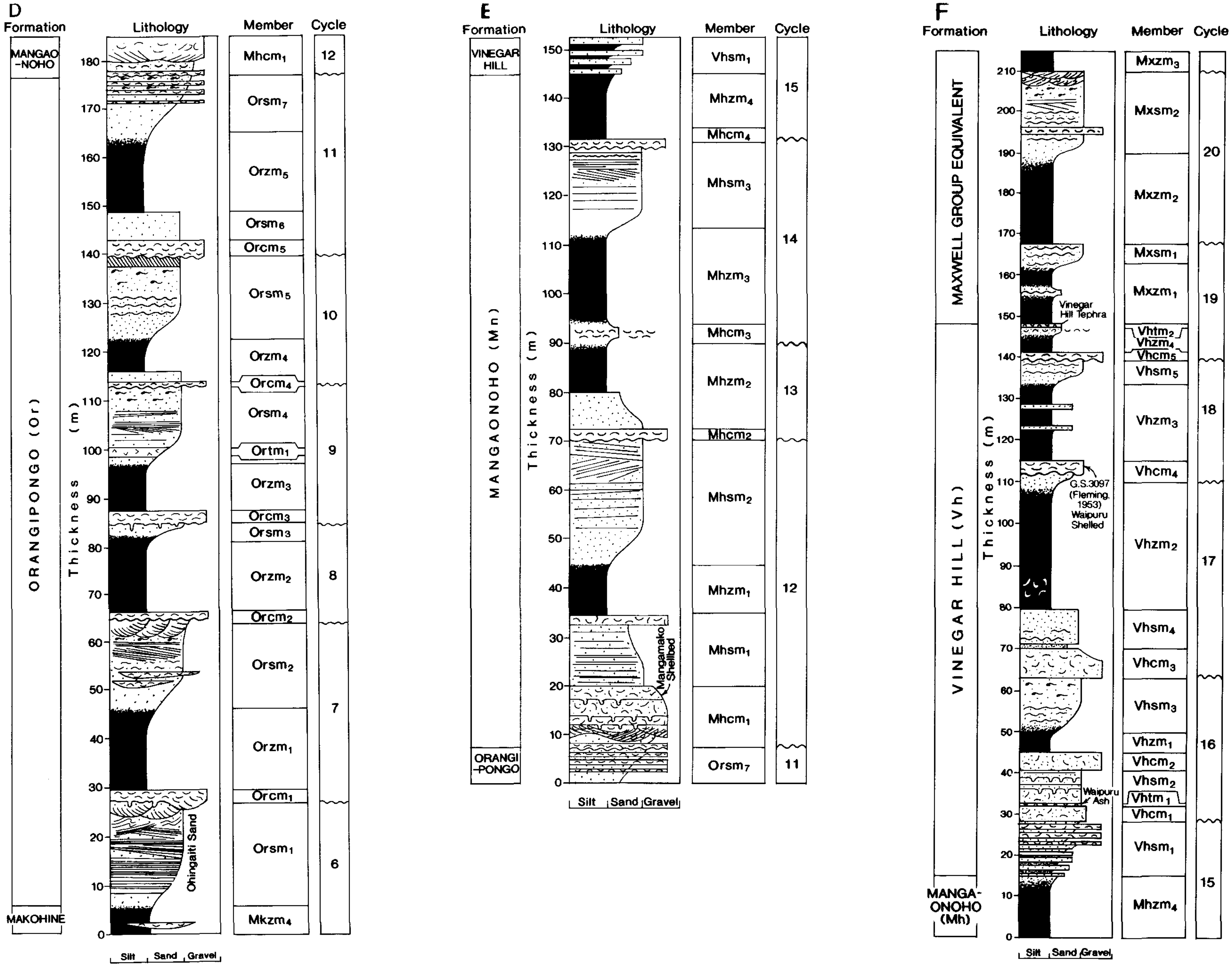


Fig. 7 Detailed stratigraphic logs for individual formations of the Rangitikei Group. Illustrated are the thicknesses, lithologies, members, and cycle boundaries for: **A**, Mangarere Formation; **B**, Tikapu Formation; **C**, Makohine Formation; **D**, Orangipongo Formation; **E**, Mangaonoho Formation; and **F**, Vinegar Hill Formation.


D
Formation
Lithology
Member
Cycle
MANGAO-NOHO
ORANGIPONGO (Or)
MAKOHINE
Thickness (m)
Ohingaiti Sand
Silt Sand Gravel
Mhcm1
Orsm7
Orzm5
Orsm6
Orcm5
Orsm5
Orzm4
Orcm4
Orsm4
Ortm1
Orzm3
Orcm3
Orsm3
Orzm2
Orcm2
Orsm2
Orzm1
Orcm1
Orsm1
Mkzm4
12
11
10
9
8
7
6
E
Formation
Lithology
Member
Cycle
VINEGAR HILL
MANGAONOHO (Mn)
ORANGI-PONGO
Thickness (m)
Mangamako Shellbed
Silt Sand Gravel
Vhsm1
Mhzm4
Mhcm4
Mhsm3
Mhzm3
Mhcm3
Mhzm2
Mhcm2
Mhsm2
Mhzm1
Mhsm1
Mhcm1
Orsm7
15
14
13
12
11
F
Formation
Lithology
Member
Cycle
MAXWELL GROUP EQUIVALENT
VINEGAR HILL (Vh)
MANGA-ONOHO (Mh)
Thickness (m)
Vinegar Hill Tephra
G.S.3097 (Fleming, 1953) Waipuru Shelled
Waipuru Ash
Silt Sand Gravel
Mxzm3
Mxsm2
Mxzm2
Mxsm1
Mxzm1
Vhtm2
Vhzm4
Vhcm5
Vhsm5
Vhzm3
Vhcm4
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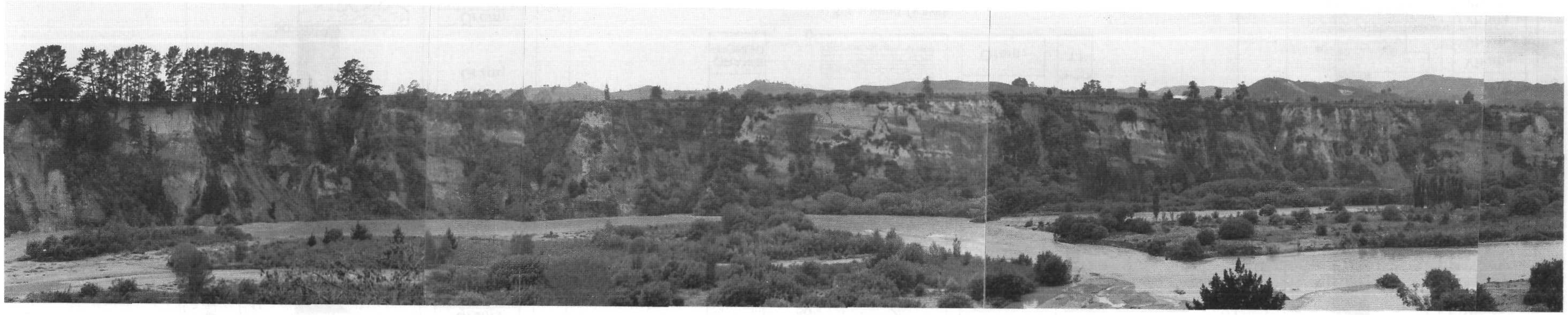

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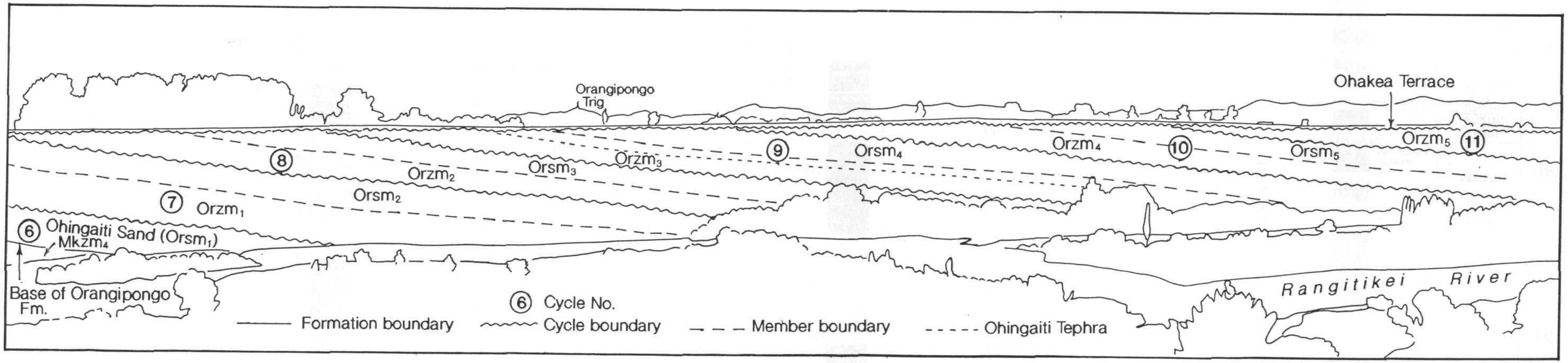

Fig. 8 **A**, Type section of the Orangipongo Formation exposed in the east bank of the Rangitikei River opposite the Rangitira Golf Course. **B**, The relationship between members and cyclothems within the Orangipongo Formation exposed at the type locality.

Fig. 9 Historical and new lithostratigraphic nomenclature, late Pliocene strata, Ohingaiti region. Italicised units occur as named members within the Rangitikei Group.

Superior Oil Company of N.Z. (1943)		Te Punga (1953)		Fleming (1953)		This paper	
				MAXWELL GROUP		RANGITIKEI GROUP	
PETANE FORMATION	Waipuru Sand	MIDDLE RANGITIKEI FORMATION	Waipuru Fossil Beds	NUKUMARU GROUP	Waipuru Shellbed		Vinegar Hill Formation *Waipuru Shellbed Mb.*
	Mangamako Sand		Mangamako Fossil Beds		Mangamako Shellbed		Mangaonoho Formation *Mangamako Shellbed Mb.*
	Ohingaiti Sand		Ohingaiti Sandstone		Ohingaiti Sand		Orangipongo Formation *Ohingaiti Sand Mb.*
LOWER NUKUMARUAN FORMATION	Tuha Sand		Tuha Sandstone	OKIWA GROUP	Tuha Sand		Makohine Formation *Tuha Sand Mb.*
	Hautawa Reef				Hautawa Shellbed		Tikapu Formation *Hautawa Shellbed Mb.*
	Basal Nukumaruan Sand		Basal Sandstone		Te Rimu Sand		Mangarere Formation *Te Rimu Sand Mb.*

with lithostratigraphic nomenclature. Group status was assigned to late Pliocene strata in western Wanganui Basin. The Upper and Lower Nukumaruan Formations were renamed Okiwa and Nukumaru Groups, respectively. The Basal Nukumaruan Sand was renamed Te Rimu Sand, based on a locality in the Whanganui River valley. Lower Okiwa Group strata, below the Hautawa Shellbed, were assigned a Mangapanian age. Strata containing *Chlamys delicatula* were assigned to the Hautawan subdivision of the Nukumaruan Stage, and Nukumaru Group strata were assigned to an upper biostratigraphic subdivision of the Nukumaruan Stage, the Marahauan Substage.

In applying the group names, Okiwa and Nukumaru, to time-equivalent strata in eastern regions of the Wanganui Subdivision, Fleming (1953) recognised potential difficulties in lithostratigraphic nomenclature. This is particularly pertinent to the Nukumaru Group, where dramatic lithologic changes occur within the group, from west to east across the basin (Fig. 10). Coarse-grained, siliciclastic sands and bioclastic lenticular limestones distinguish the group in the west but pass eastwards into finer grained sandy siltstones and siltstones. Within the Nukumaru Group, only the Ohingaiti Sand and Waipuru Shellbed maintain sufficiently consistent lithologic character to be able to be traced on field criteria across the basin. Older Okiwa Group strata are generally finer grained but display similar west–east fining.

In the Ohingaiti region, cyclothemic strata correlated with the Okiwa and Nukumaru Groups comprise broadly similar ratios of siltstone to sandstone. There is no lithologic basis for recognition of two lithologically discrete groups in this part of the basin. We propose the name **Rangitikei Group** for Okiwa and Nukumaru Group correlative strata mapped in the Ohingaiti region (Fig. 9).

NAME: Rangitikei Group derives from Te Punga (1953) who applied the name Middle Rangitikei Formation to strata between the top of the Mangaweka Formation and the Pakihikura Pumice. Te Punga's (1953) formational nomenclature is unacceptable because his formations clearly contain numerous mappable units (formations) as we demonstrate. Moreover, Te Punga's (1953) Upper, Middle, and Lower Rangitikei Formation nomenclature is no longer acceptable in modern stratigraphic codes. Consequently, we restrict the use of the name Rangitikei to the cyclothemic strata between the top of the Mangaweka Formation and the Vinegar Hill Tephra, and raise its rank to group status. Our redefinition of the name Rangitikei raises the issue of its historical preoccupation elsewhere in the Rangitikei Valley. The names Upper and Lower Rangitikei Formations applied by Te Punga (1953) to strata above and below the Rangitikei Group, respectively, have not been adopted by subsequent workers. Fleming (1953) recognised the nomenclatural difficulties and therefore included Mangaweka Mudstone as a formation of the Paparangi Group. The other units within Te Punga's (1953) Lower Rangitikei Formation are clearly formations and we are currently working on their redefinition. As for the Upper Rangitikei Formation, subsequent workers (Seward et al. 1986; Pillans et al. 1994) have applied Fleming's (1953) nomenclature by correlation with the Wanganui Subdivision, and we follow this practice here by using the name Maxwell Group for strata above the Vinegar Hill Tephra. In time, when detailed field examination is undertaken, it may be appropriate to revise the nomenclature for strata in the Rangitikei Valley above our new Rangitikei Group.

TYPE SECTION: Strata exposed in Rangitikei River valley from Mangarere Road (grid ref. T22/483496) to Vinegar Hill Bridge (T22/357380) constitute the type locality of the group.

UPPER AND LOWER BOUNDARIES: In the Ohingaiti region, the lower contact of the Rangitikei Group is unconformable with massive siliciclastic siltstone of the underlying Mangaweka Formation, and is marked by an easily recognised 1 m thick layer of bluff-forming concretionary sandstone. We place the upper boundary at a prominent 20 cm thick, pinky-white, rhyolitic tephra, which is interbedded in fossiliferous sandy siltstone previously ascribed to Maxwell Group equivalent strata. This tephra is named the Vinegar Hill Tephra and is described fully by Naish et al. (in press). In the Rangitikei River section, the Vinegar Hill Tephra occurs 130 m above the base of the Vinegar Hill Formation, which includes the Waipuru Ash (Seward 1976; Naish et al. in press). Previous workers (Seward 1976; Beu & Edwards 1984) may have miscorrelated the Waipuru Ash with a burrowed rhyolitic ash preserved in laminated silts and sands of the Tewkesbury Formation at Brunswick Road (R22/783502) in Kai-iwi

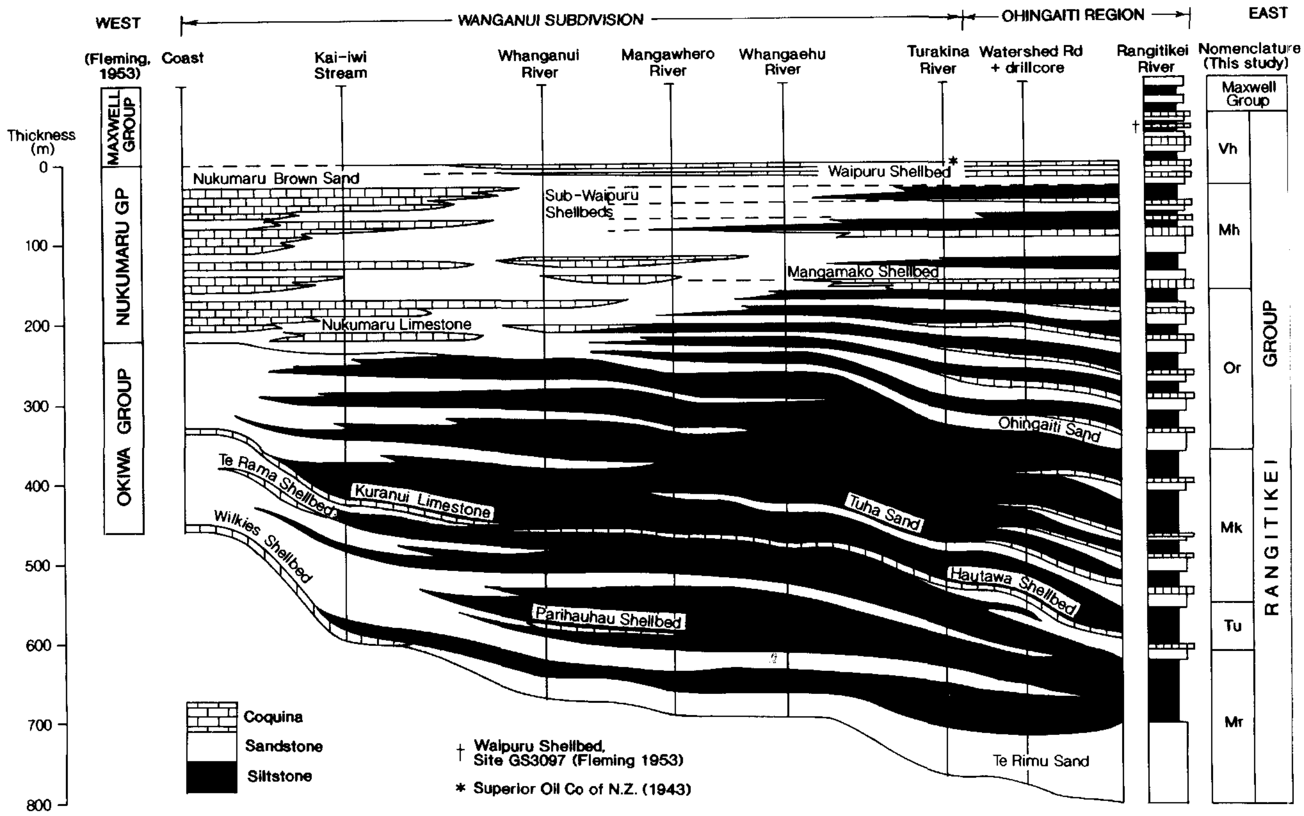

Fig. 10 Schematic basinwide east–west cross-section illustrating the stratigraphic relationships between the Rangitikei Group and the stratigraphy of Fleming (1953) and Superior Oil Co. of N.Z. (1943).

valley, western Wanganui Basin. New chemical data (Pillans pers. comm.) indicate that the tephra at Brunswick Road may be a correlative of the Vinegar Hill Tephra, and the older Waipuru Ash may not be exposed at Brunswick Road. In western Wanganui Basin, the boundary between Okiwa and Maxwell Group strata is placed at the top of the "Waipuru Shellbed" (Fleming 1953), which is problematic as the "Waipuru Shellbed" is easily confused with a number of stratigraphically younger and older, faunally similar shellbeds. Our criteria for assigning the upper boundary of the Rangitikei Group to the Vinegar Hill Tephra rather than to the Waipuru Shellbed include the following: (1) the Vinegar Hill Tephra provides a regionally extensive, distinctive lithologic and isochronous marker bed, which enables direct comparisons to be made between the Rangitikei Group and the established Wanganui Subdivision lithostratigraphy; (2) in eastern Wanganui Basin, the "Waipuru Shellbed" is difficult to distinguish unequivocally from other shellbeds and it does not mark a distinctive lithologic change in the succession; and (3) the cyclothemic strata above the Vinegar Hill Tephra contain more pumice and, in addition, regularly alternating siltstones and sandstones give way to a dominance of coarse-grained, shallow marine to nonmarine facies.

THICKNESS: (Fig. 6) The composite thickness of Rangitikei Group strata in the Rangitikei River is c. 950 m. Here the sedimentary succession is almost entirely exposed. Throughout the Ohingaiti region, Rangitikei Group is laterally extensive and generally maintains a consistent thickness and lithologic character.

AGE: A late Pliocene age (c. 2.6–1.7 Ma) has been established for the group on the basis of isothermal plateau fission track (ITPFT) dating of rhyolitic tephra (Alloway et al. 1993; Naish et al. in press), paleomagnetic data (Seward et al. 1986; Wilson 1993; Naish et al. in press), and macrofossil (Fleming 1953) and microfossil content (Beu & Edwards 1984). Key chronostratigraphic datums are illustrated in Fig. 6 for the Rangitikei River section. The Mangapanian/Nukumaruan Stage boundary is located in the Rangitikei Group at the base of the Hautawa Shellbed. It is defined by the first appearance of *Chlamys delicatula* in the Rangitikei River section (new locality), and by correlation with the occurrence of *Globorotalia crassula* and dominantly dextrally coiled *G. crassiformis* at a site in the Mangawhero Valley (Beu & Edwards 1984). The Gauss–Matuyama paleomagnetic transition (2.6 Ma; Shackleton et al. 1990; Hilgen 1991) in Rangitikei River was located by Wilson (1993) within the Mangaweka Formation c. 70 m below the base of the Rangitikei Group. Paleomagnetic determinations of Seward et al. (1986) and Naish et al. (in press) indicate that the upper Mangaonoho Formation and most of the Vinegar Hill Formation fall within the Olduvai Normal Subchron (1.95–1.77 Ma). New ITPFT ages of 1.87 Ma (±0.15 Ma) and 1.75 Ma (±0.13 Ma) on the Waipuru Ash and Vinegar Hill Tephra, respectively (Naish et al. in press), support the stratigraphic location of the Olduvai Subchron determined by Seward et al. (1986). Moreover, Edwards (1976) placed the first appearance of the coccolith *Gephyrocapsa sinuosa* in the Rangitikei River section within the Waipuru Shellbed (GS3097; Fleming 1953). *Gephyrocapsa sinuosa* is thought to have evolved near the base of the Olduvai Subchron (c. 1.9 Ma). ITPFT ages on tephra and new paleomagnetic data for the Rangitikei River section (Naish et al. in press) indicate that the Pliocene–Pleistocene boundary, as defined at Vrica, Italy (Aguirre & Pasini 1985), occurs c. 60 m below the Vinegar Hill Tephra (Fig. 6)

CONSTITUENT FORMATIONS: The Rangitikei Group comprises in ascending order: Mangarere Formation, Tikapu Formation, Makohine Formation, Orangipongo Formation, Mangaonoho Formation, and Vinegar Hill Formation. Constituent members are illustrated in Fig. 7A–F. Prominent members of each formation and their western Wanganui Basin correlatives include: $Mrcfm_1$ and $Mrsm_1$ = Te Rimu Formation; $Tucm_1$ = Hautawa Shellbed; $Mksm_1$ = Tuha Sand; $Orsm_1$ = Ohingaiti Sand; $Mhcm_1$ = Mangamako Shellbed; and $Vhcm_4$ = Waipuru Shellbed.

MANGARERE FORMATION (new)

NAME: The name Mangarere Formation derives from Mangarere Stream, which enters the Rangitikei River immediately south of the township of Mangaweka, and is applied to all strata located stratigraphically between the Mangaweka Mudstone and the base of the Tikapu Formation. Fleming (1953) applied the name Te Rimu Sand to strata in the Wanganui Subdivision previously mapped as Basal Nukumaruan Sand by Superior Oil Co. of N.Z. (1943). The name is adopted here for the lowermost sandstone member in the Mangarere Formation.

TYPE SECTION: Site 1 (Fig. 1; T22/500474), Mangarere Road.

REFERENCE SECTIONS: Site 2 (Fig. 1; T22/476475), east bank Rangitikei River on a farm track. Site 3 (Fig. 1; T22/466473), east bank Rangitikei River.

THICKNESS: c. 200 m (Fig. 7A).

AGE: Mangapanian (late Pliocene).

LITHOLOGY: (Fig. 7A) *Basal channel-fill conglomerate member ($Mrcfm_1$).* Locally, the base of the Mangarere Formation is deeply channelled (up to c. 30 m) into underlying Mangaweka Formation east of the Rangitikei River in Mangarere Stream (T22/497480; Fig. 5A) and along State Highway 43 (T22/536497). Disoriented indurated clasts of underlying Mangaweka Formation siltstone (up to 2 m diameter), and smaller (up to 50 cm diameter) blocky, dark brown silty clasts of possible pedogenic origin, are randomly supported in a silty sand matrix. At Mangarere Stream, channel-fill conglomerate is overlain by wavy laminated fine sand and silt interbeds.

Te Rimu Sand—Siliciclastic sandstone member ($Mrsm_1$). A conspicuous 1 m thick, well-cemented, bluff-forming concretionary sandstone marks the lower unconformable contact of the Mangarere Formation where it is not channelled into underlying Mangaweka Formation. Predominantly uncemented, moderately well sorted (at base), bioturbated, brownish-grey, medium-grained, low-angle and trough cross-stratified to parallel-laminated siliciclastic sandstone grades upsection into thick-bedded to massive silty sandstone. East of the Rangitikei River (Site 1, Fig. 1), near the lower contact, cross-stratified, locally cemented, coarse bioclastic sand lenses develop within finer grained silty sandstones, and grade upsection into a larger scale, low-angle, cross-stratified siliciclastic sandstone lithofacies. Soft-sediment deformation features occur commonly.

Siliciclastic siltstone member ($Mrzm_1$). Horizontally bedded, fine sandy siltstone grades upwards into massive and bioturbated, blue-grey concretionary siltstone, which becomes increasingly sandy again before grading into silty sandstone at the base of the Hautawa Formation.

DEPOSITIONAL ENVIRONMENT: Coarse-grained members of the Mangarere Formation represent a broad deepening-upwards transgressive facies assemblage. Sedimentary structures and fauna indicate deposition in shoreface to inner-shelf environments. Mid-shelf water depths are indicated at the base of $Mrzm_1$ by the in-situ occurrence of the mollusc *Lucinoma galathea.* Progressive shallowing to inner shelf depths is indicated by upward coarsening and the successive appearance upwards within $Mrzm_1$ of *Nemocardium pulchellum*, *Chlamys gemmulata*, and *Atrina pectinata zelandica*.

DISTRIBUTION: Mangarere Formation is well exposed in the north and northeast of the Ohingaiti region where it crops out in the east bank of Rangitikei River and in the south bank of Mangarere Stream. Away from Rangitikei River valley, the base of the formation is easily recognised as a low vegetated bluff, and can be traced west across the region where good exposures occur along Weston Road, near Ohingaiti Reserve on Watershed Road, and in Porewa Valley. Immediately northeast of the region, Mangarere Formation is exposed below Manuka No. 2 trig and in the Mangawharariki Valley, where it is offset by the Rauoterangi Fault.

TIKAPU FORMATION (new)

NAME: Tikapu Formation derives from Tikapu Trig (Fig. 1, 3) and is applied to all strata between the base of the Hautawa Shellbed and the base of the Tuha Sand. Superior Oil Co. of N.Z. (1943, p. 17) applied the name "Hautawa" to the prominent shellbed exposed above Hautawa Stream along "Old Hautawa Road" east of the Rangitikei–Turakina watershed (Site 6, Fig. 1; Fig. 5B). Fleming (1953) adopted the name and mapping of Superior Oil Co. of N.Z. (1943) in the Wanganui Subdivision. The name is retained here and corresponds to the basal coquina member of the Tikapu Formation ($Tucm_1$).

TYPE SECTION: Site 6 (Fig. 1; T22/325484; Fig. 5B), along "Old Hautawa Road" 4WD track at the end of West Road. This site constitutes Fleming's (1953) type locality.

REFERENCE SECTION: Site 4 (Fig. 1; T22/436457; Fig. 5C), Rangitikei River.

THICKNESS: c. 65 m (Fig. 7B).

AGE: Hautawan (late Pliocene). Hautawa Shellbed contains the age-diagnostic fauna *Chlamys patagonica delicatula*, *Phialopecten triphooki*, *Crassostrea ingens*, and *Globorotalia crassula*, and marks the boundary between the Mangapanian and Nukumaruan Stages in Wanganui Basin.

LITHOLOGY: (Fig. 7B) *Siliciclastic sandstone member ($Tusm_1$).* East of Rangitikei Valley, a conspicuous 2–3 m thick bluff-forming concretionary sandstone, which marks the lower gradational boundary of the Tikapu Formation, passes upsection into a 2 m thick interval of crudely bedded to massive and bioturbated, sparsely fossiliferous, fine siliciclastic sandstone.

Hautawa Shellbed—coquina member ($Tucm_1$). A mollusc-rich and brachiopod-rich shellbed supported in a matrix of siliciclastic fine sandstone to fine sandy siltstone unconformably overlies $Tusm_1$ in the east and rests directly upon $Mrzm_1$ in the west of the Ohingaiti region. The unconformity is marked by small-scale erosional relief and is sporadically penetrated by ophiomorpha burrows, which are preserved in the underlying sandstone. The upper portion of the shellbed becomes less fossiliferous and is sharply overlain by massive siliciclastic siltstone. The shellbed thickens westward from 0.5 m in Rangitikei River (Site 4, new locality; Fig. 1) to 4 m at the type section.

Siliciclastic siltstone member ($Tuzm_1$). Massive, blue-grey, bioturbated, concretionary, siliciclastic siltstone coarsens upsection into a fine sandy siltstone. The gradational upper contact is marked by interbeds of sandstone that progressively thicken upwards into overlying Makohine Formation.

DEPOSITIONAL ENVIRONMENT: The faunal content and sedimentary structures are consistent with an inner shelf environment of deposition for the siliciclastic sandstone member ($Tusm_1$). Hautawa Shellbed ($Tucm_1$) was deposited under conditions of terrigenous sediment starvation and represents stratigraphic condensation on an open shelf during marine transgression. Fleming (1953) described an open marine shelfal fauna dominated by *Barbatia*, *Chlamys*, *Purpurocardia*, *Tiostrea*, *Turritellidae*, *Bryozoa*, and *Brachiopoda* for the shellbed. Faunal changes upsection within the shellbed indicate a progressive increase in water depth from inner to mid-shelf environments. The successive upsection occurrence, in siltstone member $Tuzm_1$, of *Chlamys gemmulata*, *Amygdalum striatum*, *Nemocardium pulchellum*, and *Panopea zelandica* are interpreted as a shallowing from mid-shelf to inner shelf environments.

DISTRIBUTION: Tikapu Formation is well exposed in the Rangitikei River (Fig. 6B), Porewa Valley, and above Hautawa Stream. The lower coarse-grained members form a distinctive low bluff, which is easily identified in the field and can be traced from the Rauoterangi Fault west into the Makohine Stream gorge. West of Makohine Stream, the base of the formation is only sporadically exposed, but can be followed to the type section where Hautawa Shellbed is continuously exposed for several kilometres westwards towards the Turakina River. The shellbed thins dramatically towards the east. In contrast, the underlying sandstone member thickens towards the east.

MAKOHINE FORMATION (new)

NAME: The name derives from Makohine Stream (Fig. 1) and applies to all cyclothemic strata between the base of the Tuha Sand ($Mksm_1$) and the base of the Ohingaiti Sand ($Orsm_1$). Superior Oil Co. of N.Z. (1943, p. 18) introduced and applied the name "Tuha Sand" in surveys of the region east of Rangitikei River to the Ruahine Range. The name is derived from Tuha Stream, which enters the Rangitikei River from the east 3 km north of Ohingaiti township. The name and definition are retained here, and the name applies to the lowermost siliciclastic sandstone member of the Makohine Formation.

TYPE SECTION: Makohine Formation is continuously exposed in Rangitikei River from Site 21 (Fig. 1; T22/434455) near the Otara Road bridge to Site 19 (Fig. 1; T22/387438), Makohine Stream.

REFERENCE SECTIONS: $Mksm_1$ to $Mkzm_1$ (Fig. 7C) are exposed at Site 7 (Fig. 1; T22/434450), Otara Road. At Site 20 (Fig. 1; T22/438444), $Mksm_2$ to $Mkzm_3$ (Fig. 7C) crop out in cuttings along Otara Road.

THICKNESS: c. 165 m (Fig. 7C).

AGE: Hautawan (late Pliocene).

LITHOLOGY: (Fig. 7C) Makohine Formation cyclothemic strata comprise four lithologically similar siliciclastic sandstone, siliciclastic siltstone, and coquina members.

Siliciclastic sandstone members ($Mksm_{1-4}$). Mainly uncemented, sparsely fossiliferous, intensely bioturbated, brown to grey, massive to wavy laminated, siliciclastic silty sandstone grades upsection into moderately well sorted, bioturbated, low-angle and trough cross-stratified siliciclastic sandstone. Siliciclastic sandstone members $Mksm_1$ and $Mksm_2$ comprise flaser-bedded sandstone in their upper portions. Members $Mksm_2$ and $Mksm_4$ comprise probable storm and channel-fill molluscan shellbeds, respectively. Several distinctive layers of concretionary sandstone that occur at the base of $Mksm_1$ mark the base of the formation, affording it easy recognition within the Ohingaiti region (Fig. 5D).

Coquina members ($Mkcm_{1-4}$). Siliciclastic fine sandy siltstone mollusc-rich and brachiopod-rich shellbeds sharply overlie all four siliciclastic sandstone members. The lower boundary of the shellbeds is marked by erosional relief (up to 1 m at base of $Mksm_1$; Fig. 5E) and ophiomorpha burrows that penetrate into the underlying sandstones. Shellbeds are abruptly overlain by blue-grey siliciclastic siltstone.

Siliciclastic siltstone members ($Mkzm_{1-4}$). Uncemented, massive and bioturbated, blue-grey sandy siltstone and siltstone grade upsection into massive and crudely bedded, bioturbated, siliciclastic silty sandstone near the base of the overlying siliciclastic sandstone members. $Mkzm_3$ includes a 20 m thick section of normally graded, decimetre scale, fine sandy siltstone beds (Site 20, Fig. 1).

DEPOSITIONAL ENVIRONMENT: The dominant molluscan fauna, *Gari lineolata*, *Scalpomactra scalpellum*, *Panopea zelandica*, *Fellaster zelandiae*, together with the occurrence of a variety of traction-emplaced sedimentary structures, indicate siliciclastic sandstone members were deposited in transitional and shoreface depositional environments. Coquina members accumulated due to stratigraphic condensation on the inner to mid shelf during marine transgression and are dominated by the molluscs *Chlamys*, *Tawera*, *Pleuromeris*, *Tiostrea*, *Gari*, *Nucula*, *Scalpomactra*, and Brachiopoda. Siltstone members are dominated by the mid-shelf molluscan taxa *N. pulchellum*, *A. striatum*, and *Neilo australis*.

DISTRIBUTION: Except for sections in Rangitikei River, along Watershed Road, and in Porewa Stream valley, outcrops of Makohine Formation are sporadic within the Ohingaiti map region. Good but discontinuous exposures occur east of Rangitikei River near Tuha Trig (Fig. 1) and in cuttings along Peka Road. In the west, exposure is typically poor, with isolated outcrops in the hill country either side of the Porewa Valley. Tuha Sand was not mapped by Fleming (1953) in the Wanganui Subdivision, but was recognised by Superior Oil Co. of N.Z. (1943) as a "15 ft thick fine brown muddy sandstone with a fossiliferous zone at the top" in the Turakina Valley, and as a "poorly-developed fossiliferous silty sand" in the Mangawhero Valley c. 65 m above the Hautawa Shellbed.

ORANGIPONGO FORMATION (new)

NAME: Derives from Orangipongo Road and Orangipongo Trig and is applied to all cyclothemic strata between the base of the Ohingaiti Sand (Orsm$_1$) and the base of the Managamako Shellbed (Mhcm$_1$). Superior Oil Co. of N.Z. (1943, p. 19) applied the name "Ohingaiti" to a prominent sandstone clearly exposed for several kilometres along-strike in bluffs on the east bank of the Rangitikei River opposite the township of Ohingaiti (Fig. 5F). Fleming (1953) adopted the name for a sandstone in the Wanganui Subdivision. The name is retained here with member status and corresponds to the lowermost sandstone member of the Orangipongo Formation (Orsm$_1$).

TYPE SECTION: The entire Orangipongo Formation is exposed in the east bank of the Rangitikei River between Site 9 (Fig. 1: T22/393436) and Site 22 (Fig. 1; T22/394426), directly opposite the Rangitira Golf Course (Fig. 1). The type section, which is aligned subparallel to the regional dip, is illustrated in Fig. 8. The type locality for the Ohingaiti Tephra (Ortm$_1$) occurs within the section at Site 10 (Fig. 1).

REFERENCE SECTIONS: Site 19 (Fig. 1; T22/387437), State Highway 1. Site 17 (Fig. 1; T22454433), Mangamako Road.

THICKNESS: c. 170 m (Fig. 7D).

AGE: Nukumaruan (late Pliocene).

LITHOLOGY: (Fig. 7D) Orangipongo Formation cyclothemic strata comprise seven lithologically similar siliciclastic sandstone members, five lithologically similar siliciclastic siltstone members, five coquina shellbed members, and a tephra member. Figure 8 illustrates Orangipongo Formation cyclothemic strata and emphasises the relationships between the formational stratigraphy and the sedimentary cycles that occur within the formation.

Siliciclastic sandstone members (Orsm$_{1-7}$). Uncemented, sparsely fossiliferous, intensely bioturbated, massive to wavy laminated, brown, siliciclastic, silty fine sandstone grade upsection into well-sorted, bioturbated, bidirectional low-angle and trough cross-stratified siliciclastic sandstone. Intensely bioturbated flaser-bedded facies occur in the upper portions of members Orsm$_{4,5,7}$. Soft-sediment deformation and water ejection structures are also common within members. High-angle planar cross-stratified sandstone occurs at the top of Orsm$_5$ (Site 19, Fig. 1).

Coquina members (Orcm$_{1-5}$). Siliciclastic fine sandy siltstone supports a variety of mollusc and brachiopod shellbed members, which sharply overlie siliciclastic sandstone members (Fig. 5F). The lower boundaries of shellbeds may exhibit erosional relief and are often penetrated by the ichnofossil ophiomorpha. Blue-grey siliciclastic silts abruptly overlie the lower three coquina members. Orcm$_4$ and Orcm$_5$ pass gradationally upwards into sandstone.

Siliciclastic siltstone members (Orcm$_{1-5}$). Uncemented, massive and bioturbated, blue-grey, fine sandy siltstone and siltstone, sharply overlie coquina members Orcm$_{1-3}$ (Fig. 5F) and upper sandstone members. Siltstone grades upsection into massive and often crudely bedded or laminated, bioturbated, siliciclastic silty sandstone.

Ohingaiti Ash member (Ortm$_1$). A 1.5 m thick grey, rhyolitic tephra, named "Ohingaiti Ash" by Seward (1976), crops out in the east bank of the Rangitikei River in the type section opposite the Rangitira Golf Course (Fig. 1, 8). Moderately lithified, bioturbated, horizontally bedded, glassy, silty fine sands of the tephra member are interbedded within massive to decimetre-scale, crudely bedded, siliciclastic fine sandstone belonging to Orsm$_4$. The lower contact is abrupt, whereas the upper contact grades upwards into overlying fine sandstones.

DEPOSITIONAL ENVIRONMENT: Sedimentary facies and faunal characteristics of the Orangipongo Formation cyclothemic strata are similar to those of the Makohine Formation. Siliciclastic sandstone members were deposited in transitional inner shelf to shoreface environments. Coquina members that accumulated during transgressions are ascribed a shoreface to shelfal depositional environment, whereas siltstone members accumulated during episodes of sea-level highstand aggradation, and show an upsection-shoaling from mid to inner shelf depositional environments.

DISTRIBUTION: The formation is well exposed in banks of the Rangitikei River and within the deeply incised Mangamako Stream gorge. However, over much of the Ohingaiti region, exposure is generally poor and confined mainly to road cuttings. Of these, the best outcrops occur along Watershed Road, Mangamako Road, and State Highway 1 (Fig. 1). Immediately west of the mapped area, Orangipongo Formation is well exposed in cuttings towards the end of Agnews Road. Between road cuttings and river sections, the base of the Orangipongo Formation is poorly expressed geomorphologically and is seldom exposed.

MANGAONOHO FORMATION (new)

NAME: The formation is named after the settlement of Mangaonoho, located 4 km southwest of Ohingaiti township (Fig. 1), and is applied to all strata between the base of the Mangamako Shellbed and a prominent fossiliferous sandstone member (Vhsm$_1$) that marks the base of the Vinegar Hill Formation. The Superior Oil Co. of N.Z. (1943, p. 20) ascribed the name "Mangamako" to a "50 ft thick, highly fossiliferous, muddy shell-sand zone" in Mangamako Stream, a tributary of the Rangitikei River (Fig. 1). Fleming (1953) adopted "Superior's" mapping with minor emendation in the east of the Wanganui Subdivision. We retain the definition and name in this study. Mangamako Shellbed corresponds to members $Mhcm_1$ and $Mhsm_1$ (Fig. 7E).

TYPE SECTION: Site 11 (Fig. 1; T22/394417), Mangamako Stream. Between Sites 28 and 14 in the banks of the Rangitikei River (Fig. 1).

REFERENCE SECTION: Site 12 (Fig. 1; T22/328423), immediately north of the cemetery on Murimotu Road (Mangamako Shellbed; $Mhcm_1$ and $Mhsm_2$).

THICKNESS: c. 135 m (Fig. 7E).

AGE: Marahauan (late Pliocene).

LITHOLOGY: (Fig. 7E) Mangaonoho Formation strata show a cyclic signature similar to that of the Makohine and Orangipongo Formations. The formation is subdivided into members.

Mangamako Shellbed—coquina member $Mhcm_1$ and sandstone member $Mhsm_1$. This prominent basal 15 m thick member ($Mhcm_1$) comprises a lower 1 m thick siliciclastic fine sandy silt supported shellbed, which unconformably overlies Orangipongo Formation strata. The lower contact is marked by very low angle truncation of the underlying beds (Fig. 5G). Upsection, a densely packed, reworked (at base), trough cross-stratified, pebbly shell conglomerate is scoured into underlying mollusc-rich silty sands. Mollusc valves exhibit imbrication aligned parallel to bedding. In the upper portion of the shellbed, a siliciclastic fine sandstone ($Mhsm_1$) supports abundant in-situ or near-situm molluscan fauna, and passes upwards into less fossiliferous, horizontally bedded sandy siltstone. Prominent sharp discontinuities, which are penetrated by ophiomorpha burrows, occur in the upper half of the coquina member. A 20 cm thick reworked megascopic tephra was observed within Mangamako Shellbed Member ($Mhcm_1$) in Simpsons Reserve drillcore, and comprises a concentrated layer of hornblende, hypersthene, minor augite, and rare andesitic volcanic glass within siliciclastic sandy siltstone. The tephra does not appear to be present at the type section.

Coquina members ($Mhcm_2$ and $Mhcm_4$). Siliciclastic fine sandy siltstone supports mollusc and brachiopod shellbed members, which sharply overlie siliciclastic sandstone members. The lower boundaries of shellbeds exhibit erosional relief and are penetrated by the ichnofossil ophiomorpha at many sites. $Mhcm_3$ occurs conformably within sandy siltstone lithologies.

Siliciclastic sandstone members ($Mhsm_2$ and $Mhsm_3$). Brownish-grey, bioturbated, massive to laminated siliciclastic silty fine sandstone grades upsection into bidirectional low-angle cross-stratified, wavy laminated and flaser-bedded siliciclastic sandstone.

Siliciclastic siltstone members ($Mhzm_{1-4}$). Massive, blue-grey, bioturbated, siliciclastic fine sandy siltstone coarsens upsection into decimetre-scale, crude horizontally bedded and wavy laminated, fine silty sandstone. Upper contacts are gradational into siliciclastic sandstone facies.

DEPOSITIONAL ENVIRONMENT: All four coquina members represent stratigraphic condensation during a period of marine transgression. Mangamako Shellbed ($Mhcm_1$ and $Mhsm_1$) was deposited within the shore-connected sand prism in a position further shoreward than older coquina members. The faunal content and sedimentary structures show dramatic upsection deepening from nearshore (e.g., *Amalda australis* and *Ruditapes largillierti*) to inner (e.g., *Tawera*) and mid-shelf environments (e.g., *Chlamys*, *Tiostrea*, and Bryozoa). A shallow-water foreshore-shoreface fauna is dominated by *Dosinia* spp., *Bassina yatei*, *Fellaster zelandiae*, and *Lutraria solida* within the lower part of coquina member $Mhcm_4$ (Site 14, Fig. 1). Fauna preserved in coquina member $Mhcm_2$ and $Mhcm_3$ are similar to many older coquina members that accumulated in an open marine shelf environment. Siltstone members contain molluscan fauna indicative of shelfal deposition, whereas sandstone members are interpreted as having accumulated in transitional inner shelf to shoreface depositional environments.

DISTRIBUTION: Mangamako Shellbed is well exposed in Mangamako Stream. Although only sporadically exposed west of the Rangitikei River, the formation can be traced across the Ohingaiti map region due to the distinctive steep slope geomorphology produced by the basal Mangamako Shellbed member. East of the Rangitikei River the formation thins and appears to lose its distinctive lithologic character. West of Hunterville, where exposures of Mangaonoho Formation equivalent strata occur along Ongo Road, the formation coarsens dramatically towards Turakina River. Siltstone members grade laterally into fossiliferous silty sandstone and sandstone.

VINEGAR HILL FORMATION (new)

NAME: Derived from Vinegar Hill, 5 km northeast of the township of Hunterville (Fig. 1), the name Vinegar Hill Formation is applied to strata between the base of a prominent fossiliferous sandstone ($Vhsm_1$; Fig. 7F), located in the Rangitikei River 1.5 km upstream from the Vinegar Hill Bridge (Site 15, Fig. 1), and the top of the Vinegar Hill Tephra. The formation includes New Zealand Geological Survey fossil locality GS3097 (Fleming 1953) within the Waipuru Shellbed (Site 24, Fig. 1). The name "Waipuru" was applied by Fleming (1953) to the "Waipuru Fossiliferous Sand", a unit previously mapped westward from Rangitikei River to Kai-iwi Stream by Superior Oil Co. of N.Z. (1943, p. 20). The stratigraphic locality GS3097 (Fleming 1953) is shown in Fig. 7F and corresponds to an interval of fossiliferous siltstone ($Vhzm_3$) and a shellbed ($Vhcm_4$) in a road cutting on SH1 immediately north of the Hunterville–Fielding road intersection. The name derives from Waipuru Stream (Fig. 1) and is retained here with member status to maintain historical continuity of usage.

TYPE SECTION: Vinegar Hill Formation is exposed in banks of the Rangitikei River south of Site 15 (Fig. 1; T22/363388) and in cliffs opposite the Vinegar Hill Domain. Faulting complicates exposure in sections downstream of the bridge, but middle portions of the formation are well exposed along a farm track at Site 23 (Fig. 1) and along Vinegar Hill Road (Sites 16, 24; Fig. 1). The Rangitikei River section, farm track, and road exposures in the vicinity of Vinegar Hill are designated as the type locality of the formation. Upper portions of the formation, including the Vinegar Hill Tephra, are accessible in gullies between Vinegar Hill and Cooks Roads.

THICKNESS: c. 135 m (Fig. 7F).

AGE: Marahauan (late Pliocene).

LITHOLOGY: (Fig. 7F) Vinegar Hill Formation has much in common with the Makohine, Orangipongo, and Mangaonoho Formations that underlie it, as it comprises cyclothemic strata that can be subdivided into groups of lithologically distinctive members.

Coquina members (Vhcm$_{1-5}$). Within the Vinegar Hill Formation, four coquina members comprise a dense molluscan fauna supported in siliciclastic silty sandstone and vary in thickness from 1 to 5 m. It is likely that Superior Oil Co. of N.Z. (1943) included Vhcm$_{1,2,3}$ in their mapping of the "Waipuru Fossiliferous Sand". Vhcm$_{1,3,4,5}$ occupy the basal position of cycles, whereas Vhcm$_2$ occurs in a mid-cycle position.

Siliciclastic sandstone members (Vhsm$_{1-5}$). Uncemented, bioturbated, massive, and moderately fossiliferous silty fine sandstone passes upsection into wavy laminated and flaser-bedded fossiliferous sandstone. Sedimentary structures in members Vhsm$_2$ and Vhsm$_4$ have been largely obscured due to intense bioturbation; however, wavy lamination and crude horizontal bedding does occur. Vhsm$_5$ comprises flaser-bedded and wavy-laminated sandstone.

Siliciclastic siltstone members (Vhzm$_{1-4}$). Uncemented, massive and bioturbated, moderately fossiliferous sandy siltstone grades upwards into sandstone. Lower portions of Vhzm$_2$ and Vhzm$_3$ contain an abundant in-situ molluscan shelfal fauna.

Waipuru Ash member (Vhtm$_1$). A 2 cm thick, grey, bioturbated, silicic volcanic ash, named the "Waipuru Ash" by Seward (1976), is interbedded in fossiliferous sandstone member Vhsm$_4$ (Site 15, Fig. 1, T22/361387; Seward 1976; Naish et al. in press). The underlying contact is sharp, irregular, and intensely burrowed.

Vinegar Hill Tephra member (Vhtm$_2$). A 20 cm thick pinky grey silicic volcanic ash and pumice horizon preserved within fossiliferous sandy siltstone crops out in a cutting along Vinegar Hill Road (Site 16, Fig. 1, T22/350387). This unit is named the "Vinegar Hill Tephra" and described fully in Naish et al. (in press).

DEPOSITIONAL ENVIRONMENT: We report an open marine shoreface to inner shelf faunal assemblage for coquina members, the dominant molluscs being *Purpurocardia, Tiostrea chilensis lutaria, Notocorbula zelandica, Tawera subsulcata, Gari lineolata, Maorimactra ordinaria,* and *Bassina yatei.* Intense bioturbation and diagnostic open marine fauna are indicative of an inner to mid-shelf depositional environment for the siliciclastic siltstones. The occurrence of ripple-laminated and flaser-bedded structures in upper portions of sandstone members suggests tidal conditions during deposition.

DISTRIBUTION: Vinegar Hill Formation is exposed in the south of the Ohingaiti region, although the most continuous exposures are confined to the Rangitikei River valley.

DISCUSSION

Regional correlations and depositional setting

Figure 10 illustrates east–west correlations of late Pliocene sediments across Wanganui Basin, based on maps and stratigraphic columns published in Superior Oil Co. of N.Z. (1943), Fleming (1953), and in this paper. The cross-section is necessarily partly schematic, because individual cyclothems cannot be mapped across major interfluves, and therefore some correlations are inferred. It is also a composite cross-section, as each of the named sections are built up of strata that dip to the south, and therefore older units occur many kilometres to the north of the younger units. Furthermore, we have not presented new stratigraphic descriptions for strata exposed in river sections west of the Ohingaiti region, which almost certainly contain a more detailed lithostratigraphy than described by earlier workers. Nevertheless, several fundamental features of the late Pliocene stratigraphy emerge from Fig. 10.

Notwithstanding the lack of a significant lithologic distinction in the Rangitikei River section between units above and below the Ohingaiti Sand, there is clearly a major lithologic distinction across the Wanganui Subdivision between the muddy Okiwa Group and the sandy and calcareous Nukumaru Group. During deposition of the Okiwa Group and the lower Rangitikei Group, the basin depocentre was located between Mangawhero and Turakina Rivers, where the thickest and finest grained sediments now occur. The lesser accommodation generated toward the basin margins during this time (early Nukumaruan) is reflected in the occurrence of sandy regressive shoreline deposits that prograded towards the depocentre during sea-level highstands and initial stages of sea-level fall, and which now help to define the lithologic character of the cyclothems. Some sandstone units appear to have accumulated across the entire basin, and these are the horizons that Superior geologists mapped during their evaluation of its hydrocarbon prospectivity. The bidirectional interfingering nature of sandstone units implies that the sandy sediments, at least, were sourced from two directions at the time, one from the northeast and the other from the northwest.

During deposition of the Nukumaru Group and the upper part of the Rangitikei Group (late Nukumaruan), the basin depocentre was located east of its earlier position in the vicinity of the Rangitikei River valley, as judged by the thickness distribution of strata and the occurrence of finer grained deposits (Fig. 10). It is the combination of the late Nukumaruan persistence of siltstone deposition and the early Nukumaruan occurrence of sandstone in the Rangitikei River valley, a pattern resulting from depocentre migration and sediment supply, which caused the lithologic distinction between the Okiwa and Nukumaru Groups to diminish eastwards toward the Ohingaiti region, thereby warranting the erection of the Rangitikei Group. The ratio of sandstone to siltstone in late Pliocene cyclothemic strata of the Rangitikei Group exposed in the Ohingaiti region is characteristic of eastern Wanganui Basin, and our proposed lithostratigraphic nomenclature may be more applicable to eastern portions of the Wanganui Subdivision than previously established schemes.

The dominance of siltstone in the Okiwa Group and in the lower part of the Rangitikei Group, together with the occurrence of thick cyclothems, suggests that basin infilling was strongly aggradational during the early Nukumaruan. At this time, sedimentation rates probably matched subsidence rates, and similar depositional environments were maintained during accumulation of successive cycles. In contrast, during the late Nukumaruan (Nukumaru Group and upper Rangitikei Group deposition), basin infilling was strongly progradational. Cyclothems are thinner and coarser grained than the underlying cyclothems and show a significant upsection basinward shift to shallower water facies. The change from aggradation to progradation during the mid Nukumaruan is probably of tectonic origin, and results from a decrease in the rate of subsidence in the Ohingaiti region concomitant with migration of the tectonic hinge line southward into the basin, thereby resulting in coeval progressive uplift of its northern margin.

Origin of cyclicity in the Rangitikei Group

The lithostratigraphy documented in this paper for the Rangitikei River valley, between Mangaweka and Vinegar Hill, illustrates a remarkable on-land succession of nearly continuously exposed late Pliocene–early Pleistocene marine cyclothems. The 20 sedimentary cycles revealed in this part of the basin are considered to have formed through the interplay of subsidence, sediment supply, and glacio-eustatic sea-level fluctuations, but fundamentally, the alternation of fine-grained to coarse-grained members in each cycle results from climatically driven sea-level changes corresponding to oxygen isotope stages 100 to 58. Within each cycle, siltstone members accumulated in mid-shelf environments (50–100 m water depth), whereas overlying sandstone members accumulated in shallower water inner shelf and shoreface environments (0–50 m water depth). The repetitive changes in water depth of 50–100 m magnitude inferred for successive units is consistent only with glacio-eustatic sea-level changes, and correspond to an interval of Earth history (late Pliocene) when successive glaciations in the Northern Hemisphere are well documented (Shackleton et al. 1984; Raymo 1994). Moreover, the chronology of the Rangitikei River section indicates that Rangitikei Group cyclothems have accumulated during short duration, 41 ka cycles in continental ice volume attributed to a dominance of the Milankovitch obliquity orbital parameter (Raymo et al. 1989; Joyce et al. 1990).

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