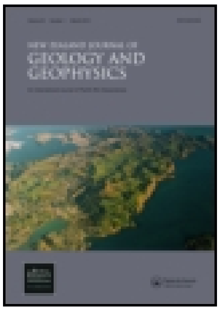

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Pliocene-Pleistocene (Nukumaruan) lithostratigraphy of the Tangoio block, and origin of sedimentary cyclicity, central Hawke's Bay, New Zealand

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Pliocene–Pleistocene (Nukumaruan) lithostratigraphy of the Tangoio block, and origin of sedimentary cyclicity, central Hawke's Bay, New Zealand

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Abstract Eleven formations are defined within the Pliocene–Pleistocene Petane Group in a 450 km² uplifted area of central Hawke's Bay (Tangoio block). In ascending order these are: **Waipunga Formation** (new), Esk Formation, **Tutira Formation** (new), **Aropaoanui Formation** (new), **Darkys Spur Formation** (new), **Mairau Formation** (new), Tangoio Formation, Te Ngaru Formation, Waipatiki Formation, Devils Elbow Formation, and Kaiwaka Formation. Petane Group strata are cyclothemic and alternate between coarse-grained lithofacies (greywacke gravel, siliciclastic and carbonate sand/sandstone and bioclastic limestone) ascribed to nonmarine and inner shelf depositional environments, and sandy/muddy-silt ("papa") ascribed to mid-shelf deposition. The Petane Group is characterised by remarkable lateral continuity of formations, contrasting with conspicuous vertical changes. This stratigraphic style is consistent with glacio-eustatic sea-level fluctuations as proposed by Vella and Beu & Edwards, whereby coarse-grained lithofacies were deposited during sea-level low stands and fine-grained lithofacies were deposited during sea-level high stands. Foraminifera extracted from low-stand lithofacies display opposite $\delta^{18}O$ signatures to that predicted for glacio-eustasy, a result of synsedimentary seawater dilution during sea-level low stands, and/or isotopic exchange during meteoric diagenesis. Stratigraphic and sedimentary criteria indicate that the Petane Group was deposited under unique circumstances of rapid basinal subsidence and a high rate of sedimentation. This offers an explanation for the general rarity of cyclothemic successions in the Pliocene–Pleistocene stratigraphic record.

Keywords Petane Group; inner and mid-shelf sedimentation; Pliocene–Pleistocene; Nukumaruan; Tangoio block; cyclothems; cyclicity; sea-level change; glacio-eustasy; $\delta^{18}O$; isotopes

INTRODUCTION

Shallow eastward-dipping (2–10°) Pliocene–Pleistocene (Nukumaruan Stage) strata crop out in a 450 km², tectonically undeformed, elevated region, referred to here as the Tangoio block, north of Napier in central Hawke's Bay (Fig. 1 & 2). Strata display exceptional cyclicity between fine-grained

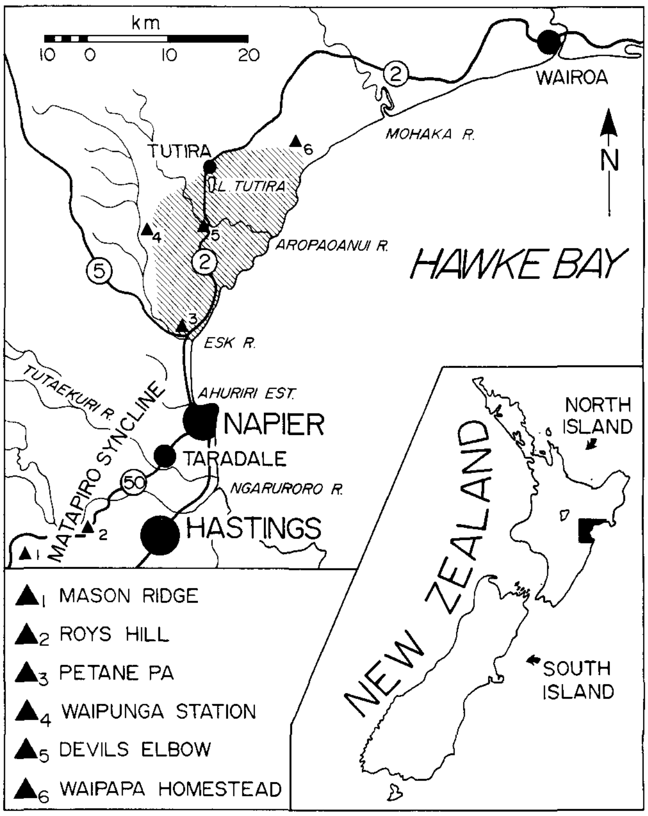

Fig. 1 Map of place names and physiographic features mentioned in the text. The Tangoio block is shaded.

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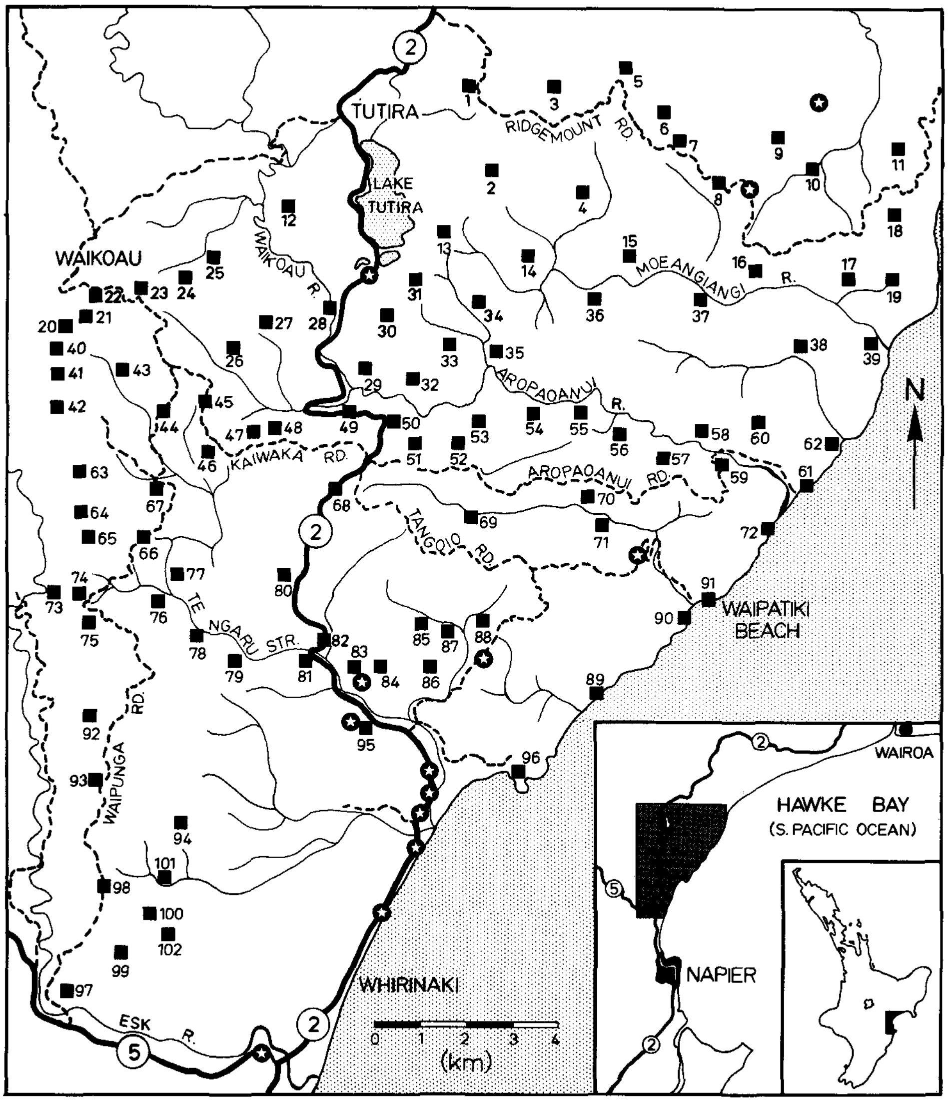

Fig. 2 Map of the Tangoio block indicating positions of logged sections (including reference sections) and other sample sites (stars). Logs for sections 1–102 are contained in Haywick (1990).

lithofacies (silt and sandy/silt) and coarse-grained lithofacies (sand/sandstone and limestone), the nature of which is fully described and interpreted in Haywick (1990) and Haywick et al. (in prep.). Five cyclothemic couplets are recognised, each of which is stratigraphically distinctive and regionally extensive across the Tangoio block (Fig. 3). Coarse-grained lithofacies are very well exposed and form prominent scarps in the Tangoio block (Fig. 4). Fine-grained lithofacies form steep slopes between scarps and are exposed in numerous slumps (Lowe 1987).

The Tangoio block is an exceptional example of late Neogene cyclothemic sedimentation and is unequalled in central Hawke's Bay for quality of exposure and stratal continuity. Distinguishing between separate cyclothems by means of an established lithostratigraphic nomenclature is vital as a precursor to chronostratigraphic compilation and for modelling the depositional and diagenetic histories of the Petane Group. Although a number of names have been employed for the Pliocene–Pleistocene strata of central Hawke's Bay, including some introduced last century (e.g., McKay 1886, 1887), no unified or embracing scheme is currently available and many names are either ambiguous, confusing, or not adequately defined. In a preliminary stratigraphic description, Beu & Edwards (1984, their fig. 6) presented a composite column of central Hawke's Bay rocks which was based upon sequences found in both the Tangoio block and inland from Napier, near Taradale. Inclusion of names derived from sections near Taradale is inappropriate for defining type and reference sections within the Tangoio block, and more appropriate names are presented here; however, the revised nomenclature incorporates, wherever possible, pre-existing names and continuity of usage.

This paper defines a formal lithostratigraphy for the Tangoio block based on detailed logging of over 100 sections (Fig. 2) and comprehensive mapping of the region by Haywick (1990) (Fig. 5). We refer all Nukumaruan strata in this block to the Petane Group (after Petane Series of McKay 1887), which consists of 11 formations. We also discuss the origin of cyclicity within the Petane Group given the tectonic setting of the Tangoio block and the prevalence of glacio-eustatic sea-level changes during the Pliocene–Pleistocene. New $\delta^{18}O$ data obtained from isotopic analysis of foraminifera are also presented.

SEDIMENTARY NOMENCLATURE

Carbonate grain content of coarse-grained lithofacies varies from 0 to 100%, and many sand and gravel-grade sedimentary

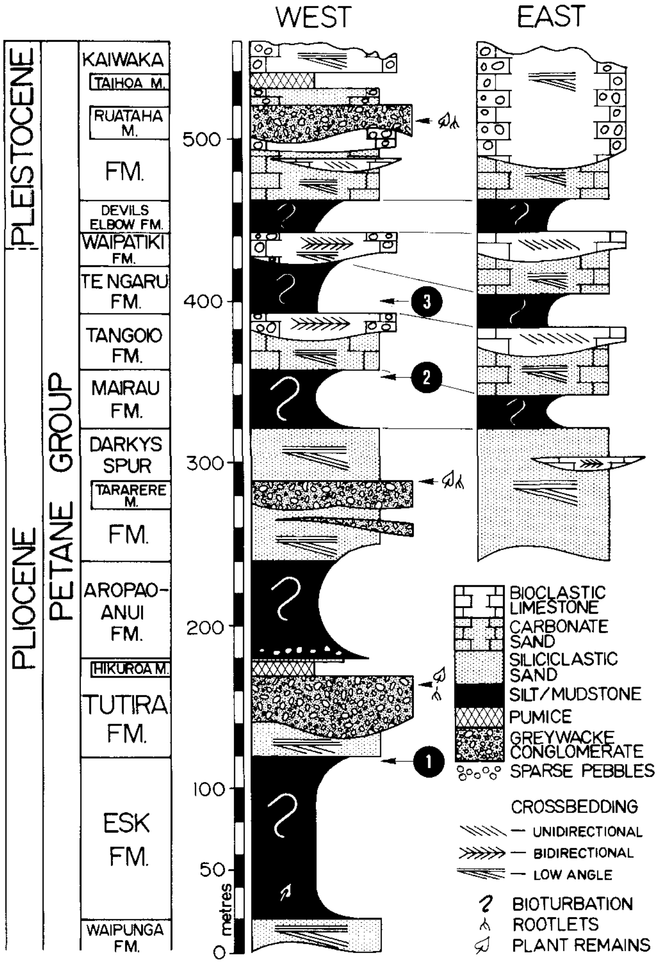

Fig. 3 Composite stratigraphic column for the Petane Group in the Tangoio block, based upon sections in the west and east. Formation thickness and lithologies are derived from type and reference sections. Refer to text for discussion of sedimentary nomenclature. Fossil data: (1) Last Appearance *Globorotalia crassiformis* (dextral), (c. 2.0 Ma; Hornibrook 1981); (2) Last Appearance *Pelicaria acuminata* (c. 1.85 Ma; Beu & Edwards 1984); (3) First Appearance *Gephyrocapsa sinuosa* (c. 1.8 Ma; Edwards 1976; Beu & Edwards 1984).

units contain between 40 and 60% $CaCO_3$. Existing nomenclatural schemes pertain either to siliciclastic sediments (e.g., Folk 1980) or to carbonate sediments (e.g., Dunham 1962) and are not readily applicable to the mixed sediments of the Petane Group. Hence, we adopt a nongenetic nomenclature to distinguish between carbonate-rich and carbonate-poor lithologies in the Tangoio block:

Sand-grade lithologies $\geq$ 50% $CaCO_3$ grains = carbonate sand/sandstone; < 50% $CaCO_3$ grains = siliciclastic sand/sandstone.

Gravel-grade lithologies $\geq$ 50% $CaCO_3$ grains/clasts = bioclastic limestone; < 50% $CaCO_3$ grains/clasts = (greywacke) gravel/conglomerate.

ISOTOPIC ANALYSIS

Foraminifera were extracted from sediment samples following methods outlined by Hornibrook et al. (1989). Individuals selected for isotopic analysis lacked obvious surficial cement and were carefully washed in distilled water and ethanol to remove loose surface contaminants that may have adhered to the tests. Samples were then cleaned ultrasonically in a very weak solution of hydrochloric acid (c. 2%) to dislodge internal sediment and/or to remove possible fine cement crusts.

$\delta^{18}O$ and $\delta^{13}C$ analysis was performed by A. Andrews of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) laboratories in North Ryde, New South Wales. Samples were heated to 400°C under vacuum for a minimum of 1 h prior to analysis to oxidise any organic material possibly retained by the shells. Isotopic analysis was performed following the procedure of McCrea (1950) and used 100% H_3PO_4 at 25°C. Prepared gases were analysed on a Micromass 602D mass spectrometer relative to the CSIRO laboratory standard. Analyses were corrected using acid-carbonate fractionation factors from Friedman & O'Neil (1977).

LITHOSTRATIGRAPHY

PETANE GROUP

(emended from McKay 1886)

HISTORY: The first stratigraphic reference to rocks in central Hawke's Bay, possibly including the Tangoio block, was by Hochstetter (1864; translated in Fleming 1959, p. 24), who referred to the strata as "Hawkes Bay Series". Hutton (1872) later assigned the rocks group status. Subsequent workers employed names attached to presumed correlatives from elsewhere in Hawke's Bay such as Napier (Limestone) Beds (Buchanan 1870) and Te Aute Limestone (McKay 1877). Bioclastic limestone beds of the Tangoio block were termed Petane Limestone by McKay (1886) and were later incorporated into a more regional Petane Series defined by McKay (1887) as including all beds between the Pohui Series (Pliocene) and the Patangata Series (?early Pleistocene). McKay (1886) derived the name Petane from a Maori pa located on the north side of the Esk River, just upstream from present State Highway 2 at Eskdale (V20/441945*; Fig. 1). The Petane Series was subdivided into Mahia, Waipatiki, and Kaiwaka Beds. Hill (1891) referred to fine-grained sediments in the upper portion of the Kaiwaka Beds as Petane Marls. Most recently, Beu & Edwards (fig 7, in Hornibrook 1983) and Beu & Edwards (1984) introduced the first detailed lithostratigraphic scheme for central Hawke's Bay (Table 1).

UPPER AND LOWER BOUNDARIES: In the Tangoio block, the Petane Group is unconformably overlain by sporadic outcrop of Castlecliffian and widespread Haweran nonmarine greywacke gravel and siliciclastic sand. The lower boundary of the Petane Group is not exposed in the Tangoio block. We tentatively place it at the lowermost siliciclastic sand exposed near Waikoau (sections 21 through 25, Fig. 2 & 5). Elsewhere in Hawke's Bay, rocks of comparable age to the Petane Group overlie Pliocene Te Aute Group with both conformable and unconformable contacts (Beu et al. 1980; Harmsen 1985).

THICKNESS: The exposed thickness of Petane Group strata in the Tangoio block is c. 550 m. The maximum thickness of outcrop in any continuous section is c. 450 m in the western portion of the Tangoio block (sections 21 through 24, Fig. 2), where almost the entire sedimentary sequence is exposed. Lower formations of the Petane Group are not exposed in eastern or southern portions of the Tangoio block.

GEOLOGICAL AGE: The age of the Petane Group has been determined as late Pliocene to early Pleistocene (Nukumaruan Stage) on the

*All map and grid references are based on the 1:50 000 NZMS 260 topographical map sheets.

Fig. 4 Oblique aerial photograph of shallow dipping (c. 3°) Petane Group strata at section 30, east of Lake Tutira. Three bluffs comprising two complete silt-limestone couplets are present in this 200 m thick section. Cyclothems can be correlated throughout the Tangoio block along incised river valleys. Cyclothem 1: Te Ngaru Formation (silt) – Waipatiki Formation (limestone); Cyclothem 2: Devils Elbow Formation (silt) – Kaiwaka Formation (limestone).

basis of micro- and macropaleontology (Hornibrook 1981; Beu et al. 1987). The Pliocene–Pleistocene boundary, as defined at Vrica, southern Italy (Aguirre & Pasini 1985), is placed within the Waipatiki Formation (Beu et al. 1987).

CONSTITUENT FORMATIONS: The group comprises, in ascending order: Waipunga Formation, Esk Formation, Tutira Formation (inclusive of the Hikuroa Member), Aropaoanui Formation, Darkys Spur Formation (inclusive of the Tararere Member), Mairau Formation, Tangoio Formation, Te Ngaru Formation, Waipatiki Formation, Devils Elbow Formation, and Kaiwaka Formation (inclusive of the Ruataha and Taihoa Members).

DISTRIBUTION AND REGIONAL RELATIONSHIPS: The Tangoio block contains only a small portion of the total succession of cyclothemic strata in central Hawke's Bay, but it is the thickest and most continuous section in the region. It also extends higher in the Nukumaruan Stage than any other documented sequence in central Hawke's Bay. Individual formations can be traced across the Tangoio block because of exceptional three-dimensional exposure. The Mairau, Tangoio, Te Ngaru, and Waipatiki Formations can also be traced southward to Taradale (Fig. 1). Sedimentological characteristics and fauna are not diagnostic enough to allow differentiation of separate cyclothems, and, with the exception of the area around Taradale, correlation outside of the Tangoio block is presently not possible with the data

Table 1 Summary of stratigraphic nomenclature applied to Pliocene–Pleistocene strata (including the Petane Group) in the Tangoio block.

McKay (1886, 1887)		Beu & Edwards (1984)	This paper		Epoch/NZ stage		Fossil datums
PETANE SERIES	Waipatiki Beds*	Kaiwaka Limestone	PETANE GROUP	Kaiwaka Fmn	Pleistocene	NUKUMARUAN	
		Devils Elbow Mst		Devils Elbow Fmn			
		Muka/Waipatiki Lst		Waipatiki Fmn	Pliocene		
		Te Ngaru Mudstone		Te Ngaru Fmn			—3— (c. 1.8 Ma)
		Tangoio Limestone		Tangoio Fmn			
	Kaiwaka Beds	Petane Mudstone		Mairau Fmn			—2— (c. 1.85 Ma)
		Park Island Lst		Darkys Spur Fmn			
				Aropaoanui Fmn			
		Conglomerate Mbr		Tutira Fmn			
		Taradale Mudstone		Esk Fmn			—1— (c. 2.0 Ma)
		Waikoau Sandstone		Waipunga Fmn			

*Comprises Petane Limestone and unnamed silt units.
Fossil data: (1) Last Appearance *Globorotalia crassiformis* (dextral) (Hornibrook 1981); (2) Last Appearance *Pelicaria acuminata* (Beu & Edwards 1984); (3) First Appearance *Gephyrocapsa sinuosa* (Edwards 1976; Beu & Edwards 1984).

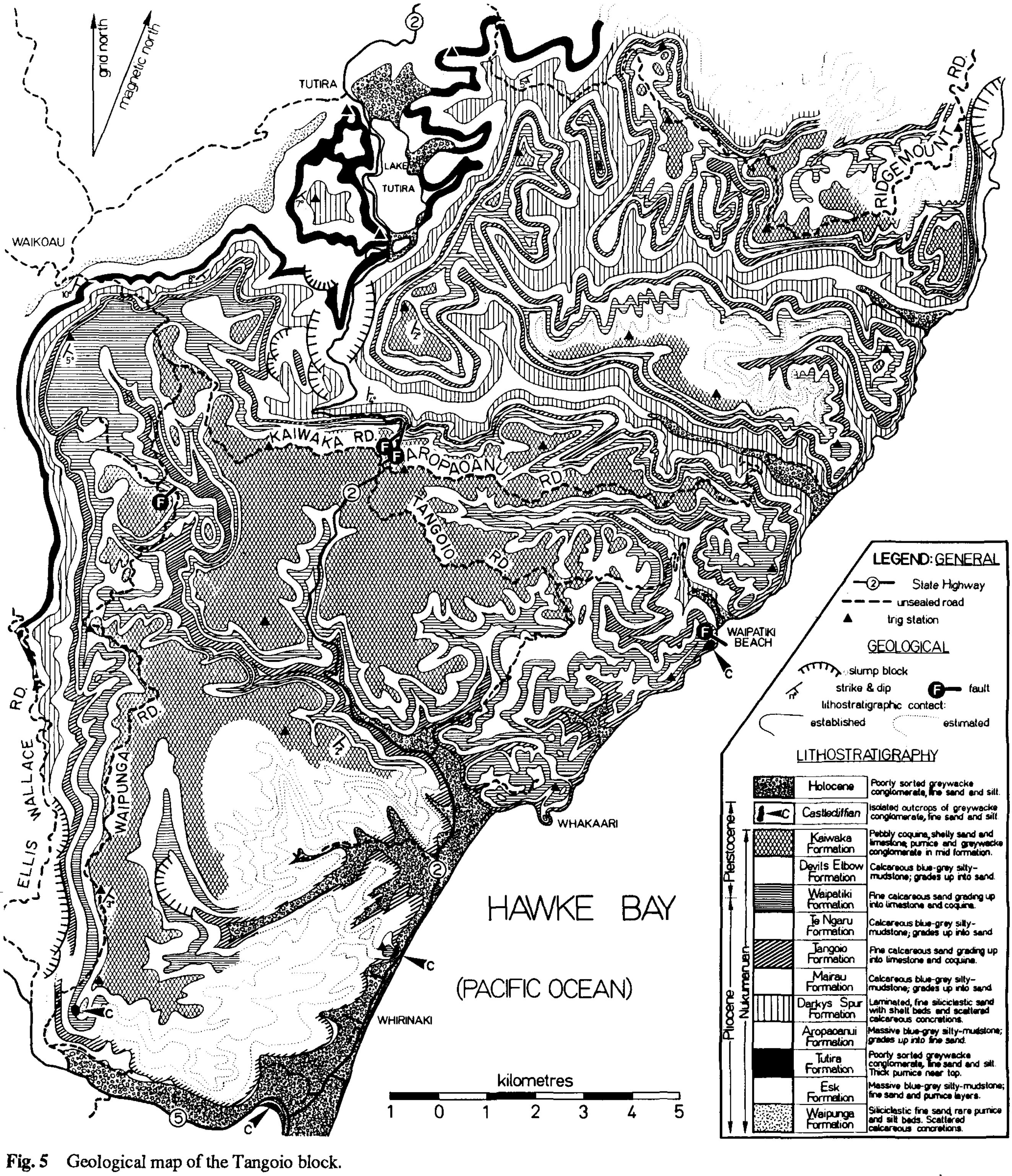

Fig. 5 Geological map of the Tangoio block.

available. Nevertheless, most Nukumaruan beds mapped in eastern central Hawke's Bay by Kingma (1971, map N134; now NZMS 260, sheet V21) display cyclicity and are possible lateral equivalents to the Petane Group. This includes strata exposed along the Matapiro Syncline (Kingma 1971, map N134) across the Ngaruroro River to Mason Ridge and Roys Hill (points 1 & 2, Fig. 1). The gently dipping western limb of the Matapiro Syncline is well exposed in numerous outcrops along the Napier–Taupo road (State Highway 50, Fig. 1), and cyclothemic lithologies continue as far as the Ruahine Range where they are truncated by the Mohaka Fault. In this region, coarse-grained lithofacies are largely composed of greywacke conglomerate rather than sand/limestone.

WAIPUNGA FORMATION

(emended from Beu & Edwards 1984)

NAME: Beu & Edwards (1984) referred to the basal sand unit exposed in the Tangoio block as Waikoau Sandstone; however, this

name is preoccupied elsewhere (Norris & Carter 1980, p. 242). We refer to this stratigraphic unit as Waipunga Formation, named after Waipunga Railway Station; V20/385015 (point 4, Fig. 1).

TYPE SECTION: Waipunga Formation is not fully exposed in the Tangoio block. The most complete section occurs in the west along the Waikoau River (section 25*; V20/422118).

THICKNESS: Maximum thickness exposed in Tangoio block is 20 m.

AGE: Nukumaruan (late Pliocene).

LITHOLOGY: Uncemented, parallel-laminated to low-angle cross-stratified siliciclastic fine sand, rarely interbedded with thin pumiceous sand and commonly interbedded or interlaminated with sandy silt. Scattered calcareous concretions and calcite-cemented intervals occur. Shelly macrofauna (especially bivalves) and comminuted plant material are common. The sediment becomes increasingly poorly sorted upsection and grades into silt of the Esk Formation.

ENVIRONMENT OF DEPOSITION: Sedimentary structures and the molluscan fauna are indicative of an inner shelf depositional environment (c. 10–50 m water depth; Haywick et al. in prep.).

DISTRIBUTION: Waipunga Formation is exposed in the northwestern portion of the Tangoio block between Waipunga Station and Tutira Village (Fig. 5).

ESK FORMATION

(emended from Smith 1877)

NAME: Smith (1877) used the name Esk Papa for a thick sequence of sandy silt exposed along the Esk River to the north of Lake Tutira. Beu & Edwards (1984) applied the name "Taradale" to this unit after the sequence recovered from the Taradale–1 oil well (Darley 1969), but the silt in that well is not clearly correlated with the sequence in the Tangoio block. Esk Formation has priority over, and is preferred to, Taradale Mudstone of Beu & Edwards (1984).

TYPE SECTION: Section 73 (V20/386042), Dunvegan Farm.

REFERENCE SECTION: Section 25 (V20/423114), Waikoau River.

THICKNESS: 100–120 m.

AGE: Nukumaruan (late Pliocene). Upper Esk Formation contains the last appearance datum of *Globorotalia crassiformis* (dextral) (c. 2.0 Ma; Hornibrook 1981; Beu & Edwards 1984; Beu et al. 1987).

LITHOLOGY: Uncemented, massive and bioturbated, blue-grey sandy silt, with common thin interbeds of pumiceous silt and sand, and minor parallel laminated intervals, particularly in lower portions of the formation. Comminuted plant material is also common in the lower part of the formation. Esk Formation contains a diverse open marine fauna throughout (Haywick 1990), and becomes increasingly sandy upsection before grading up into Tutira Formation (Fig. 6).

ENVIRONMENT OF DEPOSITION: Intense bioturbation and a diagnostic open marine fauna are indicative of mid- to outer shelf deposition (c. 50–200 m water depth; Haywick 1990).

DISTRIBUTION: Esk Formation is exposed in the northern and northwestern portions of the Tangoio block between Waipunga Station and Waipapa Homestead (W20/532173; Fig. 1 & 5). It is also exposed in cuttings on the Napier–Taupo highway to the south and west of the Tangoio block.

*Detailed logs of type and reference sections are contained within Haywick (1990), and are available upon request. Locations of these sections are indicated on Fig. 2.

TUTIRA FORMATION

(new formation)

NAME: From Tutira Station (V20/452122) and Lake Tutira (V20/460130).

TYPE SECTION: Section 12 (V20/441126), Tutira Station.

REFERENCE SECTION: Section 23 (V20/408108), Darkys Spur.

THICKNESS: 40–60 m.

AGE: Nukumaruan (late Pliocene).

LITHOLOGY: Uncemented, poorly sorted, massive to parallel-laminated siliciclastic sand grading up into trough-cross-stratified greywacke gravel. The upper Tutira Formation (Fig. 7) contains a thick volcanic ash unit (Hikuroa Member). Interbeds of continuous to lenticular siliciclastic and pumiceous sand and muddy silt are common within gravel and pumice lithofacies. Shells and shell moulds are present towards the base but decrease in abundance upsection where they are gradually replaced by comminuted plant and coaly material, minor lignite seams, and in-situ rootlets in the upper part of the formation. Greywacke gravel interdigitates eastward with siliciclastic pebbly and silty sand. The Tutira Formation is sharply overlain by the Aropaoanui Formation (Fig. 7).

ENVIRONMENT OF DEPOSITION: Lower portions of the Tutira Formation were deposited in inner shelf environments. Upper portions of the Tutira Formation were deposited in nonmarine (fluvial) and estuarine environments (Haywick 1990).

DISTRIBUTION: Tutira Formation is exposed in the northern and northwestern portions of the Tangoio block (Fig. 5) between Waipunga Station and Waipapa Homestead.

Hikuroa Member

(new member of Tutira Formation)

NAME: From Hikuroa Farm (V20/393109).

TYPE SECTION: Section 22 (V20/400105), Hikuroa Farm.

REFERENCE SECTION: Section 25 (V20/426114), Waikoau River.

THICKNESS: 8–15 m.

LITHOLOGY: Uncemented, massive to cross-stratified pumice and volcanic ash with frequent siliciclastic sand and greywacke pebble layers and lenses. Carbonaceous fragments and plant imprints are common and rare in-situ rootlets occur (Fig. 7).

ENVIRONMENT OF DEPOSITION: Nonmarine/estuarine (Haywick 1990).

AROPAOANUI FORMATION

(new formation)

NAME: From Aropaoanui River, the principal river dissecting the Tangoio block.

TYPE SECTION: Section 29 (V20/456086), Aropaoanui River.

REFERENCE SECTION: Section 2 (V20/478136), Tutira Reserve.

THICKNESS: 36–65 m.

AGE: Nukumaruan (late Pliocene).

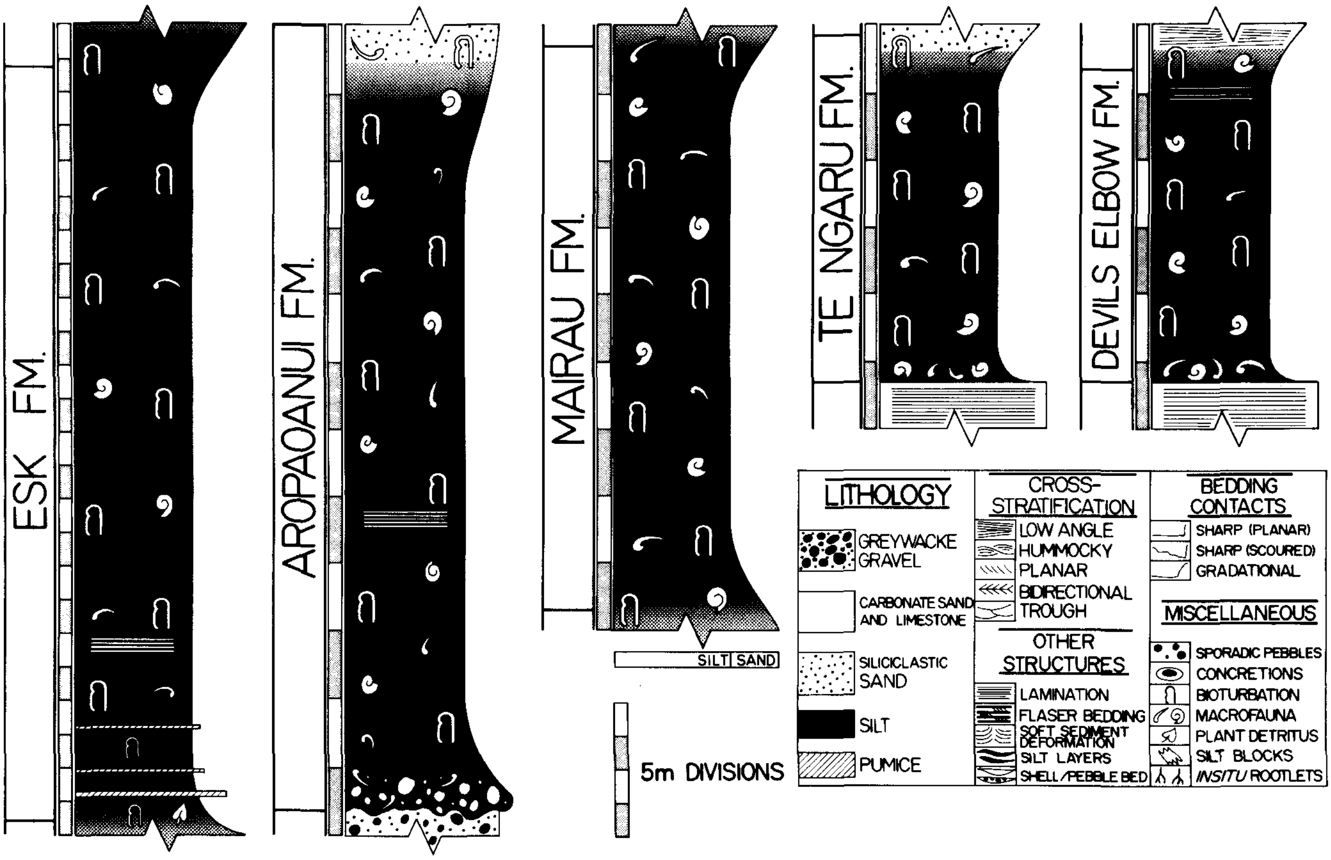

Fig. 6 Schematic stratigraphic columns of type sections for fine-grained (silt) formations in the Petane Group. From left to right: Esk Formation (section 73), Aropaoanui Formation (section 29), Mairau Formation (section 32), Te Ngaru Formation (section 79), and Devils Elbow Formation (section 49).

LITHOLOGY: The base of the formation is marked by a poorly sorted greywacke and pumice cobble layer which contains large disarticulated bivalves, and sharply overlies the Tutira Formation. This bed grades up over 2 m into uncemented, massive and bioturbated blue-grey silt containing a diverse open marine fauna (Haywick 1990). Aropaoanui Formation becomes increasingly sandy upsection and passes gradually into sand of the Darkys Spur Formation (Fig. 6 & 7).

ENVIRONMENT OF DEPOSITION: Mid to outer shelf (Haywick 1990).

DISTRIBUTION: Exposure is widespread over the western and northern portions of the Tangoio block (Fig. 5).

DARKYS SPUR FORMATION

(new formation)

NAME: Beu & Edwards (1984) referred to the thick sand in the middle of the Petane Group as Park Island Limestone. The name is inappropriate as Park Island is near Napier, and correlation between the two areas is uncertain. Darkys Spur Formation is named after a steep cliff near the community of Waikoau.

TYPE SECTION: Section 23 (V20/404106–407105), Kaiwaka Road (Darkys Spur).

REFERENCE SECTIONS: Section 9 (W20/546143), Moeangiangi Station, and section 39 (W20/568097), Ridgemount Farm (mouth of Moeangiangi River).

THICKNESS: 68–90 m (Fig. 8).

AGE: Nukumaruan (late Pliocene).

LITHOLOGY: Uncemented, parallel laminated to low-angle cross-stratified, fine siliciclastic sand, commonly containing beds or lenses of muddy sand and silt. Scattered calcareous concretions and shell layers are common lower in the formation. In the east, concretions coalesce upward into sporadically cemented carbonate sandstone, or rarely, bioclastic limestone containing a diverse shallow marine fauna (Beu 1965; Haywick 1990). Prominent greywacke gravel beds occur within the middle portion of the formation in the west (Tararere Member). This interval grades eastward into fine siliciclastic sand. Darkys Spur Formation becomes increasingly poorly sorted upsection and passes gradually into the Mairau Formation (Fig. 7).

ENVIRONMENT OF DEPOSITION: Sedimentary structures and fauna indicate that the Darkys Spur Formation was deposited in a predominantly inner shelf/strandline depositional environment (c. 0–50 m water depth). Subaerial exposure occurred in the western portion of the Tangoio block during deposition of the Tararere Member (Haywick 1990).

DISTRIBUTION: Exposure is widespread over the western and northern portions of the Tangoio block (Fig. 5).

Tararere Member

(new member of Darkys Spur Formation)

NAME: From Tararere Stream (V20/420098).

TYPE SECTION: Section 23 (V20/405105), Kaiwaka Road.

THICKNESS: 10–15 m.

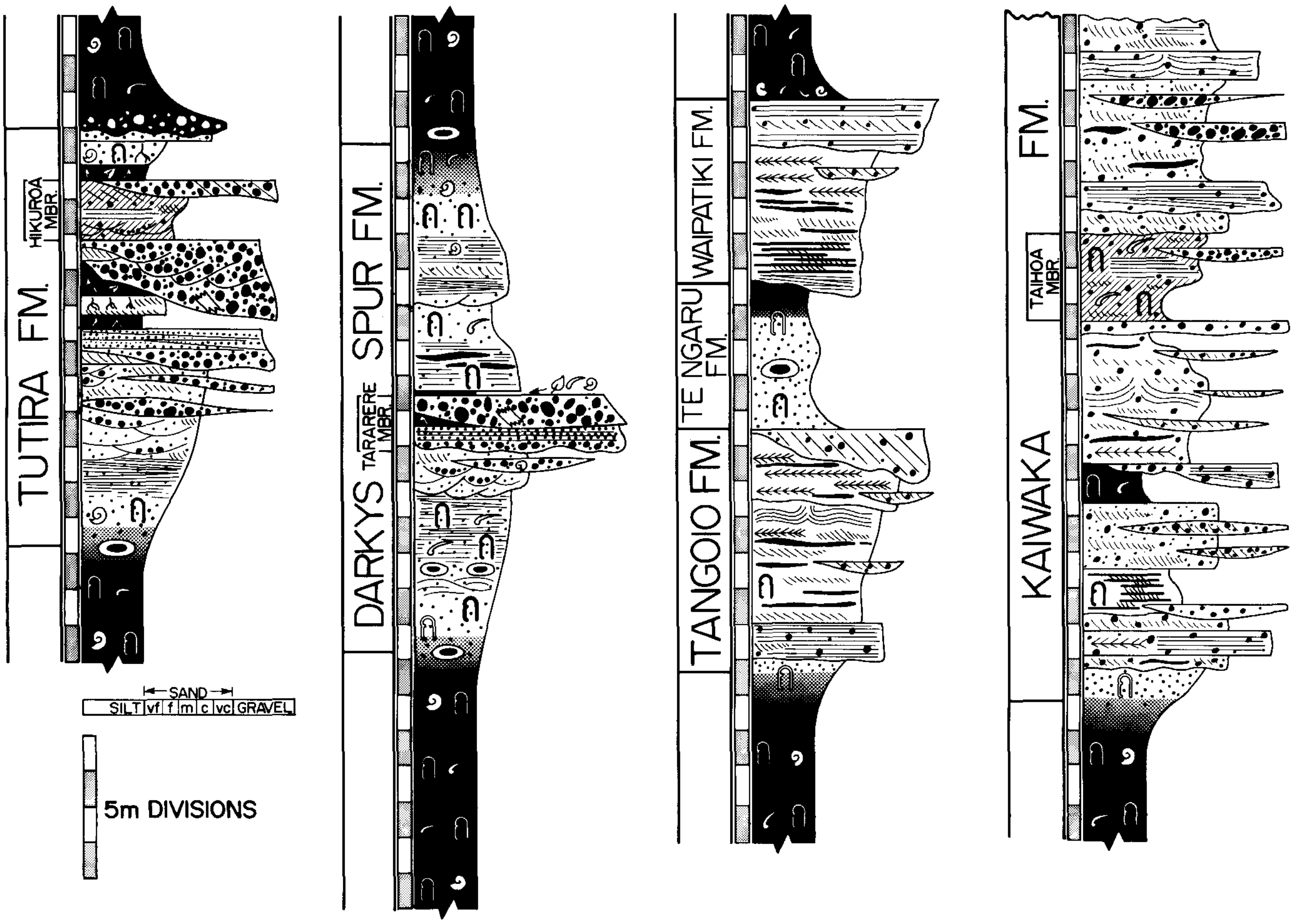

Fig. 7 Schematic stratigraphic columns of type sections for complete coarse-grained (sand/limestone) formations in the Petane Group. From left to right; Tutira Formation (section 12), Darkys Spur Formation (section 23), Tangoio and Waipatiki Formation (section 21) and Kaiwaka Formation (section 30). See Fig. 6 for legend.

LITHOLOGY: The lower Tararere Member is composed of uncemented, massive, coarse (1–2 cm) greywacke gravel. This lithology grades upsection into well sorted, decimetre-bedded, fine (2–6 mm) greywacke gravel and very coarse (1–2 mm) sand. Shelly material is sparse, mostly abraded and/or reworked, and unidentifiable. Gravel-sand interbeds are sharply overlain by lenticular beds of massive, poorly sorted greywacke gravel, siliciclastic sand, and thin, discontinuous, rootlet-bearing silt beds. The top of the member (Fig. 7) is marked by a discontinuous oyster and greywacke cobble layer (clasts 4–25 cm in size).

ENVIRONMENT OF DEPOSITION: The lower Tararere Member is interpreted as shingle beach. Lenticular gravel beds and rootlet-bearing silt beds represent nonmarine braided stream deposits. The upper contact is interpreted as a lag deposit and marks a return to shallow marine sedimentation within the Darkys Spur Formation (Haywick 1990).

DISTRIBUTION: The Tararere Member is restricted to the western portion of the Tangoio block (V20/390054–425117).

MAIRAU FORMATION

(new formation)

NAME: Beu & Edwards (1984) referred to this unit as Petane Mudstone. To avoid confusion with Petane Group, the unit is renamed Mairau Formation. The name is derived from Mairau Stream (V20/460078).

TYPE SECTION: Section 32 (V20/467087), Te Taihoa Farm.

REFERENCE SECTION: Section 60 (W20/543081), Glendale Farm.

THICKNESS: Thickens westward from 10 to 60 m (Fig. 8).

AGE: Nukumaruan (late Pliocene). Upper Mairau Formation contains the last appearance datum of *Pelicaria acuminata* (c. 1.85 Ma; Beu & Edwards 1984; Beu et al. 1987).

LITHOLOGY: Uncemented, massive and bioturbated, blue-grey muddy silt grading upsection into silty siliciclastic sand of the Tangoio Formation (Fig. 6). Fauna is diverse and indicative of open marine circulation (Haywick 1990).

ENVIRONMENT OF DEPOSITION: Midshelf (c. 50–100 m; Beu 1965; Haywick 1990).

DISTRIBUTION: Exposure is widespread over the Tangoio block (Fig. 5). Mairau Formation is one of four Tangoio block stratigraphic units able to be traced south of the study area to Ahuriri Estuary and Taradale near Napier (Fig. 1). Together with the following three formations, the distinctive cyclothemic disposition of the strata may permit future correlation of Tangoio block stratigraphic units with

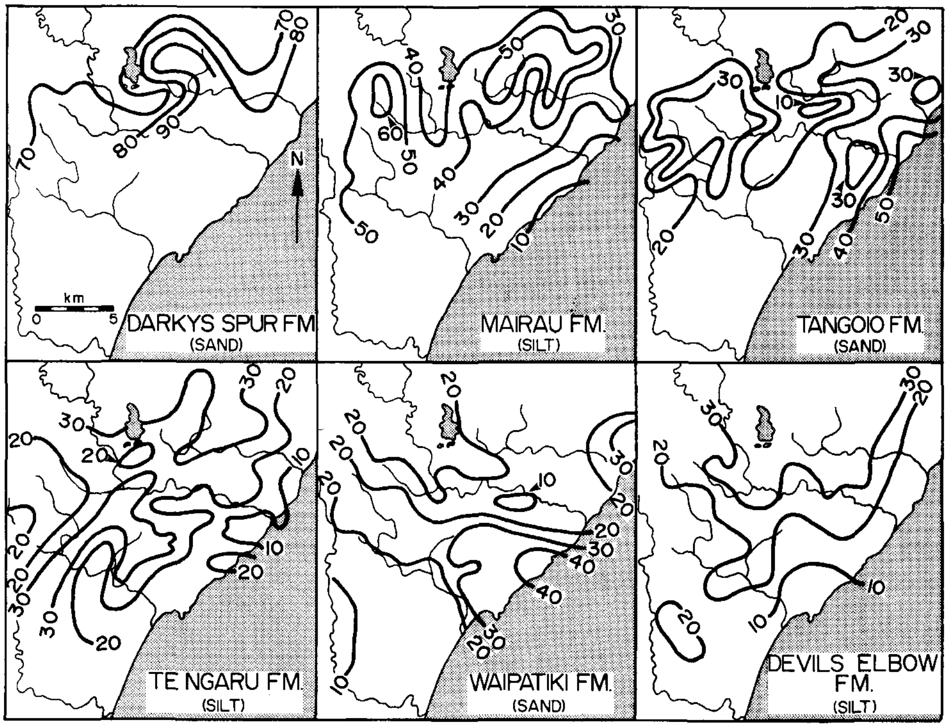

Fig. 8 Total thickness isopach maps of middle Petane Group formations. Isopachs in metres. Formations composed predominantly of coarse-grained lithofacies are labelled "sand". Fine-grained formations are labelled "silt".

those exposed southward. Mairau Formation is probably equivalent to the undefined "Waitio Pumiceous Siltstone" mapped on NZMS 1 (sheet N134) by Kingma (1971).

TANGOIO FORMATION

(emended from Beu & Edwards 1984)

NAME: Tangoio Limestone was introduced by Beu & Edwards (1984). Its name is derived from the settlement of Tangoio (V20/474010) in the Tangoio valley.

TYPE SECTION: Section 21 (V20/393098), Hikuroa Farm.

REFERENCE SECTIONS: Section 96 (V20/490004), Tangoio Quarry, and section 57 (W20/523070), Aropaoanui River.

THICKNESS: 10–50 m (Fig. 8).

AGE: Nukumaruan (late Pliocene).

LITHOLOGY: Siliciclastic, fine silty sand with mollusc-rich shellbeds and lenses grading upsection into progressively better sorted, and increasingly calcite cemented bioclastic limestone and carbonate sandstone. Cementation is ubiquitous in the upper part of the formation. Sedimentary structures are diverse and include parallel lamination, flaser bedding, low-angle cross-stratification and small to large scaled, unidirectional and bidirectional, planar cross-stratification. Soft sediment deformation is also common in portions of the formation. The uppermost bioclastic limestone unit in the Tangoio Formation contains greywacke pebbles, and upwardly increasing amounts of siliciclastic matrix. It is overlain sharply by sandy silt of the Te Ngaru Formation. The contact is marked by an accumulation of large articulated bivalves, particularly of the genera *Glycymeris* and *Ostrea*.

ENVIRONMENT OF DEPOSITION: Fauna and sedimentary structures within the Tangoio Formation are consistent with inner shelf and intertidal environments of deposition. The upper contact with the Te Ngaru Formation is interpreted as a condensed sequence developed during the transition from inner to midshelf sedimentation (Haywick 1990).

DISTRIBUTION: The formation is widespread, but especially so along the coast and in the southern portion of the Tangoio block (Fig. 5). The formation also crops out extensively to the south of the study area, particularly in the low hills west of Taradale.

TE NGARU FORMATION

(emended from Beu & Edwards 1984)

NAME: This formation was informally named Te Ngaru Mudstone by Beu & Edwards (1984). The name is derived from Te Ngaru Stream (V20/431029).

TYPE SECTION: Section 79 (V20/431029), Te Ngaru Stream.

REFERENCE SECTIONS: Section 9 (W20/545144), Moeangiangi Station, and section 21 (V20/396099), Hikuroa Farm.

THICKNESS: 10–40 m (Fig. 8).

AGE: Nukumaruan (late Pliocene). Basal Te Ngaru Formation contains the first appearance datum of *Gephyrocapsa sinuosa* (c. 1.8 Ma; Edwards 1976; Beu & Edwards 1984; Beu et al. 1987).

LITHOLOGY: Uncemented, massive and bioturbated, blue-grey, siliciclastic sandy silt with minor silty sand intervals. Grades upsection into, or is sharply overlain by, silty siliciclastic sand of the Waipatiki Formation (Fig. 6 & 7). The molluscan fauna is distinctive because of the numerous small specimens of *Pelicaria fossa* (Marwick) present in many outcrops (Beu 1965).

ENVIRONMENT OF DEPOSITION: The molluscan fauna (including *P. fossa*), is indicative of open marine, midshelf sedimentation (Beu 1965).

DISTRIBUTION: Te Ngaru Formation is widely distributed throughout the Tangoio block (Fig. 5). Like the Tangoio Formation, it can be traced southward from the Tangoio block at least as far as Taradale.

WAIPATIKI FORMATION

(emended from McKay 1887)

NAME: McKay (1887) named the uppermost strata at Petane the Waipatiki Beds. Beu & Edwards (1984) changed this to Waipatiki Limestone. The name is derived from the settlement of Waipatiki Beach (W20/528044).

TYPE SECTION: Section 21 (V20/393097), Hikuroa Farm.

REFERENCE SECTIONS: Section 91 (W20/533040), coastal area of Waipatiki Beach, and section 8 (W20/534131), Ridgemount Road.

THICKNESS: 10–40 m (Fig. 8).

AGE: Nukumaruan (Pliocene–Pleistocene). Waipatiki Formation contains the Pliocene–Pleistocene boundary (Beu & Edwards 1984).

LITHOLOGY: Siliciclastic and carbonate sand with planar cross-stratified shellbeds and lenses, grading upsection into interbedded coarse carbonate sand/sandstone and bioclastic limestone. Greywacke pebbles to 1.5 cm are common in western portions of the Tangoio block. Unidirectional and bidirectional cross-stratification is prevalent in the upper portion of the formation. Carbonate cementation is widely developed and generally increases upsection. The upper portion of the formation is well indurated and, like the Tangoio Formation, is overlain sharply by sandy silt of the overlying stratigraphic unit (Devils Elbow Formation; Fig. 6 & 7).

ENVIRONMENT OF DEPOSITION: Tide-influenced inner shelf (Haywick 1990).

DISTRIBUTION: Widespread throughout the Tangoio block (Fig. 5). Waipatiki Formation can also be traced southwards to Taradale.

DEVILS ELBOW FORMATION

(emended from Beu & Edwards 1984)

NAME: Devils Elbow Mudstone was first employed by Beu & Edwards (1984). The name is derived from the Devils Elbow descent on State Highway 2 (point 5, Fig. 1).

TYPE SECTION: Section 49 (V20/461080), Devils Elbow (State Highway 2).

REFERENCE SECTION: Section 33 (V20/473097), Aropaoanui River.

THICKNESS: Thickens westward from 10 to 40 m (Fig. 8).

AGE: Nukumaruan (early Pleistocene).

LITHOLOGY: Uncemented, massive and bioturbated, blue-grey sandy silt containing an open marine fauna (Beu 1965; Haywick 1990). Rare parallel lamination. Grades upsection into muddy, fine siliciclastic sand of the Kaiwaka Formation (Fig. 6). Devils Elbow Formation contains the most diverse, open marine, Nukumaruan molluscan fauna known (Beu 1965), including some unnamed faunal elements (Beu pers. obs.). The abundance of large, strongly sculptured *Pelicaria fossa* (Marwick) characterises the Devils Elbow Formation in many parts of the Tangoio block.

ENVIRONMENT OF DEPOSITION: Midshelf (Beu 1965; Haywick 1990).

DISTRIBUTION: Widespread, but particularly so south of the Aropaoanui River (Fig. 5). No equivalent is known outside of the Tangoio block.

KAIWAKA FORMATION

(emended from McKay 1887)

NAME: McKay (1887) defined the Kaiwaka Beds (Table 1) as the strata within the Petane Series between the bioclastic limestone beds of the Waipatiki Beds and the underlying Pohui Series. Beu & Edwards (1984) applied the name to a thick limestone unit near the top of the Nukumaruan in central Hawke's Bay. We define this unit as the Kaiwaka Formation, which is the uppermost exposed interval of Nukumaruan strata in the Tangoio block. The name is derived from Kaiwaka Road (V20/444073).

TYPE SECTION: Section 30 (V20/461101), Te Taihoa Farm.

REFERENCE SECTIONS: Section 79 (V20/430029), Te Ngaru Stream, and Section 98 (V20/399978), Waipunga Road.

THICKNESS: The upper boundary of the Kaiwaka Formation is the erosion surface which relates to the present landscape. Maximum thickness is 100 m.

AGE: Nukumaruan (early Pleistocene).

LITHOLOGY: The Kaiwaka Formation is predominantly coarse grained, cross-stratified carbonate sand/sandstone interbedded with massive to cross-stratified bioclastic limestone (Fig. 7). Greywacke pebbles (clasts to 2 cm) are common components throughout both lithologies everywhere in the Tangoio block. In the central portion of the Tangoio block, the middle Kaiwaka Formation contains a thick sequence of siliciclastic sand, silt, and greywacke gravel (Ruataha Member). Near Lake Tutira (section 30), the middle Kaiwaka Formation also contains a pumiceous silt and sand unit (Taihoa Member). Pumice layers are common constituents of the Kaiwaka Formation elsewhere in the Tangoio block, ranging in thickness from 5 cm to 1 m. At section 98 on Waipunga Road (Fig. 2), the middle Kaiwaka Formation contains a 5 m thick pumiceous silt-sand sequence which is correlative with the Taihoa Member. Lateral interdigitation of all lithologies is common within the Kaiwaka Formation.

ENVIRONMENT OF DEPOSITION: The Kaiwaka Formation was deposited in a number of contemporaneous marine, marginal marine, and fluvial environments, but is primarily a product of inner shelf sedimentation (Haywick 1990).

DISTRIBUTION: Isolated outcrops north of the Aropaoanui River, becoming very widespread in the central portion of the Tangoio block (Fig. 5).

Ruataha Member

(new member of Kaiwaka Formation)

NAME: Derived from Ruataha Farm (V20/425074).

TYPE SECTION: Ruataha Member is poorly exposed. Isolated outcrops occur on Ruataha Farm (V20/421088, 423073), on Waipunga Road (V20/413066), and sporadically along Kaiwaka and Aropaoanui Roads.

THICKNESS: Approximately 20 m.

LITHOLOGY: Uncemented, poorly sorted siliciclastic sand, interbedded with lenticular to continuous greywacke gravel and

laminated brown silt (equivalent to the Tareha laminated siltstone of Beu & Edwards 1984). Silt beds contain comminuted carbonaceous material, rare in-situ rootlets, and rare shell moulds. Sand and gravel beds contain carbonate shell material in a few localities.

ENVIRONMENT OF DEPOSITION: Dominantly fluvial, rarely estuarine (Haywick 1990).

DISTRIBUTION: Outcrop is confined to a small area approximately delineated by the junction of Kaiwaka and Waipunga Roads (V20/415091) and the homesteads of Glenview (V20/475065) and Koraki (V20/416057).

Taihoa Member

(new member of Kaiwaka Formation)

NAME: Derived from Te Taihoa Homestead (V20/452108).

TYPE SECTION: Section 30 (V20/461101), Te Taihoa Farm.

THICKNESS: 10 m.

LITHOLOGY: In the type section, Taihoa Member is massive, bioturbated, silty volcanic ash interbedded with very coarse to fine pumice sand (Fig. 7). It contains a restricted molluscan fauna comprising *Austrovenus stutchburyi* (Wood), *Macomona liliana* Iredale, and *Zeacumantus perplexus* (Marshall & Murdoch), and in-situ carbonaceous rootlets. Elsewhere (including section 98) the Taihoa Member contains significant amounts of broken and abraded shell material and common interbeds of carbonate sand/bioclastic limestone.

ENVIRONMENT OF DEPOSITION: *Austrovenus, Macomona*, and *Zeacumantus* are today common fauna within estuarine environments (e.g., Ahuriri Estuary near Napier; Fig. 1); hence, Taihoa Member at the type section is interpreted as estuarine. The pumice interval in other sections was deposited in inner shelf (nearshore) environments.

DISTRIBUTION: Taihoa Member is recognised only in the immediate area of the type section and at section 98.

TECTONIC SETTING OF THE TANGOIO BLOCK

Pliocene–Pleistocene sedimentary rocks of the Tangoio block were deposited within the forearc basin of the Hikurangi–Taupo subduction complex (Cole 1984), and represent the upper portion of the basin-fill sequence in central Hawke's Bay. The total thickness of the strata comprising the forearc basin in eastern North Island exceeds 5 km, and the succession dates from the early Miocene (Kamp et al. 1988). The lowest sedimentary units consist of abyssal/slope mudstone and sandstones. Pliocene and younger rocks were mainly deposited in shelf environments and consist of both terrigenous and carbonate lithofacies. Shallowing was induced by thrust-related uplift to the east, which, by the early to middle Pliocene, had constricted the basin into a narrow seaway (Kamp et al. 1988). The Petane Group was deposited adjacent to the western coastline of this seaway.

That the Tangoio area was a site of rapid sedimentation and subsidence during the Pliocene–Pleistocene is suggested by the thickness and lateral continuity of cyclothems and their component formations. Haywick & Henderson (in prep.) estimate that the average sedimentation and subsidence rates during deposition of the Petane Group were 2 m/1000 years. In the lower Petane Group, which contains the thickest cyclothems, sedimentation/subsidence may have been closer to 3 m/1000 years.

Isopach maps indicate subtle variations in formational thickness across the Tangoio block (Fig. 8). Coarse-grained formations contain sedimentary features such as large-scale cross-stratification indicating that, in part, they were deposited as nearshore bars and shoals (Haywick 1990). Local increases in thickness could reflect former positive sea-floor relief. This scenario cannot be readily applied to fine-grained formations. Their thickness variations are most probably related to differential subsidence due either to compaction of strata beneath the Petane Group or to synsedimentary tectonic warping of the sea floor. Given the degree of Neogene tectonism established for the Hawke Bay shelf by Lewis (1971) and Cole & Lewis (1981), the latter explanation is favoured.

ORIGIN OF CYCLICITY WITHIN THE PETANE GROUP

The alternation between fine-grained and coarse-grained formations in the Petane Group is considered to have resulted through cyclothemic sedimentation, and is attributed to glacio-eustatic sea-level changes (Vella 1963; Beu & Edwards 1984). Haywick & Henderson (in prep.) correlate the Petane Group with $\delta^{18}O$ stratigraphic records derived from North Atlantic DSDP drill cores (Shackleton et al. 1984; Raymo et al. 1989) and conclude that the cyclothems were deposited during short-duration (41 000 year) cycles in continental ice-volume (Williams et al. 1982; Joyce et al. 1990). Fine-grained formations consisting of mid-shelf lithofacies were deposited during relative sea-level high stands (interglacial periods), and coarse-grained formations consisting of nonmarine, estuarine, and innershelf lithofacies were deposited during relative sea-level low stands (glacial periods).

Sedimentary and faunal data indicate that the amplitude of sea-level change between high stand and low stand deposition was c. 75–150 m (Haywick 1990; Haywick et al. in prep.). Sea-level fluctuations of this magnitude would have caused major shifts in the isotopic composition of Pliocene–Pleistocene seawater which we attempted to gauge by comparing the $\delta^{18}O$ and $\delta^{13}C$ signatures of foraminifera extracted from 10 interglacial silt samples and 9 glacial sand samples. The analyses were restricted to samples from a narrow stratigraphic interval between the Mairau Formation and the Waipatiki Formation to give the results comparability. This interval was selected as it is well exposed across the Tangoio block thereby allowing sampling on a regional basis. The benthic foraminifera *Notorotalia* was chosen for analysis because of its common occurrence in both fine-grained and coarse-grained formations. Planktonic foraminifera are too rare within the Petane Group to invite study.

The results are surprising. *Notorotalia* from interglacial samples are characterised by reasonably consistent $\delta^{18}O$ signatures of +0.9 to +2.2‰ (mean = 1.22‰; $\sigma = 0.321$), but $\delta^{18}O$ for *Notorotalia* from glacial samples are more variable (−1.4 to +0.6‰; mean = −0.13‰; $\sigma = 0.735$). Had the isotopic compositions of the foraminifera related solely to continental ice-volume changes, ^{18}O content would have been highest in *Notorotalia* from glacial samples. Our data indicate just the opposite. We believe that the isotopic measurements do not reflect a dominant ice-volume effect. This conclusion is based upon a plot relating $\delta^{13}C$ to $\delta^{18}O$ for all 19 of the samples analysed (Fig. 9). Interglacial *Notorotalia* plot within a small field, but glacial *Notorotalia* plot more linearly ($R^2 = 0.593$).

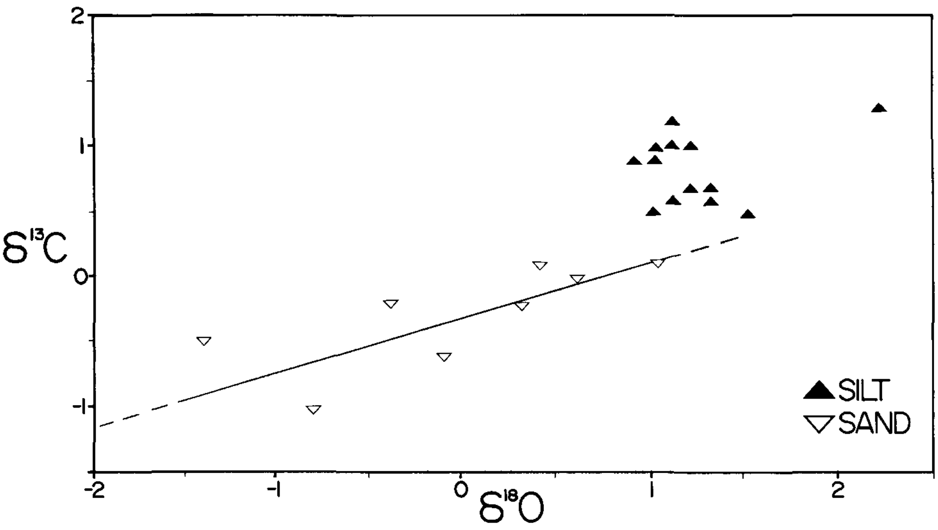

Fig. 9 Plot relating $\delta^{13}C$ and $\delta^{18}O$ of *Notorotalia* obtained from (interglacial) silt lithofacies and (glacial) sand lithofacies. Foraminifera from glacial intervals display a linear relationship between $\delta^{13}C$ and $\delta^{18}O$ ($R^2 = 0.593$). In contrast, foraminifera from interglacial intervals plot in a narrow field.

The trend is similar to that exhibited by variably diluted seawater in shallow marine bays, estuaries, and fjords (Mook 1971; Strain & Tan 1979; Geary et al. 1989), and may have been induced in the Tangoio area through similar circumstances. A salinity dip of approximately 3 or 4 ppt caused by enhanced rainfall or runoff during glacial low stands could account for both the depleted carbon and oxygen isotopic signatures of the foraminifera (Epstein & Mayeda 1953; Craig & Gordon 1965; Arthur et al. 1983). Alternatively, the foraminifera could have been diagenetically modified following deposition. Calcite cementation is common within porous coarse-grained formations, and, despite care during selection and preparation, some foraminifera extracted from sand lithofacies may have been contaminated by freshwater cement (Collen & Burgess 1979) or undergone isotopic exchange during contact with meteoric water (see Haywick 1990).

The apparent modification of $\delta^{18}O$ and $\delta^{13}C$ in glacial *Notorotalia* has important implications for isotope stratigraphy in Petane Group. Judging from the results to date, it is doubtful that a useful isotope stratigraphy for the Petane Group will ever be resolved. Similar impediments may prejudice isotope stratigraphy for coarse-grained (or mixed) shelf sequences elsewhere in New Zealand.

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