Stratigraphy of the Neogene marine sequence to the east of Dannevirke, southern Hawke's Bay, New Zealand(MEMORIAL VOLUME TO THE LATE PROFESSOR TERUHIKO SAMESHIMA)

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Stratigraphy of the Neogene marine sequence to the east of Dannevirke, southern Hawke's Bay, New Zealand

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Abstract A field survey documented the lithostratigraphy and sampled for biostratigraphic, paleomagnetic and isotopic analyses of sedimentary sections to the east of Dannevirke, Southern Hawke's Bay, New Zealand. The studied marine sequence was deposited in the forearc basin along the Hikurangi Trench from the late Miocene to the latest Pliocene. The marine sequence is divided into Moastone, Mapiri, Mangatoro, Pukerua, Te Aute, Okarae, Kumeroa, and Mangatarata Formations in ascending order. The sedimentary sequence is cut into spindle shape blocks by faults with right lateral movements. Oxygen and carbon isotopes of foraminiferal tests indicate that the sedimentary environment was shallow, with relatively higher near-bottom than surface primary production. A distinct tectonic event occurred in the latest Pliocene, 2.2 Ma, reflected in an angular unconformity at the base of the Kumeroa Formation and deformation of the formation immediately after its deposition. The event rearranged the forearc basin and terminated the deposition within it. The event was associated with volcanic activity.

Key words: New Zealand, southern Hawke's Bay, Neogene forearc basin, collision, Alpine Fault, magnetostratigraphy, biostratigraphy, oxygen and carbon isotopes

INTRODUCTION

New Zealand, which comprises two main islands, is situated on the boundary between the Indian-Australian Plate and Pacific Plate. It is associated with the Kermadec Trench system to the north, and with the Macquarie system to the south. The islands were part of the Gondwana Margin, but have been an accretionary complex since the Triassic (Spörli & Ballance 1989; Aita & Spörli 1992; Pettinga 1982), thus they are covered with forearc and backarc marine sediments and island arc volcanics related to subduction tectonics. The Alpine Fault and associated faults cut them with a northeast strike and act as a transform plate boundary (Fig. 1).

The Chatham Rise is colliding with the South Island, and the Hikurangi Trench is bending westward and closing (e.g., Allis 1986). The collisional process is recorded in the sedimentary sequence deposited on the forearc basin, and the sediments are exposed on eastern part of the North Island as result of the collisional process. Southern Hawke's Bay province provides good exposures of the Neogene marine sequences of the forearc basin (e.g., Suggate 1978). The area between east of Takapau and east of Dannevirke was selected for this study (Fig. 1). The purpose of this study is to describe the geology of the sedimentary sequences and the collisional process, based on stratigraphic work in the field and biostratigraphic and paleomagnetic investigations on the sediments.

The studied area has been mapped by the New Zealand Geological Survey and oil companies, and Lillie (1953) published his stratigraphic work with a compilation of previously published and unpublished data. There was some confusion about the stratigraphic position of the intercalated limestones, especially the "Te-Aute limestone", and Beu *et al.* (1980) re-examined the limestones based on molluscan biostratigraphy.

Magneto-bio-stratigraphic datum planes have been established and compiled for the Neogene sedimentary sequences of New Zealand and core samples from the Deep Sea Drilling

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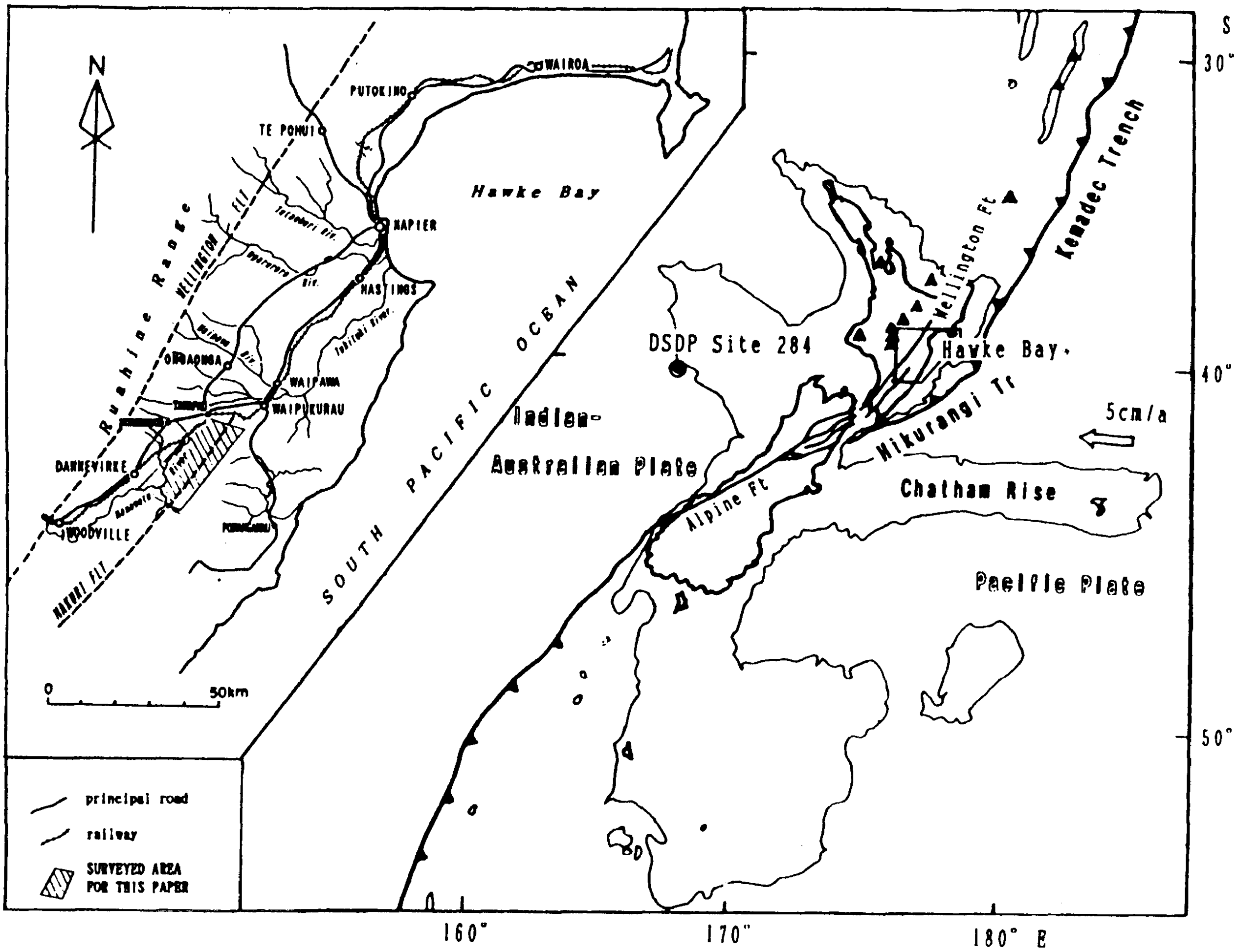


Fig. 1 Index map of the study area.

Project (Edwards 1987). This study applied the newly established datum planes directly to the stratigraphic sequence and documents the processes of subduction and collision quantitatively.

The authors carried out the field survey and sampling in the Dannevirke district during the summers of 1981-1982, 1983-1984 and 1985, more than 260 days, and the total number of the collected samples for magneto-biostratigraphic and isotopic studies are 126 from successive stratigraphic sequences and 81 from sporadic exposures.

Topographic maps on the scale 1:25000, which were used for the field work, were drawn with enlargement of the 1:63360 map from the Lands and Survey Department, and stream lines were retraced using air photographs.

STRATIGRAPHY

The Neogene marine sequence of the forearc basin in this area is composed of soft massive siltstone, sandstone, and alternating sandstone and siltstone. This sequence contains several sedimen-tary cycles and is classified into eight formations based on these cycles: the Moastone, Mapiri, Mangatoro, Pukerua, Te Aute, Okarae, Kumeroa and Mangatarata Formations, in ascending order (Figs. 2 and 3). Coquina limestone beds, which consist mainly of indurated shell fragments, are intercalated in the basal part of the sedimentary cycles. The limestone beds form a dip-slope on the topography, which is traced easily in the field. Most of the formations were deposited conform-ably upon each other, but the base of the Kumeroa Formation overlies unconformably the other formations. The basement of the Neogene marine sediments is

"Greywacke" and Paleogene rocks, mostly a pre-Neogene accretionary complex.

The sedimentary sequence is cut by northeast-trending faults and divided into spindle-shaped blocks. The bedding planes generally dip northwestward in the faulted blocks, and south-east dipping is developed along the western margin in some faulted blocks.

In this paper, the authors use the previously established stratigraphic names of Lillie (1953) as far as possible, and use new names only for the units which are newly distinguished lithologically (Fig. 4).

1. "Greywacke" and Paleogene Rocks

The term "Greywacke" has been used broadly to describe the entire indurated accretionary complex presumed to be older than Cretaceous age. In this district, the authors use the term for the rocks which constitute the basement of the Neogene marine sequence.

"Greywacke" is exposed in six areas along the eastern margins of faulted blocks in this district (Fig. 2). The "Greywacke" consists of ill-sorted massive hard dark-grey sandstone characterized by rusty weathering and sheared slickenside. The rocks are easily distinguished from Neogene marine sediments which unconformably cover them.

"Greywacke" is overlain unconformably with "Paleogene" (including early Miocene) dark-grey rocks banded with pebbles in the Mangapurakau Stream outcrop. Most of the "Greywacke" and the "Paleogene rocks" are covered unconformably by the Mapiri Formation in the north, and by the Mangatoro Formation in the central and southern parts.

"Paleogene" dark-grey siltstones with occasional glauconitic sandstone is exposed along the eastern margin of this district, and the contact with the Neogene marine sequence is a fault (Fig. 2).

2. Moastone Formation (new name)

Type Locality: Along the Pamanuka Stream, a tributary of the Mangapuaka Stream.

Distribution: the Moastone Formation is exposed along the northeastern margin of this district, and the central part along the Mangapuaka Stream and Pamanuka Stream.

Classification: The Moastone Formation is equivalent to the lower part of the "Mapiri Formation" used by Lillie (1953). The name Moastone Formation was first used by Fujii (1983ms) to distinguish lithological facies in the "Mapiri Formation".

Lithology: The Moastone Formation consists mainly of smooth dark-grey sandy siltstone. Occasional round and lenticular calcareous concretions up to 3 m in diameter, and molluscan shells are commonly contained (Photo 1). The surface of the outcrops are usually weathered white to light-grey.

Near the base of the formation, massive siltstone grades downward to sandstone with hard shelly limestone beds (50 cm maximum thickness), the lowest of which contains pebbles of hard sandstone. The formation unconformably rests upon Paleogene rocks. Sand pipes projecting into the Paleogene rocks are commonly found at the lowest boundary of the limestone.

Thickness: The formation ranges in thickness from 200 to 600 m. It thickens to the north and attains its maximum thickness at the head of Ngahape Stream.

Relation: The formation is mostly overlain conformably by the Mapiri Formation and uncon-formably by the Mangatoro Formation, and covers Paleogene rocks and "Greywacke" with basal limestone beds.

3. Mapiri Formation

Type Locality: Mapiri Point in the Wairoa Subdivision (Ongley 1930), northern Hawke's Bay. Typical exposures are developed at the head of Whatatuna Stream in the middle to eastern part of the study area.

Distribution: The Mapiri Formation crops out in the southeast of Takapau, southeast of the Turiri Range and along the Mangapuaka Stream.

Classification: The name Mapiri Formation was given by Ongley (1930) at Mapiri Point. In the Dannevirke Subdivision, Lillie (1953) used the term "Mapiri" for the rocks approximately equivalent to the strata of the Tongaporutuan Stage. The "Mapiri Formation" adopted by Lillie can be divided into a lower massive siltstone facies and an upper alternation facies. The term "Mapiri" used in this paper is equivalent to the upper part of the "Mapiri Formation" of Lillie (1953).

Lithology: The Mapiri Formation consists chiefly of an alternation of pumiceous creamy grey siltstone and fine-grained sandstone associated with fine-grained tuff beds (Photo 2).

In the southeast of Takapau, the formation is distributed along the west side of the "Greywacke". Laminated fine sandstone with bands of conglomerate ranging in thickness from 20 cm to 100 cm occur at basal part of the formation. Fragments of molluscs, lenticular calcareous concretions (20 cm maximum thickness), and very coarse-grained glauconitic sandstone are also associated with the basal part. These rocks rest directly on "Greywacke" and grade up into siltstone alternated with fine-grained sandstone and tuff beds. The maximum thickness of the sandstone in the alternation thins northward from 100 cm to 5

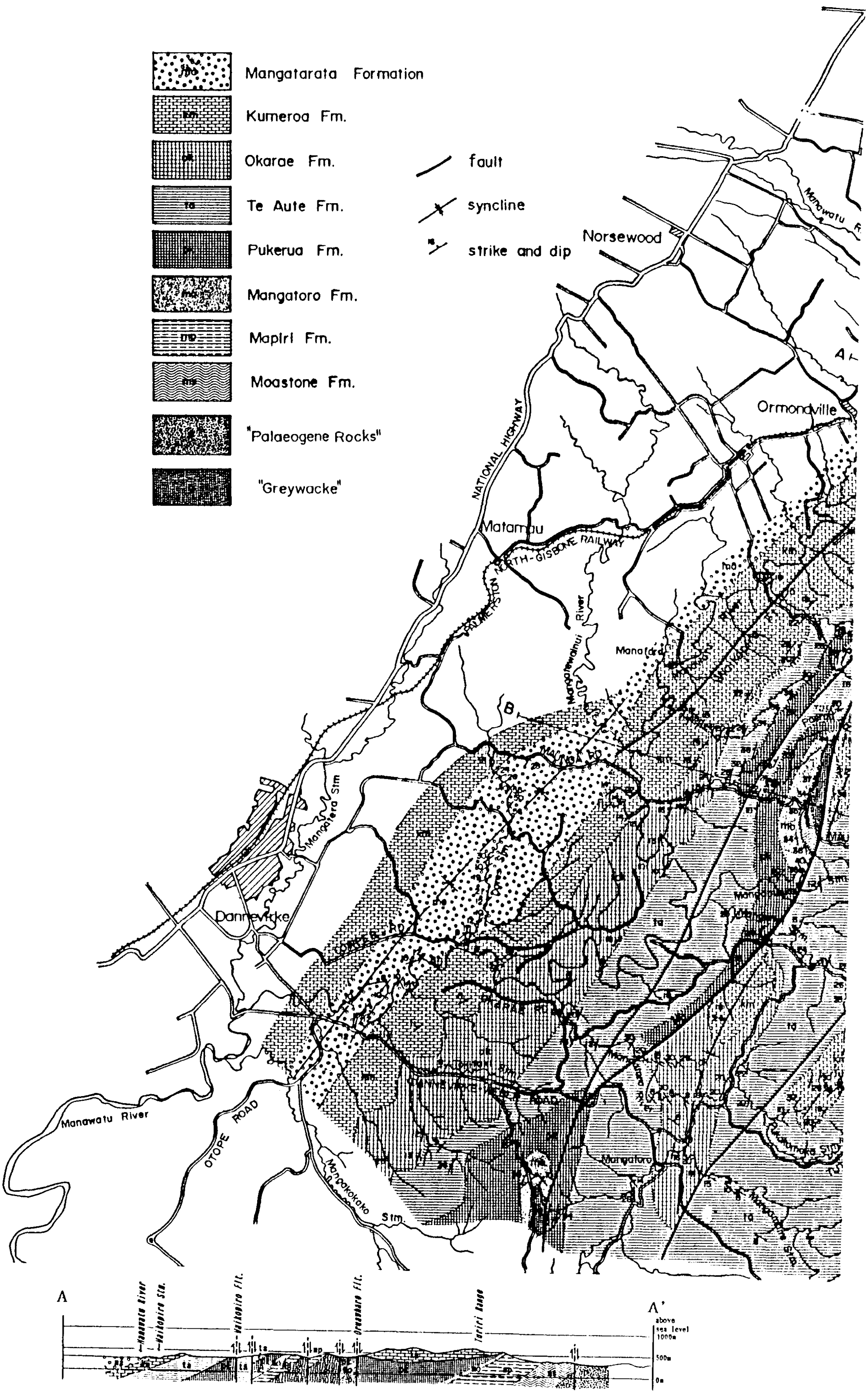
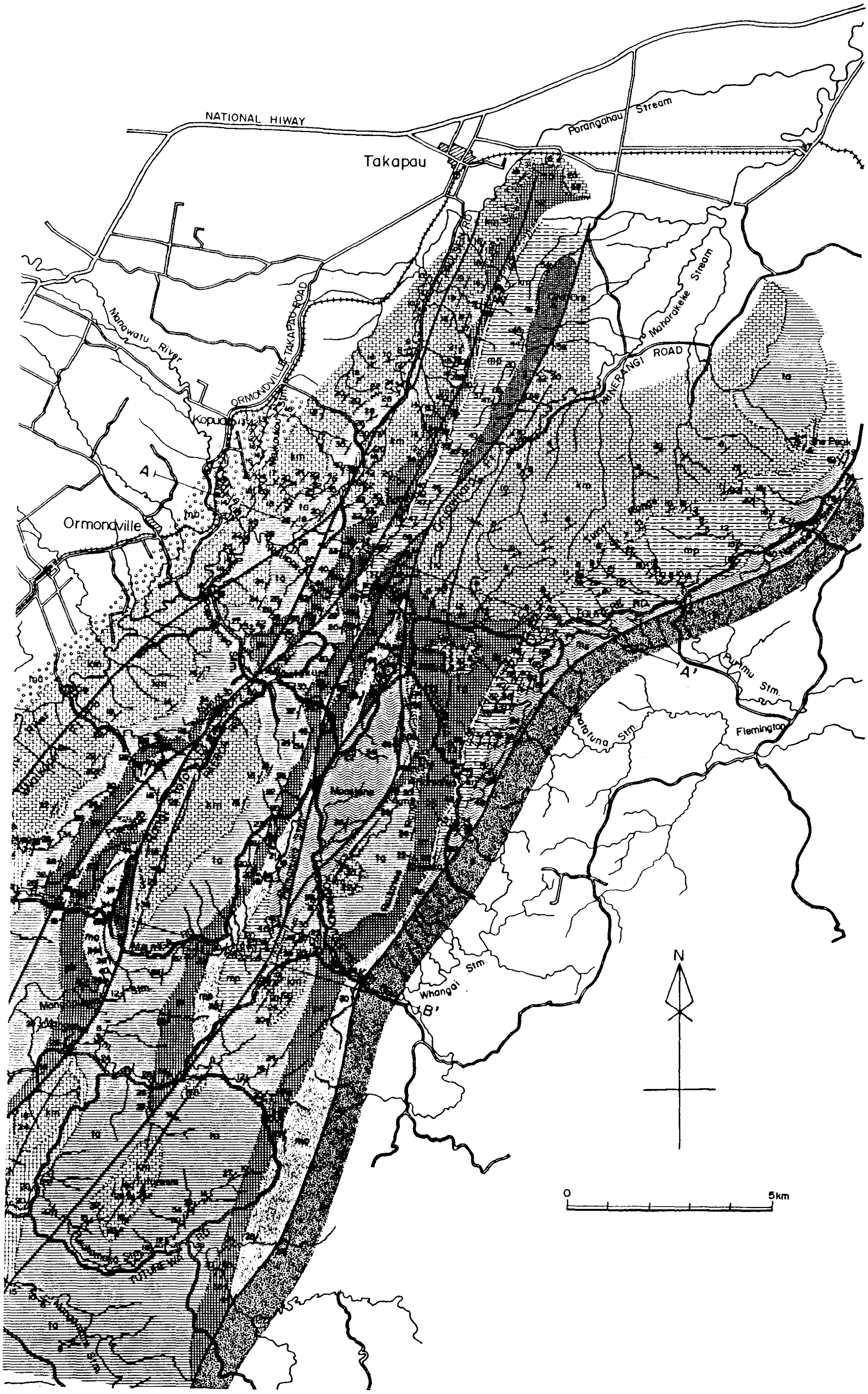


Fig. 2 Geologic map of Neogene sedimentary sequence to the east of Dannevirke, southern Hawke's Bay, New Zealand. Fm: formation


NATIONAL HIWAY
Takapau
Porangahau Stream
Maharakeke Stream
Manawatu River
ORMONDVILLE TAKAPAU ROAD
Kopua
Ormondville
A
A'
ROAD
Puremu Stm.
Flemington
Whangai Stm.
B'
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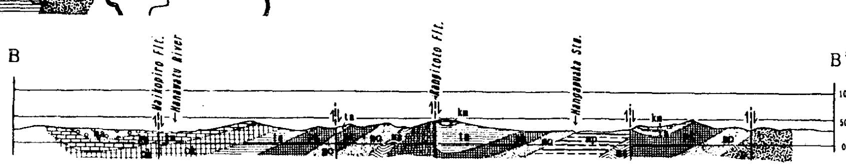
B
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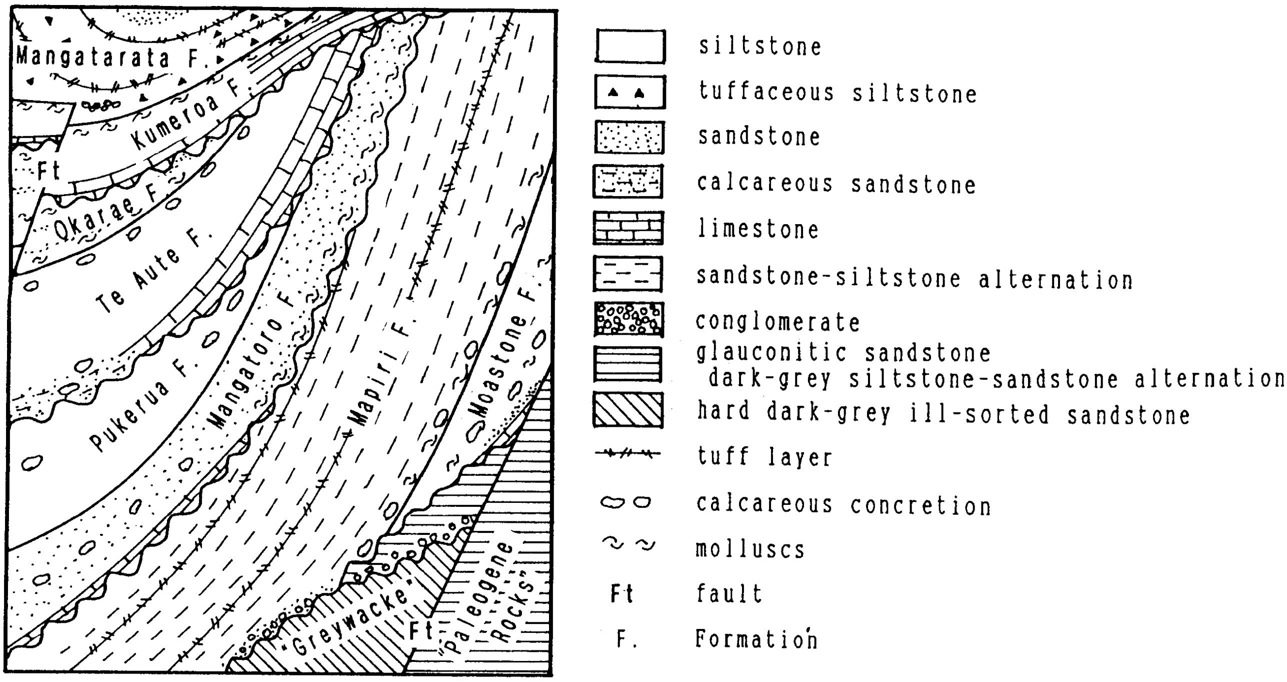


Fig. 3 Schematic cross section of Neogene sedimentary sequence to the east of Dannevirke, southern Hawke's Bay, New Zealand.

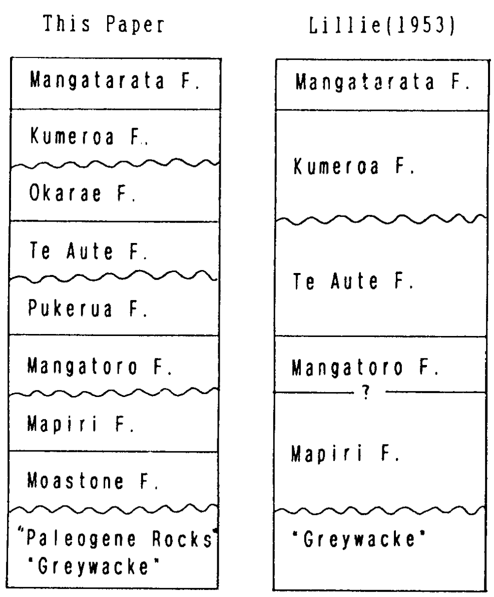


Fig. 4 Comparison of table of stratigraphic divisions between this paper and Lillie (1953). F.: Formation.

cm.

In the southeast of the Turiri Range, the Mapiri Formation consists of alternating sandstone and siltstone, and contains white tuff beds. The siltstone of the alternation is creamy grey medium-grained siltstone ranging in thickness from 20 cm to 100 cm. The maximum thickness of the sandstone of the alternation is 50 cm. The thickness of the tuff beds ranges from 5 cm to 200 cm. Grading is present in both the sandstone and tuff beds.

At Mangapuaka Stream, the Mapiri Formation consists mainly of very fine-grained sandstone and sandstone-siltstone alternations. Fragments of molluscs and lenticular calcareous concretions (20 cm in maximum thickness) are contained at the base.

Thickness: The formation thickens northward and attains a maximum thickness of 800 m to the southeast of Takapau.

Relation: The basal conglomerate of the Mapiri Formation rests unconformably on the "Greywacke" in the southeast of Takapau, and its basal facies changes into the massive dark-grey sandy siltstone of the Moastone Formation in the east of the Turiri Range and along the Mangapuaka Stream.

The Mapiri Formation is overlain unconformably by the Mangatoro and Kumeroa Formations. Angular unconformities are observed along the Turiri Range and at the head of the Whatauna Stream.

4. Mangatoro Formation

Type Locality: Opoiti Survey District of Wairoa Subdivision in northern Hawke's Bay. Typical exposures are developed along the tributary of Mangapuaka Stream to the south of Paeroa Mount and the Waikopiro Stream to the south of Rangitoto Mount in the study area.

Classification: The name Mangatoro was first used by Lillie (1953) in the Dannevirke Subdivision to rename the Opoiti Formation as defined by Ongley (1930).

Distribution: The formation is exposed, striking in a northeasterly direction, along the west side of the Mapiri Formation, Moastone Formation and "Greywacke".

Lithology: The Mangatoro Formation consists of light-grey fine-grained sandstone with occasional lenticular calcareous concretions and thin lignite layers (Photo 3). The base of the formation is marked by bands of shelly limestone or shell beds ranging in thickness from 5 cm to 200 cm. The basal limestone and shell beds contain pebbles and granules of "Greywacke".

Thickness: The Mangatoro Formation ranges in thickness from 30 m to 80 m in the northern area, and a maximum thickness of 500 m is attained in outcrop at the Mangapuaka Stream in the southern part of the study area.

Relation: The formation unconformably overlies the Moastone Formation, Mapiri Formation, "Pa-leog ene rocks" and "Greywacke". Discordance of bedding between the Mangatoro Formation and the Mapiri Formation can be clearly observed at the head of the Whatatuna Stream and the Turiri Range.

5. Pukerua Formation (new name)

Type Locality: Tributary of the Mangapurakau Stream at Pukerua, Turiri Range.

Classification: The Pukerua Formation is approximately equivalent to the lower part of the "Te Aute Formation" of Lillie (1953). The name was defined by Fujii (1985ms) based on the presence of an unconformity and lithological change in the middle part of the "Te Aute Formation", where it is equivalent to the base of the "Te Aute limestone" of Lillie (1953). In this paper, the Pukerua Formation and the Te Aute Formation are used for the lower and upper parts of the "Te Aute Formation" of Lillie (1953), respectively.

Distribution: The formation is exposed, striking northeast, along the east side of the Te Aute Formation.

Lithology: The Pukerua Formation consists of well-sorted smooth light-grey massive micaceous siltstone (Photo 4). The siltstone in rare instances contains small fragments of pumice and calcareous concretions. The concretions are boulder-sized and consist of light-grey siltstone. Molluscs are few. Parallel lamination of a very fine-grained sandstone layer occurs near the basal part of the formation, below which the siltstone becomes micaceous sandy siltstone; the latter grades downward into the massive fine sandstone of the Mangatoro Formation. The basal parallel lamination is developed typically in the eastern part of Mangapurakau Stream.

Thickness: The formation has a maximum thickness of 420 m at its type locality, Pukerua, in the northeastern part of the study area.

Relation: The Pukerua Formation overlies conformably the Mangatoro Formation. The basal limestone of the Te Aute Formation, the "Te Aute limestone", contains basal pebbles and calcareous boulders, and rests unconformably on the Pukerua Formation.

6. Te Aute Formation

Type Locality: Te Aute Hill to the northeast of the study area. Typical exposures within the study area are developed along the Papaiahoea and Waikopiro Streams.

Classification: The Te Aute limestone was first described by McKay (1877) for the limestone of the Te Aute Hills to the northeast of this district. Lillie (1953) used "Te Aute Formation" including Te Aute limestone beds, first mapped by McKay (1877) within the district. Lillie (1953) mapped the "Te Aute Formation" to coincide with beds containing the fauna of the Waitotaran Stage, in so far as possible. Following Fujii (1983ms), this paper divides the "Te Aute Formation" of Lillie (1953) into a lower Pukerua Formation and an upper Te Aute Formation. Beu *et al.* (1980) subdivided the basal limestone of the "Te Aute limestone" of Lillie (1953) into the Whetakura limestone and the Te Aute limestone because of their ages. Most of the basal limestone beds of the Te Aute Formation in this district are Whetakura limestone, and the Te Aute limestone of Beu *et al.* (1980) is exposed in the north of the Turiri Range.

Distribution: The formation is present mainly in the western and southern part of this district. In the northeastern part, only the basal limestone crops out beneath the Kumeroa Formation.

Lithology: The Te Aute Formation consists mainly of calcareous sandstone (Photo 5), sandy coquina limestone, and sandy massive siltstone. Calcareous sandstone and limestone are developed in the basal part. The calcareous sandstone contains shells, shell fragments, and numerous calcareous concretions. Lenticular or platy calcareous concretions range in thickness from 5 cm to 30 cm. The concretions and shells partly combine to form a sandy coquina limestone, the Whetakura limestone, which form a weathering-resistant feature in the local landscape (Photo 6). The base of the limestone contains hard sandstone pebbles and cobbles, and occasional boulder-sized calcareous concretions of siltstone. The boundary is clear between the base and Pukerua Formation. Many sandpipes with lengths of 10 cm to 30 cm protrude into the massive siltstone of the Pukerua Formation. The Te Aute limestone is exposed in the northern end of the Turiri Range, and consists mostly of granule-size shell fragments. The lower boundary of the limestone is not exposed.

Calcareous sandstone grades upward into bioturbated fossiliferous massive sandy siltstone. The uppermost part of the massive siltstone contains round and lenticular calcareous concretions of siltstone which range in thickness from 20 cm to 50 cm.

Thickness: The total thickness of the formation ranges from 290 m to 820 m. The basal limestone and associated calcareous sandstone is about 100 m in the north, and thins southward in the western part of this district. The basal limestone is absent at Mangapuaka Stream outcrops. In the eastern part, only the basal limestone is developed, with a thickness of 30 m, which forms a dip slope at Raikatea Range.

Relation: The Te Aute Formation unconformably overlies the Pukerua Formation and Mapiri Formation, and is unconformably overlain by the Kumeroa and Okarae Formations in the southwestern part of the study area.

7. Okarae Formation (new name)

Type Locality: Manawatu River near Okarae Road, east of Dannevirke.

Classification: Lillie (1953) divided the "Kumeroa Formation" into lower and upper parts, which contain the lower and upper Nukumaruan fauna in the Dannevirke Subdivision. The lower part thins from the east of Dannevirke to the north and is absent farther north than Manaford. The upper part rests unconformably on the lower part of the "Kumeroa Formation" as well as the Te Aute, Pukerua, Mangatoro, and Mapiri Formations. This paper uses the new name **Okarae Formation**, proposed by Yamamoto (1985ms), for the lower part of the "Kumeroa Formation" of Lillie (1953).

Distribution: The formation is exposed to the east of Dannevirke, where it has a northeasterly strike.

Lithology: The Okarae Formation consists of fossiliferous light grey siltstone and fine-grained sandstone with occasional thin tuff beds (Photo 7). The siltstone is massive and contains molluscs which are occasionally stratified. The base of the formation is characterized by shell beds which reach a maximum thickness of 50 cm.

Thickness: The formation thickens to the south and the maximum thickness reaches 490 m.

Relation: The Okarae Formation overlies conformably the Te Aute Formation and is overlain unconformably by the Kumeroa Formation.

8. Kumeroa Formation

Type Locality: Kumeroa of the Tahoraiti Survey District, to the southwest of the study area. Typical exposures within the study area are developed along the Manawatu River up to the Waikopiro Stream near Kopua, and along the Manawatu River up to the Mangapuaka River.

Classification: The upper part of the "Kumeroa Formation" defined by Lillie (1953) rests unconformably on older formations, including the lower part of the "Kumeroa Formation". This paper separates the lower part of the "Kumeroa Formation" and renames it the Okarae Formation, and uses the name **Kumeroa Formation** for the upper part of the "Kumeroa Formation" of Lillie (1953).

Distribution: This formation is distributed in the central part to western margin of the faulted blocks, and has a northeasterly orientation. The largest exposure is developed in the northeastern part, around the Turiri Range, and western margin of the study area.

Lithology: The Kumeroa Formation consists of detrital coquina limestone beds, fine-grained sandstone, and fossiliferous bluish grey siltstone. The base of the formation is marked by basal limestone ranging in thickness from 4 m to 20 m (Photo 8). The maximum thickness is attained at Turiri Range and thins southwestward. The limestone contains well preserved shells of oysters and brachiopods. The shells and matrix of sand are indurated less than other limestones in the Kumeroa Formation. Stratification is not developed within the basal limestone. The lower boundary of the basal limestone is clearly separated unconformably from the underlying formations, and numerous sandpipes intruded into the lower formations. The basal limestone grades upward into fossiliferous sandy siltstone.

Light-grey fine sandstones, with a thickness from 3 m to 100 m, contain abundant shell fragments and occasional lenticular concretions. Laminations of siltstone are abundant in the fine sandstone. The shells and their fragments are occasionally indurated to form coquina limestones, which form the basis for topographical ridges. The maximum thickness of these limestones is 30 m and changes laterally. Two to five sheets of limestone beds intercalate in the lower part of the Kumeroa Formation. The limestone beds are different in lithology from the basal limestone bed. These limestones consists of granule-size shell fragments and fine-grained sandstone, and grade both up and down to soft fine sandstone and siltstone. Parallel and cross lamination are developed within the limestone bed.

Massive siltstone with a thickness from 10 m to 100 m is developed among limestone beds in the upper part of the formation. The color of the

fresh rocks is bluish grey and the surface of the outcrops are usually weathered white. The siltstone contains molluscs which are occasionally stratified. The stratified shell beds are abundant in the top part of Kumeroa Formation (Photo 9), which can be used for identification of the boundary with the Mangatarata Formation.
Thickness: Maximum total thickness is 280 m to the west of Waikopiro Stream.
Relation: The Kumeroa Formation overlies unconformably the Okarae, Te Aute, Pukerua, Mangatoro and Mapiri Formations. Angular unconformities between the Kumeroa Formation and basal limestone of the Te Aute Formation can be clearly observed along Turiri Range, the Ahiweka Range peak Rangitoto, and south of Takapau.

The Kumeroa Formation is conformably overlain by the Mangatarata Formation in the western part of the study area.

9. Mangatarata Formation

Type Locality: Mangatarata Valley to the north of the study area. Typical exposures are developed along the Waikoukou Stream and Manawatu River near Kopua in this area.
Classification: The name Mangatarata was first used by Quennel & Brown (1937) for a group of pumiceous silts with lignites and sands interbedded with conglomerate, which occur in the Mangatarata Valley southeast of Waipukurau. The name was used by Lillie (1953) in the Dannevirke Subdivision based on the lithology. This paper follows the definition of the Mangatarata Formation of Lillie (1953).
Distribution: The formation is exposed along the southwestern margin of this area.
Lithology: The Mangatarata Formation consists of bluish grey tuffaceous siltstone, fine-grained sandstone, conglomerate, pumice tuff, and lignite.

The tuffaceous siltstone is whitish grey or greenish grey and 15 m in maximum thickness. Parallel lamination of fine-grained sandstone and lignite in the siltstone are developed abundantly in the lower part of the formation. The siltstone contains pumice of coarse sand size in the upper part of the formation.

The fine-grained sandstone is 10 m in maximum thickness, and contains round or lenticular pumice of coarse sand size to pebble size. Cross lamination, ripple marks, and slumping structures are common in the sandstone. Parallel lamination of tuffaceous fine siltstone is occasionally developed in the upper part of the formation.

White tuff layers 10 cm in thickness are common in the sandstone and siltstone. Thicker tuff layers ranging from 10 cm to a few meters in thickness are also intercalated in the formation (Photo 10). The abundance of tuff layers is greater in the upper part of the formation. Pumice tuff consisting of pebble-sized pumice crops out with a thickness of 150 cm in the Waikoukou Stream near Kopua. The thick white tuff layer can be traced in the field (Figs. 2 and 7).

Lignite beds have a maximum thickness of 70 cm. Most of the lignites are present as thin laminations within the siltstone and sandstone.

Conglomerate with a thickness of 3 m is exposed in a branch of the Waikoukou Stream. The conglomerate consists of pebbles and granules of hard dark-grey sandstone and a matrix of very coarse dark-grey sandstone.

Molluscs are rare throughout the formation but shell beds are intercalated in the basal part as thin parallel laminae with thicknesses of about 2 cm. In the Waikoukou Stream and Manawatu River, the base of the Mangatarata Formation can be distinguished by a 2 m thick bed of tuffaceous siltstone containing shells overlying a non-tuffaceous siltstone with numerous shells of the Kumeroa Formation.
Thickness: The Mangatarata Formation is more than 450 m thick in the northern part, south of Kopua. The thickness of the formation is 740 m on the west wing and about 430 m on the east wing of the synclinal structure in the east of Dannevirke.
Relation: The Mangatarata Formation overlies conformably the Kumeroa Formation, overlapping the northeasterly striking Waikopiro Faults, to the east of Dannevirke.

STRUCTURE

Faults are abundant in this district, and the sedimentary sequence was cut into spindle shape blocks (Fig. 2). The shape of the blocks and left side forward echelon arrangement of the blocks suggest that the faults are characterized by right lateral (clock wise) strike slip movement, same as for the Wellington Fault and Alpine Fault (Fig. 1). The named faults in the geologic map (Fig. 2) were traced and named by Lillie (1953).

Associated with the fault movements, the sedimentary sequence is folded. The bedding dips fall mostly within the range from 10° to 40°, westward. Eastward bedding dips are developed on the western margins of the faulted blocks along the Rangitoto and Oruawharo Faults. The shape of the folding of the faulted blocks can be observed with the structural contour map of the base of the Kumeroa Formation (Fig. 6). The dragged shapes of the base level indicate that the Waikopiro, Rangitoto and Oruawharo Faults have right lateral movements. The unconformity of the Kumeroa base contacts generally with the lower horizon of the sequence in the eastern part and a

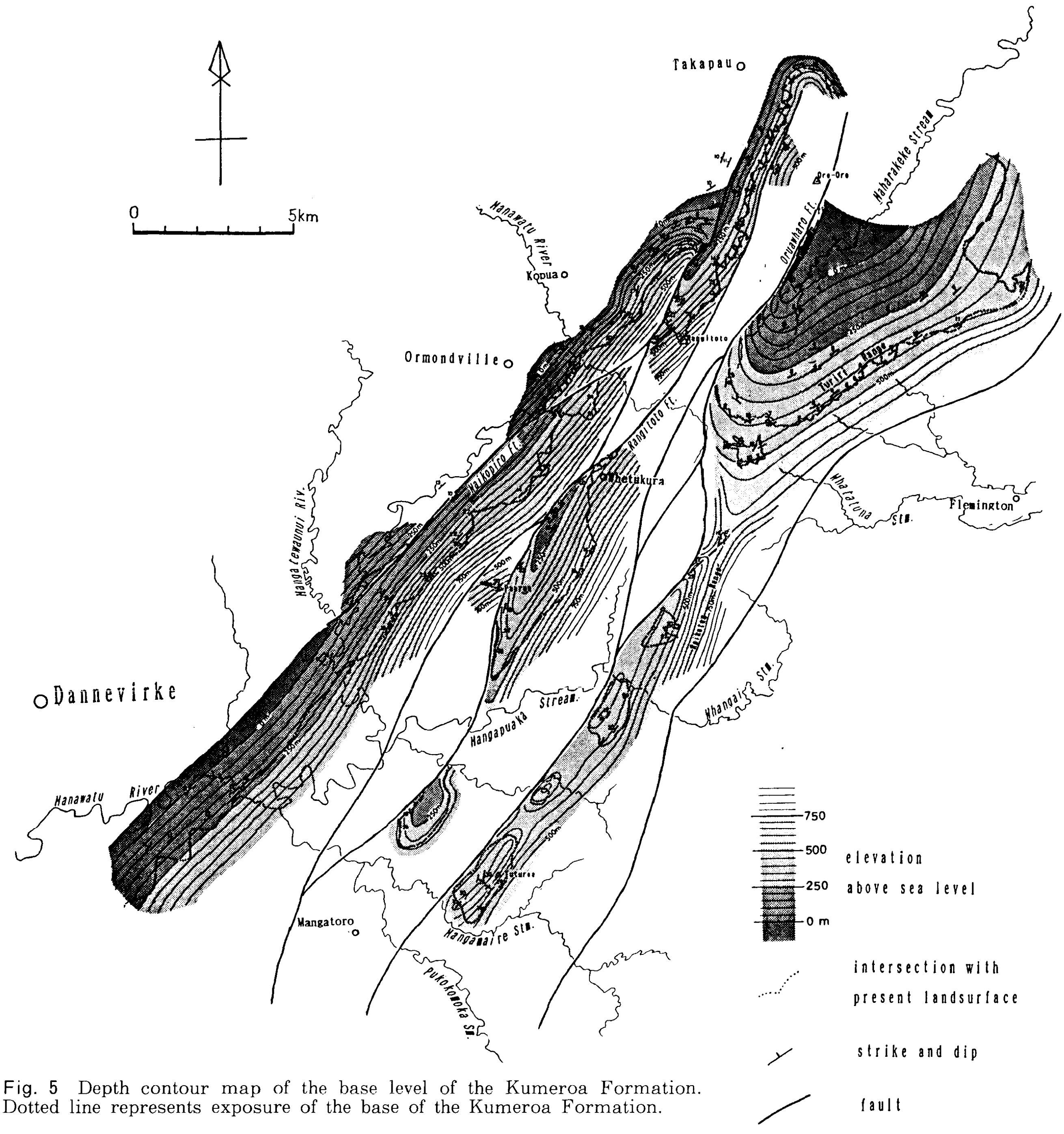


Fig. 5 Depth contour map of the base level of the Kumeroa Formation. Dotted line represents exposure of the base of the Kumeroa Formation.

higher horizon in the western part of the faulted block (Fig. 2), which is the same topographic orientation as the Kumeroa base.

The folding of the Mangatarata Formation is different from the lower sequence mentioned above, and includes a syncline that dips eastward as well as westward to the east of Dannevirke. The Waikopiro Fault overlaps with the syncline (Fig. 2).

PALEOMAGNETIC ANALYSIS

Three oriented blocks and cores were collected from 126 sites (Figs. 5 and 6). Cubic samples measuring 20-25 mm on a side were cut from the blocks with a diamond saw. Some blocks were broken during the transportation from New Zealand to Japan. Core samples with a diameter of 32 mm were taken from four horizons in the Te Aute Formation (MG 01-04) and the cores were cut into sections of 30 mm. The paleomagnetism of the samples was measured with a ring-core-type flux-gate spinner magnetometer and demag-netized

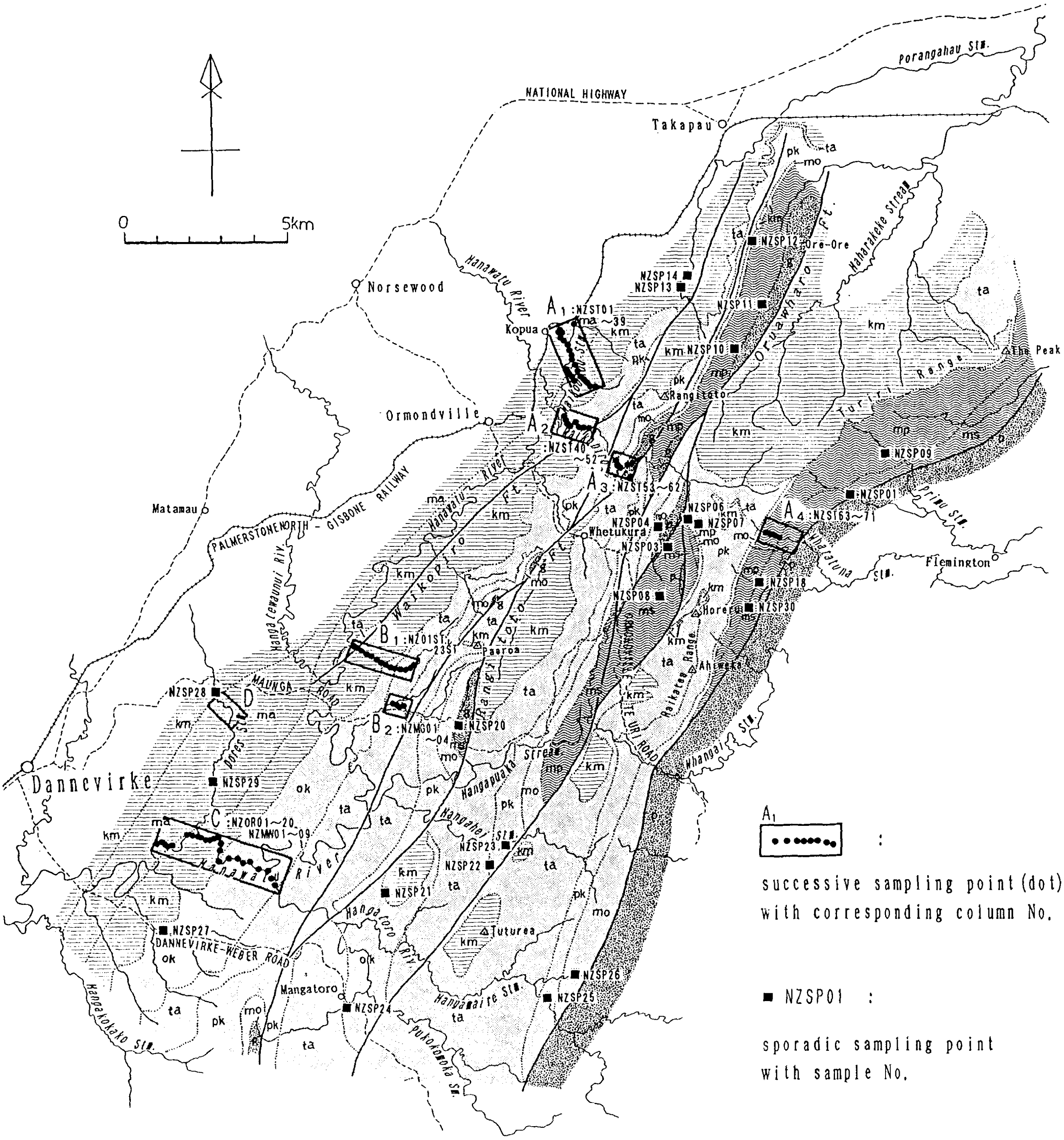


Fig. 6 Sampling routes and points for magnetic, biostratigraphic and isotopic studies of Neogene sedimentary sequence to the east of Dannevirke, southern Hawke's Bay, New Zealand.

with a current-regulated three axial alternating field demagnetizer (Koyama & Niitsuma 1983). Unstable soft components of magnetization were cleaned with 15 mT of alternating field. The magnetic intensities ranged from 1×10^{-8} kA/m to 7×10^{-5} kA/m after the AF-demagnetization. The 95% confidence limit (alpha95: Fisher 1953) of the directions of magnetization on three samples from the same site ranged from 5° for samples with 1×10^{-5} kA/m of the intensity to more than 40° for less than 1×10^{-7} kA/m of intensity. The intensity, inclination and declination are calculated and shown in Fig. 8.

Positive inclination with southward declination dominates, which represents reversed geomagnetic polarity. Negative inclination with northward declination of normal geomagnetic polarity is concentrated in the middle part of the sequence, the Te Aute Formation. The inclinations have values around the inclination for the normal and reversed geocentric axial dipole of ±57.8° (Fig. 8).

The declinations deviate clockwise 22.3° on

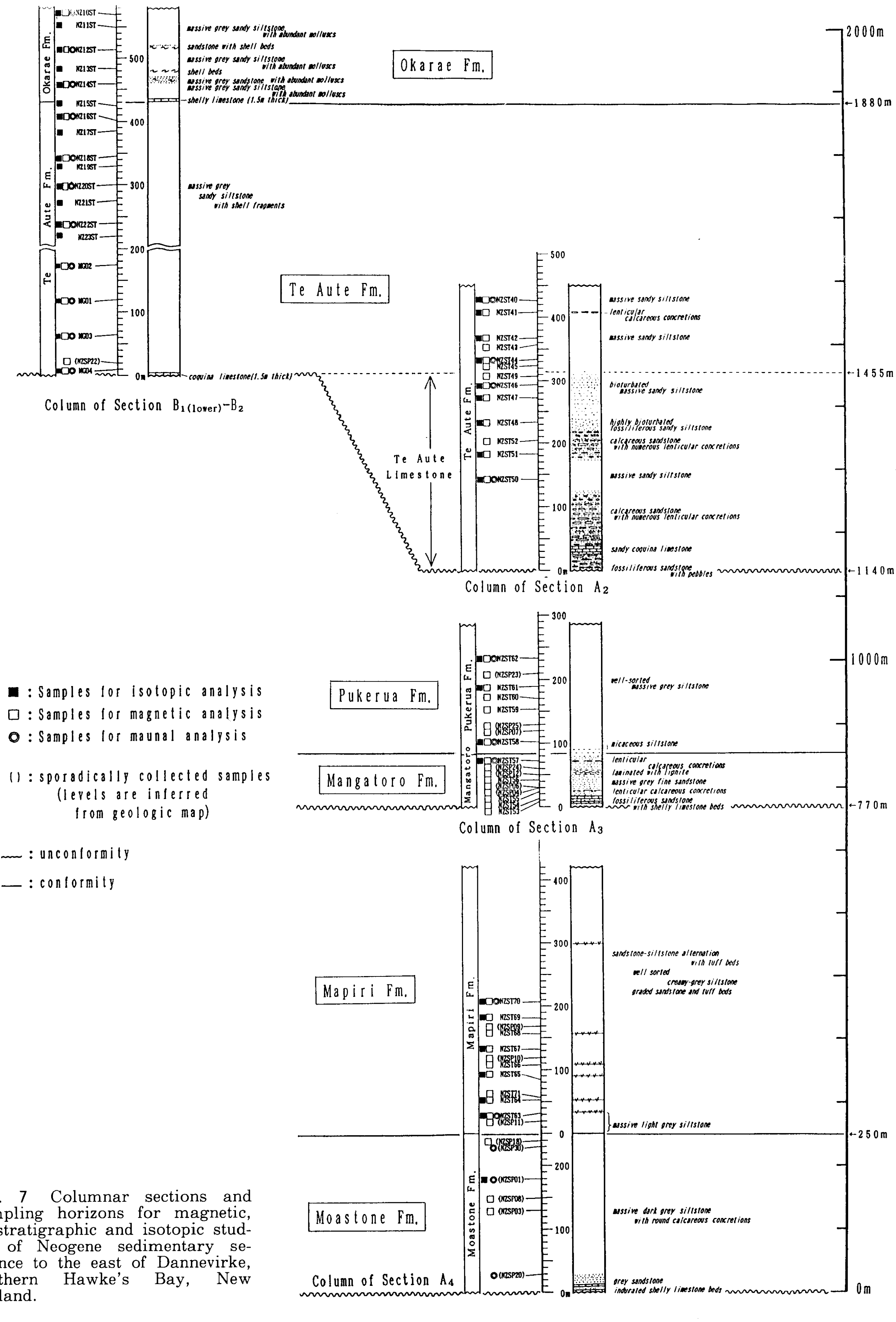
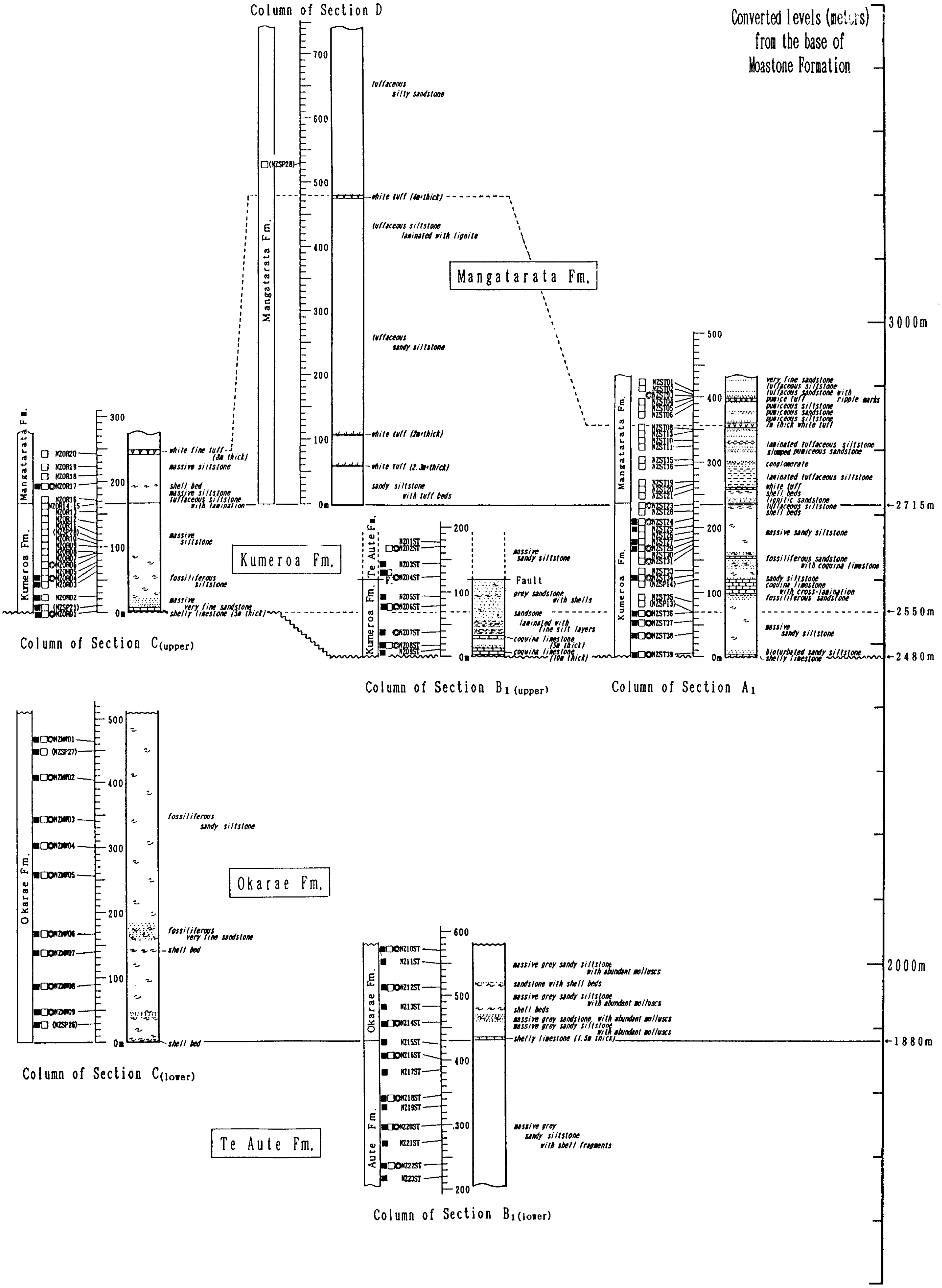


Fig. 7 Columnar sections and sampling horizons for magnetic, biostratigraphic and isotopic studies of Neogene sedimentary sequence to the east of Dannevirke, southern Hawke's Bay, New Zealand.


Column of Section D
Converted levels (meters) from the base of Moastone Formation
Mangatarata Fm.
Kumeroa Fm.
Okarae Fm.
Te Aute Fm.
white tuff (4m thick)
tuffaceous siltstone laminated with lignite
tuffaceous sandy siltstone
tuffaceous silty sandstone
white tuff (2m thick)
white tuff (2.3m thick)
sandy siltstone with tuff beds
white fine tuff (5m thick)
massive siltstone
shell bed
massive siltstone
tuffaceous siltstone with lamination
fossiliferous siltstone
massive very fine sandstone
shelly limestone (5m thick)
Fault
massive sandy siltstone
grey sandstone with shells
sandstone laminated with fine silt layers
coquina limestone (5m thick)
coquina limestone (10m thick)
very fine sandstone
tuffaceous siltstone
tuffaceous sandstone with pumice tuff
ripple marks
pumiceous siltstone
pumiceous sandstone
pumiceous siltstone
1m thick white tuff
laminated tuffaceous siltstone
slumped pumiceous sandstone
conglomerate
laminated tuffaceous siltstone
white tuff
shell beds
lignitic sandstone
tuffaceous siltstone
shell beds
massive sandy siltstone
fossiliferous sandstone with coquina limestone
sandy siltstone
coquina limestone with cross-lamination
fossiliferous sandstone
massive sandy siltstone
bioturbated sandy siltstone
shelly limestone
3000m
2715m
2550m
2480m
2000m
1880m
Column of Section C(upper)
Column of Section B1 (upper)
Column of Section A1
fossiliferous sandy siltstone
fossiliferous very fine sandstone
shell bed
shell bed
Column of Section C(lower)
massive grey sandy siltstone with abundant molluscs
sandstone with shell beds
massive grey sandy siltstone with abundant molluscs
shell beds
massive grey sandstone with abundant molluscs
massive grey sandy siltstone with abundant molluscs
shelly limestone (1.5m thick)
massive grey sandy siltstone with shell fragments
Column of Section B1(lower)

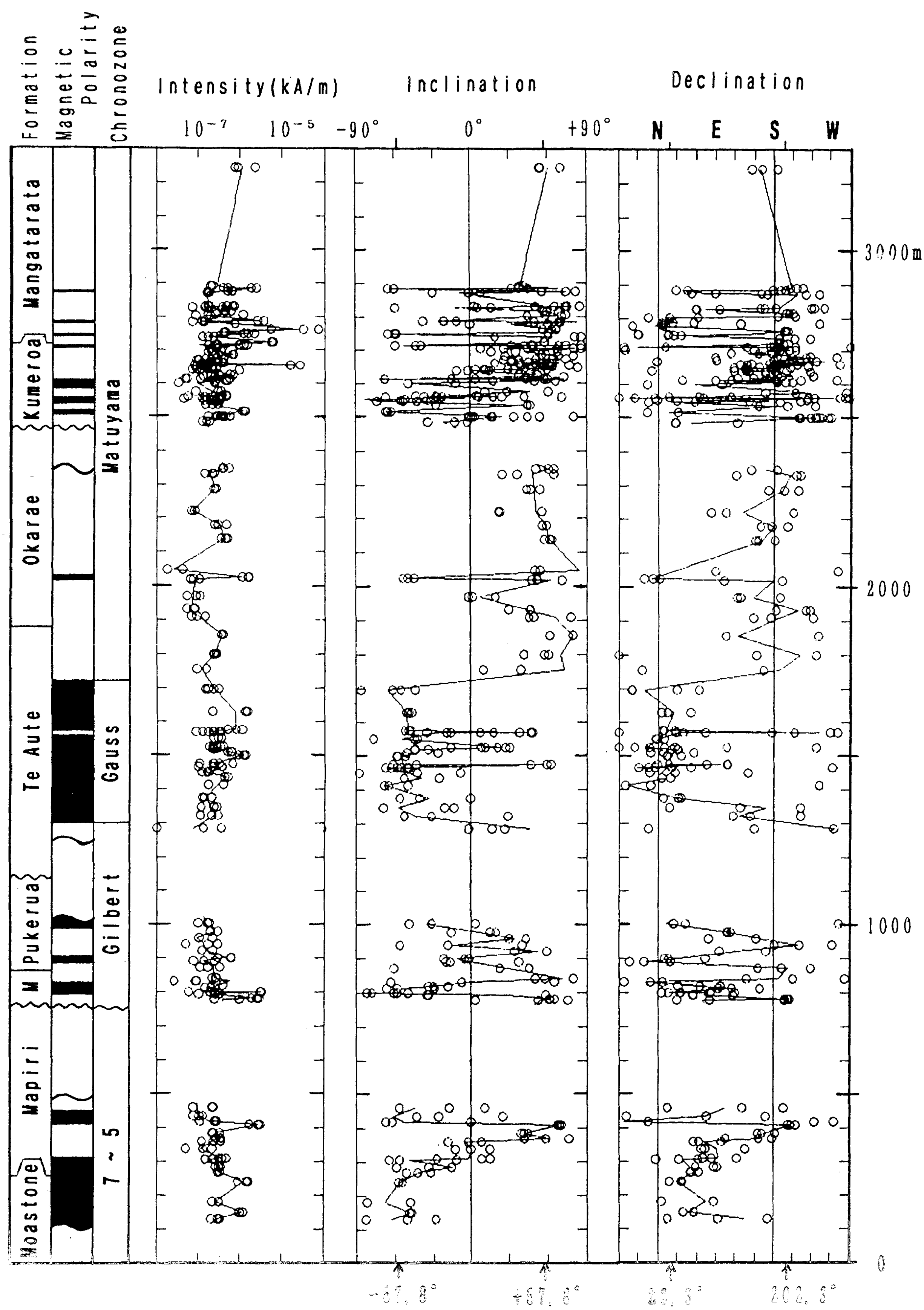


Fig. 8 Magnetostratigraphy of Neogene sedimentary sequence to the east of Dannevirke, southern Hawke's Bay, New Zealand. Circle corresponds to each measurement and line connects the average of a site.

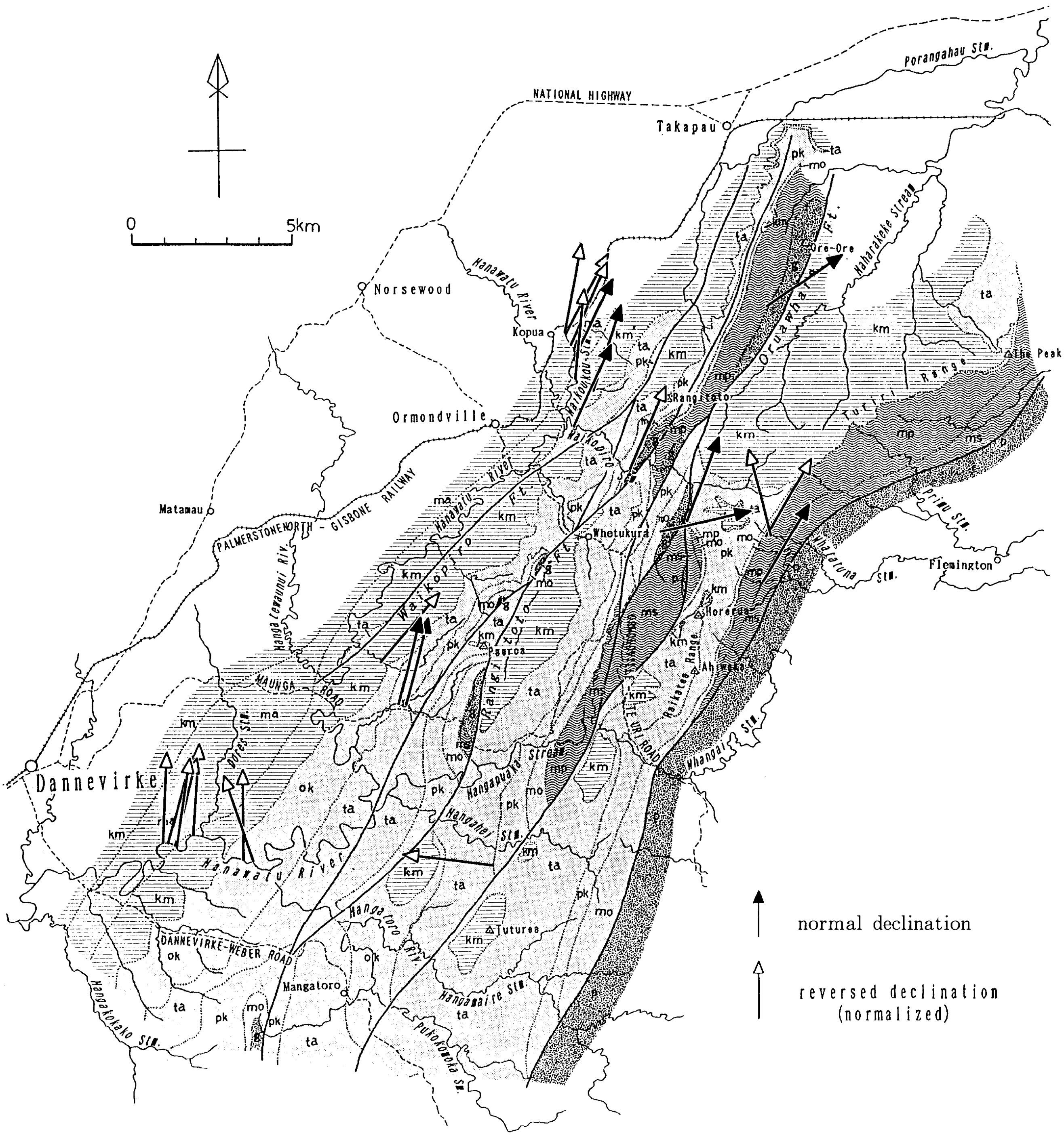


Fig. 9 Deviations in paleomagnetic declination, recorded in the Neogene sedimentary sequence to the east of Dannevirke, southern Hawke's Bay, New Zealand.

average for both normal and reversed polarity samples, with an alpha95 confidence limit of less than 20°. The deviation does not change throughout the sedimentary sequence (Fig. 8) or spatially (Fig. 9). This result indicates that the clockwise deviation has occurred after the deposition of the Mangatarata Formation and no deviation occurred during the deposition of the sedimentary sequence in this district. The clockwise deviations of paleomagnetic declinations can be explained by dragged rotation with right lateral strike slip motion. Clockwise deviations have also been reported in the eastern coastal area of North Island (Mumme *et al.* 1989; Roberts 1992).

BIOSTRATIGRAPHY

Biostratigraphic age determinations were carried out on samples from the sedimentary sequence using planktonic and benthic foraminifers, and nannofossils (Fig. 7). Distribution of the key species in this sequence are listed with the measured magnetic polarity of the samples, and reported ranges of the key species with respect to the magnetostratigraphy and New Zealand Stages, compiled by Edward (1987), are also shown in Fig. 10.

The interval with a normal polarity in the Te Aute Formation can clearly be correlated with the Gauss Normal Polarity Chronozone, above the interval with the Matuyama Reversed Polarity Chronozone and below the interval with the Gilbert Reversed Polarity Chronozone. Because the top of the sequence still has reversed polarity (Fig. 8), the deposition of the sequence terminated before the Brunhes Normal Polarity Chronozone. The interval with normal polarity in the lower part of the Kumeroa Formation is associated with the horizon at which *Globorotalia crassaformis* coiling changes from mixed to left coiling, and can be correlated with the Reunion Normal Polarity Subchronozone. Based on this correlation, the sequence does not reach the Pliocene-Pleistocene boundary, which is located just above the Olduvai Normal Polarity Subchronozone. The rate of sedimentation was extremely high, more than 183 cm / ka (1100m / 0.6Ma) for the upper part of the sequence (upper part of Te Aute Formation, Okarae, Kumeroa, and Mangatarata Formations), in contrast to less than 63 cm/ka (1700m/3Ma) for the lower part of the sequence (middle and lower part of Te Aute Formation, Pukerua, Mangatoro, Mapiri and Moastone Formations).

ISOTOPIC ANALYSIS

The carbon and oxygen isotopes of foraminiferal tests were measured using a MAT 250 mass-spectrometer at Shizuoka University, which was developed for ultra-small samples (Wada *et al.* 1982, 1984).

Notorotalia sp. (cf. *pseudofinlayi*), a benthic foraminifer and *Globigerina bulloides*, a planktonic foraminifer, commonly occurring throughout the sedimentary sequence, were used for isotopic analyses. In the case that *Notorotalia* was absent, *Uvigerina* was used. The tests of *Notorotalia* and *Uvigerina* are large enough to measure the isotopes using a single test. Because the carbon dioxide gas evolved from a single test of *Globigerina* is not sufficient, 3 to 7 tests were used for isotopic analysis. The foraminiferal tests were sketched, then crushed with a needle and cleaned with an ultra-sonic bath in methyl alcohol under a binocular microscope. The crushed test in a stainless steel thimble was reacted with saturated pyro-phosphoric acid at 60.00℃.

Size-correlated variations in carbon isotopes have been measured for the tests of *Notorotalia* that are less than 480 μm in diameter, but such variations have not been found in oxygen isotopes. The smaller test gives a lighter carbon isotopic value; thus tests of *Notorotalia* larger than 480 μm were used. Systematic differences in carbon isotopes between *Notorotalia* and *Uvigerina* were detectable; however, no differences were found in the oxygen isotopes. On average, *Notorotalia* has 0.39 ‰ heavier carbon than *Uvigerina* (Fujii 1985ms). The difference was added to the carbon isotope values for *Uvigerina*, thus making it comparable to *Notorotalia* for isotope stratigraphy.

The oxygen isotopes $\delta^{18}O_{PDB}$ range from -1 to $+1$ ‰ for planktonic and from 0 to $+2$ ‰ for benthic foraminifers (Fig. 11). The differences are consistent with the water temperature differences and influences of fresh water with lighter oxygen isotopes. The surface water was a higher temperature than bottom water, and the fresh water was stratified at the surface above fully saline water, owing to the difference in their density. The maximum difference in the oxygen isotope values was measured in the Mapiri Formation, which corresponds to the the deepest lithofacies of the sandstone-siltstone alternation and the highest abundance of planktonic foraminifers (Fig. 11).

The carbon isotopes $\delta^{13}C_{PDB}$ range from -2 to $+1.5$‰ for planktonic and from -1 to $+1$‰ for benthic foraminifers (Fig. 11). The benthic carbon isotopes are heavier than planktonic except for the Mapiri Formation. Since the surface of the open marine water column is the location of photosynthetic production (lighter carbon is selectively taken up for use in organic tissue), normally the carbonate carbon isotopes are heavier at the surface than in bottom water; the measured results indicate the reverse. The same kind of contradiction was reported for *Notorotalia* in the Plio-Pleistocene sequence of central Hawke's Bay (Haywick *et al.* 1991).

Isotopes, foraminiferal fauna and lithology of the basal parts of the Kumeroa Formation were examined along the correlative three sections A1, B1 and C from north to south (Figs. 6 and 7). The planktonic foraminiferal abundance is higher to the north (Fig. 12). The benthic foraminiferal fauna represents a deeper facies to the north, corresponding to the planktonic foraminiferal abundance. The oxygen and carbon isotopes are heavier to the north for both planktonic and benthic foraminifers. The oxygen isotopes from benthic foraminifers are consistent with the idea that there existed deeper and thus cooler water or more pelagic environments to the north, and more neritic environments with fresh water influences upon the planktonic foraminifers to the south.

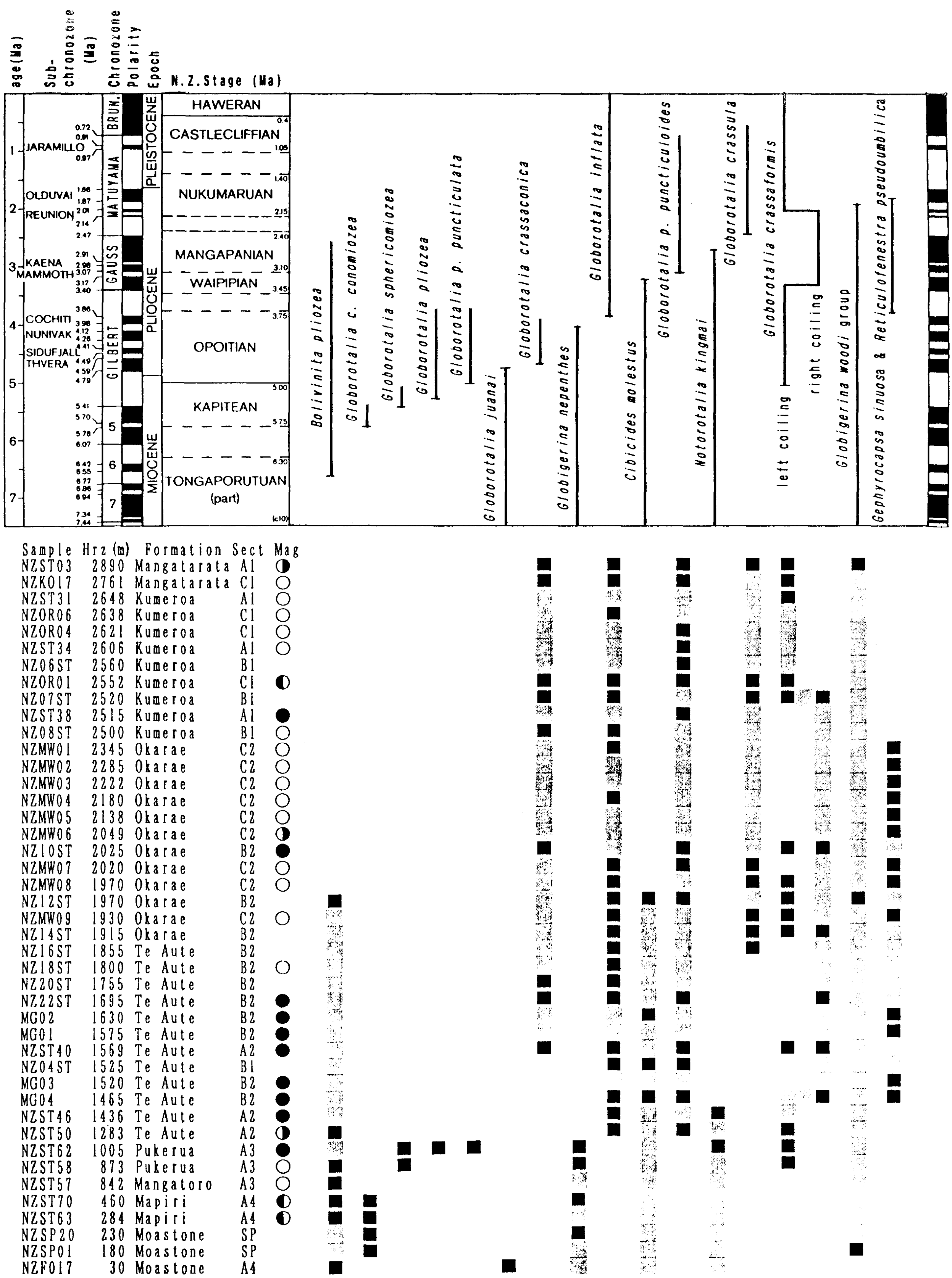


Fig. 10 Magnetic polarity and distribution chart of biostratigraphic marker species (lower) accompanied by their reported ranges (upper).

Ages of magnetostratigrapy and New Zealand Stages are based on Edward (1987). Biostratigraphic datum planes by Edward (1987) are represented with thin bars at the end of the biostratigraphic ranges (thick line) of the key species. The open ends of the biostratigraphic ranges are based on Hornibrook (1981, 1982). Hrz: horizon from the base of the Moastone Formation in meters (Fig. 7). Sect: sampling section (Fig. 6). Mag: magnetic polarity (solid circle: normal polarity; open circle: reversed polarity; left half solid circle: normally intermediate; right half solid circle: reversedly intermediate; Fig. 8). Solid square: presence of the key species.

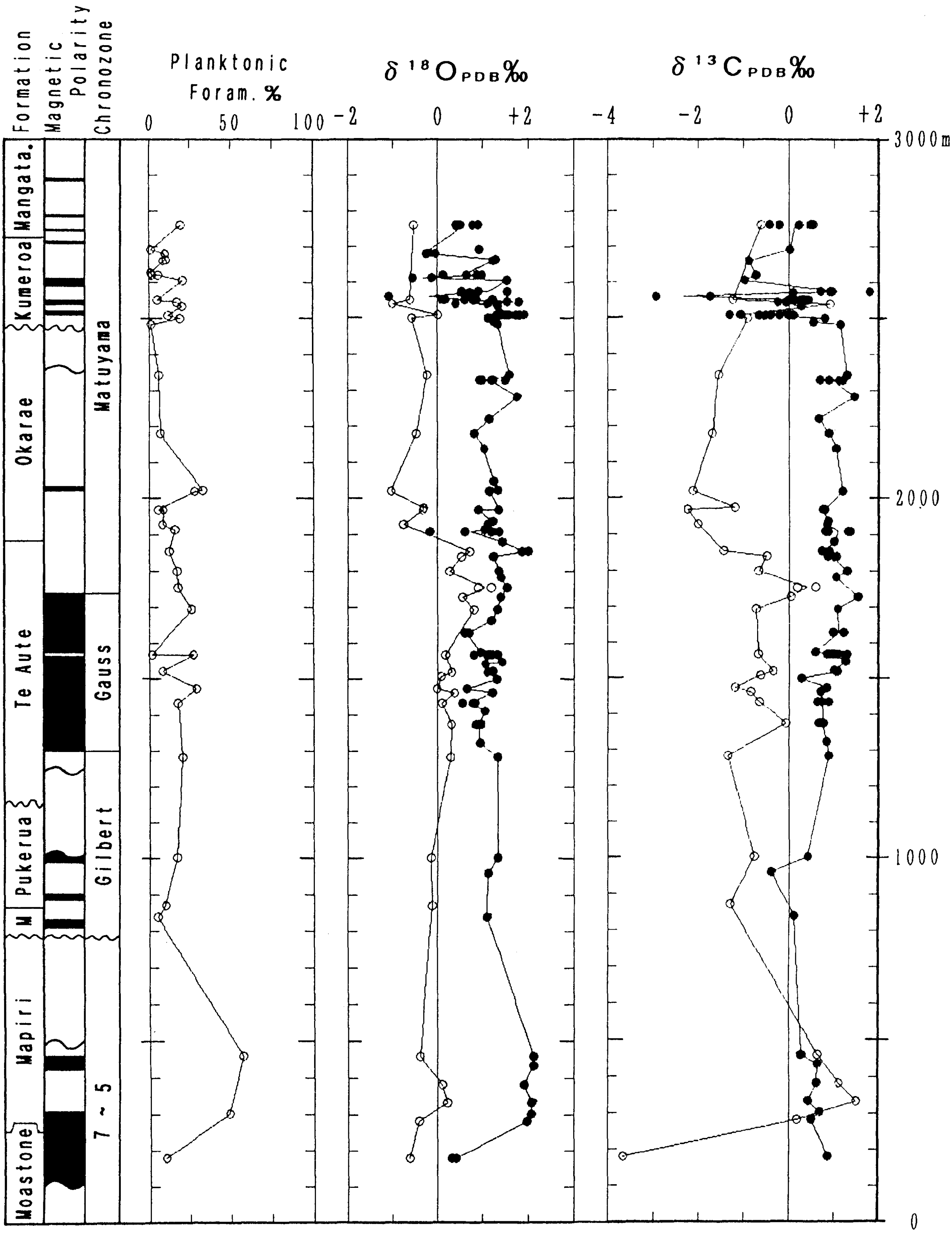


Fig. 11 Oxygen and carbon isotopes of planktonic foraminifer *Globigerina bulloides* (open circles) and benthic foraminifera (solid circles). The carbon isotopes $\delta^{13}C_{PDB}$ are converted to *Notorotalia* sp. The abundance of planktonic foraminifers is also shown. Circles corresponds to each measurement and line connects the averages of the sites.

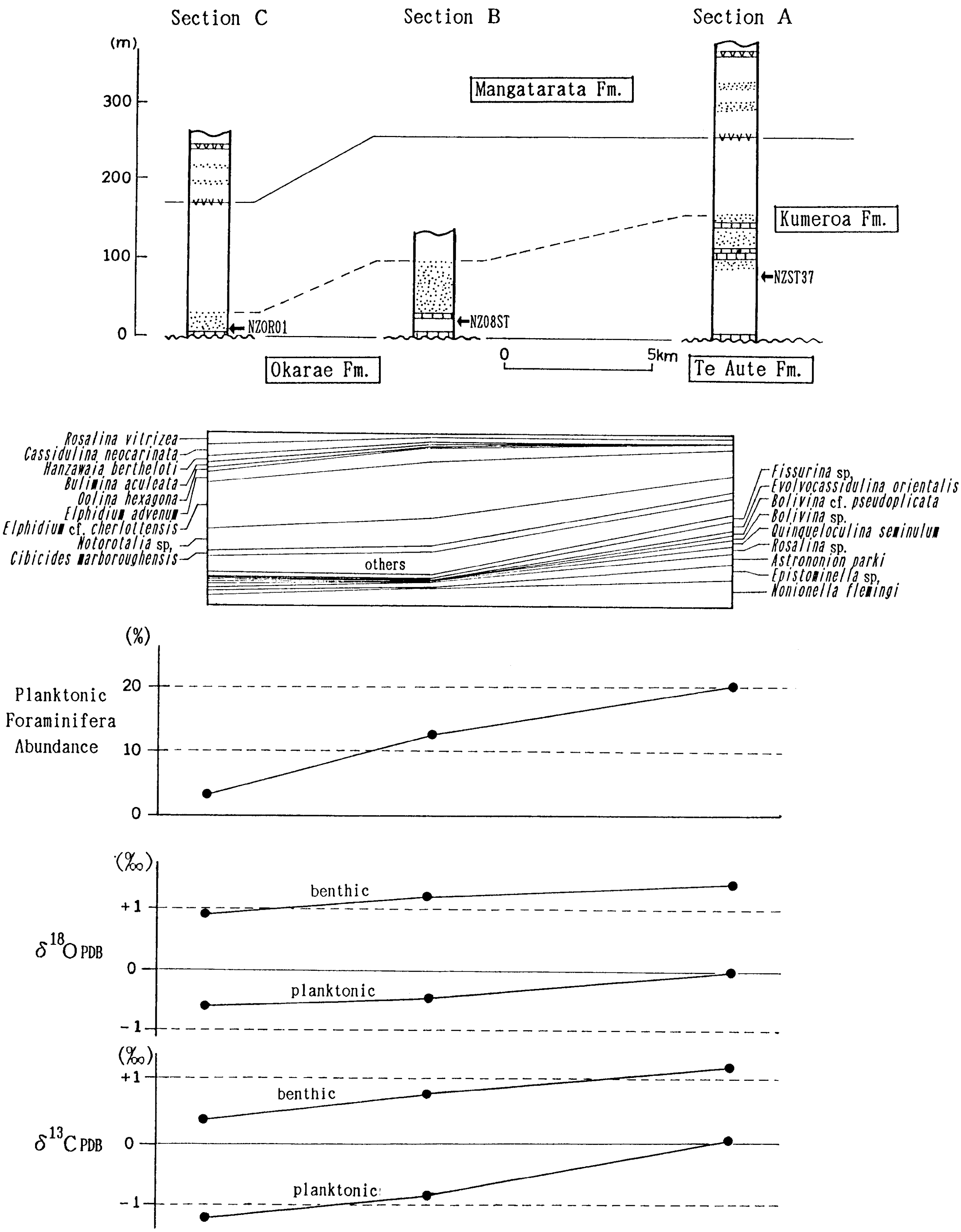


Fig. 12 Lateral changes of lithology and sampling horizons, benthic foraminiferal fauna, planktonic foraminiferal abundance, and oxygen and carbon isotopes of planktonic foraminifer *Globigerina bulloides* and benthic foraminifer *Notorotalia* sp. in the lower part of the Kumeroa Formation.

The carbon isotopes are difficult to explain by analogy with the oxygen isotopes, and indicate that the water depth was shallower than the typical pelagic chlorophyll maximum zone, approximately 40～80m, thus the bottom water was the site of the highest photosynthetic productivity.

TECTONICS

The studied sedimentary sequence gives detailed information on the tectonic evolution of New Zealand, especially the present status of the tectonics and the collisional event of the Chatham Rise along the Hikurangi Trench. The sedimentary facies, rate of sedimentation, lateral changes in the thickness and facies of the sedimentary body, unconformities, faulting and folding, and lateral rotation detected by paleomagnetism are important for the interpretation of tectonic evolution.

The sedimentary facies of the sequence (Figs. 2 and 7) shows that the forearc basin, in which this sequence was deposited, was formed upon Paleogene rocks and "Greywacke" in the late Miocene, and that the subsidence rate did not compensate for the regular supplies of sediments. The depressions were filled with sandy turbidites during deposition of the sandstone-siltstone alternation of the Mapiri Formation. Above the Mapiri Formation, the sedimentary sequence does not contain turbidites and the forearc basin was filled with regularly supplied sediments and lag sediments. The balance between the subsidence and sediment supply is represented by the cyclic facies change in the sequence.

Tuff layers indicate activities of arc volcanism associated with plate subduction along the Hikurangi Trench. Tuff layers intercalate with the Mapiri and Mangatarata Formations, and small fragments of pumice are contained in the Pukerua Formation and thin tuff beds in the Okarae Formation. The intercalation of tuff layers indicates two peaks of volcanic activities in the initiating stage (Mapiri Formation) and terminal stage (Mangatoro Formation) of the forearc basin. The close relation suggests that both the formation of the forearc basin and volcanism are parts of island arc activities, related to plate subduction.

Magneto-biostratigraphic investigation gives information on the acceleration of the subsidence rate to more than 183 cm/ka in the upper part of the sequence, and the uplift of the sequence might be inferred to be related with the acceleration.

Three unconformities in the sequence are found at the bases of the Mangatoro, Te Aute, and Kumeroa Formations (Figs. 2 and 3). The unconformity at the base of the Mangatoro Formation represents the onlap of Neogene forearc sediments onto the basement of the forearc basin, and the unconformity at the base of the Te Aute Formation is discordant only in the northeastern part of the Turiri Range of the northeastern corner of this area. The unconformity at the base of the Kumeroa Formation is the most distinct unconformity within the sequence, as it contacts discordantly most of the sequence (Okarae, Te Aute, Pukerua, Mangatoro, and Mapiri Formations). The angular unconformity indicates that large scale rearrangement occurred in the forearc basin just before the deposition of the Kumeroa Formation, and the forearc basin sequence might have been eroded up to 2000 m, if the sedimentary sequence was uniformly deposited (Fig. 7). The magneto-biostratigraphic age determination suggests that erosion occurred within a limited time from the early Matuyama Chronozone (from 2.47 Ma to 2.14 Ma; Figs. 8 and 10), and the duration of the erosion would thus be on the order of 0.1 Ma, which gives an extremely high erosion rate of 2000 cm/ka = 2 cm/a, comparable to the order of plate motion.

The shape and arrangements of faulted blocks (Fig. 2) indicate that the geology of this district is affected directly by the transform plate boundary. Because the faults cut the Kumeroa Formation, the fault activity occurred after the deposition of the Kumeroa Formation, the base of which is in unconformable contact with the lower sequence. The amplitudes of the base level are more than 1000 m in the faulted blocks (Fig. 5) and the amount of erosion accompanied with the unconformity is 2000 m. Because the amounts of the erosion and deformation have same order of magnitude and same westward dipping topographic orientation, as mentioned above, the two events can be estimated to be successive tectonic movements. Because the Waikopiro Fault overlaps with the syncline of the Mangatarata Formation (Fig. 2), which was deposited in the last stage of the marine sedimentary sequence, the distinctive tectonic movements might have happened in the final stage of the forearc basin history during the deposition of the Mangatarata Formation.

The estimation of the changes in the tectonic situation is consistent with the lateral changes in the depositional thickness and frequent intercalation of tuff layers in the Mangatarata Formation (Fig. 7).

SUMMARY

The Neogene marine sedimentary sequence to the East of Dannevirke, Southern Hawke's Bay, New Zealand was deposited in the forearc basin along the Hikurangi Trench from the late Miocene to the latest Pliocene. The marine sequence is divided, in ascending order, into the Moastone,

Mapiri, Mangatoro, Pukerua, Te Aute, Okarae, Kumeroa, and Mangatarata Formations.

The sedimentary sequence is cut into spindle shape blocks by faults with right lateral movements, same as for the Wellington Fault and Alpine Faults.

Oxygen and carbon isotopes of foraminiferal tests indicate that the forearc sedimentary basin was shallow enough that maximum primary productivity occurred near the bottom, in contrast to open marine conditions.

A distinct tectonic event occurred in the latest Pliocene, 2.2 Ma, reflected in an angular unconformity at the base of the Kumeroa Formation and deformation of the formation following its deposition. The event rearranged the forearc basin and terminated deposition in the forearc basin. The event was associated with volcanic activity.

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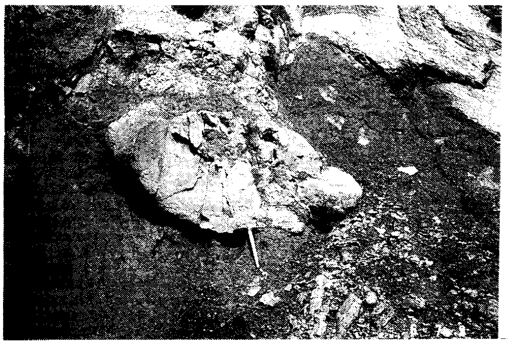
Explanation of Photographs

1: Dark grey sandy siltstone with calcareous concretions of the Moastone Formation at the type locality.
2: Alternation of sandstone and siltstone of the Mapiri Formation in the eastern part of the study area.
3: Fine sandstone containing lenticular calcareous concretions of the Mangatoro Formation at Mangapurakau Stream.
4: Well-sorted massive siltstone of the Pukerua Formation at Mangapurakau Stream in the western part of the study area.
5: Calcareous sandstone of Te Aute Formation at Popoiahoea Stream in the western part of the study area.
6: Dip slope of basal limestone of the Te Aute Formation south of Rangitoto.
7: Fossiliferous sandy siltstone of the Okarae Formation intercalating with thin tuff beds at the Magatoro River.
8: Basal limestone of the Kumeroa Formation, resting on siltstone of the Pukerua Formation east of Pukerua. Stratification is developed in the upper part of the limestone.
9: Parallel lamination with fossil shells in the top of Kumeroa Formation at Waikoukou Stream in the western part of the study area.
10: White tuff beds of the Mangatarata Formation at Waikoukou Stream in the western part of the study area.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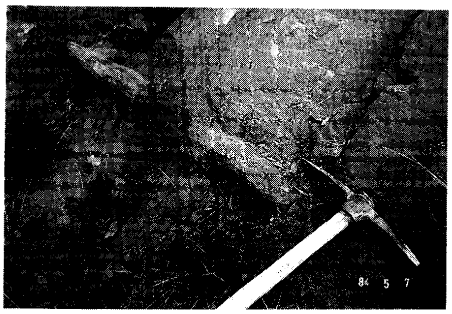
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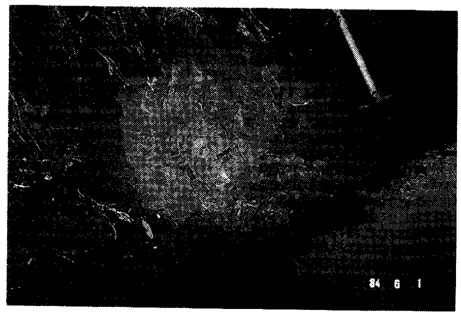
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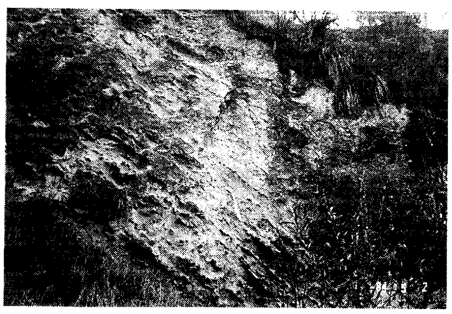
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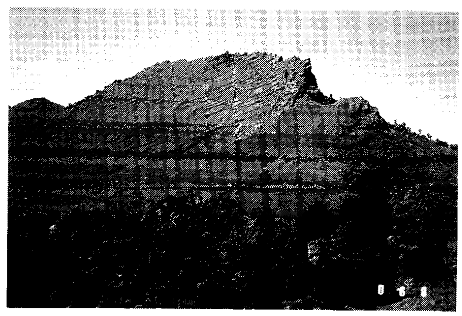
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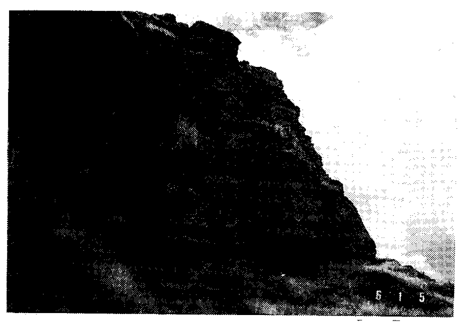
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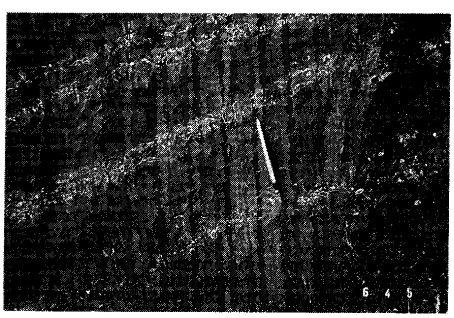
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