# PALEOENVIRONMENTAL ANALYSIS OF QUATERNARY STRATA IN THE LEVIN AREA

A thesis presented
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Quaternary Science at
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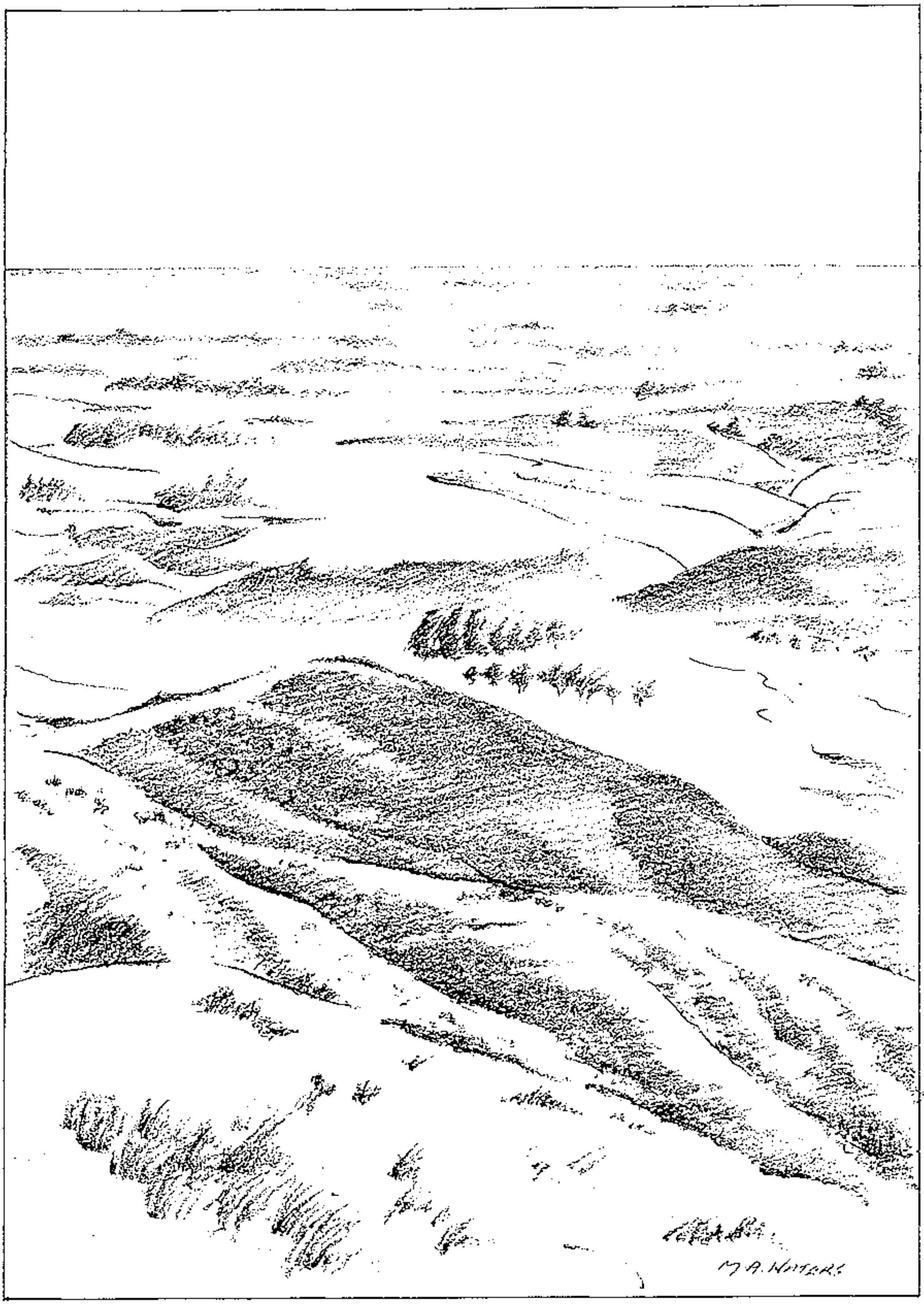


Frontispiece: Pencil sketch looking north from the Tararua foothills, south-east of Potts Hill, across the Tokomaru Marine Terrace and Manawatu River flood plain beyond.

ABSTRACT

Marine transgression during the Last Interglacial resulted in widespread inundation of the southern Manawatu area. The Otaki Formation constitutes the relatively thick blanket of predominantly marine sand deposited at the height of the transgression and is now exposed in a partially dissected marine terrace abutting the Tararua Range.

Sedimentation was controlled by basement block faulting related to a regional strike-slip tectonic regime on the south-eastern margin of the South Wanganui Basin. Wave-induced longshore currents from the north-west supplied abundant sediment to the coast.

North-east of Levin the Kairanga Trough, occupying a north-east-trending structural depression between uplifted basement blocks, formed the centre of an embayment during the transgression. Tide-dominated depositional processes predominated around the margins of the embayment. In the Forest Lakes area, the absence of seaward barriers resulted in an open wave-dominated coastline. Between Ohau and Shannon mixed wave/tide processes predominated. Stabilisation of sea level resulted in shoreline progradation which was especially marked south of Levin where a dune belt formed, mantling the coastal cliff and later migrating inland.

Retreat of the sea was followed by differential uplift and dissection of the newly exposed marine terrace. Two later marine transgressions cut treads in the earlier marine terrace, their strandlines being controlled by the previously established drainage pattern. Ameliorating climate associated with the major sea level regression of the Last Glacial was accompanied by several phases of loess and minor dune sand accumulation on the exposed marine terraces. At the same time large areas of the terrace coverbeds were removed due to river aggradation. Final truncation of the Last Interglacial marine terraces occurred during the Holocene transgression.

Tectonic warping of the marine terraces is continuing along pre-existing basement faults.

## ACKNOWLEDGEMENTS

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# CHAPTER 1

# INTRODUCTION

## 1.1 PURPOSE AND SCOPE OF STUDY

In recent years there have been major advances in the understanding of the evolution of the South Wanganui Basin including a well documented chronology of Quaternary sea level fluctuations. Much of this information has arisen from studies carried out both onshore and offshore in the Wanganui and south Taranaki areas.

Little stratigraphic and sedimentological investigation of late Quaternary strata in the southern Manawatu area has been undertaken since Oliver mapped the Otaki Formation in 1948. Thus, in the light of present knowledge, it is timely to apply modern techniques of sedimentary basin analysis in making a detailed study of the late Quaternary strata of the southern Manawatu district.

The aim of this study is to elucidate the stratigraphy, distribution, environment of deposition and post-depositional history of the Otaki Formation that underlies the Tokomaru Marine Terrace in the Levin area and to relate this to the late Quaternary history of the Wanganui Basin.

## 1.2 LOCATION OF STUDY AREA

The study area is located in the Horowhenua district, south-western North Island, and forms a rectangular strip of elevated coastal plain (*c*.200 sq. km.) between Otaki River in the south and Tokomaru River in the north (Fig. 1.1). The area is bounded to the north by the Manawatu River flood plain. The western boundary is concealed by Holocene coastal sand dunes within 3km of the coast. The Tararua Range forms the eastern boundary. Other major rivers draining the Range which cross the study area include (from south to north) Waitohu Stream, Ohau

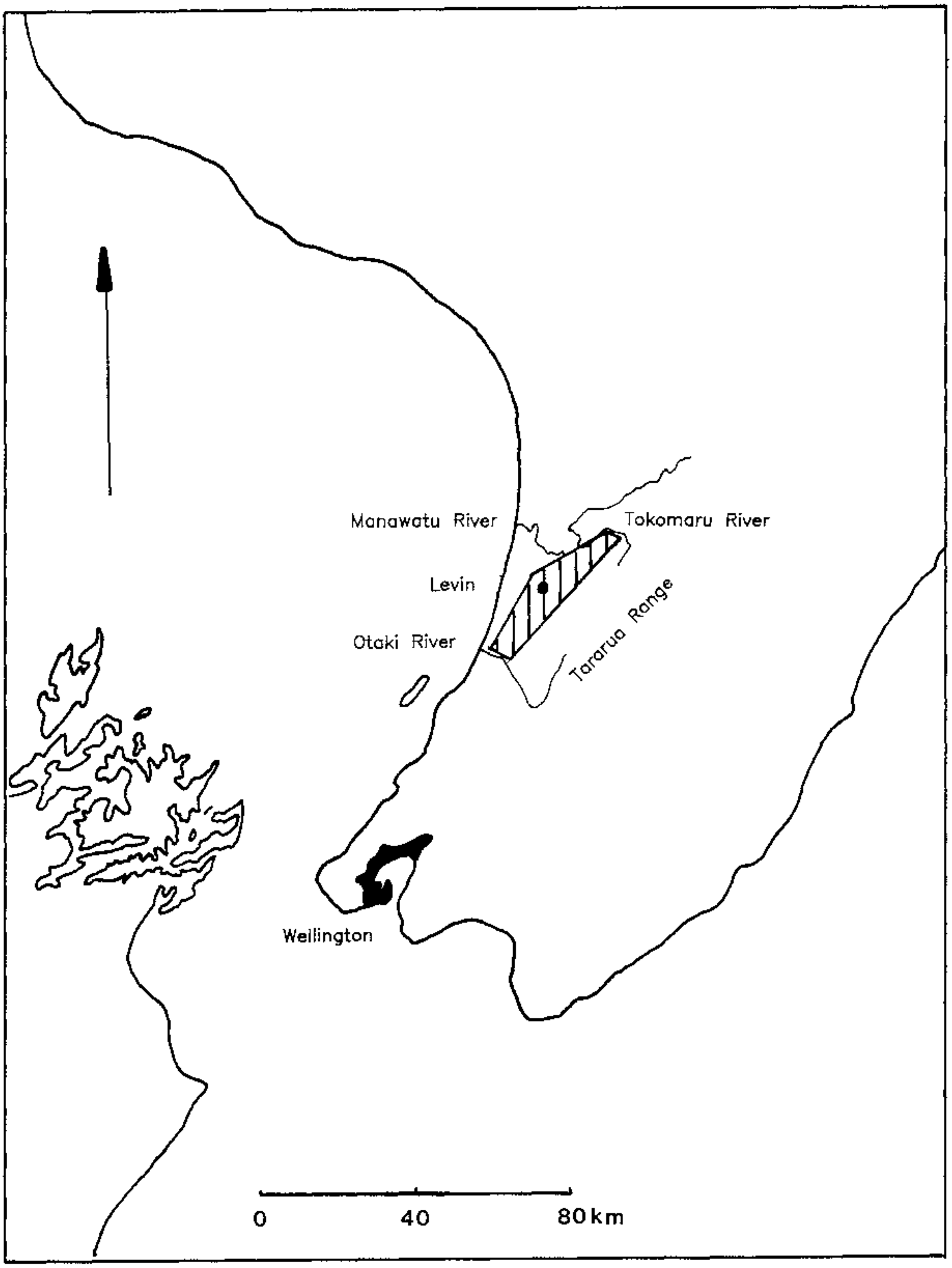


Fig 1.1 Location map of study area.

River and Mangaore Stream (Fig. 1.2).

Levin township (population 15,000), situated in the centre of the study area, services the surrounding rural community which is involved predominantly in dairy farming.

## 1.3 METHODS

Primary data was gathered through field reconnaissance with samples being collected for more detailed analysis. Additional information, supplied by the Manawatu-Wanganui Regional Council, provided subsurface data from 82 bore logs of water wells drilled directly into the Tokomaru Marine Terrace. Bore hole locations are plotted on Maps 1-4 with grid references from the NZMS 260 series along with other relevant information, tabulated in Appendix A.

### 1.3.1 Field Work

The extent of the Tokomaru Marine Terrace between Otaki River and Tokomaru River was delineated through aerial photographic interpretation and ground survey. Well exposed sections were described and measured in detail with the aid of a Brunton compass and Abney level. Their locations are plotted on Maps 1-4 with measured section descriptions and NZMS 260 series grid references given in Appendix B.

Exposure in the field area is generally poor, consisting of many small outcrops of several metres in thickness. The best outcrops occur in farm tracks, road cuttings and silage pits. Stream valleys alone yielded few good exposures.

Geological maps were prepared showing the distribution of the Otaki Formation including structural and geomorphic features along with measured section and bore hole locations (Maps 1,2,3,4).

### 1.3.2 Sampling Methodology

Sampling of the unit was carried out with the following intentions:

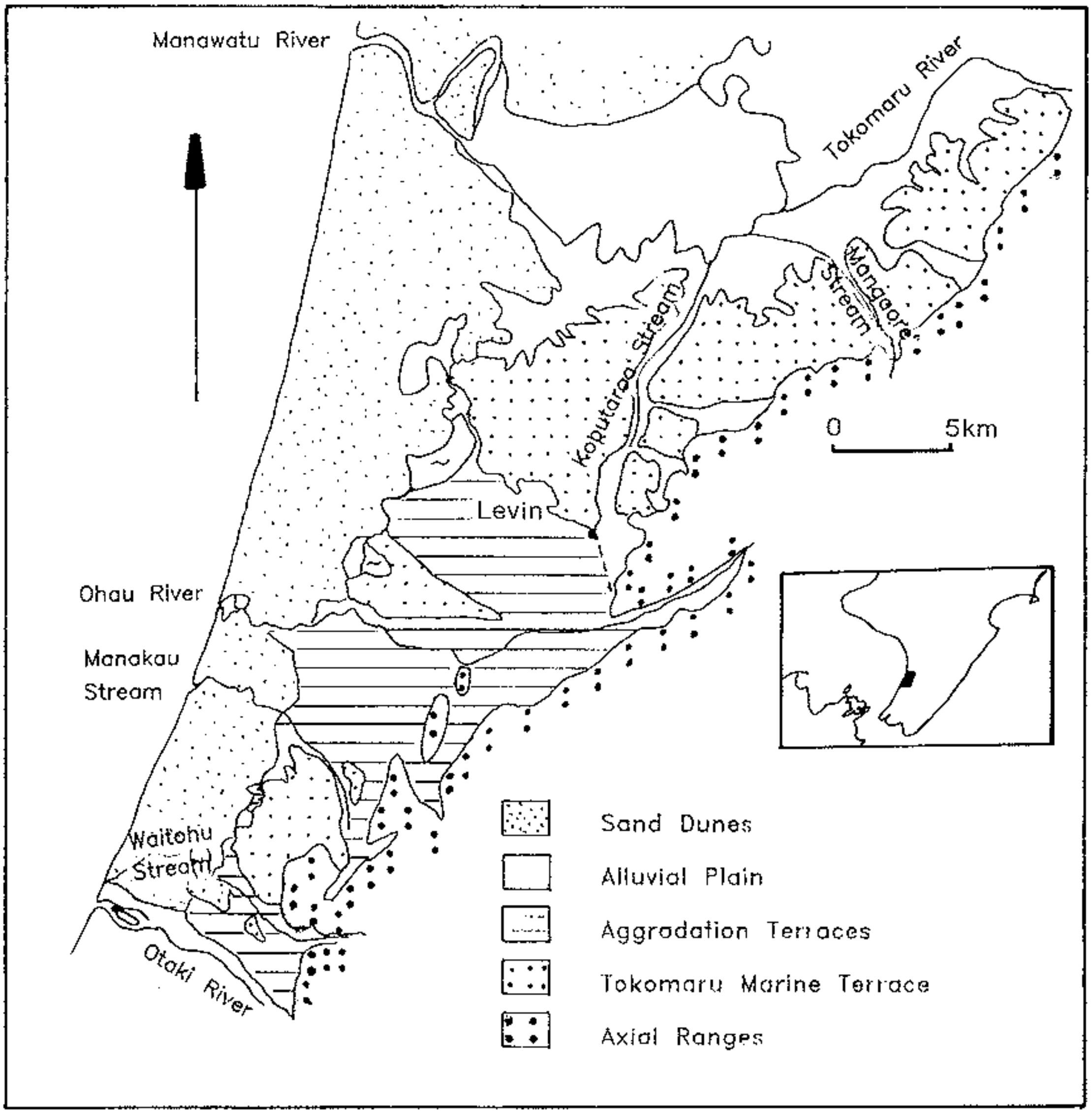


Fig 1.2

Physiography of southern Manawatu district.

1. grain size analysis

a) to delineate variations in overall grain size characteristics of the sandstone both vertically and laterally through the unit;

b) to provide descriptive data to aid in interpreting depositional environment;

2. to provide data on provenance from the petrography of detrital grains;

3. to provide paleoclimatic information from fossil pollen analysis.

Where sections of good vertical exposure were encountered sampling was carried out systematically up the sequence. In areas of poor exposure spot samples were taken with their relative position in the sequence noted. Samples of more indurated sandstone were obtained less selectively from across the study area for thin sectioning and petrographic analysis. Palynological analysis was carried out on two samples of peat by D.C. Mildenhall (DSIR Geology and Geophysics). Both peat samples came from the single occurrence of peat encountered within the Otaki Formation in the study area.

## 1.4 REGIONAL SETTING

### 1.4.1 Physiography

Four main physiographic features dominate the Horowhenua and southern Manawatu districts (Fig. 1.2). To the east, the NNE-trending Tararua Range sub-parallels the coastline and rises abruptly to heights of more than 1500m. Mesozoic rocks comprising complexly deformed, highly indurated, flysch sequences with associated spilite and chert make up the strata of the ranges and form the regional basement.

An uplifted and partially dissected marine terrace abuts the western flanks of the Tararua Range and slopes gently seaward. It is a composite structure composed of several recognisable benches comprising Pleistocene marine strata overlain by a sequence of loesses. Typically the uplifted plain forms flat topped interfluves separated by "box-shaped" swampy valleys (Fig. 1.3).[1]

River aggradation surfaces associated with the Ohau and Otaki rivers fan out westward from the ranges bisecting the older marine terraces with broad corridors of coarse alluvium leaving occasional inliers prominently preserved. The most extensive aggradation surface is correlated with the end of a widely recognised phase of river aggradation in the southern North Island attributed to the last glaciation (Milne 1973a,b). The deposits of the aggradational episode are mapped as Ohakean gravels from which Ohakean loess is derived. The upper surface of the gravels is mapped as the Ohakean terrace. To the west, the marine terraces and Ohakean terrace are truncated by the cliff formed during the Holocene high sea level (*c*.6.5kyr B.P.) giving way to a prograding coastal plain.

North of Levin the prograding coastal plain is dominated by the Manawatu River floodplain which overlies Holocene estuarine beds at shallow depth (Hesp and Shepherd 1978). A broad belt of coastal dune sands exists between the floodplain and the coast. South of Levin, coastal dunes often mantle the marine cliff which truncates the old coastal plain with dunes resting on the Ohakean terrace or older marine terraces. Elsewhere a narrow swampy area, in places developed into large lagoons, separates the cliff from the dune belt.

### 1.4.2 Geology

The study area forms part of the south-eastern margin of the South Wanganui Basin which is bounded to the east and north-east by the Tararua, Ruahine and Kaimanawa ranges and to the south by the Marlborough Sounds. The northern boundary is obscured by volcanics of the central plateau and the western

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[1] Cotton (1918) proposed the term "box-shaped" to describe the characteristically wide, flat floored, but steep sided valleys occurring in the uplifted coastal plain in southern Manawatu. Hesp and Shepherd (1978) note: "The width of many (box-shaped) valleys appears to be wider than expected in relation to the discharge of the streams that now drain them".

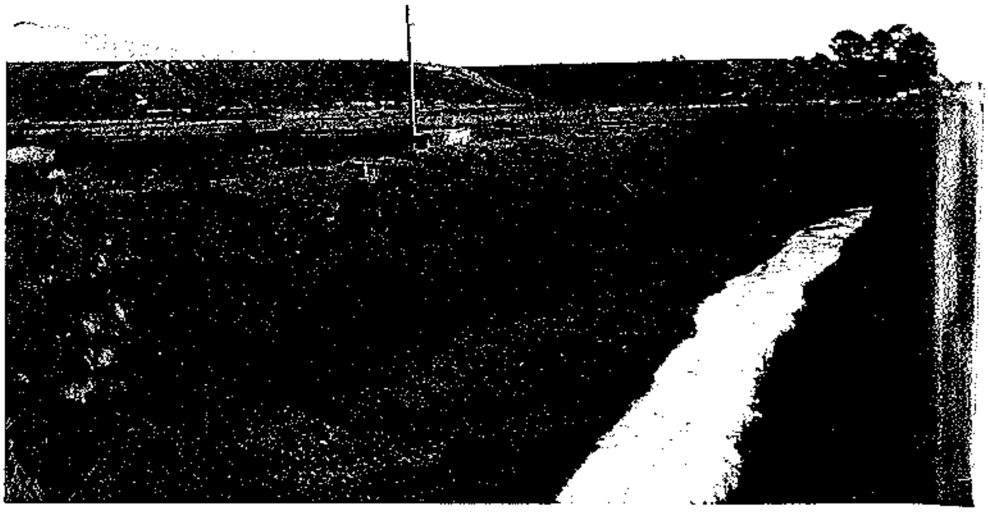

Fig 1.3

A flat topped interfluve typical of the partially dissected marine terraces in the Horowhenua district. This photograph was taken approximately 2km north of Shannon and looks south.

boundary is marked by a zone of major faults (Taranaki, Manaia) which separate it from the much older and deeper Taranaki Basin (Fig. 1.4).

Anderton (1981) describes the Wanganui Basin as a broad half graben structure trending NNE which contains up to 4km of marine Plio-Pleistocene sediments developed by progressive subsidence and onlap to the south combined with emergence and offlap to the north.

The oldest Cenozoic sediments in the South Wanganui Basin consist of two small faulted outliers of Oligocene marine sandstone within basement rock at Otaihanga and Picton. They are thought to be remnants of an extensive cover predating the formation of the basin. Elsewhere, Plio-Pleistocene strata crop out over most of the onshore part of the basin and consist of shallow marine and terrestrial sediments originally grouped into the Wanganui and Hawera Series (Fleming 1953). Recently, the Hawera Series has been deleted from the New Zealand chronostratigraphic scheme and replaced by the Haweran Stage of the Wanganui Series (Beu *et al.* 1987). In the Horowhenua district no Cenozoic strata older than Haweran age have been recognised.

North-west of the study area four oil exploration wells drilled in the South Wanganui Basin encountered basement beneath sediments no older than Pliocene (Anderton 1981). Basement consists of rocks similar to those of the axial ranges described above, being part of the Torlesse Terrane (Korsch and Wellman 1988).

Structural trends in the South Wanganui Basin comprise gentle regional dips toward a depocentre south of Wanganui cut by NE-NNE-trending faults (Anderton 1981). Along the south-eastern margin of the basin NNE-trending faults parallel the axial ranges. Here, block faulting of basement has given rise to a series of topographic highs where overlying strata have been deformed into a number of gentle anticlines described by Te Punga (1957a), some of which are still growing. In some cases basement has been thrust to heights just above present

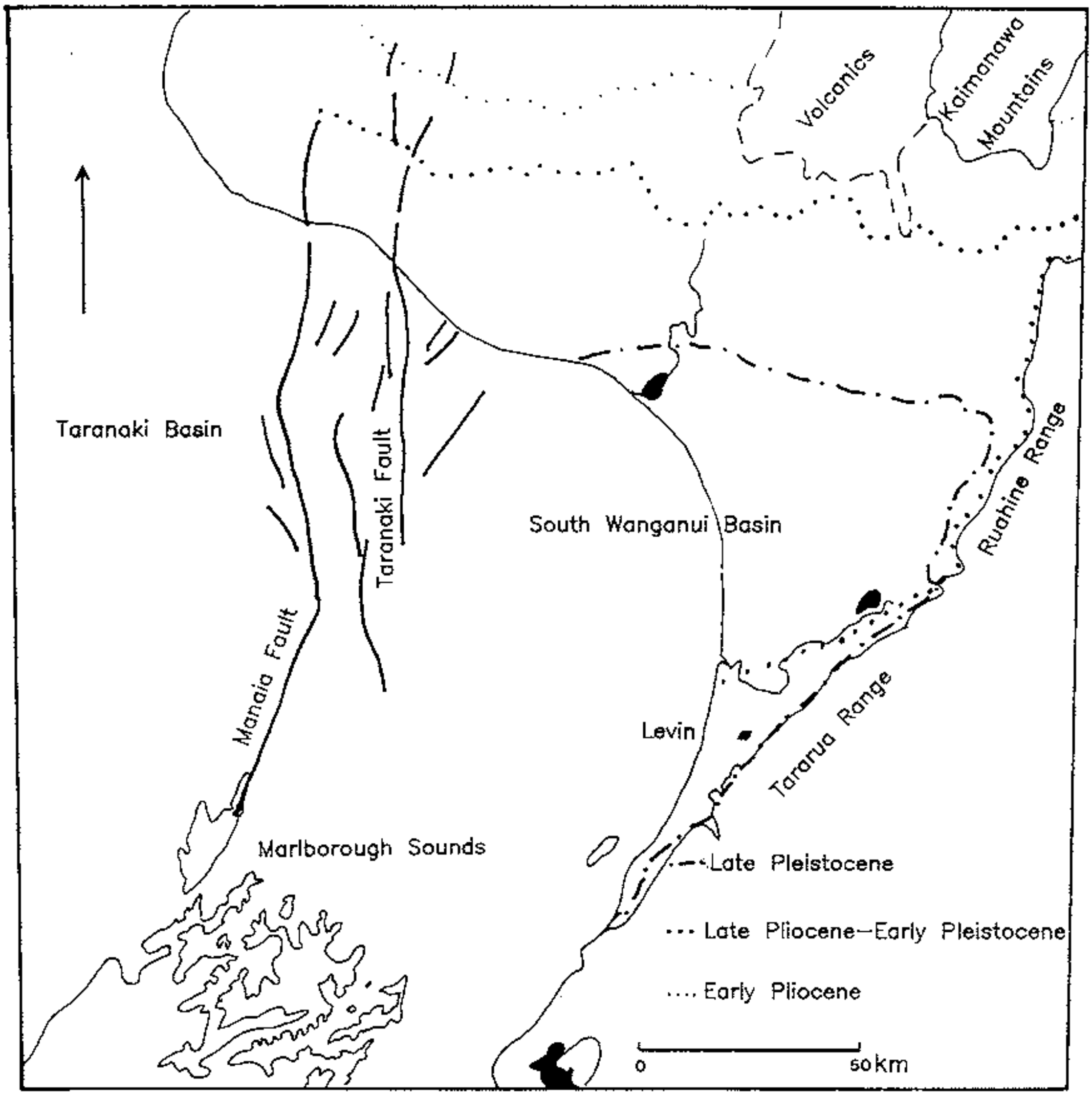


Fig 1.4

Map of the South Wanganui Basin showing basin boundaries and present distribution of early Pliocene, late Pliocene - early Pleistocene and mid-late Pleistocene sediments (after Anderton 1981).

sea level.

Bekesi (1989) studied the Poroutawhao High immediately west of Levin where wave cut basement is found 5 metres above sea level. A 2.5km. wide up-thrown block controlled by a NNE-trending high angle fault on its eastern margin was delineated and named the Levin Fault. Fleming and Hutton (1949) noted a similar fault on the eastern side of Kapiti Island. Rich (1959) recognised the Himitangi Anticline which extends for nearly 21km northwards from Foxton and probably represents the northern extension of the Poroutawhao High. To the east the Manawatu River flows along the Kairanga Trough (Rich 1959) which represents a deep downfold between the line of basement highs to the west and the axial ranges to the east. Hesp and Shepherd (1978) noted the effect of these structures on Holocene sedimentation in the lower Manawatu valley and how they have controlled its river course.

Eustatic sea level fluctuations during the Pleistocene have had a major influence on sedimentation and stratigraphy in the Wanganui Basin. During glacial maxima the coastline lay about 100km to the west of its present position and a land bridge existed across Cook Strait (Lewis and Eade 1974). Ensuing periglacial conditions led to river aggradation on the coastal plain accompanied by loess accumulation on older surfaces to the east. Milne (1973a,b) described an extensive sequence of aggradational terraces in the Rangitikei Valley and Milne and Smalley (1979) formulated a standard coverbed stratigraphy for the sequence based on associated loess deposits. This has enabled confident correlation with similar deposits in the Otaki district (Barnett 1984).

Pillans (1983) recognised a flight of twelve marine terraces in south Taranaki formed during high sea level stands over the last 0.7 million years. Quantitative dating of coverbed strata coupled with a deformation model have enabled a detailed chronology of sea level fluctuations for the late Quaternary to be established (Pillans 1990). In southern Manawatu levelled spurs and planed surfaces occur sporadically in the foothills of the Tararua Range and attest to a similar history, though chronological control is poor.

The uplifted coastal plain in the Horowhenua district has, until recently, been ascribed to one marine terrace representing shallow marine deposits laid down upon a wave cut surface during a major sea level maximum. Locally named the Tokomaru Marine Terrace (Hesp and Shepherd 1978), it has been inferred as a likely correlative of the Rapanui Terrace at Wanganui (Palmer *et al.* 1988). Pillans (1983) gives a date of 120kyr B.P. for the Rapanui strandline based on amino acid dating of wood fragments and correlation with a major worldwide high sea level event.

Palmer *et al.* (1988) noted the occurrence of two narrow treads cut in the seaward margin of the Tokomaru Marine Terrace (TMT) a few kilometres north of Otaki and suggested possible correlation with two terraces dated at *c.*100kyr and *c.*80kyr north of Wanganui. North of Potts Hill a lower tread cut in the TMT can be traced intermittently as far as Tokomaru River. These treads have been mapped in detail in the course of this study (Maps 1,2,3,4).

A summary of the late Quaternary stratigraphy for the southern North Island based on work done in several different areas is outlined in Table 1.1.

## 1.5 PREVIOUS WORK

Early studies of the area were carried out by Adkin (1910, 1919) and Cotton (1918) on what was loosely described as the old coastal plain or coastal plain formation. Each proposed quite different interpretations for its origin. Adkin (1910) considered the strata in the Levin area, which he called the Horowhenua Sandstone, to represent a double raised beach formation. He based his conclusions on the occurrence of two sandstone beds separated by a zone of yellow clay, the latter not present close to the ranges. Adkin interpreted this assemblage as a basal sand bed laid down upon a transgressive

| ERA | NZ Stages after Beu etal (1987) | N.Z. Substages | Estimated age B.P. kyr | Marine Terraces Wanganui Pillans(1990) | River Terraces Rangitikei Milne (1973) | Loess Deposits Rangitikei Milne (1973) | Waikanae Fleming (1972) |
|---|---|---|---|---|---|---|---|
| (UPPER) QUATERNARY | HAWERAN | | <0.2 | | | | Waitarere Sand |
| | | | 1 | | | | Motuiti Sand |
| | | | 1.8 | | | | Taupo Sand |
| | | Aranuian | 5.5 | | | | Foxton Sand |
| | | | 10 | | | | Paraparaumu Peat |
| | | | 12 | | | | Kena Kena Fm |
| | | | 14 | | | | |
| | | | 16 | | Ohakea | Ohakea | Te Waka Sand |
| | | Otiran | 18 | | | | Parata Gravels<br>Judgeford Loess<br>Matenga Fanglomerate |
| | | | 19 | | | | |
| | | | 25 | | | | |
| | | | 30 | | Vinegar Hill | | |
| | | | 35 | | Rata | Rata | Tiri Loess<br>Older gravels |
| | | | 40 | | | | |
| | | | 60 | Rakaupiko | Putorino | | Waimahoe Lignite (>35) |
| | | | 70 | | Porewa | Porewa | |
| | | | 80 | Hauriri | | | |
| | | Oturian | 100 | Inaha | Cliff | | Otaki dune sand)<br>Awatea Lignite)Otaki<br>Otaki beachsand)formation |
| | | | 120 | Rapanui | Greatford | | |
| | | | 125 | | | | |
| | | Waimean | 140 | | Marton | Marton | |
| | | | 170 | | | | |
| | | | 180 | | Burnand | Burnand | |
| | | Terangian | 210 | Ngarino | | | |
| | | | 230 | | | | |
| | | Waimaungan | 240 | | Aldworth | | |
| | | | 245 | | | | |

Table 1.1

Summary of late Quaternary stratigraphy for the southern North Island.

shoreline followed by a second sand bed deposited as the sea retreated, the interbedded clay representing deeper water deposits.

Cotton (1918) designated the name Otaki Series for the strata of the old coastal plain from its southern end, north of Paraparaumu, to the Manawatu River. He considered it to be an entirely aeolian deposit, in places interfingering with gravels of adjacent alluvial fans. Cotton attributed the yellow clay noted by Adkin to be formed in swamps or lakes impounded by dunes.

Oliver (1948) mapped the distribution of the coastal plain formation and discussed its composition and origin in some detail. He distinguished two lithologic units, wind deposited soft sandstone and water deposited soft sandstone, in what he renamed as the Otaki Formation, although no type section was designated. He also noted minor occurrences of conglomerate, silt and clay. In comparing the texture and composition of the Otaki Formation with the present day coastal deposits to the west, Oliver made the following observations:

1. sand in the Otaki Formation is generally more rounded than present day beach and dune sand;
2. Otaki Formation has a higher ferromagnesian content than present day beach and dune sand.

Oliver considered the Otaki Formation to be a predominantly shallow water marine deposit with minor dune sands laid down above coalescing alluvial fans.

Rich (1959) studied Late Cenozoic stratigraphy around Palmerston North and designated the name Tiritea Formation to coverbed strata that were lateral equivalents to the Otaki Formation (Oliver 1948) to the south. He described similar lithologies to Oliver and noted the predominance of conglomerate toward the mouth of the Manawatu Gorge with sand becoming dominant further south. He also noted the occurrence of micaceous and carbonaceous silts and pebbly sands containing some pumice. He attributed the depositional environment to be a shallow water marine to subaerial complex influenced by "frequent shifting of both strandline and stream courses along the base of the western flank of the axial ranges". Rich considered the Tiritea Formation to be coeval with the Halcombe Conglomerate and Mangaone sandstone (Te Punga, 1952) to the north-west.

Cowie (1963) distinguished the much younger Koputaroa Phase dune-sands[2] from what Oliver had previously included as part of the Otaki Formation in the Levin area. He noted a strongly weathered clay separated the two units which indicated a period of intense and prolonged weathering. Cowie (1963) considered the Koputaroa dune-sands to be of fluvial origin primarily on the grounds that they accumulated during the Last Glaciation when sea level was considerably lower. Shepherd (1985) studied the heavy mineral content and roundness of the Koputaroa dune-sands and suggested a marine rather than fluvial origin.

Te Punga (1962) described in detail a *c.*12m sequence of Otaki Formation resting unconformably on a greywacke wave cut platform near Waikanae. Radiocarbon dating of a wood fragment from a lignite horizon yielded an age >45,000 years but no attempt was made to correlate the sequence laterally. Paleoenvironmental inferences were limited to discussion concerning the significance of marine sponge spicules in a muddy sand bed near the base of the sequence.

Fleming (1972) expanded Te Punga's work by suggesting a paleoenvironmental history for the same sequence and incorporated it into an emerging late Quaternary stratigraphy for the Waikanae area. He recognised three informal members in the Otaki Formation; (basal) Otaki beach sand, Awatea lignite, and (upper) Otaki dune sand. He attributed the sequence to marine beach gravels and sands of a transgressive high level sea followed by beach derived dune sands that advanced as the sea retreated with lignite deposited in swamps ponded by the dunes. Chronologically, Fleming placed the Otaki Formation in

[2] Koputaroa Phase dune-sands are here on referred to as "the Koputaroa dune-sands".

the Oturian Stage (Last Interglacial) of the Hawera Series based on geomorphologic and lithologic criteria (see Table 1.1).

In the Otaki area, Palmer *et al.* (1988) recognised a Last Interglacial marine cliff truncating Martonan aggradation gravels deposited during the preceding (Penultimate) glacial period. Aeolian Otaki Formation abuts and mantles the cliff extending inland across the Martonan surface for 1.5km. Palmer *et al.* (1988) recognised up to four loess units mantling the Otaki Formation near Otaki.

## 1.6 TERMINOLOGY

Marine terrace nomenclature follows that of Pillans (1990), (Fig. 1.5).

The Tokomaru Marine Terrace in this study refers to the gently sloping, uplifted coastal plain underlain by marine, fluvial and aeolian sediments (coverbeds) that rest on the Tokomaru wave cut platform cut during the Last Interglacial sea level maximum (*c.* 120kyr B.P.).

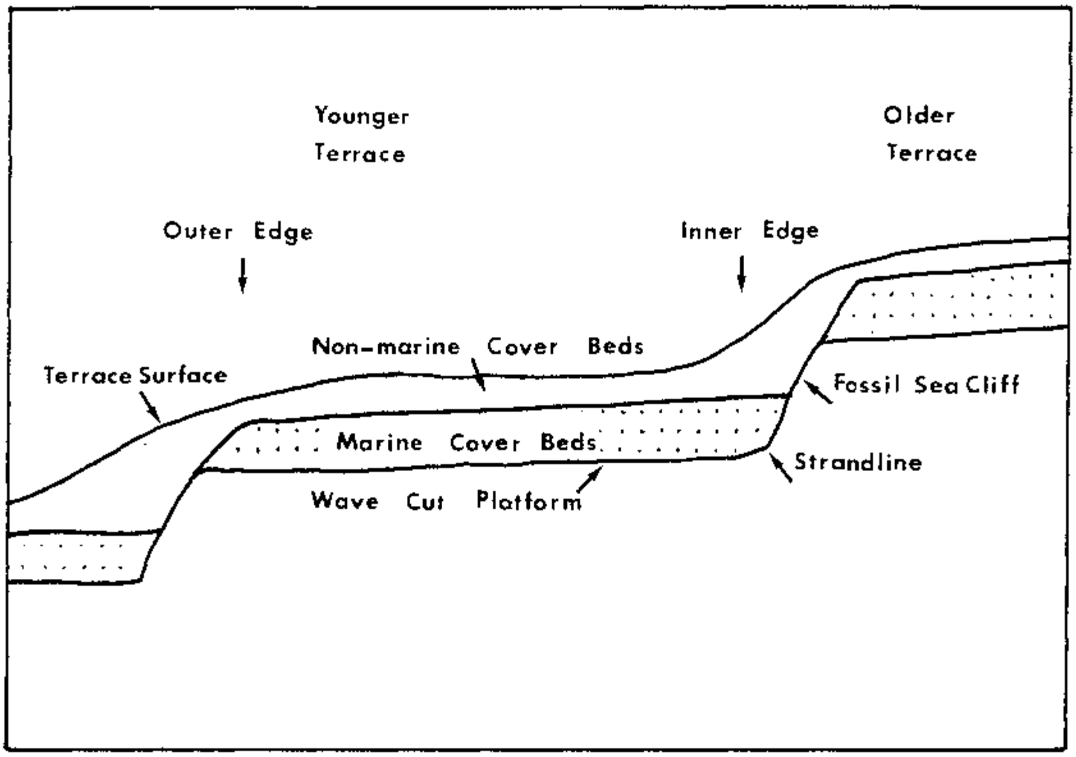


Fig 1.5
Marine terrace nomenclature (based on Pillans 1990)

# CHAPTER 2

# GEOMORPHOLOGY

## 2.1 INTRODUCTION

The field area can be conveniently divided into four areal subdivisions (Fig. 2.1). Each subdivision is controlled by distinct structural and physiographic features and is treated separately. From south to north they are designated:

1. Forest Lakes
2. Ohau
3. Levin-Potts Hill
4. Tokomaru-Makerua

## 2.2 FOREST LAKES

In the Forest Lakes area a well defined marine terrace forms a zone, up to 4km wide and 7km long, of flat to gently rolling farmland between the Otaki River in the south and Waikawa Beach Road in the north. A *c.*40m vertical cliff on the north bank of the Otaki River truncates the marine terrace while at Manakau the terrace merges more subtly into younger aggradational terraces. Foothills of the Tararua Range mark the inner edge of the terrace forming a steep escarpment north of Waitohu Stream and more rounded and subdued relief to the south. The outer edge of the terrace is marked by two narrow terraces that were cut by high sea level stands subsequent to the Last Interglacial sea level maximum. A low lying swampy area with several large lagoons separates the marine terraces from the dune belt of the present coast. Advancing tongues of sand sporadically bridge the gap and mantle the marine terraces.

Between Otaki River and Waitohu Stream, Barnett (1984) and Palmer *et al.* (1988) recognised two loess-covered terraces separated by a *c.*10m high north-east-trending fossil sea cliff.

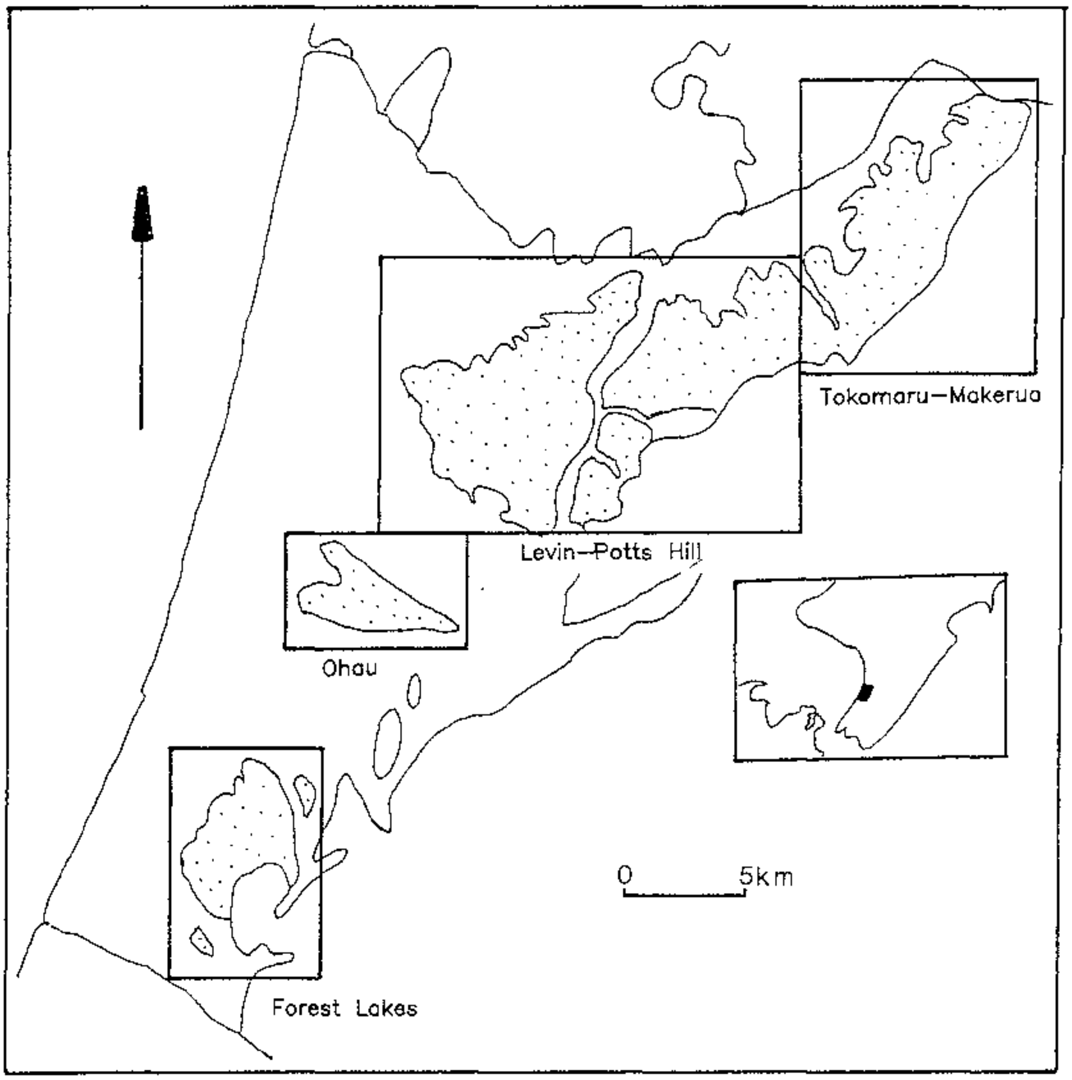


Fig 2.1

Simplified map showing the boundaries of the four areal subdivisions designated in the study area.

The higher terrace was correlated with the Marton (river) Terrace of Milne and Smalley (1979) and is underlain by at least 50m of coarse alluvium. The lower was correlated with the Tokomaru Marine Terrace (TMT) of the Manawatu (Hesp and Shepherd 1978), which in turn correlates with the Rapanui Terrace of Wanganui (Pillans 1983, 1985, 1990). Thus, the base of the cliff represents the strandline of the Last Interglacial sea level maximum. Dune sands, coeval with beach and dune sands overlying the Tokomaru wave cut platform, mantle the cliff at the back of the Tokomaru strandline and extend eastward across the Martonan terrace for several hundred metres (Map 1). About 0.6km west of the sea cliff the TMT is truncated by the concealed riser of the Ohakean terrace which is itself truncated a further 2km west by the post-glacial sea cliff (Barnett 1984, Palmer *et al*. 1988). The latter is concealed by recent dunes but south of the Otaki River is well exposed for several kilometres. North of Waitohu Stream, the Martonan terrace is not seen and the TMT extends to the base of the greywacke foothills.

At S25\944486 a waterfall has exposed a 20m vertical cliff of fresh greywacke alongside which is soft aeolian Otaki Formation (Fig. 2.2). The cliff trends 210 south, extending beneath the western edge of a prominent hillock capped by at least 20m of aeolian sand. Clearly, this represents the Last Interglacial sea cliff mantled by coeval dune sand. The sand has advanced inland a further 0.7km south-east of the cliff, mantling a localised area of subdued relief in the greywacke foothills. This cliff is correlated with the Last Interglacial sea cliff of Barnett (1984) and Palmer *et al*. (1988), south of Waitohu Stream.

On the western and northern flanks of Pukehou Hill immediately north of the exposed sea cliff, the TMT abuts a steep semi-circular escarpment rising from 60m to 220m a.s.l. A narrow apron of talus separates the terrace from its inner edge with scattered remnants of aeolian Otaki Formation clinging to the greywacke undermass.

Fig 2.2

Aeolian Otaki Formation abutting the Last Interglacial sea cliff north of Waitohu Stream near Otaki. To the left a waterfall exposes the cliff. The solid line indicates the contact between greywacke and dune sand of the Otaki Formation.

In contrast, relief on the north-eastern flank of Pukehou Hill is subdued by a mantle of aeolian sandstone which rises up to 190m a.s.l., capping the ridge. The topography here indicates a buried sea cliff similar to that described above.

Extending north-westward from Pukehou Hill, the TMT slopes gently seaward and is generally higher in altitude here than to the south, straddling a topographic high with an axis in the vicinity of Atkins Road. The terrace is dissected by a number of north-west-trending gullies arising in, and cutting deeply into, the Otaki Formation. Little water flows in the gullies which are typically flat based peat swamps with near vertical sides. South-west trending gullies at the eastern end of Forest Lakes Road drain the southern flank of the topographic high (Map 1).

Younger Marine Terraces

Two younger marine terraces cut in the TMT, first noted by Palmer *et al.* (1988), are best preserved at Forest Lakes around the shores of Lake Waitawa and have been mapped in detail in this study (Map 1). South of Forest Lakes Road the younger terraces are poorly defined. Although wave cut platforms were not identified, topographic expression of the terraces is good (Fig. 2.3).

The lower terrace, here named Post-Tokomaru Marine Terrace 2 (PTMT2), is the more extensive of the two, with the higher terrace, here named Post-Tokomaru Marine Terrace 1 (PTMT1), frequently absent or confined to narrow treads cut in spurs of TMT. A striking feature is the tightly embayed nature of the strandlines which appear to have been controlled by a pre-existing drainage pattern (Map 1).

North of Lake Kopureherehere the PTMT2 strandline swings inland trending roughly normal to the coast for 3km, crossing State Highway 1 at the intersection of South Manakau Road. Manakau Stream flows parallel to the riser 1km to the north, but is unlikely to have cut the terrace since loess covered, shallow marine sands underlie PTMT2 and fluvial deposits are absent.

Fig 2.3

A flight of three marine terraces on the eastern shore of Lake Waitawa, Forest Lakes. The photograph is taken standing on the middle terrace (PTMT1). Across the gully TMT is on the upper right and PTMT2 is on the lower left.

## 2.3 OHAU

At Ohau, the TMT exists as a triangular-shaped inlier with its apex to the east near the intersection of McLeavey and Arapaepae roads and its base around the shores of Lake Papaitonga (Map 2). North and south of the lake, coastal dune sand mantles the western boundary. Several incised gullies rising only a short distance into the terrace empty into the lake's eastern margin. Younger marine terraces are not distinguished on the western margin of the TMT in this area.

The southern boundary of the inlier is marked by a distinct cliff which gives way to gravels of the Ohau River floodplain. The cliff was probably cut during the latter part of the Ohakean aggradational phase.

The northern flank is marked by a subdued but well defined slope which drops onto a loess-covered aggradation surface that extends north for 1-2km and itself terminates abruptly against gravels overlain by a veneer of topsoil. A low riser separates the two aggradation surfaces and is seen most clearly from State Highway 1 trending west. To the east it is poorly defined.

The loess covered gravels are pre-Ohakean, probably of Ratan age.[1] The thinly covered gravels form a north-west trending zone 2.5-3km wide from the foothills to Lake Horowhenua and represent an early episode of Ohakean aggradation when the Ohau River flowed north-westwards. In later Ohakean times river capture occurred just north of the eastern end of Kimberley Road. This resulted in cliffing of the earlier Ohakean, Ratan and Tokomaru terraces as the Ohau River assumed a more westerly course.

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[1] Behind the Dairy Factory at Kuku 1km south of Ohau River (S25\992559) approximately 1.5m of Ohakean loess containing Aokautere Ash near its base, overlies tightly packed gravels. These are confidently correlated with Ratan gravels of the Rangitikei Valley and are probably the same age as those mentioned here.

## 2.4 LEVIN - POTTS HILL

North of Levin the coastal plain broadens as the coastline diverges from its parallel trend with the axial ranges and assumes a more northerly course. Here the TMT swells to reach its maximum width of 8km immediately north of Lake Horowhenua (Map 3). A low cliff truncates the northern and western margin of the marine terrace, separating it from the lower flood plain of the Manawatu River. The southern boundary bisects Levin township and is marked by a series of subdued hillocks, elongated normal to the coastline. The zone of Ohakean gravels mentioned above lies to the south. To the east TMT either abuts the foothills or is separated from it by alluvium from streams which have dissected the contact.

Koputaroa Stream drains the eastern side of the TMT along a maturely dissected valley rising in the foothills east of Levin and trends NNE before flowing into the Manawatu River near Shannon. West of Koputaroa Stream, the TMT forms a low arch about a north-east trending axis from an apex near the intersection of State Highway 1 and Koputaroa Road. Termed the Levin Anticline (Te Punga 1957a), its morphology is strongly depicted by the drainage pattern developed within it (Map 3).

East of Koputaroa Stream and north of Potts Hill, State Highway 27 follows the axis of another arch in the TMT, also clearly defined by the local drainage pattern (Shannon Anticline - Hesp and Shepherd 1978). Greater uplift in this area has resulted in deeper dissection of the TMT. At Laws Hill (S25\130667) the arch forms a protruding apex where the TMT, in fault contact with basement, has been warped upwards (Fig. 2.4).

### Younger Marine Terraces

The riser of a younger marine terrace cut in TMT on the north flank of the Shannon Anticline is clearly visible trending north-west from Laws Hill, and backs a well preserved tread to the north (Fig. 2.5). A maximum height difference of 17m separates the two surfaces beside State Highway 27 at


Fig 2.4
The Tokomaru Marine Terrace in fault contact with the greywacke foothills at Laws Hill 2km south of Shannon.
Note in the centre background how the TMT has been tilted upwards against the foothills. The photograph is taken standing on PTMT1.

Fig 2.5
Two marine terraces on the north flank of the Shannon Anticline. Looking across to the TMT from PTMT1.

(S25\118674). As at Forest Lakes, the riser is deeply embayed, and in places, breaching of promontories is evident (Map 3). North of Laws Hill the strandline swings north-east and can be traced as far as Marinoto Road. The lower terrace is tentatively correlated with PTMT1 at Forest Lakes.

On the south flank of the Shannon Anticline a younger marine terrace cannot be clearly identified, possibly the result of a higher degree of stream erosion in this area. The more intense erosion is typified by an example of stream capture which occurs close to the anticlinal axis on its south flank at S25\115668.

## 2.5 TOKOMARU - MAKERUA

The TMT in this area extends 2-4km westward from the Tararua foothills which rise steeply in a straight, north-east-trending line from Mangaore Stream in the south to Tokomaru River in the north (Map 4). These rivers rise deep in the western flanks of the Tararua Range where they have extensive catchments having been active prior to the formation of the TMT.

The inner margin of the TMT is separated from the steeply rising foothills by a well defined slope apron of colluvium, some of which displays distinct alluvial fan morphology, giving the impression of an active fault scarp (Fig. 2.6). The western edge of the terrace is truncated by the lower Manawatu River flood plain.

The TMT in this area is extensively dissected by broad, flat (box-shaped) valleys, the largest issuing from steep narrow gullies in the foothills. Close to the foothills these valleys are filled with gravelly alluvium. Aggradation terraces of Ohakean age and possibly older have been recognised and mapped in one of these valleys (Map 4). Numerous box-shaped valleys rise in the TMT itself, having incised deeply into the underlying sandstone in spite of the fact their valley floors reveal little, if any, running water. Stream capture and

Fig 2.6

An inferred fault scarp along the inner margin of the TMT north of Shannon. Note the broad colluvial fan separating the steeply rising foothills from the TMT on the right foreground.

imminent stream capture are seen at three localities along the Mangapuketea Stream.

In the lower reaches of some of the valleys, close to where they merge into the Manawatu River flood plain, Holocene estuarine sediments have been recognised underlying recent alluvium (Hesp and Shepherd 1978). The cliffed outer margin of the TMT therefore represents, at least in part, a coastal Holocene cliff rather than one cut solely by meandering of the Manawatu River.

Younger Marine Terraces

The riser of a younger marine terrace cut in the TMT can be traced almost continuously for *c*.9km from Tokomaru River to Mangaore Stream (Map 4). It is most prominently preserved immediately south of Tokomaru River at S24/220766 and south of Kaihinau Road S24/190726 where height differences separating the two surfaces are recorded at between 7 and 10m (Fig. 2.7). The lower terrace is tentatively correlated with PTMT1 at Forest Lakes.

Unlike at Laws Hill and Forest Lakes where the strandline of the younger terrace(s) is tightly embayed, here it is relatively straight. At least three alternative explanations may account for this difference:

1. a longer period of strandline stability compared with further south, in turn, reflecting localised structural (tectonic) differences (see 7.5);
2. higher wave energy at the time the strandline was cut;
3. less inhomogeneity of older terrain.

Evidence of some strandline control by a pre-existing drainage pattern occurs immediately north of Mangaore Stream where the strandline curves inland along a north trending valley (Map 4). This could indicate the Mangaore Stream flowed along a more northerly course in earlier times.

A

B

Fig 2.7

Two marine terraces north of Shannon. Photographs are taken standing on PTMT1 looking across to the TMT.
Photograph A is taken immediately south of Tokomaru River and B is taken immediately south of Kaihinau Road.

# CHAPTER 3

# STRATIGRAPHY AND FACIES ANALYSIS

## 3.1 INTRODUCTION

As stated in section 1.5.2., it is generally held that marine strata resting on the Tokomaru wave cut platform were laid down during the Last Interglacial period (Fleming 1972, Hesp and Shepherd 1978, Barnett 1984, Palmer *et al.* 1988). Culmination of the Last Interglacial transgression is inferred to correlate with a globally recognised high sea level event which occurred *c.*120kyr B.P. when sea level lay between 5 and 8m above present mean sea level (Pillans 1983). From oxygen isotope studies of deep sea cores this event is identified as oxygen isotope substage 5e (Shackleton and Matthews 1977) (Fig. 3.1).

TMT coverbed stratigraphy in the Horowhenua district typically comprises a relatively thick marine and aeolian sand deposit with minor gravels (Otaki Formation of Oliver 1948), mantled by a sequence of up to four loess units with interbedded sand.

## 3.2 OLDER PLEISTOCENE SEDIMENTS

Although not exposed in the Levin area, a considerable thickness of Pleistocene sediments underlies the Otaki Formation. Bore log data indicate at least 55m of predominantly fluvial gravel, sand, and clay underlies the Otaki Formation at Ohau (BL 26 at S25/012585, Fig. 3.2) while north-east of Lake Horowhenua (BL 61 at S25/026664) more than 70m of probable fluvial sand is recorded. West of the Tararua foothills basement dips steeply below the coastal plain attaining depths in excess of 1km below sea level within 7km of the ranges (Bekesi 1989). Clearly, a considerable thickness of Pleistocene, and possibly older, sediments is indicated.

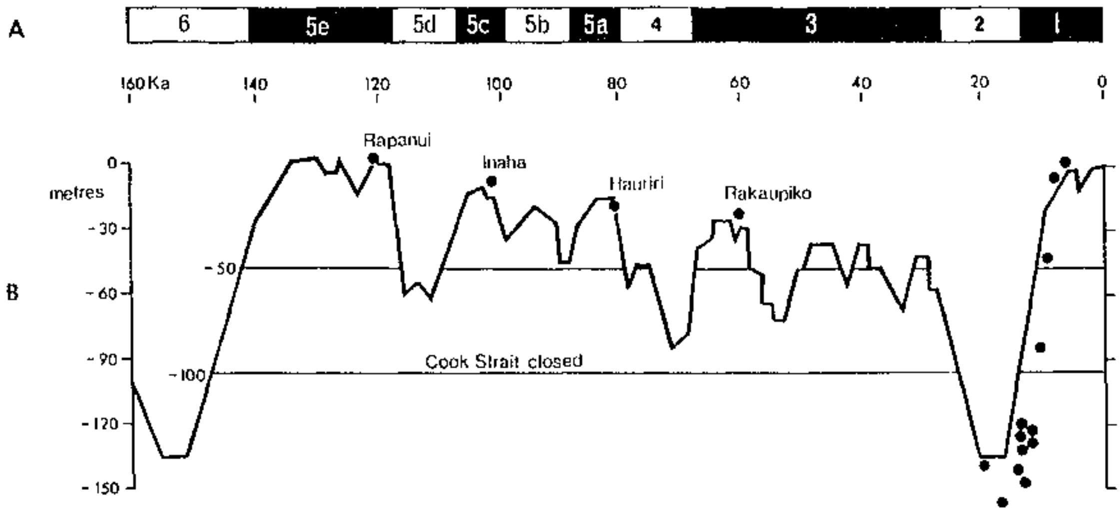


Fig. 3.1

Oxygen isotope stages (A) in relation to the sea level curve of Chappell (1983) (B). Dots represent dated sea levels in the Wanganui area (after Pillans 1985).

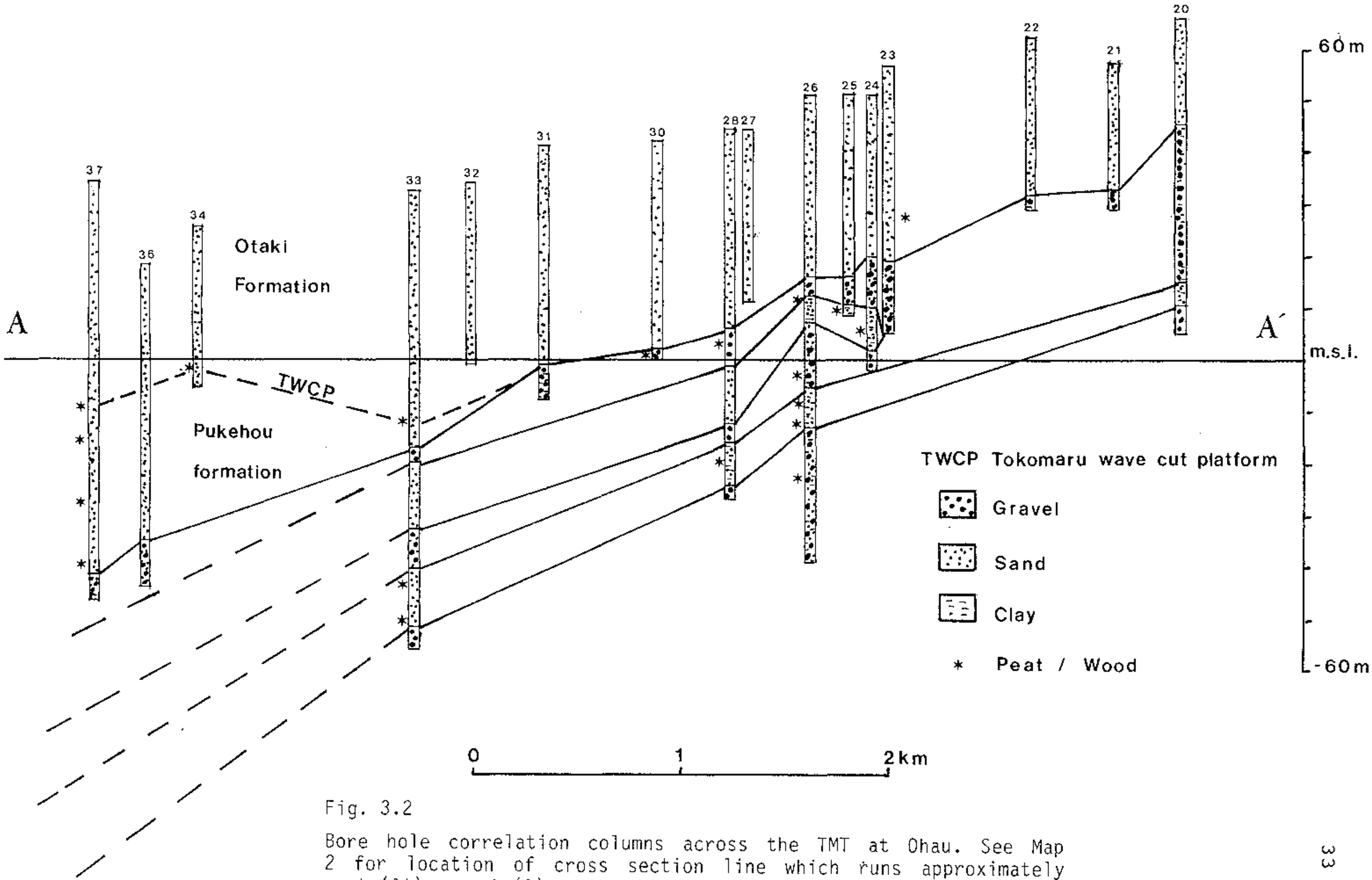


Fig. 3.2

Bore hole correlation columns across the TMT at Ohau. See Map 2 for location of cross section line which runs approximately east (A') - west (A).

### 3.2.1 Pukehou formation[1]

From bore log data of wells drilled into the TMT, the base of the Otaki Formation is identified with the first appearance of fluvial strata beneath the marine sandstone. This contact is inferred to represent the Tokomaru wave cut platform. Recognition in bore logs is based on the first appearance of either carbonaceous debris or gravel beds.[2] Typically, a fine grained carbonaceous unit underlies the Tokomaru wave cut platform. The widespread occurrence of this unit in bore holes throughout the field area warrants its recognition as a separate formation. It is here named Pukehou formation based on its occurrence in boreholes around Pukehou Hill, in close proximity to the type locality of the Otaki Formation.

Inland of the Last Interglacial strandline the Pukehou formation may also occur beneath dune sand of the Otaki Formation.

Lithology

The Pukehou formation is variously described in bore logs as blue clay, blue fine sand, blue peaty sand, grey clayey silt, or fine grey sand. Occasional thin gravel lenses (0.2-0.5m) are also present. Almost without exception, peat, wood or carbonaceous matter are noted within it. Along with the first appearance of carbonaceous matter, the Pukehou formation is distinguished from the overlying Otaki Formation by:

1) a distinct change in colour - from brown to blue/grey;
2) a change in lithology - from sand-dominated to

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[1] A type section for the Pukehou formation has not been clearly identified and recognition of its lithological characteristics is based largely on well drillers' bore logs. Therefore, it was thought nomenclature should remain informal in the interim.

[2] Bore logs indicate most gravel beds contain carbonaceous debris.

clay-dominated sediments.

Contacts and Thickness

The Pukehou formation rests sharply on fluvial gravels. Along the inner edge of the TMT the formation thins and is often absent, wedging out against the gravels beneath the Otaki Formation (Fig. 3.2).

A north-easterly thickening trend of the Pukehou formation is evident from bore holes located on the outer edge of the TMT. From 20m in thickness north of Forest Lakes (BL 7 at S25/950535, see Fig. 3.7), the unit thickens gradually to 32m at Lake Papaitonga (BL 37 at S25/978594, Fig. 3.2) then thickens markedly, reaching in excess of 70m, north-east of Lake Horowhenua (BL 61 at S25/026664). North of Levin structural evidence suggests the north-easterly thickening trend continues (see Chapter 7).

Localised thickening is evident beneath the South Manakau Stream where it cuts through PTMT2 (Fig. 3.3). A localised structural depression is indicated here which is further evidenced by the fact that the PTMT2 strandline roughly parallels the stream valley in this area (see 2.2). The shore-normal trend of the PTMT2 strandline is thus probably a result of incursion of the sea along a pre-existing, deeply incised valley during the PTMT2 transgression. The present physiography of the South Manakau Stream catchment is consistent with such an interpretation.

## 3.3 OTAKI FORMATION

### 3.3.1 Introduction

A type section for the Otaki Formation has not been previously designated and it is appropriate to do so here. However, in ascribing a type section for the formation a number of factors must be taken into account. The poor vertical exposure, horizontal attitude and relatively thick nature of the Otaki Formation inhibits exposure of a complete section of the unit. Furthermore, the base of the formation is seen only

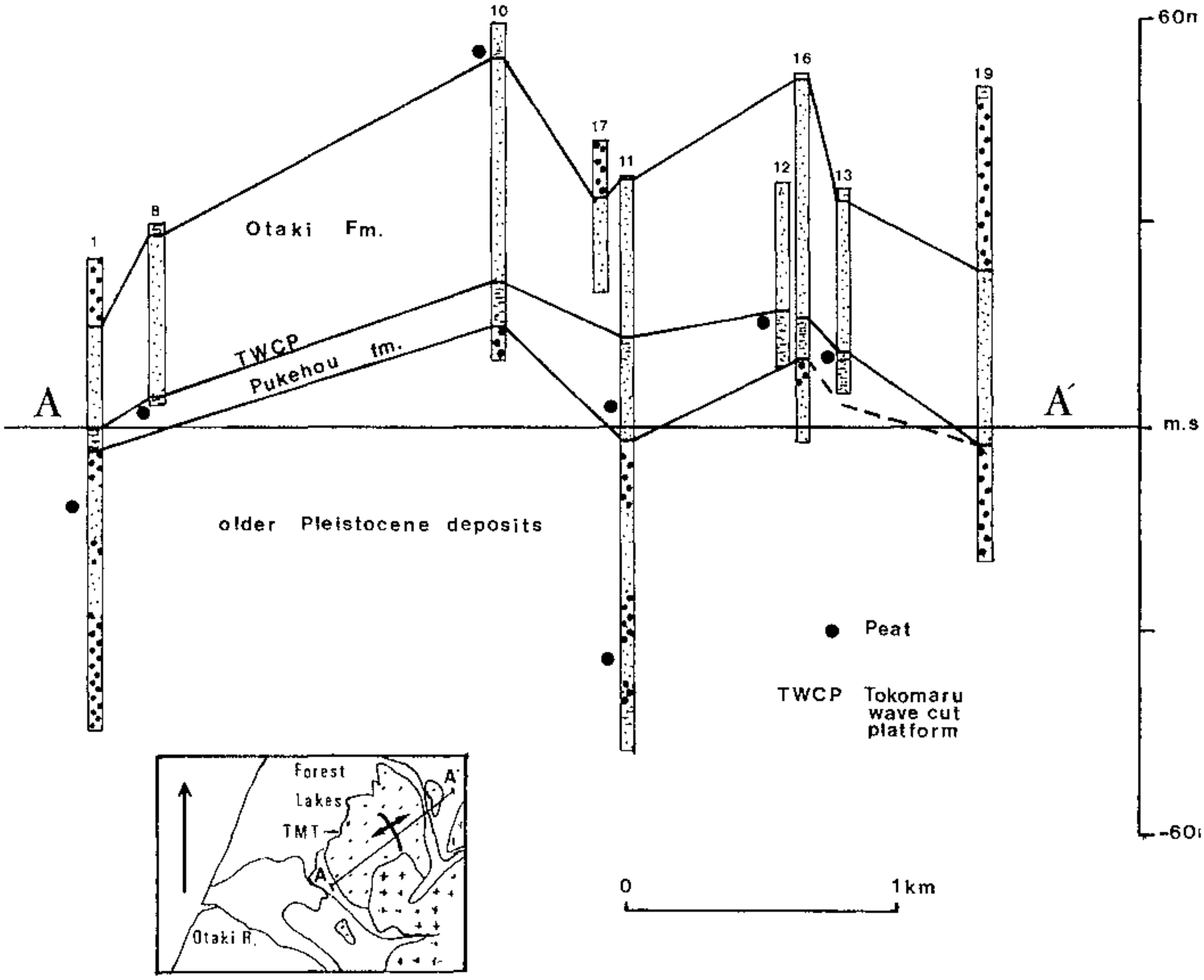



Fig. 3.3

Bore hole correlation columns across Pukehou Anticline and South Manakau Stream. See Map 1 for bore hole locations. Lithological symbols as for Fig. 3.2

at two localities; resting on the Tokomaru wave cut platform adjacent to the strandline at S25/097643; and inland of the TMT strandline at S25/131672. In both cases the overlying sequence of Otaki Formation is condensed, proving unsatisfactory for type section status.

Designation of the type section is therefore based on the following criteria:

1. a locality where closely spaced exposures collectively exhibit a representative thickness and lithological variation;
2. a locality where subsurface data is available and yields some stratigraphic control;
3. a locality close to the town of Otaki after which the formation was named by Oliver (1948).

The type section for the Otaki Formation is here designated in the Forest Lakes area at S25/945498, immediately west of Pukehou Hill along State Highway 1 (Map 1). Here, a 20m vertical section of the formation crops out almost continuously for *c*.200m. Bore log data indicate the overall thickness of the Otaki Formation in this vicinity is 25-30m (Fig. 3.3). Two members of the Otaki Formation are recognised in the type section; *c*.7m of Otaki beach sand overlain by c.13m of Otaki dune sand (Fig. 3.4).

In describing the Otaki Formation in the study area, the areal subdivisions designated in Chapter 2 are maintained enabling more precise recognition of lateral variations across the unit. This in turn enables easier detection of subtle paleoenvironmental differences.

### 3.3.2 Forest Lakes

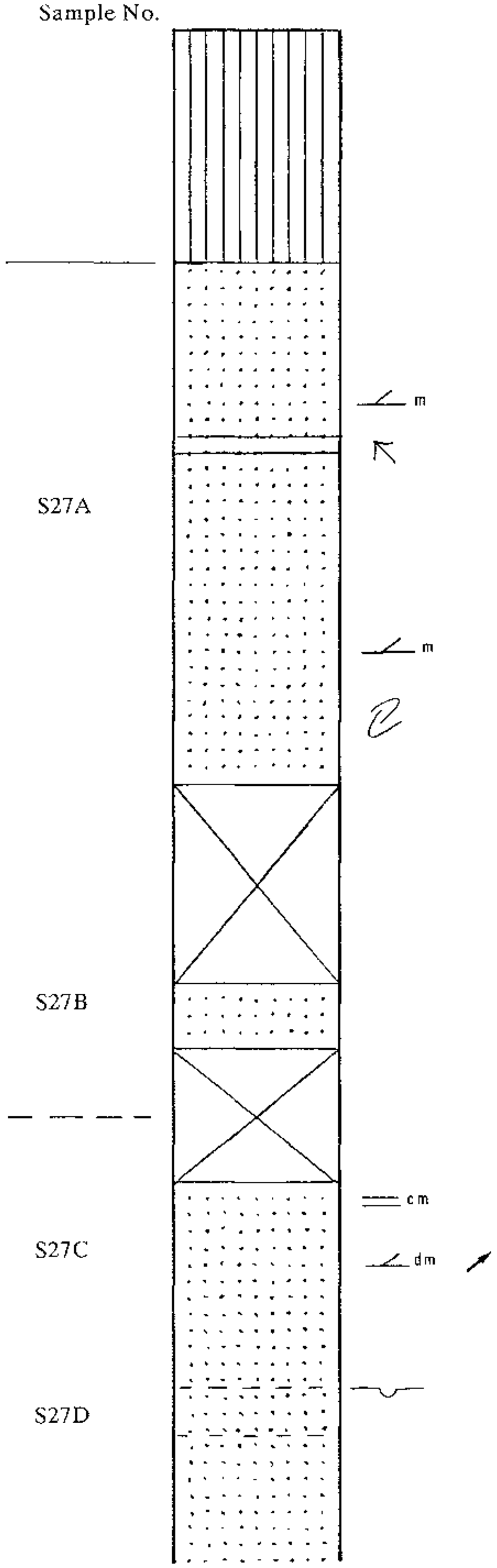
**A. Lithology and Sedimentology**

Two members of the Otaki Formation are recognised in the Forest Lakes area, Otaki beach sand and Otaki dune sand.

Otaki Beach Sand

Otaki beach sand crops out predominantly west of State Highway 1 north of Waitohu Stream. It is a light olive grey, well sorted, fine- to medium-grained sandstone with occasional

L27 S25/945498




Loess

Otaki dune sand
*c*.13m Xbdd-mass, lt ol gy, srt, f s heavy mineral conc in laminae, Xbdg deformed by high degree of intraformational slumping and small-scale faulting

30cm v pale orng, wthd M

lower section - lower conc heavy minerals, little deformation of Xbds

-- contact obscured --

Otaki beach sand
7m pll lam-cr lam, lt ol gy, srt, f-med S

one, 20cm pl-Xbd, [srt], m S, w tn lens crs, S

one, 20cm bed soft, z S, w basal 0.5cm M

**Fig. 3.4** Measured section description for the type section for the Otaki Formation. Note: a key to all symbols and abbreviations used in measured section descriptions is given in Appendix B.

sharply defined interbeds and lenses of yellow-grey to very pale orange, silty sandstone. Thin stringers of coarse sand occur sporadically. The sand is generally moderately hard and when excavated at road, rail and silage pit cuttings maintains a stable vertical face. However, outcrops of moderately soft sand are not uncommon and seem to have resulted from slight weathering.

The sandstone is parallel laminated and ripple bedded with ferromagnesian and titanomagnetite grains concentrated in laminae. In places small- to medium-scale cross-bedding occurs in single, tabular sets with asymptotic foresets that dip steeply landward (L27, S25\945498; L29, S25\945513; L31, S25\942509). Undulating laminae were seen in a silage pit south of Pukehou Hill along State Highway 1 (L6) at S25\938494. Here thin laminae of dark grains parallel the surface of undulation, having an amplitude of 8cm and wavelength of 24cm.

One well stratified silty bed, that pinches and swells (7-13cm), and at one locality (L38) at S25\954519 forms a single hummock, can be correlated for up to 2km (Fig. 3.5). Its base is well defined by 2-3mm of pale, orange clay, often forming small load casts in the underlying sand. A coarse sandy lag is occasionally present. Sharply overlying the clay, 3-4cm of grey-orange, silty, fine sand shows inverse grading into 6-10cm of grey-orange, silty, medium sand. A sharp contact separates the silty bed from the overlying well sorted, medium sand. Several thinner, silty beds sometimes coalescing or interfingering with the sandstone, occur above and below this bed but are difficult to correlate between outcrops. Palmer *et al.* (1988) interpreted the silty beds as reworked andesitic ash, however, microscopic examination of samples of the silt beds failed to find any trace of glass or any significant mafic content indicative of reworked andesitic ash. The silty beds, therefore, reflect periodic heavy influxes of fine sediment into an otherwise sand-dominated environment.

The homogeneous well sorted nature of the sandstone in conjunction with parallel lamination and single tabular sets of


Fig. 3.5

A 13cm thick silty bed (Z) in otherwise homogenous, well sorted sandstone. Note the single hummock to the left of the spade handle and the well defined clay layer at the base of the silty bed.

landward dipping cross-beds, suggest a foreshore sub-environment of a wave-dominated shoreline (Elliot 1986). Collinson and Thompson (1982) note that undulating laminae occur in the upper flow regime when the wave form on the sediment surface is in phase with the water surface wave, a feature commonly observed in small, steep streams cutting across sandy beaches. Thus, the silty beds are possibly the result of infrequent flood episodes of adjacent rivers into an open beach environment. Alternatively they could represent storm generated beds, although the absence of an obvious basal lag in most examples along with the presence of a basal clay layer and reverse grading, is not typical of modern storm generated beds.

Otaki beach sand is about 20m thick and grades up into Otaki dune sand.

<u>Otaki dune sand</u>

At the type section (S25\945498), Otaki beach sand grades into *c*.15m of Otaki dune sand, overlain by a 3.5m coverbed sequence of loess with interbedded sands. Less than 1km to the south (L6) at S25\938494, the contact is marked by a thin (2-3cm) strongly weathered silty zone with abundant clay-lined, root channels indicating a short break in sedimentation.

Otaki dune sand is thickest in the east (>20m) where it mantles the Last Interglacial sea cliff and thins toward the outer edge of the TMT. It is not found on the younger terraces.

Lithologically the dune sand resembles Otaki beach sand, but differs markedly in bedding characteristics. Large-scale, high angle cross-sets occur, frequently showing marked intraformational slumping and small scale faulting (Fig. 3.6). Cross-beds consist of alternating bands (<1cm) of concentrated dark and light minerals with occasional thin (2-3mm) silty laminae containing carbonaceous matter. Coarse sandy lags forming lenses (5-10cm), and small ripple laminae (1cm high and 5cm long) resting on large foresets, occur sporadically.

Orientations of dune foresets were measured and are discussed in Chapter 4.

A

B

Fig. 3.6

Large scale cross-bedding (A) and intraformational slumping (B) in Otaki dune sand. Note alternating bands of concentrated light and dark minerals.

### B. Contacts and Thickness

Bore hole data indicate Otaki Formation in the Forest Lakes area to be essentially a tabular shaped deposit with a maximum thickness of *c*.35m in the east (of which at least 15m is Otaki dune sand), decreasing to less than 20m on the western edge of PTMT2 (Fig. 3.7). The base of the formation is delineated in bore logs by an easily recognised and correlatable transition zone from sands and silts to gravels. The Tokomaru wave cut platform is not seen in outcrop although its cliffed inner margin is recognised and described in section 2.2.

Coverbeds resting on Otaki Formation comprise a sequence of up to four loess units, that total up to 4m thick (Palmer *et al*. 1988). The upper loess contains the Aokautere Ash. Loess sheets are typically discontinuous in the area and a complete sequence is rare. Generally one or two loess units are missing, sometimes replaced by sands. One widespread sand sheet, in places forming small topographic hummocks, occurs immediately beneath the present subsoil, and rests on a deeply weathered paleosol in the Otaki Formation. Where the paleosol is absent, dune sands rest disconformably on the Otaki Formation, in places with marked angular unconformity. The presence of Aokautere Ash interbedded with these younger sands at Forest Lakes Camp (S25\937511), confirms their correlation with the Last Glacial, Koputaroa dune-sands (Cowie 1963).

North of Manakau and around Waitohu Stream, the Otaki Formation has been partially eroded and buried beneath younger aggradation deposits. Palmer *et al*. (1988) mapped a thin band of Ohakea 1 terrace, separated from the TMT by a low riser, along the north bank of Waitohu Stream. Bore holes along North Manakau Road (BL's 15,18,19) reveal up to 3m of brown clay resting on 25-30m of gravel overlying 13-26m of sand with minor gravel. This in turn overlies tightly bound gravels. The occurrence of shells noted in the sands of BL 15 confirms its marine origin and probable correlation with the Otaki Formation. If the 3m mantle of clay represents predominantly

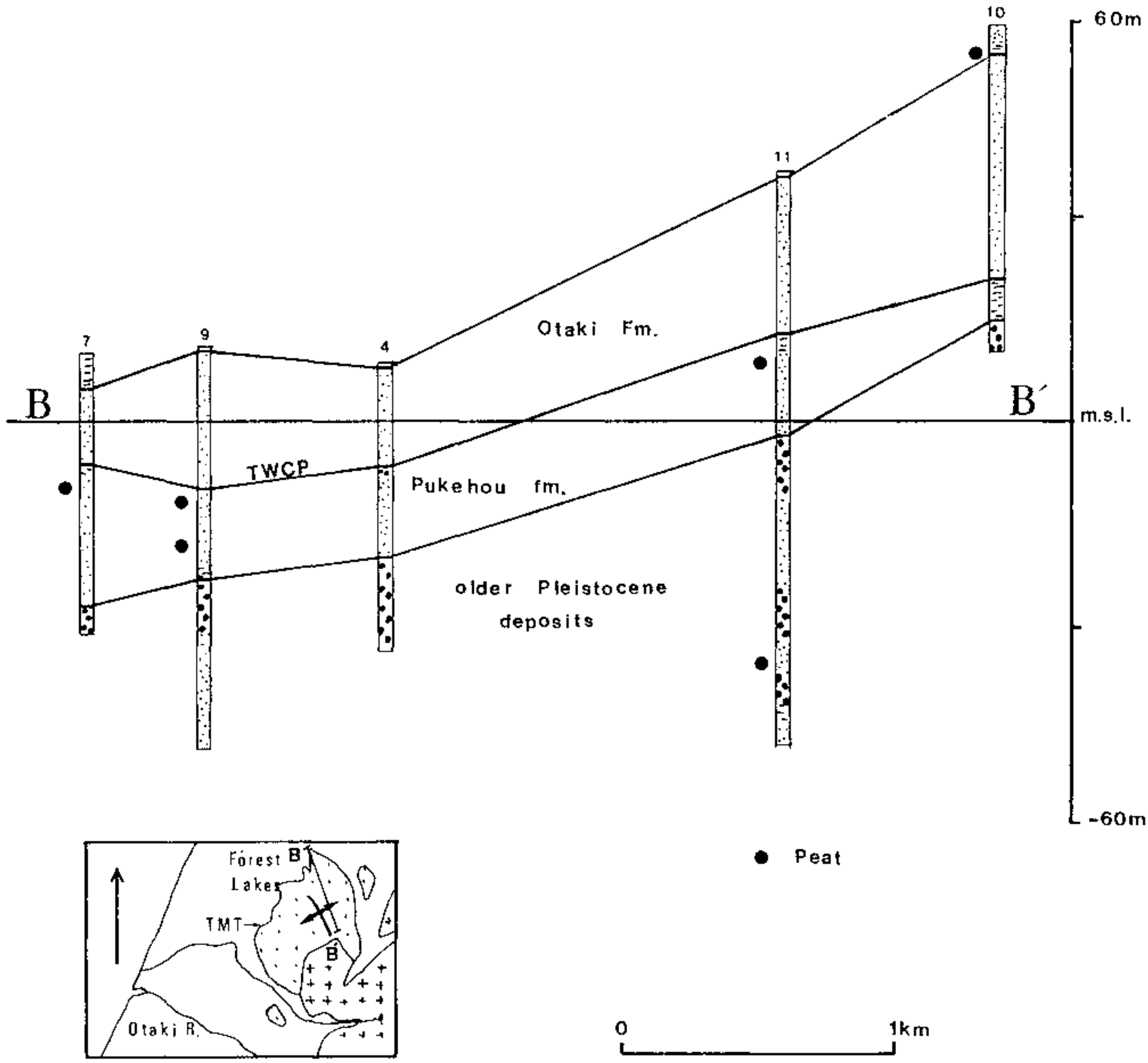



Fig. 3.7

Bore hole correlation columns along a line north-west from Pukehou Hill. See Map 1 for bore hole locations. Lithological symbols as for Fig. 3.2.

loess cover, a pre-Ohakean age for the aggradation terrace is implied, probably Ratan (see Chapter 2 footnote 1).

Weathering

A peculiar feature is observed in the Otaki beach sand at (L6) S25/938494 where yellow-brown silty sandstone with abundant Fe/Mn nodules interfingers with unweathered sandstone. Close inspection reveals that small dark ripple laminae in the unweathered sandstone continue across the sharp contact as ghost-like orange relics in the yellow-brown silty sand. This indicates the feature is a weathering phenomenon and not, as Barnett (1984) suggests, a facies change. Weathering could still account for the difference in grain size characteristics that Barnett noted across the contact. However, the weathering process producing such a pattern is in need of further investigation and beyond the scope of this study.

**C. Paleoenvironmental Inferences**

Geomorphological and sedimentological evidence points to a wave-dominated open beach environment that existed in the Forest Lakes area at the height of the Last Interglacial marine transgression. The straight, well defined, wave cut cliff cut on the inner edge of the TMT (see 2.2) testifies to formation under high wave energy conditions. In addition, the predominance of parallel and current ripple laminated, homogeneous, well sorted sandstone with occasional single, tabular sets of medium-scale cross-bedding in the Otaki Formation, is consistent with a wave-dominated open beach environment of deposition.

Otaki beach sand rests on a well preserved layer of carbonaceous mud and sand indicating erosion was slight as transgression proceeded. This suggests sea level rose quickly in the Forest Lakes area during oxygen isotope stage 5e. Transgression culminated in a period of stability as waves attacked the protruding Pukehou headland cutting back steep cliffs rising 200m and producing a straight coastline south toward Otaki River. Abundant sediment supply, chiefly derived by wave induced, longshore currents from the north-west (see

Chapter 4), resulted in progradation of the shoreline. A dune belt formed which mantled the coastal cliff and advanced inland. Similar progradational processes are occurring along the present coastline north of the Otaki River.

As sea level began to fall, top truncation of the abandoned marine terrace occurred - a feature characteristic of regressive shorelines where there is abundant sediment supply (Vail *et al.* 1977). Following withdrawal of the sea, consequent streams began cutting into the newly exposed marine terrace, enhanced by differential basement uplift closer to the ranges.

Later, sea level rose slightly, inundating the lower reaches of the stream valleys cutting a bench (PTMT1) on the shoulders and spurs of the dune capped interfluves. The strongly embayed nature of what must have been a weakly consolidated shoreline indicates a rapid short-lived transgression occurred, that failed to remove spurs and headlands giving rise to a short period of drowned topography. Low sediment supply along with probable rapid regression inhibited the development of a prograding dune facies above the exposed marine sands. A similar situation is envisaged for the cutting of the third bench (PTMT2).

### 3.3.3 Ohau

#### A. Lithology and Sedimentology

Only the top 13m of Otaki Formation has been observed from surface exposures in the Ohau area, however, bore log data provide useful supplementary information.

The dominant lithology consists of soft to moderately hard, light olive grey to light olive brown, well sorted, fine-grained sandstone. West of Ohau, 4cm to 40cm interbeds of yellow-grey to grey-orange very silty sandstone and sandy siltstone are common. These are often hard due to cementation by limonite and clay. They are finely laminated, contain weathered carbonaceous matter and root channels, and show bioturbation structures.

Sand predominates with beds usually weakly laminated to cross-bedded and sometimes massive near the top of the sequence. Concentrations of heavy minerals in ripple cross-laminae are common. In places, discontinuous bands of limonite form hard, impermeable layers in the sand.

Decimetre-bedded cross-stratification occurs at several locations. In the east, (L44) at S25/022578 bimodal cross sets (5-10cm.), with foresets dipping in opposite directions, occur in homogeneous, well sorted, fine- to medium-grained sands. The dominant direction of dip on these foresets is seaward. The seaward dipping cross-sets show reactivation surfaces and grade into an overlying, parallel laminated top set. No silty beds are present. The topset grades upward into 1m of strongly weathered paleosol overlain in turn by Koputaroa dune-sands.

In contrast, to the west, (L57) at S25/994597 a 0.8m steeply north-west dipping cross-set, which shows gentler dipping reactivation surfaces, overlies a sequence of alternating well sorted sands and silty sands. The latter are mottled and have irregular bounding surfaces that are probably erosive. Overlying the cross-set is a 20cm unit of ripple cross-laminated sands which grade into a strongly weathered paleosol.

Between these locations (L47) at S25/006583 a third occurrence of cross-stratification is noted at the same stratigraphic level. Here, 1m of steeply south dipping cross-beds directly underlie a disconformity separating the Otaki Formation from the Koputaroa dune-sands.

Bore log data reflect the above lithological observations and in addition reveal an occasional basal, fining upward sequence of coarse sands grading to fine sands which gives way to a thick sequence of silty sands.

**B. Contacts and Thickness**

The Tokomaru wave cut platform is not exposed at the surface in the Ohau area. However, bore log data from numerous wells drilled through the TMT have enabled subsurface delineation of the wave cut platform to be determined and correlated from east to west across the inlier (see Fig. 3.2).

The Pukehou formation underlies the Otaki Formation in the west, but wedges out against gravels about 2km west of State Highway 1. The Otaki Formation forms a tabular shaped deposit with a maximum thickness of *c*.45m in the vicinity of Lake Papaitonga decreasing toward the ranges to *c*.15m at Arapaepae Road.

The upper boundary of the formation is commonly seen marked by a distinct paleosol mantled by interfingering dune sand and loess, underlying a well developed soil. The covering strata were originally included as part of the Otaki Formation by Adkin (1910) and Oliver (1948), however, Cowie (1963, 1964a, 1964b) recognised the much younger Koputaroa dune-sands and coeval Ohakean loess which rested on a strongly weathered clay overlying the Otaki Formation. Both the Koputaroa dune-sands and the Ohakean loess contain the *c*.22,500 yr.B.P. Aokautere Ash.

In hand specimen it is often extremely difficult to distinguish between sandstone of the Otaki Formation and that of the Koputaroa dune-sands. Both can be poorly consolidated to weakly indurated, both can have the same colour, and both can have present day soil developed directly on them. Where obvious stratigraphic indicators are absent, criteria such as degree of weathering and the presence or absence of marine sedimentary structures were used to distinguish them.

A sequence of correlation columns across the southern side of the inlier (Fig. 3.8) illustrates the nature of the local coverbed stratigraphy. The most eastern exposure (L42 at S25/026577) reveals a thin overlying paleosol in turn overlain by carbonaceous mud containing Aokautere Ash mantled by the Koputaroa dune-sands.

Further west at L45 (S25/023578) the paleosol thickens to about one metre and possibly represents more than one soil forming period. The Koputaroa dune-sands are thinner here, do not contain Aokautere Ash and are mantled by a thin layer of loess.

In a road cutting along Railway Terrace at Ohau (L47

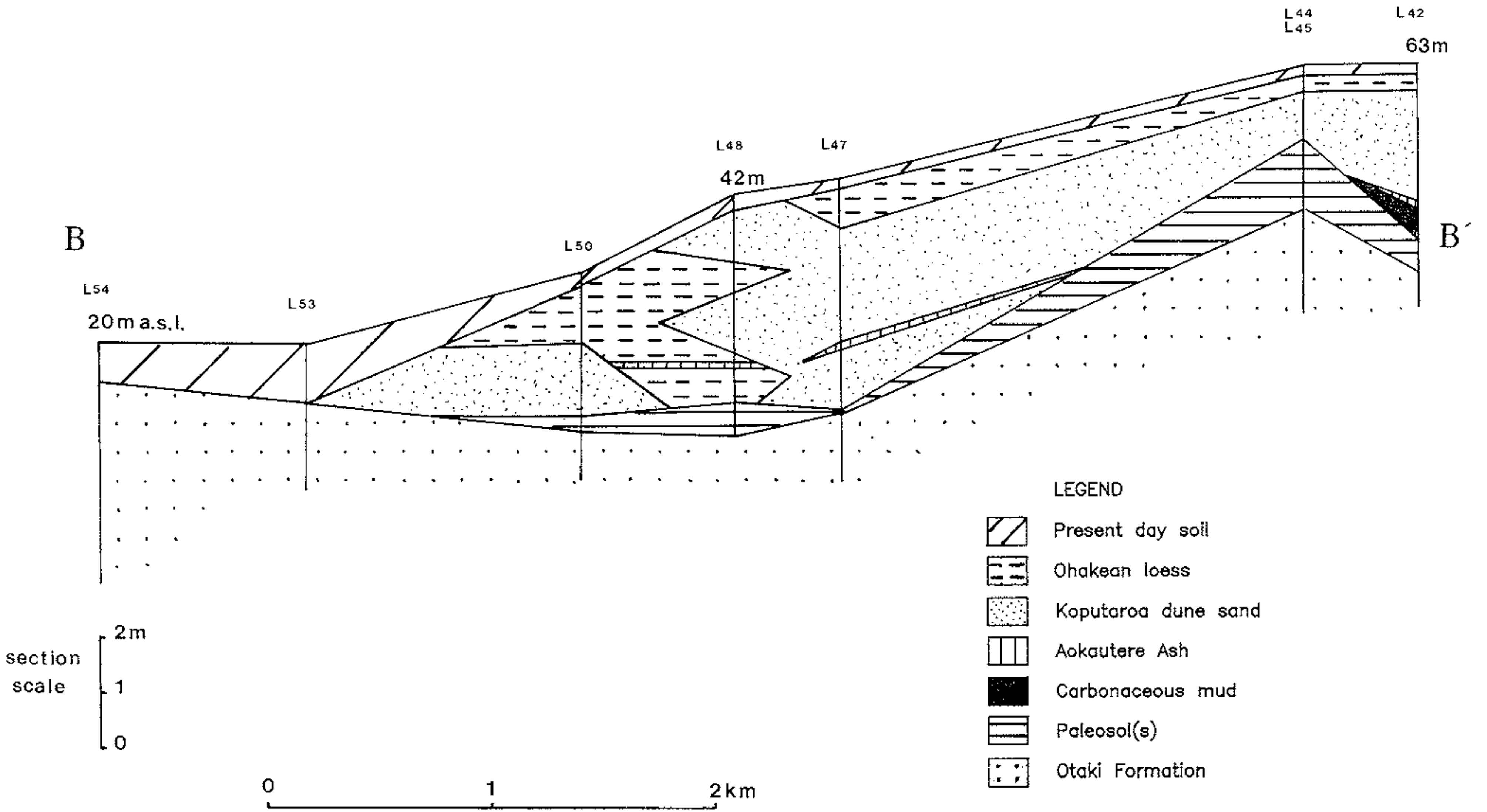



Fig. 3.8

Measured section correlation columns at Ohau illustrating the nature of the local coverbed stratigraphy. See Map 2 for location of cross section line which runs east (B') - west (B).

S25/006583), up to 3m of Koputaroa dune-sands containing 10cm of Aokautere Ash, unconformably overlie the Otaki Formation (Fig. 3.9). The unconformity is marked by a 20cm zone of strongly weathered and mottled, orange-brown sand with no obvious soil structure which grades down into massive and cross-bedded, light olive brown, well sorted, fine-grained sand with occasional rusty weathering bands typical of the Otaki Formation. About 0.5m of loess overlies the Koputaroa dune-sands.

On State Highway 1 (L48 at S25/002582), loess containing Aokautere Ash, and overlying a well developed paleosol, is seen to merge laterally into the Koputaroa dune-sands. Aokautere Ash abruptly disappears and is not present in the sand (Fig. 3.8).

Further to the west the covering strata wedge out, with present day soil developed directly on Otaki Formation. However, north of the line of profile (L52, S25/990591; L57, S25/994597) this is probably not the case.

**C. Paleoenvironmental Inferences**

The Otaki Formation in the Ohau area differs from what is seen in the Forest Lakes area in a number of ways:

1. Otaki dune sand is absent;
2. interbedded bioturbated silty layers with clay lined root channels indicating subaerial exposure are common;
3. the type of cross-bedding differs from what is seen to the south with the appearance of herringbone-type cross-stratification and, commonly occurring, reactivation surfaces.

Overall the lithology and sedimentary structures indicate periodic fluctuation of energy levels during deposition coupled with periods of subaerial to aerial exposure. A tide-dominated environment would provide such conditions in contrast to the open coast, wave-dominated environment indicated by the Otaki Formation in the Forest Lakes area. Top truncation of the TMT is masked by the extensive mantle of Koputaroa dune-sands displaying longitudinal dune morphology.

The abundant bore log data in the Ohau area enables delineation of the local cross-sectional geometry of the basin


Fig. 3.9

Ohakean loess (OL) overlying Koputaroa dune-sands (KDS) with interbedded Aokautere Ash (AA) in turn overlying the Otaki Formation (OF). The orange weathered zone near the base of the outcrop marks the disconformity between the Koputaroa dune-sands and the Otaki Formation.

in which the Otaki Formation was deposited (Fig. 3.2). This further aids paleoenvironmental reconstruction. In addition, basement structure in the area has been recently delineated by Bekesi (1988) (see Chapter 7). The presence of a westerly thickening wedge of Pukehou formation beneath the Otaki Formation, suggests a localised depression existed in the vicinity of Lake Papaitonga prior to the Last Interglacial transgression. Here fine-grained fluvial deposits and peat accumulated. It is possible that the depression was bounded to the west by the up-thrown basement block (Poroutawhao High) which presently exists on the western side of Lake Horowhenua (see 1.4.2, 7.3). If the up-thrown block did exist at that time, invasion of the sea during the Last Interglacial transgression may have occurred initially along the axis of the inferred depression from the north-east or south-west in the form of an embayment. In such a coastal environment tide and mixed wave/tide depositional processes would have predominated giving rise to the assemblage of sedimentary structures and lithologies now seen in the Otaki Formation at Ohau. Paleocurrent directions, although few and limited to the top of the sequence, indicate a northerly trend suggesting a possible outlet to the sea in a northerly direction rather than to the south (see Chapter 4).

### 3.3.4 Levin-Potts Hill

#### A. Lithology and Sedimentology

The Levin-Potts Hill area offers the thickest exposures of the Otaki Formation in the study area. Exposure is best between Potts Hill and Shannon where greater uplift along the Shannon Anticline has resulted in deep erosion into the TMT. In several places over 20m of almost continuous vertical exposure of Otaki beach sand are recorded (L77 at S25/097655, L80 at S25/105656, L85 at S25/119675). The basal sections of the Otaki Formation in this vicinity consist of sand with less obvious concentrations of ferromagnesian and titanomagnetite grains.

In general, where the top of the formation is exposed the upper *c*.5m shows an increase in hardness, often with underlying strata in the same exposure noticeably softer. Both Otaki dune sand and Otaki beach sand can show the same degree of hardness so it is unlikely that depositional processes are a major determining factor for hardness.

Otaki dune sand is thinner and seemingly less extensive than at Forest Lakes, occurring in a few exposures close to the foothills. However, the member does crop out on the western edge of the TMT (L73 at S25/048676) on the western flank of the Levin Anticline. Here, 2m of Otaki dune sand, overlain by 2m of loess and soil, rests on Otaki beach sand. The contact between the two members is sharp, marked by a 10cm bed of silty sand with an upper 3-4cm mottled horizon. The contact zone probably represents a short hiatus in deposition prior to dune sand accumulation.

At the same exposure, a more significant sedimentation break is observed in the Otaki beach sand 3m below the dune sand contact. Here, Otaki beach sand sharply overlies a 0.5m, strongly weathered, mud horizon which in turn grades down into unweathered beach sand. The upper 30cm of the lower beach sand becomes increasingly mottled toward the contact (Fig. 3.10). Approximately 100m east of this outcrop, the same sedimentation break is again observed with a hard, limonitic layer developed above the basal beach sand. The limonitic layer is made up of hard, rusty pebbles similar to that which Te Punga (1954) referred to as "buckshot gravels". Te Punga (1954) suggests that the presence of buckshot gravels within sandstone of equivalent age to the north indicates a prolonged exposure to weathering processes. The buckshot gravels possibly represent a period of weathering that took place between two marine sandstones thus indicating a relatively low sea level between two high sea level periods.

A characteristic feature of Otaki beach sand in the Levin-Potts Hill area is the frequent abundance of interbedded silty layers in otherwise well sorted, fine-grained sand. The silty beds are sometimes mottled and contain occasional root

Fig. 3.10

A paleosol separating two units of Otaki beach sand within the Otaki Formation.

channels and disseminated carbonaceous debris. Mottling is most strongly developed in silty beds that show a gradational basal contact with sand. Generally, the contacts are sharply defined with bases frequently resting on irregular scoured surfaces (Fig. 3.11A). In several places rip-up clasts of silt are seen incorporated in trough-cross-bedded sand overlying scoured surfaces (Fig. 3.11B).

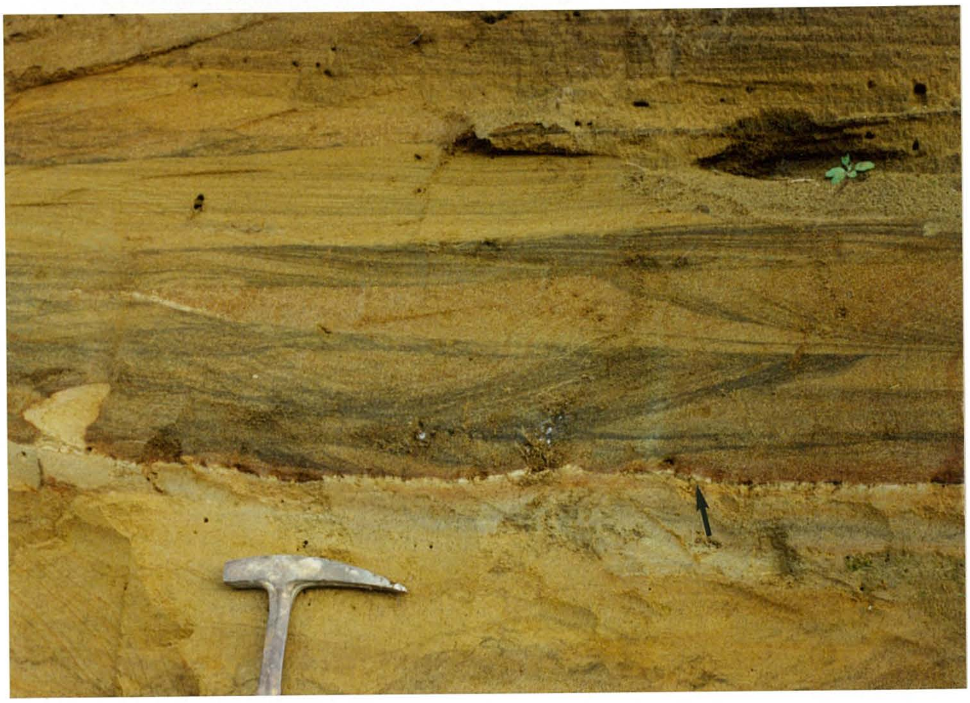
The silty zones occur either as isolated beds 10cm-50cm thick, or in regular cyclic sequences. Two types of cyclic sequence are observed:

1. sequences consisting of alternating beds of similar thickness (5-20cm) of silty sand and sandy silt (L58 at S25/080621, L91 at S25/123672, L85 at S25/119675, L93a at S25/127683);
2. sequences consisting of 2-5cm silty/muddy beds frequently resting on scoured surfaces, separated by *c*.0.5m of well sorted, parallel and current ripple-laminated fine- to medium-grained sand (L92 at S25/112693, L96 at S25/137692, L71 at S25/073642, L77 at S25/097655).

Type 1 sequences are suggestive of intertidal flat sedimentation in which sand is deposited during current and wave activity with mud being deposited during periods of slack water (Reineck and Singh 1975). Type 2 sequences are possibly the result of regular storm wave deposition in which muddy layers settle out immediately following storm periods, typical of a wave-dominated depositional environment (McCave 1970, Johnson and Baldwin 1986). Where rip up clasts occur in association with trough-cross-bedding, as shown in Fig. 3.11B, a tidal channel environment is probable. Clearly, sequences indicative of wave-dominated processes occur alongside sequences indicative of tide-dominated processes.

Along with abundant parallel and current ripple laminations so typical of Otaki beach sand, decimetre-scale cross-bedding is common, occurring in northward to westward dipping singular sets. Two localised occurrences of festooned, trough-cross-bedding occur, one in association with rip-up

A



B

Fig. 3.11

Scoured surfaces in Otaki beach sand. Note the basal mud drape on the scoured surfaces and angular rip-up clast on the left of B.

clasts (L66 at S25/077653). Two occurrences of single sets of gently dipping parallel laminated sand, bounded by horizontal, parallel laminated sand (Fig. 3.12) occur near Shannon (L96 at S25/137692, L97 at S25/097677). The latter are considered typical of a beach foreshore environment (Andrews and Van der Lingen 1969, Heward 1981, Elliot 1986).

**B. Contacts and Thickness**

The only positive identification of the Tokomaru wave cut platform in the study area is made at S25\097643 (L70), cropping out within several metres of the Last Interglacial strandline. Here, approximately 12m of Otaki Formation, comprising basal sandstone overlain by carbonaceous silt, rests unconformably on an irregular, sub-horizontal greywacke surface. The contact zone (0.5-1m) is characterised by sparse, angular to subangular clasts of greywacke pebbles, cobbles and boulders, resting on an irregular, crevassed greywacke platform. The crevasses in the rocky platform appear to have been later filled with well sorted, fine- to medium-grained sand. The sand has subsequently "cemented" the contact zone into a very hard, matrix supported, conglomerate. Sandy matrix accounts for over 50% of the conglomerate's volume. The irregular wave cut platform is interpreted as the intertidal zone of the Last Interglacial strandline. Once the strandline stabilised, abundant sediment supply resulted in shoreline progradation with subsequent burial of the rocky beach platform beneath a mantle of sand.

The base of the Otaki Formation is also seen at (L88) S25\131672. Here 5m of soft, light olive-grey, well sorted, fine- to medium-grained sand in large-scale, high angle, cross-beds, unconformably overlies 1m of blue/grey carbonaceous silt and sand containing thin (10-20cm) beds of pebbly breccia. The contact dips 30 degrees to the west and lies adjacent to a north-trending fault up-thrown to the east, which extends along the edge of the greywacke foothills. The TMT abutting the fault has been tilted to the west (Map 3; Fig.2.4). The section is interpreted as Otaki dune sand overlying older fluvial

Fig 3.12

Gently dipping, parallel laminated sandstone bounded by horizontal, parallel laminated sandstone. The spade is 1.2m long.

deposits. The contact is unlikely to represent a wave cut surface but rather an area inland of the Last Interglacial strandline where Otaki dune sand has mantled the hinterland. Vertical movement along the fault has accentuated the angular unconformity.

Otaki Formation greater than 42m thick is recorded in three boreholes around Potts Hill close to the axis of the Shannon Anticline. In contrast, substantial thinning is evident around the crest of the Levin Anticline where it reaches a minimum thickness of 11m at S25/049645 (BL 38). The deep dissection of the Shannon Anticline coupled with the presence of two well defined marine terraces on its northern flank testifies to a substantial uplift rate. This contrasts with the much less dissected surface and lower altitude of the Levin Anticline. It seems that the marked thinning of the Otaki Formation along the crest of the Levin Anticline is related to factors other than purely post-depositional uplift (see 7.4).

On the flanks of the Levin Anticline only one loess unit (Ohakean) overlying the Otaki Formation is recognised. Often it is replaced by, or interbedded with, up to 5m of Koputaroa dune-sands containing Aokautere Ash. Where a paleosol is absent a reddish weathering zone marks the disconformity between the Otaki Formation and the Koputaroa dune-sands as is seen in the Ohau area (see 3.3.3 B). The most easterly exposure of Koputaroa dune-sands occurs close to the foothills at (L69) S25/094634 where they are interbedded with Ohakean loess.

On the flanks of the Shannon Anticline several loess units overlie the Otaki Formation. McIntyre (1975) recognised a sequence of four loess units above the Otaki Formation at Pretoria Road S25/137692. The loess sequence at this locality rests on the lower marine terrace (PTMT1). The Koputaroa dune-sands, although not exposed north of Potts Hill, are also likely to be present, indicated by several conspicuous hummocks on the TMT immediately north of Potts Hill.

**C. Paleoenvironmental Inferences**

The Otaki Formation in the Levin-Potts Hill area is characterised by the following features:

1. the occurrence of two types of cyclic sequences existing more or less side by side and indicating fluctuating energy levels during deposition; one type is suggestive of tide-dominated depositional processes, the other type suggests storm wave depositional processes;

2. thickness variation with marked thinning of the Otaki Formation recorded around the crest of the Levin Anticline and maximum thickness recorded in the Potts Hill/Shannon Anticline area; an increase in thickness to the north-east along the plunge of the Levin Anticline is also evident;

3. evidence of a period of prolonged aerial exposure between deposition of two marine sand units.

Depositional processes indicative of the combined effects of moderate to high-energy wave and moderate-energy tide processes operated during deposition of the Otaki Formation in the Levin-Potts Hill area. Heward (1981) describes a mixed assemblage of sedimentary structures indicative of wave and tide depositional processes, as typical of mesotidal coastlines where tidal range at spring tides varies between 2-4m. The presence of plant root structures in some thin silty beds indicates subaerial exposure occurred sporadically and is consistent with a mixed wave-tide influenced shoreline. A similar interpretation is given for the Ohau area.

The thick sequence of Otaki Formation evident around Potts Hill implies a high sedimentation rate for the formation in this area relative to the south and west during the Last Interglacial sea level maximum (Fig. 3.13). It is probable that a north to north-east-trending structural depression existed close to the foothills north-east of Levin during deposition of the Otaki Formation. In contrast, a low sedimentation rate is implied by the thinning of the formation around the crest of the Levin Anticline indicating that a localised structural high probably existed in this area at that time.

Following maximum sea level conditions (*c*.120kyr B.P.) withdrawal of the sea was accompanied by substantial uplift

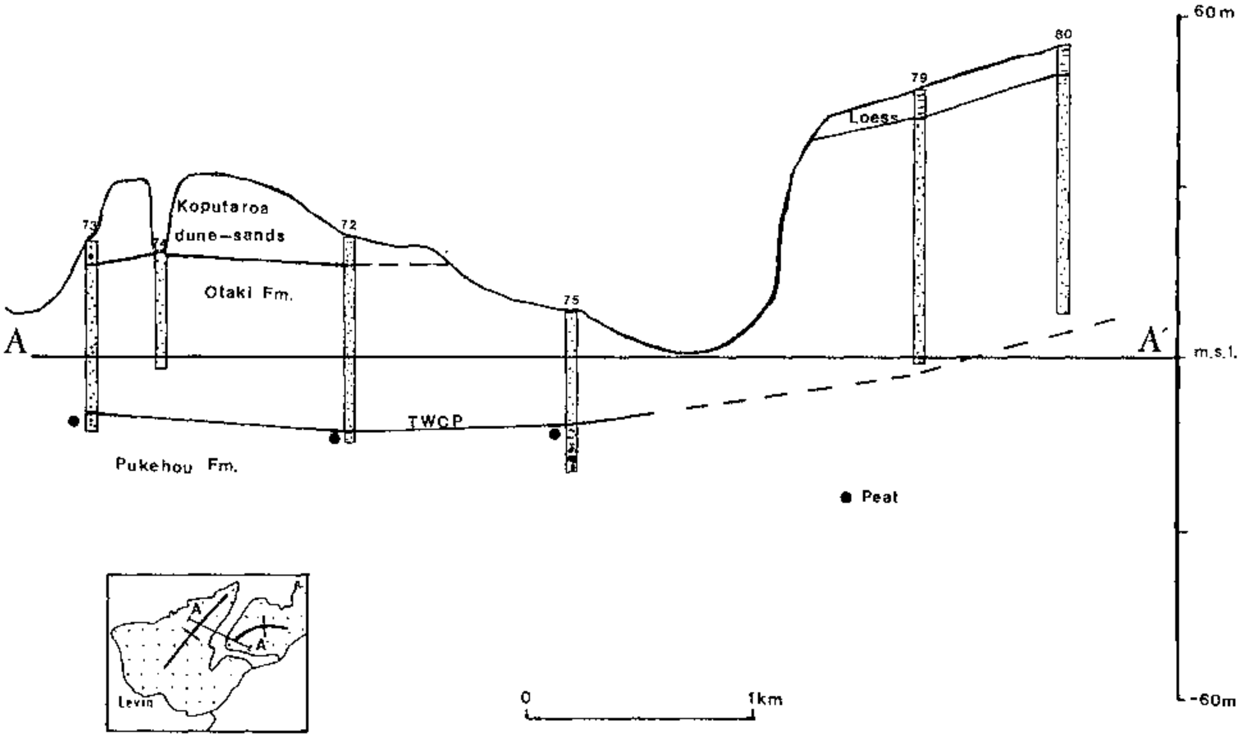



Fig. 3.13

Bore hole correlation columns across part of the Shannon and Levin anticlines. Note the greater uplift and thickness of the Otaki Formation on the Shannon Anticline relative to the Levin Anticline. See Map 3 for borehole locations.

associated with basement faults in the vicinity of Laws Hill. Corresponding growth of the Shannon Anticline resulted in rapid dissection of the TMT. Subsequent marine transgression cut a lower terrace with a strongly embayed strandline along the edge of the newly formed valleys which are now deeply dissected. The riser separating the two treads shows a clearly diminishing height difference between the two terraces away from Laws Hill, and indicates the degree of differential uplift that had already occurred prior to the later transgression. As is noted at Forest Lakes, the subsequent transgression appears to have been of relatively short duration preventing the destruction of coastal promontories.

The fact that four loess units are recognised on the lower marine terrace in this area suggests that the second terrace was probably cut during oxygen isotope stage 5c. Stage 5c is recognised in various parts of the world as a period of relative high sea level occurring *c.*100kyr B.P. (Chappell 1983). Elsewhere in the southern North Island, four loess units have been identified overlying marine terrace deposits correlated with oxygen isotope stage 5c (A.S. Palmer pers com.).

The marine sand overlying the strongly weathered paleosol on the north-western flank of the Levin Anticline indicates at least part of the anticline is mantled by a marine terrace younger than the TMT (PTMT1 or PTMT2). Widespread accumulation of Koputaroa dune-sands in the area has probably masked any low terrace riser that may be present.

### 3.3.5 Tokomaru - Makerua

#### A. Lithology and Sedimentology

North of Shannon the Otaki Formation shows the most diverse assemblage of lithologies seen in the field area. The presence of (greywacke) gravels within the formation marks a distinct change from what is found to the south. Facies relationships are complex with marked changes occurring over short distances both vertically and laterally.

Gravel occurrences in the Otaki Formation are confined to three well defined zones. Two of the zones occur where the TMT has been truncated by the Mangaore Stream and Tokomaru River respectively. Along the banks of these rivers tongues of conglomerate extend westward from the inner edge of the TMT (parallel with the rivers), interfingering with sandstone across the middle part of the terrace, and diminishing to lenses and scattered pebbles within sandstone at the western edge. The third zone occurs on the inner margin of the TMT parallel with the steeply rising foothills. Elsewhere, on the middle to outer edge of the TMT and PTMT1, gravel is not present in the sandstone.

A comparison of well exposed sections from three areas reveals the relationships between the various lithologies encountered in the Tokomaru-Makerua area.

Area 1

On the outer edge of the TMT immediately south of Tokomaru River a farm cutting exposes *c*.30m of almost continuous outcrop in the TMT (L98 at S24/223766, Fig. 3.14).

Unit 1 - The basal 4m is characterised by at least 3m of thinly interbedded, well sorted, fine sand and micaceous silty sand, overlain by at least 0.6m of carbonaceous mud with peat lenses.[3] The peat is associated with a thin (15cm) paleosol which has a speckled appearance due to the abundance of scattered mica. Concentrations of heavy minerals in the underlying sand, typical of the Otaki Formation to the south, are absent.

Unit 2 - A *c*.6m conglomerate bed (contact obscured) overlies the paleosol and consists of weakly stratified, slightly weathered, subangular to subrounded, medium pebbles (60%) with rare cobbles and no boulders, in a weathered sand matrix (40%). The upper 0.5m grades into poorly sorted, coarse sand, grading rapidly into soft siltstone.

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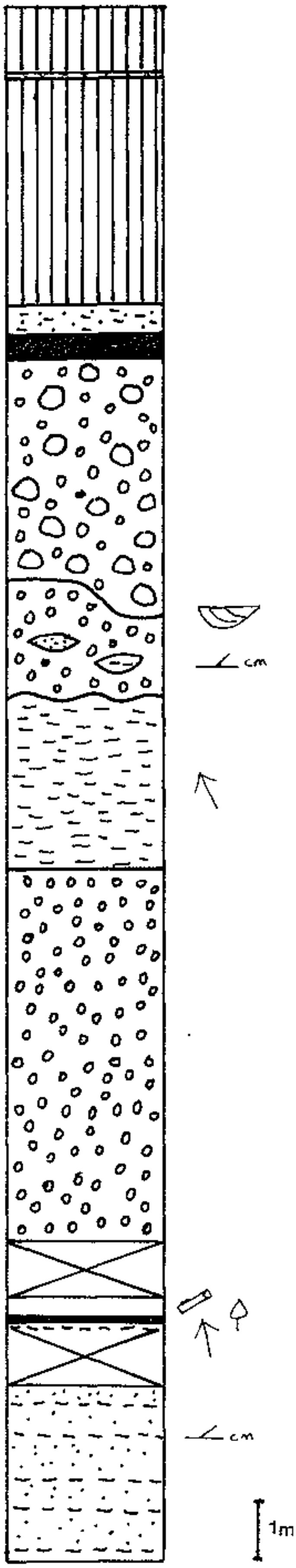
[3] This is the only occurrence of peat seen in the Otaki Formation in the field area.




| Unit | Sample No. | Description |
|---|---|---|
| | | Loess |
| 6 | N98A | Sandstone - 0.6m mass, yel-gy, soft, z f Sst |
| 5 | | Paleosol - 0.5m dk yel orng, wthd, Sst |
| 4b | | Conglomerate<br>upper - 4m [bdd], [wthd], clast suprt Cgl<br>clasts 80% - sub ang-sub rnd, crs Pbls<br>abnd Cbls, rare Bldrs<br>matrix 20% - rusty orng, wthd, crs S<br>-- sharp contact -- |
| 4a | | lower - 2m bdd, clast suprt, pbl Cgl. w<br>lens Z and Xbdd S<br>clasts 80% - sub ang-sub rnd Pbls, rare Cbls<br>matrix 20% - as above |
| 3 | | Siltstone - 3m mass, gn-gy, [wthd], micac, Zst. |
| 2 | | Conglomerate - 6m [bdd], [wthd], clast suprt, Cgl<br>clasts 60% - sub ang-sub rnd, med<br>Gwke, Pbls. rare Cbls<br>matrix 40% - yel-orng, wthd, soft, z<br>med S<br>upper 0.5m - matrix:clast increases, grades into Z |
| 1 | S24/f44<br>S24/f45 | Carbonaceous Mud - 0.6m carb M w peat lens.<br>scat mica. 15cm Paleosol |
| | N98B | Sandstone - >3m tn, ibdd, srt f Sst and z Sst |

**Fig. 3.14** Measured section description of L98

Unit 3 - Unit 3 comprises a 3m bed of massive, green-grey micaceous siltstone containing occasional root channels.

Unit 4 - A 6m conglomerate bed sharply overlies unit 3 and can be subdivided into two distinct sub-units. The basal unit (4a) comprises 2m of stratified, pebbly conglomerate with lenses of silt and cross-bedded sand. This is overlain by (unit 4b) 4m of poorly-stratified to non-stratified, coarse to very coarse pebble conglomerate with abundant cobbles and occasional boulders. A channel, 8m wide and 2m deep, containing boulders on the channel floor is also noted in unit 4b. The contact between the two units is sharp and can be traced laterally for over 200m (see L99 at S24/223767). In both units clasts account for approximately 80% of the conglomerate with 20% matrix consisting of rusty-orange, coarse sand.

Unit 5 - A 0.5m thick, strongly weathered (dark yellow orange), sandstone bed sharply overlies unit 4b.

Unit 6 - A 0.6m bed of yellow-grey, silty, fine sandstone containing occasional root channels sharply overlies unit 5. A 5m loess sequence mantles these deposits.

The upper conglomerate units (4a,b) show typical fluvial characteristics including silt lenses, channel structures and boulder-sized clasts. In contrast, clasts in unit 2 are smaller and show better sorting, silt lenses and channel structures are absent, and an overall homogeneity is apparent. Such features may reflect a marine, or mixed fluvio-marine origin for unit 2. The winnowing effect of tidal currents and waves would produce a more homogeneous and better sorted conglomerate than that formed by fluvial processes alone.

The basal facies (Unit 1) of thinly interbedded, silty fine sands and well sorted fine sands indicates a depositional environment characterised by regular fluctuations of moderate to moderately low energy levels typical of tidal flat environments. The abundance of mica suggests sediment influx from a source other than greywacke, probably from Tertiary sediments to the north. Mica may have been transported to the site directly by rivers form the north or north-east, however, from the above evidence a tidal flat or estuarine setting is more likely.

Palynological analysis of the overlying carbonaceous mud and peaty paleosol indicates the encroachment of beech/podocarp forest onto an acid peat flax swamp (D.C. Mildenhall pers. com., see Appendix E). This swampy area probably developed on the periphery of a tidal (or estuarine) flat as a result of shoreline progradation or lateral migration of an estuary.

The overlying moderately sorted, homogeneous, pebble conglomerate (Unit 2) may represent a migrating distributary channel of a nearby estuary that supplied coarse alluvium to the coast. As the channel migrated a localised lagoon formed in which carbonaceous silts were deposited (Unit 3).

With the onset of marine regression the river channels fanned out over the estuarine deposits in rapid response to a lowering of base level and rejuvenated erosion upstream (Unit 4a). The sharp transition to the coarser upper conglomerate unit (4b) perhaps reflects the influence of localised tectonic movements resulting in a rapid influx of coarser material into the river channel.

In nearby exposures rapid lateral and vertical variation in the sequence is apparent. Approximately 0.5km to the south (BL 78 at S24/222761, see also L101 at S24/223758), the lower conglomerate unit (Unit 2) is not present and the upper conglomerate unit (Unit 4) is noticeably thinner. A further 0.75km south-west of L101, at S24/215754, both conglomerate units are absent.

Toward the foothills, muddy, matrix supported conglomerates, interbedded with silts and pebbly silts, predominate and are suggestive of sediment-gravity and sheet-flood deposition. Paleosols[4], carbonaceous lenses and localised, angular unconformities are also common in what is interpreted as a proximal alluvial fan facies (see L104 L105

[4] A paleosol dipping westward at 12 degrees is seen at (L106) S24/229747 on the inner margin of the TMT and possibly represents the slope angle of the surface on which it developed.

L106). Nevertheless, apart from in sections immediately adjacent to the Tokomaru River, clast size does not increase toward the foothills as significantly as might be expected.

The overall facies assemblage in Area 1 is interpreted as a fan-delta[5] association where an alluvial fan spilled out from the foothills onto a tide-dominated, moderately low-energy, coastline. Fan-deltas characteristically occur adjacent to a highland region, which is usually fault bounded, and occupy a narrow space between the highland and a standing body of water. A fan-delta is thus composed of a subaerial component (alluvial fan) and a subaqueous component. The characteristics of the latter depend on the interplay of river mouth processes and numerous basin conditions such as wave energy, tidal flux, littoral currents, basinal subsidence and tectonic setting (McPherson *et al.* 1987). As distal deposits of an alluvial fan come into contact with shoreline deposits and processes, a complexity of interfingering facies results. Hence, as is implied by the section interpretation above, gravel beds reworked by tidal currents and waves would have become interbedded with tidal flat sands, marsh deposits and lagoonal silts. Nemec and Steele (1988) point out that fan-deltas commonly show an almost imperceptible gradation from non-marine to marine facies.

It is considered that in this area, during deposition of the Otaki Formation, the Tokomaru valley was the source of an alluvial fan which deposited an arcuate accumulation of distally finer debris onto a shallow tide-dominated coastline.

Area 2

On the north side of Mangaore Stream the marine terraces extend *c.*4km west from the foothills as opposed to only 2km west from the foothills south of Tokomaru. Here, on the outside

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[5] The term fan-delta as defined by McPherson *et al.* (1987), refers to a gravel rich delta formed where an alluvial fan is deposited directly into a standing body of water from an adjacent highland, usually fault bounded. It is sometimes referred to as a "coastal alluvial fan" (Rust and Koster 1984).

edge of the PTMT1 (L1 at S24/156716) a well exposed outcrop (Fig. 3.15) reveals a range of lithologies and sedimentary structures. The 6.5m sequence is described and interpreted below (Fig. 3.16). Two overall units are recognised.

Unit 1 - Unit 1 is composed of three sub-units. The basal sub-unit comprises 2m of well sorted, fine-grained sandstone with thin (2-3cm), bioturbated, muddy interbeds. The sandstone beds (0.3-0.4m) are either massive with rare, single sets of current ripple laminations, or are medium-scale cross-bedded with foresets dipping south-eastwards. Lenses of coarse sand occur within some foreset laminae. The basal sub-unit is sharply overlain by the second sub-unit comprising a 30cm bed of hard, graded mudstone which becomes finely laminated towards the top. The third sub-unit comprising up to 60cm of silty, fine sandstone sharply overlies the mudstone but is locally absent due to erosion. Symmetrical ripples occur on the base of this bed.

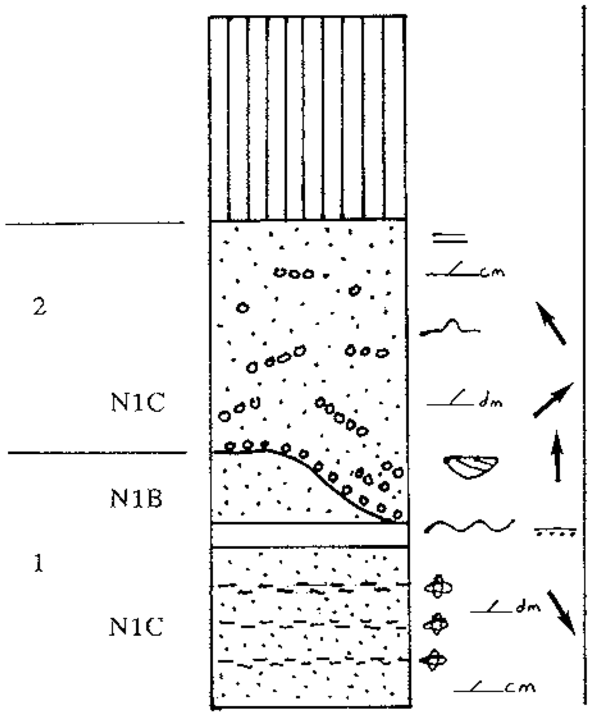
A strong unconformity which is locally channelised separates Unit 1 from Unit 2.

Unit 2 - Unit 2 comprises a basal pebbly lag deposit (<10cm thick) overlain by 3-4m of trough-cross-bedded, pebbly sandstone grading up into parallel laminated, medium-grained sandstone with occasional pebbles. The cross-beds frequently contain pebbly lags on their lower bounding surfaces. The pebbles are subangular to rounded with a maximum size of 6cm and average size of 1-2cm. They are often slightly weathered and are of predominantly greywacke and argillite origin with minor spilite and chert. One well preserved channel at the base of Unit 2 has completely eroded the upper sub-unit of unit 1 and rests directly on the hard mudstone bed which has resisted channel erosion (Fig. 3.15). Convolute bedding is well developed in places (Fig 3.17) and climbing ripple laminations occur sporadically, both being indicative of high rates of sediment accumulation (Seward 1986). High concentrations of heavy minerals in thick, black laminae are distinctive throughout the unit (Fig. 3.15) in contrast to unit 1 which is

Fig 3.15

Part of the well exposed outcrop at (L1) S24/156716. Note the well preserved channel filled with cross-bedded pebbly sandstone (centre middle) grading up into parallel laminated sandstone with occasional pebbles. The channel has completely eroded part of an underlying sandstone bed (centre left) which rests sharply on a 30cm bed of hard mudstone, but has not eroded into the mudstone. Tape measure is 1.4m. See Fig.3.16 for detailed section description.

L1 S24/156716




Top of section at c.27m a.s.l

Loess

Sandstone - basal pbl lag (<10cm) overlain by 3-4m soft-[hd], gy, trgh Xbdd, pbl, m Sst. grades up into pll lam, m Sst w occasional Pbls
Pbls - subang-rnd Gwke
max 6cm, av - 1-2cm

-- unconformity --

Sandstone - 20-40cm mass, gy-orng, wthd z f Sst

Mudstone - 30cm f lam pale yel-orng [soft] Zst/Mst

Sandstone - 2m mass-Xbdd, soft, v pale orng, srt f s, w tn ibdd M layers

Fig. 3.16 Measured section description of L1


Fig. 3.17

Convolute lamination in the Otaki Formation north of Shannon. Scale is in metres.

almost devoid of heavy mineral concentrations.

The facies assemblage observed in unit 1 reflects irregular fluctuation of energy levels. The well sorted sandstone beds with landward dipping cross-sets and coarse sand lenses indicate relatively high-energy landward directed marine currents. These beds are separated by thin, bioturbated muddy beds reflecting periodic cessation of the high-energy currents allowing deposition of mud and silt from suspension. The mud has in turn been reworked by marine organisms on the sea floor. Such sequences have been recognised in storm-dominated offshore environments in the zone between mean fairweather wave base and mean storm wave base (Elliot 1986). Deposition of predominantly sand in this zone is related to frequent storms during which wave-induced currents affect the sea floor. During fairweather periods wave influence does not extend to the sea floor in this zone allowing the deposition of mud and silt from suspension.

The hard, laminated mudstone bed immediately overlying the basal sub-unit represents an extended period of low-energy deposition, possibly indicative of temporarily deeper water conditions below storm wave base. The upper sub-unit of silty sandstone perhaps represents a return to shallower water offshore conditions.

In contrast, Unit 2 reflects an environment in which sustained high energy conditions prevailed and where the sedimentation rate was high. The presence of a distinct unconformity between the two units, abundant pebbles[6] and high concentrations of ferromagnesian minerals in thick black laminae, testifies to a high-energy depositional environment. The abundance of trough-cross-bedding with generally northward dipping foresets, and the presence of a well preserved north-trending channel, may suggest that tide-induced current activity predominated.

The Unit is interpreted as a sub-tidal channel deposit

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[6] The subangular nature of many of the pebbles indicates close proximity to source.

dominated by high-energy, north-trending, tide-induced currents. The upward gradation from cross-bedding to parallel lamination indicates a progressive change in flow conditions from the lower to upper flow regime, reflecting a decrease in water depth and increased dominance of wave depositional processes (Reineck and Singh 1975).

The overall facies assemblage represented in Units 1 and 2 reflects a change from offshore wave-dominated processes to nearshore tide-dominated processes grading into nearshore wave-dominated processes. Unit 1 probably represents the climax of a marine transgression during which mud began accumulating below storm wave base in low-energy conditions. During this time the adjacent Mangaore Stream, rising deep in the axial ranges, was discharging a continuous supply of coarse alluvium to the coast. Subsequent regression (or shoreline progradation) resulted in distributary channels at the mouth of the Mangaore Stream extending seaward, scouring the underlying marine deposits and dumping abundant gravelly sediment into the nearshore zone. Here, interaction with waves and long shore currents, also carrying abundant sediment, produced an assemblage of sedimentary structures consistent with a high energy nearshore environment where the sedimentation rate was high. Clifton *et al*. (1971) describes a similar sequence occurring in a Quaternary marine terrace deposit in California.

The high energy, shallow marine deposits overlying deeper water, lower energy deposits evident here, contrast with those of Area 1, where fluvial and sub-aerial deposits overlie low-to moderate-energy marginal marine beds. This might be expected considering that the exposure here is 4km seaward from the inner edge of the TMT as opposed to 2km at Tokomaru.

In a similar way as at Tokomaru, conglomerate becomes increasingly dominant over sandstone toward the inner margin of the TMT adjacent to the present day Mangaore Stream valley as seen at S24/159704, with the eventual disappearance of sandstone noted at S25/167693. However, pebbly sediments rapidly disappear laterally with no trace of pebbles seen 1km north-east of S24/159704 at S24/170708. A fan-delta association similar to that seen adjacent to the Tokomaru River is possible near the inner margin of the TMT. However, in this case the shoreline into which the fan-delta prograded possessed considerably higher wave energy than is evident to the north.

Area 3

Approximately midway between areas 1 and 2 and 1.5km inland from the outer edge of PTMT2 (L118 at S24/187731), a 10m vertical section of the Otaki Formation is exposed in a farm track cutting. Three units are recognised in the sequence (Fig. 3.18).

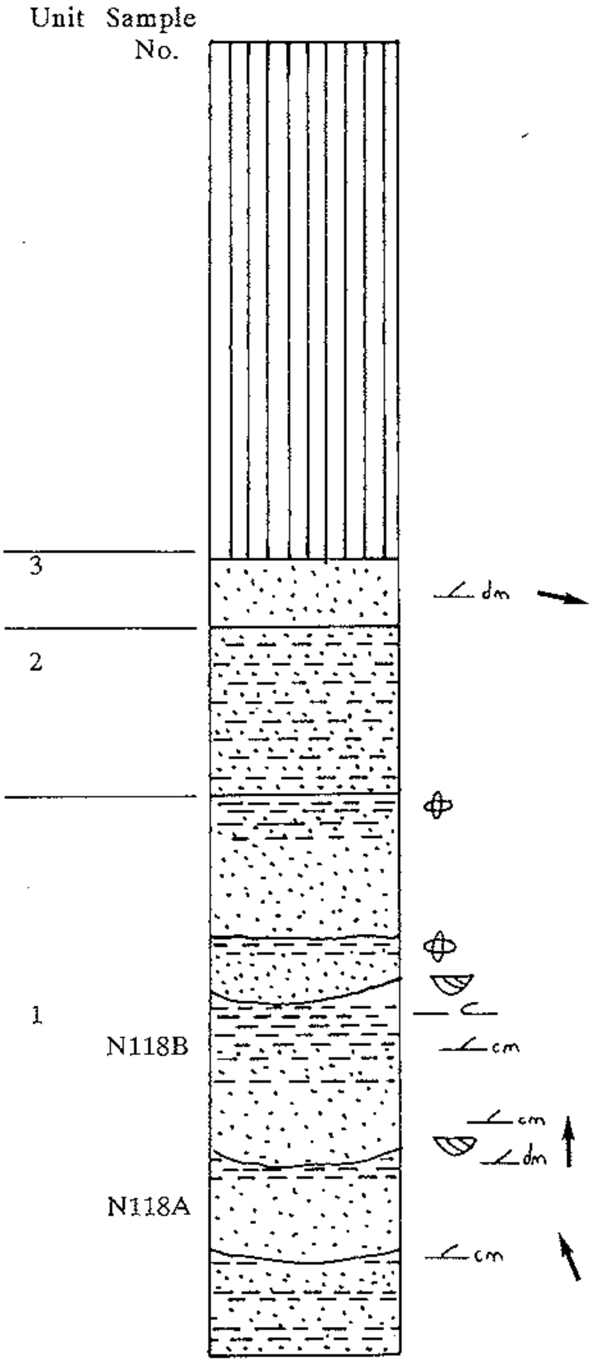
Unit 1 - The basal 7m comprises a series of fining upwards sub-units 0.5-2m thick. In general, each sub-unit begins with well sorted, fine- to medium-grained sandstone, occasionally with a thin, coarse-grained lag resting on a shallow dish-shaped, scoured surface. The basal beds frequently show small-scale festooned cross-bedding where the long axes of the trough-cross-beds are parallel with the scoured channels trending northwards. The cross-beds grade into current ripple and flat laminated, silty fine sandstone, in turn grading into 20-30cm of moderately hard siltstone, often showing bioturbation structures. Micaceous grains are common in silty layers near the base of the sequence and heavy minerals are concentrated in cross-laminae.

2. Unit 2 sharply overlies unit 1 and comprises 2m of thinly interbedded (2-3cm) sandy siltstone and silty, fine sandstone.

3. Unit 3 sharply overlies unit 2 and comprises approximately 1m of laminated to massive, well sorted, medium-grained sandstone with a 0.4m zone of low angle, planar cross-bedding, very similar to what is seen near Shannon (see Fig. 3.12).

The sequence above is interpreted as a sand-dominated, tidal flat facies assemblage. The fining upwards sequences resting on scoured surfaces in the basal unit probably represent lateral migration of shallow tidal creeks in the

L118 S24/187731




Loess

Sandstone - 0.8m lam-mass, lt ol gy, m Sst, w tn, crs S lens. some low angle pl-Xbdd

Sandstone/Siltstone - 2m tn ibdd, pale orng wthd [soft], z f Sst and s Zst

Sandstone/Siltstone - 7m fining upwards subunits consisting of:-

top - f lam-mass, pale orng, wthd, [hd] s Zst
- f lam, yel-gy, soft, z f Sst
- lam, dsk-yel, soft, srt, f Sst
- trgh-Xbdd, dsk-yel, soft, srt, f-m Sst
base - crs S lag
-- scoured surface --

Sandstone - 0.5m f lam, dsk-yel, [hd], z f Sst w abnd mica, ibdd w mass, yel-brn, wthd, soft srt, f Sst

**Fig. 3.18** Measured section description of L118 shallow subtidal zone. The interlayering of sandstone and siltstone beds seen in Unit 2 indicates the increased influence of wave activity. Reineck and Singh (1975) note that such interlayered bedding is common in mixed intertidal flats[7], and is probably the result of sand layers deposited during tidal current and wave activity, with silt layers deposited in periods of slack water. Unit 3 indicates that wave processes predominated in the deposition of a distinctly coarser sand bed, in which the occurrence of parallel laminations inclined at low angles is suggestive of a beach face depositional environment.

Two kilometres north-east of L118 at (L111) S24/207736, a 6m exposure reveals a well preserved channel containing a coarse-grained sandy lag and large rip-up clasts of siltstone along its base (Fig. 3.19). The channel fill is made up of decimetre-scale cross-beds of medium-grained sandstone, grading into parallel laminated medium-grained sandstone. A 20cm strongly mottled silt bed containing abundant root channels and with an upper 3-4cm paleosol, rests on the channelised unit. This is in turn overlain by at least 30cm of weakly laminated to massive, well sorted, medium sand. The sequence probably represents a shallow subtidal or intertidal channel environment where abandonment of the channel was followed by a period of supratidal exposure during which a thin paleosol developed. Subsequent return of the sea resulted in deposition of the overlying sand bed by wave processes.

Well exposed sections at two other localities in the same vicinity show a similar pattern of tide-dominated depositional processes changing to wave-dominated processes near the top of the sequence. The transition is marked either by a paleosol (L113 at S24/204741) or evidence of supratidal exposure (L115 at S24/208740). On a tide-dominated coastline where intertidal

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[7] Reineck and Singh (1975) proposed the terms sand flats, mixed flats and mud flats to subdivide respectively the lower, middle, and upper parts of the area between low tide and high tide on the intertidal flats.

Fig 3.19

Probable intertidal channel with large rip-up clasts of silt along its base. Note the small faults in parallel laminated sandstone below the channel (lower centre).

channels are constantly migrating it would not be unusual for localised areas on the tidal flat to be exposed for extended periods enabling the colonisation of vegetation and development of soil.

Toward the foothills near the inner margin of the TMT, rapid facies changes occur. Less than 1km south-east of L118 at (L119) S24/191723, up to 4m of unstratified, angular to subangular, pebble conglomerate unconformably overlies hard, parallel laminated and current ripple laminated, fine-grained sandstone. Coarse-grained, sandy (weathered) matrix comprises 10% of the bed and occasional silt lenses are present. The conglomerate is mantled by 1.5m of loess.

A further 0.7km to the south-east at (L120) S24/197715 an abrupt change in the overall vertical sequence is seen. Three facies units are recognised (Fig. 3.20). Facies 1 (F1) at the base of a c.12m exposure in the TMT, comprises a 3m bed of tightly packed, weakly imbricated, subangular to rounded pebble conglomerate (average clast size 0.5cm with maximum 3cm). Coarse-grained, sandy matrix increases in abundance from 5% in the lower 1m to 30% in the upper 0.5m of the bed, grading into F2, comprising 7m of alternating beds of pebbles, silt and sand (with silt predominant). This in turn is sharply overlain by F3 comprising 1.5m of unstratified conglomerate. Clasts in F3 are subangular to subrounded with an average size of 3-4cm and a maximum size of 10cm.

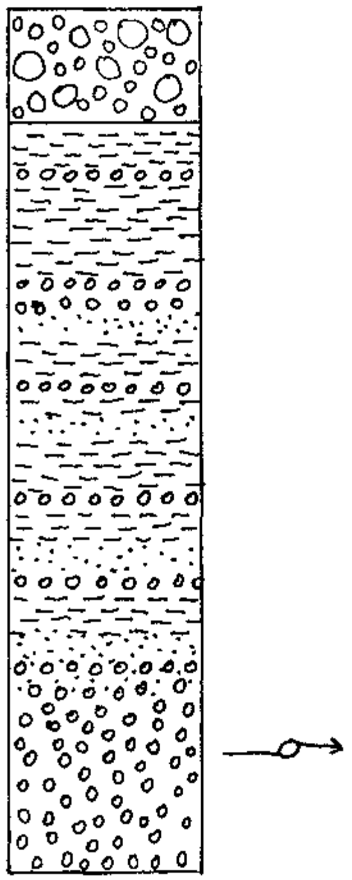
At scattered outcrops along the inside edge of the TMT a similar vertical sequence is noted. Tightly packed non-stratified pebble conglomerates (F1) locally fining upward over 1m and showing imbrication and/or weak stratification occur in basal sections. Middle sections contain silt beds with 3-20cm bands of coarse pebbles (F2). The upper terrace deposits comprise at least 2m of coarse, clast supported conglomerate (F3) or angular, (silty) matrix supported breccia (F4). The breccia beds are strongly weathered in contrast to the conglomerate beds which show weak to moderate weathering.

The sequence of facies described above is typical of a

L120 S24/197/715

Unit

F3



F2

F1

<u>Conglomerate</u> - 1.5m mass, [srt] crs pbl, Cgl
clasts 95% - sub ang-sub, rnd,Gwke pbls; max 10cm, av 3-4cm
matrix 5% - crs S

-- sharp contact --

<u>Pebbly Silt</u> - 7m alternating beds Pbls, Z, S, Z predominates
Pbls - sub rnd-rnd, [wthd] max 3cm, av 0.5cm occur in 5-30cm beds
Z - lt gy, mass-[lam] s Z
S - [srt] z S in tn horz beds

-- gradational contact --

<u>Conglomerate</u> - 3m tightly pkd, [bdd], clast suprt, [imb] Cgl
clasts 95-70% (decreasing up) - sub ang-sub rnd, Gwkc pbls, max 3cm, av 0.5cm
matrix 5-30% (increasing up) - crs S

**Fig.** 3.20 Measured section description of L120 stream-dominated alluvial fan assemblage where bed load deposits (F1 and F3), and sheet flood deposits (F2) are interbedded with minor sediment-gravity flow deposits (F4) (Collinson 1986). The abrupt facies change from an alluvial fan-dominated assemblage to a tidal flat assemblage (over 1.7km) is therefore indicative of an overall fan-delta association (Miall 1990, McPherson *et al.* 1987). The alluvial fan appears to have emanated from the headwaters of the Mangapuketea Stream (Map 4). The fan-delta emptied into an initially tide-dominated coastal environment in which wave processes appear to have become increasingly dominant.

**B. Contacts and Thickness**

Although the contact is not seen, the fan-delta facies association within the coverbeds of the inner edge of the TMT strongly suggests the TMT is fault bounded against the foothills. This is in contrast to a wave-cut cliff margin as seen in the Forest Lakes area. This interpretation is consistent with the present geomorphic evidence of a fault scarp along the boundary between the Mangaore Stream and Tokomaru River (see 2.4). Recent normal faulting in the TMT and other evidence of tectonic activity in this area is discussed in Chapter 7.

Lack of bore hole data between Shannon and Tokomaru makes it difficult to determine the local thickness variation and geometry of the Otaki Formation in the area. One bore hole has been drilled into the TMT immediately south of Tokomaru River at (BL 78) S24/222761. Here *c*.20m of brown gravel, sand and clay (Otaki Formation) is reported overlying 7m of blue sand and clay (Pukehou formation) in turn overlying >8m of tightly packed blue gravel (older Pleistocene deposits). The base of the Otaki Formation at this point is at *c*.17m a.s.l. If this bore log correlation is correct, then the 21m section of Otaki Formation exposed at (L98) S24/223766 represents an almost complete sequence through the Formation in this area. However, the marked vertical and lateral facies changes evident in the Otaki Formation in the Tokomaru-Makerua area make it difficult to clearly delineate its base, unlike to the south.

McIntyre (1975) studied the loess coverbed sequence resting on the western edge of the PTMT1 at Makerua (S24/180742) where he identified four loess units (totalling 9.5m) mantling the Otaki Formation. The sequence overlies two sandstone beds separated by a strongly weathered paleosol. The presence of a well developed paleosol within the Otaki Formation near the top of the sequence is also noted at many other nearby exposures (see L98, L99, L100, L102, L103, L111, L113). These occur both on the TMT and PTMT1 but generally show a higher degree of weathering on the lower terrace. For example, at (L100, PTMT1) S24/219767 below a 5m loess sequence, 0.5m of soft, weakly stratified, well sorted, fine sandstone sharply overlies a 0.7m strongly weathered sandy zone comprising 40cm of weakly cemented limonitic concretions (buckshot gravels of Te Punga 1954). This in turn grades into a lower bed of soft, unstratified, yellow-grey, well sorted, fine-grained sandstone.

At many localities the loess sequence is incomplete and toward the inner margin of the TMT becomes thinner, being replaced by sediment-gravity deposited material.

### C. Paleoenvironmental Inferences

During the Last Interglacial sea level maximum, the coastline in the Tokomaru-Makerua area comprised a series of coalescing fan-deltas discharging into a relatively low energy, tide-dominated, shallow marine environment (Fig. 3.21). A wave-cut origin for the cliffed margin of the foothills in this area is therefore unlikely. Rather, the cliff represents a syndepositional (and presently active) fault scarp. Palynological evidence (see Chapter 6) indicates temperate climatic conditions prevailed during fan-delta deposition which would account for the predominance, in the alluvial fan facies, of water laid deposits as opposed to sediment-gravity flows. Scholle and Spearing (1982) note that alluvial fans slope more gently in areas of higher precipitation and more steeply in arid areas. Facies indicating deposition by sediment-gravity

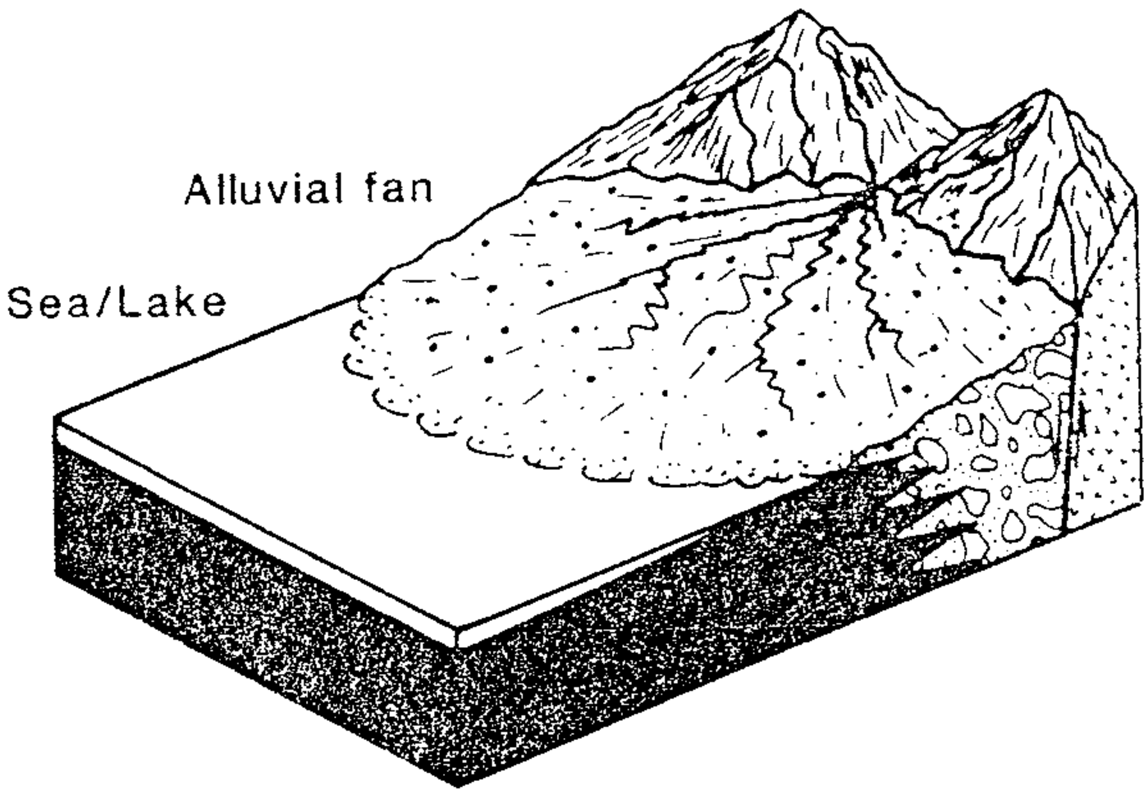



Fig. 3.21

Diagram illustrating a Fan-delta association (after McPherson et al 1987).

flows were only observed close to the foothills and near the top of the TMT.

Following the Last Interglacial transgression a sharp lowering of sea level occurred. This caused an immediate response by fluvial processes in the fan-delta areas resulting in rapid influx of coarser detritus into stream channels which extended seaward across coastal marine deposits. The abrupt contact between the two upper conglomerate units seen south of Tokomaru River may suggest an episode of tectonic uplift accompanied the regression. The bed of conglomerate sharply overlying sandstone on the TMT south of Kaihinau Road probably indicates the same.

Later, a marine transgression occurred during which a relatively straight shoreline was cut on the edge of the TMT. Subsequent regression was followed by the formation of a strongly weathered soil on both marine terraces. This was followed by a brief period of localised dune sand deposition prior to loess accumulation.

Four loess units resting on the lower terrace probably indicates that this terrace correlates with oxygen isotope stage 5c. The higher terrace reveals a similar loess sequence (although only three loess units were positively identified) with the same strongly weathered paleosol near the top of the Otaki Formation overlain by a layer of sand. As mentioned previously, the TMT is widely recognised as the lateral equivalent to the Rapanui Terrace in Wanganui dated at *c.*120kyr B.P. (oxygen isotope stage 5e) which correlates with a worldwide recognised period of high sea level (Pillans 1985).

### 3.3.6 Summary

Stratigraphic and lithofacies analysis of the Otaki Formation between Otaki River and Tokomaru River reveals a number of trends.

1. The Otaki Formation thickens to the north-east, sub-parallel with the axial ranges. The underlying Pukehou formation reflects a similar trend. Maximum measurable thickness of the

Otaki Formation (>45m) occurs north-east of Levin on the flanks of the Shannon Anticline.

2. North-easterly thickening of the Otaki Formation is accompanied by a gradual change in marine sedimentation from a wave-dominated depositional environment in the Forest Lakes area, through mixed wave tide- (Ohau - Levin-Potts Hill), to an increasingly tide-dominated depositional environment north of Shannon.

3. Fluvial deposition in the Otaki Formation occurs along the inner edge of the TMT north of Shannon.

4. The inner edge of the TMT in the Forest Lakes area abuts a clearly defined wave cut cliff whereas north of Shannon a fault bounded margin is inferred.

Lower marine terraces cut on the outer edge of the TMT indicate the Otaki Formation comprises sediment laid down during several high sea level episodes. Assuming the TMT correlates with the Rapanui Terrace near Wanganui then the lower two terraces may correlate with the Inaha (PTMT1) and Hauriri (PTMT2) terraces at Wanganui. The Inaha and Hauriri terraces are inferred to have been cut at *c*.100kyr B.P (oxygen isotope substage 5c) and *c*.80kyr B.P. (oxygen isotope stage 5a) (see Fig. 3.1.). Thus, Otaki Formation sedimentation probably spans at least 40,000 yrs.

# CHAPTER 4

# PALEOCURRENT ANALYSIS

## 4.1 INTRODUCTION

Meaningful interpretation of paleocurrent indicators is only possible in conjunction with detailed facies analysis since a variety of sedimentary environments can produce similar sedimentary structures that have quite different paleocurrent implications. For example, foreset dip directions of planar cross-beds related to lateral migration of a stream or tidal channel are oriented perpendicular to current flow. In contrast, similar looking cross-bedding can result from subtidal longshore currents in which current direction is parallel to the foreset dip direction (Elliot 1986).

Three main environments of deposition are recognised in the Otaki Formation in the Levin area; aeolian, fluvial and shallow marine. Within these environments various subenvironments are recognised in which a variety of depositional processes and energy levels have been operative. Although the overall paleoslope and paleoshoreline orientation of the Otaki Formation is obvious, subtle paleocurrent indicators of wind, wave-current and tidal-current direction aid in the detailed reconstruction of the paleoenvironment. This is particularly relevant in a tectonically active environment such as on the south-eastern margin of the Wanganui Basin (see Chapter 7).

Paleocurrent indicators within the Otaki Formation are abundant comprising predominantly cross-bedded strata of various types with occasional exposures of channels and scours. Current ripple laminations are by far the most abundant paleocurrent indicator but also the most variable in orientation.

## 4.2 DATA COLLECTION AND PROCESSING

Paleocurrent measurements were taken mainly from cross-bedded sets of decimetre scale or larger. Individual cross-set dip azimuths, where possible, were measured by taking two apparent dip readings at right angles then plotting them on a Schmidt net to obtain the true dip direction. No correction for stratal dip was necessary. Channel orientations were measured along their longitudinal axes. A total of 83 paleocurrent measurements were recorded.

The type of cross-beds, along with their foreset dip angles, were noted in the field and considered in relation to the facies units in which they occurred. However, for the purpose of overall trend analysis types of cross-bedding are grouped together according to the three major facies variations represented in the Otaki Formation; aeolian, marine and fluvial. Data is further grouped according to three field sub-areas, Forest Lakes (southern), Ohau / Levin-Potts Hill (central) and Tokomaru-Makerua (northern). Data is tabulated in Appendix C.

Four current rose diagrams are plotted from the tabulated data (Fig. 4.1). They include:

1. combined aeolian;
2. central marine;
3. northern marine;
4. combined marine.

The small number of measurements recorded under fluvial and southern marine precluded the use of current rose diagrams for these groups.

## 4.3 DISCUSSION

The paleowind pattern in the Levin area, as revealed in the Otaki Formation (Fig. 4.1A), indicates a weakly bimodal trend. Winds from the WNW predominated with a secondary maximum coming from the south-west. Present day wind rose diagrams in

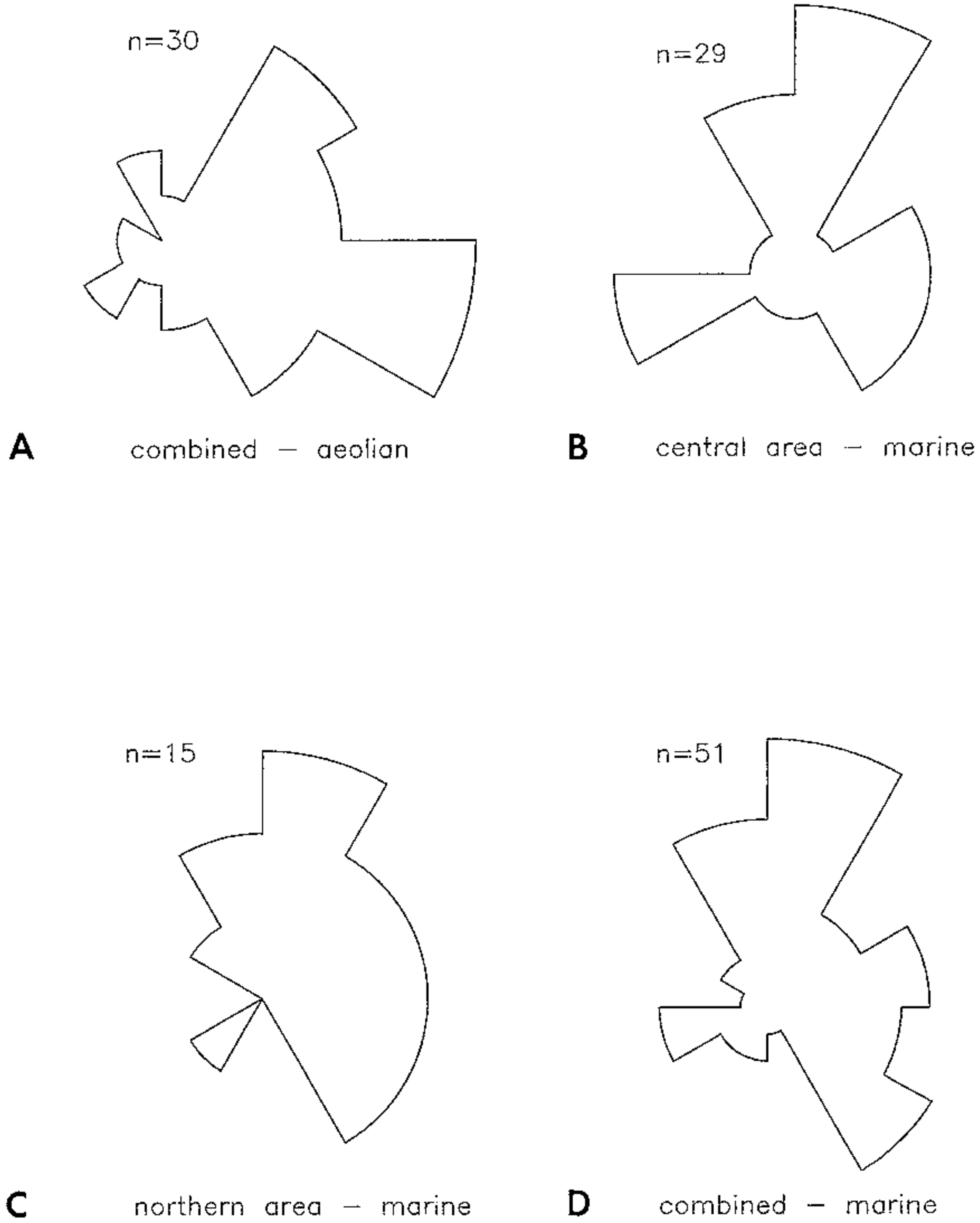



Fig. 4.1 Current rose diagrams of dip azimuths from cross-bedded sandstone in the Otaki Formation.

the Levin area show a very similar pattern (Rich 1959).

The polymodal paleocurrent patterns revealed in the marine facies are typical of coastal marine currents and paleocurrent patterns reported elsewhere (Van der Lingen and Andrews 1968, Pettijohn 1975, Reading 1986, Miall 1990). Trends can be reasonably interpreted in terms of shoreline processes such as tides, waves and longshore currents. Several factors enhance the interpretation.

1. The orientation of the paleoshoreline is known.
2. Paleowind directions are known.
3. Facies analysis shows an overall trend of tide-dominated depositional processes predominating to the north and wave dominated processes predominating to the south.
4.Localised structural trends on the basin margin are known (see Chapter 7).

Two shore-normal, bimodal trends and a shore-parallel, unimodal trend can be recognised in the combined marine data (Fig. 4.1D). The shore-normal trends comprise a dominant north-west - south-east bimodal orientation with a sub-dominant WSW-ENE bimodal orientation. Such a pattern is probably the result of onshore directed wave-generated currents driven by the prevailing WNW and south-west winds. Tidal action related to these currents resulted in their bimodal expression.

Proctor and Carter (1989) comment on the significant present day effect of meteorological forcing of the shelf circulation along the western approaches to Cook Strait. They note that north-westerly winds are likely to enhance the net alongshore drift along the Wanganui coast.

At Forest Lakes and Laws Hill where younger marine terraces occur on the flanks of gentle anticlines, north-west facing strandlines are well preserved whereas strandlines on the south and south-east flanks are difficult to delineate. This probably reflects the direction of prevailing wave power and therefore the dominant direction of wave-induced currents.

The well defined NNE-oriented, shore-parallel trend is seen strongly in both the central and northern areas

(Fig.4.1B,C) and reflects the presence of north to NNE-trending tidal channels north of Shannon. North-east of Levin the present day NNE-trending Koputaroa Stream, shows the same trend. In addition, two fluvial channel paleocurrent readings in the Otaki Formation at Tokomaru show a north-west orientation.

Geophysical data in the Levin area indicate a localised basement trough exists between the foothills and a NNE-trending up-thrown basement block on the western side of Lake Horowhenua. The trough deepens to the NNE beneath the lower Manawatu River flood plain (Bekesi 1988). Other structural evidence (see Chapter 7) indicates that recent down-warp has occurred on the eastern margin of the floodplain south of Tokomaru. It is therefore possible that a structural depression, giving rise to a localised depocentre along the eastern margin of the present Manawatu River flood plain, controlled the direction of tidal currents in the central and northern areas during deposition of the Otaki Formation.

# CHAPTER 5

# GRAIN SIZE PARAMETERS AND MINERALOGY

## 5.1 GRAIN SIZE PARAMETERS

### 5.1.1. Methodology

Sampling was carried out primarily to delineate vertical and lateral variations in grain size characteristics within sandstone of the Otaki Formation. A comparison with Koputaroa dune-sands is also made.

Thirty samples of Otaki Formation and three samples of Koputaroa dune-sands were analysed. Soft sandstone was selectively chosen so that pretreatment disaggregation procedures were unnecessary.[1] Where possible, at outcrops of good vertical exposure, samples were taken at various levels up the sequence. The field occurrence of each sample in relation to its associated sedimentary structures and interpreted environment of deposition is included in Table 5.1.

Samples were disaggregated by hand and oven dried for at least 48hours. Each sample was mechanically sieved for 10 min. through sieves stacked at 1/2 phi intervals (sieves ranging 0.5phi - 4.0phi) on a Rotap mechanical shaker. Each fraction was examined under a binocular microscope and corrections made for aggregate particles. Corrections were made by subtracting the estimated percentage of aggregates in each fraction from the weight of the fraction and the total weight of the subsample (after Lewis 1981). Statistical measures of Folk and Ward (1957) were calculated on computer and are presented in Table 5.2.

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[1] The induration (and weathering) of Otaki Formation sandstone is considerably variable both vertically and laterally throughout the unit and does not appear to be facies controlled. This variation is probably due to localised weathering processes and requires further detailed investigation.

| Sample No. | Location | Facies Interpretation |
|---|---|---|
| *southern area* | | |
| S27A | L27 S25/945398 | Dune l-x |
| S27B | " " | Dune/Backshore |
| S27C | " " | Beach m-x |
| S27D | " " | Beach pll lam |
| *central area* | | |
| C73A | L73 S25/048676 | Beach pll-cr lam |
| C73B | " " | " " |
| C66A | L66 S25/077653 | Beach/Bar m-x |
| C66B | " " | Beach pll-cr lam |
| C66C | " " | Tidal channel m-x |
| C66D | " " | " " |
| C77A | L77 S25/097655 | Beach |
| C77B | " " | Beach pll-cr lam |
| C77C | " " | " " |
| C77D | " " | Beach pll lam, m-x |
| C78A | L78 S25/104654 | Beach cr lam |
| C82A | L82 S25/122653 | Beach mass |
| C82B | " " | Beach m-x |
| C87A | L87 S25/128669 | Beach m-x |
| *northern area* | | |
| N1A | L1 S24/156716 | Beach mass |
| N1B | " " | " " |
| N1C | " " | Tidal channel m-x |
| N118A | L118 S24/187731 | Tidal flat |
| N118B | " " | " " cr lam |
| N129A | L129 S24/182703 | Beach mass |
| N98A | L98 S24/223766 | Sandy Loess? |
| N98B | " " | Tidal flat |
| N103A | L103 S24/222758 | Tidal flat |
| N111A | L111 S24/207736 | Tidal channel m-x |
| N130A | L130 S24/180742 | Beach / channel m-x |
| N100A | L100 S24/219767 | Dune? mass |
| *Koputaroa dune-sands* | | |
| KDS1 | S25/077683 | Dune |
| KDS2 | S25/073642 | " |
| KDS3 | S25/086583 | " |
| *Holocene dune-sands (Shepherd 1987)* | | |
| FDS1 | S24/147814 | Dune |
| FDS2 | S24/164836 | " |
| FDS3 | " | " |

Key
l-x - large-scale cross-bed    m-x - medium-scale cross-bed
pll lam - parallel laminated    mass - massive
cr lam - current ripple laminated

Table 5.1 Location and description of samples selected for grain size analysis.

| Sample No. | Mean (phi) | S.D. (phi) | Skewness | Kurtosis | Mud (%) |
|---|---|---|---|---|---|
| *southern area* | | | | | |
| S27A | 2.70 | 0.37 | -0.02 | 1.37 | 1.84 |
| S27B | 2.65 | 0.37 | -0.06 | 1.26 | 2.06 |
| S27C | 2.23 | 0.72 | +0.16 | 1.44 | 5.41 |
| S27D | 2.50 | 0.52 | 0.00 | 1.23 | 3.67 |
| *central area* | | | | | |
| C73A | 2.47 | 0.42 | +0.12 | 1.02 | 2.35 |
| C73B | 2.43 | 0.45 | +0.25 | 1.21 | 2.95 |
| C66A | 2.69 | 0.45 | +0.04 | 1.00 | 0.65 |
| C66B | 2.43 | 0.43 | +0.06 | 1.01 | 0.48 |
| C66C | 2.11 | 0.57 | -0.03 | 1.00 | 1.46 |
| C66D | 2.16 | 0.49 | -0.03 | 1.06 | 1.49 |
| C77A | 2.54 | 0.43 | +0.04 | 1.05 | 2.39 |
| C77B | 2.54 | 0.48 | +0.04 | 1.18 | 3.60 |
| C77C | 2.55 | 0.51 | +0.13 | 1.30 | 4.46 |
| C77D | 2.39 | 0.53 | +0.10 | 1.19 | 3.20 |
| C78A | 2.44 | 0.44 | +0.16 | 1.14 | 3.20 |
| C82A | 2.50 | 0.69 | -0.02 | 1.75 | 5.31 |
| C82B | 2.82 | 0.48 | +0.17 | 1.48 | 3.60 |
| C87A | 2.66 | 0.53 | +0.12 | 1.27 | 4.05 |
| *northern area* | | | | | |
| N1A | 2.54 | 0.72 | +0.27 | 1.38 | 8.79 |
| N1B | 2.82 | 0.88 | +0.35 | 1.11 | 14.87 |
| N1C | 2.22 | 0.70 | -0.21 | 1.34 | 1.14 |
| N118A | 2.46 | 0.54 | +0.18 | 1.36 | 4.52 |
| N118B | 2.49 | 0.60 | +0.26 | 1.50 | 7.71 |
| N129A | 2.50 | 0.63 | +0.17 | 1.45 | 7.46 |
| N98A | 3.02 | 0.74 | +0.30 | 1.06 | 14.58 |
| N98B | 2.85 | 0.57 | +0.19 | 1.37 | 6.88 |
| N103A | 2.72 | 0.57 | +0.19 | 1.37 | 5.82 |
| N111A | 2.14 | 0.94 | +0.03 | 1.56 | 8.53 |
| N130A | 2.16 | 0.69 | -0.17 | 1.02 | 1.60 |
| N100A | 2.78 | 0.48 | +0.12 | 1.39 | 3.03 |
| *Koputaroa dune-sands* | | | | | |
| KDS1 | 2.64 | 0.39 | -0.02 | 1.16 | 1.85 |
| KDS2 | 2.54 | 0.46 | +0.02 | 1.12 | 2.73 |
| KDS3 | 2.60 | 0.38 | -0.09 | 1.08 | 1.10 |
| *Holocene dune-sands (Shepherd 1987)* | | | | | |
| FDS1 | 2.56 | 0.38 | -0.28 | 0.96 | trace |
| FDS2 | 2.54 | 0.37 | -0.01 | 0.86 | 0.10 |
| FDS3 | 2.49 | 0.37 | -0.08 | 0.85 | trace |

Table 5.2 Grain size statistical parameters.

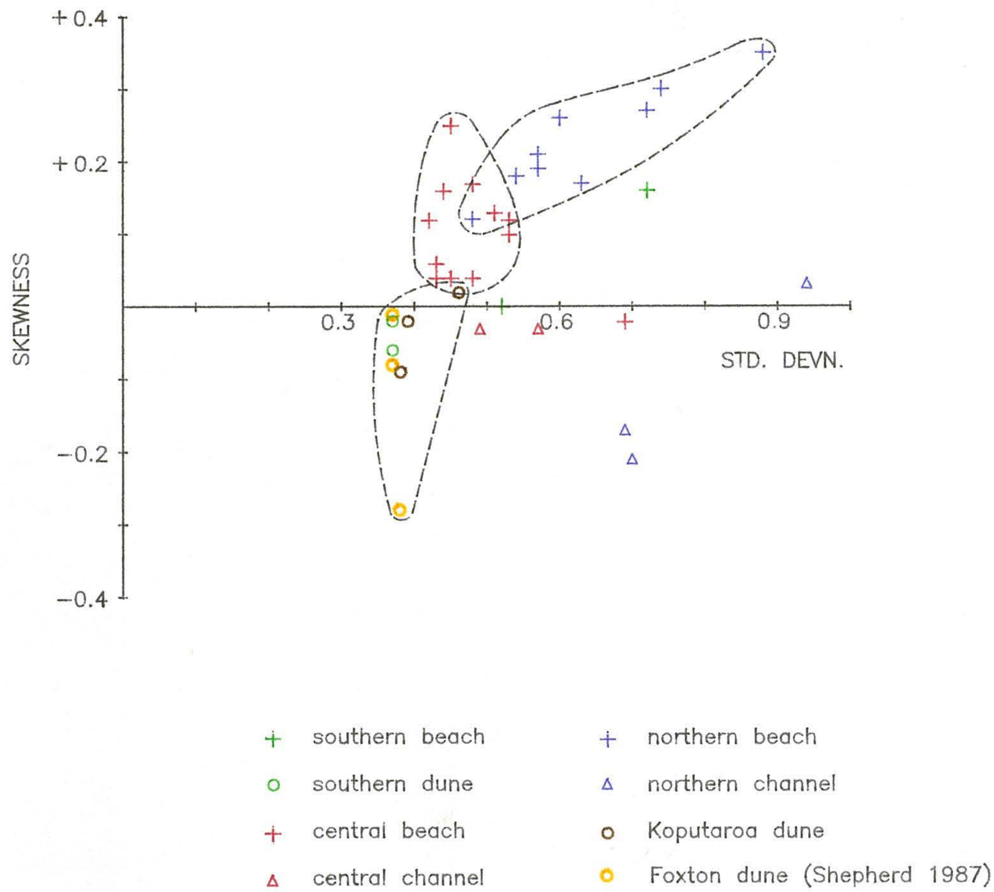
5.1.2 Discussion

Mean grain size varies little throughout the exposed sandstone of the Otaki Formation. All samples fall into the fine sand category (2-3phi) of Folk (1974) with 80% falling in the range 2.4-2.9phi. There is little evidence of a regional vertical trend in mean grain size. Individual exposures may fine slightly upwards (L27), coarsen slightly upwards (L66), reverse trend (L1), or remain the same (L77). It is clear from field evidence that these minor variations are controlled by localised vertical facies changes. For example, dune sands are slightly finer than beach sands which are in turn slightly finer than tidal channel sands.

A plot of skewness versus standard deviation (sorting) and standard deviation versus mean (Fig. 5.1) reveals two areally distinct populations clearly recognisable on the basis of degree of sorting. Beach sands from the central and southern areas are well sorted to moderately well sorted whereas beach sands from the northern area are moderately well sorted to moderately sorted (Folk 1974, verbal classification). Furthermore, northern area beach sands are more positively skewed than those to the south and show an apparent linear increase in skewness with increase in standard deviation. Clearly, the higher mud content of the beach sands to the north compared with beach sands in the central and southern areas, explains these trends (Table 5.2). This in turn reflects field observations, indicating the occurrence of tidal flat sedimentation in the Otaki Formation north of Shannon. Here comparatively lower wave energy conditions allowed deposition of mud along with sand.

Tidal channel sands show a slightly lower mean grain size than beach sands, indicative of a higher energy environment. The slight to moderate negative skewness can be attributed to coarse lag deposits along the base of the channels.

One anomalous beach sand sample from the central area (C82A) shows a symmetrical grain size distribution with poor sorting (high St.Devn.). Inspection of the raw data (see



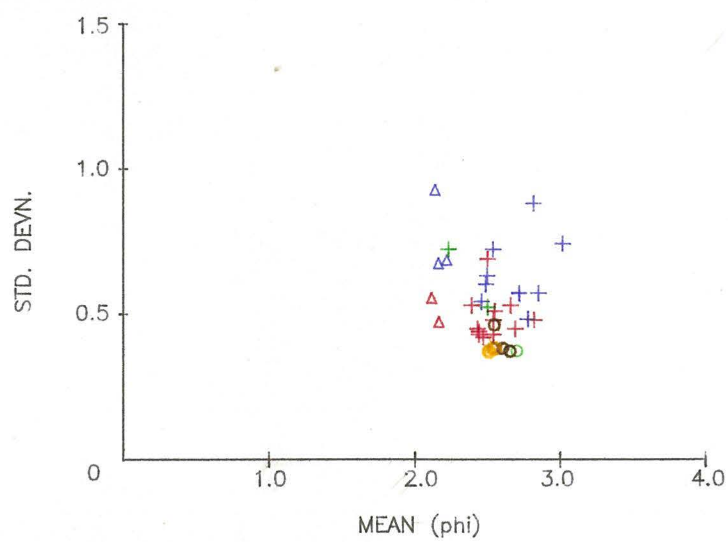




Fig.5.1 Scatter plots of skewness versus standard deviation and standard deviation versus mean. Samples are classified according to their field location and generalised facies interpretation given in Table 5.1. Data from samples of Koputaroa dune sand (Koputaroa dune) and Holocene dune sand (Foxton dune) are also plotted.

Appendix D) reveals a trimodal distribution. One subsidiary mode occurs in the >0.5 phi fraction which contains abundant pumice pebbles. The other subsidiary mode occurs in the mud fraction which probably contains a high proportion of weathered rhyolitic ash.[2] This sample occurs close to the base of the Otaki Formation and probably represents reworked, late Castlecliffian pyroclastic debris. It is the only clearly recognisable occurrence of rhyolitic ash within the Otaki Formation.

A comparison of dune sands from the Otaki Formation (*c*.>100kyr B.P.), Koputaroa Phase (*c*.25kyr-15kyr B.P.) and Foxton Phase (<2.5kyr B.P., Shepherd 1987) of southern Manawatu reveals a similarity in grain size characteristics. Of particular note is a characteristic weak to moderate negative skewness present in all but one of the samples. This is significant since dune sands are generally reported to be positively skewed (Friedman 1961, 1967). However, Andrews and Van der Lingen (1969), in a study of skewness values in beach sands concluded that skewness values commonly reflect grain size characteristics inherited from the source rocks. The same is probably true for dune sands. Hence, the virtually identical grain size distributions of these three generations of dune sand strongly indicates a common source of sediment supply.

## 5.2 MINERALOGY

### 5.2.1 Introduction

A brief mineralogical investigation was carried out in order to identify the main source(s) of the sandstone that comprises the bulk of the Otaki Formation. Six samples of indurated Otaki beach sand were impregnated with epoxy resin and thin sectioned for microscopic analysis. Sample locations and field descriptions are given in Table 5.3.

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[2] A significant amount of volcanic glass was observed in the sand size fractions under the binocular microscope.

| Sample No. | Location | Field Description |
|---|---|---|
| TS6 | L6 S25/938494 | [hd] pll lam beach sand |
| TS52 | L52 S25/990591 | hd pll lam (Fe cemented) beach sand |
| TS62 | L62 S25/069620 | [hd] m-x beach sand |
| TS70 | L70 S25/097643 | hd weakly lam beach sand above greywacke wave cut platform |
| TS77 | L77 S25/097655 | hd silty sand layer in well sorted beach sand |
| TS93 | L93a S25/127683 | [hd] silty beach sand |

Key

hd - hard

[hd] - moderately hard

pll lam - parallel laminated

m-x - medium scale cross-bedded

**Rough Mineral Analyses**
**%**

| | Quartz | Feldspar | Rock Fragments | Heavy Minerals |
|---|---|---|---|---|
| TS6 | 35 | 25 | 20 | 20 |
| TS59 | 45 | 30 | 20 | 5 |
| TS62 | 35 | 29 | 30 | 15 |
| TS70 | 20 | 30 | 40 | 10 |
| TS77 | 30 | 25 | 40 | 5 |
| TS93 | 20 | 30 | 40 | 10 |

Table 5.3 Sample locations, field descriptions and rough mineral analyses of thin sectioned samples of indurated sandstone of the Otaki Formation.

5.2.2 Texture

The sandstone is homogeneous in composition, loosely to moderately packed with a high degree of porosity (c.35% in TS77, estimated visually). No interstitial matrix is apparent. In one sample (TS59) pore spaces are filled with what appears to be an iron-oxide cement. Average grain size is consistently around 0.2mm with sorting ranging from poorly sorted (TS93, TS70) to well sorted (M1,M39,M48). Quartzo-feldspathic grains are generally equant and subangular to subrounded. Occasional twinned and/or oscillatory-zoned plagioclase feldspars show a degree of idiomorphism. Ferromagnesian grains are often elongate and typically rounded to well rounded.

5.2.3 Composition

Quartz - Quartz occurs in monocrystalline grains frequently displaying moderate to strong undulose extinction. Grains are generally subangular although subrounded grains are common. Quartz ranges in abundance from 20-45% of the sandstone composition.

Feldspar - Three types of feldspar grains are distinguished:

1. subrounded, altered, plagioclase with weakly developed (relict) twinning;
2. subangular microcline showing well developed cross-hatched twinning;
3. angular to subangular (subhedral) plagioclase often showing oscillatory zonation and/or well developed lamellar twinning.

Plagioclase of type 3 has a composition ranging from Andesine to Labradorite as determined by the Michel-Levy method. Total feldspar composition comprises roughly 20-30% of the sandstone.

Rock Fragments - Rock fragments make up a large proportion of the detrital composition of the sandstone ranging from 20-40%. They are generally subrounded with occasional large rounded grains. The vast majority are sedimentary rock fragments (SRF's) comprising polycrystalline aggregates of quartz and feldspar and microcrystalline aggregates of quartz.

The latter are probably chert fragments. Highly birefringent, very fine grained aggregates are probably argillite fragments, however, some of these could represent completely altered feldspar grains. Rare volcanic rock fragments (VRF's) comprising aggregates of zoned plagioclase also occur (TS93).

Heavy Minerals - A characteristic feature of the Otaki Formation is the abundance of heavy minerals. In the 6 samples examined heavy minerals make up between 5 and 20% of the detrital grain composition comprising predominantly clinopyroxene and green/brown hornblende. Clinopyroxene is generally more abundant than hornblende. Both occur as subrounded to rounded grains occasionally existing as slightly abraded euhedral grains. Mica is rare, occurring in TS93. Two well rounded grains of probable detrital glauconite were also recognised in TS93.

### 5.2.4 Discussion

A cursory look at the mineralogy of sandstone from the Otaki Formation enables two sources of sediment to be clearly identified. The predominance of sedimentary rock fragments of polycrystalline quartz, chert and argillite, coupled with the relative abundance of rounded, and often altered, feldspar indicates the major source of sediment was greywacke of the North Island axial ranges. Abundant sedimentary rock fragments in a sandstone indicates brief transport from source (Folk 1974). Similarly, the presence of abundant recycled sedimentary feldspar grains suggests a rapidly uplifted and eroded source area since feldspar is comparatively easily decomposed (Folk 1974).

The secondary source is clearly of andesitic volcanic origin indicated by the common occurrence of subhedral, zoned, calcic plagioclase and abraded euhedral grains of pyroxene and hornblende. Clearly, volcaniclastic sediment is derived from the Taranaki area and the central volcanic region and has been delivered to the coast either by rivers or directly as a result of volcanic eruptions. Once at the coast it was transported south by longshore currents.

Oliver (1948), in comparing sands of the Otaki Formation with sands of the present day coast, observed a greater degree of grain roundness in the Otaki Formation. He considered that the greater degree of grain roundness was indicative of an additional major sedimentary source of sediment for the Otaki Formation, a source he maintained, which is much less conspicuous in present day coastal sand. Oliver considered these more rounded grains were derived from Tertiary sediments from the Wanganui-Rangitikei area. He reasoned that due to the fact that the coastal plain was much narrower than present during deposition of the Otaki Formation with most streams and rivers supplying gravel to the coast, the ratio of greywacke derived sand to that derived from the Tertiary sediments to the north would have been much lower. Undoubtedly, Tertiary sediments would have contributed to the Otaki Formation in part, however, the abundance of lithic fragments and recycled feldspar grains of greywacke origin noted in this study do not support Oliver's contention that Tertiary sediments were a *major* contributing source.

An additional minor source of sediment from rocks of the South Island is also possible, and alluded to by the following lines of evidence:

1. the relative abundance of unweathered microcline in thin sections;
2. the abundance of mica in the finer grained sandstones in the north of the study area which may originally have been derived from South Island granites or schists;
3. the presence of two types of garnet in a heavy mineral analysis carried out by Oliver (1948);
4. the presence of pebbles of distinctive igneous, metamorphic and sedimentary rocks typical of D'Urville Island and western Marlborough Sounds in post-Castlecliffian conglomerates of northern Manawatu (Te Punga 1953);
5. sedimentation, transport and tidal circulation patterns in northern Cook Strait and their inferred responses due to the

late Quaternary closure of Cook Strait (Lewis and Eade 1974, Heath 1976, Proctor and Carter 1989).

Detailed mineralogical investigation of late Quaternary and present day coastal sands in south-west North Island is required before a fuller understanding of sediment provenance can be achieved.

# CHAPTER 6

# PALEONTOLOGY AND PALYNOLOGY

## 6.1 PALEONTOLOGY

In spite of the range of shallow marine sub-environments identified within the Otaki Formation, no marine fossils were found. Moreover, periodic testing of strata in the field using HCl failed to locate any trace of calcium carbonate. Several microfaunal preparations of grey-green to blue-grey silt were also analysed, however, no foraminifera were found.

Earlier workers have commented on the dearth of marine fossils occurring in the Otaki Formation (Oliver 1948, Rich 1959). However, north and south of the field area Rich (1959) and Te Punga (1962) reported the occurrence of siliceous sponge spicules in strata of lateral equivalence to the Otaki Formation.

It is generally held that weathering and leaching above the water table, resulting in the removal of calcium carbonate in solution, is responsible for the apparent absence of calcareous marine fossils in outcrops of the Otaki Formation (Oliver 1948, Te Punga 1957b,1962). Near Palmerston North, Te Punga (1957b) noted iron-oxide casts and moulds of Austrovenus stutchburyi and Paphies australe in strata of Late Pleistocene age. The calcareous remains had been completely destroyed by decalcification.

In borelogs of wells drilled directly into the marine terraces within the study area, no mention is made of any marine fossil occurrence. However, in two wells drilled through river terraces in the Ohau-Manakau area, shells have been noted at depth. At S25/997574 shells of the bivalve Austrovenus stutchburyi were identified occurring 68m below ground level (41m below sea level) and dated at >36.7kyr B.P. (L.J. Brown, pers. com.).[1] Correlation of this sample with the Otaki Formation seems unlikely since less than 2km to the north-west

[1] The driller's log of this well was not located.

at S25/005589 (BL 30) the base of the Otaki Formation has been determined at around present mean sea level. At S25/980302 (BL 15) shells are reported as occurring 40m below ground level (6m a.s.l.) within gravelly sand. This strata is correlated with the Otaki Formation (see 3.3.2B). However, no information regarding the classification or age of these shells is available.

In several bore holes north of the study area marine fossils from strata of probable equivalent age to the Otaki Formation have been collected and analysed by others.[2] At T24/315888, corroded fragments of Austrovenus stutchburyi were identified from strata 15m below m.s.l. (T24/f23). The same species was identified c.2.5m above m.s.l. at T24/327893, along with fragments of the gastropod Zeacumantus lutulentus (T24/f22). At S24/267583 a large number of species were identified from a shellbed occurring 66m below sea level (S24/f24). They include the following species:

Bivalvia: Tiostrea chilensis lutaria
Xenostrobus sp.
Austrovenus stutchburyi
Bassina yatei *
Macomona liliana
Veneridae sp.

Gastropoda: Notoacmaea helmsi
Zethalia zelandica *
Cominella glandiformis
Xymene plebeius plebeius
Duplicaria tristis *

Echinoidea: Fellaster zelandiae *

A.G. Beu (pers.com. 1984) noted that samples T24/f22 and T24/f23 contained predominantly estuarine dwelling species, indicating an environment where salinity is significantly

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[2] Samples containing fossil fragments were collected by students and staff of the Department of Soil Science, Massey University and forwarded to DSIR Geology and Geophysics where they were formally recorded and analysed by A.G. Beu and D.C. Mildenhall in 1984. Results of their analyses were sent to Dr V.E. Neall, Massey University, in several personal communications during 1984. These results have been kindly made available to the writer.

lowered relative to ocean water. In contrast, S24/f24 contained a mixed assemblage of fossils indicating both an estuarine and an open sandy beach environment (species indicating an open beach environment are marked *). This could represent a more distal estuarine environment where open beach processes operated within or adjacent to an estuary. An "attempted" U/Th date was carried out on a shell sample from S24/f24 which yielded an age of 67kyr B.P.(V.E. Neall, pers. com.). However, it was thought that due to a number of factors relating to the dating method and the youthfulness of the sample this age is likely to be a minimum age (V.E. Neall, pers com.).

Tentative correlation of these fossiliferous strata with the Otaki Formation to the south seems reasonable. The increasing depth of the fossil occurrences away from the ranges reflects the overall structural trend of the lower Manawatu Valley as seen in the study area to the south (see Chapter 7). A deep embayment related to a late Quaternary estuary of the Manawatu River in the vicinity of Palmerston North seems likely from the above fossil evidence, and has been postulated previously (Rich 1959).

A recent analogue in the area has been well documented by Hesp and Shepherd (1978) and Shepherd (1987). Shepherd (1987) found estuarine fossils (Austrovenus stutchburyi radiocarbon dated at 7110yr B.P.) below recent alluvium near Opiki, proving that the lower Manawatu River floodplain comprised a large estuary extending inland to at least as far as Opiki during the maximum Holocene sea level rise.

## 6.2 PALYNOLOGY

At one locality in the study area a zone of carbonaceous mud with leaf impressions and peaty lenses crops out in the Otaki Formation (L98 at S24/223766; see 3.3.5A for detailed section description). Two samples (S24/f44; S24/f45) were collected for pollen analysis in order to ascertain paleoclimatic conditions at the time of Otaki Formation deposition. Analysis was kindly carried out by D.C. Mildenhall (DSIR Geology and Geophysics) whose complete report is included in Appendix E.

Pollen analysis of both samples indicates an acid flax swamp environment which became progressively influenced by an encroaching forest. The presence in S24/f45 of the root parasite Dactylanthus taylori, which at present only occurs as far south as Kaitoke in the North Island, is inferred to indicate climate was at least as warm as the present day. Mildenhall also noted that the presence of the spore Polypodiisporites radiatus in both samples indicates the sample could be as old as Castlecliffian. Polypodiisporites radiatus is an extinct spore which ranges from the late Oligocene to middle Pleistocene (Pocknall and Mildenhall 1984). Field evidence does not support a Castlecliffian age for the samples since they occur above the inferred Tokomaru wave cut platform which was probably cut *c.*120kyr B.P. Thus, the presence of Polypodiisporites radiatus in these samples provides new evidence that the species did not become extinct until post-Castlecliffian times. Alternatively, these spores have been recycled from older Pleistocene or Tertiary deposits. D.C. Mildenhall (pers com) rejects a recycled origin on the basis of the preservation condition of the spores.

Pollen analyses were also carried out on T24/f22,f23 (see above) by Mildenhall (pers.com. 1984). In summarising the assemblage represented in these two samples, Mildenhall notes;

> "The assemblage is clearly Quaternary and interglacial, probably younger than Castlecliffian.....This type of pollen rain can only come from a temperate coastal broad-leaf / podocarp forest. Conditions were wet, humid, and probably slightly warmer than the present day".

Pollen analysis thus clearly confirms a warm interglacial climate prevailed during cutting of the TMT and deposition of the Otaki Formation.

# CHAPTER 7

# STRUCTURE

## 7.1 INTRODUCTION

The regional fault pattern of the South Wanganui Basin is briefly described in Chapter 1 and is interpreted by Anderton (1981) as

> "a divergent wrench system where the fault zones at the western and south-eastern margins of the Basin represent the primary wrench faults".

Dextral strike slip is observed on the presently active wrench faults (Wellington, Ruahine, West Wairarapa Faults) in the axial ranges to the east (Kingma 1967, Lensen 1977). Anderton (1981) also describes the en echelon fault patterns of the three major fault trends in the Manawatu and Rangitikei areas (Turakina, Rangitikei and Rauoterangi Zones) as indicative of wrench deformation (Fig. 7.1).

Deep basement block faults related to this regional pattern have produced a series of horsts and grabens in the Manawatu and Rangitikei areas. Bounded by near vertical normal and reverse faults with characteristic rapid lateral changes in throw, these blocks have resulted in warping of the overlying Late Tertiary and Quaternary strata (Anderton 1981). Horsts have resulted in gentle doming of the overlying strata producing a series of growing anticlines (Mount Stewart, Marton and Levin Anticlines of Te Punga 1957a). Half-grabens have resulted in synclines which form localised depocentres and control the courses of the major rivers. The Kairanga Trough exemplifies the latter. Anderton (1981) contends that most of the fault growth of this area occurred during mid-late Pleistocene time and thereby would have exerted control over sedimentation patterns during deposition of the Otaki Formation.

The main structural features in the Manawatu district west of the axial ranges are illustrated in Fig. 7.2,

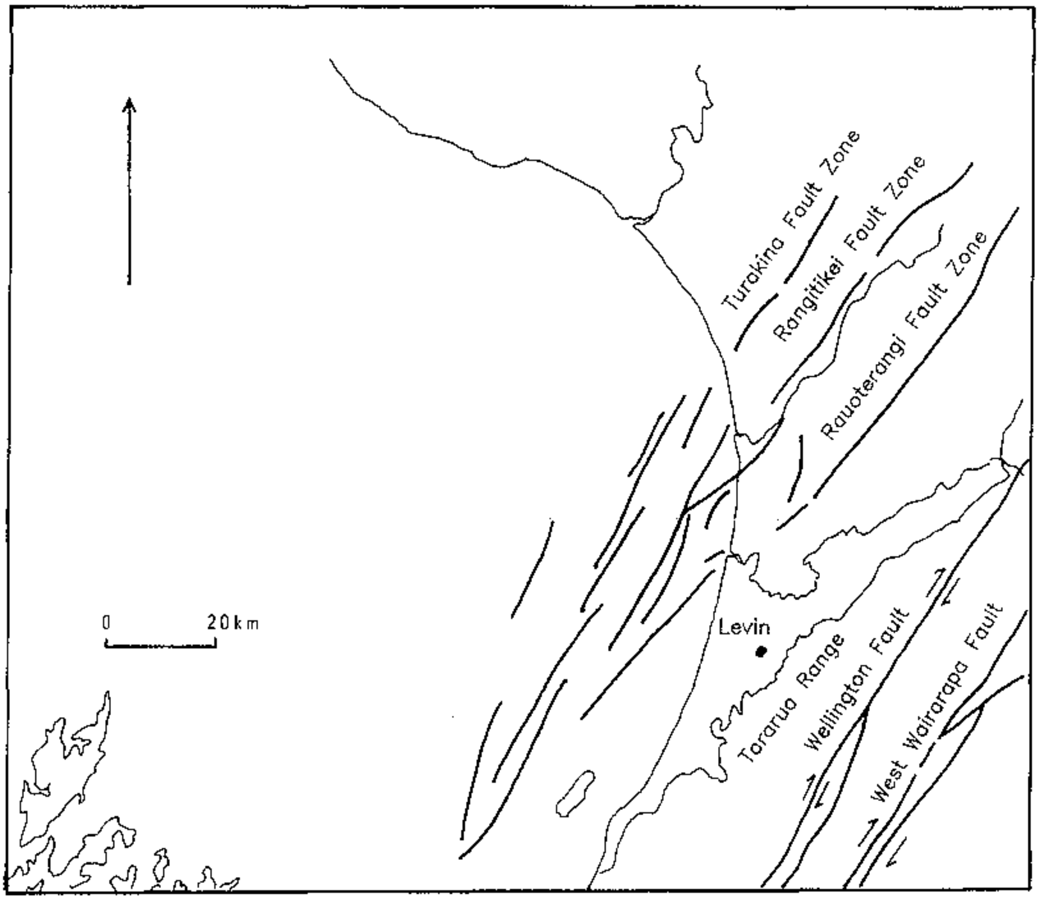


Fig. 7.1

Major fault trends along the south-east margin of the South Wanganui Basin (after Anderton 1981).

demonstrating the nature and extent of late Quaternary tectonic warping. Many of the features have been described by others and are cited in the text. However, additional information concerning some previously recognised structures, and new information on previously unrecognised structural elements in the area is discussed below.

## 7.2 FOREST LAKES

Barnett (1984) mapped a north-east-trending fault adjacent to Ringawhati Road that vertically offsets the Martonan terrace by 3-7m, up-thrown to the west. He noted the southern extension of this fault at Blackburn Road (Blackburn Road Fault), 5km south of Otaki River, where Otaki dune sand is offset along a linear trace observed from air photographs. Extending the fault trace to the north-east, it follows a linear depression which separates a line of uplifted basement blocks to the west from the main Tararua Range to the east (Map 1, Fig. 7.2). If this represents the same fault observed at Blackburn Road then active movement clearly post-dates the accumulation of Otaki dune sand.

A topographic high noted around Atkins Road marks a low, broad, anticline, here named the Pukehou Anticline, which has a NNW-trending axis separating the Manakau Stream catchment to the north and the Waitohu Stream catchment to the south. Bore log data across the arch confirm differential uplift of the Tokomaru wave cut platform along its crest (Fig. 3.3). The riser of the TMT in this vicinity comprises a well defined marine cliff which has been partially subdued by a mantle of Otaki dune sand. Differential uplift of the area was probably occurring at the time the cliff was cut and has since continued at a slow but steady rate.

Assuming the cliff was cut *c*.120kyr B.P. and that sea level at that time was 5-8m above present mean sea level (Chappell and Veeh 1978), an uplift rate of *c*.0.3m/kyr is calculated for the TMT near the axis of the Pukehou Anticline

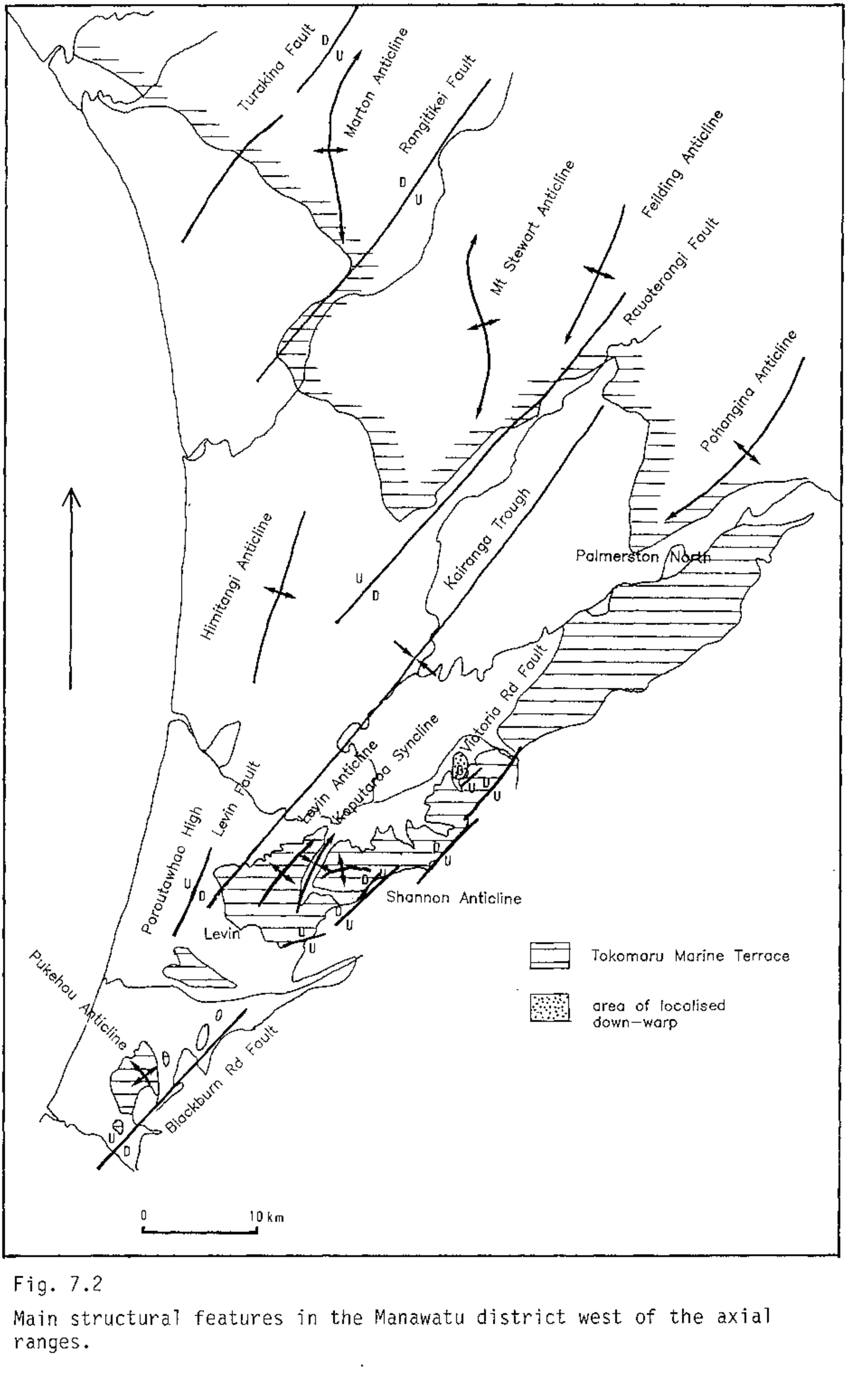


Fig. 7.2

Main structural features in the Manawatu district west of the axial ranges.

in the vicinity of Atkins Road. This uplift rate is based on borelog data (BL10) and type section exposure (L27 at S25/945498) which indicates the top of the Otaki beach sand around Atkins Road is *c*.40m a.s.l.

## 7.3 OHAU

The basement structure around Levin has been elucidated by Bekesi (1989) who delineated basement dipping steeply west of the Tararua Range to a depth of *c*.1km below sea level in the vicinity of Lake Horowhenua. On the western side of the Lake a north-east-trending, high angle, reverse fault (Levin Fault) was delineated with basement west of the fault up-thrown approximately 1km, giving rise to the Poroutawhao High. Unweathered greywacke has been found up to 5m a.s.l. in bore holes west of Lake Horowhenua (Bekesi 1989). The intervening basement trough deepens along a north-east-trending axis from Lake Papaitonga, extending beneath the lower Manawatu River flood plain.

Although the age of the Levin Fault is not known, sedimentological evidence suggests the Poroutawhao High was in existence during deposition of the Otaki Formation. This is consistent with Anderton's (1981) contention that most of the major fault growth in the area took place in the middle-late Pleistocene.

A possible northern extension of the Poroutawhao High extends for approximately 21km north of Foxton. Termed the Himitangi Anticline (Rich 1959), its presence is also indicated by gravity data (Hunt 1981). Hesp and Shepherd (1978) argued that during the Holocene transgression both the Poroutawhao High and Himitangi Anticline formed barriers to the sea, east of which estuarine sediments accumulated. Thus, it is possible that, as is likely with the Poroutawhao High, the Himitangi Anticline also formed a topographic high during the Last Interglacial transgression.

On the eastern margin of the TMT at Ohau, a minimum uplift rate of 0.44m/kyr is calculated whereas on the western edge of the TMT, 5.25km to the west, the minimum uplift rate is 0.17m/kyr. As at Forest Lakes these values are based on the present height of the top of marine strata of the Otaki Formation.

7.4 LEVIN - POTTS HILL

North of Levin the topographically well defined Levin Anticline (Te Punga 1957a) is superimposed on the eastern flank of the deep north-east-trending basement trough delineated by Bekesi (1989). The Levin Anticline itself trends north-eastward, plunging beneath the Manawatu River flood plain 5km west of Shannon. A small syncline (Koputaroa Syncline, Rich 1959) occupied by the Koputaroa Stream, which flows north-eastward into the Manawatu River, parallels the Levin Anticline to the east. Although Bekesi's gravity survey did not indicate a basement high beneath the Levin Anticline, it could be present. Hunt (1980) noted that known basement uplifts beneath the Mount Stewart and Marton anticlines have no gravitational expression,

> "presumably because they are too deep or too small to provide a gravity signature on the scale of the residual anomaly map".

Abundant bore log data enable structural contours of the Tokomaru wave cut platform to be drawn across the Levin Anticline (Fig. 7.3). These reflect topographic contours across the anticline (Fig. 7.4) thus proving that surface contours of the TMT reflect subsurface structure. Around the crest of the Anticline at *c*.55m a.s.l., the Otaki Formation thins to 11m.

North of Potts Hill the TMT is arched about an ENE-trending axis forming the Shannon Anticline (Hesp and Shepherd 1978), (Fig. 7.4) rising to a crest at Laws Hill *c*.120m a.s.l. The crest of the Anticline abuts a steep greywacke escarpment which is in localised fault contact with the TMT. Close to the fault the TMT has been tilted westward (see Fig. 2.4). The flanks of the Shannon Anticline have been deeply dissected and

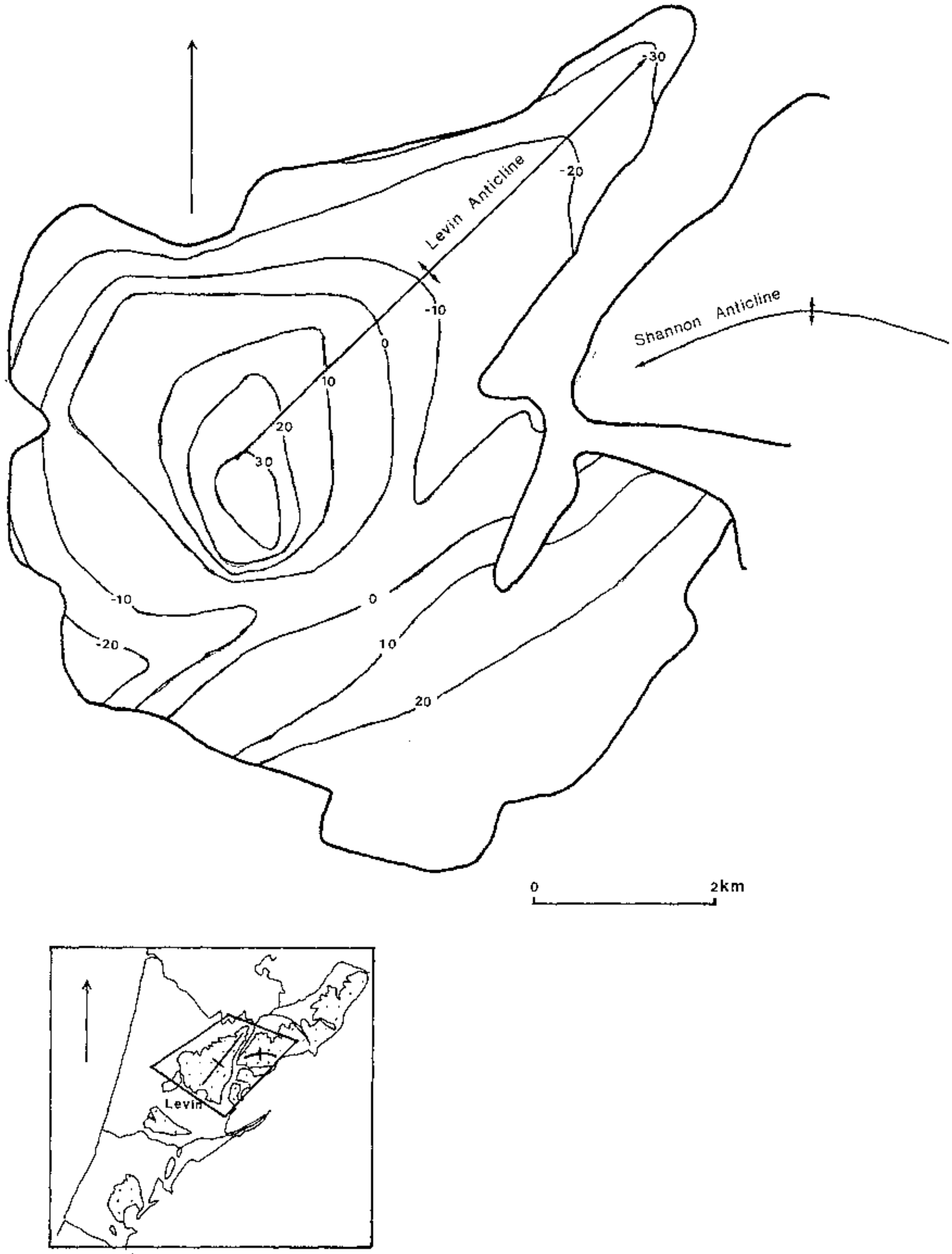


Fig. 7.3

Structural contour map of the Tokomaru wave cut platform across the Levin Anticline. Contours in metres above mean sea level.

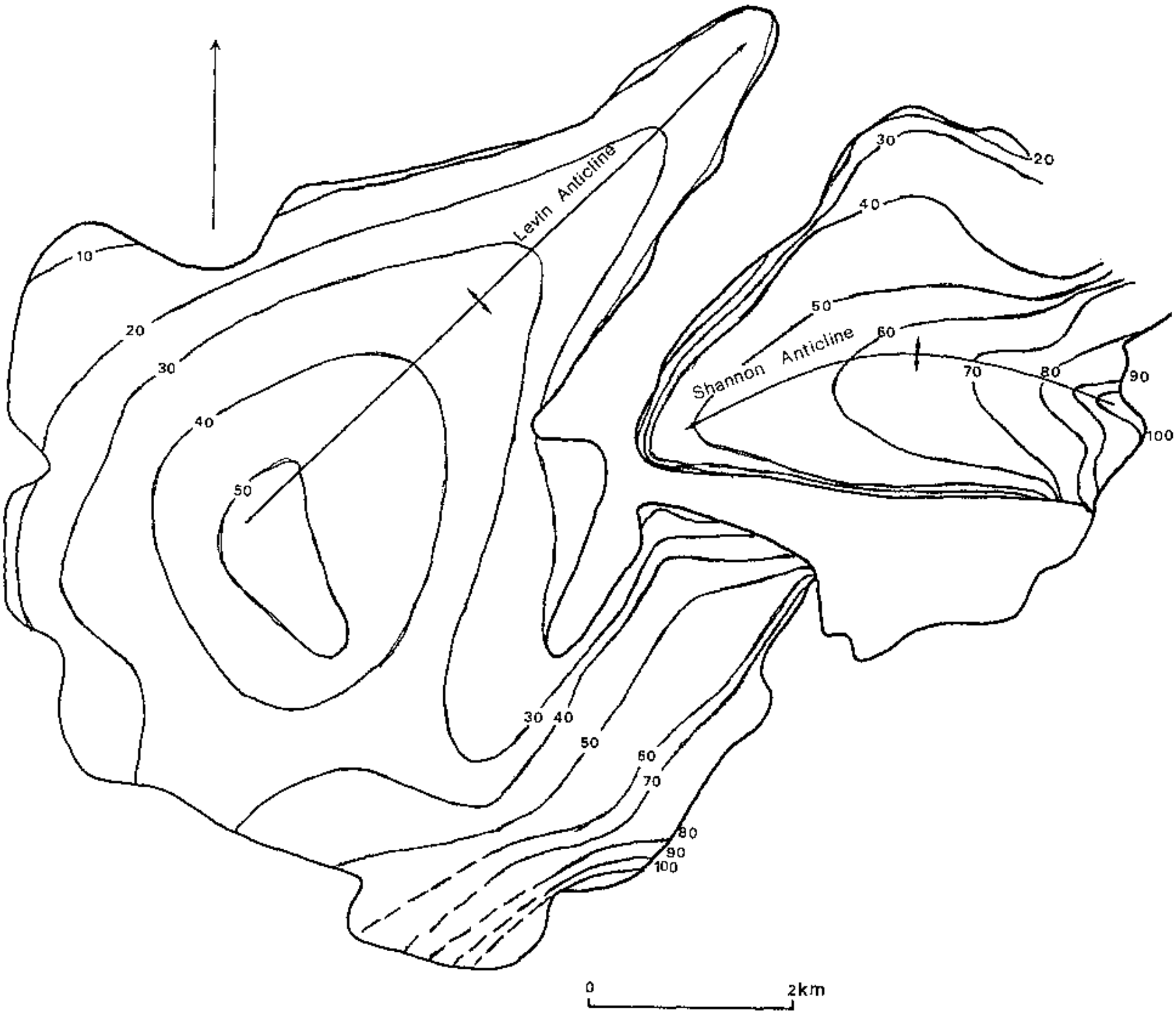



Fig. 7.4

Topographic contour map across the Levin and Shannon anticlines. Contours in metres above mean sea level.

a well defined lower marine terrace is cut on its northern side. Approximately 1km north-west of the crest of the Shannon Anticline a measured section in the lower marine terrace reveals a thickness of more than 26m of Otaki Formation (L85 at S25/119675). Approximately 0.5km north of the anticlinal crest a minimum uplift rate of 0.55m/kyr is calculated for the TMT. This contrasts with a minimum uplift rate of 0.35m/kyr at the crest of the Levin Anticline[1].

With virtually double the amount of uplift on the Shannon Anticline compared with the Levin Anticline one might expect the former to show greater thinning of the Otaki Formation, whereas the reverse is the case. The marked thinning of the Otaki Formation around the crest of the Levin Anticline may reflect syndepositional growth of the Anticline, thus producing a localised high where the sedimentation rate was low. Either a progressively decreasing uplift rate or a period of tectonic quiescence, followed by more recent uplift would account for the relatively low relief and "consequent" drainage pattern now exhibited along the flanks of the Anticline. Such complexities are consistent with the regional tectonic environment. Movements along individual faults in oblique strike slip tectonic settings are often local and spasmodic (Miall 1990). Rich (1959) noted the possibility of rejuvenation of movement along ancient faults affecting late Quaternary strata east of Palmerston North. A simplified cross section (Fig. 7.5) across the Shannon Anticline, Levin Anticline and Poroutawhao High illustrates the inferred structural complexity of the area.

East of Potts Hill aerial photographs reveal a distinct north-east-trending fault trace which is visible for at least 4km along the western edge of the foothills (Map 3). Strata generally appear down-thrown to the west, however, in places, little vertical displacement is obvious. Here, the fault trace occupies a depression between two surfaces of similar altitude.

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[1] This is assuming that the marine terrace surface at the crest of the Levin Anticline corresponds to the TMT and not a younger marine terrace.

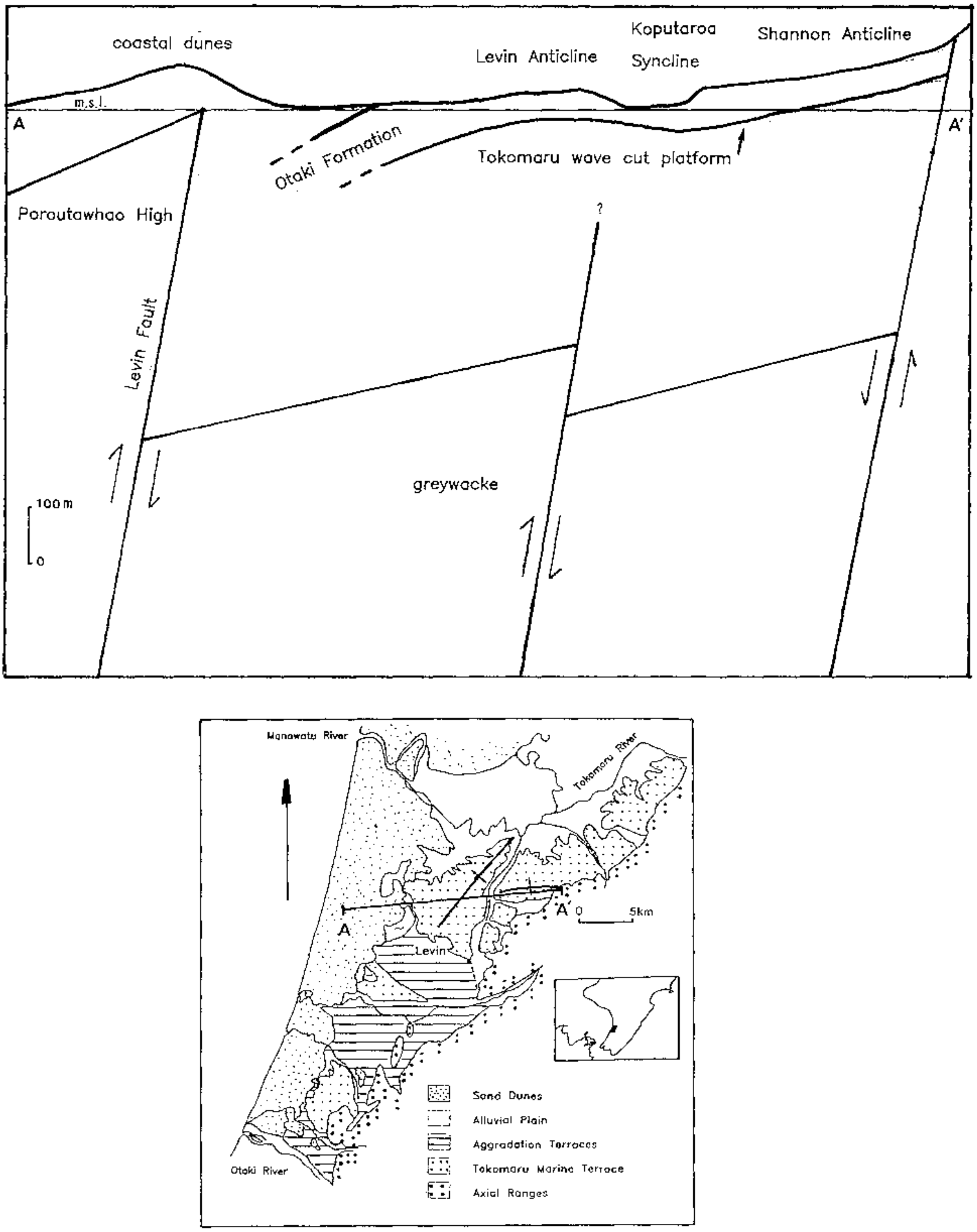



Fig. 7.5

Simplified cross-section across the Shannon Anticline, Levin Anticline and Poroutawhao High.

No obvious lateral displacement can be depicted along the fault.

Four kilometres south of Potts Hill along the inner edge of the TMT, a north-east-trending basement fault, down-thrown to the north-west, has locally displaced marine strata of the Otaki Formation by *c*.30m. Here, Otaki beach sand was encountered in a slip (L58 at S25/080621) at *c*.110m a.s.l.

## 7.5 TOKOMARU - MAKERUA

Geomorphic and stratigraphic evidence points to the existence of an active fault separating the TMT from the Tararua foothills between the Mangaore Stream and Tokomaru River. The fault was active during deposition of the Otaki Formation and is presently active (see 3.3.5C).

At two localities small faults were observed in outcrops of the Otaki Formation. At S24\192722 a swarm of faultlets showing diverse style and orientation has vertically displaced blocks of moderately hard sandstone by 1-20cm (Fig. 7.6A).

Along Victoria Road (S24\208745), a normal fault, trending north-east and down-thrown to the north-west, has displaced soft sandstone by 20cm (Fig. 7.6B). The fault plane dips 75deg. at 310 and is visible for 4m from the base of the outcrop to the top of the Otaki Formation. Ohakean loess directly overlies the Otaki Formation truncating the fault trace, and thus indicating little or no movement has occurred along the fault since the beginning of Ohakean loess accumulation *c*.25kyr B.P. Well developed purple weathering bands in the sandstone, displaced 20cm, suggest the fault was first active a considerable time after deposition of the sandstone (*c*.<100kyr B.P.).

At three localities in the vicinity of the Victoria Road fault, the normally horizontal strata of the Otaki Formation exhibit dips of 8 and 9 degrees to the north-west (Map 4). Approximately 3km to the north at S24\219765, a 5m sequence of loess coverbeds in PTMT1 dips 10 degrees WSW. The intersection

A

B

Fig. 7.6

Small scale faulting in the Otaki Formation south of Tokomaru. Note the displacement of purple weathering bands at the top of the spade handle in photograph B.

of the two dip directions corresponds to a localised topographic low along the eastern margin of the regional topographic low, comprising the lower Manawatu River floodplain (Fig. 7.2). Around this area the outer edge of the PTMT1 merges subtly into the floodplain. It appears the marine terraces have been locally down-warped in this vicinity. Tectonic down-warping in the lower Manawatu Valley has been previously suggested by Gibb (1983), who cites evidence from dated Holocene marine fossils (Austrovenus stutchburyi) found *c*. 5.6m below mean sea level in a bore hole at S24\147802.

East of the Rauoterangi Fault, Anderton (1981) recognised a major fault angle depression in the Manawatu area. It may extend northwards to dominate the area to the west of the Ruahine Range. A basement low at the centre of this graben-like structure lies about 10km north-west of Palmerston North and forms the locus of a strong, local, negative gravity anomaly (Rich 1959). Presently occupied by the Oroua Valley and lower Manawatu River floodplain, the trough (Kairanga Trough of Rich 1959) has acted as a major depocentre in mid to late Quaternary time being filled with more than 1km of post-Nukumaruan sediment (Anderton 1981).

The small scale faulting at Victoria Road is likely to be a consequence of recent down-folding of the Quaternary cover strata, in response to basement block faulting on the eastern margin of the Kairanga Trough. Yeats (1984) cites numerous examples of small-scale, "bending-moment" faults which occur on the hinges of folded strata. Of particular significance are examples from strata of the same age as the TMT near Cape Kidnappers, Hawke's Bay. Here a *c*.120kyr B.P. marine terrace, warped across the active Kidnappers Anticline, exhibits displacement along normal faults parallel to the anticlinal axis. Similar mechanisms are envisaged to have produced the Victoria Road fault.

The straight PTMT1 strandline north of Shannon compared with at Laws Hill and Forest Lakes also suggests either relative tectonic down-warping or relative tectonic quiescence along the eastern margin of the lower Manawatu River flood plain. If, as could be inferred from geomorphic evidence (see 2.2), the PTMT1 transgression was of relatively short duration, localised subsidence along the Kairanga Trough would have allowed the strandline to have remained active for a longer period. Hence, a straighter coastline would result.

7.6 SUMMARY

Structural evidence indicates that the late Quaternary sedimentation patterns in the southern Manawatu area have been controlled by three major structural features. These are:

1. the pre-Quaternary uplifted basement block of the Tararua and Ruahine ranges which forms the eastern margin of the basin and in places is in clear fault contact with the Otaki Formation;
2. a line of basement highs to the west associated with mid to late Quaternary uplift along the Rauoterangi Fault zone;
3. an elongate basement trough between the uplifted blocks which developed in response to localised tensional stresses.

Since deposition of the Otaki Formation, continual and/or spasmodic movement along numerous basement faults, typical of an oblique, strike-slip tectonic regime, has progressively warped the marine terraces. Superimposed upon this is continued regional uplift of the Tararua Range resulting in progressively higher rates of marine terrace uplift closer to the Range.

# CHAPTER 8

## PALEOENVIRONMENTAL SYNTHESIS AND GEOLOGICAL HISTORY OF THE OTAKI FORMATION

A series of diagrams (Fig. 8.1) is used to portray the inferred paleoenvironmental changes that accompanied deposition of the Otaki Formation in the Levin area.

Borelog data indicate a coastal plain of relatively low relief existed over much of the southern Manawatu area immediately prior to the culmination of the Last Interglacial marine transgression (Fig. 8.1A). This is evident from the lateral extent and thickness of the Pukehou formation, comprising silts and sands with abundant carbonaceous debris underlying the Otaki Formation. The Pukehou Formation thickens to the north-east with a marked increase in thickness occurring north-east of Lake Papaitonga. This reflects the north-east-trending basement trough (Kairanga Trough) which extends from around Lake Papaitonga (basement depth c.700m below sea level, Bekesi 1989) to north-east of Fielding (Rich 1959, Anderton 1981). The maximum depth to basement in the Trough is >2km below sea level, occurring along its central axis south of Feilding (Anderton 1981). Clearly, the Kairanga Trough acted as a major fluvial depocentre prior to the deposition of the Otaki Formation. Between Shannon and Tokomaru, the eastern margin of the Kairanga Trough was fault bounded against the ranges with a series of alluvial fans spilling out onto the plain.

At the same time a series of topographic highs associated with basement uplift along the Rauoterangi Fault zone existed on the western margin of the Trough (Anderton 1981). In the case of the Poroutawhao High, basement was exposed at the surface. However, in the Mount Stewart and Himitangi areas earlier Pleistocene strata were probably exposed. These structures would have exerted considerable control over the regional drainage pattern as is the case in the present day.

South of Levin the low lying coastal plain sloped gently

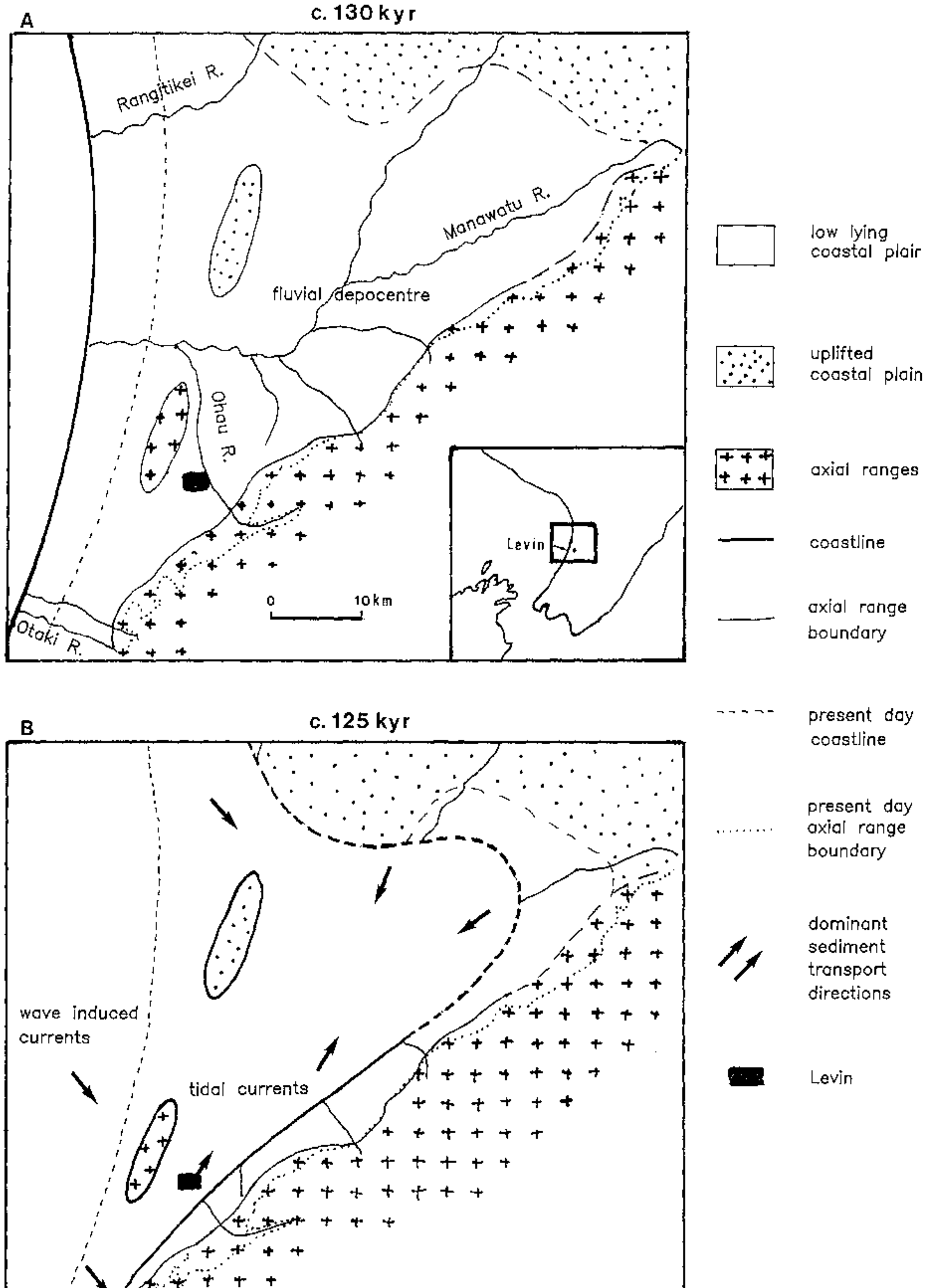
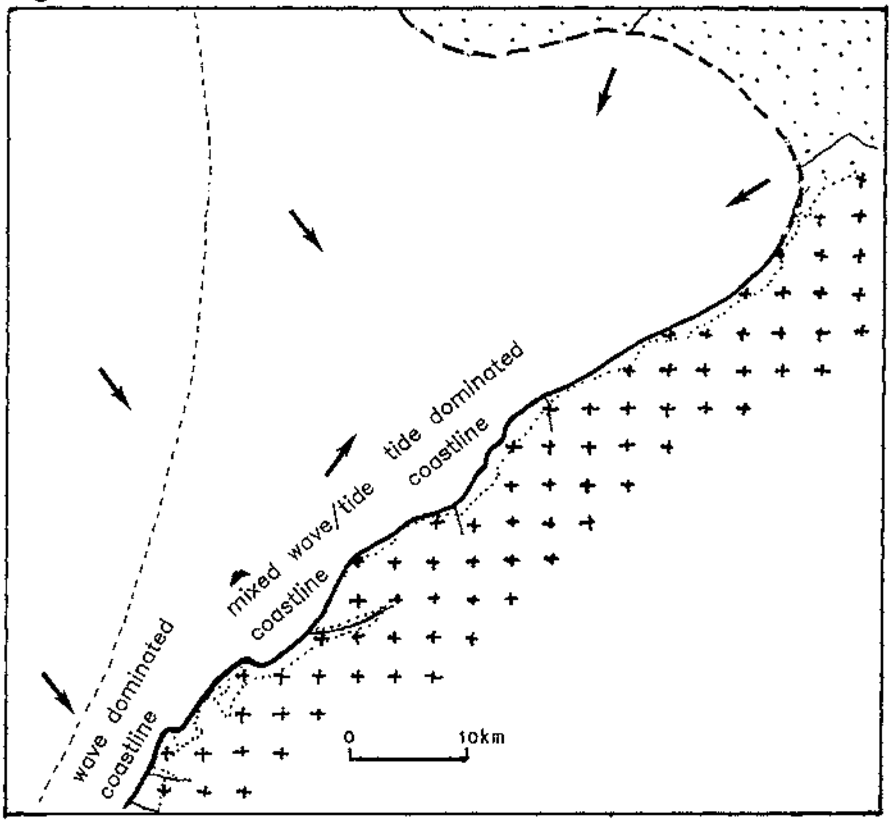



Fig. 8.1 Sequence of diagrams illustrating the inferred paleoenvironmental changes that accompanied deposition of the Otaki Formation.

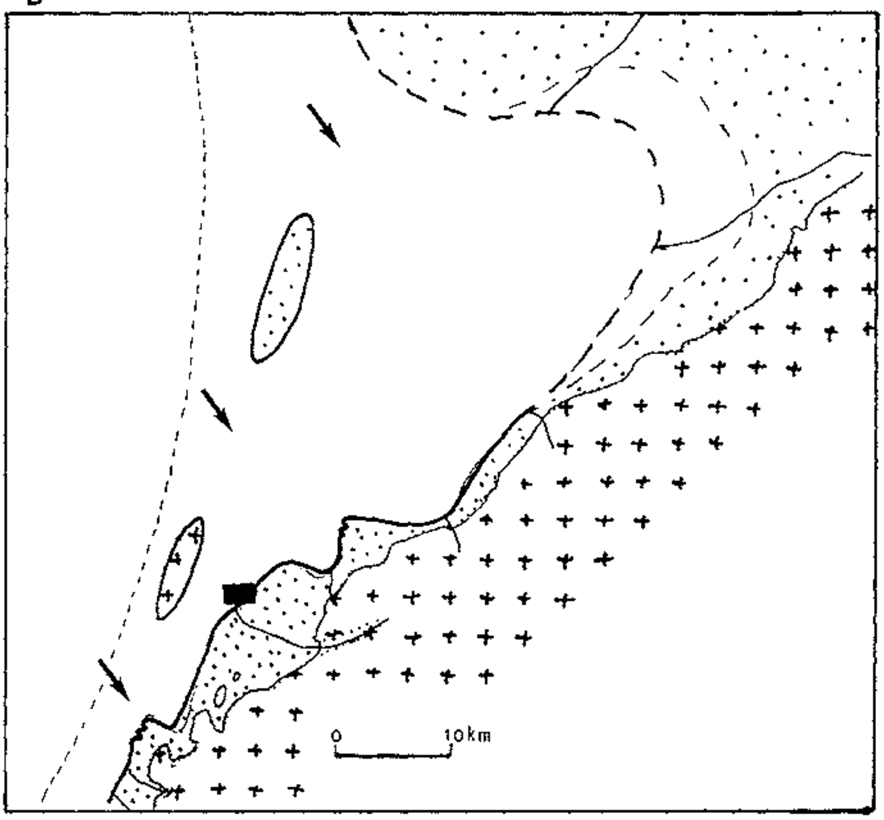
C

c.120 kyr




D

c.100 kyr



seaward, bisected by occasional incised valleys of rivers rising in the ranges. The Ohau River may well have flowed north-westwards along the southern extremity of the Kairanga Trough immediately east of the Poroutawhao High, forming a tributary to the Manawatu River.

When marine transgression occurred in response to worldwide climatic warming *c.*140kyr B.P. (oxygen isotope stage 5e), the topographic highs formed barriers to the encroaching sea resulting initially in the formation of an embayment in the Kairanga Trough area (Fig. 8.1B). Probable outlets to the open sea existed between the Himitangi and Mt Stewart topographic highs to the north, and between the Himitangi and Poroutawhao highs to the south (the latter being in the vicinty of the present day Manawatu River mouth). When transgression reached its maximum (*c.*120kyr B.P.) most barriers were breached and more extensive marine conditions prevailed (Fig. 8.1C). However, sedimentation patterns continued to be influenced by local basin structure.

Tidal processes dominated north of Shannon where sedimentation patterns were controlled primarily by the deepening Kairanga Trough and less by longshore, wave-induced currents as seen in the Otaki Formation to the south. North of Shannon this is reflected in the strong NNE paleocurrent trend, particularly of fluvial and tidal channels. North of the study area the Kairanga Trough received most of its sediment from the Manawatu River and its tributaries. The increased amount of gravel in the Otaki Formation noted north of Tokomaru (Oliver 1948, Rich 1959) reflects this. Also, a brackish marine fauna in the Otaki Formation near Palmerston North confirms an estuarine-type environment existed in that area. Alluvial fans along the fault-controlled coastline between Shannon and Tokomaru developed into fan-deltas which emptied into a tide-dominated coastline with wave energy becoming more influential to the south.

Between Shannon and Ohau mixed wave-tide processes operated with wave-induced longshore currents, chiefly from the north-west, superimposed upon a strong north-east trending tidal current regime. The considerable thickness of Otaki Formation in the Potts Hill area relative to the south and west may indicate a localised structural low existed on the south-eastern margin of the Kairanga Trough which has since undergone rapid deformation. Similarly, thinning around the crest of the Levin Anticline indicates a localised structural high existed on the southern margin of the Kairanga Trough during Otaki Formation deposition. In contrast to the Shannon Anticline, slow spasmodic uplift is apparent here.

Weather patterns and ocean current systems were similar to the present day with longshore currents providing abundant sediment from the north-west. The sediment was derived predominantly from three sources:

1. reworked coastal plain sediments;
2. rivers draining the central North Island;
3. direct andesite volcanic input from Taranaki.

Present geophysical data suggests closure of the Kairanga Trough occurs south of Ohau corresponding closely with the probable southern limit of the Poroutawhao High immediately to the west. In the Forest Lakes area, the presence of a mature[1] cliffed shoreline forming the riser of the TMT testifies to high wave energy conditions during the TMT transgression. Coastal erosion was probably enhanced by wave deflection around the southern edge of the Poroutawhao High, as is seen south of Kapiti Island along the Raumati and Paekakariki coastlines today. Clearly, the absence of seaward barriers in the Forest Lakes area allowed wave processes to control deposition once the shoreline stabilised. Wave induced longshore currents predominantly from the north-west brought an abundant supply of sediment to the coast which prograded rapidly after culmination

[1] Mature cliffed shoreline here refers to the latter stages in the life history of a shoreline of submergence where coastal erosion has cut deeply into the bedrock producing a straight shoreline with high cliffs (Strahler 1968). A present day analogy exists between Paekakariki and Pukerua Bay *c*.40km to the south.

of the TMT transgression.

The maximum sediment deposition in the Otaki Formation occurred after culmination of the TMT transgression when sea level appears to have remained stable for some time prior to regression. During this time the sedimentation rate was high particularly north of Ohau where the tensionally created Kairanga Trough acted as a localised depocentre on the margin of the Wanganui Basin.

The thickness of marine strata overlying the Tokomaru wave cut platform (10->40m) contrasts significantly with its probable correlative, overlying the Rapanui wave cut platform at Wanganui (8-15m, Pillans 1985). The difference in thickness reflects greater basinal subsidence in the southern Manawatu area compared with Wanganui.

As sea level receded, the top of the TMT was bevelled producing the characteristic flat terrace surface seen over much of the field area. Localised basement block faulting continued, in association with regional uplift of the Tararua Range. This resulted in warping of the overlying marine terrace along previously established basement faults with the activation of several new faults, namely beneath the Shannon and Pukehou anticlines.

Two subsequent marine transgressions, probably occurring during oxygen isotope substages 5c and 5a (*c*.100kyr B.P. and *c*.80kyr B.P. respectively; see Fig. 3.1), cut treads on the outer edge of the TMT (PTMT1, Fig. 8.1D; PTMT2). PTMT2 is only clearly preserved at Forest Lakes. Geomorphological evidence indicates the later transgressions were relatively short-lived and therefore probably contributed little to the overall thickness of the Otaki Formation.

After the PTMT2 transgression, worldwide climatic cooling led to further lowering of sea level with consequently large areas of the marine terrace cover being removed and/or buried by aggrading rivers. Differential uplift was accompanied by correspondingly intense dissection within the terraces themselves. The Holocene transgression led to final truncation of the terrace set with subsequent burial and modification of the margin by aeolian and fluvial activity.

## 8.1 CONCLUDING COMMENTS

The late Quaternary evolution of the southern Manawatu district has been shown to be controlled by the interplay of three main factors:

1. basement block faulting on the edge of the Wanganui Basin related to a regional, divergent strike-slip tectonic setting;
2. late Quaternary eustatic sea level fluctuations;
3. an abundant sediment supply.

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# APPENDIX A

## SUMMARY OF BORE LOG DATA

<u>Reference</u>

| | |
|---|---|
| BL NO. | Bore log number used in the text and maps in this study. |
| MWRC REF.NO. | Manawatu-Wanganui Regional Council grid reference and well number. Detailed drillers' logs for each bore hole analysed in this study are lodged in the Manawatu -Wanganui Regional Council headquarters, Palmerston North. |
| NZMS 260 REF. | New Zealand Topographical Map, 1:50,000 scale, NZMS 260 series grid reference of well site. |
| R.L. | Reduced level of ground surface at well site (m.s.l. = 0m). Data is unavailable for some sites. |
| DEPTH | Depth of well in metres. |
| TWCP | Depth of Tokomaru wave cut platform in metres below ground surface. |

| BL NO. | MWRC REF.NO. | NZMS 260 REF. | R.L. m. | DEPTH m. | TWCP m. |
|---|---|---|---|---|---|
| 1 | 0371 331.00 | S25 934 488 | ---- | 60 | 25 |
| 2 | 0371 411.00 | S25 930 485 | ---- | 59 | -- |
| 3 | 0371 421.00 | S25 926 489 | ---- | 41 | 18 |
| 4 | 0371 521.00 | S25 951 523 | 8.66 | 43 | 17 |
| 5 | 0371 541.00 | S25 937 505 | ---- | 13 | -- |
| 6 | 0371 591.00 | S25 930 495 | ---- | 30 | 25 |
| 7 | 0371 641.00 | S25 950 535 | 9.49 | 41 | 16 |
| 8 | 0371 671.00 | S25 936 493 | ---- | 27 | 26 |
| 9 | 0371 701.00 | S25 951 531 | 10.83 | 60 | 21 |
| 10 | 0372 021.00 | S25 960 503 | 59.78 | 49 | 40 |
| 11 | 0372 031.00 | S25 964 513 | 36.77 | 75 | 24 |
| 12 | 0372 071.00 | S25 973 520 | 52.05 | 27 | 19 |
| 13 | 0372 071.01 | S25 976 523 | ---- | 29 | 24 |
| 14 | 0372 071.02 | S25 973 519 | ---- | 20 | 19 |
| 15 | 0372 081.00 | S25 980 532 | 46.32 | 66 | 46? |
| 16 | 0372 091.00 | S25 975 520 | 36.26 | 54 | 36 |
| 17 | 0372 101.00 | S25 965 507 | 41.97 | 22 | 21 |
| 18 | 0372 111.00 | S25 982 530 | 56.75 | 50 | 48 |
| 19 | 0372 111.01 | S25 973 519 | 52.66 | 70 | 52 |
| 20 | 0362 691.00 | S25 028 578 | 66.34 | 61 | 20 |
| 21 | 0362 781.00 | S25 026 582 | 58.32 | 29 | 25 |
| 22 | 0362 771.00 | S25 022 583 | 62.77 | 34 | 30 |
| 23 | 0362 881.00 | S25 015 583 | 57.26 | 52 | 38 |
| 24 | 0362 891.00 | S25 015 586 | 51.05 | 53 | 31 |
| 25 | 0362 731.00 | S25 014 584 | 51.63 | 43 | 35 |
| 26 | 0362 971.00 | S25 012 585 | ---- | 41 | 35 |
| 27 | 0362 591.00 | S25 007 582 | 44.39 | 33 | -- |
| 28 | 0362 281.00 | S25 008 586 | 44.49 | 71 | 38 |
| 29 | 0362 761.00 | S25 008 590 | 45.10 | 43 | 34 |
| 30 | 0362 901.00 | S25 005 589 | ---- | 41 | 40 |
| 31 | 0362 661.00 | S25 001 593 | 41.11 | 49 | 42 |
| 32 | 0362 741.00 | S25 993 583 | 34.10 | 35 | -- |
| 33 | 0362 681.00 | S25 997 599 | 32.77 | 90 | 45 |
| 34 | 0362 931.00 | S25 983 593 | 25.43 | 30 | 28 |
| 35 | 0362 001.00 | S25 980 587 | 18.75 | 16 | -- |
| 36 | 0362 231.00 | S25 982 597 | 18.25 | 62 | 22? |
| 37 | 0362 181.00 | S25 978 594 | 34.44 | 81 | 39 |
| 38 | 0363 001.00 | S25 062 612 | 57.51 | 45 | 25 |
| 39 | 0363 291.00 | S25 056 613 | ---- | 43 | 24 |
| 40 | 0363 271.00 | S25 083 626 | 50.66 | 51 | 12? |
| 41 | 0363 101.00 | S25 076 629 | 43.56 | 51 | 24 |
| 42 | 0363 201.00 | S25 062 628 | 35.26 | 28 | 19 |
| 43 | 0363 161.00 | S25 056 636 | 34.96 | 23 | 37 |
| 44 | 0363 211.00 | S25 071 641 | 28.71 | 64 | 14 |
| 45 | 0363 051.00 | S25 069 643 | 29.01 | 25 | 20 |
| 46 | 0363 081.00 | S25 067 644 | 15.77 | 26 | 20 |
| 47 | 0363 041.00 | S25 047 642 | 43.50 | 33 | -- |
| 48 | 0363 011.00 | S25 049 645 | 45.80 | 36 | 15 |
| 49 | 0362 941.00 | S25 044 643 | ---- | 35 | 22 |
| 50 | 0362 491.00 | S25 042 643 | 43.50 | 38 | -- |

| BL NO. | MWRC REF.NO. | NZMS 260 REF. | R.L. m. | DEPTH m. | TWCP m. |
|---|---|---|---|---|---|
| 51 | 0362 841.00 | S25 028 638 | ---- | 31 | -- |
| 52 | 0362 015.00 | S25 026 648 | ---- | 63 | 38 |
| 53 | 0362 271.00 | S25 027 644 | 20.01 | 53 | 29 |
| 54 | 0362 011.00 | S25 028 649 | 31.32 | 55 | 37 |
| 55 | 0352 061.00 | S25 022 653 | 16.97 | 27 | -- |
| 56 | 0352 081.00 | S25 033 654 | 40.17 | 40 | 40 |
| 57 | 0353 181.01 | S25 047 656 | ---- | 50 | 22 |
| 58 | 0352 201.00 | S25 041 657 | 44.53 | 37 | 22 |
| 59 | 0352 381.00 | S25 025 658 | 17.90 | 43 | 15 |
| 60 | 0352 421.00 | S25 024 661 | 23.71 | 30 | -- |
| 61 | 0352 131.00 | S25 026 664 | 22.28 | 109 | 34 |
| 62 | 0352 391.00 | S25 036 663 | 30.96 | 36 | 21 |
| 63 | 0352 431.00 | S25 045 660 | ---- | 53 | 21 |
| 64 | 0352 101.00 | S25 030 667 | ---- | 34 | -- |
| 65 | 0352 091.00 | S25 033 670 | 17.99 | 42 | -- |
| 66 | 0352 401.00 | S25 041 667 | 13.47 | 29 | 18 |
| 67 | 0352 121.00 | S25 040 676 | 11.84 | 104 | 33? |
| 68 | 0353 131.00 | S25 057 658 | 35.29 | 37 | 29 |
| 69 | 0353 211.00 | S25 052 664 | ---- | 24 | -- |
| 70 | 0353 281.00 | S25 057 666 | ---- | 25 | -- |
| 71 | 0353 251.00 | S25 066 686 | 13.69 | 20 | 16? |
| 72 | 0353 161.00 | S25 067 673 | 20.66 | 35 | 27 |
| 73 | 0353 091.00 | S25 060 677 | 20.32 | 31 | 30 |
| 74 | 0353 081.00 | S25 063 677 | 18.20 | 20 | -- |
| 75 | 0353 141.00 | S25 077 672 | 8.14 | 28 | 20 |
| 76 | 0353 111.00 | S25 084 686 | 17.30 | 34 | -- |
| 77 | 0353 201.00 | S25 082 692 | 4.23 | 13 | -- |
| 78 | 0345 171.00 | S24 222 761 | ---- | 43 | 42 |
| 79 | 0353 101.00 | S25 088 660 | 46.95 | 48 | -- |
| 80 | 0353 291.00 | S25 095 660 | 46.46 | 47 | -- |
| 81 | 0353 121.00 | S25 097 665 | ---- | 48 | -- |
| 82 | 0353 171.00 | S25 091 704 | 7.20 | 58 | -- |

# APPENDIX B

## MEASURED SECTION DESCRIPTIONS

KEY TO SYMBOLS USED

**Lithology**

- Gravel
- Sand
- Silt
- Clay
- Loess
- Paleosol
- Tephra
- Absent data

**Sedimentary Structures**

- Lenses
- Channel
- Symmetrical ripples
- Load casts
- Horizontal stratification
- Graded bedding
- Convolute bedding
- Slump structures
- Rip-up clasts
- Pull-over, flame structures
- Pebble imbrication
- Plant root structures
- Bioturbation, mottling
- Carbonaceous debris
- Plant remains
- Cross-bedding (with scale)
- Lenticular bedding
- Paleocurrent direction

Note
1. Scale for Sections is 1cm = 1m unless otherwise specified.
2. For paleocurrent directions north is the top of the page.
3. Section descriptions are not always in exact numerical order although never more than a page out of sequence.

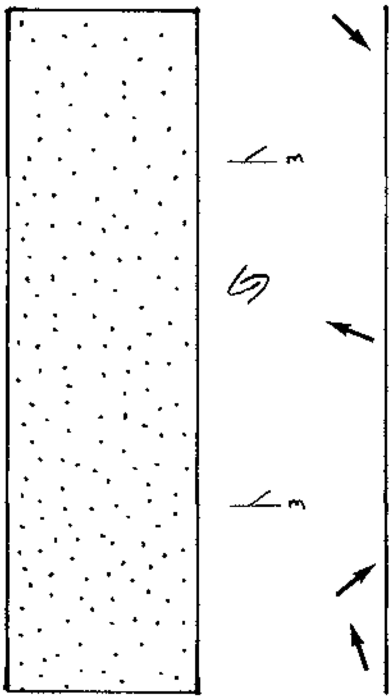
## LIST OF ABBREVIATIONS USED

| | |
|---|---|
| abnd | abundant |
| altn | alternating |
| av | average |
| bdd | bedded |
| Bldr | Boulder |
| brn | brown |
| carb | carbonaceous |
| Cbl | Cobble |
| Cgl | Conglomerate |
| conc | concentrated |
| cr lam | current ripple laminated |
| crs | coarse |
| dk | dark |
| dm | decimetre |
| dsk | dusky |
| f | fine |
| Gwke | Greywacke |
| gy | grey |
| hd | hard |
| horz | horizontal |
| ibdd | interbedded |
| imb | imbricated |
| KDS | Koputaroa dune-sands |
| L | Loess |
| lam | laminae, laminated |
| len | lens |
| lge | lge |
| lt | light |
| M | Mud |
| Mst | Mudstone |
| mass | massive |
| max | maximum |
| med | medium |
| micac | micaceous |
| ol | olive |
| orng | orange |
| O.Sst | Otaki Sandstone |
| Pbl | Pebble |
| pk | pink |
| pkd | packed |
| pl-Xbdd | planar-cross-bedded |
| pll | parallel |
| rpl | ripple |
| S | Sand |
| s | sandy |
| Sst | Sandstone |
| sub ang | subangular |
| sub rnd | subrounded |
| suprt | supported |
| tn | thin, thinly |
| trgh-Xbdd | trough-cross-bedded |
| v | very |
| w | with |
| wh | white |
| wthd | weathered |
| Xddd | cross-bedded |
| Z | Silt |
| z | silty |
| Zst | Siltstone |

Note

1. When using terms in their comparative sense underlining means "very" e.g. hd = very hard, and brackets means "slightly /poorly", e.g. [wthd] = slightly weathered; [srt] = poorly sorted

L4 S25/936472

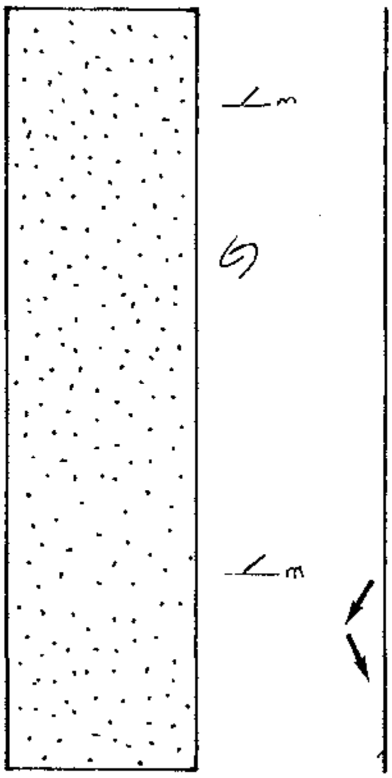


Sandstone

- 9m lge Xbdd, [soft] lt ol brn srt f Sst
- altn lt and dk lam
- occasional ibdd silty lam (2-3mm)
- occasional small rpl lam resting on lge foresets

Dune sand facies

L3 S25/942481



Sandstone - 10m lge Xbdd, soft yell-brn srt f Sst

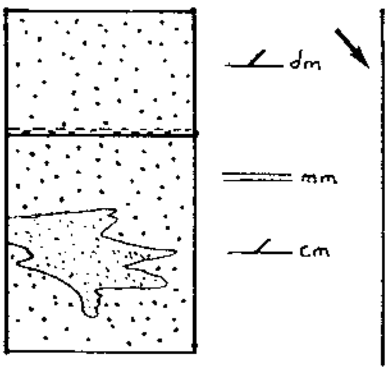
- intraformational slumping and faulting well developed

Dune sand facies

L6 S25/938494

Sample

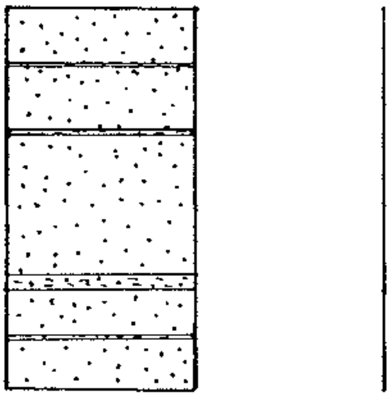
TS6




Sandstone - 1.5m Xbdd, [hd] lt ol gy, srt f Sst
contact zone = 2cm wthd z S
- 4m pll-lam-cr lam [hd] lt ol gy srt f S
interfingering weathering bands across bedding

= beach sand

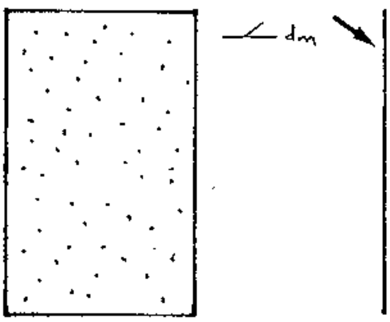
L21 S25/937511



Sandstone - 5m [lam] -mass, soft [wthd] gy orng, srt f Sst, with occasional (3-20cm) beds of f lam z f - m S
- sharp contacts

= beach - shallow marine sand

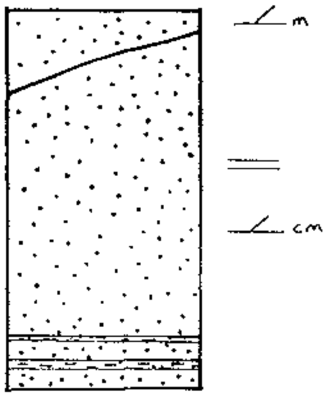
L13 S25/938491




Sandstone 4.5m [hd] [wthd] gy-yel srt f Sst
top 0.5m - Xbdd
below 4m - lam- cr lam - mass
occasional tn (1cm) z beds

= beach sand

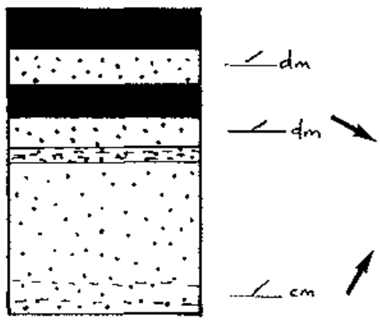
L22 & 23 S25/943502, 944502




Sand 0.3-1m Xbdd soft orng-brn
srt f S = Koputaroa dune sand
- angular unconformity -
Sandstone 4.5m pll-cr lam [soft]
srt f - m S
basal 1m = two beds (10-20cm)
[hd] z f Sst.

- Otaki beach sand

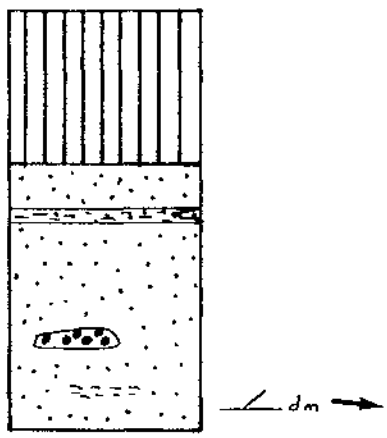
L29 S25/945513




Sml 0.5m
Sand 0.5m Xbdd soft yel -brn srt
f S = KDS
Paleosol 0.4m
Sandstone 0.4m Xbdd [soft] yel -gy
srt f Sst.

0.2m v pale orng z f Sst
3m cr lam [soft] lt ol gy [srt]
m-f Sst

L31 S25/942509

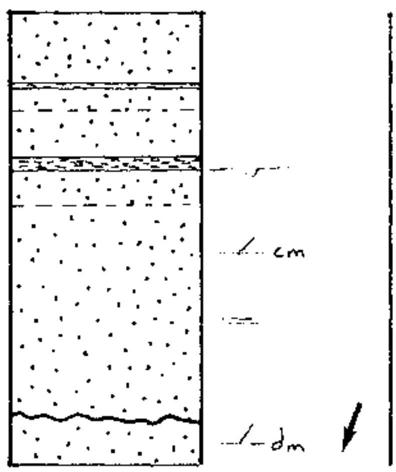



Loess and Soil 2m

Sandstone 3.5m lam lt ol gy [hd]
srt m - f Sst, occasional cr lam,
stringers of crs S, lens z S,
interfigering with S

one pl Xbdd set at base

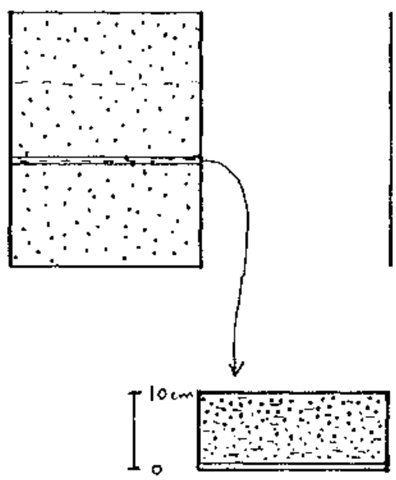
L34 S25/964512




Sandstone - 6m pll lam - cr lam, soft, lt ol gy srt f Sst with tn ibdd, [hd], v pale orng z f S (1-20cm)

one truncated pl Xbd set at base

L35 S25/961514

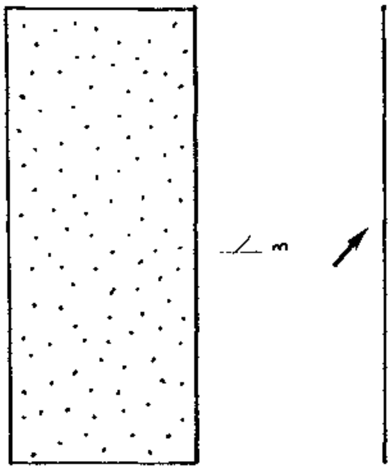



Sandstone - 3.3m pll lam, soft, lt ol gy srt f Sst with occasional tn beds z f S one 10cm reverse graded bed (see below)

reverse graded bed

6cm lam z m S
4cm mass z f S
3mm M

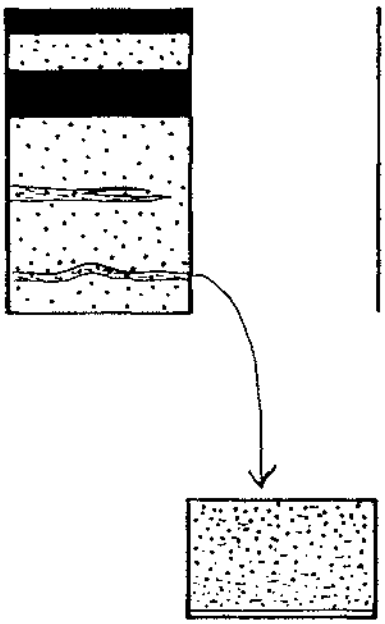
L37 S25/973514



<u>Sandstone</u> - 6m lge xbdd lt ol gy [hd] <u>srt</u> f Sst

= Otaki dune sand

L38 S25/954519

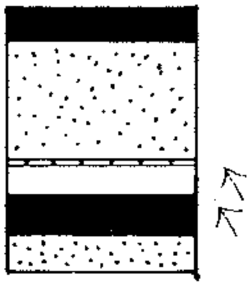


<u>Soil</u> 0.3m
<u>Sand</u> 0.5m orng brn soft <u>srt</u> f S
= KDS
<u>Paleosol</u>-0.6m <u>wthd</u> rusty orng paleosol
<u>Sandstone</u>-2m [lam] gy orng [wthd] [soft] f Sst with ibdd tn pale pk wh soft z f S, splits along bedding planes - one 15cm reverse graded hummocky bed (see below)

10cm mass yel gy [srt] z m S )
5cm f lam gy orng [srt] z f s )

2-3mm v pale orng M

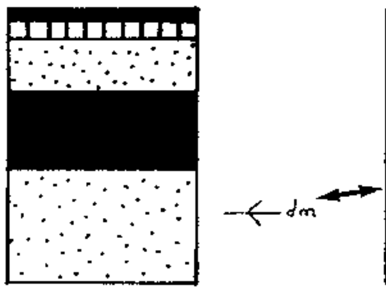
L42 S25/026577



Soil 0.5m
Sand 1.5m mass, brn soft srt f Sst = KDS

Tephra 8cm gy wh pumiceous z = Aokautere Ash
Mud - 0.4m pale of M, carbonaceous
Paleosol 0.5m wthd Paleosol
Sandstone 0.5m mass lt ol gy [hd] srt f Sst = ot Sst

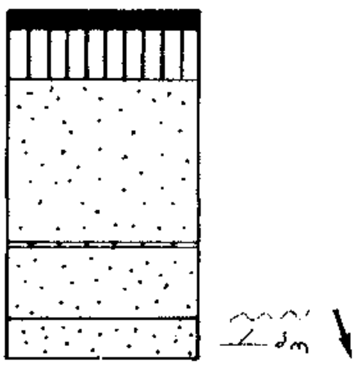
L44 + L45 S25/022578 023578



Soil 0.2m
Loess 0.2m pale yel orng L
Sand 0.7m mass, dk yel orng [soft] srt f S = KDS
Paleosol -1m orng brn wthd

Sandstone 1.5m Xbdd lt ol gy [hd] srt f Sst - reactivation surfaces on Xbdds = Ot. Sst.

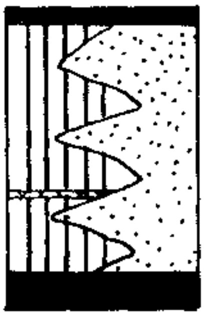
L47 S25/006583



Soil 30cm
Loess 40cm
Sand 1.5m mass, yel brn, soft, srt f S = K.D.S.
Tephra 8cm pale yel brn pumiceous Z

- weathered horizon -
Sandstone 1m Xbdd lt ol brn [wthd] soft srt f S

L48 S25/002582

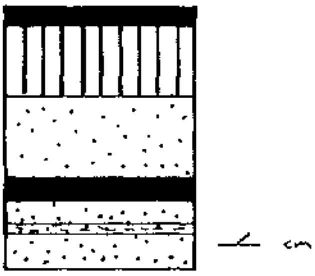


Soil 20-30cm

Sand and Loess 3m, ibdd, mass, brn, soft srt f S (KDS) and Loess. Aokautere Ash present in loess but absent in sand

Paleosol - 0.5m wthd Paleosol

L50 S25/996582



Soil 20cm

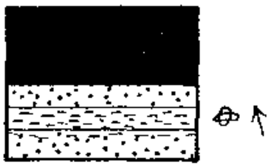
Loess - 1m

Sand - 1m mass, gy orng soft srt f S (KDS)

Paleosol - 30cm yel brn [hd] Paleosol

Sandstone 0.8m pll lam, lt ol gy, srt f S with ibdd gy orng z f S

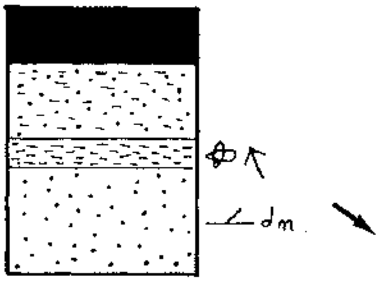
L 53 S25/987584



Soil 1m

Sandstone - 1m soft, dsk yel, srt f Sst with ibdd f lam, pale ol [hd] s Z, gradational basal contact, undulating, sharp, upper contact

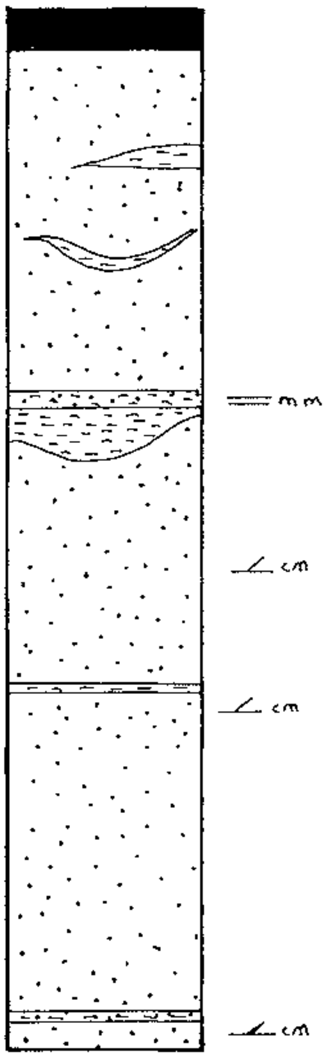
L54 S25/979584



Soil - 0.7m

Sandstone - 1m [lam] orng brn, [hd] wthd, z f S, sharply overlying 40cm, mass, yel gy, s Z gradationally overlying 1.5m Xbdd yel gy soft srt f S

L52 S25/990591




Soil 0.5m

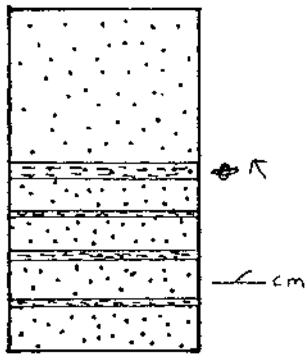
Sandstone 4.5m [lam] orng brn [soft] f Sst with z lenses

25cm bed f lam, hd, grn gy z f Sst

Silt 0.4m, mass, yel brn, s Z undulating basal contact

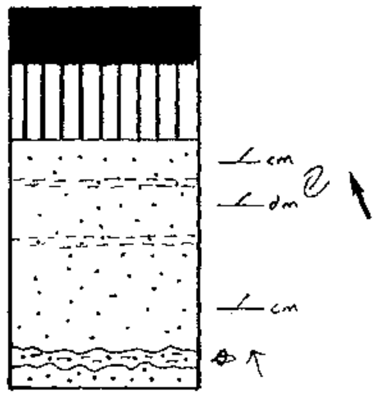
Sandstone 7.5m, lam, lt ol gy, [soft] srt f Sst with occasional beds of [hd] z f Sst

L56 S25/991596




Sandstone 4.5m lam, lt ol gy, soft srt f S with frequent interbeds (4-20cm) hd, z f S

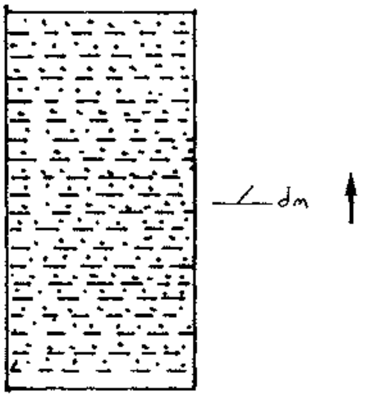
L57 S25/994597




Soil 0.4m

Loess 1m

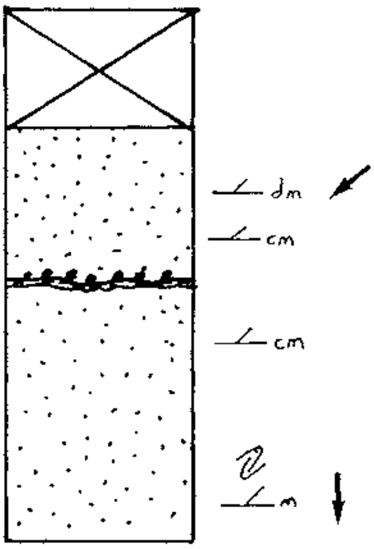
Sandstone Xbdd lt ol gy, soft srt f S with reactivation surfaces, ibdd z S, contacts sometimes sharp and irregular, or gradational



L58 S25/080621

Sandstone - 5m tn ibdd, lt ol gy srt f Sst and z S containing carbonaceous debris; occasional low angle Xbdg in srt Sst

Sample



C66D

C66C

C66B

C66A

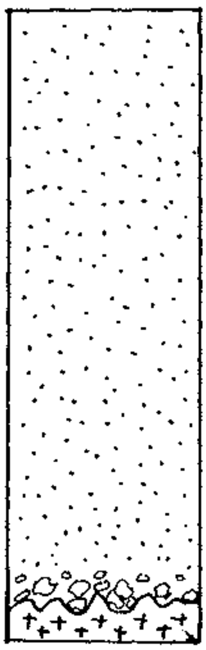
L66 S25/077653

Sandstone - 2m Xbdd, orng brn soft, srt, m Sst; basal crs lag with rip-up clasts above undulating mud bed, sharp contacts

Sandstone - 1.6m pll lam - cr lam, yel orng, soft, wthd srt f Sst

Sandstone - 1.2m Xbdd, lt ol gy, soft, srt f Sst

Sample



T§70

L70 S25/097643

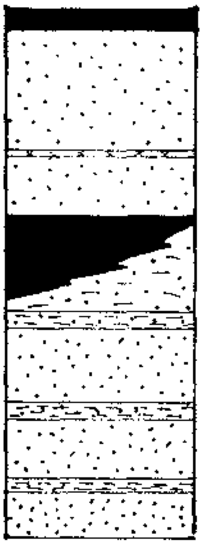
Sandstone - 7m lam [hd] lt ol gy f Sst with occasional silty interbeds

Breccia - 0.5m cemented Breccia

- unconformity - (wavecut platform)

Greywacke

L71 S25/073642



Soil - 30cm

Sand - 2.2m mass, brn [soft] [hd] srt f S containing 10cm Aokautere Ash = KDS

Paleosol - 1m wedging out to 20cm wthd brn orng

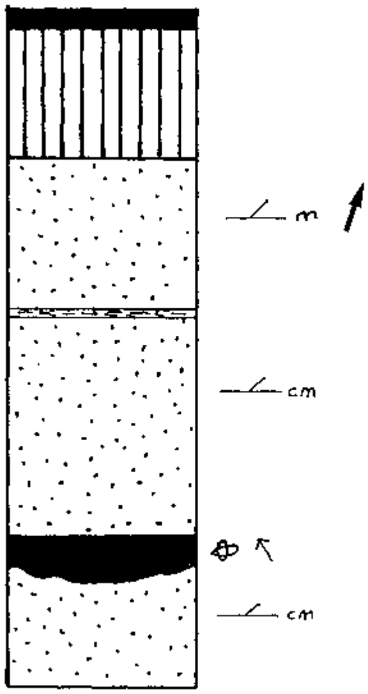
Sandstone - 3-4m mass, ol brn, [hd] srt f Sst with ibdd (20-30cm) hd dsk yel, f lam, wthd s Z

L73 S25/048676

Sample

C73B

C73A




Soil - 20cm

Loess - 1.6m

Sandstone - 2m lge Xbdd lt og brn [hd] srt f S = Otaki dune sand

Silty Sandstone - 10cm yel gy z f S weak paleosol on top (3-4cm)

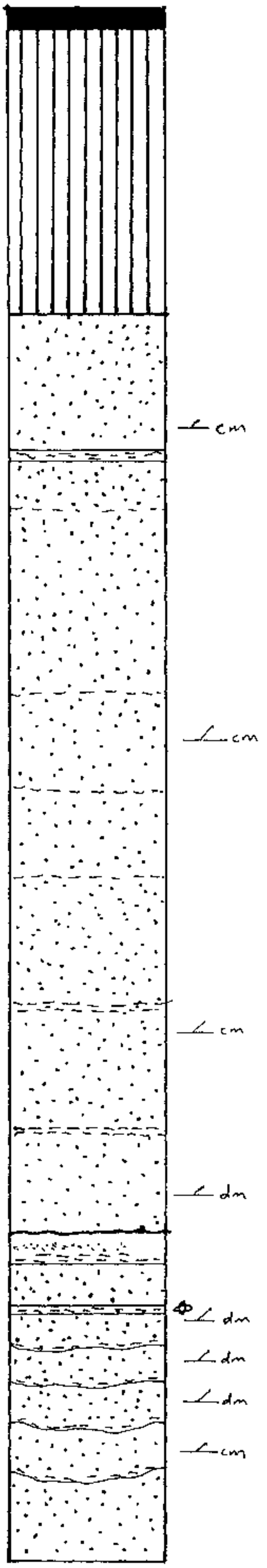
Sandstone - 2.9m pll lam - cr lam lt ol gy, soft, srt m S

Paleosol - 55cm red orng-gy wthd M grades laterally into hd limomtic layer with 'buckshot' gravels

Sandstone - 1.6m pll lam, pale ol, soft srt m Sst

L77 S25/097655

Samples




Soil - 30cm

Loess - 4.5m

Sandstone

mass lt ol brn hd srt f Sst with occasional hd z f S beds

C77D

pll lam - cr lam brn gy soft f Sst

eroded surface

Mud - 15cm pal ol M encloses lens of lt ol gy, z f S

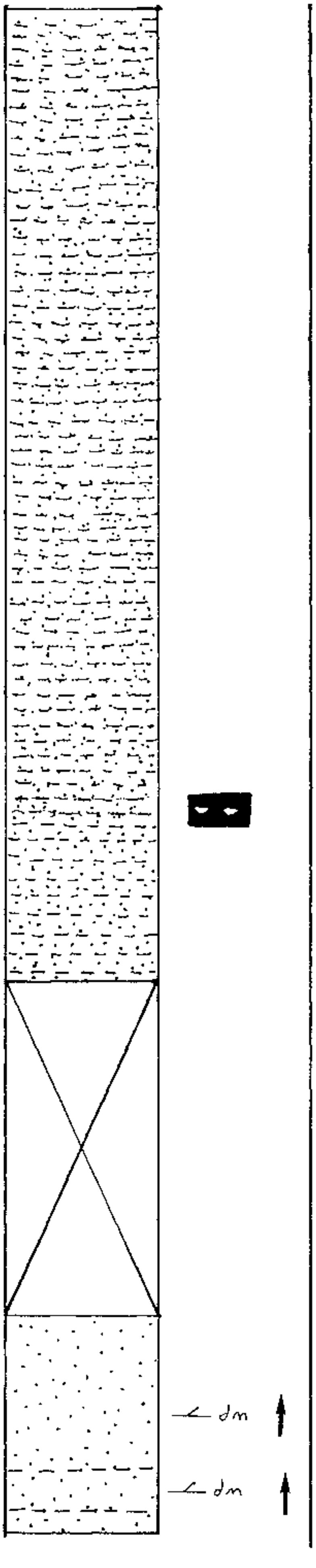
C77C

5m sequence of Xbdd, lt ol brn srt f S units with scoured mud draped bases

C77B

C77A

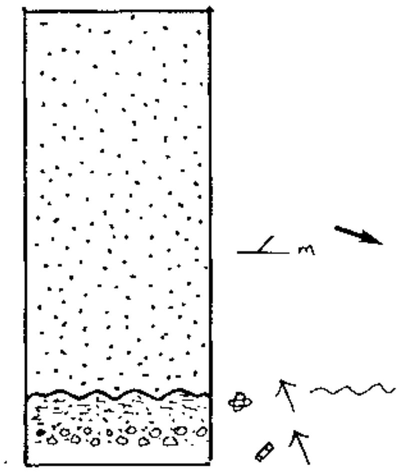
L85 S25/119675




Sandstone - 15m alternating beds of mass yel gy soft [srt] f S and f lam [soft] z S with laminae of crs S and occasional rnd granules

- silty beds thicker and more frequent towards top

Sandstone - 3.5m Xbdd, lt ol brn srt f Sst occasional thin [hd] silty beds

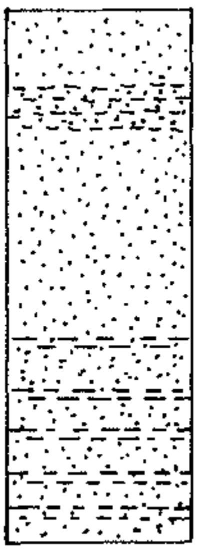


L88 S25/131672

Sandstone - 5m Xbdd lt ol gy,
soft, srt f Sst

- unconformity -

Sandy Silt - 30cm grades into 0.6m
breccic sand, in turn grading
into 20cm gy M

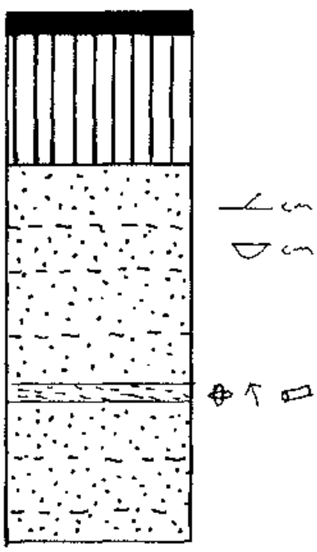


L91 S25/123672

Sandstone - 1m mass lt ol gy z Sst
1m ibdd z S and s Z

mass lt ol gy [hd] srt f Sst

3m alternating beds of f lam dk
yel orng [soft] z f Sst and f
lam s Zst



L92 S25/112693

Soil - 30cm

Loess - 1.7m

Sandstone

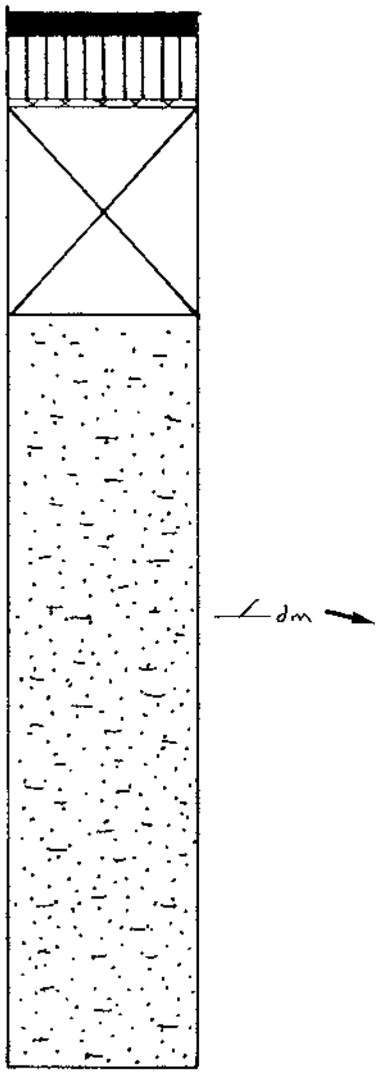
5m, lt ol gy, [hd] srt Sst with
occasional interbeds z f S

Siltstone - 10cm pale yel brn
carbonaceous Zst

Sandstone - as above

L89 SA25/108683

Sample



Soil 30cm

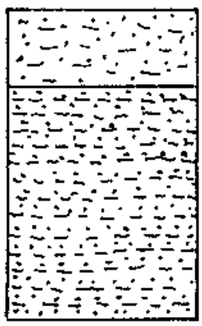
Loess ?

Sandstone 10m lam orng brn
[soft] [wthd] z f S

single crossbed set

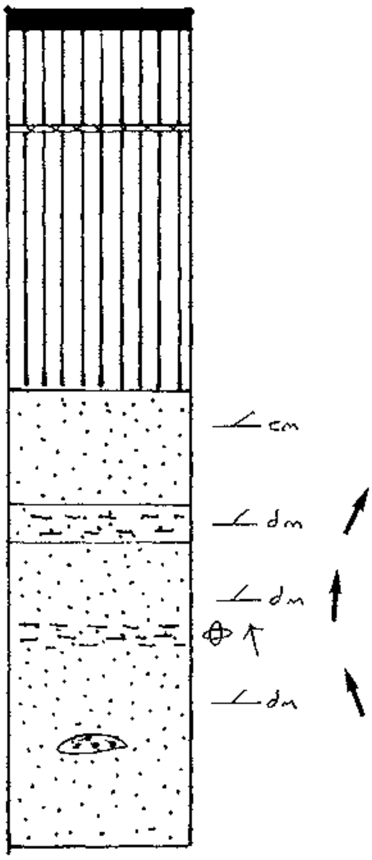
L93a S25/127683

TS93



Sandstone - 1m [lam]- mass,
yel gy hd z f Sst
grades into 3m ibdd lt
ol gy, srt f S and f lam,
hd z f S - splits along
bedding planes.

L96 S25/137692



Soil 30cm

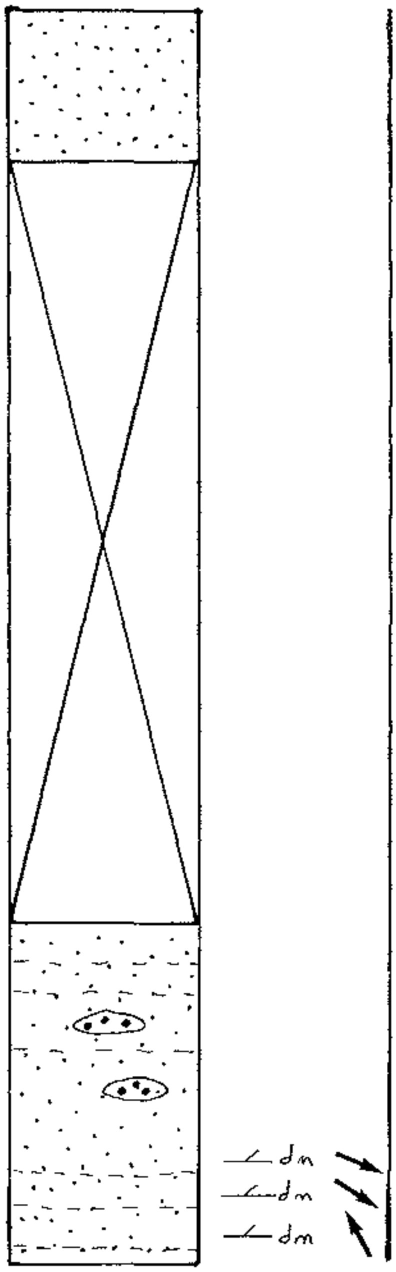
Loess 5m including Aokautere Ash

Sandstone 1.5m pll lam, lt ol gy, hd srt f Sst

0.5m gently dipping pll lam lt ol gy Sst (alternating fine and crs layers)

4m - similar sequences to above with occasional v silty beds and crs S lenes.

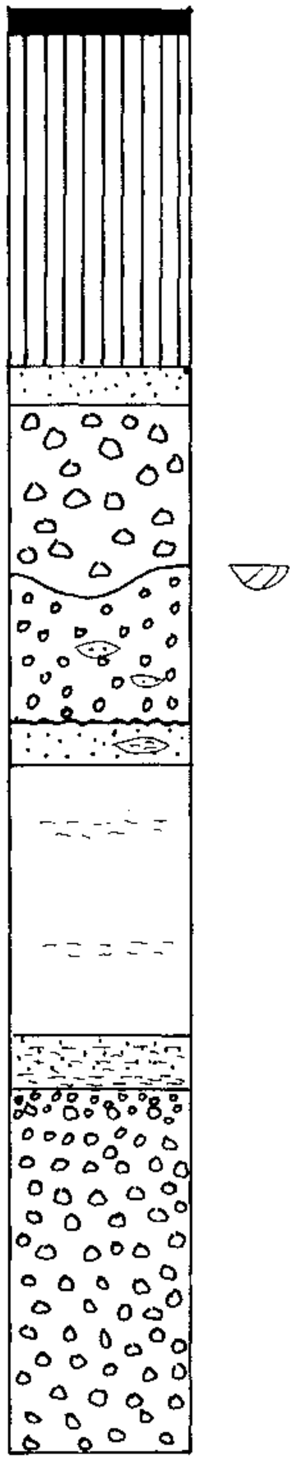
L97 S25/097677




Sandstone - 2m mass, lt ol gy
hd srt f Sst

Sandstone - 4.5m lam - Xbdd [z]
f S with frequent tn (3-4cm)
beds z f S - crs lenses
common
- one 30cm Xbdd [srt] m - crs S

L99 S24/223767

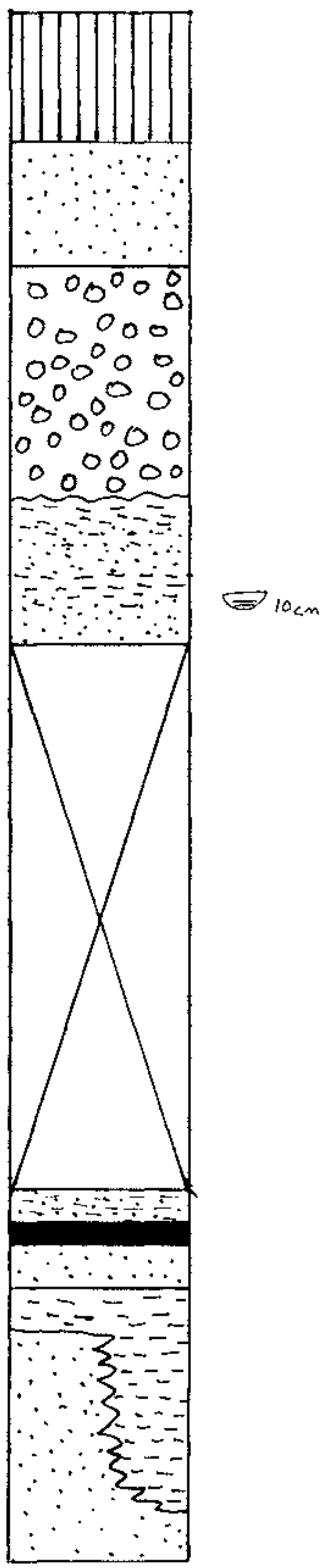


Loess and soil - obscured to
terrace top

Sandstone - 0.5m mass, dk yel orng,
wthd hd, f Sst
- shart contact -
Conglomerate - see L98 in text
for identical description
(Unit 4)

- erosive contact -
Siltstone and Sandstone
0.5m mass, yel gy, soft [srt] z f
S with mud lenses grades into
3.5m f lam, yel gy Mst,
locally silty, grades into
lam yel gy [wthd] z f S with
tn ibdd M layers
Conglomerate - see L98

L101 S24/223758




Loess & soil - 2m

Sandstone - 1.5m mass yel gy [hd]
z f Sst

Conglomerate - 3m see L98
(Unit 4b)

- erosive contact -

Sandstone - 2m fining upward units
of lam, lt ol gy, [srt] f S grd into
grn gy soft Z or M wthd
at top
occasional small channels with
fine pebble lags

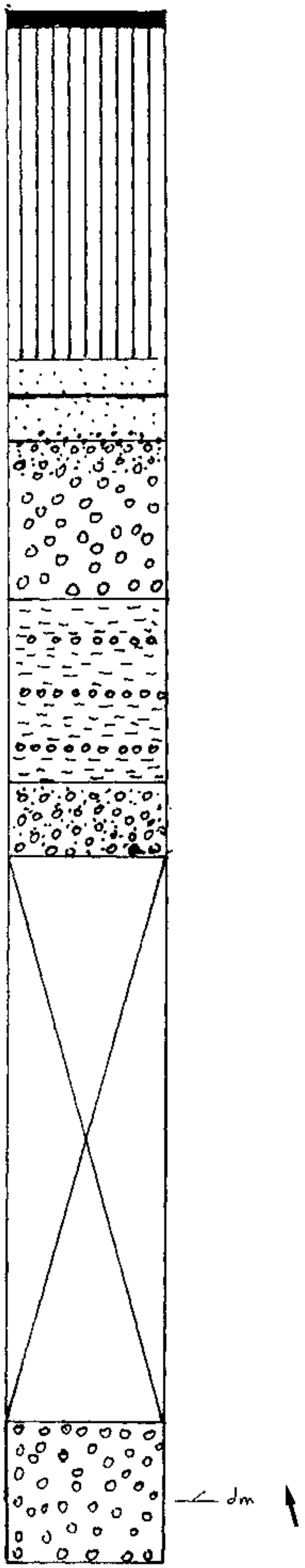
Sandstone - 0.4m lam yel gy [soft]
z f Sst

Paleosol - 0.3m

Sandstone - 0.4m lt ol gy f Sst

Sandstone + Siltstone - 3.5m lam,
pale ol [wthd] soft, v f Sst
with crs S bands (2-3cm)
grades laterally into mass,
grn gy Z st.

L102 S24/227762




Loess + Soil - 5.5m

Sandstone - 1m mass lt ol brn
[hd] z f Sst with band of red
blk limonite

Conglomerate - 2.5m pebble Cgl
grades up into Sst
- basal - clast suprt

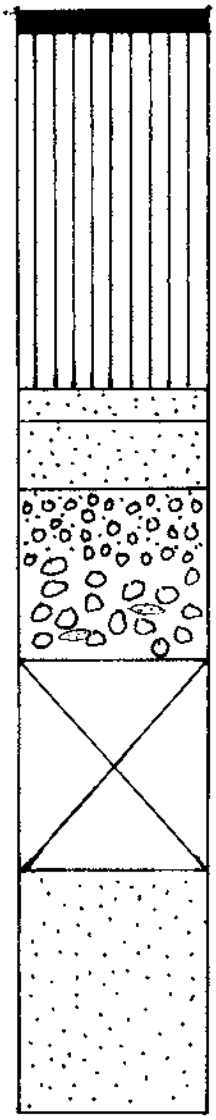
Pebbly Siltstone - 3m mass grn gy
Zst with beds of wthd fine
pebble Cgl.

Conglomerate - >1m s Cgl. or
pebbly Sst
- matrix suprt.

Conglomerate - 2m stratified clast
suprt pebble Cgl
70% clasts- largest 10cm, av
1-2cm
30% matrix - m - crs S

Sample

L103 S24/222758±



Soil - 30cm

Loess - 5m

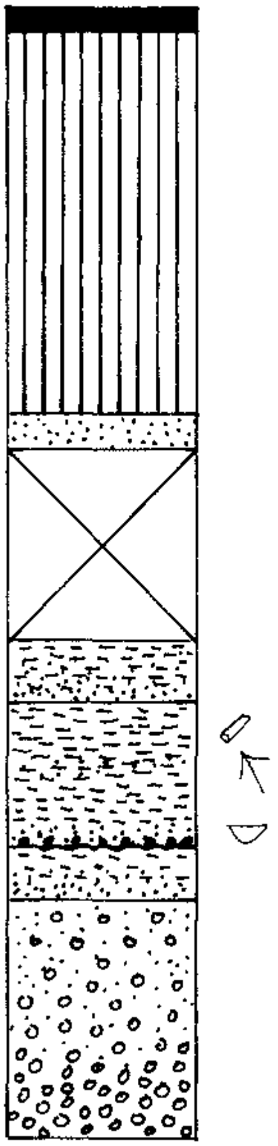
Sandstone - 0.4m mass yel gy
[wthd] z f SSt
- 0.8m mass, rusty orng,
wthd Sst

Conglomerate
- >2.2m matrix suprt, pbl Cgl
clasts - 50% sub ang - subrnd
pbls.
matrix 50% crs S
upper 1m - weakly stratified
lower 1m-clast size larger -
(5-10%Cbls) lenses f S

Sandstone
- 3.5m mass pal ol soft srt
f Sst

N103A

L104 S24/223752



Soil - 30cm

Loess - 5m

Sandstone - 0.4m mass, yel gy, soft srt f Sst

Sandstone/Siltstone

- 3.4m of fining upward units of basal crs S, often on eroded surface, grading through f Sst to Zst
  Zst with abundant carbonaceous debris and wthd at top

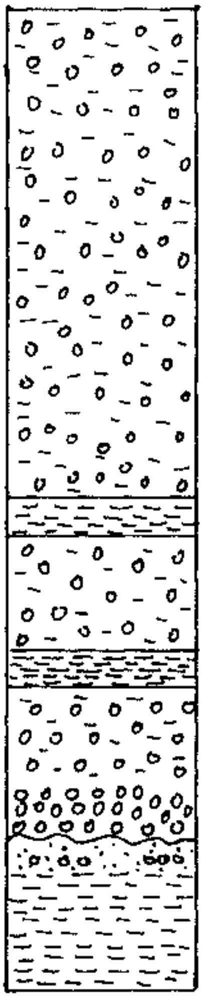
Conglomerate

3m weakly stratified, matrix suprt sub ang - subrnd, s pbl Cgl. clasts - decrease near top to 20%

- av size -<1cm decr up

matrix - rusty orng crs S incr to 80% at top

L105 S24/227747



Conglomerate

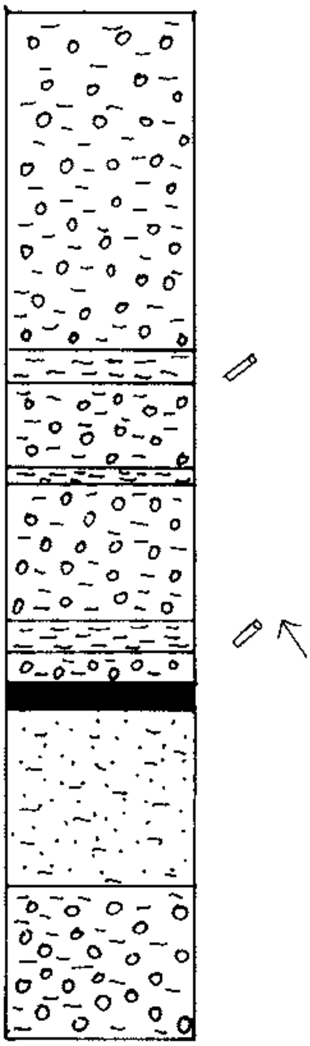
11m weakly stratified ang-sub ang
matrix suprt Cgl
clasts - av. size 1-2cm
matrix - Z and C

with ibdd mass yel gy Z

basal Cgl - 0.3m clast suprt
- eroded surface -

Siltstone - 2m mass, bl gy [soft]
Zst top 20cm becoming sandy
with pbl lenses

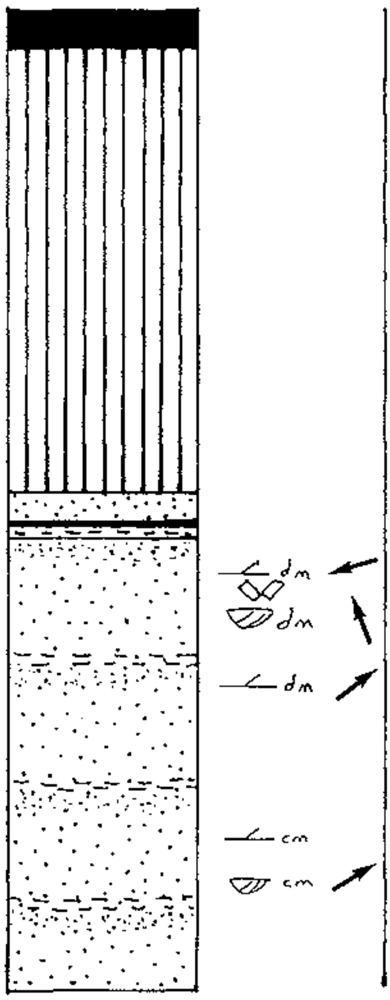
L106 S24/229747



Conglomerate
9m weakly stratified matrix
suprt ang - subang Cgl. clasts -
small pebbles
matrix - Z - s Z
contains rip up clasts of hd Zst
ibdd Zst often with carbonaceous
debris

Paleosol - 40cm wthd Paleosol
Sandstone - 2.5m mass, yel gy,
wthd [hd] [srt] z f Sst
grades into overlying
Paleosol
- sharp contact -
Conglomerate - 2m matrix suprt,
ang-subang
Cgl with C lenses
clasts - 40% mainly pbls -
cbls common
matrix - brn orng wthd C

Sample




N111A

L111 S24/207736

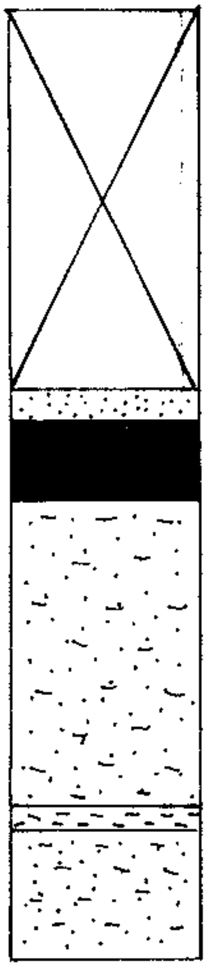
Soil - 40cm

Loess - 5.5m

Sandstone- 30cm [lam]-mass lt ol gy (locally wthd) hd srt f Sst

Siltstone - 20cm [fissile] orng wthd soft Zst grades up into 3-4cm Paleosol

Sandstone - 6m lt ol gy [hd] [srt] Sst consistingof 0.5 - 1m sequences of: Xbdd crs - m Sst grading up into pll lam f Sst and Zst one channel with lge rip up clasts (lgst - 35x12cm) of mass, yel gy, soft, wthd Zst with abnd root channels.



L113 S24/204741

Terrace surface

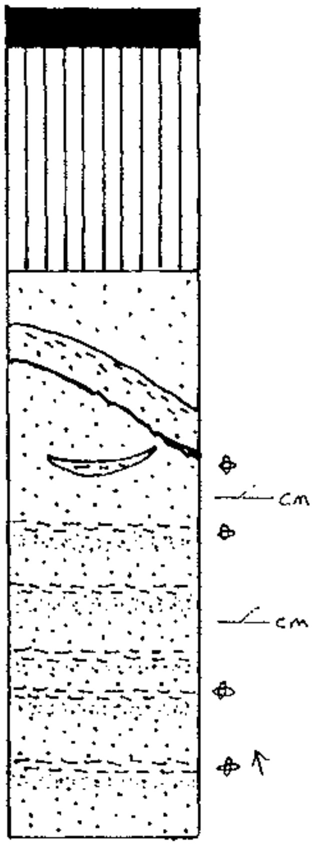
Sandstone - 0.4m, mass, lt ol gy hd srt f Sst

Paleosol - 1m

Sandstone - 6m mass, yel gy, soft z f Sst with ibdd hd dk ol brn Zst

abnd mica

L115 S24/208740




Soil - 30cm,

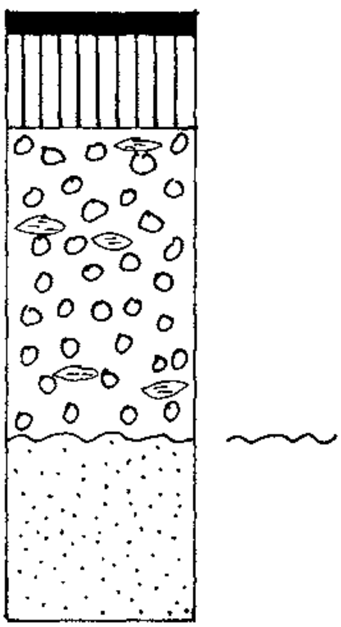
Loess

Sandstone 1-2m c r lam, lt ol gy hd f Sst

Silty Sandstone - 7m altn, lt ol gy, hd f Sst with yel orng wthd Zst (mottled) in fining upwards sequences 0.5-1m thick

occasional lenticular lenses Z and C

L119 S24/191723



Soil - 20cm

Loess - 1m

Conglomerate - 4m unstratified clast suprt sub-ang Cgl with lenses Z

clasts - 90% - av 1-2cm, max 10cm

matrix - 10% crs S

- unconformity -

Sandstone - 2m pll lam - cr lam lt ol gy hd f Sst

# APPENDIX C

## PALEOCURRENT DATA

| Location | Structure Type | Current Direction (Azimuth) |
|---|---|---|
| *southern area* | | |
| S25/947478 | A-lx | 225 |
| S25/942481 | A-lx | 240 |
| S25/942481 | A-lx | 120 |
| S25/936472 | A-lx | 055 |
| S25/936472 | A-lx | 340 |
| S25/936472 | A-lx | 292 |
| S25/936472 | A-lx | 332 |
| S25/935465 | A-lx | 267 |
| S25/938494 | M-mx | 128 |
| S25/938494 | M-mx | 150 |
| S25/937487 | A-lx | 120 |
| S25/937487 | A-lx | 125 |
| S25/945498 | M-mx | 060 |
| S25/947482 | A-lx | 100 |
| S25/944486 | A-lx | 090 |
| S25/943489 | A-Lx | 135 |
| S25/957496 | A-lx | 170 |
| S25/951500 | A-lx | 095 |
| S25/951500 | A-lx | 059 |
| S25/952499 | A-lx | 190 |
| S25/952499 | A-lx | 015 |
| S25/945503 | A-lx | 112 |
| S25/976522 | A-lx | 150 |
| S25/939505 | A-lx | 130 |
| S25/942517 | A-lx | 165 |
| S25/945513 | M-sx | 020 |
| S25/942509 | M-mx | 085 |
| S25/964512 | M-mx | 200 |
| S25/973514 | A-lx | 045 |
| S25/956517 | M-mx | 350 |
| S25/958517 | A-lx | 120 |
| *central area* | | |
| S25/022578 | M-mx | 260 |
| S25/122578 | M-sx | 260 |
| S25/022578 | M-sx | 080 |
| S25/979584 | M-sx | 125 |
| S25/994597 | M-mx | 336 |
| S25/080621 | M-mx | 000 |
| S25/080621 | M-mx | 000 |
| S25/075618 | M-mx | 350 |
| S25/069620 | M-mx | 260 |
| S25/069620 | A-lx | 095 |
| S25/077653 | M-mx | 180 |
| S25/077653 | M-mx | 230 |
| S25/087644 | M-mx | 005 |
| S25/094644 | A-lx | 079 |

| | | |
|---|---|---|
| S25/048676 | A-lx | 035 |
| S25/054669 | A-lx | 063 |
| S25/108657 | M-mx | 210 |
| S25/114657 | M-mx | 290 |
| S25/122653 | M-mx | 145 |
| S25/119675 | M-mx | 000 |
| S25/119675 | M-mx | 355 |
| S25/128669 | M-mx | 250 |
| S25/131672 | A-lx | 105 |
| S25/106685 | M-mx | 100 |
| S25/106685 | M-mx | 000 |
| S25/127684 | M-mx | 073 |
| S25/137692 | M-sx | 010 |
| S25/137692 | M-mx | 035 |
| S25/137692 | M-mx | 330 |
| S25/137692 | M-mx | 120 |
| S25/137692 | M-mx | 135 |
| S25/137692 | M-mx | 335 |
| S25/072622 | M-mx | 085 |
| S25/071622 | M-mx | 100 |
| S25/080622 | A-lx | 140 |
| *northern area* | | |
| S24/156716 | M-c | 000 |
| S24/156716 | M-mx | 005 |
| S24/156716 | M-mx | 150 |
| S24/156716 | M-mx | 062 |
| S24/156716 | M-mx | 325 |
| S24/223706 | F-c | 330 |
| S24/223767 | M-mx | 095 |
| S24/208744 | M-mx | 080 |
| S24/227762 | F-c | 340 |
| S24/207736 | M-mx | 060 |
| S24/207736 | M-mx | 055 |
| S24/207736 | M-mx | 225 |
| S24/207736 | M-c | 150 |
| S24/187742 | M-sx | 340 |
| S24/187731 | M-c | 000 |
| S24/187731 | M-c | 340 |
| S24/187731 | M-mx | 100 |

Key

l - large-scale
m - medium-scale
s - small-scale
x - cross-bed
c - channel

A - aeolian
M - marine
F - fluvial

Locations - Grid Refs. from NZMS 260 series

# APPENDIX D

## GRAIN SIZE ANALYSIS RAW DATA

SAMPLE No.

S27A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.001 | 0.002 | 0.002 |
| 1.000 | 0.001 | 0.002 | 0.004 |
| 1.500 | 0.067 | 0.138 | 0.143 |
| 2.000 | 0.701 | 1.448 | 1.591 |
| 2.500 | 9.740 | 20.125 | 21.716 |
| 3.000 | 29.694 | 61.354 | 83.070 |
| 3.500 | 6.393 | 13.209 | 96.279 |
| 4.000 | 0.907 | 1.874 | 98.153 |
| 4.500 | 0.894 | 1.847 | 100.000 |

S27B

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.001 | 0.002 | 0.002 |
| 1.000 | 0.001 | 0.002 | 0.004 |
| 1.500 | 0.048 | 0.096 | 0.100 |
| 2.000 | 0.684 | 1.371 | 1.471 |
| 2.500 | 12.419 | 24.890 | 26.361 |
| 3.000 | 30.307 | 60.742 | 87.103 |
| 3.500 | 5.006 | 10.033 | 97.136 |
| 4.000 | 0.418 | 0.838 | 97.974 |
| 4.500 | 1.011 | 2.026 | 100.000 |

S27C

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.011 | 0.021 | 0.021 |
| 1.000 | 0.355 | 0.688 | 0.709 |
| 1.500 | 4.606 | 8.926 | 9.635 |
| 2.000 | 12.388 | 24.007 | 33.643 |
| 2.500 | 19.092 | 36.999 | 70.642 |
| 3.000 | 9.921 | 19.226 | 89.868 |
| 3.500 | 1.710 | 3.314 | 93.182 |
| 4.000 | 0.723 | 1.401 | 94.583 |
| 4.500 | 2.795 | 5.417 | 100.000 |

S27D

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.010 | 0.020 | 0.020 |
| 1.000 | 0.086 | 0.175 | 0.195 |
| 1.500 | 1.628 | 3.306 | 3.501 |
| 2.000 | 4.476 | 9.089 | 12.589 |
| 2.500 | 17.672 | 35.883 | 48.472 |
| 3.000 | 19.396 | 39.384 | 87.856 |
| 3.500 | 3.393 | 6.889 | 94.745 |
| 4.000 | 0.778 | 1.580 | 96.325 |
| 4.500 | 1.810 | 3.675 | 100.000 |

C73A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.001 | 0.002 | 0.002 |
| 1.000 | 0.006 | 0.011 | 0.013 |
| 1.500 | 0.227 | 0.420 | 0.433 |
| 2.000 | 3.707 | 6.852 | 7.285 |
| 2.500 | 25.549 | 47.226 | 54.511 |
| 3.000 | 20.473 | 37.844 | 92.355 |
| 3.500 | 2.438 | 4.507 | 96.861 |
| 4.000 | 0.424 | 0.784 | 97.645 |
| 4.500 | 1.274 | 2.355 | 100.000 |

C73B

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.001 | 0.002 | 0.002 |
| 1.000 | 0.008 | 0.019 | 0.021 |

| | | | |
|---|---|---|---|
| 1.500 | 0.242 | 0.569 | 0.590 |
| 2.000 | 3.678 | 8.643 | 9.233 |
| 2.500 | 23.664 | 55.608 | 64.841 |
| 3.000 | 10.916 | 25.652 | 90.492 |
| 3.500 | 2.378 | 5.588 | 96.080 |
| 4.000 | 0.411 | 0.966 | 97.046 |
| 4.500 | 1.257 | 2.954 | 100.000 |

C66A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.001 | 0.002 | 0.002 |
| 1.000 | 0.003 | 0.006 | 0.008 |
| 1.500 | 0.055 | 0.107 | 0.114 |
| 2.000 | 1.804 | 3.500 | 3.615 |
| 2.500 | 14.917 | 28.941 | 32.556 |
| 3.000 | 23.502 | 45.598 | 78.154 |
| 3.500 | 9.086 | 17.628 | 95.782 |
| 4.000 | 1.839 | 3.568 | 99.350 |
| 4.500 | 0.335 | 0.650 | 100.000 |

C66B

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.004 | 0.008 | 0.008 |
| 1.000 | 0.053 | 0.102 | 0.109 |
| 1.500 | 0.748 | 1.436 | 1.545 |
| 2.000 | 5.717 | 10.972 | 12.517 |
| 2.500 | 24.541 | 47.100 | 59.617 |
| 3.000 | 17.639 | 33.853 | 93.471 |
| 3.500 | 2.916 | 5.596 | 99.067 |
| 4.000 | 0.231 | 0.443 | 99.511 |
| 4.500 | 0.255 | 0.489 | 100.000 |

C66C

| SIEVE | WEIGHT | WT. PCT. | CUM WT. PCT. |
|---|---|---|---|
| 0.500 | 0.100 | 0.197 | 0.197 |
| 1.000 | 0.933 | 1.835 | 2.032 |
| 1.500 | 6.186 | 12.169 | 14.201 |
| 2.000 | 13.992 | 27.525 | 41.727 |
| 2.500 | 18.193 | 35.790 | 77.517 |
| 3.000 | 8.903 | 17.514 | 95.031 |
| 3.500 | 1.478 | 2.908 | 97.938 |
| 4.000 | 0.302 | 0.594 | 98.532 |
| 4.500 | 0.746 | 1.468 | 100.000 |

C66D

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.050 | 0.096 | 0.096 |
| 1.000 | 0.210 | 0.403 | 0.499 |
| 1.500 | 3.576 | 6.865 | 7.364 |
| 2.000 | 14.092 | 27.053 | 34.417 |
| 2.500 | 23.106 | 44.357 | 78.774 |
| 3.000 | 8.904 | 17.093 | 95.867 |
| 3.500 | 1.124 | 2.158 | 98.025 |
| 4.000 | 0.253 | 0.486 | 98.510 |
| 4.500 | 0.776 | 1.490 | 100.000 |

C77A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.002 | 0.003 | 0.003 |
| 1.000 | 0.115 | 0.199 | 0.202 |
| 1.500 | 0.466 | 0.806 | 1.009 |
| 2.000 | 2.913 | 5.039 | 6.048 |
| 2.500 | 22.311 | 38.597 | 44.645 |
| 3.000 | 25.284 | 43.740 | 88.385 |
| 3.500 | 4.351 | 7.527 | 95.912 |
| 4.000 | 0.978 | 1.692 | 97.604 |
| 4.500 | 1.385 | 2.396 | 100.000 |

C77B

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 0.500 | 0.091 | 0.167 | 0.167 |
| 1.000 | 0.083 | 0.152 | 0.319 |
| 1.500 | 0.437 | 0.802 | 1.121 |
| 2.000 | 3.649 | 6.695 | 7.816 |
| 2.500 | 20.044 | 36.773 | 44.589 |
| 3.000 | 23.157 | 42.484 | 87.073 |
| 3.500 | 4.156 | 7.625 | 94.698 |
| 4.000 | 0.894 | 1.640 | 96.338 |
| 4.500 | 1.996 | 3.662 | 100.000 |

C77C

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.101 | 0.212 | 0.212 |
| 1.000 | 0.056 | 0.118 | 0.330 |
| 1.500 | 0.468 | 0.984 | 1.314 |
| 2.000 | 2.365 | 4.973 | 6.287 |
| 2.500 | 18.207 | 38.285 | 44.573 |
| 3.000 | 19.372 | 40.735 | 85.308 |
| 3.500 | 3.860 | 8.117 | 93.425 |
| 4.000 | 1.004 | 2.111 | 95.536 |
| 4.500 | 2.123 | 4.464 | 100.000 |

C77D

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.087 | 0.157 | 0.157 |
| 1.000 | 0.330 | 0.594 | 0.751 |
| 1.500 | 1.782 | 3.210 | 3.961 |
| 2.000 | 8.065 | 14.527 | 18.488 |
| 2.500 | 23.586 | 42.484 | 60.972 |
| 3.000 | 16.196 | 29.173 | 90.145 |
| 3.500 | 2.892 | 5.209 | 95.355 |
| 4.000 | 0.780 | 1.405 | 96.760 |
| 4.500 | 1.799 | 3.240 | 100.000 |

C78A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.001 | 0.002 | 0.002 |
| 1.000 | 0.005 | 0.009 | 0.011 |
| 1.500 | 0.094 | 0.179 | 0.190 |
| 2.000 | 5.183 | 9.845 | 10.035 |
| 2.500 | 26.314 | 49.984 | 60.019 |
| 3.000 | 17.512 | 33.264 | 93.283 |
| 3.500 | 1.278 | 2.428 | 95.711 |
| 4.000 | 0.530 | 1.007 | 96.718 |
| 4.500 | 1.728 | 3.282 | 100.000 |

C82A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 2.294 | 4.118 | 4.118 |
| 1.000 | 0.451 | 0.810 | 4.927 |
| 1.500 | 1.375 | 2.468 | 7.396 |
| 2.000 | 4.204 | 7.546 | 14.942 |
| 2.500 | 18.643 | 33.465 | 48.407 |
| 3.000 | 20.790 | 37.319 | 85.726 |
| 3.500 | 3.909 | 7.017 | 92.743 |
| 4.000 | 1.082 | 1.942 | 94.685 |
| 4.500 | 2.961 | 5.315 | 100.000 |

C82B

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.004 | 0.007 | 0.007 |
| 1.000 | 0.036 | 0.060 | 0.067 |
| 1.500 | 0.131 | 0.219 | 0.286 |
| 2.000 | 0.659 | 1.100 | 1.386 |
| 2.500 | 10.916 | 18.227 | 19.613 |
| 3.000 | 32.468 | 54.214 | 73.827 |
| 3.500 | 10.854 | 18.124 | 91.950 |
| 4.000 | 2.641 | 4.410 | 96.360 |
| 4.500 | 2.180 | 3.640 | 100.000 |

C87A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.241 | 0.456 | 0.456 |
| 1.000 | 0.060 | 0.113 | 0.569 |
| 1.500 | 0.358 | 0.677 | 1.246 |
| 2.000 | 2.283 | 4.316 | 5.562 |
| 2.500 | 15.898 | 30.056 | 35.618 |
| 3.000 | 23.588 | 44.595 | 80.213 |
| 3.500 | 6.566 | 12.414 | 92.627 |
| 4.000 | 1.754 | 3.316 | 95.943 |
| 4.500 | 2.146 | 4.057 | 100.000 |

N1A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.043 | 0.085 | 0.085 |
| 1.000 | 0.179 | 0.354 | 0.439 |
| 1.500 | 1.762 | 3.483 | 3.922 |
| 2.000 | 6.881 | 13.601 | 17.523 |
| 2.500 | 18.397 | 36.363 | 53.886 |
| 3.000 | 13.534 | 26.751 | 80.637 |
| 3.500 | 3.632 | 7.179 | 87.816 |
| 4.000 | 1.716 | 3.392 | 91.208 |
| 4.500 | 4.448 | 8.792 | 100.000 |

N1B

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.068 | 0.150 | 0.150 |
| 1.000 | 0.415 | 0.913 | 1.062 |
| 1.500 | 0.884 | 1.944 | 3.006 |
| 2.000 | 5.381 | 11.834 | 14.841 |
| 2.500 | 14.570 | 32.043 | 46.884 |
| 3.000 | 11.648 | 25.617 | 72.501 |
| 3.500 | 3.402 | 7.482 | 79.982 |
| 4.000 | 2.340 | 5.146 | 85.129 |
| 4.500 | 6.762 | 14.871 | 100.000 |

N1C

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 2.767 | 4.702 | 4.702 |
| 1.000 | 1.280 | 2.175 | 6.878 |
| 1.500 | 3.826 | 6.502 | 13.380 |
| 2.000 | 9.568 | 16.260 | 29.640 |
| 2.500 | 21.961 | 37.321 | 66.961 |
| 3.000 | 15.525 | 26.384 | 93.345 |
| 3.500 | 2.770 | 4.707 | 98.052 |
| 4.000 | 0.475 | 0.807 | 98.860 |
| 4.500 | 0.671 | 1.140 | 100.000 |

N118A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.017 | 0.035 | 0.035 |
| 1.000 | 0.012 | 0.025 | 0.059 |
| 1.500 | 0.396 | 0.809 | 0.868 |
| 2.000 | 5.817 | 11.880 | 12.748 |
| 2.500 | 20.495 | 41.856 | 54.604 |
| 3.000 | 17.016 | 34.751 | 89.356 |
| 3.500 | 2.321 | 4.740 | 94.096 |
| 4.000 | 0.674 | 1.376 | 95.472 |
| 4.500 | 2.217 | 4.528 | 100.000 |

N118B

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.008 | 0.016 | 0.016 |
| 1.000 | 0.024 | 0.047 | 0.063 |
| 1.500 | 0.322 | 0.633 | 0.696 |
| 2.000 | 5.479 | 10.779 | 11.475 |
| 2.500 | 21.723 | 42.736 | 54.211 |
| 3.000 | 15.838 | 31.158 | 85.369 |
| 3.500 | 2.506 | 4.930 | 90.299 |

| | | | |
|---|---|---|---|
| 4.000 | 1.008 | 1.983 | 92.282 |
| 4.500 | 3.923 | 7.718 | 100.000 |

N129A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.024 | 0.047 | 0.047 |
| 1.000 | 0.094 | 0.183 | 0.230 |
| 1.500 | 1.236 | 2.411 | 2.641 |
| 2.000 | 6.181 | 12.056 | 14.697 |
| 2.500 | 18.587 | 36.255 | 50.952 |
| 3.000 | 16.963 | 33.087 | 84.039 |
| 3.500 | 3.381 | 6.595 | 90.634 |
| 4.000 | 0.974 | 1.900 | 92.533 |
| 4.500 | 3.828 | 7.467 | 100.000 |

N98A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.040 | 0.079 | 0.079 |
| 1.000 | 0.018 | 0.036 | 0.115 |
| 1.500 | 0.072 | 0.143 | 0.258 |
| 2.000 | 1.689 | 3.354 | 3.613 |
| 2.500 | 9.735 | 19.334 | 22.947 |
| 3.000 | 19.222 | 38.176 | 61.123 |
| 3.500 | 8.570 | 17.021 | 78.143 |
| 4.000 | 3.660 | 7.269 | 85.412 |
| 4.500 | 7.345 | 14.588 | 100.000 |

N98B

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.007 | 0.014 | 0.014 |
| 1.000 | 0.006 | 0.012 | 0.025 |
| 1.500 | 0.112 | 0.216 | 0.241 |
| 2.000 | 1.099 | 2.121 | 2.362 |
| 2.500 | 9.748 | 18.809 | 21.171 |
| 3.000 | 24.549 | 47.369 | 68.540 |
| 3.500 | 10.112 | 19.512 | 88.052 |
| 4.000 | 2.623 | 5.061 | 93.113 |
| 4.500 | 3.569 | 6.887 | 100.000 |

N103A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.004 | 0.008 | 0.008 |
| 1.000 | 0.027 | 0.052 | 0.060 |
| 1.500 | 0.417 | 0.805 | 0.865 |
| 2.000 | 1.963 | 3.791 | 4.656 |
| 2.500 | 14.470 | 27.942 | 32.598 |
| 3.000 | 22.860 | 44.143 | 76.741 |
| 3.500 | 7.180 | 13.865 | 90.606 |
| 4.000 | 1.850 | 3.572 | 94.178 |
| 4.500 | 3.015 | 5.822 | 100.000 |

N111A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 2.109 | 4.164 | 4.164 |
| 1.000 | 2.838 | 5.603 | 9.766 |
| 1.500 | 4.655 | 9.190 | 18.956 |
| 2.000 | 9.942 | 19.628 | 38.584 |
| 2.500 | 16.902 | 33.368 | 71.952 |
| 3.000 | 7.203 | 14.220 | 86.173 |
| 3.500 | 1.592 | 3.143 | 89.316 |
| 4.000 | 1.091 | 2.154 | 91.469 |
| 4.500 | 4.321 | 8.531 | 100.000 |

N130A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.936 | 1.615 | 1.615 |
| 1.000 | 2.805 | 4.840 | 6.456 |
| 1.500 | 6.239 | 10.766 | 17.222 |
| 2.000 | 10.240 | 17.671 | 34.893 |

| | | | |
|---|---|---|---|
| 2.500 | 18.543 | 31.999 | 66.892 |
| 3.000 | 15.428 | 26.623 | 93.515 |
| 3.500 | 2.434 | 4.200 | 97.715 |
| 4.000 | 0.392 | 0.676 | 98.392 |
| 4.500 | 0.932 | 1.608 | 100.000 |

N100A

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.000 | 0.000 | 0.000 |
| 1.000 | 0.021 | 0.038 | 0.038 |
| 1.500 | 0.101 | 0.184 | 0.223 |
| 2.000 | 0.784 | 1.431 | 1.653 |
| 2.500 | 11.750 | 21.444 | 23.097 |
| 3.000 | 28.232 | 51.524 | 74.621 |
| 3.500 | 10.108 | 18.447 | 93.069 |
| 4.000 | 2.133 | 3.893 | 96.961 |
| 4.500 | 1.665 | 3.039 | 100.000 |

KDS1

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.000 | 0.000 | 0.000 |
| 1.000 | 0.000 | 0.000 | 0.000 |
| 1.500 | 0.011 | 0.021 | 0.021 |
| 2.000 | 0.538 | 1.021 | 1.042 |
| 2.500 | 14.995 | 28.447 | 29.489 |
| 3.000 | 29.065 | 55.139 | 84.628 |
| 3.500 | 5.913 | 11.218 | 95.845 |
| 4.000 | 1.211 | 2.297 | 98.143 |
| 4.500 | 0.979 | 1.857 | 100.000 |

KDS2

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.026 | 0.050 | 0.050 |
| 1.000 | 0.041 | 0.078 | 0.128 |
| 1.500 | 0.395 | 0.755 | 0.884 |
| 2.000 | 3.565 | 6.818 | 7.702 |
| 2.500 | 19.484 | 37.263 | 44.964 |
| 3.000 | 22.534 | 43.096 | 88.060 |
| 3.500 | 3.730 | 7.134 | 95.194 |
| 4.000 | 1.086 | 2.077 | 97.271 |
| 4.500 | 1.427 | 2.729 | 100.000 |

KDS3

| SIEVE | WEIGHT | WT. PCT. | CUM. WT. PCT. |
|---|---|---|---|
| 0.500 | 0.000 | 0.000 | 0.000 |
| 1.000 | 0.018 | 0.034 | 0.034 |
| 1.500 | 0.232 | 0.442 | 0.477 |
| 2.000 | 1.869 | 3.563 | 4.039 |
| 2.500 | 14.457 | 27.558 | 31.597 |
| 3.000 | 30.385 | 57.920 | 89.518 |
| 3.500 | 4.371 | 8.332 | 97.850 |
| 4.000 | 0.547 | 1.043 | 98.892 |
| 4.500 | 0.581 | 1.108 | 100.000 |

APPENDIX E

## POLLEN ANALYSIS OF TWO SAMPLES FROM THE OTAKI FORMATION (METRIC SHEET S24)

D C Mildenhall
18th October, 1990
File S24/772
Report DCM 126/90

Two pollen samples were collected from just south of Tokomaru Stream in a farm track cutting in a terrace immediately behind a cowshed. The bed sampled occurs just below a lower conglomerate (Fig.1) partly obscured by vegetation and is c.17m below the top of the Otaki Sandstone. the grid reference is S24/223766.

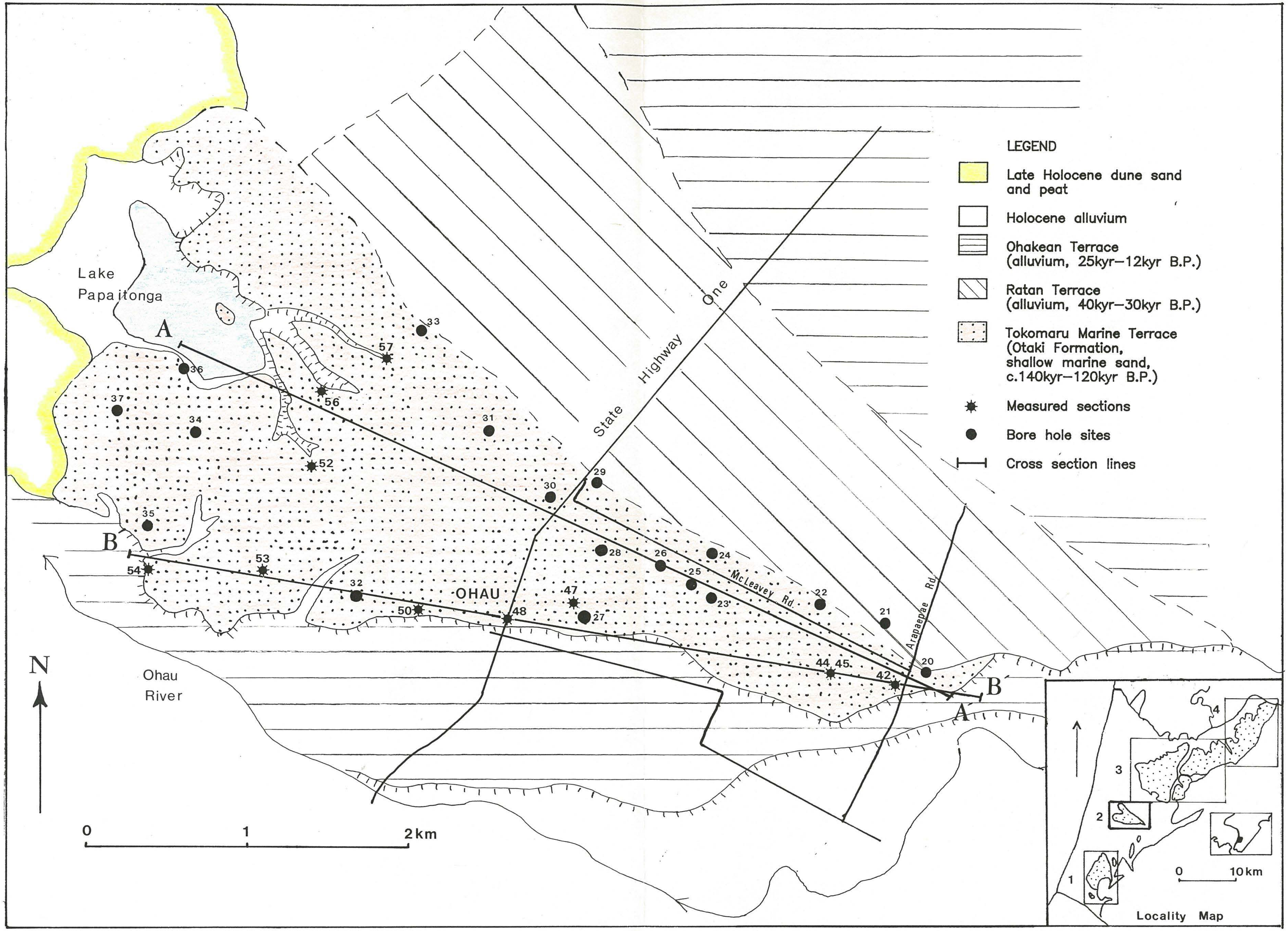
| Fossil record no. | Slide no. | Lithology/environment | Age |
|---|---|---|---|
| S24/f44 | L14637 | fine sand & silt/swamp | WC? |
| S24/f45 | L14638 | " /lagoonal marsh | WC? |

Sample S24/f44 contains abundant well preserved plant material but relatively sparse spores and pollen representative of derivation from an acid peat flax swamp with beech/podocarp forest nearby. There were relatively few taxa identified and it was not possible to determine whether the climate was warm or cold although the lack of distinctive cold climate pollen types would seem to indicate an interglacial peat.

The palynoflora is dominated by monolete spores (35% of the total spores plus pollen assemblage) with the total pollen represented by Cyperaceae (possibly including Gahnia) (31%), <Coprosma> (15%), <Nothofagus fusca> group (11%), <Phormium tenax> (9%), Gramineae (8%), Restionaceae (5%), Compositae (Tubuliflorae) (5%), <Podocarpus/Prumnopitys> (5%) and <Myrsine> (3%). Some of the pollen grains, especially the beeches, were darker in colour than the others and may be recycled. The presence of the spore (Polypodiisporites radiatus Pocknall & Mildenhall may indicate a Castlecliffian age. Pollen from trees formed 18% and herbs 54% of the total pollen flora from a total count of only 102 grains.

Sample S24/f45, from immediately above S24/f44, is very similiar to f44 and the environment is also an acid flax swamp, except that it contains many more taxa and many more grains in total. A count of 260 grains was made. The presence in this sample of <Dactylanthus taylori> would indicate an interglacial palynoflora. <D.taylori is a root parasite which only occurs in the North island down to Kaitoke near Wellington. This would suggest that the climate was at least as equitable as the present day.

The palynoflora is dominated by the following taxa:- undifferentiated monolete spores (15% of the total palynoflora), <Cyathea> (5% of the total palynoflora), and with precentages based only on the total pollen, Cyperaceae (37%), <Nothofagus fusca> group (19%), <Coprosma> (11%), <Phormium tenax> (7%), Compositae (Tubuliflorae) (4.5%), ‹Podocarpus/Prumnopitys› (4%), Gramineae (3.5%), and ‹Nothofagus menziesii› (2.5%). A number of pollen grains could not be identified as they occurred as "ghosts", possibly as a result of transport to the site of deposition; other grains of darker colour may have been recycled. Polypodiisporites radiatus was also present in this sample, which could be as old as Castlecliffian. Pollen from trees form 33% of the total pollen and herbs 50% indicating encorachment onto the site of the surrounding forest and a possible drying out of the swamp. However, abundant available flowing water was still present to allow for the growth of flax (‹Phormium tenax›), ‹Myriophyllum, Haloragis› and Restionaceae.




Map 2: Geology, Ohau