

PETROLEUM REPORT SERIES

PR4880

Title **Lithofacies, paleoenvironments and sequence stratigraphy of the Late Oligocene Aotea Formation (Te Kuiti Group), central-western North Island, New Zealand**

Operator

Author Peter J.J. Kamp, Anand R.P. Tripathi, and Campbell S. Nelson

Date 2014

Summary This report presents a comprehensive facies and sequence stratigraphic analysis of the Late Oligocene Aotea Formation within the Late Eocene – Earliest Miocene Te Kuiti Group in the Waikato-King Country Basin in central-western North Island, New Zealand. The Aotea Formation is a mixed carbonate-siliciclastic succession with four facies associations: limestone (Waimai Limestone Member), calcareous sandstone (Hauturu Sandstone Member, Kihi Sandstone Member), calcareous siltstone (Patikirau Siltstone Member) and chemogenic facies (upper parts of Kihi Sandstone Member, Patikirau Siltstone Member and Waimai Limestone Member). These facies are established from field descriptions supplemented by laboratory textural and petrographic data and are inferred to have accumulated in different sectors of a shelf environment. The Aotea Formation comprises one sequence for which key surfaces and systems tracts are described and interpreted. The lower sequence boundary is a wave-planed surface. It, together with the subsequent onlap deposits represent a marked basinward shift in the position of coastal onlap arising from basin inversion focussed along the western margin of the basin, followed by marked subsidence in the northern part of the basin.

This report has been compiled from material submitted to the New Zealand Government under legislation or voluntarily by exploration companies. An acknowledgement of this work in the following bibliographic format would be appreciated:

Kamp, P.J.J., Tripathi A.R.P., and Nelson, C.S. 2014. Lithofacies, paleoenvironments and sequence stratigraphy of the Late Oligocene Aotea Formation (Te Kuiti Group), central-western North Island, New Zealand. Ministry of Business, Innovation and Employment, New Zealand, unpublished Petroleum Report PR4880, 45 p.

Contents

List of Figures	ii
Tables	vi
Introduction	1
Lithofacies overview	2
Limestone lithofacies (L1 - L5).....	7
Mixed carbonate-siliciclastic sandstone lithofacies (S1 - S4).....	17
Mixed carbonate-siliciclastic siltstone lithofacies (Z1)	22
Chemogenic lithofacies association (C1 - C2).....	22
Lithofacies distribution and paleoenvironmental implications	30
Distribution and depositional paleoenvironment of the lower facies group.....	30
Distribution and depositional paleoenvironment of the upper facies group	32
Sequence stratigraphy	33
Lower sequence boundary.....	33
Downlap Surface (DLS).....	33
Transgressive Systems Tract (TST).....	35
Highstand Systems Tract (HST).....	37
Condensed section	39
Qualitative model of Aotea sequence.....	40
Control on sequence architecture	40
A model Aotea sequence for the northern region.....	40
A model Aotea sequence for the southern central region.....	42
Summary	43
Acknowledgements	43
References	43

List of Figures

<i>Fig. 1:</i> Map of central-western North Island showing the distribution of the Te Kuiti Group and other units. Note the location of key stratigraphic columns.....	1
<i>Fig. 2:</i> A new chronostratigraphic scheme for the Te Kuiti Group and the transition to the Waitemata and Mahoenui Groups. Note the occurrence of six unconformity-bound sequences (TK1 – TK6) (Kamp et al. 2014b).....	2
<i>Fig. 3:</i> Map showing the distribution of the lower group of lithofacies in Aotea Formation (see Table 2) and key paleogeographic elements.	3
<i>Fig. 4:</i> Map showing the distribution of the upper group of lithofacies in Aotea Formation (see Table 2) and key paleogeographic elements.	4
<i>Fig. 5:</i> Correlation of Aotea Formation members from Waimai Valley in the north (Column J) to Awakino Tunnel (Column A) in the south. The datum is the base of Orahiri Formation or its correlative (Te Akatea Formation) in the north.	5
<i>Fig. 6:</i> General extent and thickness distribution of Aotea Formation.....	6
<i>Fig. 7:</i> (facing page) Field photographs of the typical carbonate lithofacies in the Aotea Formation. (a) A unit of rhodolith-bearing conglomerate (Lithofacies L1) onlapping Mesozoic basement rocks in the Honikiwi section (C-25), interpreted as a transgressive lag deposit formed in an advancing shoreline. (b) Massive pebbly grainstone/packstone lithofacies (L1) passing upwards into Horizontally bedded grainstone/packstone (Lithofacies L3) with common scattered granules and pebbles. These facies are inferred to be transgressive marking gradual onlap and submergence of elevated basement areas. Photo location: Honikiwi Road (C-25). (c) Low to moderate angle tabular cross-bedded grainstone lithofacies (L2) typical of Waimai Limestone Member in the northern region, Waikawau Beach, Port Waikato (PW-11). Note well-defined set boundaries bounding the foresets. The Waikorea Sandstone Member of Whaingaroa Formation is erosionally truncated (arrow) and overlain by prominently cross-bedded skeletal grainstone in the lower half of the photo. Exposure is approximately 3 m high. (d) Low- angle tabular Cross-bedded (arrows) grainstone lithofacies (L2), Waimai Limestone Member. Note recessed siliciclastic-rich bedding planes. Hammer for scale. Photo location: Waikorea (TA-2). (e) Horizontally bedded grainstone/packstone lithofacies (L3) in Waimai Limestone Member exposed near Te Akau (TA-9). Note thickness variation in individual beds. Hammer for scale. (f) Sandy-silty grainstone lithofacies (L4) in Waimai Limestone Member. This facies is common in the southern and central regions where it represents transition between Hauturu Sandstone and Waimai Limestone members. Exposure is approximate 4 m high. Photo location: Makaka, north of Aotea Harbour (AK-1). (g) Close-up of the Sandy-silty grainstone lithofacies (L4). Note its resemblance to Fine to medium grained sandstone Lithofacies S1 (Hauturu Sandstone Member). Photo location: Makaka (AK-1), north of Aotea Harbour. (h) Horizontally bedded grainstone/packstone lithofacies (L3) passing upward into Low-angle tabular Cross-bedded grainstone lithofacies (L2) (arrow), which in turn grade upwards into Massive bioturbated grainstone/packstone lithofacies (L5), which is abruptly overlain by massive poorly cemented slightly to moderately glauconitic siltstone Lithofacies Z1 (Patikirau Siltstone Member). Entire succession is broadly transgressive and displays the complete spectrum from moderate to high energy inner-mid shelf skeletal grainstone at the base, to deep water outer shelf siltstone at the top. Hammer for scale (circled). Photo location: Waikaretu (PW-9).....	11
<i>Fig. 8:</i> Schematic cross sections showing the major lithofacies and their thickness trends within Waimai Limestone Member in the northern region. Also shown is the nature of the sequence boundary below the Waimai Limestone, and the relationship with overlying units. Location map shows selected stratigraphic columns used to construct schematic cross-sections, and detailed petrographic analysis (refer Fig. 9). Location A, PW-1A; B, PW-1; C, PW-5; D, PW-8; E, PW-9; F, TA-3; G, TA-5.....	12
<i>Fig. 9:</i> Summary of average whole rock and bioclast compositional trends amongst lithofacies within Waimai Limestone Member in the locations shown in Fig 8.....	13
<i>Fig. 10:</i> Photomicrographs of representative samples from lithofacies in the Waimai Limestone Member, and overlying condensed units. (a) Bryozoan/echinoderm/bivalve/calcareous red algae in a cross-bedded sparry grainstone Lithofacies L2, location E (Fig. 8). Sample 120. (b) Echinoderm/benthic/planktic foraminiferal assemblage along with common glauconite, in Lithofacies L3, location D (Fig. 8). Sample 96. (c) Bryozoan/echinoderm/benthic foraminiferal assemblage in a Cross-bedded sparry grainstone Lithofacies L2, location F (Fig. 8). Sample 177. (d) Echinoderm/calcareous red algae/benthic foraminifera along with glauconite in a Mixed grainstone/	

packstone Lithofacies L5, location B (Fig. 8). Sample 25. (e) Planktic foraminifera-rich wackestone with abundant glauconite pellets and infills, Lithofacies C2, location A (Fig. 8). Sample 8. (f) Planktic/benthic foraminiferal assemblages in a wackestone (Lithofacies C2) with abundant glauconite pellets and infills, supportive of a deep-water depositional environment, location B (Fig. 8). Sample 26. 15

Fig. 10 (continued): Photographs of representative samples from lithofacies types in Waimai Limestone Member and Mangiti Sandstone Member. (g) Echinoderm/benthic foraminiferal assemblage with glauconite pellets in a Mixed grainstone/packstone L3 facies, location G (Fig. 8). Sample 196. (h) Echinoderm/benthic foraminifera/bryozoan in a Calcareous sandstone S3 facies, location G (Fig. 8). Sample 197. (i) Echinoderm/benthic foraminifera/calcareous red algae/bivalves in lithofacies L4, location AK-1. Sample 349. (j) Bryozoan/echinoderm/benthic foraminiferal assemblage in a Mixed grainstone/packstone lithofacies L4, location AK-1. Sample 350. (k) Echinoderm/bryozoan/calcareous red algae in Cross-bedded grainstone lithofacies L2, location AK-1. Sample 353. (l) Echinoderm/bivalve/benthic foraminiferal assemblages in Calcareous sandstone lithofacies S1, location AK-1. Sample 355. 16

Fig. 11: (facing page) Field photographs of Variably calcareous fine to medium sandstone Lithofacies S1 (Hauturu Sandstone Member) in the basin. (a) Massive buff coloured friable sandstone exposed near Kokakoroa Road, Te Anga (C-40). (b) Medium to thick bedded calcareous sandstone packages, often amalgamated, Kihi Road (S-13). Exposure is approximately 20 m high. (c) Typical weathering character consisting of alternating recessive and laterally discontinuous ellipsoidal shaped well-cemented slabs, exposed near Mangaotaki, west of Piopio (C-145). (d) Massive friable fine to medium sandstone gradually passing upward into low angle cross-bedded sandstone with medium to coarse echinoderm coquina. Photo location: Awakino Tunnel (C-191). (e) Extensively burrowed sandstone bed with scattered rounded to subrounded granules and bivalves (whole shells and broken pectinid fragments), and echinoderm fragments. Photo location: Kihi Road (S-13). (f) Pebble-granule band with abundant bivalve molds chaotically oriented, a common occurrence in this lithofacies. Photo location: Kaimango (C-8). (g) Extensive burrow networks present near the lower unconformable contact of this unit with the Glen Massey Formation. Photo location: Okapu, east of Aotea Harbour (AK-5). (h) Sandstone bed containing abundant echinoderm debris as well as unidentified skeletal fragments, a common feature of this lithofacies. Photo location: Kihi Road (S-13). 19

Fig. 12: Field photographs of mixed carbonate-siliciclastic sandstone lithofacies in the Aotea Formation across the basin. (a) Sharp facies transition between Fine to medium sandstone Lithofacies S1 (Hauturu Sandstone) and well cemented Calcareous silty sandstone Lithofacies S2 (Kihi Sandstone). Note the sharp break (arrow) in the weathering profile marking the facies transition. Exposure is about 8 m high. Photo location: Hautapu Hill (C-4). (b) Interbedded Calcareous sandstone and sandy siltstone Lithofacies S3 (Mangiti Sandstone) sharply overlying massive siltstone unit (Kotuku Siltstone Member of Whaingaroa Formation). The Mangiti Sandstone and Kotuku Siltstone are separated by an erosional surface (arrow). Exposure is approximately 10 m high. Photo location: near Matakītaki Road, Glen Murray (PW-7). (c) Buff coloured fine to very fine calcareous sandstone interbedded with thin sandy siltstone (Lithofacies S3) from the lower part of the Mangiti Sandstone at its type locality of Mangiti Road, north of Raglan Harbour (TA-12). Note prominent vertical solution cavities imparting a blocky appearance is a typical weathering feature of this facies. (d) Bioturbated bluish-grey muddy sandstone Lithofacies S4 (Kihi Sandstone) exposed along Honikiwi Road (AK-14). Note exfoliation weathering is a typical feature of this facies. (e) Close-up showing rounded-subrounded granules scattered within Bioturbated muddy sandstone Lithofacies (S4). Note light rusty brown patches marking the presence of burrows. Photo location: Honikiwi Road (AK-14). (f) Mottling due to extensive soft-bodied infaunal burrowing activity is common within the Muddy sandstone Lithofacies S4. Photo location: Honikiwi Road (AK-14). 20

Fig. 13: Photographs of the typical field expression of various lithofacies in the Aotea Formation across the basin. (a) Medium to dark bluish-grey Massive sandy siltstone Lithofacies Z1 (Patikirau Siltstone Member) overlying Interbedded calcareous sandstone and sandy siltstone Lithofacies S3 (Mangiti Sandstone; visible at the left hand corner), exposed in a sea cliff at its type locality, Patikirau Bay, Raglan Harbour (TA-20). Note thin silty sandstone interbeds in the lower and upper-middle part of the section. The exposure is approximate 50 m high. (b) Massive to moderately bedded grainstone/packstone Lithofacies L5 of Waimai Limestone abruptly passing upward into moderately glauconitic Massive sandy siltstone Lithofacies Z1 (Patikirau Siltstone). Photo location: Waikaretu Limestone quarry (PW-9). (c) Large *Lentipecten hochstetteri* shells in highly glauconitic sandstone of Lithofacies C1. Photo location: Honikiwi Road (AK-14). (d) Close-up showing medium to coarse sand glauconitic pellets scattered in extensively burrowed sandstone Lithofacies C1 from the upper part of Aotea Formation (Kihi Sandstone). Photo location: Waitomo Valley Road (C-32). (e) *Thalassinoides* burrows in Cross-bedded grainstone Lithofacies L2. Photo location: Waikaretu Limestone Quarry (PW-9). (f) Extensive *Thalassinoides* burrow network preserved in a fallen block of Horizontally bedded grainstone/packstone Lithofacies L3. Photo location: Baker Road, east of Limestone Downs (PW-4). 23

<i>Fig. 14:</i> Map showing the location of five transects illustrated in Figs. 15 - 19.....	24
<i>Fig. 15:</i> Northwest-southeast transect A-A' across the northern part of the basin (see Fig.14 for location). Datum: Sequence boundary (SB 4) between Whaingaroa Formation (seq. 3) and Aotea Formation.....	25
<i>Fig. 16:</i> (<i>this page and opposite</i>) North-south transect B-B' along the western side of the northern region (see Fig. 14 for location). Datum: Sequence boundary between Whaingaroa Formation (seq. 3) and Aotea Formation (seq. 4).	26
<i>Fig. 17:</i> Southwest-northeast transect C-C' across the northern side of Aotea Harbour (see Fig. 14 for location). Datum is sequence boundary between Glen Massey Formation (seq. 2) and Aotea Formation (seq. 4).	28
<i>Fig. 18:</i> Northwest-southeast transect D-D' across the central-southern region of the basin (see Fig. 14 for location). Datum is sequence boundary between Glen Massey Formation (seq. 2) and Aotea Formation (seq. 4) on the western (left) end, and Whaingaroa Formation (seq. 3) and Aotea Formation (seq. 4) on the eastern (right) end. Note Aotea sequence laps basement at location C-32.	28
<i>Fig. 19:</i> Northeast-southwest transect across the southern region (see Fig. 14 for location). Datum is sequence boundary between Glen Massey Formation (seq. 2) and Aotea Formation (seq. 4) on the western (left) side, and Whaingaroa Formation (seq. 3) and Aotea Formation (seq. 4) on eastern (right) side. Note that the Aotea Formation at C-51 is inferred to have been subsequently eroded.	29
<i>Fig. 20:</i> Hauturu Sandstone Member (Lithofacies S1) thickness distribution map. Isopach data derived from outcrops and drill holes (circles). Contour interval is 10 m. A sediment fairway into the adjoining eastern margin of Taranaki Basin is suggested by the observed thickness trend in the vicinity of Kawhia Harbour.	31
<i>Fig. 21:</i> Photographs of the typical field expression of sequence boundaries in the Aotea sequence across the basin. (a) Arrow points to the truncated older sequence (Ahirau Sandstone Member of Glen Massey Formation) below the sequence boundary and overlying highly calcareous Fine to medium sandstone and sandy limestone Lithofacies S1-L4 (Hauturu Sandstone). Photo location: Kaimango (C-8). (b) Scoured contact (arrow) inferred as sequence boundary between massive calcareous silty sandstone (Ahirau Sandstone Member of Glen Massey Formation) and fine to medium grained calcareous sandstone (Hauturu Sandstone) containing abundant granule-pebbles with common medium to large burrows. This basal pebbly unit immediately overlying the contact is inferred to represent the transgressive lag deposits before passing upward (above the sharp overhang in the photo) into alternating friable to well cemented medium to coarse sandstone with common gritty-pebbly bands of Lithofacies S1. Photo location: Mahoe Road (C-24). (c) Sharp contact (arrow) inferred as a sequence boundary between medium bluish-grey sandy siltstone (Ngapaenga Siltstone Member of Whaingaroa Formation) and overlying moderately to well cemented coarse sandstone Lithofacies S1 (Hauturu Sandstone). Note the presence of large burrow tubes to the left of hammer. Photo location: Mangaotaki, west of Piopio (C-145). (d) Sequence boundary (arrow) showing erosional relief and a burrowed contact between fine silty sandstone (Ahirau Sandstone Member of Glen Massey Formation) and overlying burrowed fine to medium grained sandstone Lithofacies S1 (Hauturu Sandstone) exposed near Harbour Road, Kawhia (R15/807440). Photo courtesy D. Fergusson (1986). (e) Arrow pointing to erosionally truncated calcareous silty sandstone (Waikorea Sandstone Member) below sequence boundary with Waimai Limestone above. The boundary displays centimetre scale relief, and is extensively burrowed. Photo location: Kaawa stream valley, near Limestone Downs (PW-3). (f) Sequence boundary displaying centimetre scale erosional relief separating massive calcareous siltstone and sandy siltstone of an older sequence (Whaingaroa Formation) from the overlying bedded calcareous sandstone with thin silty interbeds of Lithofacies S3 of Mangiti Sandstone. Exposure is approximately 25 m high. Photo location: near Te Kotuku Trig. north of Raglan Harbour (TA-12).....	35
<i>Fig. 22:</i> (<i>page facing</i>) Field photographs of typical lithofacies relationships in the Aotea Formation, and inferred systems tracts and sequence boundaries in the northern and central regions. (a) Normal deepening upward succession, showing a conformable transition from Fine to medium calcareous sandstone (Lithofacies S1; Hauturu Sandstone) to Massive muddy sandstone (Lithofacies S4; Kihī Sandstone). The arrow points to a conformable facies contact and possibly indicates the initiation of early highstand deposition. Photo location: Shea Road (AK-4). Exposure is about 6 m high. (b) Conformable facies contact (arrow) between the Cross-bedded sandy silty grainstone/packstone lithofacies (L4) (Waimai Limestone/Hauturu Sandstone) and Massive calcareous silty sandstone Lithofacies S2 (Kihī Sandstone). The facies transition indicates an abrupt decrease in energy level across the contact, possibly due to deepening. Photo location: Makaka, north of Aotea Harbour (AK-1). (c) Alternation of fine calcareous sandstone Lithofacies S1 and Calcareous silty sandstone Lithofacies S2 (Hauturu	

Sandstone) comprises much of the upper part of Aotea sequence at this location. The overlying cross-bedded sandy limestone (Mangaotaki Limestone Member of Orahiri Formation) is separated by the sequence boundary at the narrow ledge (arrow). Exposure is about 25 m high. Photo location: Mangaohae Stream (C-56). (d) Sandy grainstone Lithofacies L4 (Waimai Limestone/Hauturu Sandstone) inferred to be transgressive deposits gradually passing upward into early highstand deposits comprising Massive calcareous silty sandstone Lithofacies S2 (Kihi Sandstone). Photo location: Te Raumauku near Honikiwi (C-28). (e) Thin-bedded calcareous sandy siltstone Lithofacies S2 (Kihi Sandstone) gradually passing upwards into dark coloured Glauconitic silty sandstone Lithofacies C1 representing condensed sediment. Exposure is about 12 m high. Photo location: near Bromley and Honikiwi Road intersection (S16/976364). (f) Basement onlap succession made up of basal lenticular Pebbly-gritty grainstone/packstone Lithofacies L1 (Waimai Limestone) overlain by bedded Muddy sandstone Lithofacies S4 (Kihi Sandstone). Note highly irregular top of Mesozoic basement. The entire succession is broadly transgressive and displays inner shelf carbonates at the base, to mid-outer shelf siltstone at the top (not shown in photograph). Photo location: SH3, near Mangaotaki Bridge (C-166). Road marker for scale. (g) Wave-planed surface (arrow) inferred as sequence boundary at the contact between Calcareous fine to medium sandstone Lithofacies S1 (Hauturu Sandstone) and sandy limestone (Mangaotaki Limestone) of the overlying Orahiri Formation at Mangaotaki (C-145). 37

Fig. 23: Field photographs of typical lithofacies relationships in Aotea sequence, and inferred systems tract and sequence boundaries in the northern region. (a) Aotea sequence consisting of Cross-bedded grainstone Lithofacies L2 passing upward into Massive to irregularly bedded grainstone/packstone Lithofacies L5 (Waimai Limestone), which in turn passes upward into Moderately glauconitic sandy siltstone Lithofacies Z1 (Patikirau Siltstone). The lower sequence boundary (arrow) is a wave-planed surface cutting into moderately calcareous silty sandstone (Waikorea Sandstone Member of Whaingaroa Formation). Note dark coloured massive sandy siltstone (Patikirau Siltstone) passing upward into light coloured calcareous siltstone (Carter Siltstone Member of Te Akatea Formation). The upper arrow points to a paraconformity inferred to be a correlative conformity. Photo location: Waikaretu limestone quarry (PW-9). (b) Horizontally bedded grainstone/packstone Lithofacies L3 (Waimai Limestone) is separated by a sequence boundary (arrow) from the underlying Waikorea Sandstone Member of Whaingaroa Formation. The lower 10-15 cm of limestone unit is also moderately glauconitic suggesting a minor hiatus. Note the presence of thin silty interbeds in the lower middle part of the outcrop marking the gradual upward transition to Interbedded calcareous sandstone and sandy siltstone Lithofacies S3 (Mangiti Sandstone). Exposure is approximately 8 m high. Photo location: Bothwell Road, west of Glen Murray. (PW-8). (c) A typical deepening/fining upward cycle in the Aotea sequence. Wave-planed surface (arrow) cutting into the underlying calcareous silty sandstone (Waikorea Sandstone) interpreted as a sequence boundary, is overlain by low-angle Cross-bedded skeletal grainstone Lithofacies L2, which passes upward into Massive to irregularly bedded grainstone/packstone Lithofacies L5 (Waimai Limestone). The highly glauconitic and fossiliferous glauconitic packstone/wackestone Lithofacies C2 marks the condensed sediment indicating drowning of the carbonate platform. Photo location: Port Waikato (PW-1). (d) The gently undulating contact (arrow) inferred as a sequence boundary between calcareous silty sandstone (Waikorea Sandstone) and the overlying tabular low angle Cross-bedded grainstone Lithofacies L2 (Waimai Limestone). Exposure is about 10 m high. Photo location: Waikorea-Matira (TA-2). (e) Bedded calcareous sandstone Lithofacies S3 of Mangiti Sandstone at the shore level gradually passes upwards through an interbedded transition zone into Massive sandy siltstone Lithofacies Z1 of Patikirau Siltstone. Note thin calcareous sandstone beds at the transition interval. The arrow points to a paraconformity (inferred as a correlative conformity) between the Patikirau Siltstone and Raglan Limestone of the Te Akatea Formation. Exposure is approximate 50 m high. Photo location: Patikirau Bay, Raglan Harbour (TA-20). (f) Moderately calcareous silty sandstone (Waikorea Sandstone) is erosionally truncated (arrow) and overlain by interbedded calcareous sandstone and sandy siltstone (Mangiti Sandstone). Exposure is approximately 8 m high. Photo location: Matakītaki Road, near Glen Murray (PW-7). 39

Fig. 24: Organisation of Aotea depositional sequence within a sequence stratigraphic framework along a northwest-southeast profile (approximately from Port Waikato to Huntly; transect A-A' on Fig. 14). The sequence boundary erosionally truncates the underlying Whaingaroan Formation (seq. 3) as observed on the western margin, whereas to the east it is inferred to be a correlative conformity. 41

Fig. 25: Organisation of Aotea depositional sequence within a sequence stratigraphic framework along a northwest-southeast profile (approximately from east of Kawhia Harbour to south of Otorohanga; transect D-D' on Fig. 14). The sequence boundary truncates a progressively older sequence in a westward direction. The Aotea sequence laps onto a paleo-basement high to the east. This high (Piopio High) separates the southern region into two parts (Figs 3,4). TST comprising calcareous fine to medium sandstone (Hauturu Sandstone) is restricted mainly to the west of this intra-basinal high. 41

Tables

<i>Table 1:</i> Aotea Formation lithofacies.....	8
<i>Table 2:</i> Lithofacies distribution within Aotea Formation.....	30

Introduction

This report documents the lithofacies, paleoenvironments and sequence stratigraphy of the Late Oligocene Aotea Formation, which occurs in the lower part (Okoko Subgroup) of the Te Kuiti Group in central-western North Island (Figs 1 and 2). The Te Kuiti Group is a

mixed carbonate and siliciclastic sedimentary succession that overlies Mesozoic basement and accumulated in the Waikato-King Country Basin, immediately east of Taranaki Basin (Kamp et al. 2014a). The lithostratigraphy of the Aotea Formation has been described in detail in Tripathi et al. (2008).

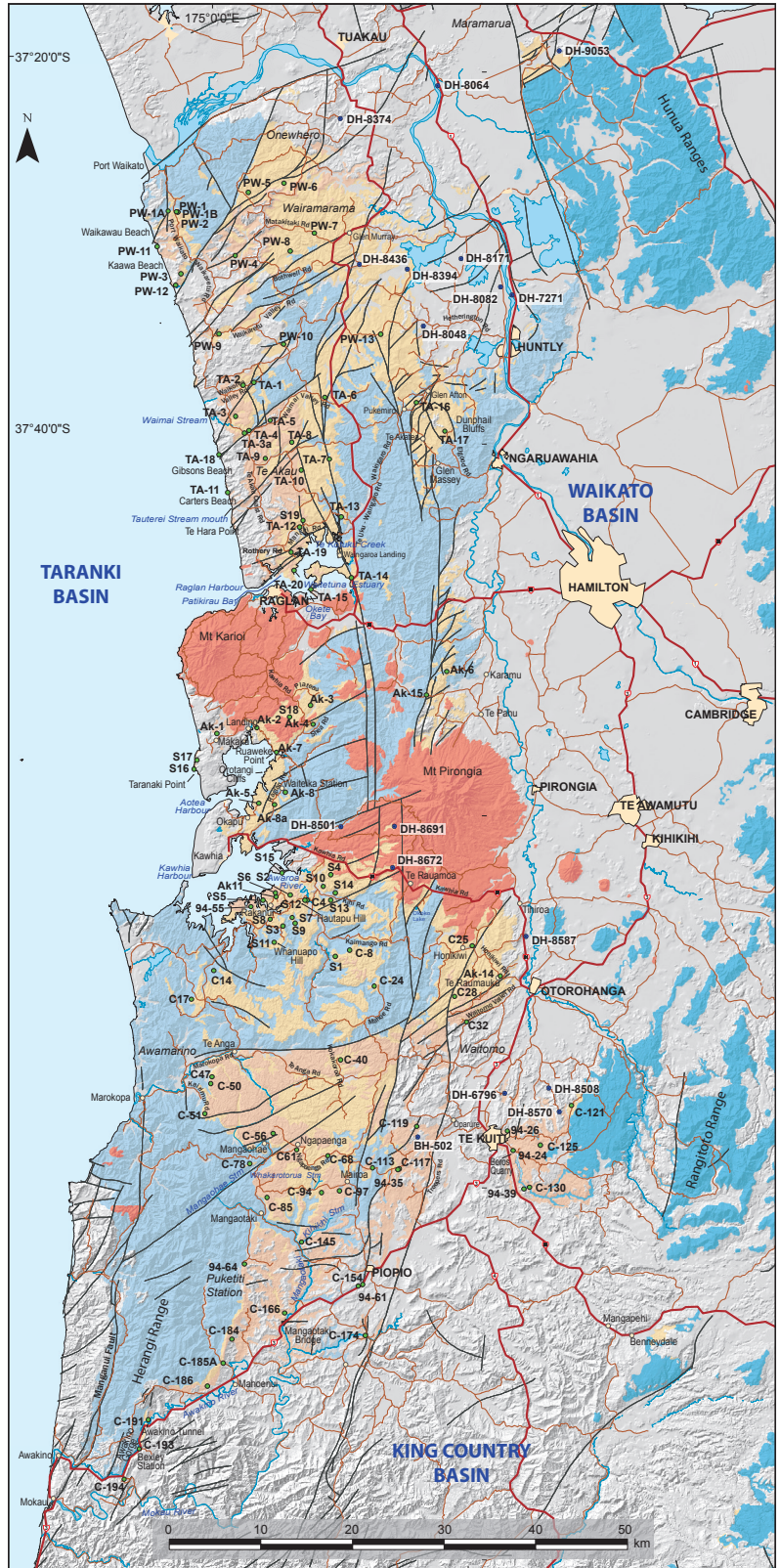
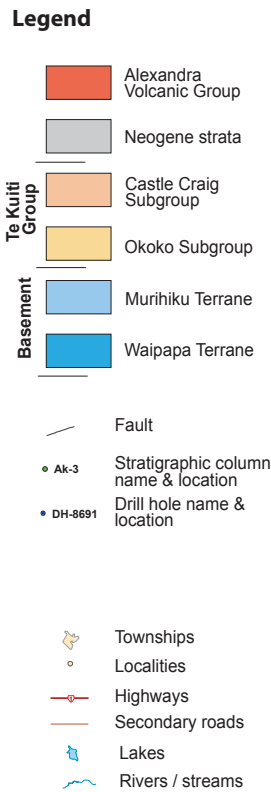


Fig. 1: Map of central-western North Island showing the distribution of the Te Kuiti Group and other units. Note the location of key stratigraphic columns.

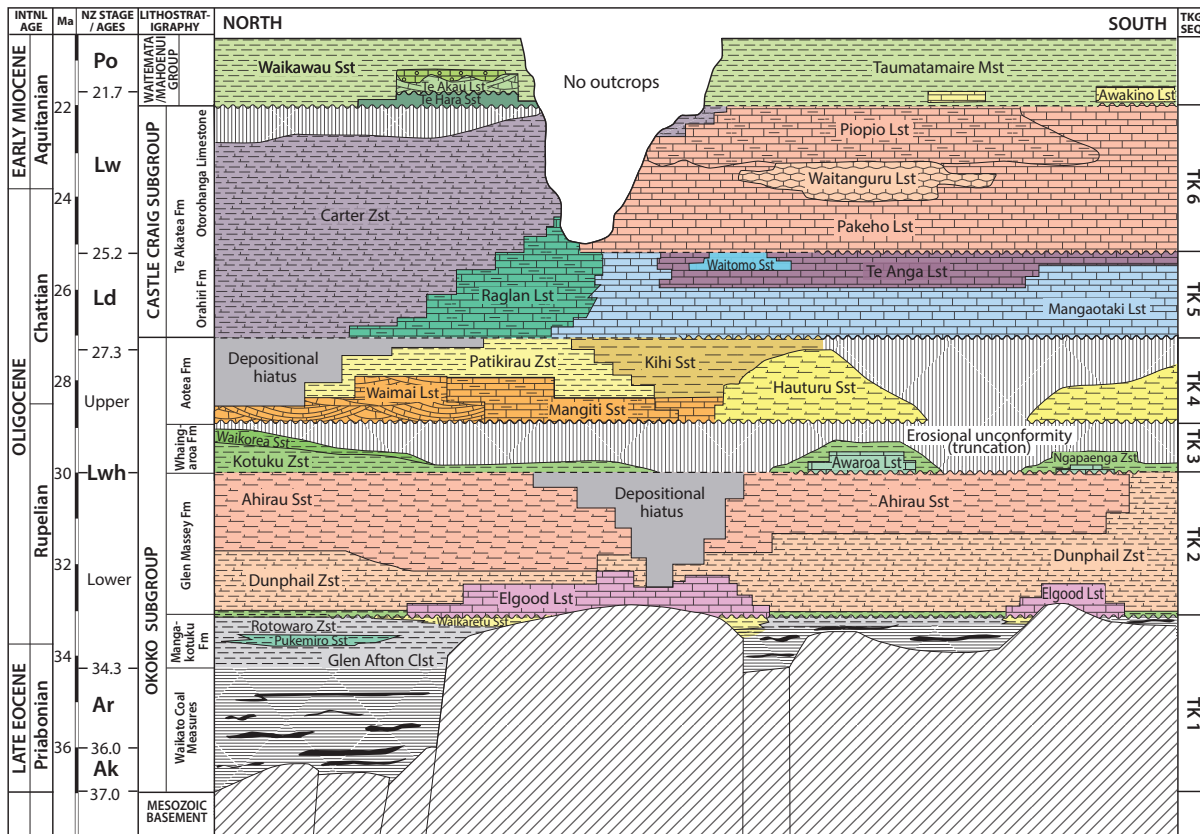


Fig. 2: A new chronostratigraphic scheme for the Te Kuiti Group and the transition to the Waitemata and Mahoenui Groups. Note the occurrence of six unconformity-bound sequences (TK1 – TK6) (Kamp et al. 2014b).

The Aotea Formation exhibits more lithofacies diversity than any of the other formations in the Te Kuiti Group (Nelson 1978a; Kamp et al. 2014a) and through conventional facies analysis coupled with stratigraphic correlation we map the lithofacies across the depositional area for both the lower and upper parts of the formation (Figs 3 and 4). The lithofacies diversity results from several factors: (i) The start of accumulation of the formation followed an interval of uplift and differential erosion of the underlying formations, meaning that there was a basinward (downward) step in the position of coastal onlap; (ii) The introduction of a quartzofeldspathic fine to medium sandstone (Hauturu Sandstone Member) via longshore drift into the southwestern part of the basin, this sandstone having an origin beyond the basin's margins; (iii) Rapid subsidence of the northern part of the basin, leading to upper bathyal conditions and condensed sedimentation, whereas sediments accumulated in shelf environments in the southern part of the basin.

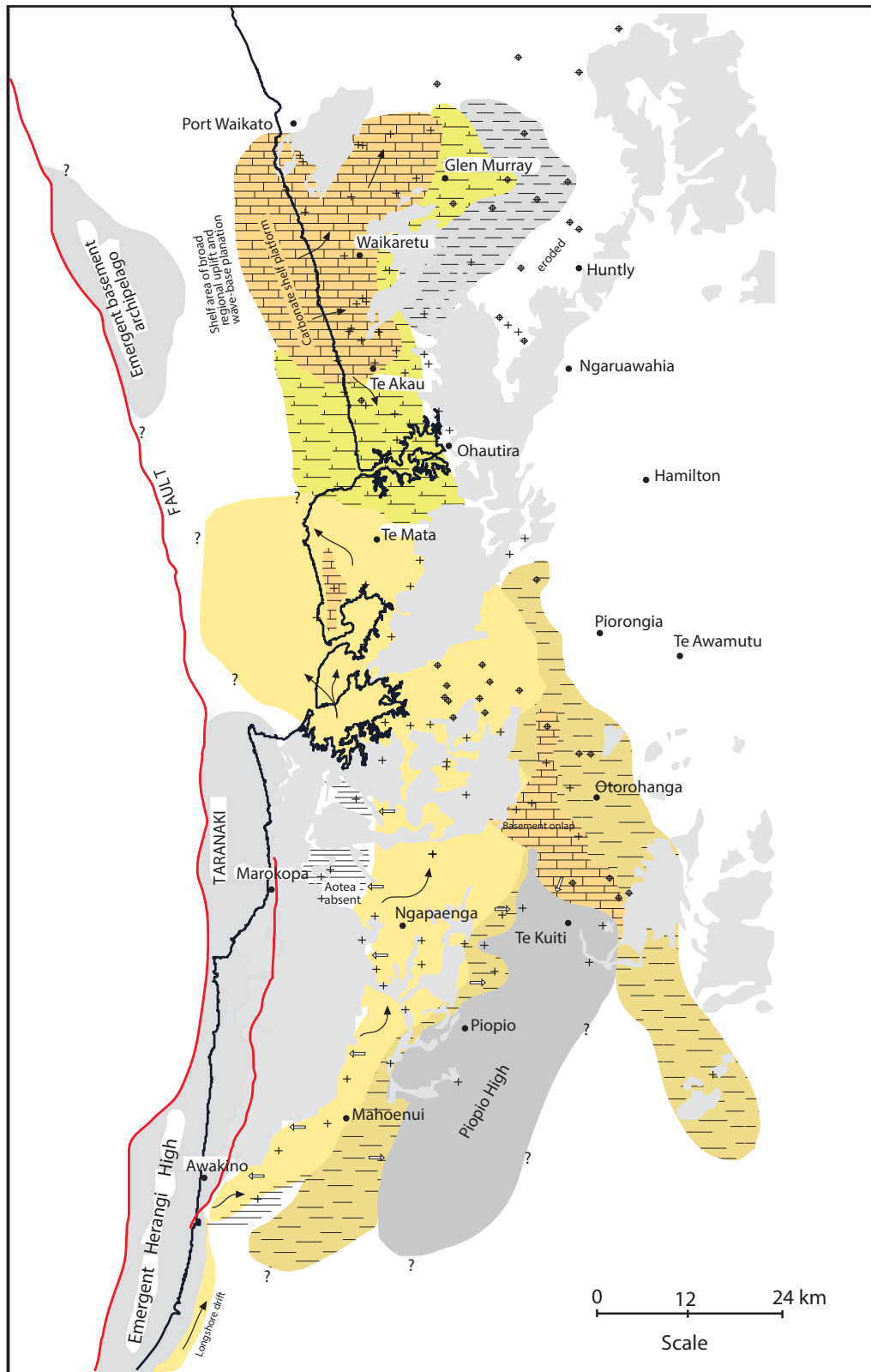
Lithofacies analysis forms the basis for interpretation of the depositional paleoenvironments

within Aotea Formation and, together with observations about key surfaces, the subsequent development of a sequence stratigraphic framework for the formation.

The report is thus divided into three main parts. The first describes the lithofacies identified on the basis of sedimentological and faunal features; the second considers the sequence stratigraphic character of the formation through the identification of surfaces and discontinuities marking significant shifts in linked depositional systems; and the third considers the distinctive style of sequence architecture in the Aotea Formation and attempts to develop a simplified Aotea model sequence for both the northern and southern regions.

Lithofacies overview

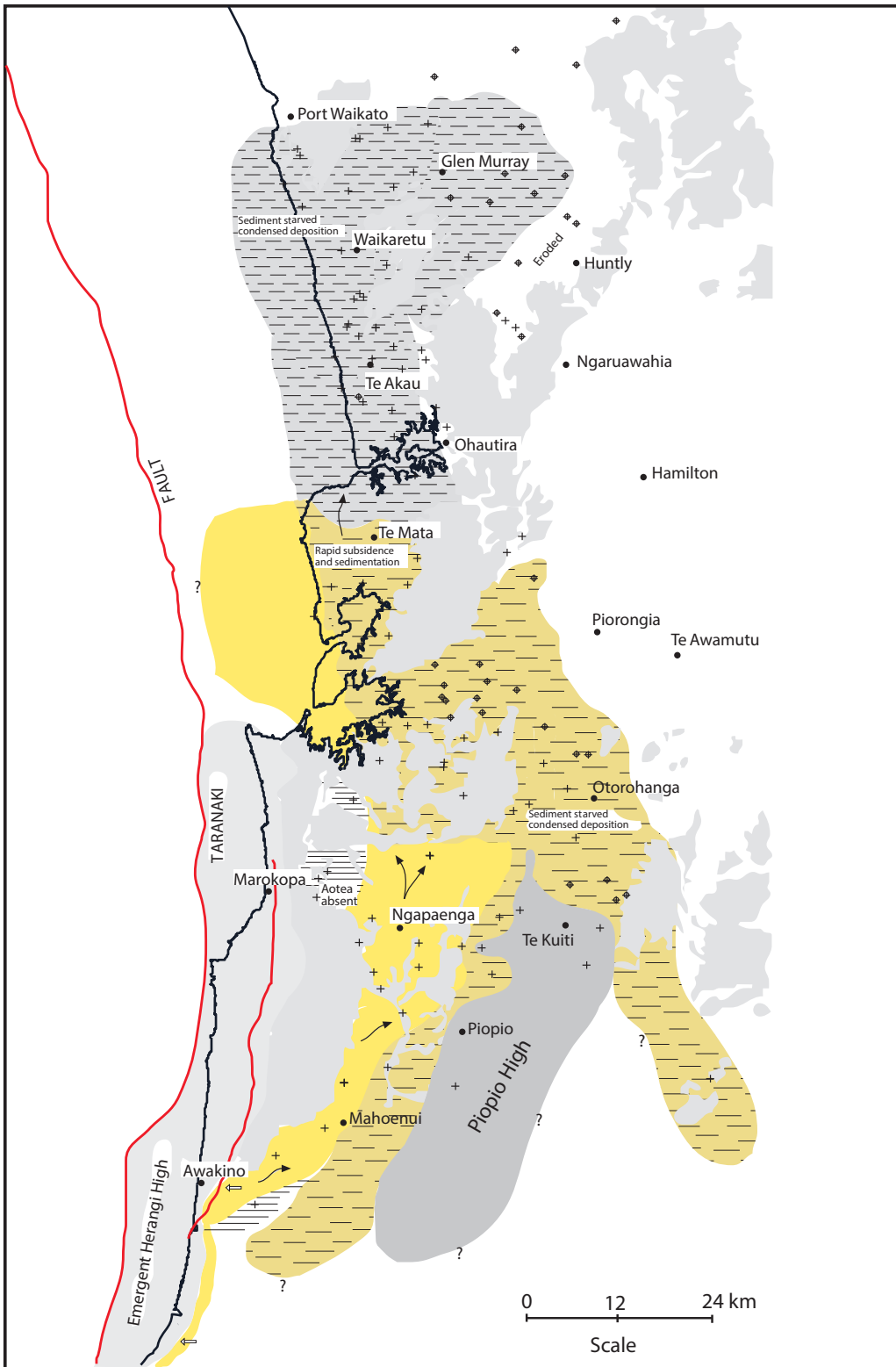
Figure 5 illustrates for a north – south section the broad lithofacies pattern within Aotea Formation and how this is reflected in the name of members within the formation. Aotea Formation unconformably overlies Whaingaroa Formation, except where the latter is completely eroded, in which case it rests upon Glen Massey



LEGEND

Mesozoic basement outcrop	Transgressive shoreline complex	Variably calcareous fine to medium	Sandy limestone (lithofacies L4)
Pre-existing basement high	Inferred sediment transport direction	Muddy sandstone (lithofacies S4)	Limestone (lithofacies L2, L3)
Interval subsequently eroded	Active faults	Interbedded calcareous sandstone	Sandy siltstone (lithofacies Z1)

Fig. 3: Map showing the distribution of the lower group of lithofacies in Aotea Formation (see Table 2) and key paleogeographic elements.



LEGEND










- | | | |
|--|---|--|
|  Mesozoic basement |  Transgressive shoreline complex |  Variably calcareous fine to medium |
|  Pre-existing basement high |  Inferred sediment transport direction |  Muddy sandstone (lithofacies S4) |
|  Interval subsequently eroded |  Active faults |  Sandy siltstone (lithofacies Z1) |

Fig. 4: Map showing the distribution of the upper group of lithofacies in Aotea Formation (see Table 2) and key paleogeographic elements.

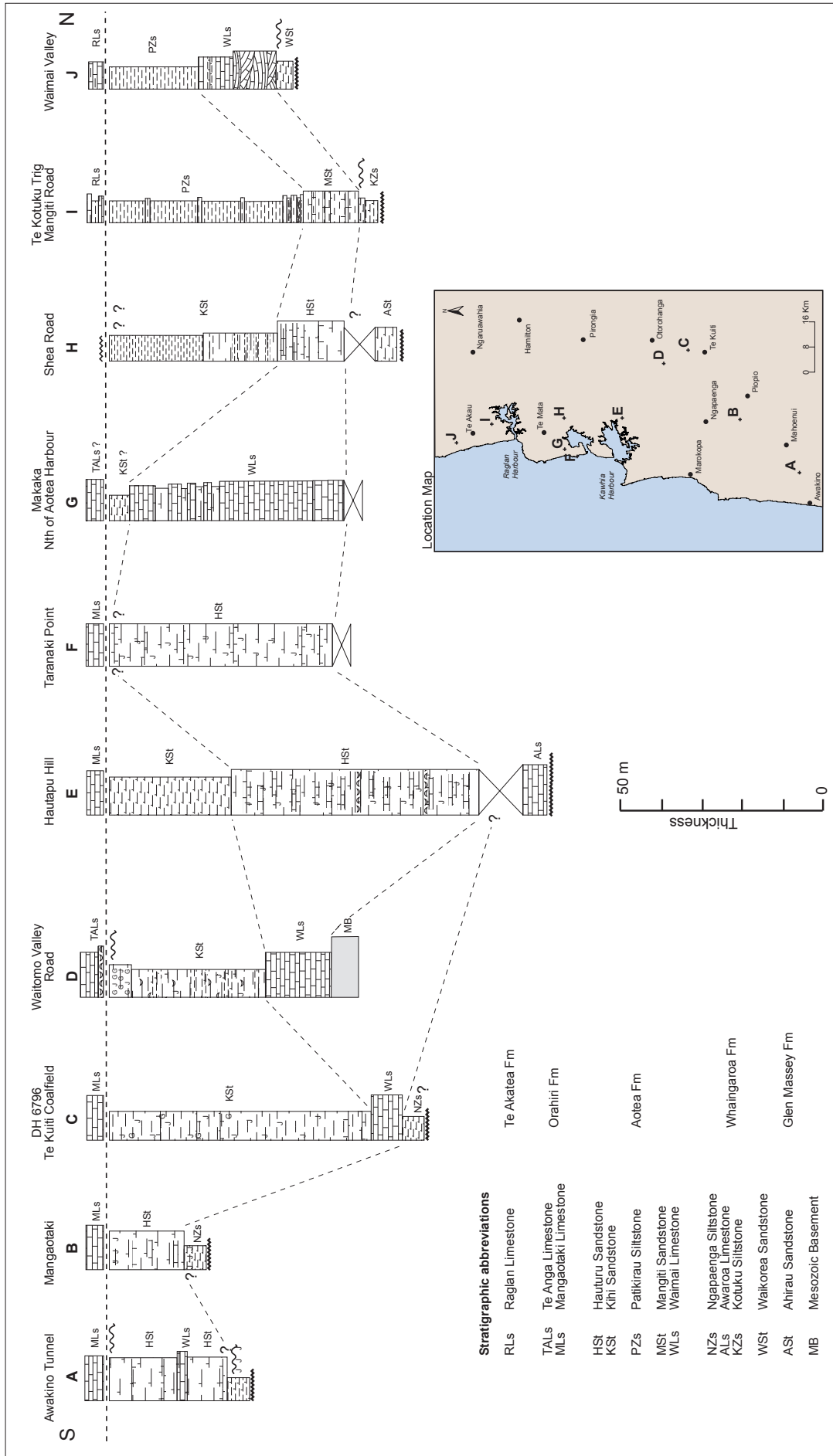


Fig. 5: Correlation of Aotea Formation members from Waimai Valley in the north (Column J) to Awakino Tunnel (Column A) in the south. The datum is the base of Orahiri Formation or its correlative (Te Akatea Formation) in the north.

Formation (Kamp et al. 2014c). The erosion of the Whaingaroa Formation probably occurred via subaerial erosion processes, but the sequence boundary this formed was subsequently lowered by wave planation during the ensuing coastal onlap. In the southern parts of the basin Aotea Formation is unconformably overlain by Orahiri Formation, whereas in the north and east this contact is conformable (with Carter Siltstone), reflecting marked subsidence and condensed sedimentation in the upper part of the formation (Fig. 2).

The thickness of the Aotea Formation (Fig. 6) is quite variable, with the thickest parts occurring east of Kawhia Harbour where it is up to 180 m thick. In the southern region, the formation occurs as a north-south band that thins to the west towards the Herangi Range. In the northern region, Aotea Formation comprises a thin succession (2 - 70 m) comprised of a variety of rock types including cross-bedded limestone, interbedded fine calcareous sandstone and siltstone, and sandy siltstone.

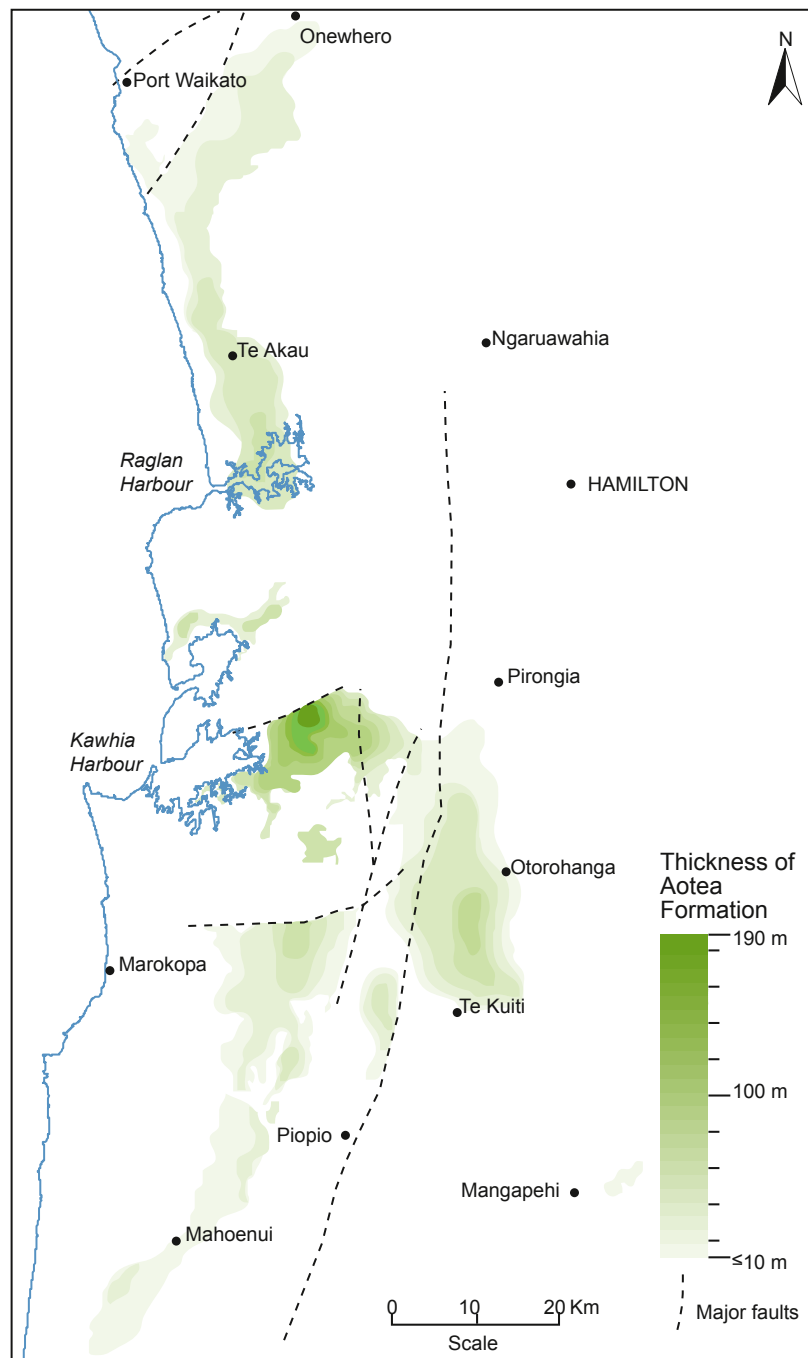


Fig. 6: General extent and thickness distribution of Aotea Formation.

Facies classifications have been prepared in previous investigations of the Aotea Formation (Hopkins 1966; Nelson 1973, 1978a; Fergusson 1986). White & Waterhouse (1993) recognised significant lithofacies variations within the Aotea Formation between the Aotea-Kawhia and Raglan Harbour areas, and broadly subdivided these into four members (viz: Hauturu Sandstone Member and Kihi Sandstone Member in the Aotea-Kawhia Harbour area, and Mangiti Sandstone Member and Patikirau Siltstone Member in the Raglan Harbour area). Paleocurrent and associated lithofacies analysis for the Waimai Limestone Member was carried out by Anastas (1997) and Anastas et al. (1997). Where appropriate, these prior facies schemes have been modified and/or incorporated into the basinwide lithofacies scheme for the Aotea Formation presented here.

Variably calcareous sandstone and muddy sandstone predominate within Aotea Formation in the central and southern parts of the basin, whereas limestone and marl predominate north of Raglan Harbour where there was a much reduced siliciclastic input. Four broad lithofacies types have been identified within Aotea Formation: (i) limestone, (ii) mixed carbonate-siliciclastic sandstone, (iii) mixed carbonate-siliciclastic siltstone, and (iv) chemogenic lithofacies. The essential features of each of these facies are summarised in Table 1.

Typical expressions of limestone facies in the field are illustrated in Fig. 7 and their vertical and lateral relationship across the basin are shown in a series of schematic cross-sections in Fig. 8. Figure 9 depicts how the average whole-rock composition and proportion of different bioclast types within limestone facies of Aotea Formation vary between localities in the basin. Photomicrographs of some of the limestone and chemogenic lithofacies are illustrated in Fig. 10. The typical field expression of the mixed carbonate-siliciclastic sandstone and chemogenic lithofacies are illustrated in Figs 11 - 13. The vertical and horizontal relationships between the various lithofacies are depicted in north-south and east-west transects in Figs 14 - 19.

Limestone lithofacies (L1 - L5)

Limestone lithofacies occur in the lower part of Aotea Formation in the Waimai (Limestone Member) and are best developed in the Port Waikato and Te Akau areas (Fig. 3) where they form large-scale cross-bed and horizontal sets up to 18 m thick. The limestone lithofacies also occur in the central and southern regions, but are generally thin, contain greywacke pebbles and granules and onlap basement highs.

The limestone lithofacies accumulated in inner- to mid-shelf water depths. Thin section description of representative samples of the Waimai Limestone Member from the northern region shows that the bioclast fraction (averaging 70%) principally comprises echinoderms, bryozoans, benthic and planktic foraminifera, and to lesser extent bivalves and calcareous red algae. Barnacles are rare. The modal size of bioclasts varies from about 0.10-1.20 mm (very fine to coarse sand) and can show a bimodal size distribution with fine and coarse sand modes. Bioclasts characteristically show abraded margins. The modal grain size of the insoluble siliciclasts, consisting mainly of quartz, feldspar and minor amounts of igneous and sedimentary rock fragments, lies in the range of fine to very fine sand, which is moderately to well sorted. Pyrite grains and glauconite are ubiquitously present in minor quantities both as pellets and infills. The intrinsic matrix-cement generally makes up 10-25% of limestone facies, with sparite being more common than micrite.

The Waimai Limestone Member in the southern region has coarser bioclast sizes, and higher contents of calcareous red algae and siliciclastic sand (up to 40%, Nelson 1973), possibly indicating a shallower water depositional setting than for the northern region. Five limestone lithofacies have been distinguished (Table 1).

L1. Pebbly grainstone/packstone

The Pebbly grainstone/packstone lithofacies is limited in occurrence to the southern region, especially where Waimai Limestone Member onlaps basement. This facies is characterised by moderately to poorly sorted, rounded to subrounded, greywacke pebbles and cobbles (up

Table 1: Aotea Formation lithofacies.

Lithofacies	Field characteristics; sedimentary structures; bedding type	Carbonate content	Grain size and sorting; clast abrasion	Typical fauna; bioturbation	Typical example	Paleoenvironmental interpretation
Limestone lithofacies						
L1 Pebbly grainstone/ packstone	Common to abundant subrounded basement pebbles and cobbles; fabric supported by bioclastic silty fine sst; rare horizontal bedding	52-73%	Moderately well sorted medium to coarse grainstone-rudstone, with occasional large abraded pectinid shell fragments	Fragmented bivalves, large benthic foraminifera (<i>Amphistegina</i> sp.), echinoid and bryozoan fragments, some rhodoliths	Basal part of Waimai Lst (Fig. 7a, b)	Inner shelf adjacent to rocky shoreline
L2 Cross-stratified grainstone	Tabular cross-beds (up to 25° dip) 2-15 cm thick in 0.3-4.5 m thick cross bed sets	56-94%	Medium to coarse grainstone; rare pebbles; seams of well sorted sandstone	Bryozoans, echinoderms, benthic foraminifera, occasional bivalves, coralline red algae; rare planktic foraminifera and barnacles	Waimai Lst in northern west (Figs 7c, d; 13e)	High energy (storm and tidal currents) inner to mid shelf
L3 Horizontally bedded grainstone /packstone	Well developed bedding 2-10 cm thick separated by seams 0.1-1.5 cm thick	48-83%	Moderately well sorted fine to medium grainstone	Echinoderms, benthic foraminifera; bryozoans and bivalves less common	Waimai Lst in the eastern parts of northern region (Figs 7e; 13f)	Wave-dominated inner to mid shelf
L4 Sandy-silty grainstone	Wavy bedding 2-15 cm thick; occasional low-angle (<10°) cross-bedding	51-88%	Medium to coarse grainstone; moderately well sorted medium quartz sand	Echinoderms, benthic foraminifera, bryozoans, bivalves and calcareous red algae	Represents transition between Hauturu Sst and Waimai Lst (Fig. 7f, g) in central/southern regions	Inner to mid shelf
L5 Massive to irregularly bedded, bioturbated grainstone/packstone	Massive to weak horizontal lamination; variably bioturbated	48%	Fine grainstone-packstone; clasts slightly abraded	Echinoderms, delicate branching bryozoans and benthic foraminifera	Comprises upper part of Waimai Lst in the northern region (Fig. 7h)	Wave (storm)-dominated inner to mid shelf

Mixed carbonate-siliciclastic sandstone lithofacies

S1	Variably calcareous fine to medium sandstone	Cemented sandstone bands (cms thick) alternate with friable low-angle beds with shell hash and pebbles; alsocretionary sandstone bands; abundant bioturbation	26-56%; carbonate rich and poor zones	Moderately well sorted fine to medium sandstone	Echinoderms, bryozoans and benthic foraminifera with occasional minor calcareous red algae and bivalves	Hauturu Sandstone most common in southwest of southern region. (Figs 5; 11a-c; 12a)	Storm dominated foreshore to inner shelf
S2	Massive to thin bedded calcareous silty sandstone	Massive, well cemented, fine calcareous sandstone and silty sandstone; moderately bioturbated	26-39%	Fine to very fine sandstone to siltstone, poorly to moderately sorted	Benthic foraminifera, rare bivalves, echinoid spines	Kihi Sandstone (Figs 10a; 12a)	Mid to outer shelf
S3	Interbedded calcareous sst-stone and sandy siltstone	Calcareous fine sandstone beds (few to 10s cm thick) alternate with bioturbated siltstone	46-65%	Moderately well sorted, fine to very fine sandstone; and siltstone	Rare scattered echinoderm fragments; sparse macrofossils	Mangiti Sandstone (Figs 10b, c; 12 b, c)	Mid shelf
S4	Massive bioturbated muddy sst	Moderately cemented, bioturbated, muddy sandstone; occasional pebble-granule bands	47-55%	Fine to very fine muddy sandstone	Common <i>Janupecten polemicus</i> , <i>Panopea worthingtoni</i> and other bivalve fragments	Kihi Sandstone in eastern areas (Figs 11d, e, f; 12d-f)	Low energy mid shelf, above storm wave base

Mixed carbonate-siliciclastic siltstone lithofacies

Z1	Massive variably calcareous sandy siltstone	Moderately calcareous massive blue-grey siltstone	29-73%	Siltstone with minor fine to very fine sandstone beds	Planktic and benthic foraminifera; sparse macrofossils	Patikirau Siltstone in northern region (Figs 11a, b; 13a, b)	Outer shelf to ?upper bathyal
----	---	---	--------	---	--	--	-------------------------------

Chemogenic lithofacies

C1	Glauconitic siltstone and sandstone	Glauconite grains, coated pellets and glauconite infilling of bioclasts	27-48%	Fine to medium greensand	Scattered whole and fragmented bivalves (<i>Janupecten polemicus</i> , <i>Lentipecten hochstetteri</i>); solitary corals (<i>Flabellum</i> sp.); echinoid plates and spines, some whole	Common in some areas near the top of Aotea Formation (Figs 11c, d; 13c, d)	Sediment starved mid to outer shelf
C2	Glauconitic packstone/wackestone	Glauconite occurs as abundant pelletal and glauconitised shells and infills in moderately bedded packstone/wackestone; bioturbation abundant	48-82%	Medium to fine sandstone to siltstone	Common bivalve shell fragments, occasional whole echinoderms; foraminifera	Waimai Lst in northwest	Sediment starved inner to mid shelf

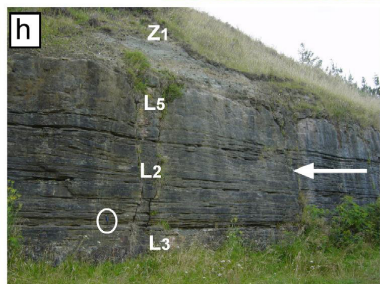
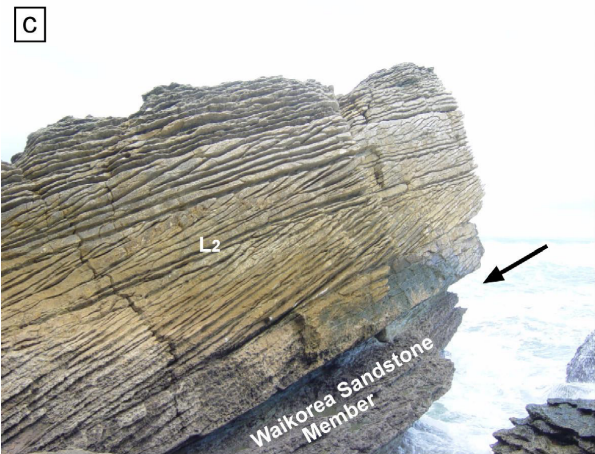


Fig. 7: (facing page) Field photographs of the typical carbonate lithofacies in the Aotea Formation. (a) A unit of rhodolith-bearing conglomerate (Lithofacies L1) onlapping Mesozoic basement rocks in the Honikiwi section (C-25), interpreted as a transgressive lag deposit formed in an advancing shoreline. (b) Massive pebbly grainstone/packstone lithofacies (L1) passing upwards into Horizontally bedded grainstone/packstone (Lithofacies L3) with common scattered granules and pebbles. These facies are inferred to be transgressive marking gradual onlap and submergence of elevated basement areas. Photo location: Honikiwi Road (C-25). (c) Low to moderate angle tabular cross-bedded grainstone lithofacies (L2) typical of Waimai Limestone Member in the northern region, Waikawau Beach, Port Waikato (PW-11). Note well-defined set boundaries bounding the foresets. The Waikorea Sandstone Member of Whaingaroa Formation is erosionally truncated (arrow) and overlain by prominently cross-bedded skeletal grainstone in the lower half of the photo. Exposure is approximately 3 m high. (d) Low-angle tabular Cross-bedded (arrows) grainstone lithofacies (L2), Waimai Limestone Member. Note recessed siliciclastic-rich bedding planes. Hammer for scale. Photo location: Waikorea (TA-2). (e) Horizontally bedded grainstone/packstone lithofacies (L3) in Waimai Limestone Member exposed near Te Akau (TA-9). Note thickness variation in individual beds. Hammer for scale. (f) Sandy-silty grainstone lithofacies (L4) in Waimai Limestone Member. This facies is common in the southern and central regions where it represents transition between Hauturu Sandstone and Waimai Limestone members. Exposure is approximate 4 m high. Photo location: Makaka, north of Aotea Harbour (AK-1). (g) Close-up of the Sandy-silty grainstone lithofacies (L4). Note its resemblance to Fine to medium grained sandstone Lithofacies S1 (Hauturu Sandstone Member). Photo location: Makaka (AK-1), north of Aotea Harbour. (h) Horizontally bedded grainstone/packstone lithofacies (L3) passing upward into Low-angle tabular Cross-bedded grainstone lithofacies (L2) (arrow), which in turn grade upwards into Massive bioturbated grainstone/packstone lithofacies (L5), which is abruptly overlain by massive poorly cemented slightly to moderately glauconitic siltstone Lithofacies Z1 (Patikirau Siltstone Member). Entire succession is broadly transgressive and displays the complete spectrum from moderate to high energy inner-mid shelf skeletal grainstone at the base, to deep water outer shelf siltstone at the top. Hammer for scale (circled). Photo location: Waikaretu (PW-9).

to 15 cm diameter). Clasts are supported within a limestone or calcareous sandstone/siltstone matrix that may exhibit crude horizontal bedding (Column C-25, Honikiwi). The majority of the clasts near basement are encrusted by red algae forming rhodoliths (Fig. 7a). Other common biota include echinoderm fragments, bryozoans and benthic foraminifera, especially *Amphistegina* sp., *Arenodosaria antipoda* and *Notorotalia spinosa* (e.g. S15/f8504, f8505, Kamp et al. 2014b). Planktic foraminifera are rare. Occasional large pectinid bivalve shell fragments are also present. Glauconitised shells and clasts are common together with glauconite pellets, especially in the lower part. The size of greywacke clasts within the limestone reduces upward, pebbles at the base of Waimai Limestone being replaced by granules, which then passes up-section into Horizontally bedded grainstone (Lithofacies L3, Fig 7b). Facies L1 corresponds to Nelson's (1973, 1978a) Basal Beds (AoA) in the Waitomo (C-32) and Honikiwi (C-25) areas.

Interpretation: This facies is similar to the Pebbly grainstone (L1) facies of Glen Massey Formation (Kamp et al. 2014c). It is inferred to have formed as a transgressive lag at the base of Waimai Limestone during marine encroachment onto basement. Coralline algae, including rhodoliths, large benthic foraminifera (*Amphistegina*) and other biogenic components in this facies suggest a shallow marine inner shelf environment of deposition (James et al. 1999; Nalin et al. 2008).

L2. Cross-stratified grainstone:

The Cross-stratified grainstone lithofacies occurs mainly in the lower part of the Waimai Limestone between Port Waikato (PW-11, PW-3 & PW-4, Fig. 15) and Waimai Valley (PW-9, TA-2 & TA-3, Fig. 16). This lithofacies is characterised by moderate (10-20°) to low angle (<10°) cross-beds (2 - 15 cm thick) within 0.3 - 4.5 m thick sets and cosets that extend laterally for a few tens of metres. The base and top of cross-beds are sharp (Fig. 7c). Seams 0.5 - 1.5 cm thick with siliciclastic content separate cross-beds (Fig. 7d). The grainstone is bioclast-rich (av. 72%) and spar cemented (av. 15%). Bioclasts are typically of medium to coarse sand size. Siliciclastic content is low (av. 5%) and includes quartz,

feldspar and rock fragments, although solitary rounded to subrounded pebbles and granules are occasionally present in seams. The bioclasts comprise echinoderms (av. 28%), bryozoans (av. 17.6%), benthic foraminifera (*Discorotalia tenuissima*, *Rotaliatina sulcigera*, *Notorotalia* cf. *spinosa* e.g. R13/f8557) and less commonly bivalve or calcareous red algal components (Fig. 10a, c & k). Planktic foraminifera average only 2% of samples. Glauconite and/or pyrite are usually present in small quantities (av. 5%). Trace fossils include *Thalassinoides* (Fig. 13 e, f) and/or *Scolicia*, and *Arenicolites* (Anastas 1997) are common especially at the base of cross-beds. Skeletal grains are moderately well sorted and abraded.

Lithofacies L2 passes gradationally upwards into Massive to irregularly bedded, bioturbated grainstone-packstone (Lithofacies L5) and it passes eastwards into Horizontally bedded grainstone lithofacies (L3, Fig. 8).

Interpretation: Lithofacies L2 was deposited

within a large (>30 km long) carbonate dune field in a current-dominated NNE-SSW-oriented seaway (Anastas et al. 1997) roughly parallel to the basin axis. Paleocurrent data for the northern region indicate an E-NNE direction of net sediment transport, reflecting the influence of basement topography on current direction along the western margin of the basin (Anastas et al. 1997). The profuse cross-bedding indicates an inner to mid shelf environment of deposition. The decrease upwards in cross-bed thickness suggests waning mean current velocities (Anastas et al. 1997).

L3. Horizontally bedded grainstone/packstone:

The Horizontally bedded grainstone lithofacies (L3) comprise the major part of Waimai Limestone, occurring within the northern region (e.g. Onewhero PW-8 & PW-7, Fig. 15; Te Akau TA-9, Fig. 16). In some locations, such as TA-2 and TA-3 (Fig. 16), L3 is intercalated with Cross-stratified grainstone Lithofacies L2, which represents a transition between Cross-stratified grainstone facies L2 and Interbedded calcareous

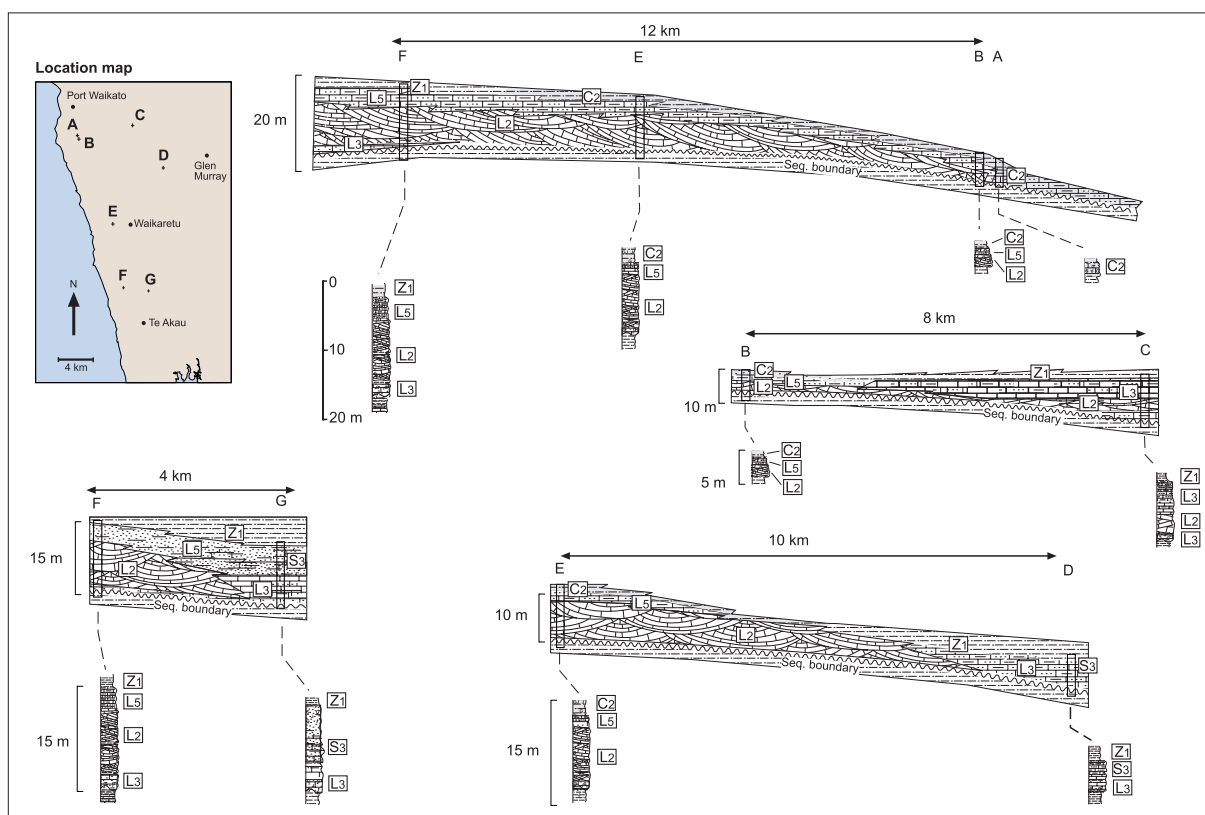


Fig. 8: Schematic cross sections showing the major lithofacies and their thickness trends within Waimai Limestone Member in the northern region. Also shown is the nature of the sequence boundary below the Waimai Limestone, and the relationship with overlying units. Location map shows selected stratigraphic columns used to construct schematic cross-sections, and detailed petrographic analysis (refer Fig. 9). Location A, PW-1A; B, PW-1; C, PW-5; D, PW-8; E, PW-9; F, TA-3; G, TA-5.

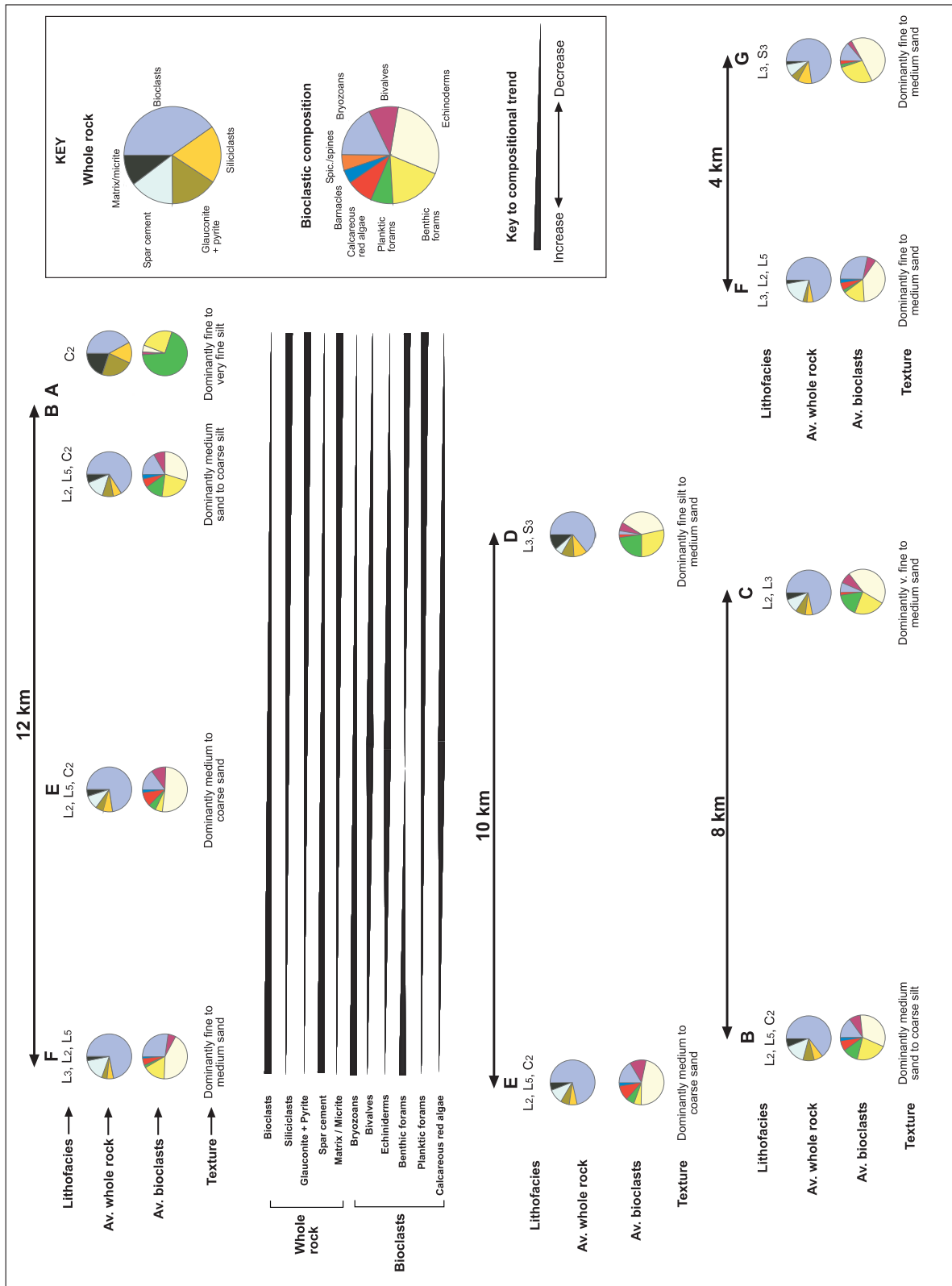


Fig. 9: Summary of average whole rock and bioclast compositional trends amongst lithofacies within Waimai Limestone Member in the locations shown in Fig 8.

sandstone and sandy siltstone facies S3 (best exemplified at location TA-11a, Fig. 16). This facies is characterised by horizontal beds or flags ranging between 2 and 18 cm thick, separated by 0.5 to 1.5 cm thick seams with concentrations of siliciclastic fine sandstone (Fig. 7e). Some of the thickest beds in the lower part of Waimai Limestone show internal bedding or layering. Bioclasts are typically of medium sand size, averaging 69% of the whole rock composition, and composed of echinoderm fragments (av. 29%), benthic foraminifera (av. 17%), planktic foraminifera (9%), bryozoan grains (av. 7%) and bivalve (av. 5%) components (Fig. 10b & g). Calcareous red algae, barnacles, sponge spicules and echinoderm spines form minor components. The micrite matrix (av. 8%) and spar cement (av. 10%) content is highly variable. Glauconite and/or pyrite pellets and infills are ubiquitous, averaging 7% (Fig. 10g).

Interpretation: This facies is similar to the Horizontally bedded grainstone (Lithofacies L4) in Glen Massey Formation (Kamp et al. 2014c) and is also inferred to have been deposited in an inner to mid shelf environment, characterised by an interplay between wave and storm currents (e.g. Nelson 1978b).

L4. Sandy-silty grainstone

The Sandy-silty grainstone lithofacies (L4) is thickest (up to 60 m) north of Aotea Harbour (locality AK-1, Fig. 17) where it comprises the majority of Waimai Limestone. The facies typically comprises grain-supported, spar-cemented grainstone beds rich in bioclasts (av. 70%). The bioclasts are coarse grained (av. 0.60 mm), especially at locality TA-1, and typically of medium to coarse sand size. The bioclasts are variably dominated by echinoderms (av. 21%), benthic foraminifera (av. 18 %), bryozoans (av. 12%), and to a lesser extent by bivalves (av. 8%) and calcareous red algae (9%) (Fig. 10i & j). Other bioclasts include rare barnacles and sponge spicules. Planktic foraminifera are rare. In places, discontinuous shell hash often consisting of echinoid coquinas (including rare whole echinoderms) are observed. Skeletons are slightly abraded. Siliciclasts are of medium to coarse sand size quartz, feldspar and igneous rock fragments. Other minor components include glauconite

and pyrite. The micrite matrix averages only 2%, while spar cement averages 12%. This facies typically intergrades with the Variably calcareous fine to medium sandstone Lithofacies S1 (localities AK-1 & AK-2, Fig. 17 and localities C-8 to C-4, Fig. 18). This facies exhibits peculiar cavernous weathering characteristics, which in places resemble variably calcareous fine to medium sandstone Lithofacies S1, however it is commonly more calcareous than S1, and may include discrete moderately cemented sandstone beds (Fig. 7f & g). It contains irregular to slightly undulating beds ranging in thickness from 2 to 12 cm, but massive to weakly bedded units are also common. Beds are cross-stratified at many localities, especially those north of Aotea Harbour. Lithofacies L4 is inferred to be a transitional facies between Waimai Limestone and Hauturu Sandstone.

Interpretation: Lithofacies L4 represents deposition in an inner to middle shelf environment with episodic storms. The occurrence of echinoid coquina and granule beds probably reflect storm emplacement (e.g. Nelson et al. 1988). The cross-stratification reflects the migration of megaripples and sand waves across the shelf in response to storm and tidal currents (Anastas et al. 1997).

L5. Massive to irregularly bedded, bioturbated grainstone/packstone

This lithofacies is restricted to the upper parts of the Waimai Limestone Member in northwestern parts of the basin (exemplified by localities PW-9, TA-2 & TA-3, Fig. 16). The lithofacies has a dull grey colour with common greyish-green patches. This lithofacies is massive to irregularly bedded (Fig. 7h), some bedding exhibiting diffuse and irregular upper and lower contacts. Bioclasts average 68% of the whole rock composition and are dominantly fragmental and of fine sand size (av. 0.13 mm). Echinoderms, benthic foraminifera and delicate branching bryozoans variously dominate the skeletal grains (Fig. 10d). Other bioclasts include bivalves, planktic foraminifera and rare red algae. Siliciclastic particles are generally fine to medium sand size quartz and feldspar and may comprise up to 6% of samples (Fig. 10d). Moderate concentrations of glauconite and pyrite occur throughout the

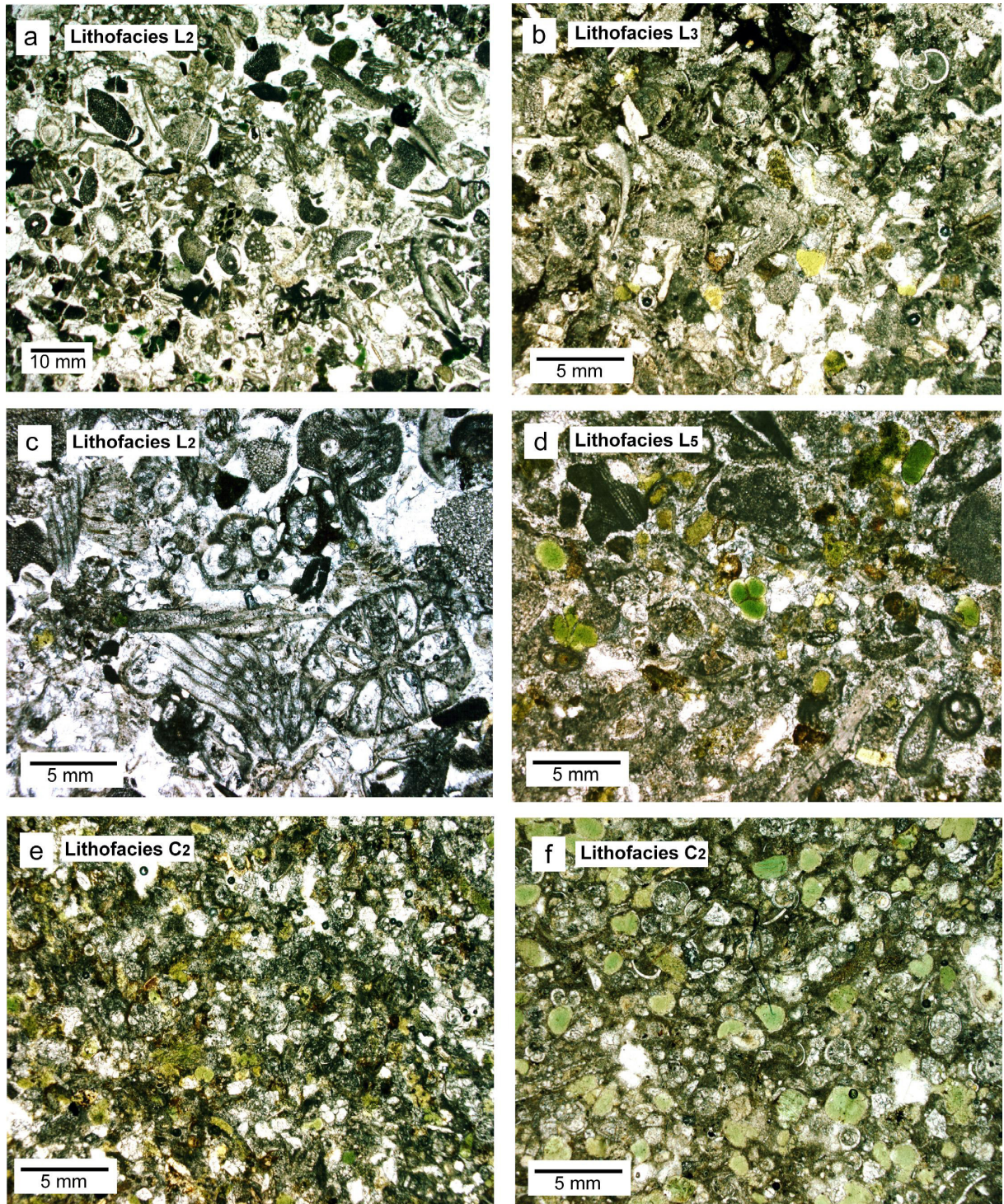


Fig. 10: Photomicrographs of representative samples from lithofacies in the Waimai Limestone Member, and overlying condensed units. (a) Bryozoan/echinoderm/bivalve/calcareous red algae in a cross-bedded sparry grainstone Lithofacies L2, location E (Fig. 8). Sample 120. (b) Echinoderm/benthic/planktic foraminiferal assemblage along with common glauconite, in Lithofacies L3, location D (Fig. 8). Sample 96. (c) Bryozoan/echinoderm/benthic foraminiferal assemblage in a Cross-bedded sparry grainstone Lithofacies L2, location F (Fig. 8). Sample 177. (d) Echinoderm/calcareous red algae/benthic foraminifera along with glauconite in a Mixed grainstone/packstone Lithofacies L5, location B (Fig. 8). Sample 25. (e) Planktic foraminifera-rich wackestone with abundant glauconite pellets and infills, Lithofacies C2, location A (Fig. 8). Sample 8. (f) Planktic/benthic foraminiferal assemblages in a wackestone (Lithofacies C2) with abundant glauconite pellets and infills, supportive of a deep-water depositional environment, location B (Fig. 8). Sample 26.

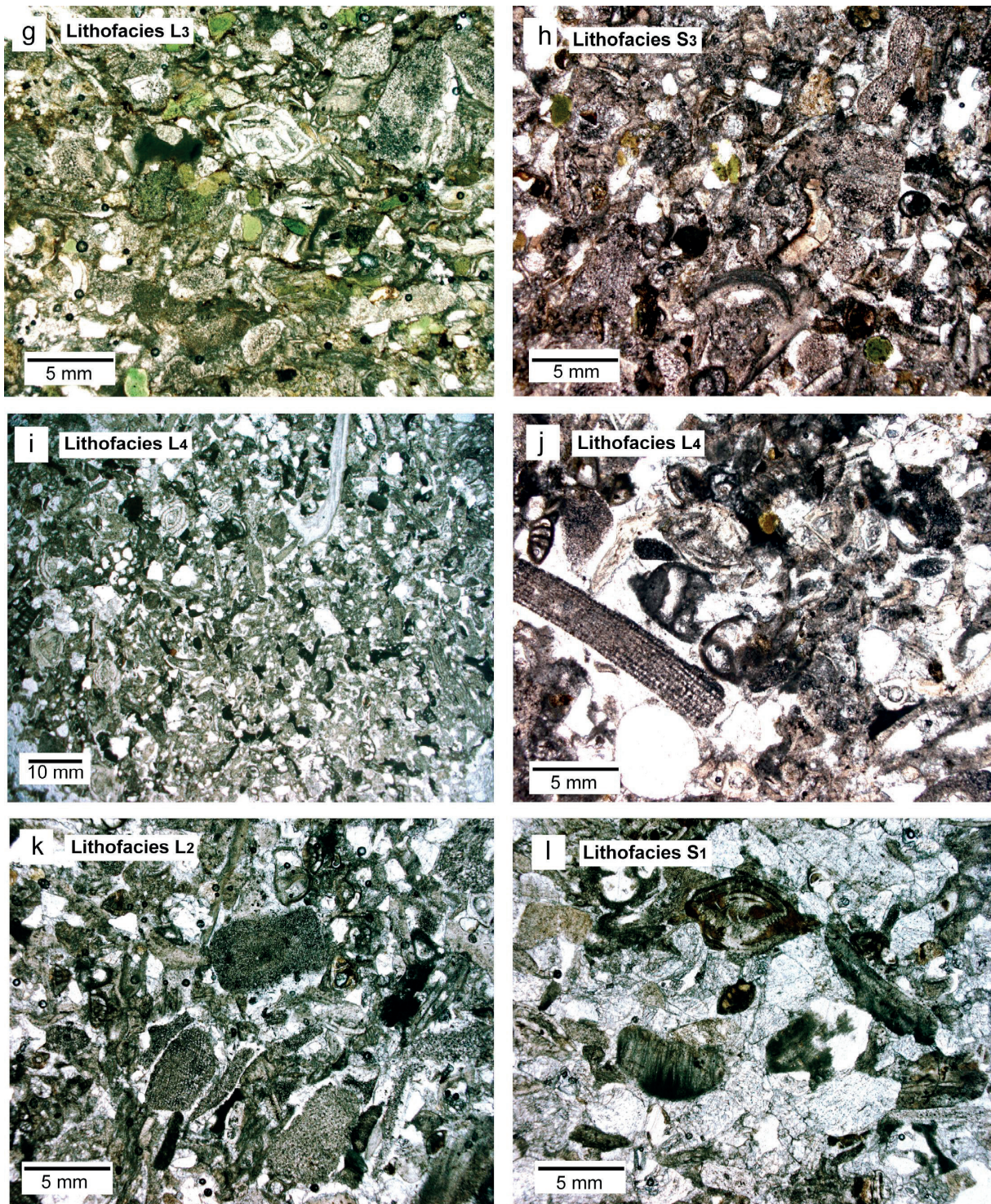


Fig. 10 (continued): Photographs of representative samples from lithofacies types in Waimai Limestone Member and Mangiti Sandstone Member. (g) Echinoderm/benthic foraminiferal assemblage with glauconite pellets in a Mixed grainstone/packstone L3 facies, location G (Fig. 8). Sample 196. (h) Echinoderm/benthic foraminifera/bryozoan in a Calcareous sandstone S3 facies, location G (Fig. 8). Sample 197. (i) Echinoderm/benthic foraminifera/calcareous red algae/bivalves in lithofacies L4, location AK-1. Sample 349. (j) Bryozoan/echinoderm/benthic foraminiferal assemblage in a Mixed grainstone/packstone lithofacies L4, location AK-1. Sample 350. (k) Echinoderm/bryozoan/calcareous red algae in Cross-bedded grainstone lithofacies L2, location AK-1. Sample 353. (l) Echinoderm/bivalve/benthic foraminiferal assemblages in Calcareous sandstone lithofacies S1, location AK-1. Sample 355.

grainstone-packstone interval. This facies passes vertically into either Massive variably calcareous sandy-siltstone of Lithofacies Z1 or Glauconitic packstone/wackestone of Lithofacies C2 (Fig. 8).

Interpretation: Lithofacies L5 was deposited in mid to possibly deeper shelf water depths. The relative paucity of physical sedimentary structures compared with underlying Cross-stratified grainstone (L2) and the intensity of bioturbation probably reflects a deeper paleobathymetry. This is further corroborated by the content of delicate bryozoans (Anastas 1997; Nelson et al. 1978b). Common greyish-green muddy patches are probably compressed burrows, suggesting the substrate was non-cohesive (Anastas 1997).

Mixed carbonate-siliciclastic sandstone lithofacies (S1 – S4)

Variably calcareous sandstone and muddy-sandstone (hereafter referred to as sandstone facies) comprise the majority of the Aotea Formation over much of the central and southern parts of the basin. Sandstone facies constitute all of Aotea Formation in the Aotea Harbour to Awakino areas of the basin, except where thin basal limestone facies (Waimai Limestone Member) occur. The Hauturu Sandstone and Kihi Sandstone comprise the sandstone facies, are exposed extensively in the hill country east of Aotea and Kawhia harbours and probably occur in the subsurface beneath most of Karioi and Pirongia volcanoes (White & Waterhouse 1993) as well as areas to the south. To the east of Aotea and Kawhia harbours, the sandstone facies are up to 180 m thick.

The Hauturu Sandstone comprises Variably calcareous fine to medium sandstone (Lithofacies S1) with negligible silt, and forms distinctive well cemented hard sandstone bands within otherwise softer and often friable sandstone. The Kihi Sandstone differs in having higher silt content and in being a silty fine to very fine sandstone (Lithofacies S4). This facies grades into Hauturu Sandstone (S1) but it also stratigraphically overlies it, especially in the Aotea and Kawhia areas.

Four mixed carbonate-siliciclastic sandstone lithofacies are distinguished in the Aotea Formation. The essential characteristics of these lithofacies are summarised in Table 1.

S1. Variably calcareous fine to medium grained sandstone

Lithofacies S1 makes up the Hauturu Sandstone, exemplified at localities C-4 and C-8 (Fig. 18). In the southern part of the basin this facies constitutes almost the entire Aotea Formation (e.g. localities C-56 & C-68, Fig. 19), which is also the case at Taranaki Point (S-16, Fig. 17). Lithofacies S1 is the Banded Sandstone Beds (Ao-5) of Aotea Formation described by Nelson (1978a). Sandstone is of fine to medium grade with carbonate content ranging from a few percent up to 56% (Nelson 1973). The thickness distribution of S1 is depicted in Fig. 20. Lithofacies S1 is typically well-cemented sandstone forming concretionary bands (up to few tens of centimetres long) alternating with friable to poorly cemented sandstone (Fig. 11c). In several locations east of Kawhia Harbour, the facies consist of thick-bedded sandstone packages (5 to 10 m thick) overlain by comparatively thin-bedded sandstone, often amalgamated (Fig. 11b). Internal stratification features are subtle but include small to medium scale low-angle cross-stratification in fine to medium sandstone, with some indications of hummocky cross-stratification (Fig. 11d). Maximum foreset dips rarely exceed 10°. Rounded to subrounded granule to pebble bands are common within some sandstone beds (Fig. 11f). The facies frequently consists of densely bioturbated beds up to tens of centimetres thick. Robust mm diameter subvertical to inclined *Skolithos* and/or *Thalassinoides* burrows are common. Shell hash layers, some containing pholad bored bivalves, are also common, especially in Hautapu Hill and Kihi Road exposures (Fig. 11e, f, g & h). The terrigenous fraction is typically about 57%, moderately well sorted fine to medium quartzofeldspathic sandstone, with less common rock fragments, glauconite and pyrite. The coarse sand-sized bioclasts comprise echinoderm fragments, bryozoans, benthic foraminifera, and occasionally calcareous red algae (Fig. 10l) (Nelson 1973).



Fig. 11: (facing page) Field photographs of Variably calcareous fine to medium sandstone Lithofacies S1 (Hauturu Sandstone Member) in the basin. (a) Massive buff coloured friable sandstone exposed near Kokakoroa Road, Te Anga (C-40). (b) Medium to thick bedded calcareous sandstone packages, often amalgamated, Kihi Road (S-13). Exposure is approximately 20 m high. (c) Typical weathering character consisting of alternating recessive and laterally discontinuous ellipsoidal shaped well-cemented slabs, exposed near Mangaotaki, west of Piopio (C-145). (d) Massive friable fine to medium sandstone gradually passing upward into low angle cross-bedded sandstone with medium to coarse echinoderm coquina. Photo location: Awakino Tunnel (C-191). (e) Extensively burrowed sandstone bed with scattered rounded to subrounded granules and bivalves (whole shells and broken pectinid fragments), and echinoderm fragments. Photo location: Kihi Road (S-13). (f) Pebble-granule band with abundant bivalve molds chaotically oriented, a common occurrence in this lithofacies. Photo location: Kaimango (C-8). (g) Extensive burrow networks present near the lower unconformable contact of this unit with the Glen Massey Formation. Photo location: Okapu, east of Aotea Harbour (AK-5). (h) Sandstone bed containing abundant echinoderm debris as well as unidentified skeletal fragments, a common feature of this lithofacies. Photo location: Kihi Road (S-13).

Interpretation: The variably calcareous fine to medium sandstone was deposited in a wave, tide and storm-dominated inner to mid shelf environment. The common occurrence of trough cross-stratification indicates high-energy conditions (e.g. Dott & Bourgeois 1982; Swift et al. 1983; Walker 1984). The abundance of burrows indicates that there were also fair-weather conditions between storm events. Bioturbation was able to keep pace with physical sedimentation (e.g. Howard 1978). Winnowed granule and pebble lags along with shell hash layers were probably reworked from the adjacent beach environment and deposited under the influence of storm currents (e.g. Driese et al. 1991). The presence of benthic foraminifera such as *Gyroidinoides* sp., *Amphistegina* sp., *Elphidium* sp. (e.g. R15/f8509), *Anomalinoidea fasciatus*, *Arenodosaria* sp. and *Notorotalia* sp. (e.g. R16/f7559) indicate high-energy inner to mid shelf environments (Hayward 1986; Cooper et al. 2004).

S2. Massive to thin-bedded calcareous silty sandstone

Massive to thin-bedded calcareous silty sandstone lithofacies comprise Kihi Sandstone within the Aotea-Kawhia area, stratigraphically overlying Hauturu Sandstone. This facies occurs mainly in the upper part of the Aotea succession (e.g. localities AK-2, AK-3, AK-4, Fig. 17 and localities C-4 and C-8, Fig. 18). This facies was encountered in the majority of the West Kawhia Coalfield drill hole sections and was described by Phelps (1985) as Upper Aotea Sandstone stratigraphically overlying Hauturu Sandstone. Farther south, it is commonly interbedded with Lithofacies S1 (localities C-56 & C-94, Fig. 19). Lithofacies S2 resembles the Massive bioturbated muddy-sandstone Lithofacies S4, in that it is chiefly composed of siltstone and fine to very fine sandstone. However, unlike Lithofacies S4, Lithofacies S2 consists of thin beds of calcareous sandy siltstone and fine sandstone, which are comparatively well cemented and resistant to weathering. They form a distinctive bulbous weathering profile and may exhibit uneven surface and/or lapiez weathering features and often exhibit sharp facies transitions with underlying Lithofacies S1 (Fig. 12a). Bioturbation is common and locally can be extensive. Bioclasts average 47% of the whole rock composition and are dominantly fragmental and comprise medium to coarse echinoderm fragments, bryozoans and benthic foraminifera. Other bioclasts include scattered bivalves (e.g. pectinids and *Panopea* sp.) and rare calcareous red algae. This facies is similar to the Massive Ripply Sandstone Beds (Ao-3) of Aotea Formation described by Nelson (1978a) and occur at the same stratigraphic position.

Interpretation: The Massive to thin-bedded calcareous silty-sandstone lithofacies is similar in character to Alternating calcareous silty sandstone and sandy siltstone Lithofacies S3 of Glen Massey Formation. The presence of common shallow water benthic foraminifera such as *Arenodosaria antipoda* and *Cibicides maculatus* along with several deeper water species such as *Anomalinoidea fasciatus*, *Melonis maorica*, *Semivulvina capitata* and *Haeuslerella*

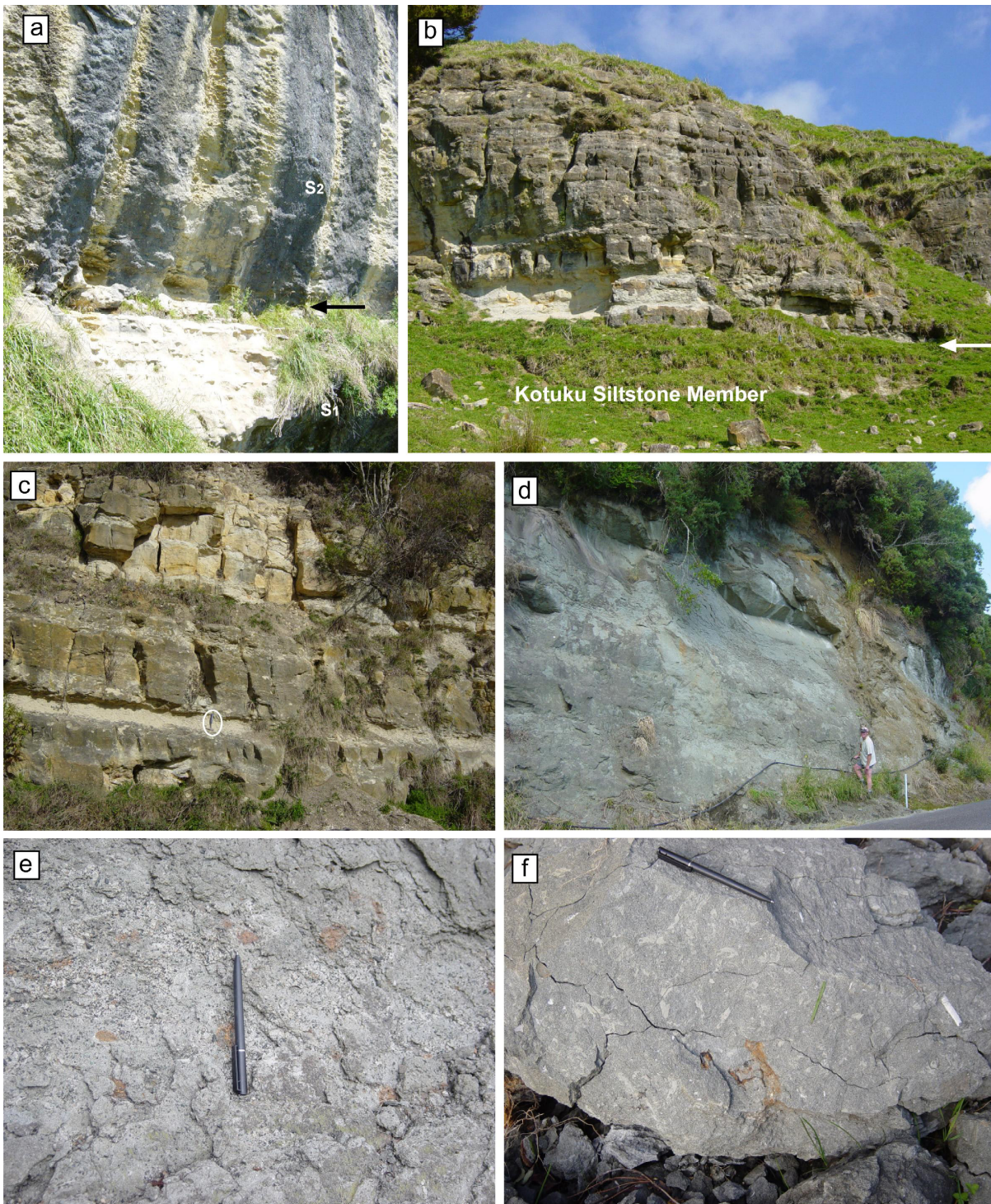


Fig. 12: Field photographs of mixed carbonate-siliciclastic sandstone lithofacies in the Aotea Formation across the basin. (a) Sharp facies transition between Fine to medium sandstone Lithofacies S1 (Hauturu Sandstone) and well cemented Calcareous silty sandstone Lithofacies S2 (Kihi Sandstone). Note the sharp break (arrow) in the weathering profile marking the facies transition. Exposure is about 8 m high. Photo location: Hautapu Hill (C-4). (b) Interbedded Calcareous sandstone and sandy siltstone Lithofacies S3 (Mangiti Sandstone) sharply overlying massive siltstone unit (Kotuku Siltstone Member of Whaingaroa Formation). The Mangiti Sandstone and Kotuku Siltstone are separated by an erosional surface (arrow). Exposure is approximately 10 m high. Photo location: near Matakītaki Road, Glen Murray (PW-7). (c) Buff coloured fine to very fine calcareous sandstone interbedded with thin sandy siltstone (Lithofacies S3) from the lower part of the Mangiti Sandstone at its type locality of Mangiti Road, north of Raglan Harbour (TA-12). Note prominent vertical solution cavities imparting a blocky appearance is a typical weathering feature of this facies. (d) Bioturbated bluish-grey muddy sandstone Lithofacies S4 (Kihi Sandstone) exposed along Honikiwi Road (AK-14). Note exfoliation weathering is a typical feature of this facies. (e) Close-up showing rounded-subrounded granules scattered within Bioturbated muddy sandstone Lithofacies (S4). Note light rusty brown patches marking the presence of burrows. Photo location: Honikiwi Road (AK-14). (f) Mottling due to extensive soft-bodied infaunal burrowing activity is common within the Muddy sandstone Lithofacies S4. Photo location: Honikiwi Road (AK-14).

textilariformis (e.g. R15/f8510) indicate a mid to outer shelf depositional environment, with some transport of inner shelf fauna into deeper water during episodic storms.

S3. *Interbedded calcareous sandstone and sandy-siltstone*

The interbedded calcareous sandstone and sandy siltstone lithofacies comprise the major part of the Mangiti Sandstone in the vicinity of Raglan Harbour (e.g. localities TA-12 and TA-15, Fig. 16). This member occurs in the lower part of Aotea Formation, and grades upward into Massive variably calcareous sandy siltstone of Lithofacies Z1. Lithofacies S3 also constitutes a small proportion of Aotea Formation in drillhole sections in eastern areas (e.g. PW-7 and DH 8048, Fig. 15). It generally consists of well cemented fine to very fine calcareous sandstone in beds 20-50 cm thick, with thin (1-10 cm) interbeds of sandy siltstone (Fig. 12b). Contacts between fine calcareous sandstone beds and silty sandstone interbeds are usually diffuse. The sandstone bed thicknesses decrease upwards with a reciprocal increase in the thickness of siltstone beds, reflecting an overall thinning and fining upward succession. The beds are cut by vertical solution cracks that impart a blocky appearance to many outcrops (Fig. 12c). Trace fossils include vertical to subvertical tubes (4-6 cm), which occur at the base of the sandstone beds and along top surfaces, and are associated with thin sandy siltstone interbeds. Echinoid plates and spines are occasionally present (Fig. 10h).

Interpretation: Lithofacies S3 constitutes the majority of Mangiti Sandstone in the Raglan Harbour area and in the areas lying east of Port Waikato and Te Akau. This member is a correlative of Waimai Limestone (Lithofacies L2) in the southern and eastern parts of the northern region (Figs. 15 & 16). Anastas (1997) attributed the absence of cross-stratification in the Mangiti Sandstone to accumulation in protected (from wave action) areas that existed locally in an otherwise current-dominated seaway. However, we prefer a deeper-water middle to outer shelf environment of deposition characterised by high-energy storm deposition of sandstone alternating with low-energy background accumulation

of burrowed hemipelagic sandy siltstone. The presence of benthic foraminifera such as *Melonis maorica*, *Rectuvigerina striatissima*, *Martinotiella communis*, *Lenticulina* sp., and *Haeuslerella textilariformis* (e.g. R14/f55, f60, f61) suggest a mid shelf to (?uppermost) bathyal water depth (e.g. Hayward 1986; Hayward et al. 1989).

S4. *Massive bioturbated muddy sandstone*

Massive bioturbated muddy sandstone of Lithofacies S4 occurs mainly within the Kihi Sandstone Member, and comprises the major part of it in central-eastern areas - Honikiwi and Waitomo Valley (localities C-28, C-32, DH 6796 and DH 8570, Fig. 18). The facies also constitutes a minor proportion of Kihi Sandstone in the Shea Road section (locality AK-4, Fig. 17). The Massive bioturbated muddy sandstone lithofacies are the same as the Massive Muddy Sandstone Beds (Ao-2) of Aotea Formation described by Nelson (1978a). The dominant lithology is massive variably calcareous muddy sandstone and sandy mudstone that often exhibit exfoliation-weathering features (Fig. 12d). Internal stratification is rare. In places (e.g. Waitomo Valley Road and Mangaotaki Bridge) it may include more-and-less resistant beds of slightly calcareous and muddy sandstone ~50-80 cm thick alternating with massive sandy mudstone beds of similar thickness. Basement derived granules and small pebbles are scattered within muddy sandstone in some beds (Fig. 12e). Bioturbation is locally very extensive and often so thoroughly burrow-homogenised that no physical sedimentary structures are visible (Fig. 12f). Burrows include subvertical to inclined 3-5 cm long tubular structures, and mottling due to extensive soft-bodied infaunal churning. Epifaunal bivalves such as *Janupecten polemicus*, *Chlamys williamsoni*, *Lentipecten hochstetteri*, *Cucullaea* sp. and infaunal *Panopea worthingtoni* are common. A rich foraminiferal assemblage from this facies includes *Anomalinoidea fasciatus*, *Arenodosaria antipoda*, *Haeuslerella textilariformis*, *Melonis maorica*, *Gyroidinoidea allani*, *Bulimina pupula*, *Rectuvigerina striatissima*, *Sphaeroidina bulloides*, *Semivulvina capitata*, *Hanzawaia scopos*, *Vaginulinopsis cristellata* and *Notorotalia spinosa* (e.g. S16/f6523-6524, f6536-6542, f6011, f6014-6015).

Interpretation: The massive bioturbated muddy sandstone facies (S4) within Kihi Sandstone exhibits subtle differences from Lithofacies S2 described earlier: there is increased silt content and a greater degree of bioturbation. The high density of burrows and the fine texture suggests a moderate to low energy mid to outer shelf depositional environment. However, the occurrence of crude bedding in some sections and the presence of scattered granules and pebbles are indicative of changes in energy levels probably due to episodic storm events (e.g. Hamblin & Walker 1979). The foraminifera within this facies indicate a depth range of mid shelf (e.g. *Arenodosaria antipoda*, *Bulimina pupula*, *Notorotalia spinosa*) to outer shelf depths from the occurrence of several deep-water species e.g. *Haeuslerella textilariformis*, *Melonis maorica*, *Sphaeroidina bulloides* and *Semivulvina capitata* (e.g. Hayward 1986; Hayward et al. 1999). The shallow-water benthic foraminifera may have been reworked seawards into deeper water.

Mixed carbonate-siliciclastic siltstone lithofacies (Z1)

Only one mixed carbonate-siliciclastic siltstone lithofacies (hereafter referred to as the siltstone lithofacies) has been identified in the Aotea Formation (Table 1). It comprises the major part of Aotea Formation within the Raglan Harbour area, but it probably also extends into the subsurface beneath the coalfields in the northern region.

Z1. Massive variably calcareous sandy siltstone

This facies consists mainly of massive, grey, variably calcareous sandy siltstone and siltstone with occasional thin concretionary horizons. Bedding is often discernible (within otherwise massive siltstone) from the occurrence of thin interbeds of silty sandstone, as exposed in coastal cliffs around Raglan Harbour (Fig. 13a). The siltstone is slightly to moderately cemented and typically exhibits crumbly weathering characteristics. This lithofacies contains isolated burrows but in places mottling indicates pervasive bioturbation. The intensity of burrowing generally increases and is abundant in upper parts of the member below Raglan Limestone Member. Lithofacies Z1 is locally capped by Glauconitic siltstone-sandstone

Lithofacies C1 in the vicinity of Raglan Harbour, but more extensively to the north (Fig. 8), reflecting stratigraphic condensation.

Lithofacies Z1 comprises the bulk of the Patikirau Siltstone Member, exemplified at localities TA-2 to TA-15 (Fig. 16). It stratigraphically overlies Lithofacies S3 (Mangiti Sandstone) at localities TA-12 & TA-15 (Fig. 16) and Lithofacies L5 (Waimai Limestone) in northern areas (localities TA-2 & TA-3, Fig. 16), and grades laterally into Glauconitic packstone/wackestone (Lithofacies C2) in the Port Waikato area (localities PW-11 to PW-4, Fig. 15 and locality PW-9, Fig. 16). This facies also comprises a major part of Aotea Formation in northeastern areas such as in Onewhero (DH 8048, Fig. 15) and intergrades laterally with Lithofacies C2 in the west (localities PW-4, PW-3 & PW-11, Fig. 15). However, the easternmost extent of this facies is unknown because of poor exposure and minor lithological differences between it (Z1) and overlying Carter Siltstone Member of Te Akatea Formation.

Interpretation: The regional extent of this fine-grained facies implies a quiet depositional environment, probably at outer shelf water depths. However, the presence of thin sandy siltstone interbeds indicates that the seafloor was supplied with sandstone during storm action. The presence of *Sphaeroidina bulloides*, *Cibicides novozelandicus*, *Sipholina australis* and *Haeuslerella textilariformis* indicates that the water depth may have been in the range outer shelf to possibly upper bathyal, with transport of inner and mid shelf faunas (e.g. *Arenodosaria antipoda*, *Bulimina pupula*, *Melonis maorica* in R14/f92-94) into deeper water (e.g. Hayward 1986; Van Markhoven et al. 1986).

Chemogenic lithofacies association (C1 – C2)

The chemogenic lithofacies identified within the Aotea Formation are similar to those described for Glen Massey Formation (Kamp et al. 2014c). The lithofacies includes high concentrations (>10%) of glauconite, which accumulated in a shelf setting characterised by extremely low terrigenous or carbonate sedimentation rates, probably associated with relative sea-level rise

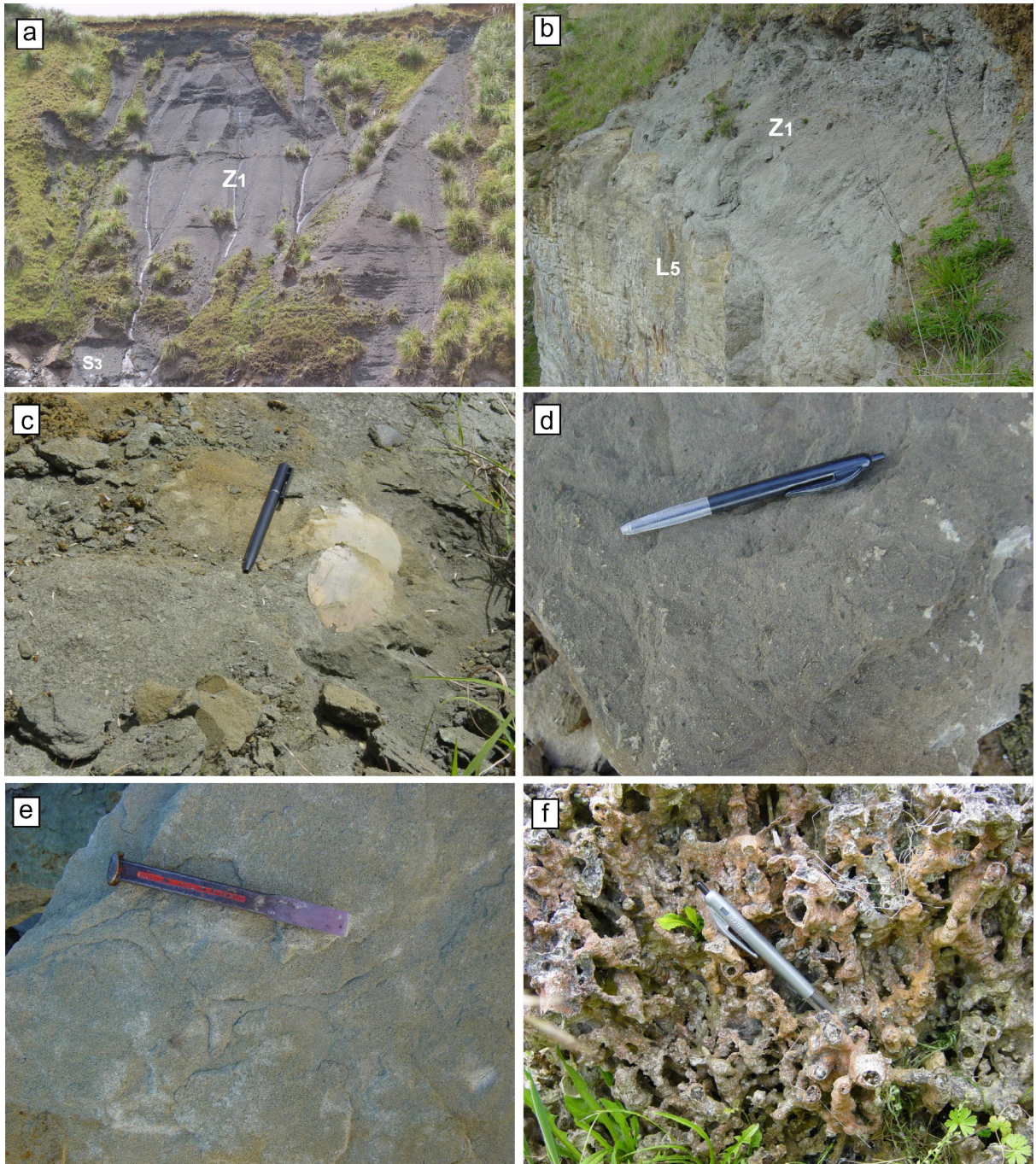


Fig. 13: Photographs of the typical field expression of various lithofacies in the Aotea Formation across the basin. (a) Medium to dark bluish-grey Massive sandy siltstone Lithofacies Z1 (Patikirau Siltstone Member) overlying Interbedded calcareous sandstone and sandy siltstone Lithofacies S3 (Mangiti Sandstone; visible at the left hand corner), exposed in a sea cliff at its type locality, Patikirau Bay, Raglan Harbour (TA-20). Note thin silty sandstone interbeds in the lower and upper-middle part of the section. The exposure is approximate 50 m high. (b) Massive to moderately bedded grainstone/packstone Lithofacies L5 of Waimai Limestone abruptly passing upward into moderately glauconitic Massive sandy siltstone Lithofacies Z1 (Patikirau Siltstone). Photo location: Waikaretu Limestone quarry (PW-9). (c) Large *Lentipecten hochstetteri* shells in highly glauconitic sandstone of Lithofacies C1. Photo location: Honikiwi Road (AK-14). (d) Close-up showing medium to coarse sand glauconitic pellets scattered in extensively burrowed sandstone Lithofacies C1 from the upper part of Aotea Formation (Kihi Sandstone). Photo location: Waitomo Valley Road (C-32). (e) *Thalassinoides* burrows in Cross-bedded grainstone Lithofacies L2. Photo location: Waikaretu Limestone Quarry (PW-9). (f) Extensive *Thalassinoides* burrow network preserved in a fallen block of Horizontally bedded grainstone/packstone Lithofacies L3. Photo location: Baker Road, east of Limestone Downs (PW-4).



Fig. 14: Map showing the location of five transects illustrated in Figs. 15 - 19.

(e.g. Posamentier et al. 1988; Loutit et al. 1988; Amorosi 1995). However, the stratigraphic position of chemogenic lithofacies within the Aotea Formation differs slightly from those in the Glen Massey Formation. In Aotea Formation this facies is most common near the top of S4 Lithofacies (Kihi Sandstone) in central-eastern areas, or at the top of Z1 lithofacies (Patikirau Siltstone) in central-northern areas.

Two chemogenic lithofacies have been distinguished (Table 1).

C1. Glauconitic siltstone and sandstone

This lithofacies is similar to the Glauconitic Sandstone Beds (Ao-4) described by Nelson (1978a) in the Waitomo District. It constitutes the uppermost 4 - 5 m of the Kihi Sandstone, but only in the Honikiwi-Waitomo Valley area (localities C-28 & C-32, Fig. 18) and to the north of Te Kuiti (DH 6796 & DH 8570, Fig. 18). It probably comprises the bulk of the Aotea succession at locality C-107 west of Troopers Road (Fig. 19) and in the Mangapehi-Benneydale area (av. 5-20% pelletal glauconite, Nelson 1973). The upper part of Patikirau Siltstone (Z1) is comprised of the Glauconitic siltstone and sandstone C1 lithofacies around Raglan Harbour (locality TA-12, Fig. 16). The facies is

characterised by the presence of green to greenish black glauconite pellets of fine to medium sand size and may contain scattered glauconitised rock fragments. Whole pectinid shells (*Janupecten polemicus*, *Lentipecten hochstetteri*), *Dentalium* sp. and solitary corals (*Flabellum* sp.) (Fig. 13c) are common within C1 lithofacies. Bioturbation (including *Ophiomorpha*-like burrows, Nelson & Hume 1977) is generally very extensive and the intensity increases progressively upwards within the facies. The facies comprises 50% bioclasts, dominated by planktic (37%) and benthic foraminifera (10%). Bivalve and echinoderm bioclasts form minor components. Matrix/micrite content is substantially high (25%). Siliciclasts are dominantly sand and coarse silt-sized quartz and feldspar grains. Other significant components include glauconite and pyrite that form 11% of the whole rock composition (Nelson 1973).

Interpretation: The presence of this facies at the top of Aotea Formation in central-eastern parts of the study area reflects sediment starvation associated with increasing water depths.

C2. Glauconitic packstone/wackestone

A glauconitic packstone/wackestone lithofacies comprises the uppermost part of the Aotea Formation mainly within the Port Waikato and

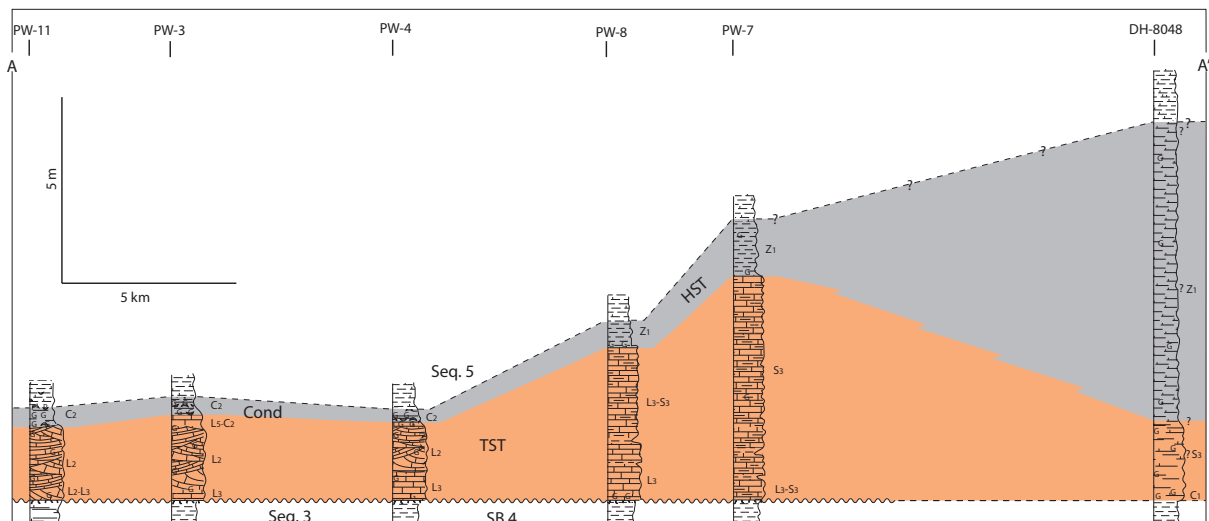
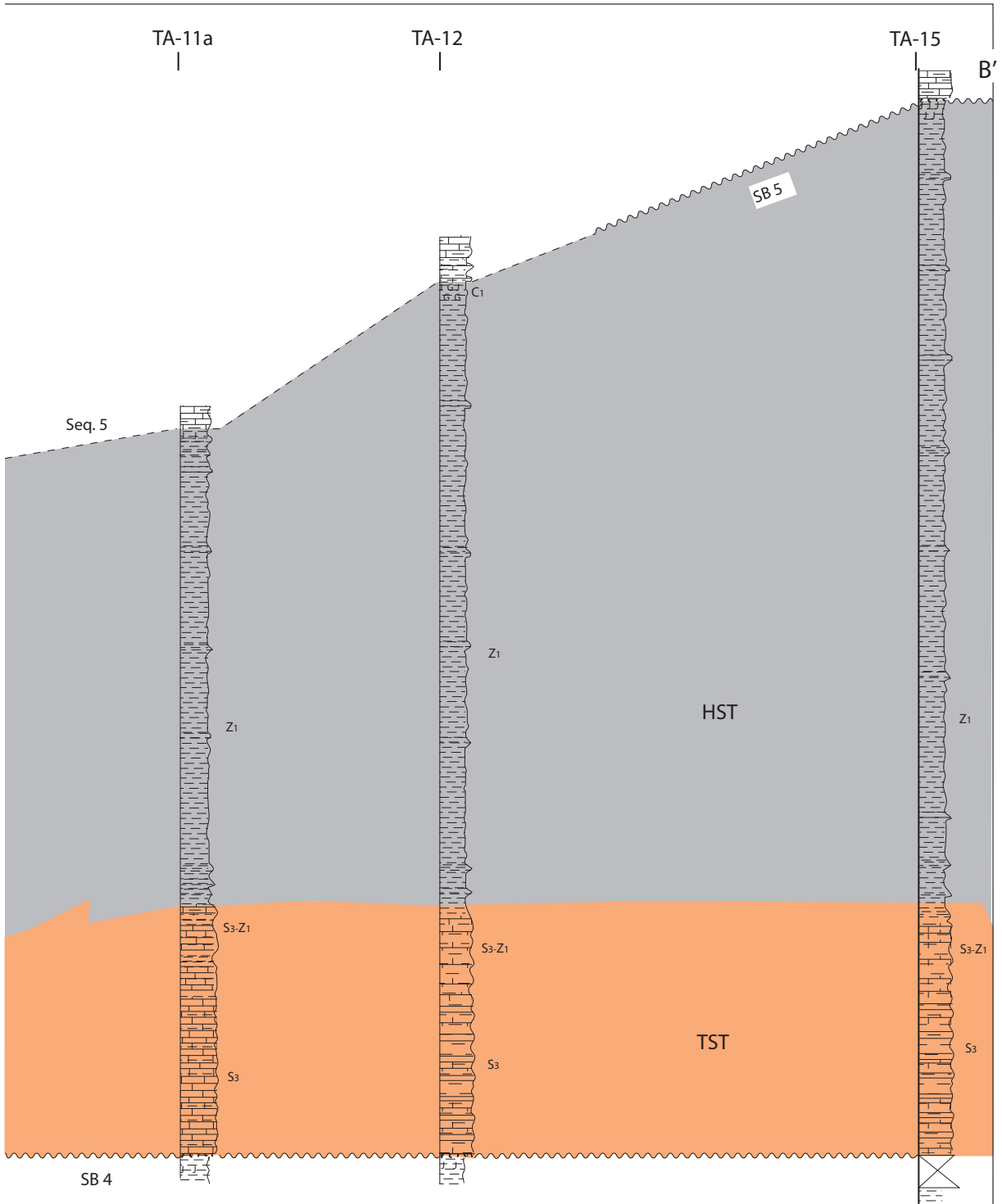


Fig. 15: Northwest-southeast transect A-A' across the northern part of the basin (see Fig.14 for location). Datum: Sequence boundary (SB 4) between Whaingaroa Formation (seq. 3) and Aotea Formation.



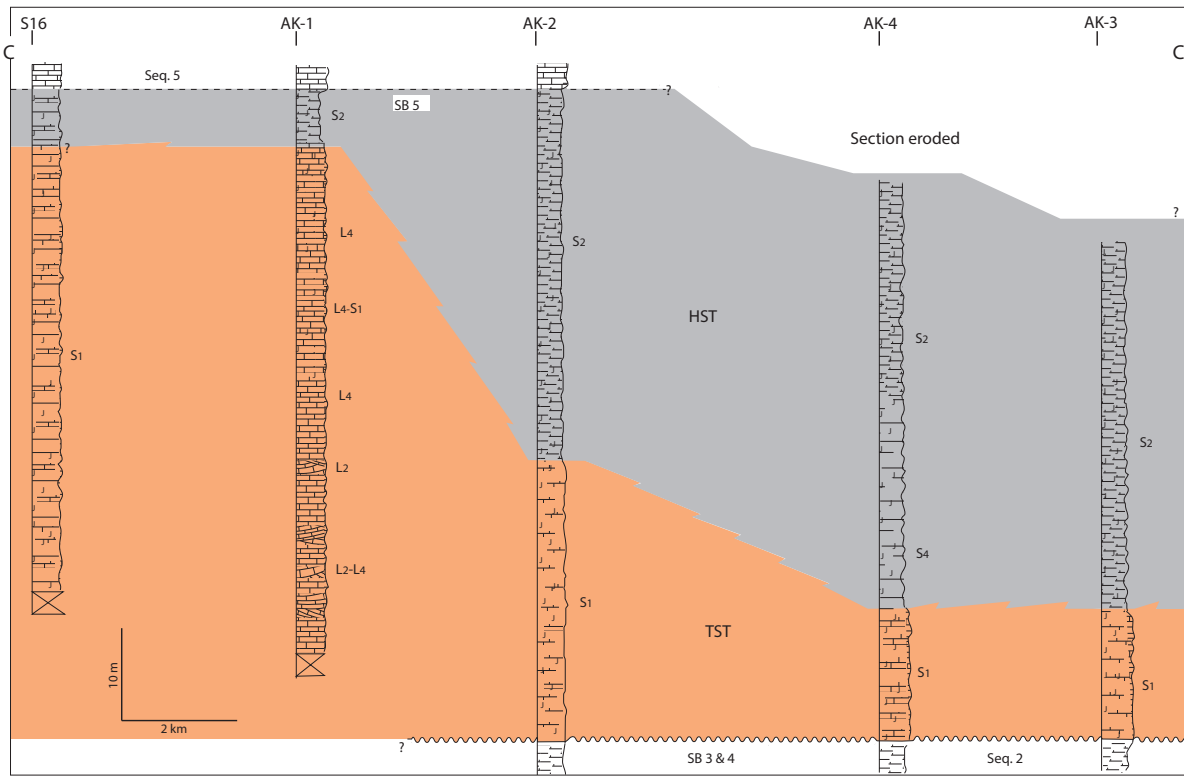


Fig. 17: Southwest-northeast transect C-C' across the northern side of Aotea Harbour (see Fig. 14 for location). Datum is sequence boundary between Glen Massey Formation (seq. 2) and Aotea Formation (seq. 4).

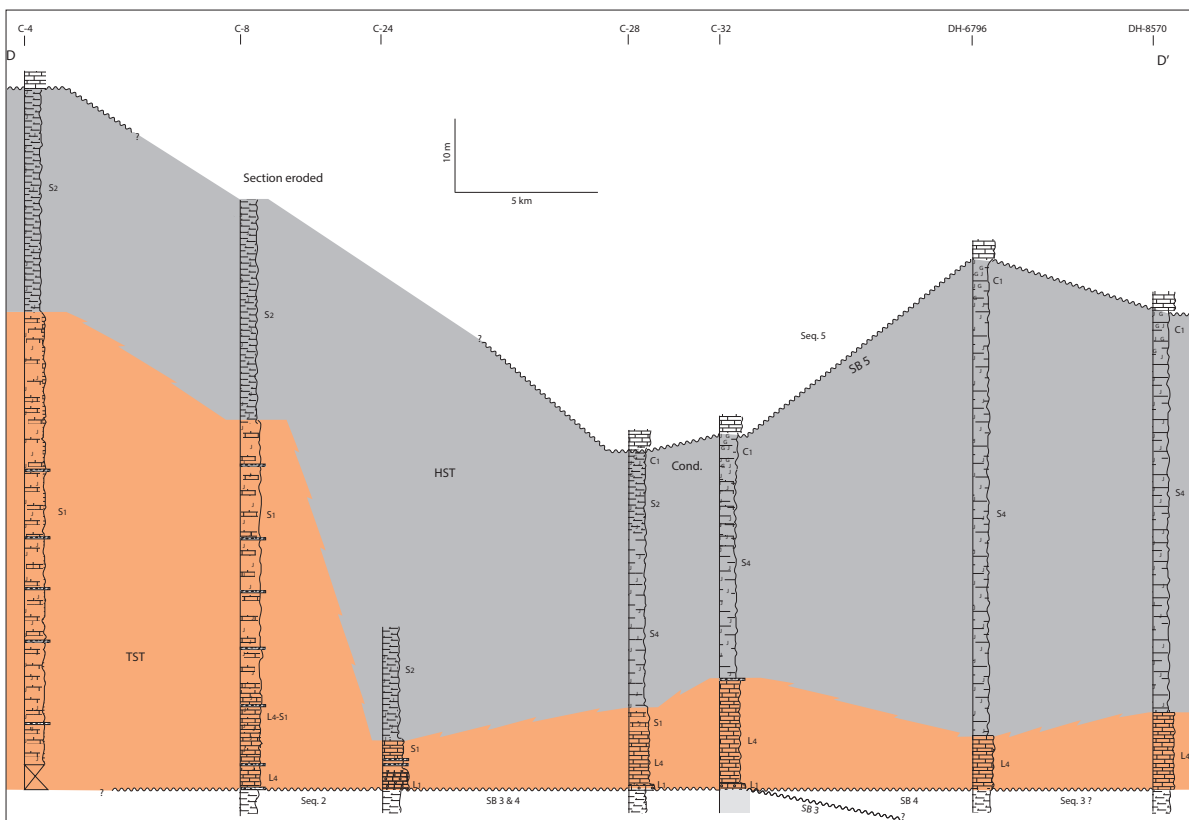


Fig. 18: Northwest-southeast transect D-D' across the central-southern region of the basin (see Fig. 14 for location). Datum is sequence boundary between Glen Massey Formation (seq. 2) and Aotea Formation (seq. 4) on the western (left) end, and Whaingaroa Formation (seq. 3) and Aotea Formation (seq. 4) on the eastern (right) end. Note Aotea sequence laps basement at location C-32.

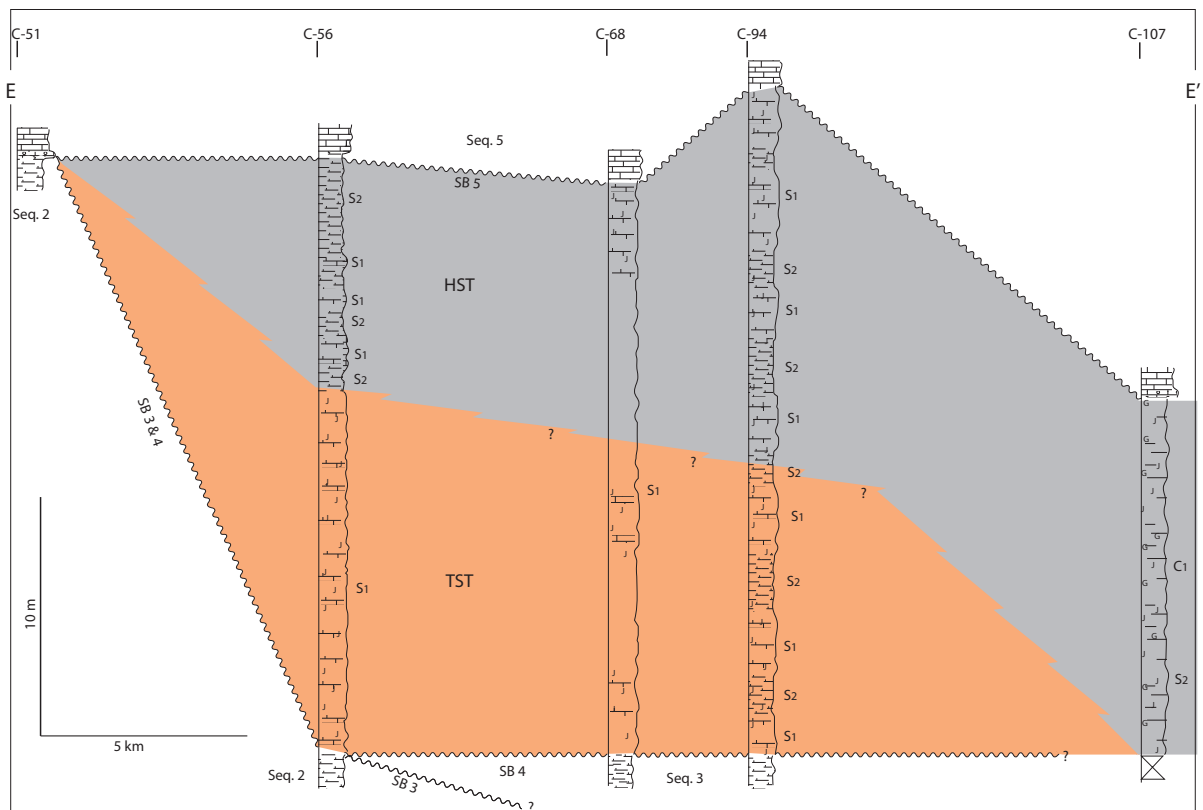


Fig. 19: Northeast-southwest transect across the southern region (see Fig. 14 for location). Datum is sequence boundary between Glen Massey Formation (seq. 2) and Aotea Formation (seq. 4) on the western (left) side, and Whaingaroa Formation (seq. 3) and Aotea Formation (seq. 4) on eastern (right) side. Note that the Aotea Formation at C-51 is inferred to have been subsequently eroded.

Waikaretu areas, exemplified by localities PW-11, PW-3 and PW-4, Fig. 15, and locality PW-9, Fig. 16. It forms the upper parts of Waimai Limestone and grades upwards into calcareous siltstone/marl (Carter Siltstone). In the Port Waikato area, whole *Lentipecten*, *Terebratulina*, *Dentalium*, and *Flabellum* are common macrofauna within the facies. There, Lithofacies C2 represents condensed sediments with bioclasts comprising 43% of the total components. Planktic (av. 30%) and benthic foraminifera (av. 10%) dominate the carbonate components. Other bioclasts include echinoderms and rare bivalves. Glauconite and pyrite comprise around 23% of the total sediment make-up. Glauconite is common as infills within planktic foraminiferal tests and as scattered pellets. The micrite matrix accounts for 20% of the average whole rock composition. Siliciclasts are dominated by subangular to subrounded quartz and feldspar of mainly very fine sand size (Fig. 10e & f).

Interpretation: Glauconitic packstone/wackestone Lithofacies C2 is similar to the Glauconitic sandy-silty grainstone/packstone Lithofacies C3 described for Glen Massey Formation (Kamp et al. 2014c). Both facies were deposited in outer shelf to upper bathyal settings characterised by low rates of sedimentation. The presence of this facies in the upper part of Horizontally bedded grainstone Lithofacies L3, or above Lithofacies L5 is indicative of increased water depth driving the condensation and formation of chemical minerals (e.g. Loutit et al. 1988; Amorosi 1995). This inference is also supported by the increase in content of planktic foraminifera and the high density of bioturbation in the facies.

Lithofacies distribution and paleo-environmental implications

The wide spectrum of Aotea Formation lithofacies and their distribution between the northern and southern regions are summarised in Table 2. The vertical and lateral facies transitions across the basin are depicted in selected measured sections along north-south and east-west transects in Figs 16 - 19. The measured sections provide control over the facies and thickness distribution from landward (west) to basinward (east) areas. From the detailed facies descriptions, it is apparent that the Aotea Formation can be subdivided into two broad facies groups. The vertical succession within these groups is marked by sharp transitions and reveals overall deepening upwards. The lower group of facies are comprised of carbonate sediment (L1-L5) belonging to the Waimai Limestone, or by variably calcareous fine to medium sandstone (S1, S3) belonging to Hauturu Sandstone Member and Mangiti Sandstone. They accumulated in relatively high energy neritic environments.

In contrast, the upper group of facies consists mainly of bioturbated fine muddy sandstone, and sandy siltstone (Lithofacies S2-S4 and Z1) belonging to Kihi Sandstone and Patikirau Siltstone. The facies at the top of these members include condensed intervals (Lithofacies C1 and C2) indicating low-energy deep-water environments with terrigenous sediment starvation. The geographic distribution of facies within the lower and upper facies groups within Aotea Formation are shown in Figs 3 and 4, respectively.

Distribution and depositional paleo-environment of the lower facies group

The transition from Whaingaroa Formation to Aotea Formation was marked by a large basinward shift in the position of coastal onlap. This is evident from the unconformity between these formations, which shows evidence of wave planation during the passage into Aotea Formation, particularly along the western margin of the basin. During accumulation of the lower part of Aotea Formation a shore-connected wedge of sandstone (Hauturu Sandstone, Lithofacies S1) accumulated along the eastern margin of Herangi High, and concurrently shelfal muddy sandstone (Kihi Sandstone, Lithofacies S4) accumulated farther east. A carbonate shelf formed along the northwestern margin (Port Waikato - Te Akau) of the basin as well as around the northern fringe of the Piopio High (west of Otorohanga) (Fig. 3).

Lithofacies S1 (Hauturu Sandstone) is the most proximal facies in Aotea Formation, consisting of mixed carbonate and terrigenous components. It comprises horizontally to cross-bedded fine to medium sandstone often with local abundance of burrows, fragmented shell debris and granules. This facies is interpreted as having been deposited as a shore-connected wedge of sandstone along the basin's southwestern margin influenced by wave and storm currents. Its character and distribution strongly suggest that the terrigenous sediment was transported northwards from a source area well to the south of the basin by long-shore drift, including along the eastern margin of Herangi High. The transport of this sand across the shoreface was chiefly accomplished

Table 2: Lithofacies distribution within Aotea Formation.

		North		South	
Upper group of facies	Member	Facies	Member	Facies	
	Patikirau Siltstone	Z1, C2	Kihi Sandstone	S2, S4, C1	
Lower group of facies	Mangiti Sandstone	S3	Hauturu Sandstone	S1, L4	
	Waimai Limestone	L2 - L5	Waimai Limestone	L1, L3, L4	

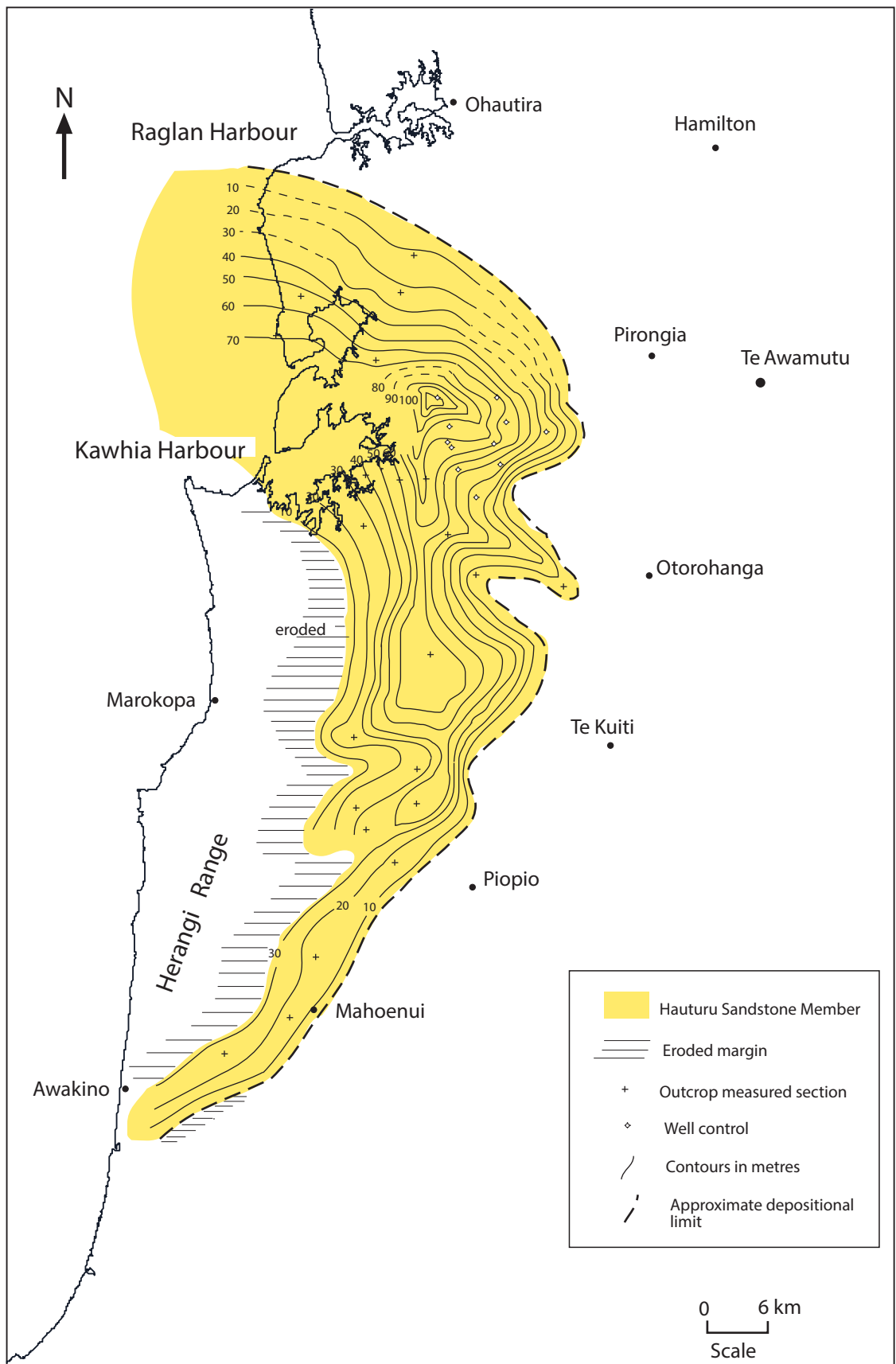


Fig. 20: Hauturu Sandstone Member (Lithofacies S1) thickness distribution map. Isopach data derived from outcrops and drill holes (circles). Contour interval is 10 m. A sediment fairway into the adjoining eastern margin of Taranaki Basin is suggested by the observed thickness trend in the vicinity of Kawhia Harbour.

through offshore (eastward) directed storm flows. Lithofacies S1 is thickest east of Kawhia Harbour (Fig. 20). It passes eastward into massive bioturbated muddy sandstone (Lithofacies S4, Kihi Sandstone) (see transect D-D' & E-E', Figs. 18 and 19).

The middle to outer shelf was dominated by massive bioturbated muddy sandstone (Lithofacies S4) corresponding to Kihi Sandstone. This lithofacies consists chiefly of fine to very fine sandstone and muddy sandstone with scattered pectinid bivalves and extensive bioturbation, and was deposited in a moderate to low energy mid to outer shelf environment. The intermittent occurrence of granule and pebble bands could have formed as tempestites during storm events. Most of the Kihi Sandstone exposures in the Otorohanga and Piopio areas are representative of this facies.

In the central-eastern region, a carbonate "platform" fringed a basement high (Piopio High, Fig. 3) (Transect D-D', Fig. 18). This limestone facies contains bryozoans, scattered bivalves including pectinids, large benthic foraminifera, and locally abundant rhodoliths and rounded to subrounded basement clasts (Lithofacies L1), which were deposited in shallow water. The facies marks the onset of subsidence and marine transgression across parts of the high. The basal Pebbly limestone lithofacies (L1) forms lenses passing upward into horizontally bedded Sandy silty grainstone (Lithofacies L4).

Along the northwestern margin (Port Waikato-Te Akau) of the basin, a carbonate platform/shelf developed over and around a basement high, inferred to have been located west of the present day coastline (Fig.3). This high also influenced deposition of the underlying Glen Massey Formation and Whaingaroa Formation. The low to medium angle tabular cross-bedded skeletal grainstone (Lithofacies L2, Waimai Limestone) was deposited at inner-shelf depths (see transect B-B', Fig. 16) with a gradual slope to the east (and south). The skeletal sand generated in shallow water around the high was transported eastwards and reworked by offshore-directed tidal and bottom currents. This is evident in paleocurrent data from cross beds in the Waimai

Limestone, indicating a highly variable pattern of unidirectional flow, mainly eastwards (Anastas 1997).

The Interbedded calcareous sandstone and sandy siltstone Lithofacies S3 (Mangiti Sandstone) accumulated between the Variably calcareous fine to medium sandstone Lithofacies S1 (Hauturu Sandstone) in the south and the carbonate lithofacies in the northwest (Waimai Limestone). The siliciclastic and carbonate components in this lithofacies are characteristically mixed (46-65 wt% CaCO₃) because of contributions of carbonate components from the west and contributions of siliciclastic sand from the south (Transect A-A', Fig. 15). The character of the interbedded facies resulted from alternating storm and fair-weather conditions in the basin.

Distribution and depositional paleo-environment of the upper facies group

Figure 4 summarises the distribution of the lithofacies in the upper part of the Aotea Formation. Lithofacies S1 (Hauturu Sandstone) passes upward into Massive to thinly bedded calcareous silty sandstone Lithofacies S2 (Kihi Sandstone) in the central to western part of the basin, indicating a retrogradational stacking pattern. This fining-upward shelf succession is best exposed in the Aotea-Kawhia Harbour area (Transect D-D', Fig. 18). Concurrently, to the north in the Waitomo-Honikiwi area, limited sediment supply led to accumulation of condensed fossiliferous sandstone and siltstone with high glauconitic concentrations (Lithofacies C1). In eastern and offshore areas, such as at Mangapehi, condensed C1 facies form most of the stratigraphic thickness of the Aotea Formation (Transect E-E', Fig. 19). However, southwestern parts (east of Marokopa-Awakino) of the basin remained at inner to mid shelf depths and continued to accumulate S1 or S2 lithofacies, reflecting proximity to a paleoshoreline along the eastern margin of the Herangi High.

In the vicinity of Raglan Harbour and in areas to the north, fining upwards within the lithofacies succession is reflected in the accumulation of Massive variably calcareous sandy siltstone Lithofacies Z1 (Patikirau Siltstone), which

overlies Lithofacies S3 (Mangiti Sandstone) (Transect B-B', Fig. 16). Farther north, the Cross-bedded limestone Lithofacies L2 passes upward into Massive to horizontally bedded grainstone/packstone Lithofacies L3 and L5 (Waimai Limestone), which in turn is overlain by a fossiliferous (including planktic foraminifera) highly glauconitic condensed section (Lithofacies C2) (Transect A-A', Fig. 15). This indicates substantial foundering of the shelf area to at least outer shelf and possibly upper bathyal conditions, with extremely limited sediment supply.

Sequence stratigraphy

The new stratigraphic context for Aotea Formation (Tripathi et al. 2008) together with the facies analysis undertaken here, provide a framework for sequence stratigraphic analysis of the formation. The following sections apply sequence stratigraphic concepts to Aotea Formation, including definition of key surfaces bounding the systems tracts, the extent of linked depositional systems (systems tracts) and their internal facies make-up, and development of a model Aotea sequence.

Lower sequence boundary

The lower bounding surface of Aotea Formation along the western side of the basin is an erosional unconformity and it passes into a correlative conformity to the east. The unconformity surface formed initially by subaerial erosion, in the process removing substantial parts of the Whaingaroa Formation (Tripathi et al. 2008) (Fig. 21a-f), and the surface was subsequently lowered by wave planation during the ensuing coastal onlap. In the Awakino Tunnel section (Nelson 1978a; Nelson et al. 1994) the base of Aotea sequence is a wave cut surface with glauconitic infilled burrows extending down into outer shelf calcareous siltstone (Dunphail Siltstone Member of Glen Massey Formation). Where parts of the Whaingaroa Formation are preserved, such as near Kawhia, Ngapaenga and Mangaotaki, there is a sharp contact between outer shelf sandy siltstone (Ngapaenga Siltstone Member) and overlying transgressive shoreface fine to medium calcareous sandstone (Hauturu

Sandstone) (Fig. 21d). In sections along the western margin of the northern region between Port Waikato and Raglan there is a sharp planar surface across the top of Whaingaroa Formation (Fig. 21e, f). In places a lag deposit overlies the lower sequence boundary. This is well developed at Kaimango Road and Mahoe Road sections (Fig. 21b). Transgressive lag deposits are also well developed in the base of Waimai Limestone where it overlies basement in sections west of Otorohanga (e.g. Honikiwi).

Downlap Surface (DLS)

On seismic reflection data sets, a downlap surface (DLS) separates retrograding strata below from prograding strata above. This surface approximates the stratigraphic position of a maximum flooding surface (MFS) and separates a TST from overlying HST (e.g. Posamentier et al. 1988; Van Wagoner et al. 1988). In the Aotea sequence, the downlap surface often corresponds to a sharp lithofacies transition between transgressive limestone or calcareous sandstone and overlying muddy sandstone and siltstone, belonging to an aggradational to retrogradational HST. This sharp transition is best observed in the stratigraphic sections located inland from Aotea-Kawhia Harbour, where massive muddy sandstone (Lithofacies S4) of the Kihī Sandstone sharply overlies variably calcareous fine to medium sandstone (S1) of the Hauturu Sandstone (Fig. 22a & b).

In the study area the transition from TST to HST is not always marked by a sharp lithofacies change. In some cases, the contact may correspond to a gradational (extending over 1-2 m) but distinct up-sequence increase in fine terrigenous sediment. This is best observed in cliff sections around Raglan Harbour. The DLS is usually a transitional interval corresponding to the contact between Mangiti Sandstone (S3) and Patikirau Siltstone (Z1). This transition consists of sandy siltstone (Z1) with thin interbeds of calcareous sandstone (S3), passing upward into sandy siltstone (Z1) (Fig. 23e). In inland sections, this transition is poorly exposed but often evident from a break in weathering profile. Farther north (Port Waikato to Waikaretu), the DLS corresponds to a limestone to glauconitic

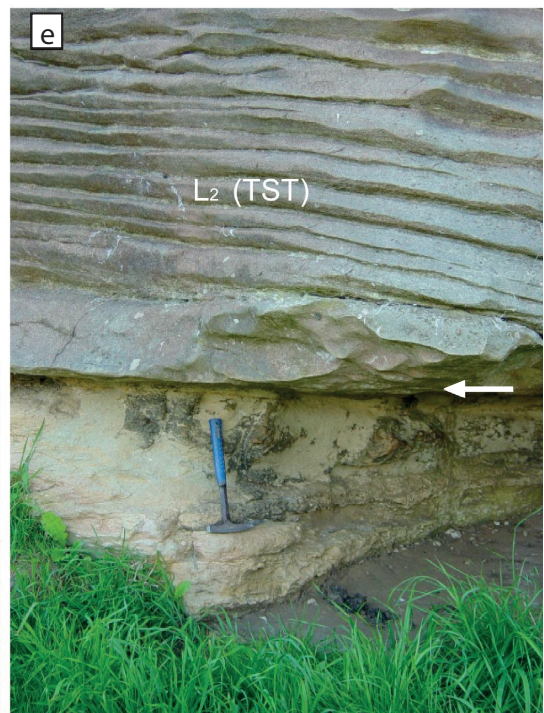
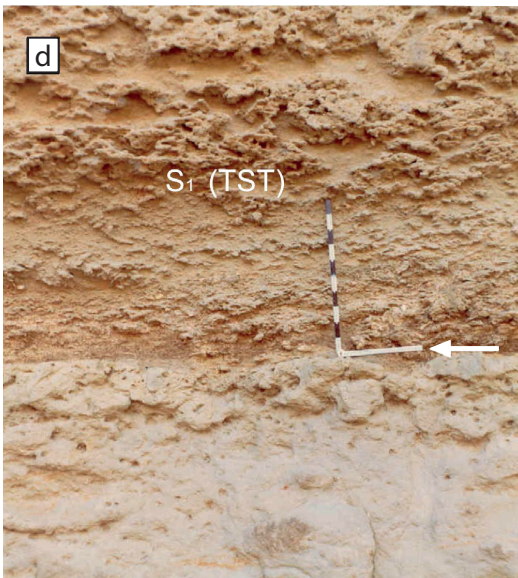
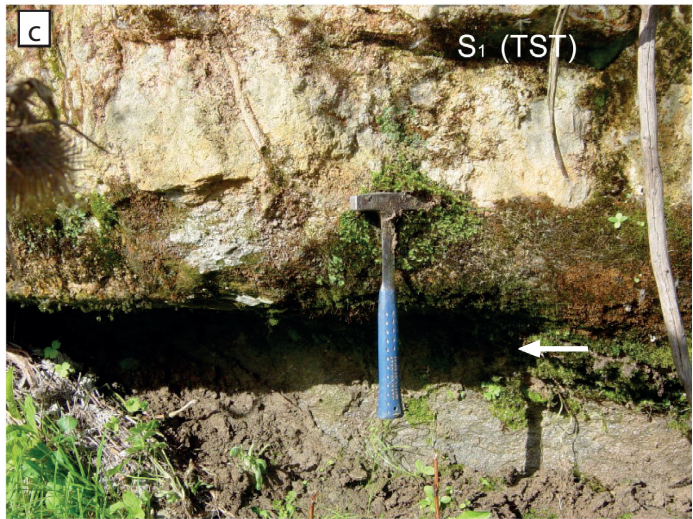
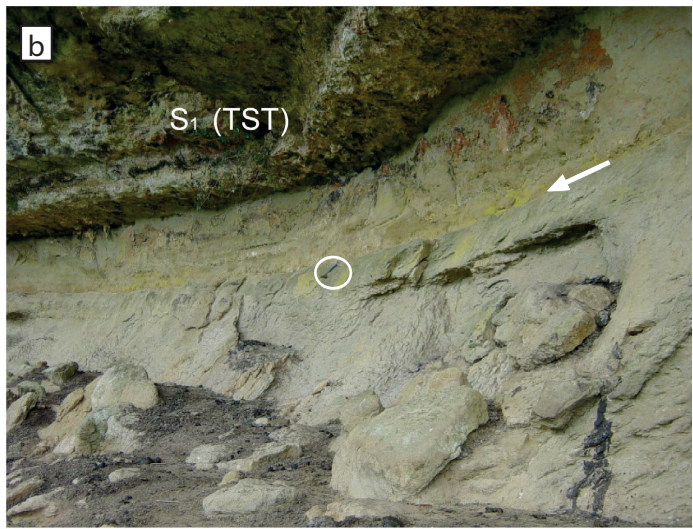


Fig. 21: Photographs of the typical field expression of sequence boundaries in the Aotea sequence across the basin. (a) Arrow points to the truncated older sequence (Ahirau Sandstone Member of Glen Massey Formation) below the sequence boundary and overlying highly calcareous Fine to medium sandstone and sandy limestone Lithofacies S1-L4 (Hauturu Sandstone). Photo location: Kaimango (C-8). (b) Scoured contact (arrow) inferred as sequence boundary between massive calcareous silty sandstone (Ahirau Sandstone Member of Glen Massey Formation) and fine to medium grained calcareous sandstone (Hauturu Sandstone) containing abundant granule-pebbles with common medium to large burrows. This basal pebbly unit immediately overlying the contact is inferred to represent the transgressive lag deposits before passing upward (above the sharp overhang in the photo) into alternating friable to well cemented medium to coarse sandstone with common gritty-pebbly bands of Lithofacies S1. Photo location: Mahoe Road (C-24). (c) Sharp contact (arrow) inferred as a sequence boundary between medium bluish-grey sandy siltstone (Ngapaenga Siltstone Member of Whaingaroa Formation) and overlying moderately to well cemented coarse sandstone Lithofacies S1 (Hauturu Sandstone). Note the presence of large burrow tubes to the left of hammer. Photo location: Mangaotaki, west of Piopio (C-145). (d) Sequence boundary (arrow) showing erosional relief and a burrowed contact between fine silty sandstone (Ahirau Sandstone Member of Glen Massey Formation) and overlying burrowed fine to medium grained sandstone Lithofacies S1 (Hauturu Sandstone) exposed near Harbour Road, Kawhia (R15/807440). Photo courtesy D. Fergusson (1986). (e) Arrow pointing to erosionally truncated calcareous silty sandstone (Waikorea Sandstone Member) below sequence boundary with Waimai Limestone above. The boundary displays centimetre scale relief, and is extensively burrowed. Photo location: Kaawa stream valley, near Limestone Downs (PW-3). (f) Sequence boundary displaying centimetre scale erosional relief separating massive calcareous siltstone and sandy siltstone of an older sequence (Whaingaroa Formation) from the overlying bedded calcareous sandstone with thin silty interbeds of Lithofacies S3 of Mangiti Sandstone. Exposure is approximately 25 m high. Photo location: near Te Kotuku Trig. north of Raglan Harbour (TA-12).

packstone-wackestone (C2) contact, suggesting a sharp reduction in carbonate sediment supply as highstand conditions developed.

Transgressive Systems Tract (TST)

A transgressive systems tract is bounded by a sequence boundary or TSE (transgressive surface of erosion) at its base and by a MFS (maximum flooding surface)/DLS at its top. The TST comprises all contemporaneous strata having retrogradational stacking patterns deposited during the early stage of base-level rise. The development of a TST is directly controlled by the rate of increase in accommodation (a function of the rate of eustatic sea-level change and the rate of subsidence) and the rate of sediment supply. The TST in the Aotea sequence may potentially be thick, due to relatively high sediment accumulation rates stimulated by the available accommodation, or they may be thin due to lack of terrigenous and/or carbonate sediment supply and a regime of rapid relative sea-level rise with marked flooding of the shelf. Numerous studies have documented the factors controlling the architecture of transgressive facies and relationships to the rates of sediment supply, rate of relative sea-level rise, and the position of the particular outcrop in relation to paleo-position on the shelf (e.g. Nummendal & Swift 1987; Demarest & Kraft 1987; Naish & Kamp 1997).

In the southwestern and central regions of the basin, the Aotea sequence consists of a thick TST, comprising mainly mixed carbonate-siliciclastic sandstone (Lithofacies S1 and L4) belonging to Hauturu Sandstone. The lower, variably calcareous sandstone beds (Lithofacies S1) are included in the TST because of their stratigraphic position and overall vertical and lateral facies architecture. The TST reaches a maximum thickness of up to 120 m east of Kawhia Harbour, where it comprises packages of burrowed calcareous fine to medium sandstone (S1) probably stacked in a retrogradational (deepening-up) pattern, suggesting that the rate of subsidence exceeded the rate of sediment supply. This facies is interpreted to have accumulated in inner to mid shelf environments, with the sediment having been derived from a shoreline along the eastern margin of the Herangi High.

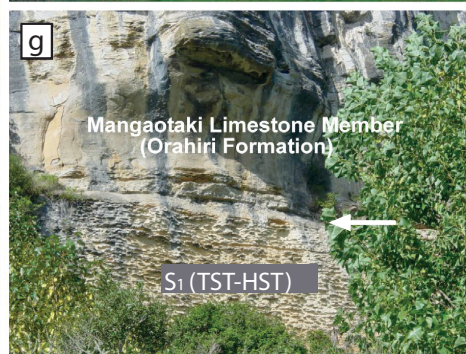
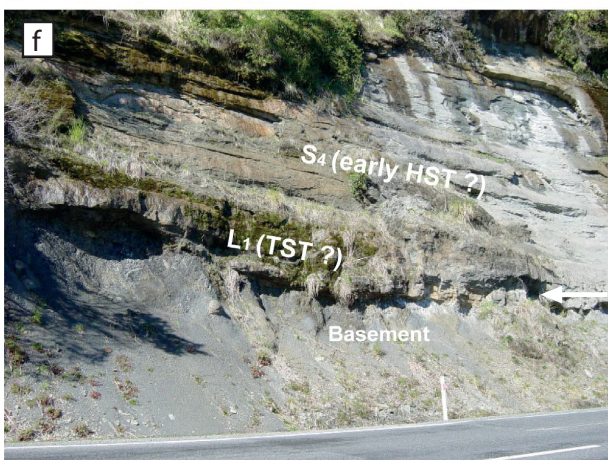
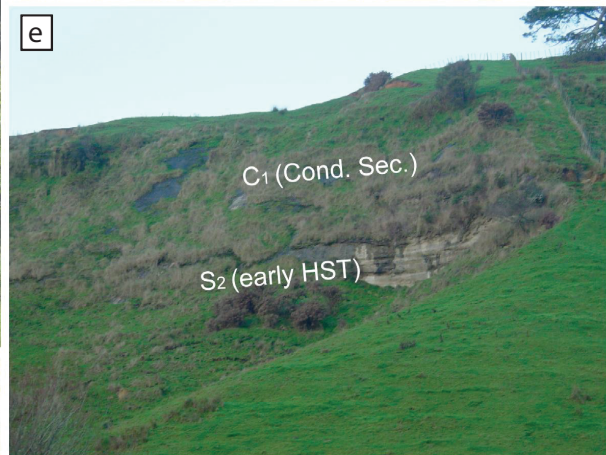


Fig. 22: (page facing) Field photographs of typical lithofacies relationships in the Aotea Formation, and inferred systems tracts and sequence boundaries in the northern and central regions. (a) Normal deepening upward succession, showing a conformable transition from Fine to medium calcareous sandstone (Lithofacies S1; Hauturu Sandstone) to Massive muddy sandstone (Lithofacies S4; Kihī Sandstone). The arrow points to a conformable facies contact and possibly indicates the initiation of early highstand deposition. Photo location: Shea Road (AK-4). Exposure is about 6 m high. (b) Conformable facies contact (arrow) between the Cross-bedded sandy silty grainstone/packstone lithofacies (L4) (Waimai Limestone/Hauturu Sandstone) and Massive calcareous silty sandstone Lithofacies S2 (Kihī Sandstone). The facies transition indicates an abrupt decrease in energy level across the contact, possibly due to deepening. Photo location: Makaka, north of Aotea Harbour (AK-1). (c) Alternation of fine calcareous sandstone Lithofacies S1 and Calcareous silty sandstone Lithofacies S2 (Hauturu Sandstone) comprises much of the upper part of Aotea sequence at this location. The overlying cross-bedded sandy limestone (Mangaotaki Limestone Member of Orahirī Formation) is separated by the sequence boundary at the narrow ledge (arrow). Exposure is about 25 m high. Photo location: Mangaohae Stream (C-56). (d) Sandy grainstone Lithofacies L4 (Waimai Limestone/Hauturu Sandstone) inferred to be transgressive deposits gradually passing upward into early highstand deposits comprising Massive calcareous silty sandstone Lithofacies S2 (Kihī Sandstone). Photo location: Te Raumauku near Honikiwi (C-28). (e) Thin-bedded calcareous sandy siltstone Lithofacies S2 (Kihī Sandstone) gradually passing upwards into dark coloured Glauconitic silty sandstone Lithofacies C1 representing condensed sediment. Exposure is about 12 m high. Photo location: near Bromley and Honikiwi Road intersection (S16/976364). (f) Basement onlap succession made up of basal lenticular Pebbly-gritty grainstone/packstone Lithofacies L1 (Waimai Limestone) overlain by bedded Muddy sandstone Lithofacies S4 (Kihī Sandstone). Note highly irregular top of Mesozoic basement. The entire succession is broadly transgressive and displays inner shelf carbonates at the base, to mid-outer shelf siltstone at the top (not shown in photograph). Photo location: SH3, near Mangaotaki Bridge (C-166). Road marker for scale. (g) Wave-planed surface (arrow) inferred as sequence boundary at the contact between Calcareous fine to medium sandstone Lithofacies S1 (Hauturu Sandstone) and sandy limestone (Mangaotaki Limestone) of the overlying Orahirī Formation at Mangaotaki (C-145).

The TST thickness diminishes toward the north and east (basinward) away from the Herangi High (Fig. 20). The reduction in thickness is gradational and coupled with a facies transition to more open shelf lithofacies (S3, Mangiti Sandstone) to the north (Raglan Harbour area), or to bioturbated muddy sandstone (S4, Kihī Sandstone) in neighbouring more basinal areas to the east (west of Otorohanga).

A comparatively thin TST comprising mainly pebbly to sandy horizontally bedded grainstone/packstone (Lithofacies L1, L2, L4), was deposited in the central-eastern areas on the northern and western fringes of the Piopio High (Figs 3, 4). These transgressive limestone facies contain common large benthic foraminifera, calcareous algae, rhodoliths and fragmented large bivalves interpreted to have been deposited in a neritic setting not far from the rocky shoreline carbonate factory around the Piopio basement high.

The TST within the Aotea sequence in the northern region is never thick (reaching a maximum of 18-20 m in the Waimai Limestone) and is composed largely of low to medium-angle cross-bedded skeletal limestone (Lithofacies L2) or horizontally bedded grainstone/packstone (L3). The thickness of the transgressive limestone facies reduces towards the northwest (Port Waikato and the vicinity of the modern coastline), where it is generally 2-3 m thick. Facies within the Waimai Limestone are arranged such that the cross-bedded facies (L2) pass upward into Horizontally bedded grainstone (L3), which in turn passes into Massive to irregularly bedded planktic foraminiferal-rich grainstone/packstone (L5), capped by condensed facies (C2) recording the drowning of the carbonate shelf. This pattern is illustrated in Figs 8 and 9. Cross-bedded limestone facies (L2) are not present in the east (e.g. Glen Murray). In these areas the TST consists of horizontally bedded grainstone/packstone (L3) and interbedded calcareous sandstone and sandy siltstone (S3, Mangiti Sandstone). This mixed carbonate and siliciclastic composition in the east is the result of reworking of carbonate material from the west into deeper portions of the shelf where silt and fine to very fine sand accumulated in a low energy environment.

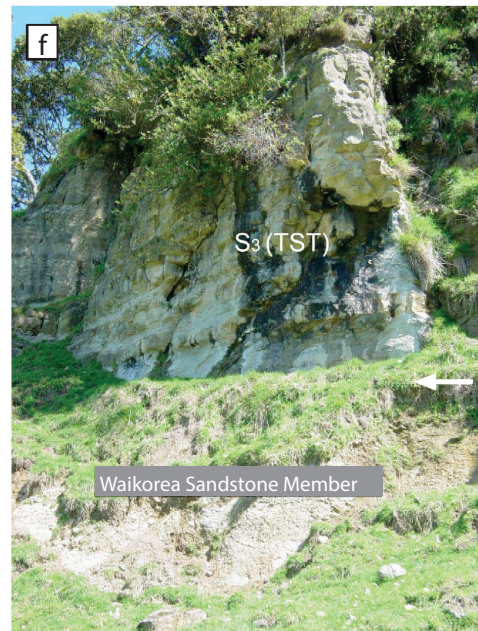
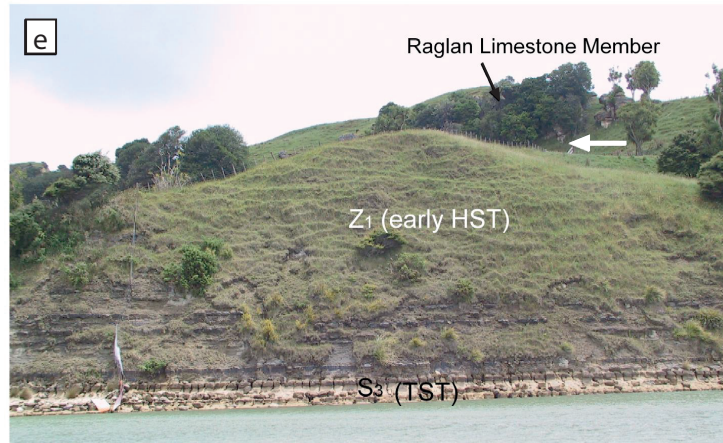
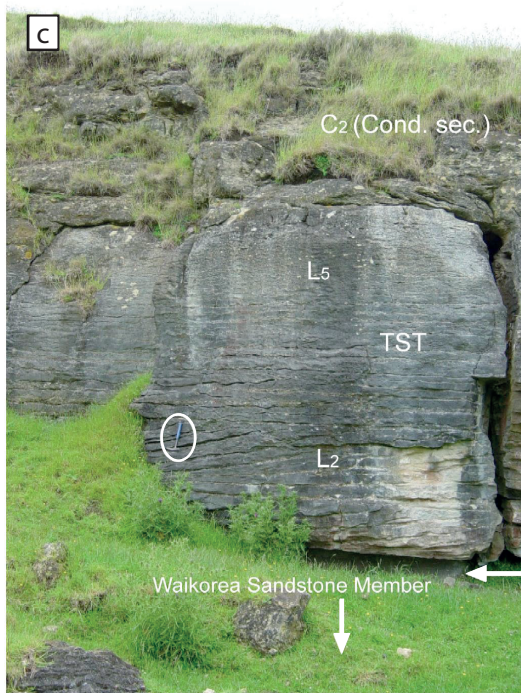
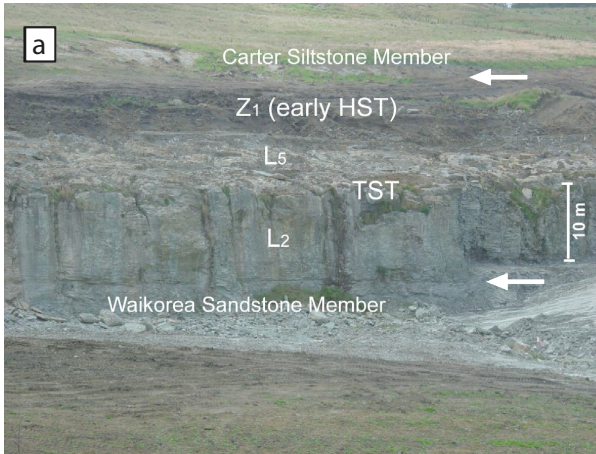


Fig. 23: Field photographs of typical lithofacies relationships in Aotea sequence, and inferred systems tract and sequence boundaries in the northern region. (a) Aotea sequence consisting of Cross-bedded grainstone Lithofacies L2 passing upward into Massive to irregularly bedded grainstone/packstone Lithofacies L5 (Waimai Limestone), which in turn passes upward into Moderately glauconitic sandy siltstone Lithofacies Z1 (Patikirau Siltstone). The lower sequence boundary (arrow) is a wave-planed surface cutting into moderately calcareous silty sandstone (Waikorea Sandstone Member of Whaingaroa Formation). Note dark coloured massive sandy siltstone (Patikirau Siltstone) passing upward into light coloured calcareous siltstone (Carter Siltstone Member of Te Akatea Formation). The upper arrow points to a paraconformity inferred to be a correlative conformity. Photo location: Waikaretu limestone quarry (PW-9). (b) Horizontally bedded grainstone/packstone Lithofacies L3 (Waimai Limestone) is separated by a sequence boundary (arrow) from the underlying Waikorea Sandstone Member of Whaingaroa Formation. The lower 10-15 cm of limestone unit is also moderately glauconitic suggesting a minor hiatus. Note the presence of thin silty interbeds in the lower middle part of the outcrop marking the gradual upward transition to Interbedded calcareous sandstone and sandy siltstone Lithofacies S3 (Mangiti Sandstone). Exposure is approximately 8 m high. Photo location: Bothwell Road, west of Glen Murray. (PW-8). (c) A typical deepening/fining upward cycle in the Aotea sequence. Wave-planed surface (arrow) cutting into the underlying calcareous silty sandstone (Waikorea Sandstone) interpreted as a sequence boundary, is overlain by low-angle Cross-bedded skeletal grainstone Lithofacies L2, which passes upward into Massive to irregularly bedded grainstone/packstone Lithofacies L5 (Waimai Limestone). The highly glauconitic and fossiliferous glauconitic packstone/wackestone Lithofacies C2 marks the condensed sediment indicating drowning of the carbonate platform. Photo location: Port Waikato (PW-1). (d) The gently undulating contact (arrow) inferred as a sequence boundary between calcareous silty sandstone (Waikorea Sandstone) and the overlying tabular low angle Cross-bedded grainstone Lithofacies L2 (Waimai Limestone). Exposure is about 10 m high. Photo location: Waikorea-Matira (TA-2). (e) Bedded calcareous sandstone Lithofacies S3 of Mangiti Sandstone at the shore level gradually passes upwards through an interbedded transition zone into Massive sandy siltstone Lithofacies Z1 of Patikirau Siltstone. Note thin calcareous sandstone beds at the transition interval. The arrow points to a paraconformity (inferred as a correlative conformity) between the Patikirau Siltstone and Raglan Limestone of the Te Akatea Formation. Exposure is approximate 50 m high. Photo location: Patikirau Bay, Raglan Harbour (TA-20). (f) Moderately calcareous silty sandstone (Waikorea Sandstone) is erosionally truncated (arrow) and overlain by interbedded calcareous sandstone and sandy siltstone (Mangiti Sandstone). Exposure is approximately 8 m high. Photo location: Matakītiki Road, near Glen Murray (PW-7).

Highstand Systems Tract (HST)

A highstand system tract (HST) forms during the late stage of relative sea-level rise through the early part of sea-level fall. The HST in the Aotea sequence comprises fine-grained siliciclastic facies and mainly outer shelf facies are preserved in the geological record.

The HST of the Aotea sequence in the southern and central parts of the basin comprises up to 80 m of massive highly bioturbated muddy sandstone (S4) and thin bedded silty sandstone (S2) (Kihī Sandstone). Massive sandy siltstone (Z1) up to 70 m thick occurs around Raglan Harbour (Patikirau Siltstone). These facies are inferred to have been deposited in an outer shelf setting. The HST deposits are comparatively thick in this central Aotea-Kawhia-Raglan Harbour area, probably as a result of high rates of sediment supply combined with accommodation space. The HST is thin in northern and eastern parts of the basin and is comprised of highly burrowed glauconitic sandstone (Lithofacies C1, top of Kihī Sandstone Member at Waitomo and Honikiwi) due to lower rates of sediment supply. In the vicinity of Port Waikato, the highstand deposits are only a few metres thick and are highly condensed, being marked by phosphate nodules and glauconitic marl.

In the southwestern part of the basin the HST (as well as the TST) lies within the Hauturu Sandstone (Lithofacies S1 intercalated with facies S2 at C-56, Figs 19 and 22c). It is envisaged that the sandy shoreline facies migrated westward within the TST and early part of the HST, but the distance was limited as the shoreline was hinged to the eastern margin of the Herangi High and accumulation of facies S1 persisted. There was insufficient accommodation generated at the shoreline to allow the accumulation of S2 and S4 facies. In the section at site C-68 (Fig. 19), the whole Aotea sequence preserved is comprised of Lithofacies S1. An alternative interpretation is that in southwestern sections the HST component of the sequence is no longer preserved due to subsequent erosion and HST facies are not represented in the geological record.

Condensed section

The condensed section in Aotea Formation is marked by high (>5 - 40%) concentrations of glauconite and corresponds to an interval of very low rates of sedimentation. This section is normally associated with the maximum flooding surface (MFS) and/or the top of transgressive deposits, especially in more distal parts of the paleoshelf (Loutit et al. 1988). However, in the case of Aotea sequence the condensed section usually occurs within the HST, forming a cap (2 - 4 m thick) of intensely burrowed glauconitic sandstone/siltstone (Lithofacies C1) above either massive muddy sandstone or sandy siltstone (Lithofacies S4, Z1), such as in the Waitomo Valley, Honikiwi and Raglan Harbour sections (Fig. 23e). These sections are characterised by high concentrations of glauconite pellets (locally up to 40%), rich fossil assemblages and burrows infilled with glauconitic sandstone/siltstone, suggesting firmground or hardground development. In these areas, the facies represent partial condensation of the HST, triggered by waning terrigenous sediment supply. Similar condensed sections occur widely in the Port Waikato-Waikaretu area overlying Waimai Limestone and thin Patikirau Siltstone facies. There, the stratigraphic condensation involves the whole of the HST (e.g. locality A in Fig. 8).

Qualitative model of Aotea sequence

Successful application of sequence stratigraphic models to outcrop sections requires two or three-dimensional modeling of the sedimentary succession and its stratal patterns. Such models idealise reality in the sense that they provide simplified representation of how the lithofacies architecture and stratigraphic surfaces are expected to be expressed in the field. The lack of outcrop in key localities hampers resolution and reliability of the predicted sequence stratigraphic model. For example, the most landward parts of the Aotea sequence along the Herangi High have either been removed through uplift and erosion, or, in the Port Waikato-Waikaretu area, lie offshore to the west. Similarly, more basinward parts have either been removed by erosion or remain in the subsurface and are not accessible. Nevertheless, the qualitative model developed here shows a 1st order stratigraphic

framework for the Aotea sequence (Figs 24, 25). The smaller scale features are shown in simplified stratigraphic columns across the model sequence. However due to lack of outcrop windows in some of the key areas, some assumptions have had to be made, particularly along the landward and basinward portions of the paleoshelf.

Control on sequence architecture

It is apparent that local vertical crustal movement (subsidence and uplift) is the main control on development of the Aotea sequence, chiefly through determining relative sea-level change. This has determined the overall facies distribution and stacking pattern. The sediment flux and proximity to the shoreline supplying the terrigenous sandstone (Hauturu Sandstone) had a significant influence upon the thickness of the TST and HST in the southwestern region. Basic differences in depositional setting between the northern and southern parts of the basin are expressed in the stratigraphic architecture, illustrated in Figs 24 and 25. Figure 24 represents the sequence architecture for a west-east shore normal profile in the northern region, whereas Fig. 25 represents the sequence architecture for a NW-SE profile in the central region.

A model Aotea sequence for the northern region

A simplified view of the distribution of Aotea lithofacies and sequence architecture along a west - east cross-shelf transect is depicted in Fig. 24. Prior to accumulation of the Aotea sequence, uplift along the western margin elevated shelfal siltstone facies of the underlying Whaingaroa Formation into a subaerial environment. Wave erosion during the subsequent coastal onlap wave-planed the Whaingaroa strata and formed a sharp flat surface (TSE). This sequence boundary passes basinward into a correlative conformity.

During the ongoing transgression in the early part of the Aotea sequence, the bulk of the coarse skeletal sand generated around the rocky shorelines was reworked across the shelf assisted by wave and storm currents. The TST in inner to mid-shelf settings is represented by Cross-bedded, moderately well sorted skeletal grainstone (Lithofacies L2) passing upward into Massive

to irregularly bedded, bioturbated grainstone/packstone (L5). The cross-bedded grainstone facies accumulated as skeletal sand megadunes on mainly inner parts of the contemporary shelf that sloped to the east. Paleocurrent directions measured by Anastas (1997) indicate mainly west to east migration of the carbonate dune fields with some local NNE and SSW transport as well. The grainstone is mainly composed of echinoderms, bryozoans, benthic foraminifera, and a minor proportion of calcareous red algae and fragmented bivalves. The cross-bedded grainstone passes offshore into horizontally bedded skeletal grainstone (L3) reflecting a low energy environment. Further offshore, Lithofacies L3 pass through intercalated silty/sandy limestone and calcareous silty sandstone (S2) into interbedded fine calcareous sandstone and siltstone (S3) that probably accumulated at outer shelf depths. The proportion of siliciclastics increases in a seaward direction.

The upper parts of the TST are characterised by increasing intensity of bioturbation and an increasing percentage of planktic foraminifera and slightly higher siliciclastic content, suggesting increasing paleobathymetry. Rapid transgression can result in cessation of carbonate productivity (e.g. Simone & Carannante 1988) reducing the delivery of carbonate sediment seaward. Accommodation that continues to develop into the subsequent highstand may therefore only be occupied by siliciclastic sediment provided this is available (e.g. Gillespie & Nelson 1997). For the Aotea sequence in the northern region, sufficient terrigenous sediment was not available to fill the accommodation space and this is reflected in progressive deepening. Interestingly, sedimentation rates were much lower in the inner parts of the shelf compared with outer parts. This gave rise to a thin HST made up of condensed deposits over a thin backstepping inner to mid shelf carbonate-dominated TST.

A model Aotea sequence for the southern central region

A simplified model of the distribution of lithofacies and systems tracts in the Aotea sequence in the south-central region is illustrated in Fig 25. The western margin of the basin lay

along the Herangi High, which is not shown in the model. Prior to the start of accumulation of the Aotea sequence the basin margin was uplifted, which resulted in subaerial exposure of the Whaingaroa Formation. This sequence boundary was modified by subsequent wave erosion during coastal onlap, forming a TSE (e.g. Swift 1976). TST deposits that accumulated immediately basinward of the paleo-shoreline are formed of packages of variably calcareous, moderately well sorted, cross-bedded to bioturbated fine to medium sandstone (S1). These beds have a wedge-shaped geometry thinning towards the paleo-shoreline and thickening out into the basin. This mixed carbonate-siliciclastic wedge is inferred to be shore-connected, and the seaward transport of the sediment from the shoreface onto the shelf resulted from a combination of wave, tide and storm-induced currents. Shell hash and basement-derived pebbles are common throughout these transgressive mixed carbonate-siliciclastic facies, pointing to material having been reworked from the adjacent beach environment. Most of the coarse-grained sediments were deposited in the inner shelf with finer fractions being winnowed and deposited in mid to outer shelf areas as muddy sandstone (S4) where they were heavily bioturbated.

The part of TST made up of limestone (L1, L3, L4) is restricted to the flanks of basement highs and also in shoal areas above submerged basement knolls. These deposits display broadly similar characteristics to the carbonate deposits on the contemporary inner to mid shelf in the northern region.

As relative sea level continued to rise, sand supply was gradually cut-off to the mid shelf areas leading to the accumulation of muddy sandstone (S4) and thin-bedded calcareous siltstone (S2), both classified as early HST deposits. As a result the stratigraphic profile of a fully developed Aotea sequence in the Aotea-Kawhia area fines upward, which is an expression of retrogradation. An unusual thickness profile can develop if a sandstone shore-connected wedge continues to accumulate during the highstand, which may have been the case with the Aotea sequence in the southern region (Fig. 25). Out in the basin, condensed glauconitic sandstone formed at

the top of the HST as a result of the waning of terrigenous sediment supply. The Aotea sequence appears not to contain RST (regressive system tract) deposits.

Summary

Detailed description of exposures of Aotea Formation across central-western North Island has distinguished a wide spectrum of lithofacies that can be grouped into four main associations named: (i) limestone lithofacies; (ii) mixed carbonate-siliciclastic sandstone lithofacies; (iii) mixed carbonate-siliciclastic siltstone lithofacies; and (iv) chemogenic lithofacies. The facies occurring in the lower part of the formation, especially along the western margin, are comprised of limestone (L1-L5) belonging to the Waimai Limestone Member, or by variably calcareous fine to medium sandstone (S1, S3) belonging to Hauturu Sandstone Member or Mangiti Sandstone Member. They accumulated in relatively high-energy shelf environments. The facies comprising the upper part of the formation consist mainly of bioturbated fine muddy sandstone and sandy siltstone (S2-S4, Z1) belonging to Kihī Sandstone Member or Patikirau Siltstone Member. They pass up-section into condensed intervals (C1, C2) indicating low-energy deep water environments with terrigenous sediment starvation.

The Aotea sequence has a lower sequence boundary, which is an erosional unconformity (transgressive surface of erosion, TSE). The transgressive systems tract (TST) within the Aotea sequence in southwestern and central regions comprises a combination of mixed carbonate-siliciclastic sandstone and limestone of variable thickness (120 - <1 m). However, the TST within the Aotea sequence in the northern region is relatively thin (20 - <1 m) and is largely comprised of cross-bedded skeletal limestone (L2) or interbedded calcareous sandstone and sandy siltstone (S3). The downlap surface (DLS) corresponds to a sharp lithofacies transition between the TST and overlying highstand systems tract (HST). The HST of the Aotea sequence in the Aotea-Kawhia-Raglan Harbour areas typically comprises highly bioturbated calcareous sandstone and siltstone (S2, S4, Z1) up

to 80 m thick. These facies are inferred to have been deposited in an outer shelf setting. The HST in more northern and eastern parts of the study area is relatively thin and often capped by highly condensed deposits (C1, C2).

Acknowledgements

We thank the many land owners in the Waikato and King Country for the provision of access to their properties, and also Betty-Ann Kamp for cartographic assistance. We acknowledge the New Zealand Ministry for Business, Innovation and Employment for research funding (Contract: UOWX0902).

References

- Anastas, A.S. 1997: Physical sedimentology of the Cenozoic Te Kuiti Group limestones, North Island, New Zealand. PhD thesis, lodged in the Library, Queen's University, Ontario, Canada.
- Anastas, A.S.; Dalrymple, R.W.; James, N.P.; Nelson, C.S. 1997: Cross-stratified calcarenites from New Zealand: subaqueous dunes in a cool-water, Oligo-Miocene seaway. *Sedimentology* 44: 869-891.
- Amorosi, A. 1995: Glaucony and sequence stratigraphy: a conceptual framework of distribution in siliciclastic sequences. *Journal of Sedimentary Research* B65: 419-425.
- Cooper, R.A.; Agterberg, F.P.; Alloway, B.V.; Beu, A.G.; Campbell, H.J.; Cooper, R.A.; Crampton, J.S.; Crouch, E.M.; Crundwell, M.P.; Graham, I.J.; Hollis, C.J.; Jones, C.M.; Kamp, P.J.J.K.; Mildenhall, D.C.; Morgans, H.E.G.; Naish, T.R.; Raine, J.I.; Roncaglia, L.; Sadler, P.M.; Schioler, P.; Scott, G.H.; Strong, C.P.; Wilson, G.J.; Wilson, G.S. 2004. In: *The New Zealand Geological Timescale* (Ed. Cooper, R.A.). Institute of Geological & Nuclear Sciences Monograph 22: 284 p.
- Demarest, J.M.; Kraft, J.C. 1987: Stratigraphic record of Quaternary sea levels: Implications for more ancient strata. In: *Sea-level Fluctuations and Coastal Evolution* (Ed. Nummedal D, Pilkey OH, Howard JD). Society of Economic Paleontologists and Mineralogists (SEPM) Special Publication 41: 241-259.

- Dott, R.H.; Bourgeois, J. 1982: Hummocky stratification: significance of its variable bedding sequences. *Bulletin of the Geological Society of America* 93: 663-680.
- Driese, S.G.; Fischer, M.W.; Easthouse, K.A.; Marks, G.T.; Gogola, A.R.; Schoner, A.E. 1991: Model for genesis of shoreface and sandstone sequences, southern Appalachians: paleoenvironmental reconstruction of early Silurian system. In: *Shelf Sand and Sandstone Bodies-Geometry, Facies and Sequence Stratigraphy* (Ed. Swift, D.J.P.; Oertel, G.F.; Tillman, R.W.; Thorne, J.A.) Special Publication of International Association of Sedimentologist 14: 309-338.
- Fergusson, D.A. 1986: Geology of inland Kawhia: emphasis on Te Kuiti Group stratigraphy and sedimentation. Unpublished MSc thesis, lodged in the Library, University of Waikato, Hamilton, New Zealand.
- Gillespie, J.L.; Nelson, C.S. 1997: Mixed siliciclastic-skeletal carbonate facies on Wanganui shelf, New Zealand: A contribution to the temperate carbonate model. In: *Cool water carbonates* (Ed. James N.P.; Clarke, J.A.D.). SEPM (Society for Sedimentary Geology) Special Publication 56: 127-140.
- Hamblin, A.P.; Walker, R.G. 1979. Storm-dominated shallow marine deposits: the Fernie-Kootenay (Jurassic) transition, southern Rocky Mountains. *Canadian Journal of Earth Sciences*, 16: 1673-1690.
- Hayward, B.W. 1986: A guide to paleoenvironmental assessment using New Zealand Cenozoic foraminiferal faunas. *New Zealand Geological Survey Report Paleontology* 109.
- Hayward, B.W. 1993: The tempestuous 10 million year life of a double arc and intra-arc basin - New Zealand's Northland Basin in the Early Miocene. In: *South Pacific sedimentary basins. Sedimentary basins of the world 2*. Amsterdam, Elsevier: 113-142.
- Hayward, B. W.; Brook, F. J.; Isaac, M. J. 1989: Cretaceous to middle Tertiary stratigraphy, paleogeography and tectonic history of Northland, New Zealand. In: *Geology of Northland-accretion, allochthons and arcs at the edge of the New Zealand microcontinent* (Ed. by Spörli, K.B.; Kear, D.), *Royal Society of New Zealand Bulletin* 26: 47-62.
- Hayward, B.W.; Grenfell, H.R.; Reid, C.M.; Hayward, K.A. 1999: Recent New Zealand shallow-water benthic foraminifera: taxonomy, ecologic distribution, biogeography, and use in paleoenvironmental assessment. *Institute of Geological and Nuclear Sciences Monograph* 21, 258 p.
- Hopkins, J.C. 1966: The Te Kuiti Group in the West Piopio area. Unpublished MSc thesis, lodged in the Library, University of Auckland, Auckland, New Zealand.
- Howard, J. D. 1978: Sedimentology and trace fossils in Basan; Trace fossils concepts. *Society of Economic Paleontologists and Mineralogists (SEPM) Short Course No. 5*: 11-42.
- James, N.P.; Collins, L.B.; Bone, Y.; Hallock, P. 1999: Sub-tropical carbonates in a temperate realm: modern sediments on the southwest Australian Shelf. *Journal of Sedimentary Research* 69: 1297-1321.
- Kamp, P.J.J., Tripathi, A.R.P.; Nelson, C.S. 2014a: Paleogeography of the Late Eocene to earliest Miocene Te Kuiti Group, central-western North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, DOI:10.1080/00288306.2014.904384
- Kamp, P.J.J.; Tripathi A.R.P.; Nelson, C.S.; Hendy, A.J.W. 2014b: Biostratigraphy, Sr isotope chronology and chronostratigraphy of the Late Eocene – earliest Miocene Te Kuiti Group, Waikato – King Country Basin, New Zealand. Ministry of Business, Innovation and Employment, New Zealand, unpublished Petroleum Report PR4878, 31 p.
- Kamp, P.J.J.; Tripathi, A.R.P.; Nelson, C.S. 2014c. Facies analysis and sequence stratigraphy of the Early Oligocene Glen Massey Formation (Te Kuiti Group), King Country-Waikato Basin, New Zealand. Ministry of Business, Innovation and Employment, New Zealand, unpublished Petroleum Report PR4879, 47 p.
- Loutit, T.S.; Hardenbol, J.; Vail, P.R.; Baum, G.R. 1988: Condensed sections: The key to age dating and correlation of continental margin sequences. In: *Sea-level changes: An integrated approach* (Ed. Wilgus, C.K.; Hastings, B.S.; Christopher, G. St.; Kendall, C.; Posamentier, W.; Ross, C.A.; Van Wagoner, C.J.). *Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications* 42: 183-213.

- Naish, T.; Kamp, P.J.J.. 1997: Sequence stratigraphy of sixth-order (41 k.y.) Pliocene-Pleistocene cyclothems, Wanganui basin, New Zealand: A case for the regressive systems tract. *Geological Society of America Bulletin* 109: 979-999.
- Nalin, R.; Nelson, C.S.; Basso, D.; Massari, F. 2008: Rhodolith-bearing limestones as transgressive marker beds: fossil and modern examples from North Island, New Zealand. *Sedimentology* 58: 249-274.
- Nelson, C.S. 1973: Stratigraphy and sedimentology of the Te Kuiti Group in Waitomo County, South Auckland. Unpublished PhD thesis, lodged in the Library, University of Auckland, Auckland, New Zealand.
- Nelson, C.S. 1978a: Stratigraphy and paleontology of the Oligocene Te Kuiti Group, Waitomo County, South Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics* 21: 553-594.
- Nelson, C.S. 1978b: Temperate shelf carbonate sediments in the Cenozoic of New Zealand. *Sedimentology* 25: 737-771.
- Nelson, C.S.; Hume, T.M. 1977: Relative intensity of tectonic events revealed by the Tertiary sedimentary record in the North Wanganui Basin and adjacent areas, New Zealand. *New Zealand Journal of Geology and Geophysics* 20: 369-392.
- Nelson, C.S.; Kamp, P.J.J.K.; Young, H.R. 1994: Sedimentology and petrography of mass-emplaced limestone (Orahihi Limestone) on a Late Oligocene shelf, western North Island, and tectonic implications for eastern margin development of Taranaki Basin. *New Zealand Journal of Geology and Geophysics* 37: 269-285.
- Nelson, C.S.; Keane, S.L.; Head, P.S. 1988: Non-tropical carbonate deposits on the modern New Zealand shelf. *Sedimentary Geology* 60: 71-94.
- Nummedal, D.; Swift, D.J.P. 1987: Transgressive stratigraphy at sequence-bounding un-conformities: Some principles derived from Holocene and Cretaceous examples. In: *Sea-level fluctuation and coastal evolution* (Ed. Nummedal, D.; Pilkey, O.H.; Howard, J.D.), Society of Economic Paleontologists and Mineralogists Special Publication (SEPM) 41: 241-259.
- Phelps, D.J. 1985: New Zealand Coal Resources Survey: West Kawhia Coalfield geological assessment of coal resources. Unpublished report for the Ministry of Energy: 86 p.
- Posamentier, H.W.; Vail, P.R. 1988: Eustatic controls on clastic deposition II - Sequence and systems tract models. In: *Sea-level changes: An integrated approach* (Ed. Wilgus, C.K.; Hastings, B.S.; Christopher, G. St.; Kendall, C.; Posamentier, W.; Ross, C.A.; Van Wagoner, C.J.) Society of Economic Paleontologists and Mineralogists Special Publications (SEPM) 42: 125-154.
- Simone, L.; Carannante, G. 1988: The fate of foramol ("temperate-type") carbonate platforms. *Sedimentary Geology* 60: 347-354.
- Swift, D.J.P. 1976: Continental shelf sedimentation. In: *Marine Sediment Transport and Environmental Management* (Ed. Stanley, D.J.; Swift, D.J.P.), 255-311. John Wiley & Sons, New York.
- Swift, D.J.P.; Figueiredo, A.G.; Freeland, G.L.; Oertel, G.F. 1983: Hummocky cross-stratification and megaripples; a geological double standard? *Journal of Sedimentary Research* 53: 1295-1317.
- Tripathi A.R.P.; Kamp, P.J.J.; Nelson, C.S. 2008. Te Kuiti Group (Late Eocene-Oligocene) lithostratigraphy east of Taranaki Basin in central-western North Island, New Zealand. Ministry of Economic Development, New Zealand. Unpublished Petroleum Report PR3900, 70 p.
- Van Markhoven, F.; Berggren, W.A.; Edwards, A.S. 1986: Cenozoic cosmopolitan deep-water benthic foraminifera: *Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine*: 421 p.
- Van Wagoner, J.C.; Posamentier, H.W.; Mitchum, R.M. Jr.; Vail, P.R.; Sarg, T.S.; Loutit, T.S.; Hardenbol, J. 1988: An overview of the fundamentals of sequence stratigraphy and key definitions. In: *Sea-level changes: An integrated approach* (Ed. Wilgus, C.K.; Hastings, B.S.; Christopher, G. St.; Kendall, C.; Posamentier, W.; Ross, C.A.; Van Wagoner, C.J.). Society of Economic Paleontologists and Mineralogists (SEPM) Special Publications 42: 39-45.
- Walker, R.G. 1984: Shelf and shallow marine sands. In: *Facies models* (Ed. Walker, R.G.). Geoscience Canada Reprint Series 1, second edition Toronto: Geological Association of Canada Publication: 141-170.
- White, P.J.; Waterhouse, B.C. 1993: Lithostratigraphy of the Te Kuiti Group: a revision. *New Zealand Journal of Geology and Geophysics* 36: 255-266.