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Title **Facies analysis and sequence stratigraphy of Early Oligocene Glen Massey Formation (Te Kuiti Group), Waikato - King Country Basin, New Zealand**

Operator

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Summary This report presents a comprehensive facies and sequence stratigraphic analysis of the Early Oligocene Glen Massey Formation, one of eight formations within the Late Eocene to earliest Miocene Te Kuiti Group in the Waikato-King Country Basin in central-western North Island, New Zealand. The Glen Massey Formation is a mixed carbonate-siliciclastic succession with three main facies associations: limestone (Elgood Limestone Member), calcareous siltstone (Dunphail Siltstone Member) and calcareous sandstone (Ahirau Sandstone Member). These facies, established from field descriptions supplemented by laboratory textural and petrographic data, accumulated in a continental shelf setting above coal measure and marginal marine units in basal Te Kuiti Group or above the Mesozoic basement rocks along the eastern margin of Taranaki Basin. The formation comprises one sequence for which key surfaces are identified and described and used to establish the extent of systems tracts, representing different parts of a relative sea-level cycle. A model sequence shows the distribution of facies within systems tracts in a cross-shelf profile.

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Introduction

The main purpose of this report is to document the sequence stratigraphic architecture of the Early Oligocene Glen Massey Formation, which occurs within the lower part of the Te Kuiti Group. The Te Kuiti Group is a mixed carbonate-siliciclastic sedimentary succession that overlies basement in central-western North Island and accumulated in the Waikato and King Country Basin, immediately east of Taranaki Basin (Fig. 1). It comprises eight formations of mainly mixed carbonate-siliciclastic deposits whose litho- and chrono-stratigraphy have recently

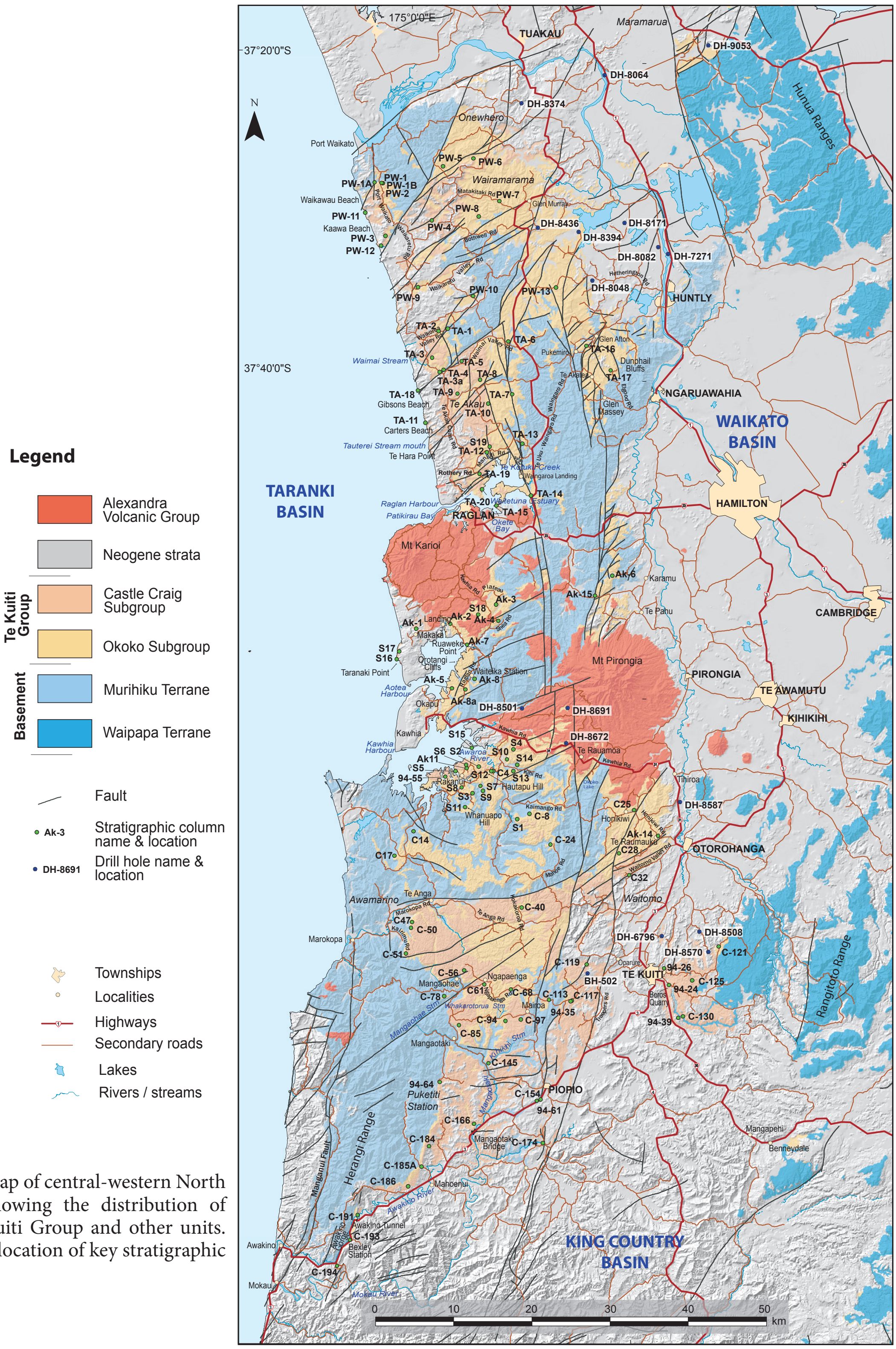


Fig. 1: Map of central-western North Island showing the distribution of the Te Kuiti Group and other units. Note the location of key stratigraphic columns.

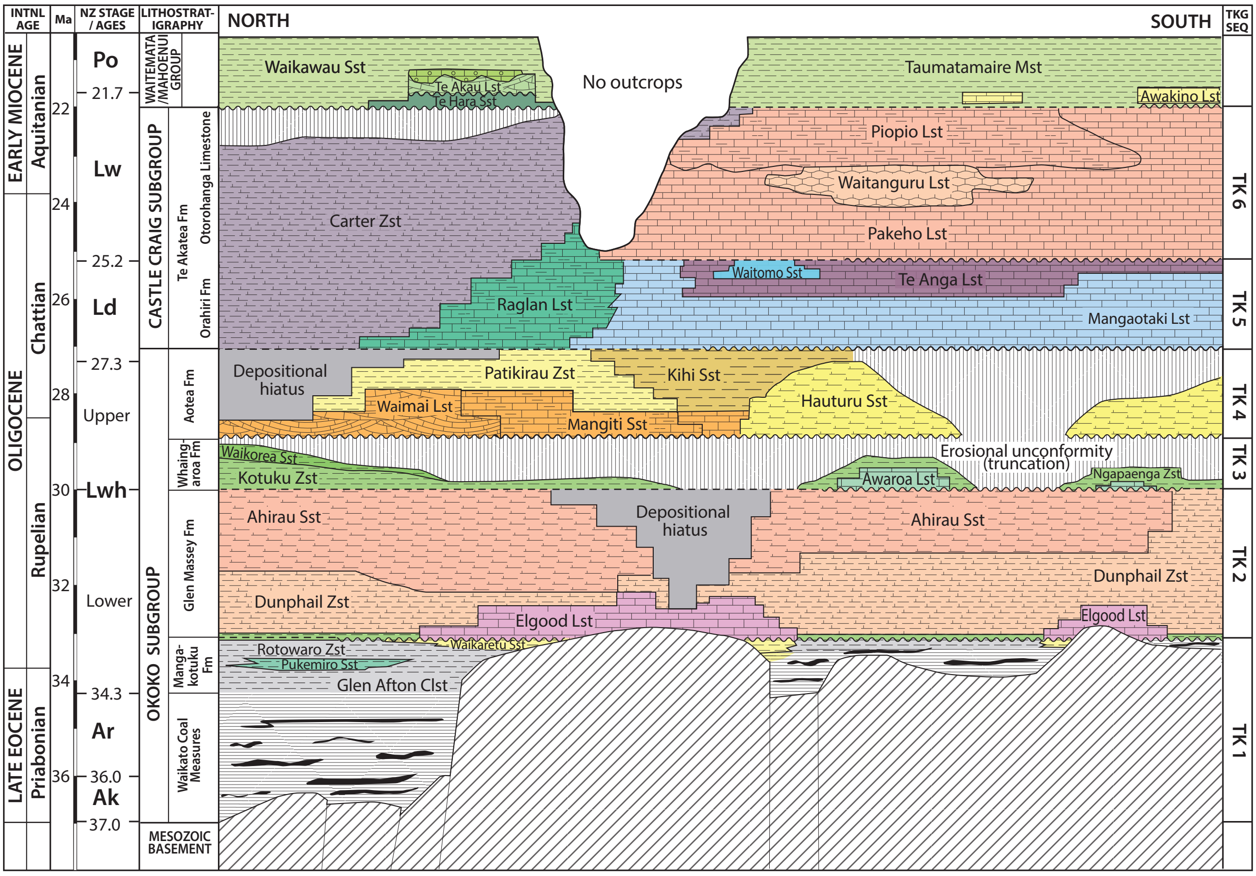


Fig. 2: A new chronostratigraphic scheme for the Te Kuiti Group and the transition to the Waitemata and Mahoenui Groups. Note the occurrence of six unconformity-bound sequences (TK 1 – TK 6). Figure from Tripathi et al. (2008) based on biostratigraphy in Kamp et al. (2014a).

been reassessed (Fig. 2). The group accumulated in shelf and upper bathyal environments during the Oligocene, marking the start of a prolonged period (Oligocene – Late Miocene) of subsidence and sedimentation related to the development of the modern Australia-Pacific plate boundary system. Although the Glen Massey Formation does not comprise the earliest marine facies of the Te Kuiti Group (marginal marine facies occur within the upper part of the underlying Waikato Coal Measures (Edbrooke at el. 1994)), it does represent the first occurrence of fully marine environments across much of the basin from Port Waikato in the north to Awakino in the south (Fig. 3).

The paleoenvironments represented within the Glen Massey Formation, together with its sequence architecture, show that the formation formed as a result of a cycle of relative sea-level change. The formation also demonstrates the occurrence of a higher order cycle of relative sea-level change (3rd to 4th order) within the 2nd order (50 m.y. duration) tectonically-driven cycle of relative sea-level change represented by the Late Cretaceous and Cenozoic marine inundation of New Zealand and the subsequent regression (King et al. 1999).

Our approach to developing an understanding of the sequence stratigraphic architecture of the Glen Massey Formation has been to first describe the facies and their associations, followed by interpretation of their depositional paleoenvironments. In the context of sequence stratigraphy, facies analysis links depositional features to environmental processes; and facies associations to contemporary depositional systems (Walker & James 1992). Sequence stratigraphy, which is concerned primarily with the identification and description of key surfaces, thereby provides a chronostratigraphic template dividing a sequence into systems tracts (otherwise known as linked depositional systems) that represent different parts of a relative sea-level cycle. In this regard, a model sequence has been developed

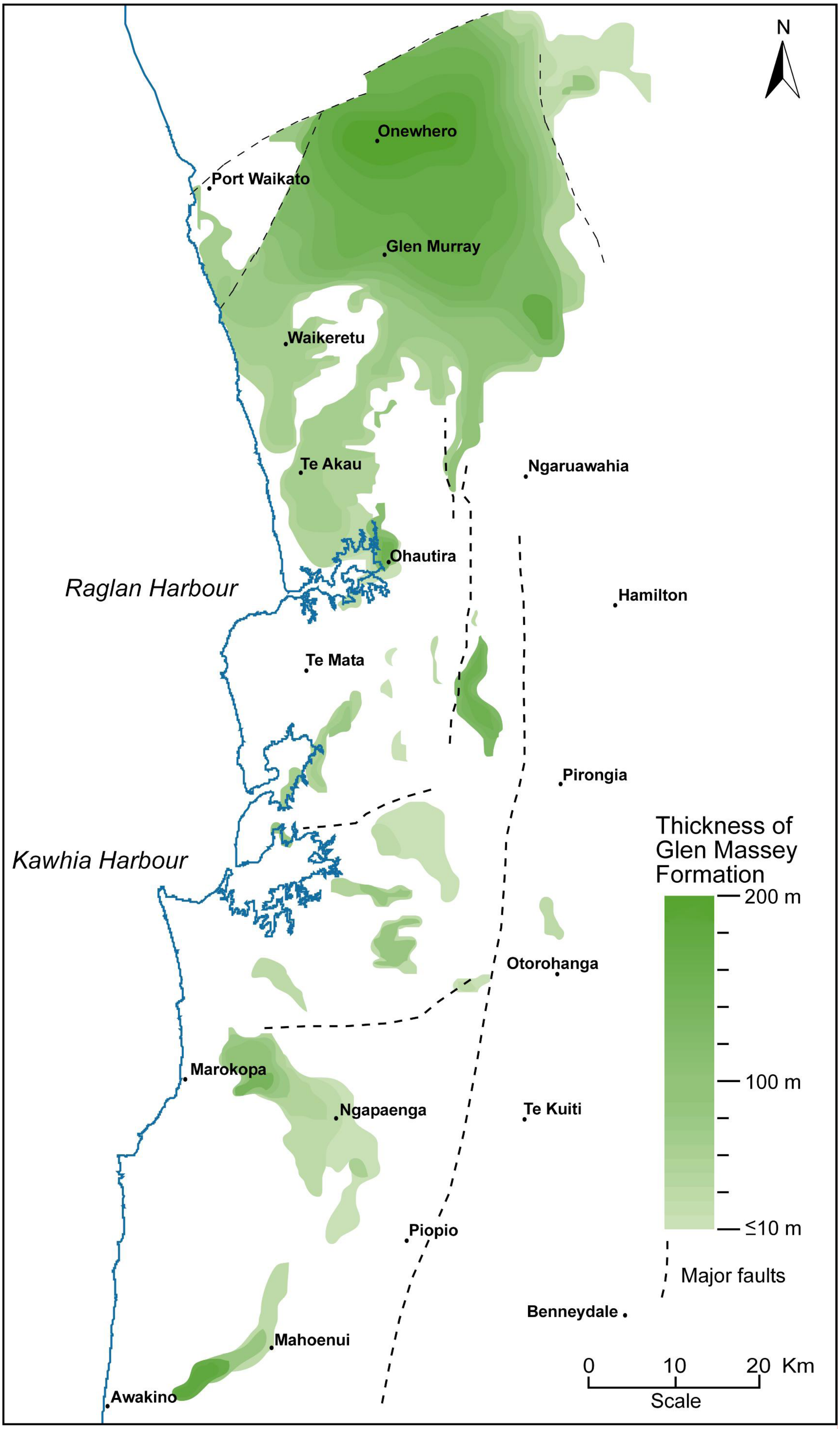


Fig. 3: Map showing the generalised distribution and thickness (m) of the Glen Massey Formation.

for the Glen Massey Formation, illustrated as a cross-shelf profile, showing the horizontal and vertical distribution of systems tracts and facies.

Lithofacies analysis

Overview

Our facies analysis of Glen Massey Formation has been built on mapping and correlation of its members throughout central-western North Island between Port Waikato and Awakino (Tripathi et al. 2008; Kamp et al. 2008). One of the lithostratigraphic advances in that work was demonstration that the formation extends to the south of Raglan Harbour, whereas previously its extent was only known north of Raglan (Fig. 2). Glen Massey Formation comprises a diverse assemblage of carbonate and mixed carbonate-siliciclastic strata that have reasonably good lateral facies continuity. Previous investigations (e.g. Kear & Schofield 1959; Kear 1963, 1987; White & Waterhouse 1993) have traditionally subdivided the Glen Massey Formation into three major lithofacies types, viz: limestone (Elgood Limestone Member), calcareous siltstone (Dunphail Siltstone Member) and calcareous sandstone (Ahirau Sandstone Member). The distribution of the latter two facies throughout the outcrop area is depicted in Figs 4 and 5, and of the limestone in Fig. 11.

In a broad sense this field-based tripartite lithofacies subdivision is expanded upon here, supplemented by laboratory textural and petrographic data. Primary sedimentary structures are often difficult to discern in outcrop exposures because of extensive bioturbation and a degree of diagenetic overprinting in the limestones.

Methods

Closely spaced and detailed measured outcrop sections together with Coal Resources Survey drillhole core-log data make up the database for this investigation. Correlations between measured sections were made using significant stratigraphic discontinuities bounding the formation and within it. Samples representative of the field lithologies were collected from key stratigraphic sections and sub-samples of a selection of these were digested using dilute acid (10% HCl) to determine their $CaCO_3$ percentage. The insoluble residue was then used to establish the siliciclastic texture using a fully computerised Malvern laser-based particle size analyser. The objective was to quantitatively document the vertical variations in $CaCO_3$ content and variations in siliciclastic grain size distributions to aid in the characterisation of the various lithofacies.

A ternary plot depicting the $CaCO_3$-sand-mud % for samples clearly segregates the three members of the Glen Massey Formation (Fig. 6). Textural and compositional changes upward within the Glen Massey Formation for selected sections (Fig. 7) are illustrated in a series of detailed measured logs (Fig. 8a-i). A basal limestone facies (ELM) is overlain by a fine-grained mixed carbonate-siliciclastic facies (Dunphail Siltstone Member), above which grain size gradually increases upward to the top of the Ahirau Sandstone Member.

The Glen Massey Formation is characterised by a diverse array of facies, fourteen of which have been differentiated in this study (Table 1). In general, most facies can be grouped into one of four lithofacies associations, namely limestone, mixed carbonate-siliciclastic sandstone, mixed carbonate-siliciclastic siltstone and chemogenic facies. Individual facies and their associations are interpreted in terms of depositional processes and paleobathymetry and they have been given brief descriptive names (e.g. low-angle cross-bedded limestone). Paleoenvironmental interpretations have been made for each of the facies and their associations. The diagnostic characteristics of all lithofacies are summarised in Table 1. A series of lithofacies cross-sections for the Glen Massey Formation have been constructed by linking the more landward zones (towards the west) with more basinal ones (towards the east) and these are illustrated in Fig. 9a-e. The locations of the columns and selected cross-sections are shown in Fig. 7.

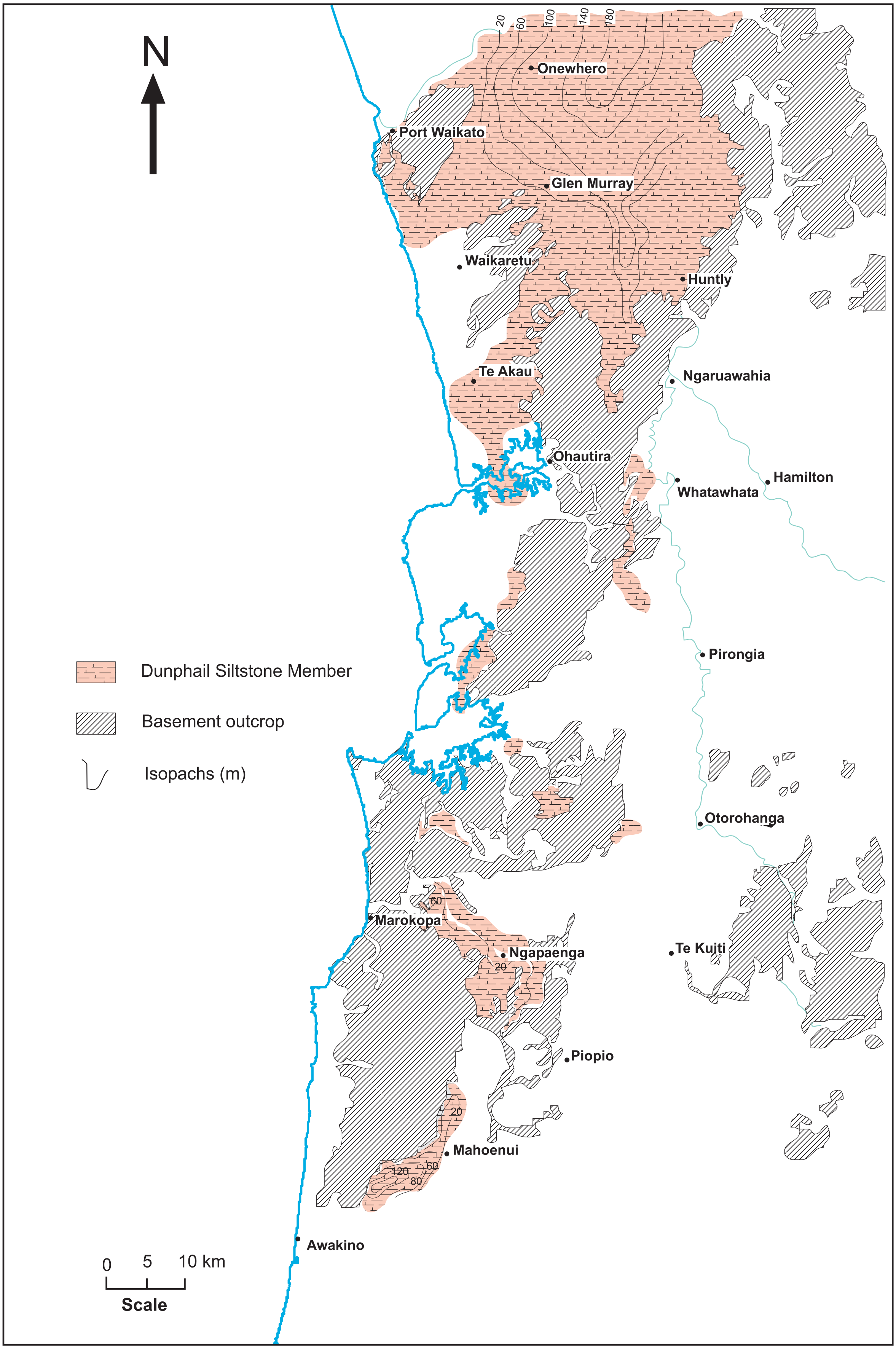


Fig. 4: Map showing the generalised distribution of the Dunphail Siltstone Member and isopachs (m) of its thickness.

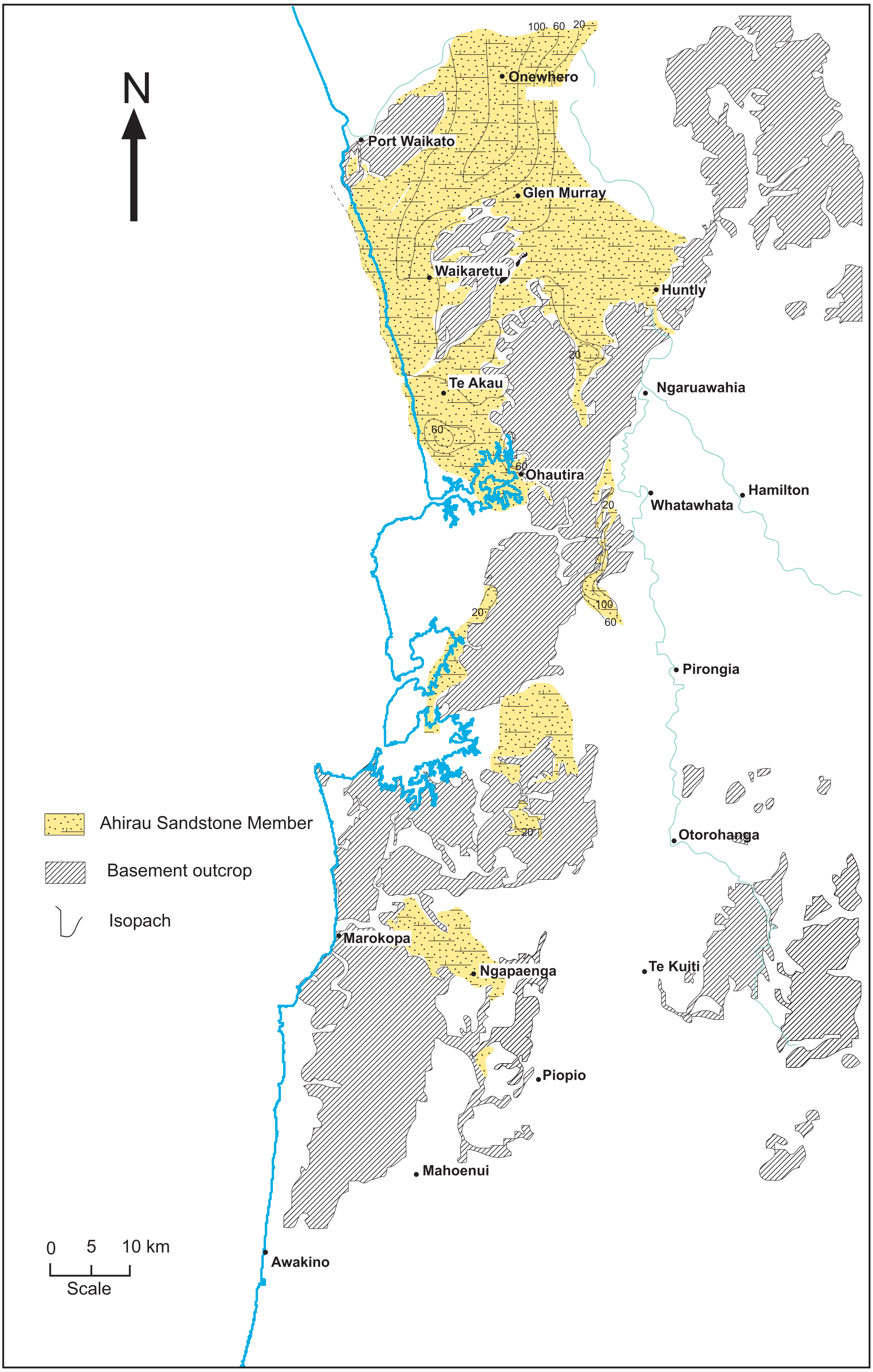


Fig. 5: Map showing generalised distribution of the Ahirau Sandstone Member and isopachs (m) of its thickness.

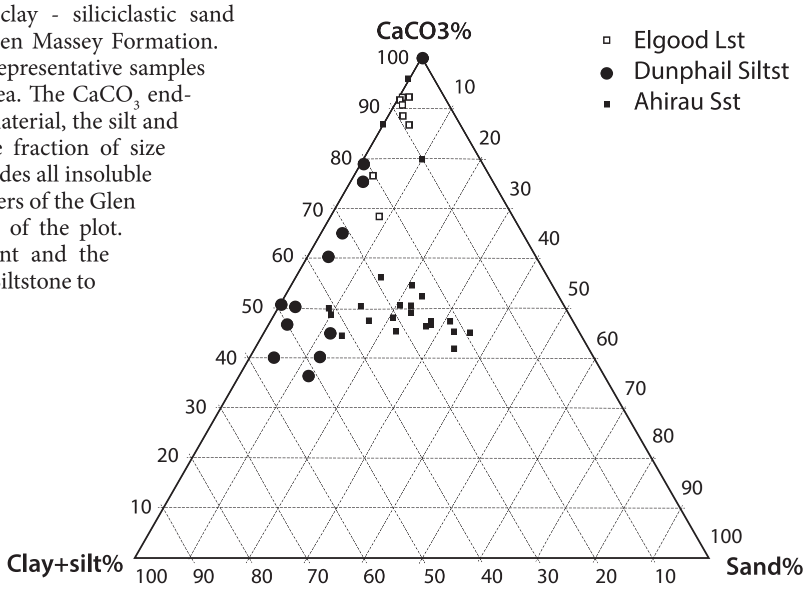


Fig. 6: $CaCO_3$ - siliciclastic silt and clay - siliciclastic sand percentages in a ternary plot for the Glen Massey Formation. These data are based on 51 analyses of representative samples of the formation in the Port Waikato area. The $CaCO_3$ end-member includes all soluble carbonate material, the silt and clay end-member includes all insoluble fraction of size <63 µm, and the sand end-member includes all insoluble fraction of size >63 µm. The three members of the Glen Massey Formation lie in separate areas of the plot. Note the high overall carbonate content and the increase in sand content from Dunphail Siltstone to Ahirau Sandstone.

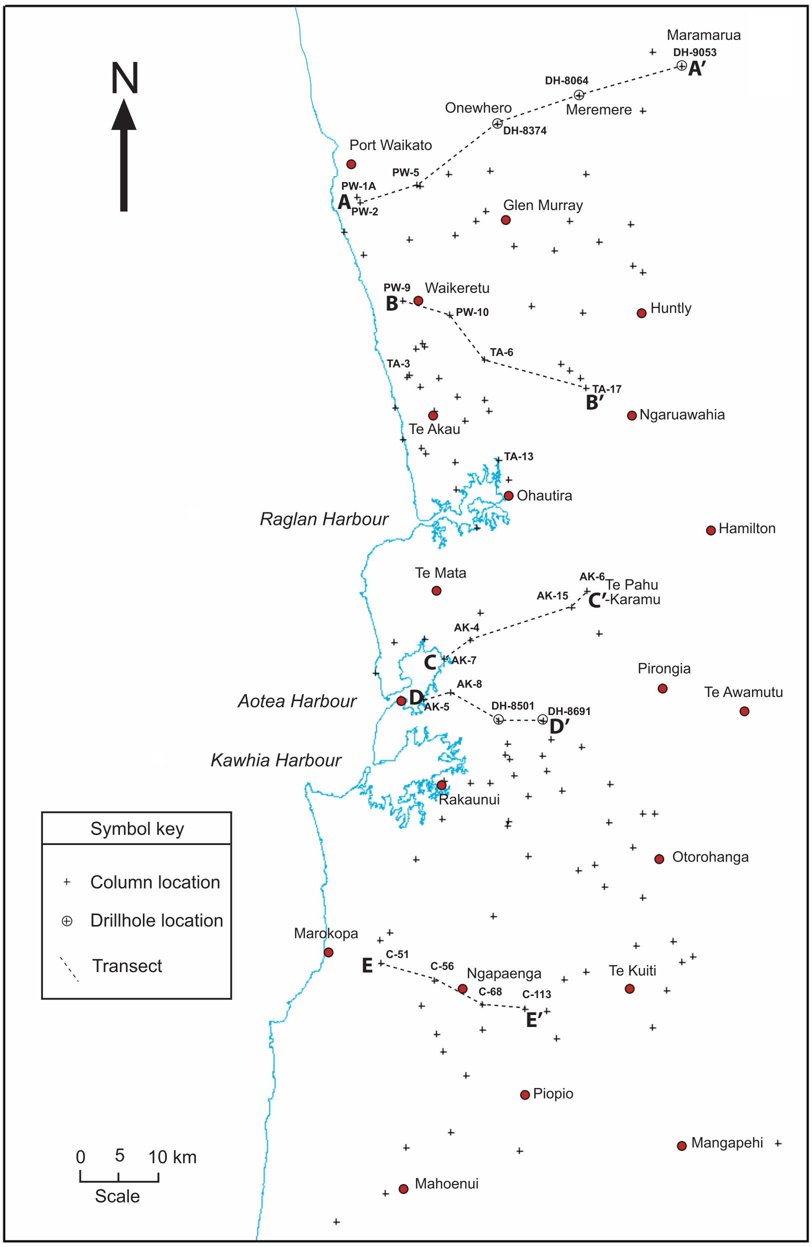
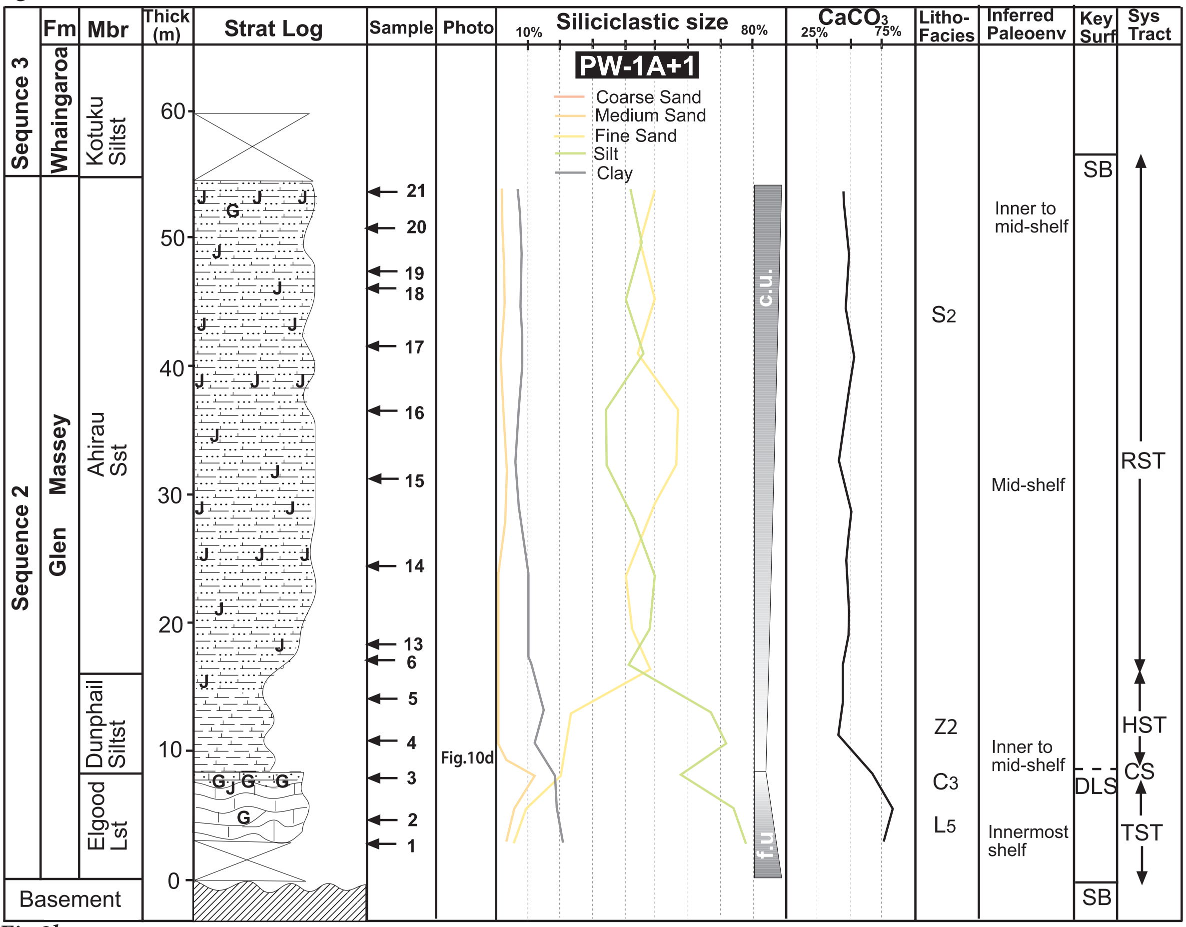


Fig. 7: Map showing the stratigraphic column sites for the Te Kuiti Group (Kamp et al. 2008), and selected columns and drill hole locations used for cross sections (See Fig. 8a-i) through Glen Massey Formation.

Fig. 8: (following pages) Textural and compositional changes through selected stratigraphic columns PW-1A, PW-2, PW-5, TA-3, TA-17, TA-13, C-51, C-56 and C-68 (see Fig. 7 for column locations). The sections reflect local variations in unit thickness and vertical lithofacies relationships. Siliciclastic textures include grain size (coarse, medium, fine sand, silt and clay) of insoluble fraction. The $CaCO_3$ content (wt %) includes all soluble carbonate material. Lithofacies codes defined in Table 1. Inferred depositional environment, systems tracts and key stratigraphic surfaces are shown in right hand columns.

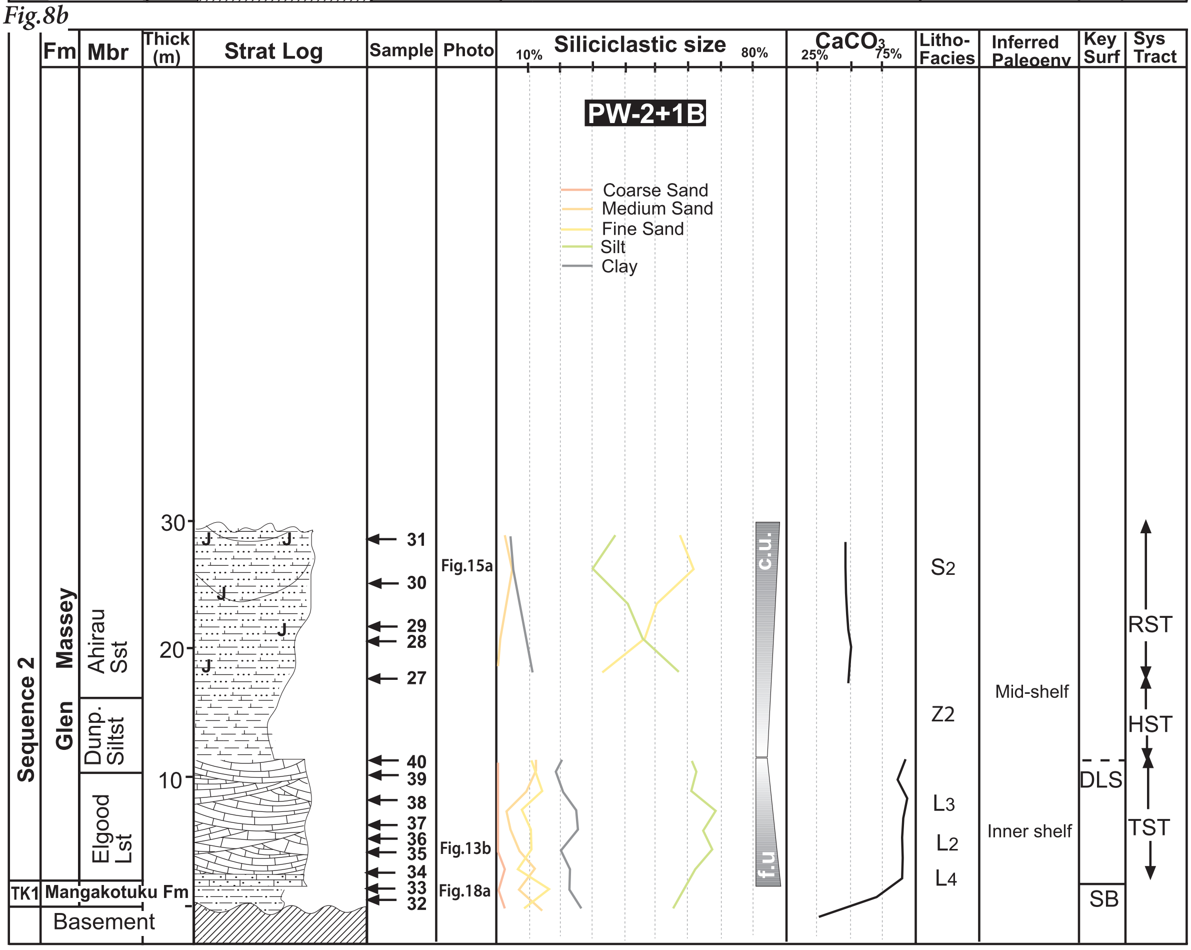
Abbreviations:
SB, Sequence boundary
DLS, Downlap surface
CS, condensed section
f.u., fining upwards
c.u., coarsening upwards
TST, Transgressive systems tract
HST, Highstand systems tract
RST, Regressive systems tract

Fig.8a



Fm
Mbr
Thick (m)
Strat Log
Sample
Photo
Siliciclastic size
10%
80%
CaCO3
25%
75%
Litho-Facies
Inferred Paleoenv
Key Surf
Sys Tract
PW-1A+1
Coarse Sand
Medium Sand
Fine Sand
Silt
Clay
Sequence 3
Whaingaroa
Kotuku Siltst
Sequence 2
Glen Massey
Ahirau Sst
Dunphail Siltst
Elgood Lst
Basement
60
50
40
30
20
10
0
21
20
19
18
17
16
15
14
13
6
5
4
3
2
1
Fig.10d
c.u.
f.u.
S2
Z2
C3
L5
Inner to mid-shelf
Mid-shelf
Inner to mid-shelf
Innermost shelf
SB
DLS
SB
RST
HST
CS
TST

Fig.8b



Fm
Mbr
Thick (m)
Strat Log
Sample
Photo
Siliciclastic size
10%
80%
CaCO3
25%
75%
Litho-Facies
Inferred Paleoenv
Key Surf
Sys Tract
PW-2+1B
Coarse Sand
Medium Sand
Fine Sand
Silt
Clay
Sequence 2
Glen Massey
Ahirau Sst
Dunp. Siltst
Elgood Lst
TK1
Mangakotuku Fm
Basement
30
20
10
31
30
29
28
27
40
39
38
37
36
35
34
33
32
Fig.15a
Fig.13b
Fig.18a
c.u.
f.u.
S2
Z2
L3
L2
L4
Mid-shelf
Inner shelf
DLS
SB
RST
HST
TST

Fig.8c

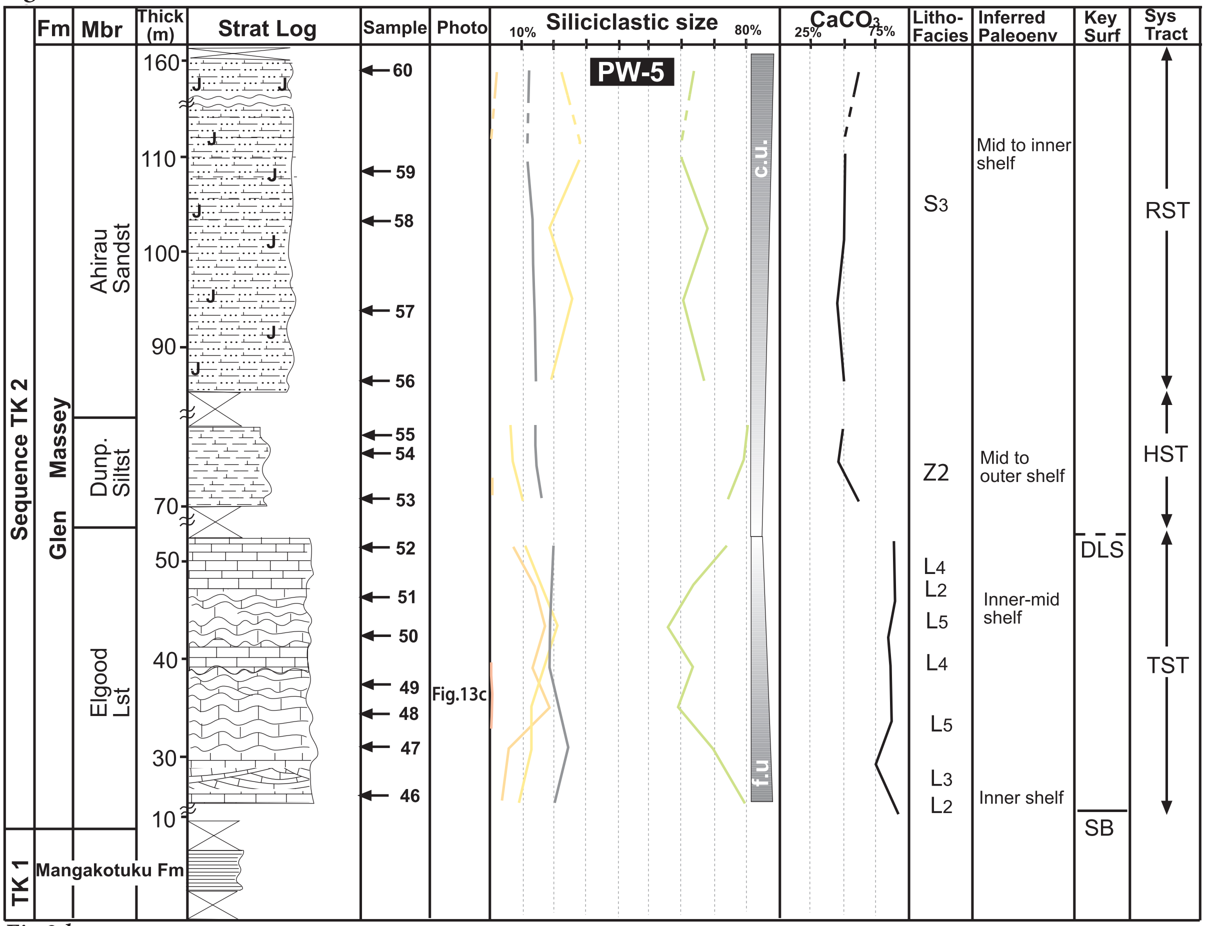

Fm
Mbr
Thick (m)
Strat Log
Sample
Photo
Siliciclastic size
10%
80%
CaCO3
25%
75%
Litho-Facies
Inferred Paleoenv
Key Surf
Sys Tract
PW-5
Sequence TK 2
Glen Massey
Ahirau Sandst
Dunp. Siltst
Elgood Lst
TK 1
Mangakotuku Fm
160
110
100
90
70
50
40
30
10
60
59
58
57
56
55
54
53
52
51
50
49
48
47
46
Fig.13c
c.u.
f.u
S3
Z2
L4
L2
L5
L4
L5
L3
L2
Mid to inner shelf
Mid to outer shelf
Inner-mid shelf
Inner shelf
DLS
SB
RST
HST
TST

Fig.8d

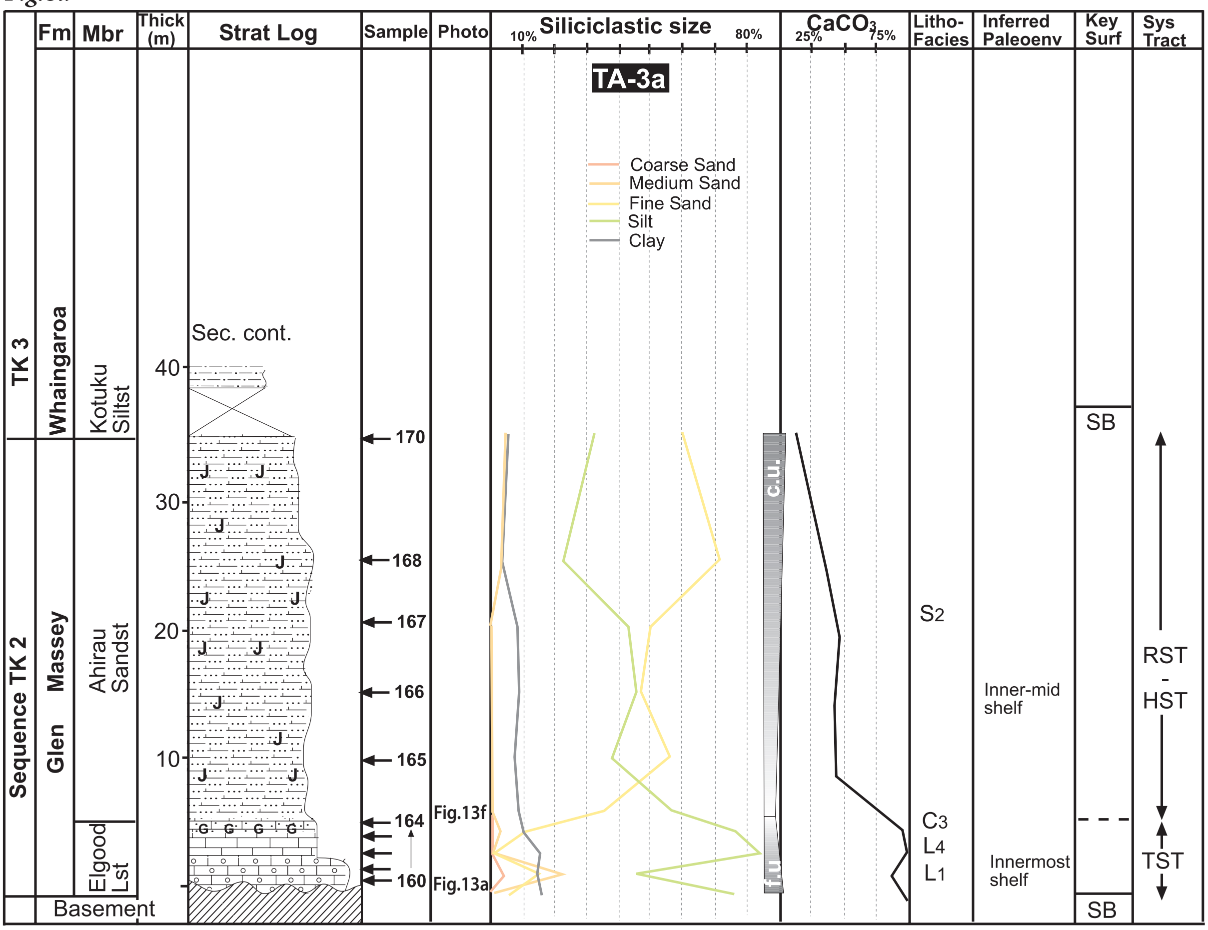
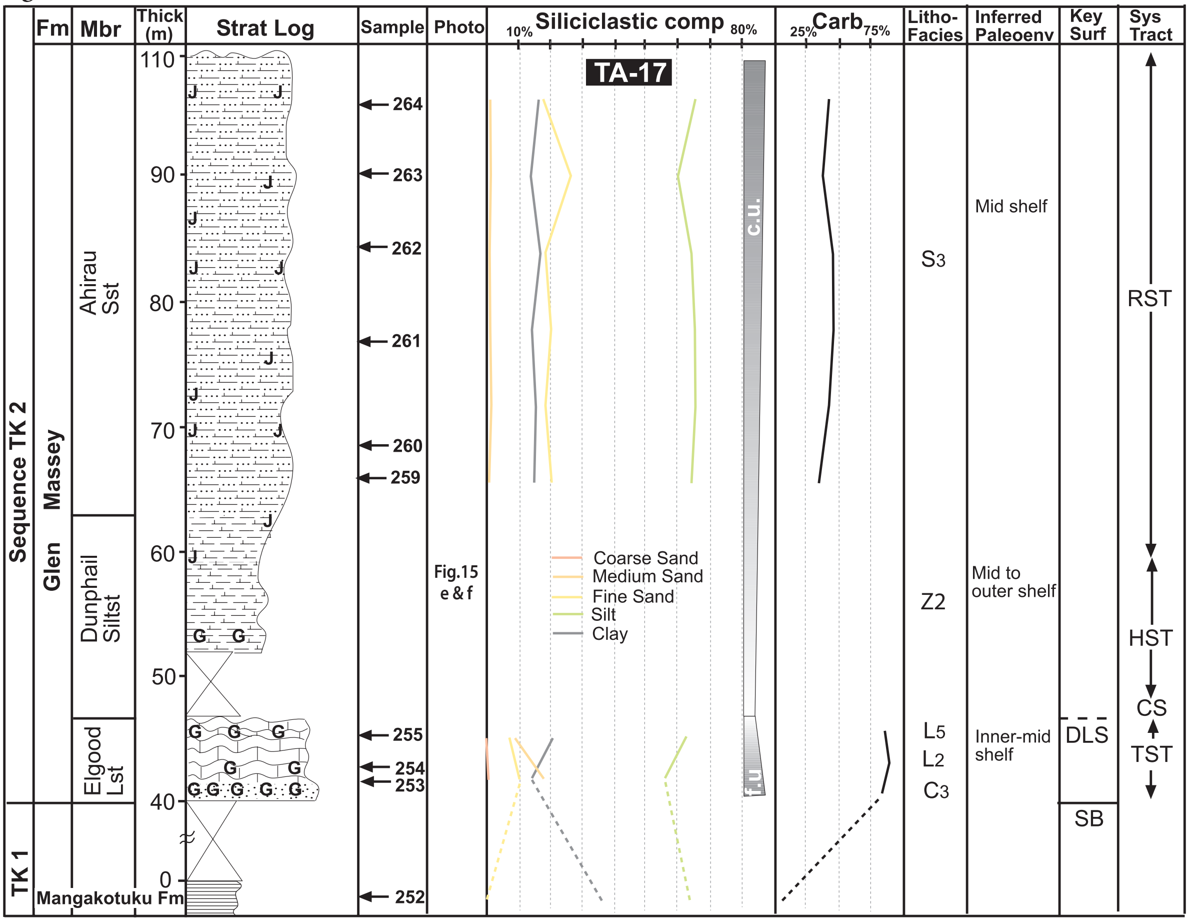
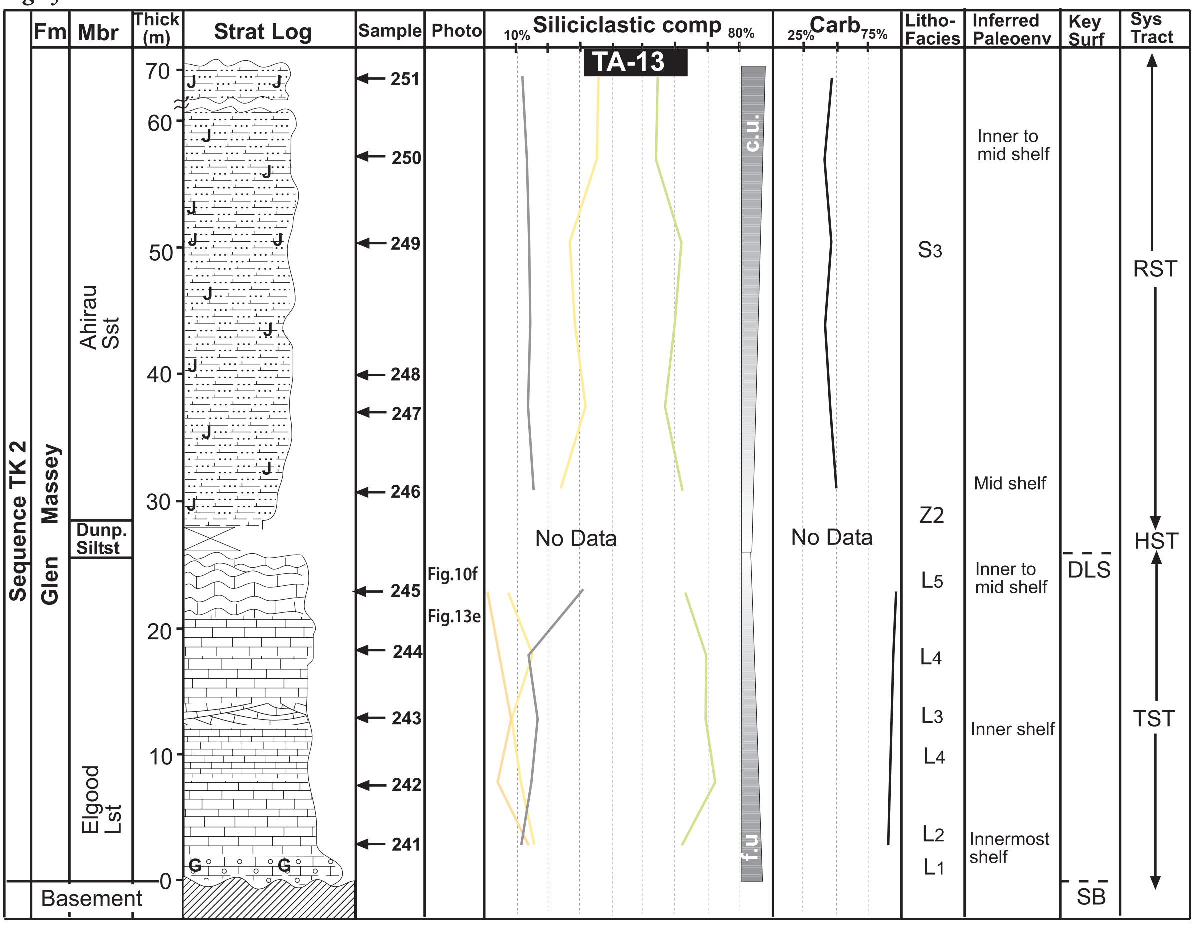

Fm
Mbr
Thick (m)
Strat Log
Sample
Photo
Siliciclastic size
10%
80%
CaCO3
25%
75%
Litho-Facies
Inferred Paleoenv
Key Surf
Sys Tract
TA-3a
Coarse Sand
Medium Sand
Fine Sand
Silt
Clay
TK 3
Whaingaroa
Kotuku Siltst
Sequence TK 2
Glen Massey
Ahirau Sandst
Elgood Lst
Basement
Sec. cont.
40
30
20
10
170
168
167
166
165
164
160
Fig.13f
Fig.13a
c.u.
f.u
S2
C3
L4
L1
Inner-mid shelf
Innermost shelf
SB
SB
RST
-
HST
TST

Fig.8e



Fm
Mbr
Thick (m)
Strat Log
Sample
Photo
Siliciclastic comp
10%
80%
Carb
25%
75%
Litho-Facies
Inferred Paleoenv
Key Surf
Sys Tract
TA-17
Sequence TK 2
TK 1
Glen Massey
Ahirau Sst
Dunphail Siltst
Elgood Lst
Mangakotuku Fm
264
263
262
261
260
259
255
254
253
252
Fig.15 e & f
Coarse Sand
Medium Sand
Fine Sand
Silt
Clay
c.u.
f.u.
S3
Z2
L5
L2
C3
Mid shelf
Mid to outer shelf
Inner-mid shelf
DLS
SB
RST
HST
CS
TST

Fig.8f



Fm
Mbr
Thick (m)
Strat Log
Sample
Photo
Siliciclastic comp
10%
80%
Carb
25%
75%
Litho-Facies
Inferred Paleoenv
Key Surf
Sys Tract
TA-13
Sequence TK 2
Glen Massey
Ahirau Sst
Dunp. Siltst
Elgood Lst
Basement
251
250
249
248
247
246
245
244
243
242
241
Fig.10f
Fig.13e
No Data
No Data
c.u.
f.u.
S3
Z2
L5
L4
L3
L4
L2
L1
Inner to mid shelf
Mid shelf
Inner to mid shelf
Inner shelf
Innermost shelf
DLS
SB
RST
HST
TST

Fig.8g

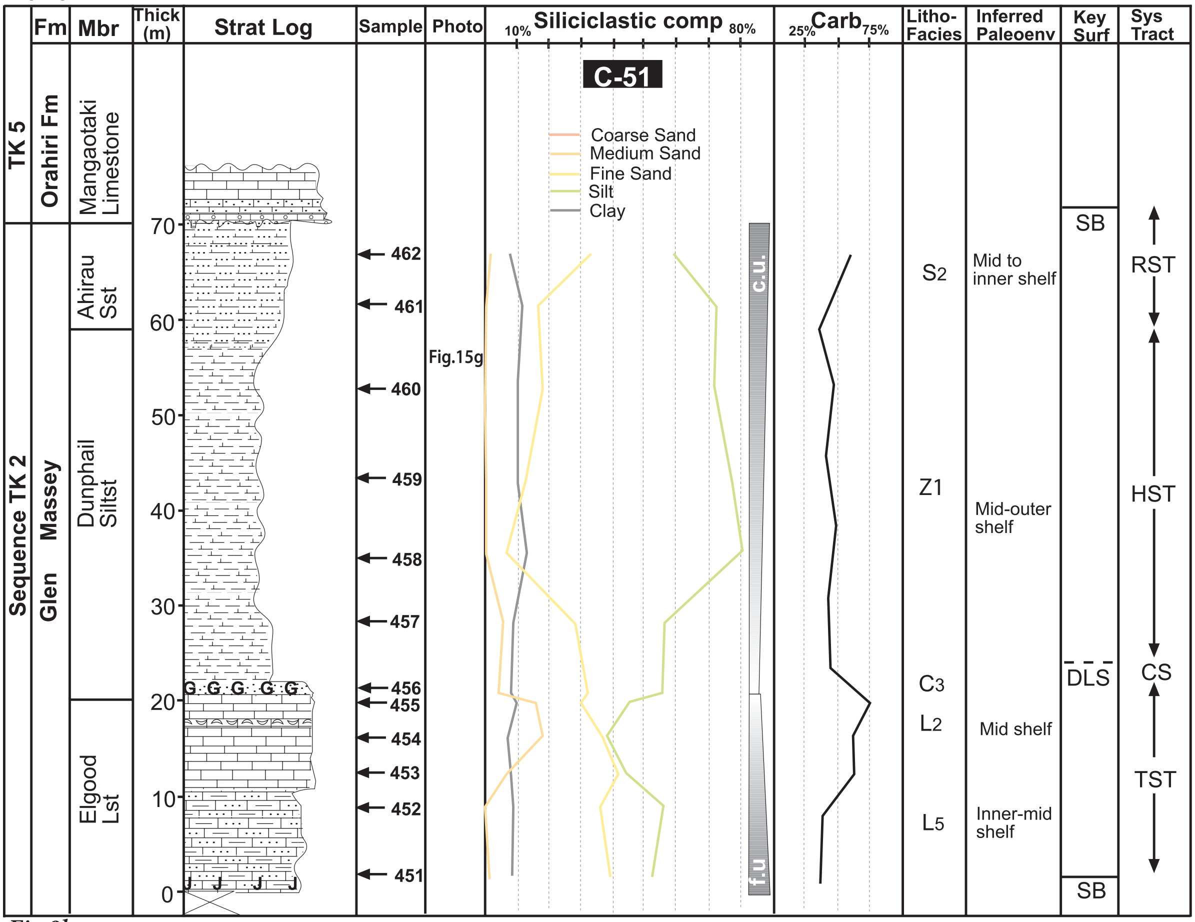


Fig.8h

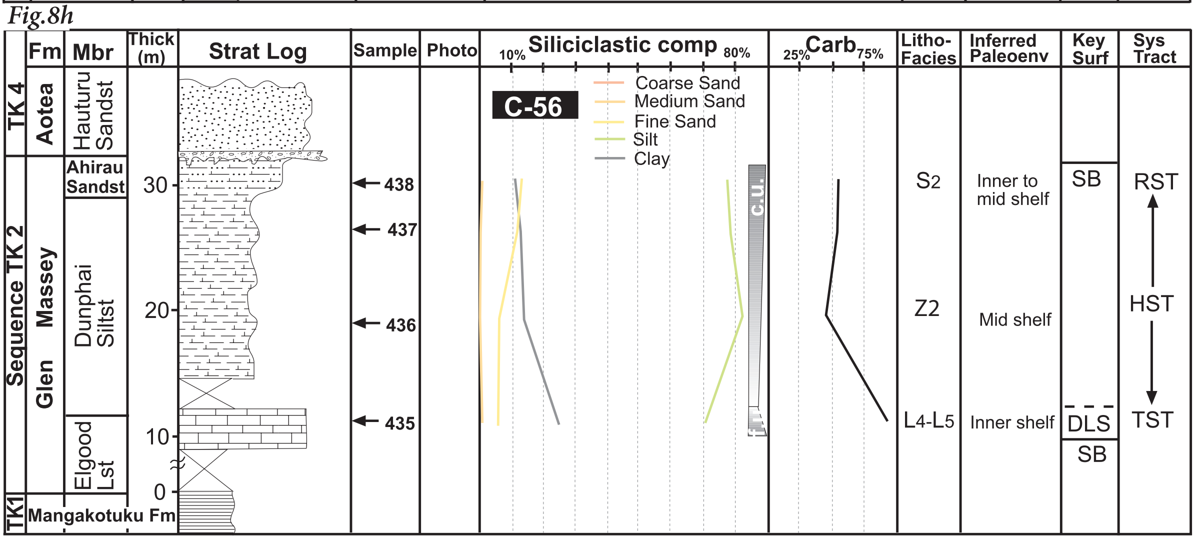


Fig.8i

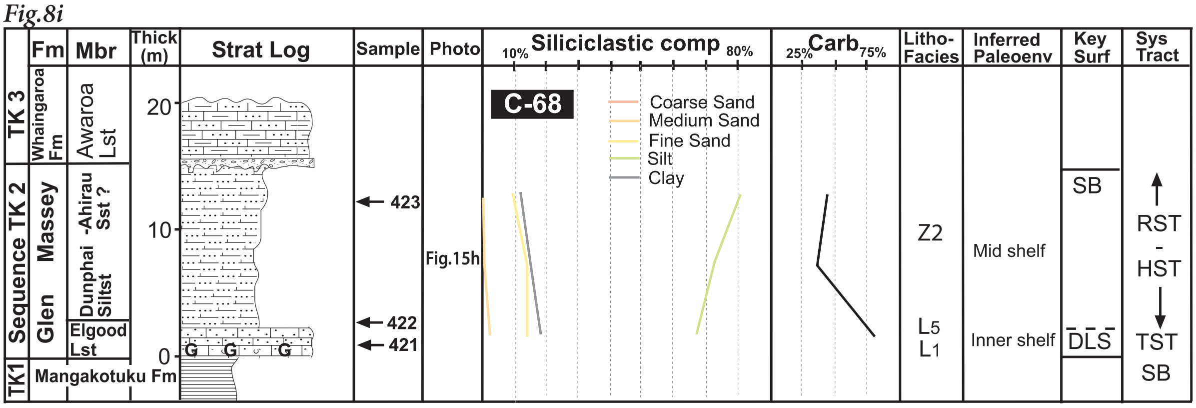


Table 1: Summary of sedimentary lithofacies for the Glen Massey Formation

Lithofacies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Interpretation
Limestone lithofacies association (Elgood Limestone Member)						
L1 Pebbly grainstone	Common to abundant subrounded clasts averaging 1-10 cm derived from basement; fabric supported by coarse sparry limestone; poor bedding development, often massive in appearance	84-95%	Medium to coarse grainstone-rudstone, frequent large bivalve fragments, very abraded	Fragmented bivalves, notably oysters and pectinids, clasts occasionally encrusted by calcareous red algae, including rhodoliths up to 8-10 cm across	Commonly occurs as transgressive basal lag, tens of cm thick (Fig. 10a & g)	Nearshore to innermost shelf, adjacent to rocky shoreline
L2 Shelly grainstone	Disarticulated bivalves haphazardly scattered through the limestone or occasionally concentrated into beds; poor to moderate bed development, irregular (bifurcating) interflag seams may give outcrop a knobbly appearance	85-91%	Medium to coarse rudstone-grainstone, rare pebble granule clasts, moderately to very abraded	Pectinids, bryozoans, echinoids, *Amphistegina* and coralline red algae	Common at base of limestone unit (Fig. 10b)	Nearshore to inner shelf
L3 Cross-stratified grainstone	Sigmoidal to tabular cross-beds are low ($<10^0$) to moderate angle (10^0-25^0), in sets from less than 0.5 to up to 1.5 m thick, traceable laterally for a few tens of metres; set base and tops are sharp; well developed bedding is characteristic, typically 2-15 cm thick; bedding planes are often rich in siliciclasts	88-94%	Moderately to well sorted, medium to coarse grainstone; very to moderately abraded; siliciclastic particles in bedding planes are generally of fine sand to silt grade, rare granule size clasts	Bryozoans, echinoderms, bivalves, red algae and benthic foraminifera	Common along the western margin or developed locally about the flanks of paleo-highs (Fig. 10c)	Subaqueous dunes migrating parallel to shore
L4 Horizontally bedded grainstone	Beds typically well developed and 2-10 cm thick, separated by bedding planes (0.1-1.5 cm) rich in siliciclastic particles; freshly broken surfaces have a homogeneous crystalline appearance	68-97%	Moderately sorted, fine to medium grainstone, moderately abraded	Echinoderms, bryozoans, bivalves, occasional casts/moulds of gastropods, large benthic foraminifera	Widespread along the basin margin, commonly thick-en and thin over short distances (Fig. 10d)	Inner to mid shelf

Lithofacies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Interpretation
L5 Massive to moderately bedded grainstone-packstone	Irregular bed development, frequently even massive in appearance; undulatory bifurcating interflag seams; rare horizontal lamination, variably bioturbated (irregular inclined burrows)	36-92%	Fine grainstone-packstone, abraded	Abundant echinoids, bryozoans, planktic and benthic foraminifera	Locally well developed (Fig. 10e & f)	Lower inner to mid-outer shelf, wave (storm) dominated setting
Mixed carbonate-siliciclastic sandstone lithofacies association (Ahirau Sandstone Member)						
S1 Calcareous pebbly-gritty sandstone	Poorly to moderately well cemented; massive; rounded to subrounded granule and pebble basement clasts, fabric supported by calcareous fine silty sandstone; clast size shows crude normal grading	25-77%	Fine to coarse grained, poorly sorted	Occasional bivalve pectinids and oysters, red algae including rhodoliths; common glauconitised clasts and shell fragments, *Amphistegina*	Common above the contact with basement and at the base of over-lying limestone, may represent transgressive lag deposits (Fig. 10g)	Innermost shelf, proximal to rocky coastline, with a moderately high siliciclastic influx
S2 Calcareous silty fine sandstone	Well cemented, massive fine calcareous sandstone and sandy siltstone; heavily bioturbated; low preservation of primary sedimentary structures although low-angle cross bedding present locally	36-63%	Fine to very fine sandstone to siltstone, poorly to moderately sorted	Scattered pectinids, echinoid spines, high diversity of trace fossils of mainly *Cruziana* ichnofacies	Facies is well developed along the western margin (Fig. 15a & b)	Inner to mid-shelf with moderate to strong bottom currents driven by wind and/or tides interacting with the inherited topography
S3 Alternating calcareous silty fine sandstone and sandy siltstone	Consists of alternating calcareous fine sandstone and sandy siltstone; beds range from few centimetres to decimetre thick, with variable carbonate content; bioturbation present throughout but not abundant	33-61%	Fine to very fine sandstone and siltstone, poorly to moderately sorted	Scattered bivalves, planktic and benthic foraminifera	Commonly forms the upper part of the Glen Massey Formation in northern region (Fig. 15c)	Moderate energy in mid to outer shelf depths below fair-weather wave base but above storm wave base

Lithofacies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Interpretation
S4 Massive muddy sandstone	Massive muddy sandstone; moderately cemented; heavily bioturbated	45-54%	Fine to very fine sandstone to siltstone, poorly sorted	Scattered pectinids and other bivalve fragments, occasional large burrows	Commonly overlies limestone units (L4) (Fig. 15h)	Mid shelf
Mixed carbonate-siliciclastic siltstone lithofacies association (Dunphail Siltstone Member)						
Z1 Interbedded calcareous siltstone and sandy limestone	Alternating fine sandy siltstone and sandy limestone beds from a few centimetres up to a metre thick; usually grades above into Massive calcareous siltstone (Z2)	40-78%	Fine to very fine sandstone and siltstone, poorly to moderately sorted	Bivalve shell fragments common in the sandy limestone beds; evidence for heavy bioturbation present in silty intervals	Commonly occurs as a transition between under-lying limestone (L4) and overlying massive calcareous siltstone (Z2) (Fig. 15d)	Mid to outer shelf, between fair weather and storm wave base
Z2 Massive calcareous siltstone	Massive blue-grey siltstone, well cemented. No obvious structures. Occasional concretionary bands with ellipsoidal shaped concretions up to 10 cm in size (Fig. 15g)	33-79%	Fine silt with occasional traces of very fine to fine sandstone, moderately sorted	Planktic and benthic foraminifera, sparse macrofossils	Widespread throughout basin (Fig. 15e, f & g)	Outer shelf (to possibly upper bathyal)
Chemogenic lithofacies association						
C1 Phosphate nodule bed	Scattered phosphate nodules up to 6 mm size in a heavily bioturbated, well cemented, glauconitic fine sandstone- siltstone	45-47%	Fine to very fine sandstone to siltstone, poorly to moderately sorted	Rare bivalve shell fragments (mainly pectinids); abundant burrows	Not common; occurs as phos-phatised hard-grounds at top of Ahirau Sandstone Member in Port Waikato area (Fig. 16a)	Mid shelf, upwelling

Lithofacies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Interpretation
C2 Glauconitic calcareous siltstone-sandstone	Glauconite occurs as silt and/or fine to medium sand size pellets and also as extrinsic filling within bioclasts; moderately to heavily bioturbated	68%	Fine sandstone to siltstone	Scattered whole and fragmented bivalves, echinoid plates and spines frequently glauconitised; large benthic and/or planktic foraminifera	Common in certain areas generally occurring as basal facies representing a condensed trans-gressive deposit or in places marks the transition between TST and HST (Fig. 16b)	Sediment starved shelf
C3 Glauconitic sandy-silty grainstone-packstone	Glauconite occurs as abundant pelletal and detrital medium to fine sand grains in a moderately bedded grainstone-packstone	73-82%	Medium to fine sandstone to siltstone	Common bivalve shell fragments, *Amphistegina* benthic foraminifera; bioturbation not obvious	Common in some transgressive deposits (Fig. 16c)	Sediment starved inner- mid shelf

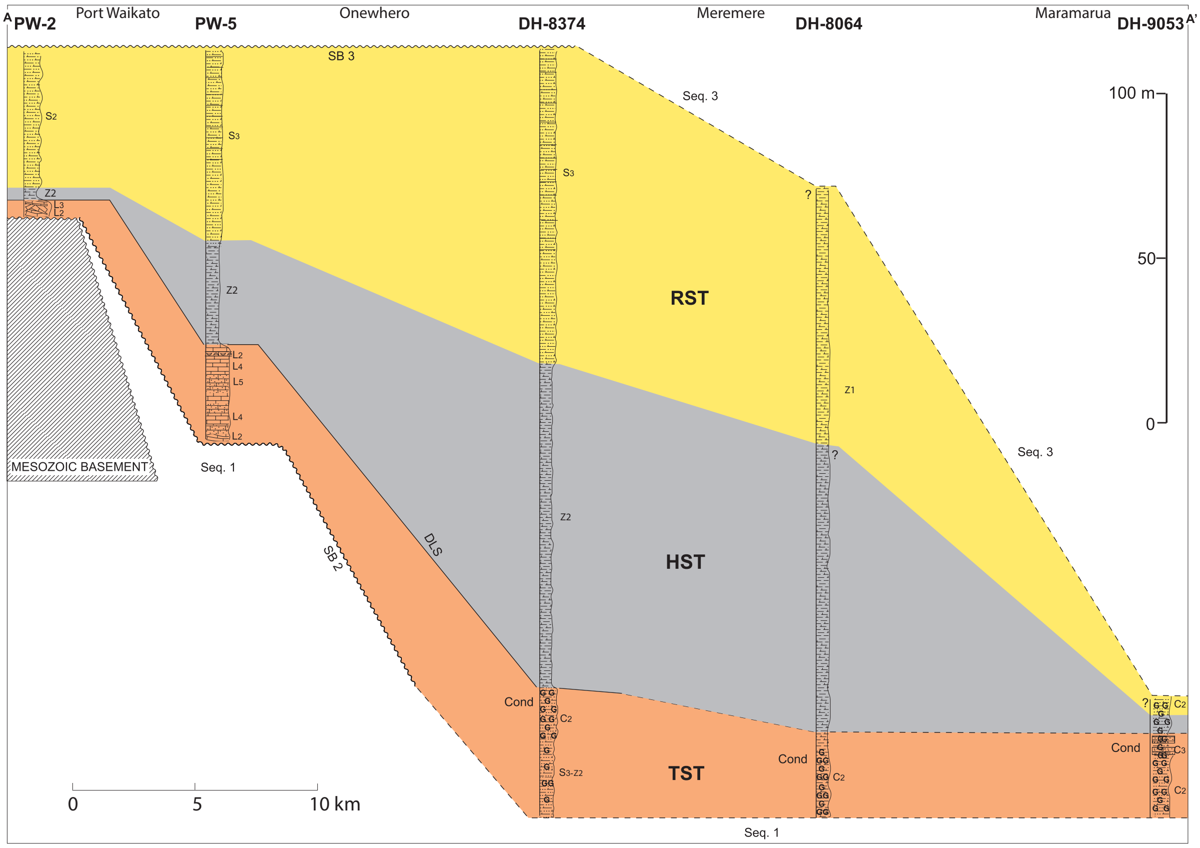


Fig. 9a: Cross section A-A' through Glen Massey Formation (location shown in Fig. 7)

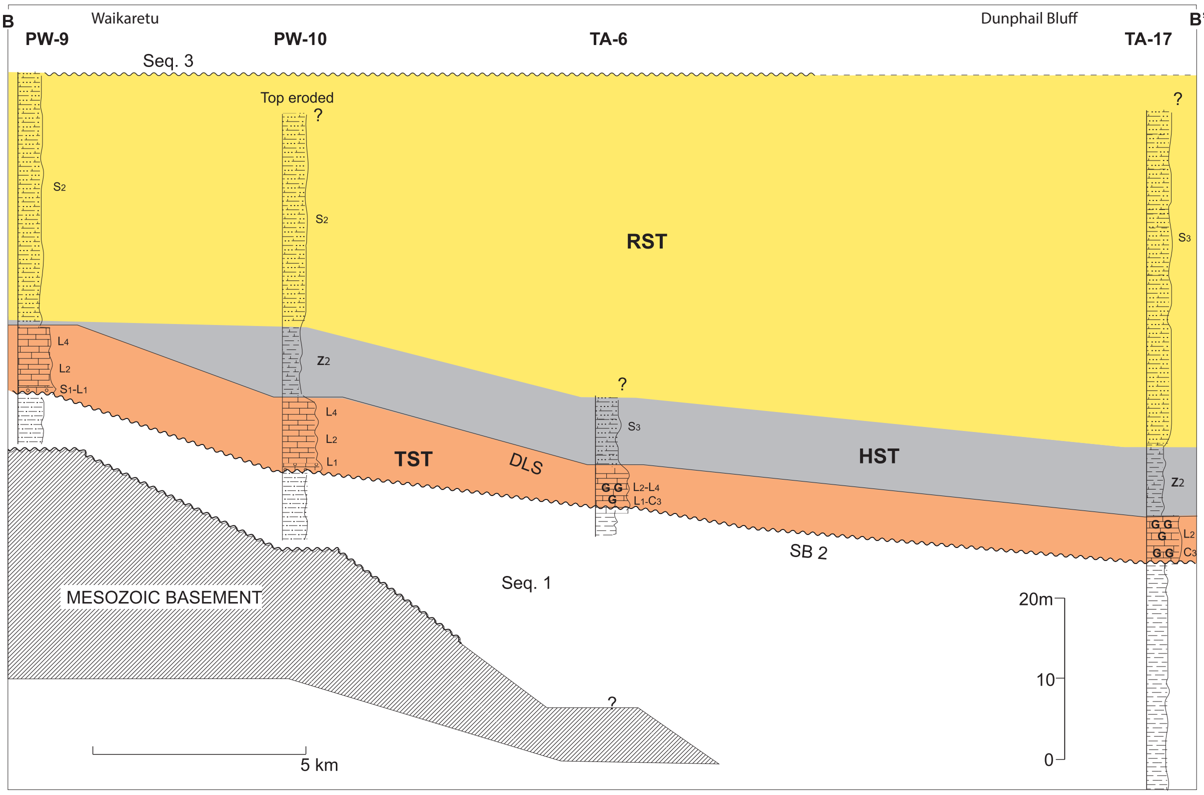


Fig. 9b: Cross section B-B' through Glen Massey Formation (Location shown on Fig. 7)

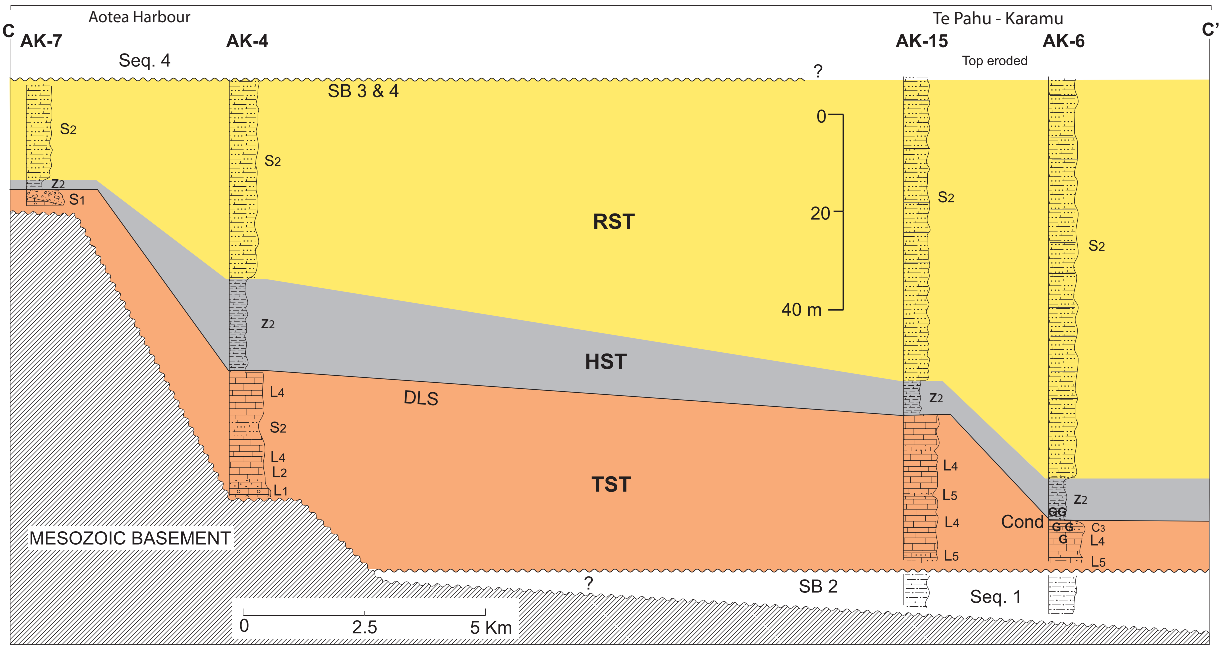


Fig. 9c: Cross section C-C' through Glen Massey Formation (location shown on Fig. 7).

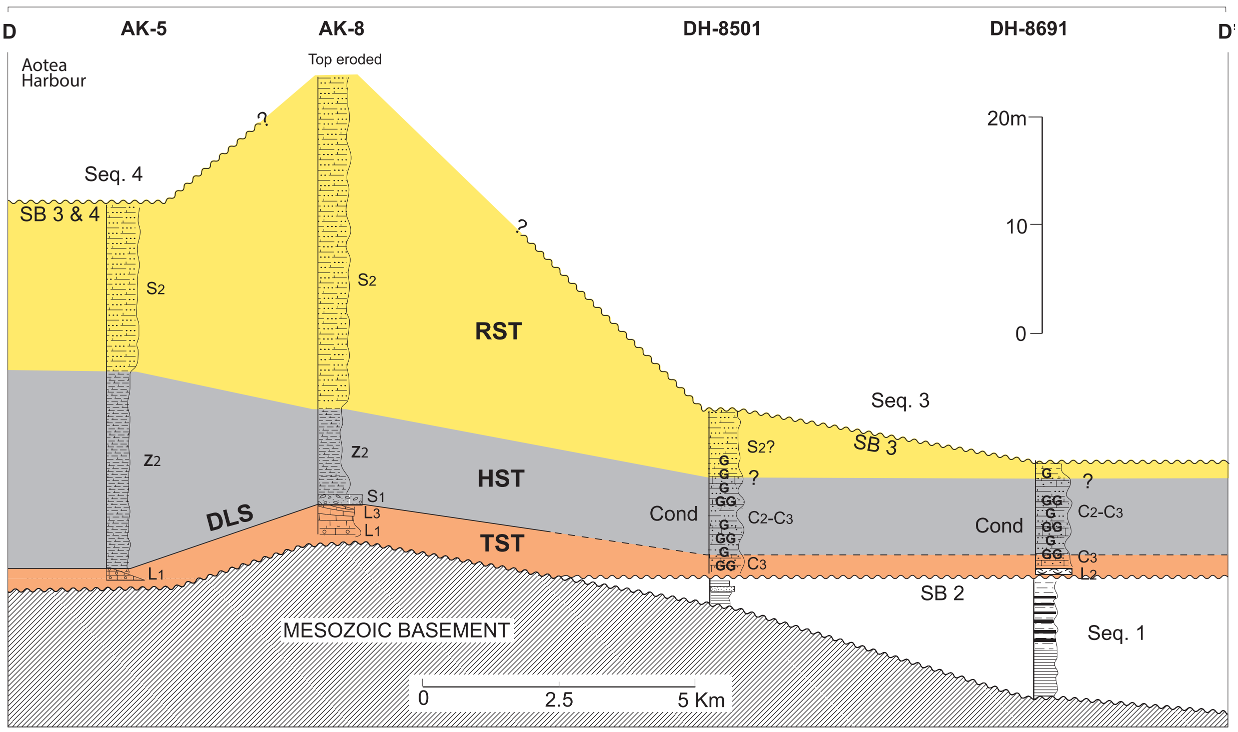


Fig. 9d: Cross section D-D' through Glen Massey Formation (location shown on Fig. 7).

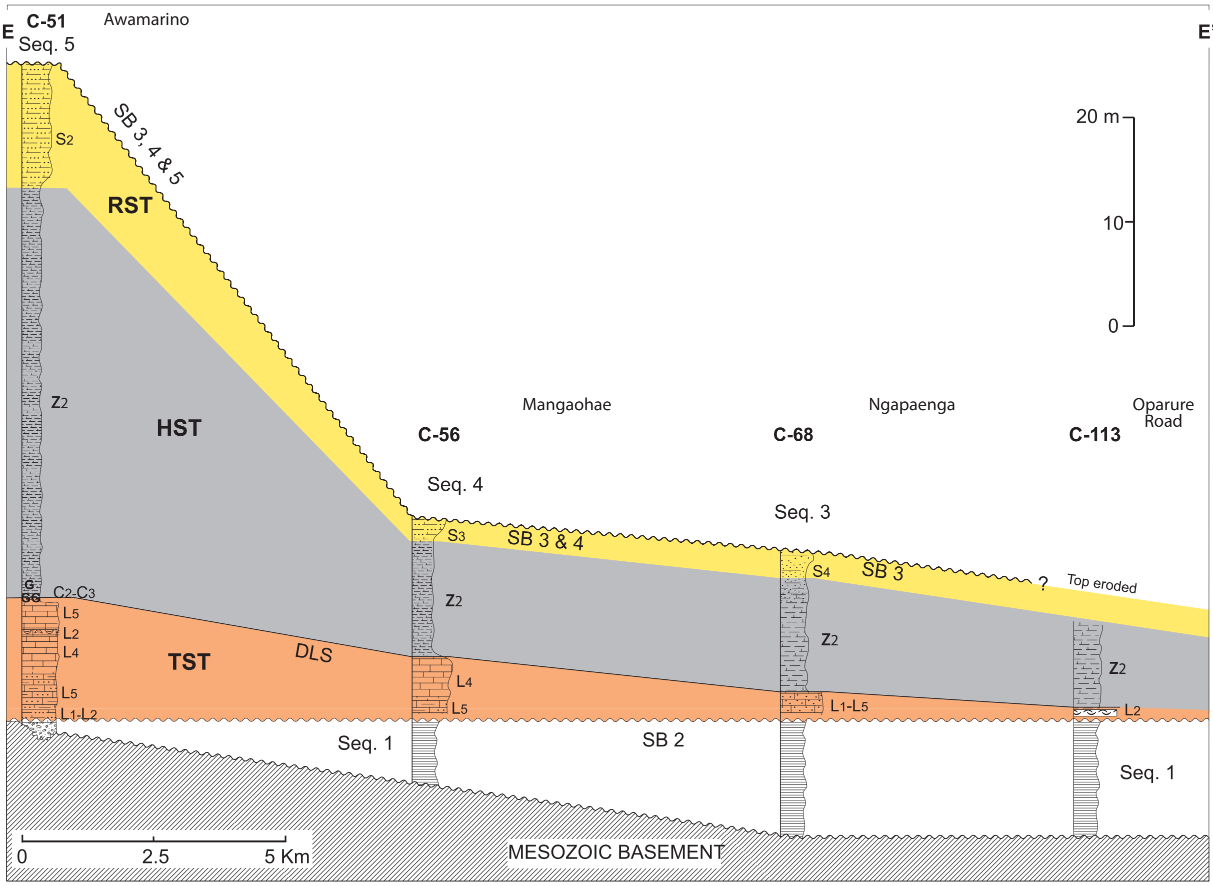


Fig. 9e: Cross section through Glen Massey Formation (location shown on Fig. 7).

Lithofacies

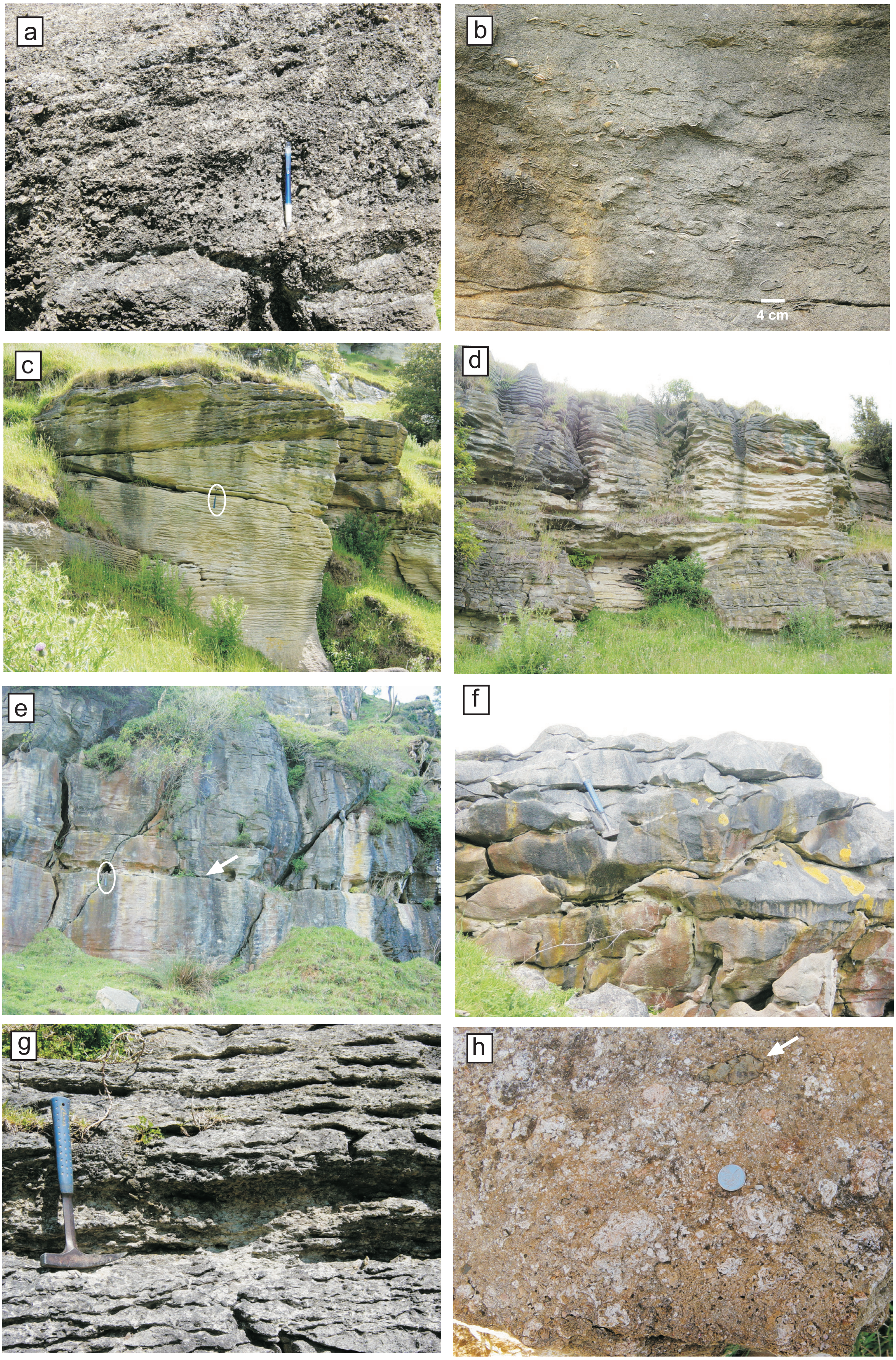
(see summary in Table 1)

Limestone lithofacies association (L1 to L5; Elgood Limestone Member)

Limestone lithofacies include a spectrum of skeletal-rich, sparry grainstone to mixed grainstone/packstone rock types in the Elgood Limestone Member. Calcium carbonate content is the most effective basis to separate limestone lithofacies from mixed siliciclastic-carbonate lithofacies, the latter having only moderate $CaCO_3$ content, averaging about 50%. In places, the limestone lithofacies reach thicknesses of 30 m or more (e.g. TA-13), although overall they contribute less than 10% of the total thickness of the Glen Massey Formation. They are conspicuous because of the flaggy nature of many of the limestone occurrences (Fig. 10).

The Elgood Limestone Member is mainly composed of skeletal material derived from shallow water epibenthic communities living

Fig. 10: (facing page) Field photographs of lithofacies in the Elgood Limestone Member. (a) Pebbly grainstone lithofacies (L1) occurring at the base of Elgood Limestone Member at Plateau Road (AK-3). The facies includes common rounded-subrounded basement pebbles in a gritty-sandy bioclast-rich matrix. This is a common recurring facies along the basin margin where Elgood Limestone Member onlaps basement. Pen (14 cm) for scale. (b) Small bivalve coquina composed mostly of whole and broken pectinids floating in a mixed bioclastic fine sandy-silty matrix, a typical example of Shelly grainstone lithofacies (L2). Coarse grainstone occurs in the lower part of the photograph, taken near Waikaretu Limestone Quarry (PW-9). (c) Tabular cross-bedded grainstone, a typical example of Cross-stratified grainstone lithofacies (L3). Cross-set boundaries are strongly recessed, accentuating foreset truncation. Hammer for scale. Photo location: Port Waikato-Waikaretu Road (PW-2). (d) Horizontally bedded grainstone lithofacies (L4) showing well developed flagginess. Individual beds vary in thickness from 8-15 cm and are separated by recessed (interflag) seams. Exposure approximately 5 m thick, near Waikaretu Limestone Quarry (PW-9). (e) Massive to weakly bedded grainstone-packstone (L5). Arrow points to thin, intensely bioturbated (Thalassinoides), strongly recessed horizon indicating a period of non-deposition or very slow deposition related to a flooding event. Photo location: Quarry Road, Te Pahu-Karamu (AK-15). Hammer for scale. (f) Typical "knobbly" weathering characteristic possibly due to high (50%) matrix content. This irregularly bedded grainstone-packstone (L5) occurs at the top of Elgood Limestone Member at Halliday Road. (TA-13). (g) Contact interval between Cross-bedded grainstone (L3) and overlying Pebbly



sandy/silty bed (S1) comprising abundant rounded-subrounded basement clasts in a glauconite-rich mixed siliciclastic-carbonate matrix. Hammer rests on contact. Photo location: Waiteika, Aotea Harbour (AK-8). (h) Rhodoliths (nodules of encrusting coralline algae) along with various clasts of granule to cobble size incorporated into a red algal pebbly grainstone (L1). This facies is typical near the base of Elgood Limestone where it onlaps basement. Coin for scale. Photo location: Awamarino (C-50).

on rocky, gravelly and coarse shelly sea bottoms around ridges, banks and islands that provided stable firm substrates (Nelson 1978a). These shallow-water skeletal-rich limestones show a close association with structural paleo-highs along the western margin of the study area (Fig. 3). Strong bottom currents generated by a combination of oceanic and/or tidal current flows amongst uneven topography, particularly when storm assisted, played a significant role in the generation and dispersal of skeletal hash from the shallow-water carbonate factories along the basement ridges and highs (e.g. Nelson 1978a; Anastas et al. 1997). The bioclastic fraction (averaging c. 77%) of the Elgood Limestone Member is dominated by high-energy taxa such as bryozoans, echinoderms, benthic foraminifera (especially *Amphistegina*), calcareous red algae, and to a lesser extent bivalves (Fig. 11). Planktic foraminifera, barnacles, sponge spicules, echinoderm spines, and gastropods occur in minor quantities. The modal size of bioclasts decreases steadily from about medium sand (1-1.25 mm) near the base to fine sand (0.25 - 0.5 mm) near the top of the member. Grain sizes are occasionally bimodal involving the introduction of very coarse sand to granule size bivalve fragments amongst medium to fine carbonate sand. Bioclasts characteristically have moderately to very abraded margins, and are poorly to moderately sorted. The modal grain size of the siliciclasts, consisting of quartz, feldspar and sedimentary and volcanic rock fragments, lies in the range of medium to fine sand. Grains are commonly subangular to subrounded and moderately to poorly sorted. Glauconite is generally of minor importance, but becomes very common (20-40%) near the top of the Elgood Limestone Member and occasionally at its base. Intrinsic matrix-cement occupies 10-20% of the limestone, with higher values (>30%) near the base being mainly sparite, or near the top being mainly micrite.

The limestone lithofacies range in $CaCO_3$ content (% by weight) from about 62% to 98%, with an average of 86% (see Fig. 11 for average wt% $CaCO_3$). In places, $CaCO_3$ content displays a steady increase up-section (e.g. columns TA-13 and C-51, Fig. 8f & h). On inner-shelf areas and over paleo-highs the limestone facies are dominated by cross-bedded skeletal grainstone, while farther offshore these facies pass into either horizontally bedded wackestone-packstone or variably sandy-silty skeletal grainstone (Fig. 12). Five limestone lithofacies have been distinguished in this study, their main characteristics being summarised in Table 1.

L1 - Pebbly grainstone

This facies usually directly overlies basement and occurs commonly along the western margin (cross sections A-A' to E-E' in Fig. 9). It often passes up into either lithofacies L2, L3 or L4 (Fig. 8d, f & i). Moderately to poorly sorted, rounded to subrounded basement pebbles and occasionally cobbles (size up to 10 cm), occur in beds up to a few tens of centimetres thick and rarely as much as 2.5 m thick (Fig. 10a). The beds are poorly stratified and may show crude normal-grading. Clasts are supported by a sandy or granule-rich calcareous matrix. Fragmented large bivalves such as pectinids and oysters are common along with large benthic foraminifera (Fig. 13a). Pebbles and shell fragments are sometimes glauconitised and bored. Occurrences of rhodoliths associated with this facies have been recorded in some sections (e.g. PW-9, C-50) (Nalin et al. 2008).

Interpretation: This facies was deposited during marine inundation in coastal zones. Pebbles, granules and coarse siliciclastic sand were derived from basement by wave erosion and current reworking in the innermost shelf environment. The coarse skeletal fragments are derived from rocky shoreline communities, including oysters and pectinids. In some locations, fragments of coralline red algae and rhodoliths (nodules of encrusting coralline algae) (Fig. 10h) dominate the sediments and may have accumulated on the lee side of islands where water flow was high but wave energy not so intense (e.g. James 1997; James et al. 2001; Nalin et al. 2008). The common occurrence of benthic foraminifera (*Amphistegina* sp., *Elphidium* sp. and *Cibicides maculatus*) indicates deposition in the shallow photic zone of the shelf (e.g. Hayward 1986; Hornibrook et al. 1989; Lukasik et al. 2000).

L2 - Shelly grainstone

This facies has restricted occurrence and is readily identified by its weak to moderate bedding and

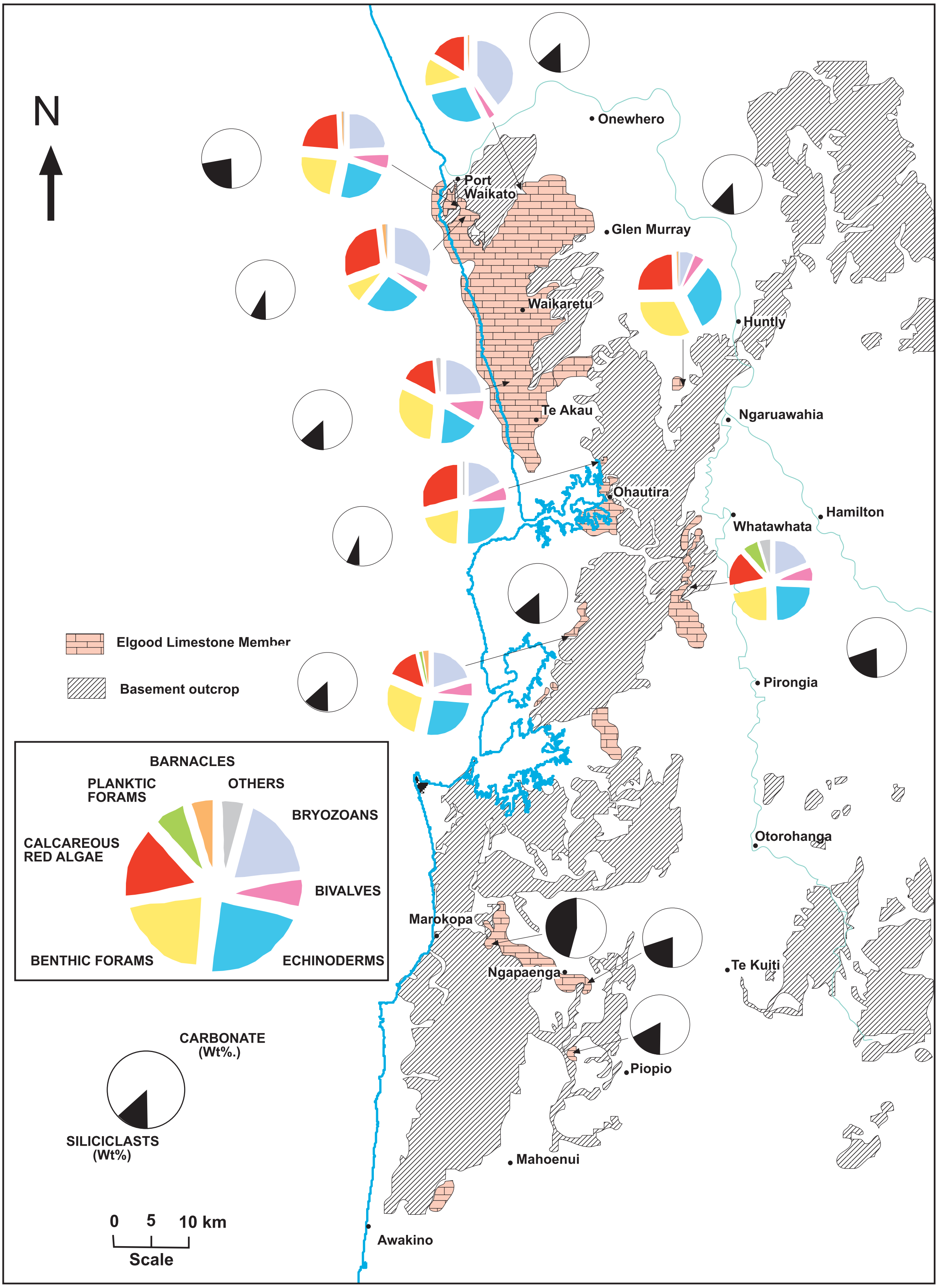


Fig. 11: Map showing the generalised distribution of the Elgood Limestone Member of Glen Massey Formation, and pie-diagrams of its average whole rock bioclastic and carbonate versus siliciclastic composition. Distribution of the member west of the present day coastline is inferred.

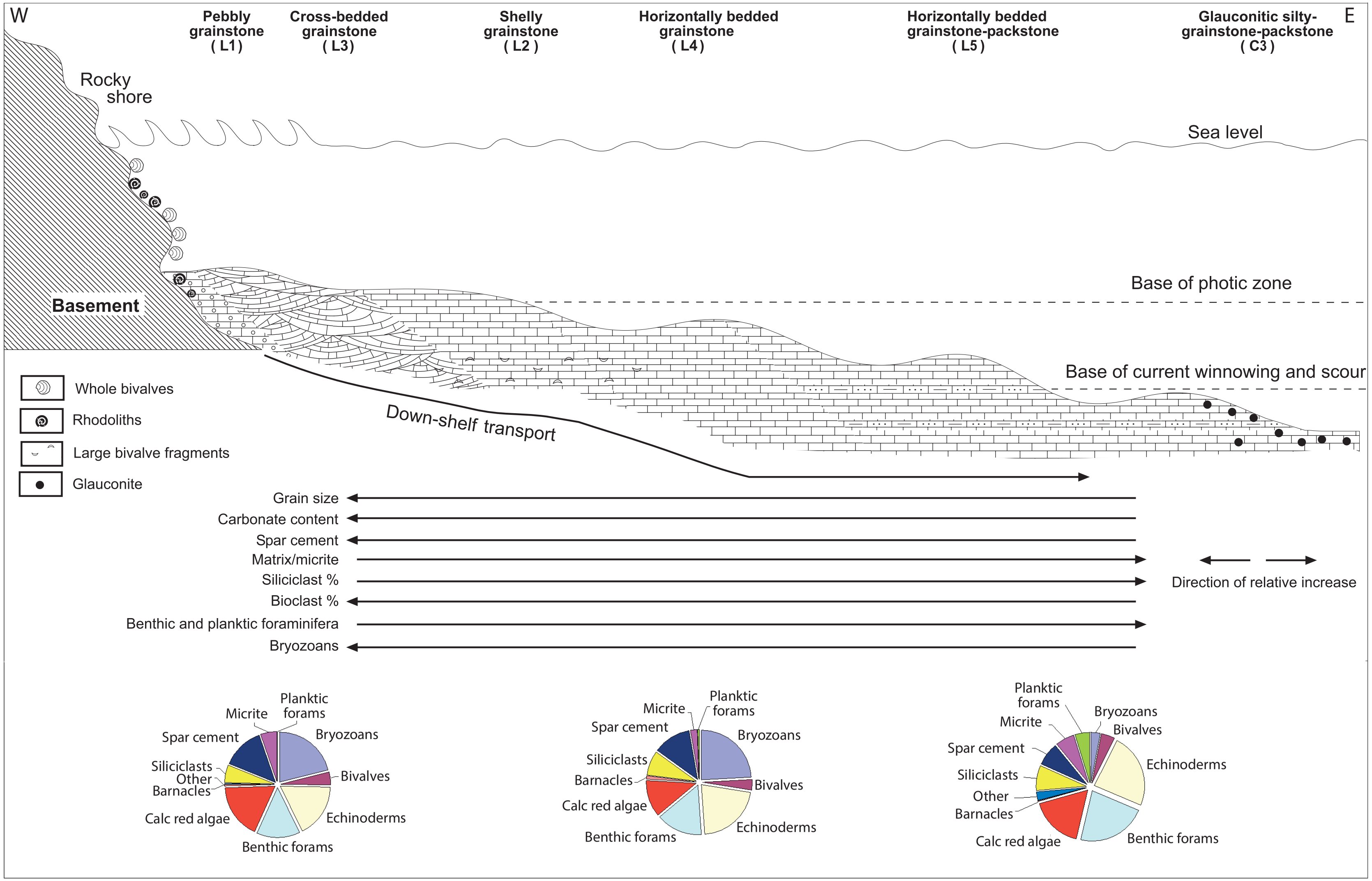


Fig. 12: Schematic dip section from the western basin margin to a more offshore eastern part, depicting the main constituents of the Elgood Limestone Member: rock type, biotic composition and interpreted depositional environments. This transect incorporates data from different stratigraphic levels. Note that not all facies occur at any given time on the shelf. The zone of dominant carbonate production and accumulation is inferred to be located in the inner- and mid-shelf position. Summary of general petrographic trends and pie diagrams show average proportion of bioclasts, siliciclasts, spar cement and matrix/micrite content derived from modal analysis. The faunal compositional data show that bryozoans, echinoderms, calcareous red algae and benthic foraminifers are the major skeletal carbonate contributors.

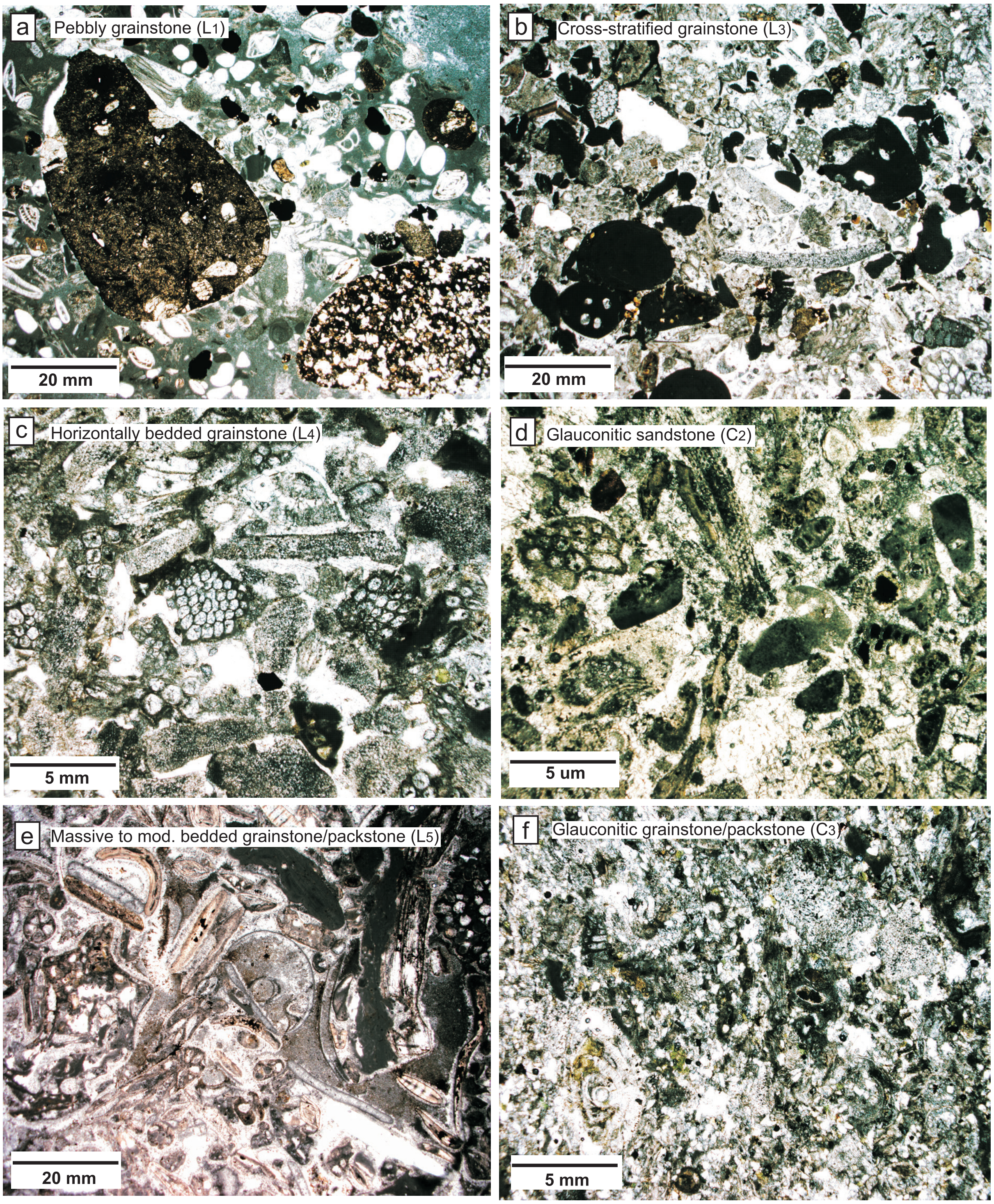


Fig. 13: Photomicrographs of representative samples of Elgood Limestone lithofacies in the northern region (Port Waikato-Raglan Harbour). (a) Benthic foraminiferal-rich with igneous rock fragments derived from Murihiku Terrane (basement) in a coarse bioclastic grainstone. Sample from the base of Elgood Limestone near Te Akau (TA-3) (sample 160). (b) Bryozoans, echinoderms, calcareous red algae and bivalves in coarse sparry grainstone from near Port Waikato (PW-2) (sample 35). (c) Bryozoan-echinoderm-benthic foraminiferal sparry grainstone from Onewhero (PW-5) (sample 49). (d) Glauconitic sandy grainstone containing echinoid and bryozoan grains in a sparry matrix. Sample from top of Elgood Limestone Member near Port Waikato (PW-1A) (sample 3). (e) Benthic foraminifera, echinoderms and calcareous red algae in a mixed grainstone/packstone from near Raglan Harbour (TA-13) (sample 245). (f) Echinoderms and benthic foraminifera with glauconite in a mixed grainstone/packstone matrix from top of Elgood Limestone Member, near Te Akau (TA-3) (sample 164).

relatively high macrofossil density. Randomly oriented bivalves are mostly pectinids (*Lentipecten*, *Chlamys*) supported by a bioclastic spar-cemented grainstone with minor terrigenous fine sand-silt matrix (<15%). Bivalves are rarely in life position and are mostly disarticulated (Fig. 10b). Occasional oyster clusters and solitary corals (*Flabellum* sp.) are observed. Accessory fauna include bryozoans, echinoids and large benthic foraminifera. The facies generally occurs in association with pebbly grainstone lithofacies (L1) along the western margin (cross sections A-A', B-B', Fig. 9a & b). However, this facies also formed sporadically in more offshore shelf settings where it is represented by thin shellbed accumulations (cross sections D-D' & E-E', Fig. 9d & e).

Interpretation: This facies accumulated immediately seaward of basement highs and also in shoal areas above submerged basement knolls in nearshore - inner shelf environments. This epifaunal bivalve dominated lithofacies is most commonly associated with sandy substrates in shallow shelf waters (Nelson 1978a; James et al. 2001). The occurrence of this facies in more offshore settings represents stratigraphic condensation, and is inferred to be an equivalent of the "compound shellbeds" described by Naish & Kamp (1997) in Wanganui Basin.

L3 - Cross-stratified grainstone

This cross-stratified facies exhibits tabular and occasionally complex sigmoidal foreset configurations. Individual cross-beds have <10° - 25° dips, occur in sets and cosets 0.3-1.5 m thick, and are generally separated by 0.5-1.5 cm thick siliciclastic-rich seams (Fig. 10c). Set bases and tops are sharp. Rocks are skeletal-rich limestone composed largely of bryozoans, echinoids, bivalve shell fragments and benthic foraminifera (Fig. 13b & 14c). The seams (bedding planes) consist of very fine sandstone and rarely subangular granules. This facies is generally well developed near basement and may pass laterally and vertically into L4, the Horizontally bedded grainstone lithofacies (cross section A-A', Fig. 9a).

Interpretation: Cross-stratification resulted from the migration of subaqueous dunes by storm and/or tidal currents, enhanced by complex topography (e.g. Anastas 1997; Pomar & Tropeano 2001). The high degree of bioclast fragmentation and abrasion indicates a high level of physical reworking. This effectively limited the amount of bioturbation, leading to generally good preservation of cross-bed sedimentary structures (e.g. Lukasik et al. 2000).

L4 - Horizontally bedded grainstone

This facies is the most widespread in the Elgood Limestone Member and has well developed flags, which mimic bedding (Fig. 10d). The seam thicknesses vary between a few millimetres and 1.5 - 2 cm and can be regular to undulating, or irregular and bifurcating. Physical sedimentary structures are rare and consist of occasional horizontal laminations and wave-ripples. The main constituents are fragmented skeletons derived primarily from bryozoans, echinoderm plates and/or spines, benthic foraminifera, bivalves and coralline red algae (Figs. 13c & 14a, d & e). The siliciclastic content includes fine to very fine sand size quartz and feldspar, and to a lesser extent glauconite pellets. This facies commonly occurs in the mid to upper parts of the Elgood Limestone Member along the western margin of the basin. In more offshore (eastern) settings, this facies often occurs in association with L5, the Massive to moderately bedded grainstone-packstone lithofacies (cross sections B-B', C-C', E-E', Fig. 9b, c & e).

Interpretation: The skeletal sand forming the bulk of this facies was derived by dislodgement, fragmentation and abrasion of components of the rocky shoreline communities by the physical action of waves and currents, especially during storm events. These physical processes are important mechanisms for skeletal grain formation and modification (e.g. Nelson 1978a). The horizontal bedding style, the absence of cross-bedding and the fine to medium grained character of this facies support redeposition on the shelf as sand sheets during storms through the action of wave and wind-driven bottom currents (Nelson 1978b). This mechanism also resulted in selective sorting and the segregation of carbonate grainstone from the siliciclastic seams between flags.

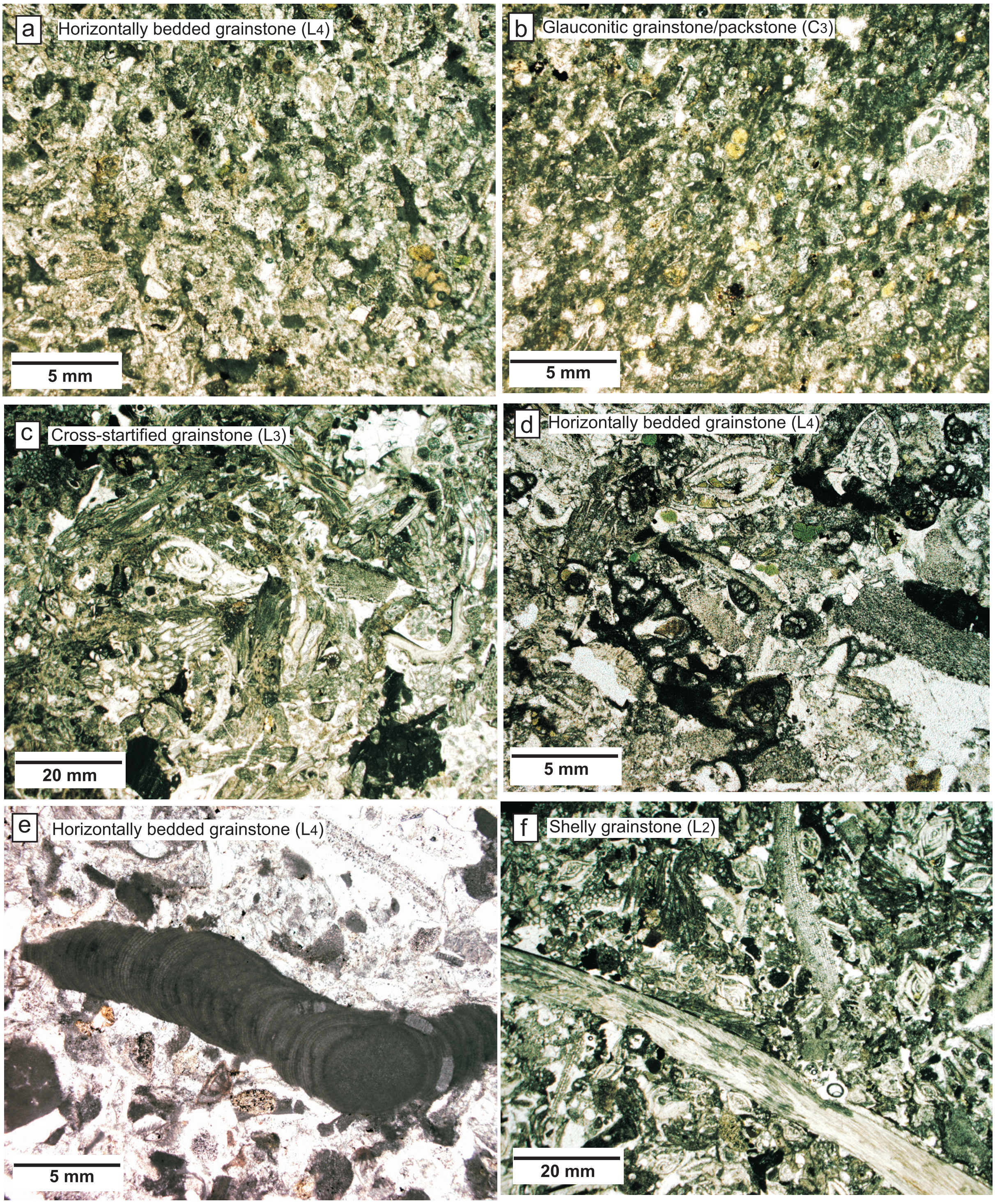


Fig. 14: Photomicrographs of representative samples of Elgood Limestone lithofacies in the central region (Raglan-Te Pahu-Aotea Harbour). (a) Fine-grained bioclastic grainstone of lithofacies L4; benthic foraminifera, echinoiderms, planktic foraminifera and glauconite pellets are evident. Sample from lower part of Elgood Limestone Member at Waikoha Road, near Te Pahu-Karamu (AK-6) (sample 328). (b) Bivalve-echinoderm-planktic/benthic foraminiferal assemblages in a glauconite-rich matrix of micritised silty packstone. Sample from near top of Elgood Limestone Member at Waikoha Road, near Te Pahu-Karamu (AK-6) (sample 332). (c) Coarse bryozoan-dominated grainstone of lithofacies L3, at Waitiki near Aotea Harbour (AK-8) (sample 378). (d) Benthic foraminifera, echinoderms, calcareous red algae and glauconite (pellets and infills) in a sparry grainstone from near Aotea Harbour (AK-4) (sample 304). (e) Red coralline algae with lithics and bivalve fragments in a matrix of sparry grainstone (polarised light). Sample from base of Elgood Limestone Member at Halliday Road near Raglan Harbour (TA-13) (sample 241). (f) Bivalve-rich-benthic foraminiferal (*Amphistegina*) grainstone, Shea Road near Aotea Harbour (AK-4) (sample 302).

L5 - Massive to moderately bedded grainstone-packstone

Bedding in this facies is commonly irregular to slightly undulating, but also often massive (Fig. 10e). The main skeletal types are bryozoans, echinoderm plates and spines, and planktic and benthic foraminifers (Fig. 13e). In places, discontinuous shell hash beds, often rich in whole and fragmented echinoderms along with occasional scattered granule size siliciclasts, are also observed. Siliciclastic material is generally sand or silt size and locally includes significant amounts of glauconite. Bioturbation is characteristic of this facies and in places has completely destroyed sedimentary structures (e.g. Lukasik et al. 2000). This facies occurs commonly in deeper water positions of the carbonate paleoshelf (cross sections C-C', E-E', Fig. 9c & e).

Interpretation: This facies is inferred to have been deposited in wave (storm) dominated settings with bioturbation occurring during fair-weather conditions. The occurrence of echinoid coquina and terrigenous granules in this facies likely also resulted from storm reworking on the shelf. The overall fine texture and intensity of bioturbation, coupled with the content of planktic foraminifera, reflect a mid to outer shelf depositional setting (e.g. Boreen et al. 1993).

Mixed carbonate-siliciclastic sandstone lithofacies association (S1 to S4; Ahirau Sandstone Member)

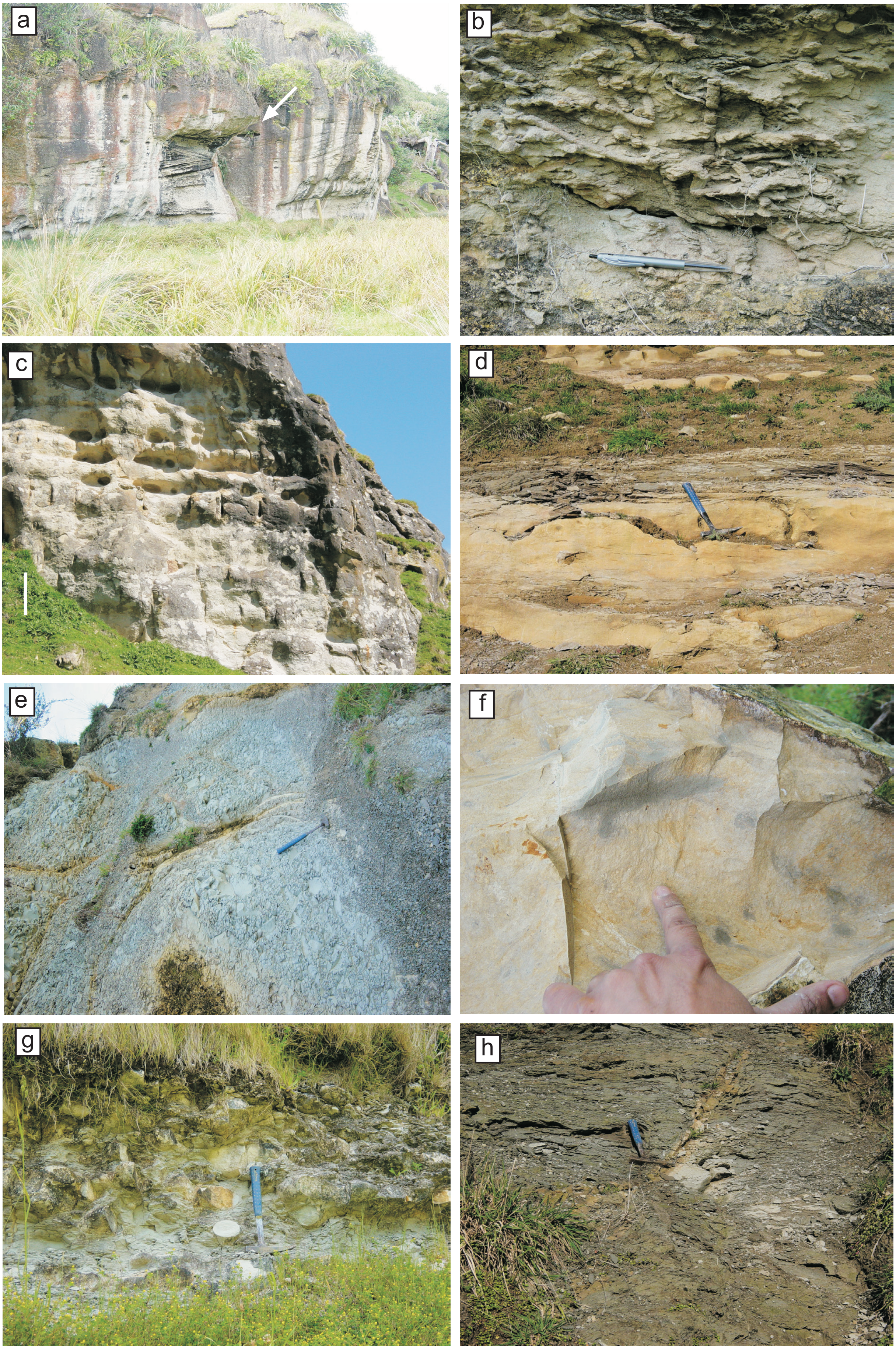
The mixed carbonate-siliciclastic sandstone lithofacies association, typical in Ahirau Sandstone Member, has a carbonate content of up to about 70%. It is better cemented and more resistant to erosion than the underlying mixed carbonate-siliciclastic siltstone lithofacies of the Dunphail Siltstone Member and as a result it stands proud in the landscape as bluffs (Fig. 15a). There is however a grain size gradation from the Dunphail Siltstone into the Ahirau Sandstone, and the latter fines markedly in a basinward (easterly) direction, merging with the underlying siltstone facies.

S1 - Calcareous pebbly-gritty sandstone

This facies typically occurs in 0.2 - 1.0 m thick units and is characterised by conspicuous concentrations of grit (1 - 4 mm) with common to abundant rounded to subrounded pebbles (av. 2 - 3 cm) supported in a fine calcareous sandstone-siltstone matrix. Scattered bivalve fragments, glauconite pellets and glauconitised clasts and shell fragments are also common. Coralline red algae, including rhodoliths, are common near the base. This facies generally occurs in association with the Pebbly grainstone lithofacies (L1) overlying basement, although in rare instances may sharply overlie cross-stratified limestone (facies C3) (cross sections A-A' to C-C' & E-E', Fig. 9). It passes up into either L1 or Massive calcareous siltstone lithofacies Z2.

Interpretation: The common occurrence of the benthic foraminifera *Arenodosaria antipoda* and *Melonis dorreeni*, along with coralline red algae and rhodoliths, supports accumulation in shallow waters (inner shelf) (e.g. Hayward 1986; Hayward et al. 1989; James et al. 2001; Cooper et al. 2004). The common to abundant pebbles are inferred to have been sourced from nearby

Fig. 15: (facing page) (a) Trough cross-stratification (pointed to by arrow) in Calcareous silty fine sandstone facies (S2) passes to more massive unit above, near Waikawau Stream bridge, Port Waikato-Waikaretu Road (PW-2). Fence post for scale. (b) Extensive burrow network (?*Rhizocorallium*) consisting of a mixed association of vertical, inclined and horizontal structures is a common feature in Calcareous silty fine sandstone lithofacies (S2). Location Waimai Stream (PW-2), pen (14 cm) for scale. (c) Typical weathering character of Alternating calcareous silty fine sandstone and siltstone lithofacies (S3), near Bothwell Road (PW-8). Note positive relief on more sandy beds compared to recessed silty interbeds. Bar for scale is 30 cm. (d) Photo of Interbedded calcareous siltstone and sandy limestone facies (Z1). Hammer for scale. Photo location Bothwell Road (PW-8). (e) "Frittered" surface, a typical weathering character of massive calcareous siltstone facies (Z2), at Dunphail Bluff (TA-17). Hammer for scale. (f) Close-up of "stirred or mottled" structure indicating pervasive bioturbation apparent in the massive calcareous siltstone lithofacies (Z2) at Dunphail Bluff (TA-17). (g) Concretionary bands define bedding characteristics in the upper part of massive calcareous siltstone lithofacies (Z2), near Awamarino (C-51). Hammer for scale. (h) "Frittered" surface weathering typical of moderately bioturbated Massive muddy sandstone lithofacies (S4), forming the upper part of Glen Massey Formation near Ngapaenga (C-68). Hammer for scale.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exposed basement and transported offshore by storm processes.

S2 - Calcareous silty fine sandstone

This facies consists of intensely burrowed, variably calcareous fine sandstone. Primary inorganic sedimentary structures in places include large-scale trough cross bedding (e.g. Fig. 15a). *Skolithos* trace fossils are abundant and characterised by a mixed association of vertical, inclined, and horizontal structures of low diversity (Fig. 15b). *Zoophycus* trace fossils also occur in lower parts of the Ahirau Sandstone. Scattered whole pectinids (e.g. *Chlamys williamsoni, Lentipecten hochstetteri*), occasional *Cucullaea* sp., echinoiderm plates and/or spines are common. Calcareous silty fine sandstone occurs mostly in the Ahirau Sandstone Member along the western margin (cross sections A-A' to E-E', Fig. 9).

Interpretation: The common occurrence of the benthic foraminifera *Gaudryina reussi, Vaginulinopsis cristellata, Rectuvigerina striatissima, Euuvigerina maynei, Melonis maorica, Notorotalia stachei, Rotaliatina sulcigera* and *Cibicides thiara* indicates inner to mid-shelf depths of sediment accumulation (e.g. Hayward 1986; Hornibrook et al. 1989; Cooper et al. 2004). The profusion of burrows belonging to the *Skolithos* ichnofacies is indicative of relatively high levels of wave and current energy, as typically developed in slightly muddy, unconsolidated to shifting substrates (Lukasik et al. 2000; Pemberton et al. 2001). Locally, the presence of low-angle trough cross-stratification indicates deposition affected by wave-driven currents. The coarsening upwards into this facies suggests the increasing current activity is related to decreasing water depth to inner shelf conditions.

S3 - Alternating calcareous silty fine sandstone and sandy siltstone

This lithofacies consists of silty sandstone and sandy siltstone interbeds in which the thickness of beds ranges from 10 to 90 cm and inter-bed contacts are abruptly gradational (Fig. 15c). Bivalves, including mainly pectinids (e.g. *Chlamys williamsoni, Lentipecten hochstetteri, Janupecten polemicus*), are common with occasional *Panopea* sp. Trace fossil types are similar to those in lithofacies S2, but there is comparatively less bioturbation overall. This facies is characteristic of the upper part of the Ahirau Sandstone Member in central parts of the northern region (cross sections A-A' to D-D', Fig. 9).

Interpretation: This facies represents an open shelf depositional environment. Subhorizontal bedding planes probably record high-energy (storm) events. Storm-driven currents transported fine siliciclastic sediment to mid- to outer shelf water depths where it was mixed with epifauna (Nelson et al. 1988). The common occurrence of benthic foraminifera such as *Cibicides thiara, Melonis maorica, Vaginulinopsis cristellata* and *Euvigerina maynei*, supports the interpretation of mid- to possibly outer shelf depths of sediment accumulation (e.g. Hayward 1986; Hornibrook et al. 1989).

S4 - Massive muddy sandstone

This facies gradationally overlies Massive calcareous siltstone lithofacies Z2, and by contrast is characterised by an increase in the content of fine to very fine siliciclastic sandstone compared with lithofacies Z2 (Fig. 15h). It is moderately burrowed, variably calcareous, and contains scattered bivalve (mainly pectinid) fragments. Facies S4 occurs mainly in the upper parts of the Glen Massey Formation in southwestern parts of the basin. It grades laterally into Massive calcareous siltstone (lithofacies Z2) in an offshore direction (cross section E-E', Fig. 9).

Interpretation: The introduction of fine to very fine sandstone (compared with the underlying lithofacies Z2) is probably due to storm-driven currents carrying fine to very fine sand in suspension out into the mid-shelf environment below storm wave-base (e.g. Lukasik et al. 2000; Pemberton et al. 2001).

Mixed carbonate-siliciclastic siltstone lithofacies association (Z1, Z2; Dunphail Siltstone Member)

Z1 - Interbedded calcareous siltstone and sandy limestone

This facies consists of sandy limestone beds 5-20 cm thick, alternating with 10-30 cm-thick calcareous siltstone beds. The bedding is discrete with the individual sandy limestone beds having sharp bases and tops (Fig. 15d). The interbedded siltstone is variably bioturbated. This facies commonly overlies facies L5, and in turn pass up into Z2. It occurrence is restricted to Bothwell Road and Matakitaki Trig within the Onewhero area, where it forms the lower part of the Dunphail Siltstone Member.

Interpretation: The sandy limestone components were transported from inner-shelf areas and deposited at mid- to outer shelf depths by storm processes, interrupting suspension sedimentation of fine calcareous silt in an overall low-energy shelf environment (e.g. Nelson 1978a).

Z2 - Massive calcareous siltstone

This facies forms the bulk of the Glen Massey Formation in central and eastern areas of the basin (Fig. 4). The siltstone is grey to brownish and massive with rare concretionary horizons (Nelson 1973) (Fig. 15g). The siltstone is mottled reflecting pervasive burrowing (Fig. 15e & f). In places this facies contains scattered whole and fragmented bivalves. The carbonate content is in the range 30-80% and the siltstone may contain small amounts of fine to very fine terrigenous sand. Occasionally a few thin very glauconitic laminae are present, especially near the base or top of this facies. In western exposures of the formation, this facies commonly passes upward into sandstone facies S1-S4 (cross sections A-A' to E-E', Fig. 9).

Interpretation: This facies accumulated in outer shelf to possibly upper bathyal depths. The wide extent of this facies suggests environments removed from any coarse siliciclastic input, and therefore relatively deep. The benthic foraminifers *Cibicides thiara, Semivulvulina capitata, Gyroidinoides allani, Sphaeroidina bulloides, Cibicides perforatus,* and *Globocassidulina subglobosa* suggest outer shelf to upper bathyal water depths (e.g. Hayward 1986; Hornibrook et al. 1989).

Chemogenic lithofacies (C1 to C3)

Although glauconite is present throughout the Glen Massey Formation, locally it can reach unusually high concentrations (>10%). The name chemogenic lithofacies is used here for facies rich in glauconite and/or phosphate commonly associated with abundant burrowing.

At Dunphail Bluffs, the type locality of Glen Massey Formation, a medium to coarse glauconitic calcareous sandstone occurs at the base of the formation (Kear & Schofield 1959, 1978). Glauconite (or greensand) is also abundant at the base of the formation in the Huntly Coalfield and in western parts of the Kawhia Coalfield, where we infer it to represent stratigraphic condensation.

The colour and morphology of the glauconite grains suggest that allochthonous (reworked) grains are more common than autochthonous (in place) material in the Te Kuiti Group, although both may occur within the same unit (Nelson 1973, 1978b). The morphology of glauconite in the Glen Massey Formation is dominated by ovoidal forms (c. 60%) suggesting some degree of reworking (Compton 1989). Both allocthonous and autochthonous glauconite in New Zealand are attributed to very slow sedimentation rates (Nelson 1978b).

Several authors have related the abundance of glauconite and other authigenic minerals to extremely low terrigenous sedimentation rates associated with times of relative sea-level rise (e.g. Posamentier et al. 1988; Loutit et al. 1988; Amorosi 1995). The events that produce high concentrations of authigenic minerals are commonly associated with marine hiatuses and often occur either as thin but continuous zones of burrowed, slightly lithified beds (omission surfaces) or marine hardgrounds (Loutit et al. 1988). Three chemogenic lithofacies have been identified in this study.

C1 - Phosphate nodule bed

This facies is characterised by scattered authigenic phosphate nodules and an abundance of cm-scale subhorizontal and inclined burrows within calcareous silty fine sandstone lithofacies (S2), such as at Waikawau Beach (PW-11) near Port Waikato. This facies is also moderately glauconitic and abruptly overlain by massive siltstone (Kotuku Siltstone Member) of the Whaingaroa Formation (Fig. 16a).

Interpretation: The phosphate nodule bed is inferred to be a marine phosphatic hardground/firmground formed during deepening of a former relatively shallow-water, high-energy environment during times of low sediment accumulation. The phosphatic and glauconitic concentration associated with the hardground indicates its formation was likely related to local upwelling during drowning. The abundance of burrowing suggests open marine, well oxygenated and nutrient-rich conditions, probably induced by the upwelling. These types of hardground are common on high-energy shelves with cool, upwelling waters and very low terrigenous sedimentation rates, such as the modern-day cool-water carbonate shelf edge off South Australia (James et al. 1992; Boreen et al. 1993).

C2 - Glauconitic calcareous siltstone-sandstone

This facies is characterised by pale to dark green glauconite pellets up to 0.4 mm size, scattered in massive, intensely burrowed fine to medium sandstone and/or siltstone (Fig. 13d). These sandstone and siltstone beds are typically poorly to moderately cemented, and contain scattered bivalve fragments, which are frequently glauconitised (Fig. 16b). This facies occurs as multiple glauconite-rich horizons near the base of the Glen Massey Formation, forming a distinct stratigraphic marker in many drill hole sections

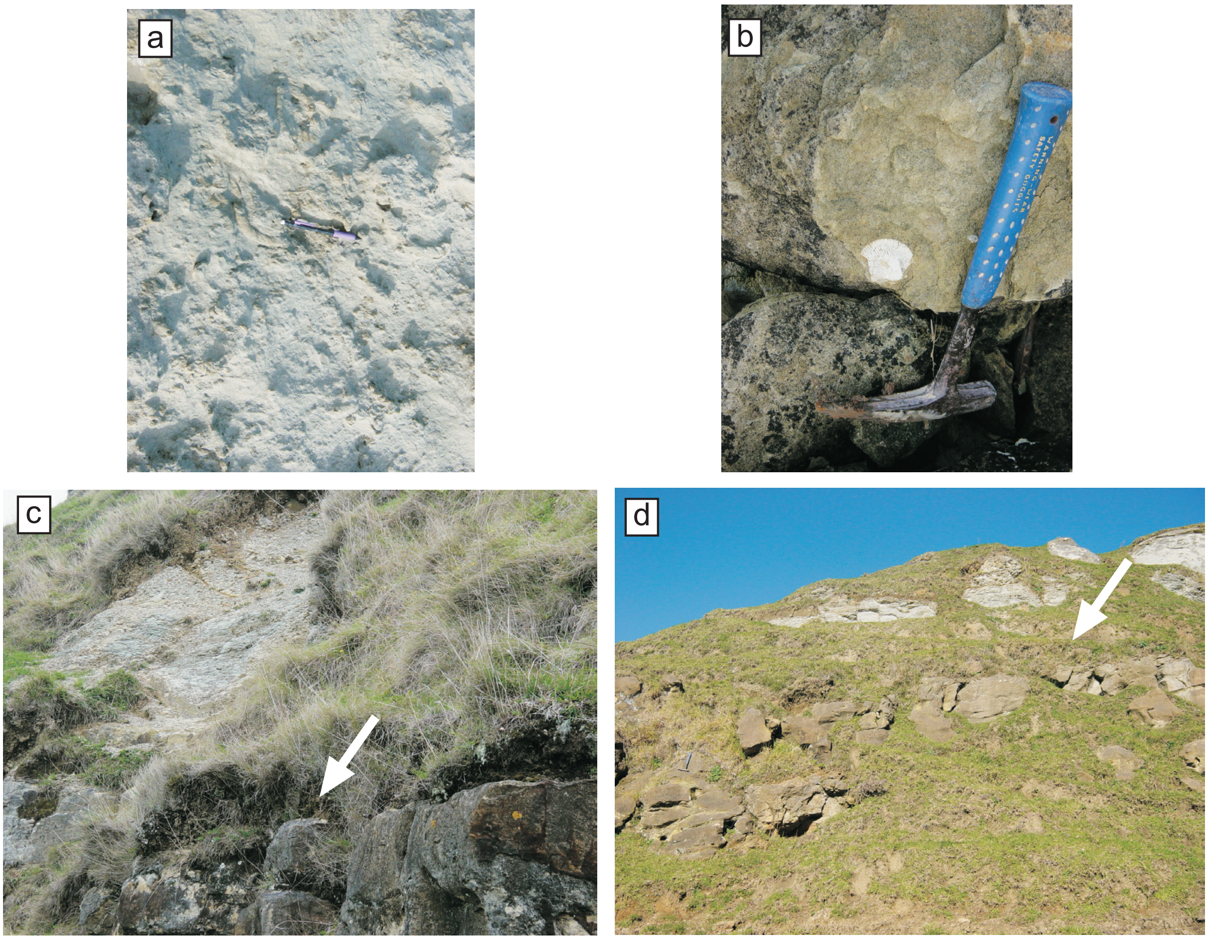


Fig. 16: (a) Surface comprising moderately glauconitic silty sandstone with phosphate nodules (lithofacies C1), and abundant subhorizontal and inclined burrows. This surface is inferred to be a marine firmground, forming a conformable but sharp lithostratigraphic contact between the Glen Massey Formation and the overlying Whaingaroa Formation at Waikawau Beach (PW-11). Pen (14 cm) for scale. (b) Large pectinid coquina in highly glauconitic calcareous sandstone (lithofacies C2) at Waitetuna Estuary, Raglan Harbour (TA-14). Hammer for scale. (c) Outcrop expression of maximum flooding surface (pointed by arrow). This surface comprises grainstone-packstone with a high concentration of glauconite (lithofacies C3). Transgressive and highstand systems tracts occur below and above the maximum flooding surface, respectively. Bar for scale is 30 cm long. Photo location: Waikoha Road, Te Pahu-Karamu (AK-6). (d) Massive to moderately bedded grainstone-packstone (lithofacies L5) capped by glauconitic sandstone (pointed by arrow) that represents the maximum flooding surface overlain by massive calcareous siltstone (lithofacies Z2). Hammer for scale. Photo location: Port Waikato (PW-1A).

within the Huntly region (Kear & Schofield 1959, 1978; Edbrooke 1984) (cross section A-A' & D-D', Fig. 9). Along the western margin of the basin, this facies occurs in close association with calcareous pebbly-gritty sandstone (lithofacies S1), overlying a significant regional unconformity.

Interpretation: Greensand or glauconitic sandstone at the base of Glen Massey Formation has been reported over much of the Huntly Coalfield area (Kear & Schofield 1978; Edbrooke 1984). This facies accumulated in low-energy deep water conditions indicative of sediment starvation. It includes both autochthonous glauconite reflecting a sediment starved outer-shelf area and allochthonous glauconite, which was probably remobilised seawards by storm-driven currents (e.g. Amorosi 1995). Sporadic occurrences of this facies along the western basin margin, especially in association with the high energy deposits of lithofacies S1, is probably due to localised sediment bypass during an initial rise in relative sea level.

C3 - Glauconitic sandy-silty grainstone-packstone

The Glauconitic grainstone-packstone lithofacies occurs in close association with the limestone facies, and is characterised by a high concentration of glauconite (>10%), either near the base of the Pebbly and/or Shelly grainstone lithofacies (L1/L2) or more commonly near the top of the Massive to moderately bedded grainstone-packstone (L5) at the top of the Elgood Limestone Member (cross section C-C' to E-E', Fig. 9). The occurrence of facies C3 near the base of L1/L2 is most noticeable at a few localities along the western margin, where it also contains variable amounts of siliciclastic medium to coarse sandstone, pectinids and oyster shell fragments, large benthic foraminifera (*Amphistegina*) and coralline algae. In some localities facies C3 interfingers or grades laterally into glauconitic calcareous siltstone-sandstone (lithofacies C2). The facies also occurs as finely disseminated glauconite-rich horizons in the uppermost portion of moderately bedded grainstone-packstone (lithofacies L5) and lowermost massive calcareous siltstone (lithofacies Z2). It displays variable bioturbation, and relatively abundant bivalves and planktic foraminifera (Figs 13f, 14b & 16c, d).

Interpretation: The presence of this facies at the base of pebbly and/or shelly grainstone (lithofacies L1/L2) is interpreted to result from sea-level rise resulting in sediment starvation (e.g. Amorosi 1995). The co-occurrence of large benthic foraminifera (e.g. *Amphistegina*) and calcareous red algae reflects shallow-water reworking by waves and tidal currents (James et al. 2001). The presence of facies C3 at the top of lithofacies L5 is also indicative of increased water depth and resultant sediment starvation at the top of the Elgood Limestone Member (transgressive systems tract) (e.g. Loutit et al. 1988; Amorosi 1995).

Facies distribution and paleoenvironmental interpretations

The lithofacies described above and summarised in Table 1 are associated with particular members of the Glen Massey Formation, as shown in Table 2. In addition, the lateral and vertical distribution of the facies is shown in five transects (Fig. 9a-e).

Significant marine flooding across the basin marked the onset of accumulation of the Glen Massey Formation. In the Elgood Limestone Member, inner shelf high-energy limestone lithofacies (L1-L3) grade eastward into horizontally bedded to massive grainstone/

Table 2: Lithofacies distribution within the members of the Glen Massey Formation.

Members	Lithofacies
Ahirau Sandstone	S2, S3, S4, C1
Dunphail Siltstone	S1, Z1, Z2
Elgood Limestone	S1, L1, L2, L3, L4, L5, C2, C3

packstone facies (L4-L5) deposited in mid to outer shelf environments (Fig. 12). These facies in turn grade into calcareous siltstone/sandstone (sandy marl) with relatively high concentrations of glauconite (Lithofacies C2, C3) (Fig. 12), which also developed across the top of the member. Overall, the depositional setting is interpreted to have been a low-gradient shelf, with shallow water areas to the west and deeper water areas to the east (Kamp et al. 2014b). The strong development of limestone lithofacies in the northwest compared with the central and southern areas (Fig. 2) suggests that it was more distant from siliciclastic sediment input or within an area of siliciclastic sediment bypass.

The limestone lithofacies pass upward via greensand development into mainly Calcareous siltstone lithofacies (Z2) of the Dunphail Siltstone Member. This facies is thickest (up to 180 m) in the east and northeast (Fig. 4), and comprises most of the formation in the south (Fig. 9e). In western and northwestern parts of the basin facies Z2 grades upward into well cemented Calcareous silty fine sandstone (S2), which in turn passes laterally to the east into alternating calcareous fine silty sandstone and siltstone (S3). Lithofacies S1 and S2 accumulated in an inner to mid shelf environment and occur in the upper parts of the Ahirau Sandstone Member. These vertical facies transitions and their inferred depositional paleoenvironments imply that the Glen Massey Formation is made up generally of lower deepening and upper shoaling components.

Sequence stratigraphy

This section applies sequence stratigraphic concepts and terminology to the Glen Massey Formation. Sequence stratigraphy (Mitchum 1977) is fundamentally about the identification of key surfaces and stratal patterns within linked depositional systems (systems tracts) between key surfaces. The consideration of these elements establishes the sequence architecture of the Glen Massey Formation and the occurrence of a relative sea-level cycle.

Mitchum's (1977) definition of the term "sequence" as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities is adopted here. Sequence stratigraphy is the recognition and correlation of stratigraphic surfaces (sequence boundary, transgressive surface of erosion, downlap surface and maximum flooding surface), which represent changes in depositional patterns in sedimentary rocks. Such changes were generated by the interplay of subsidence, sediment flux and changes in sea level, which can be determined from sedimentological analysis and geometric relationships (Embry 2001). The identification and correlation of key stratigraphic surfaces provide the framework for grouping facies within linked depositional systems or systems tracts. In this study, "relative sea level" means the integration of eustatic changes in sea level with changes in the rate of subsidence and sediment flux; relative sea level controls the rate of change in accommodation, which is fundamentally expressed in the stratal patterns of onlap, downlap, toplap and offlap.

Overview and general setting

Kear & Schofield's (1959) observations may be considered to be the first identification of stratigraphic cyclicity in the Te Kuiti Group, whereby unconformities provided the basic subdivision of the Te Kuiti Group. The importance of unconformities in subdividing the Te Kuiti Group was explicitly emphasised by Nelson (1973, 1978a), who stated that "formations and members are commonly bounded by unconformities, mainly disconformities…" A novel study investigating cyclicity in the Te Kuiti Group succession and the relationship between sedimentation, unconformities and changes in base level, which are directly relevant to sequence stratigraphy, was made by Vella (1967) prior to the birth of the modern concepts of sequence stratigraphy. He proposed a global sea-level cycle chart that linked the cyclicity observed in New Zealand's Eocene and Oligocene strata (including the Te Kuiti Group) to similar age strata occurring in other parts of the world, based on the underlying assumption that glacio-eustacy is the main driving force behind the cyclicity. This study utilises the insights from these previous studies, and builds upon them to interpret Glen Massey Formation in a sequence stratigraphic context.

Good exposures of the Glen Massey Formation along the western sector of the basin provide reasonably continuous outcrop of mixed carbonate-siliciclastic basin margin facies over the scale of hundreds of metres. However, it is more difficult to construct lateral facies transitions from inner shelf to outer shelf and upper bathyal paleoenvironments to the east because of widely spaced outcrop section and drill holes.

Sequence architecture

The sequence architecture of the Glen Massey Formation comprises the following surfaces and system tracts in ascending stratigraphic order: (i) a basal unconformity (sequence boundary) superposed by a transgressive surface of erosion or its correlative conformity; (ii) a variably thick (<1-30 m) transgressive systems tract (TST) composed of limestone facies (lithofacies L1-L5); (iii) a maximum flooding surface (MFS) closely associated with a downlap surface (DLS); (iv) a highstand systems tract (HST) some 1-40 m thick that typically comprises an aggradational interval of calcareous siltstone (lithofacies Z2); (v) Z2 in turn gradationally passes upward into a regressive systems tract (RST) some 2-80 m thick that comprises progradational calcareous silty sandstone (lithofacies S2-S4) (Fig. 17). The different styles depicted in Fig. 17 represent the different motifs or expressions of sequence architecture observed in the field as a result of different rates of subsidence and sediment flux influenced largely by position on the paleoshelf. The Glen Massey "sequence" in more offshore positions contains a thin glauconitic facies (C2) reflecting stratigraphic condensation. The following sections describe and interpret the key sequence stratigraphic surfaces and systems tracts in the Glen Massey sequence. The interpretation of stratigraphic surfaces is based on two types of observations: the type of stratigraphic contact (conformable or unconformable) and the nature of the facies (depositional systems) either side of the key surfaces.

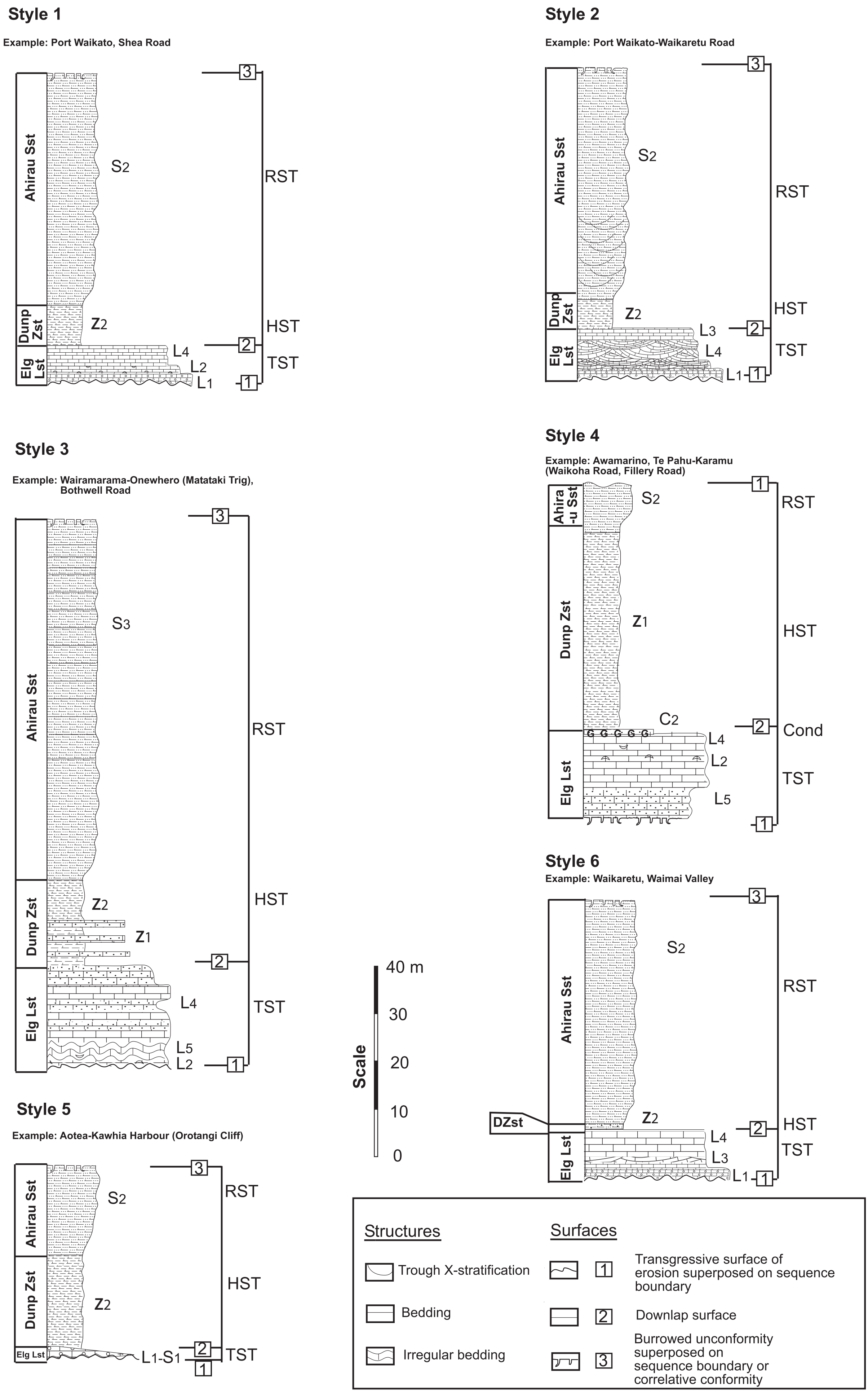
Sequence boundary

The boundary at the base of the Glen Massey sequence represents a flooding surface (Van Wagoner 1995). It is also a transgressive surface of erosion (TSE) or ravinement surface (Nummendal & Swift 1987; Posamentier & Allen 1999), particularly where it overlies basement. It is a sharp planar surface resulting from wave planation superimposed on a pre-existing subaerial erosion surface (Fig. 18a, b & c). In the deeper water setting of the eastern part of the basin there is probably a correlative conformity. TSEs are commonly overlain by a thin lag deposit, including granules, coarse sandstone and shell hash, indicating a variable degree of erosion by waves and current action in the process of their formation (Fig. 18d). During sediment transport, coarse clasts and large bivalve fragments are left behind as a transgressive lag on top of the wave-planed ravinement surface (e.g. Swift 1976). The greatest amount of erosion is associated with the zones of highest energy, normally being the wave zone, and as sea level rises on wave-dominated coastlines, the zone of erosion will be translated landward. A sharp contact with overlying lag deposits including rhodoliths (Nalin et al. 2008) occurs along the western basin margin, comprising architectural styles 2, 10 and 13 (Fig. 17).

A different type of flooding surface involves the development of omission. In this case the substrate beneath the flooding surface is characterised by evidence of missing time shown by extensive burrowing or the accumulation of glauconite indicative of non-deposition or condensed sedimentation (e.g. Catuneanu 2006). In the field area, omission surfaces are represented in the Glen Massey sequence by styles 4 and 14 (Fig. 17), which formed in basinal areas to the east where they delineate an abrupt contact between Waikato Coal Measures and Mangakotuku Formation.

Downlap surface

The downlap surface (DLS) is a surface that can be mapped in seismic reflection profiles where dipping beds are overlain by beds with a shallower dip. In outcrop sections a DLS can be inferred between beds that accumulated during marine onlap (submergence) versus strata that accumulated during offlap (emergence). The DLS usually coincides with, or lies a short distance above, the maximum flooding surface


Style 1
Example: Port Waikato, Shea Road
Ahirau Sst
Dunp Zst
Elg Lst
S2
Z2
L4
L2
L1
RST
HST
TST
3
2
1
Style 2
Example: Port Waikato-Waikaretu Road
Ahirau Sst
Dunp Zst
Elg Lst
S2
Z2
L3
L4
L1
RST
HST
TST
3
2
1
Style 3
Example: Wairamarama-Onewhero (Matataki Trig), Bothwell Road
Ahirau Sst
Dunp Zst
Elg Lst
S3
Z2
Z1
L4
L5
L2
RST
HST
TST
3
2
1
Style 4
Example: Awamarino, Te Pahu-Karamu (Waikoha Road, Fillery Road)
Ahira -u Sst
Dunp Zst
Elg Lst
S2
Z1
C2
L4
L2
L5
RST
HST
Cond
TST
1
2
1
Style 5
Example: Aotea-Kawhia Harbour (Orotangi Cliff)
Ahirau Sst
Dunp Zst
Elg Lst
S2
Z2
L1-S1
RST
HST
TST
3
2
1
Scale
40 m
30
20
10
0
Style 6
Example: Waikaretu, Waimai Valley
Ahirau Sst
DZst
Elg Lst
S2
Z2
L4
L3
L1
RST
HST
TST
3
2
1
Structures
Trough X-stratification
Bedding
Irregular bedding
Surfaces
1 Transgressive surface of erosion superposed on sequence boundary
2 Downlap surface
3 Burrowed unconformity superposed on sequence boundary or correlative conformity

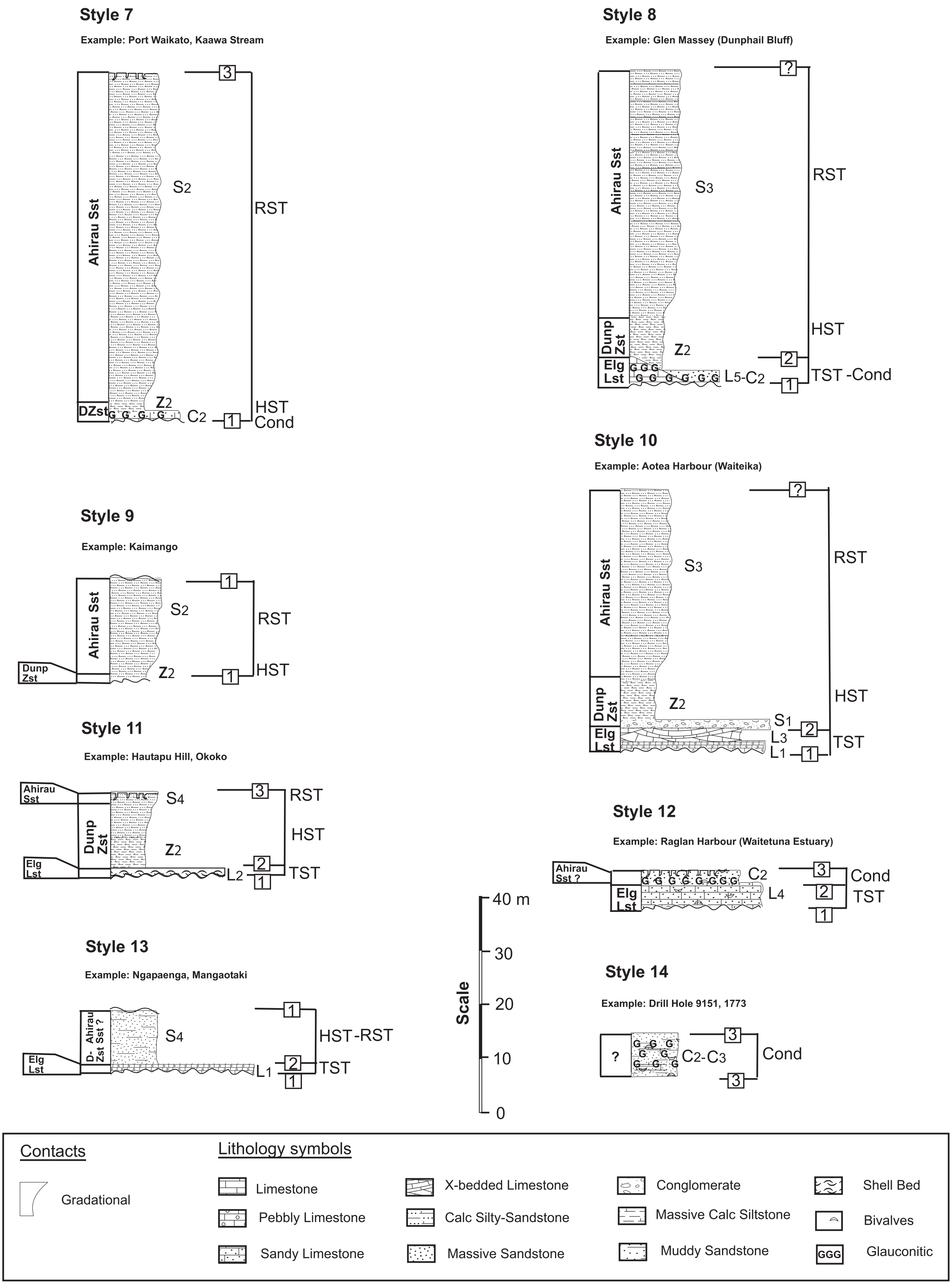


Fig. 17: Logs for Glen Massey Formation showing vertical lithofacies successions within component system tracts and stratigraphic surfaces. See Table 1 for lithofacies abbreviations. Systems tracts abbreviations: TST, transgressive systems tract; HST, highstand systems tract; RST, regressive systems tract; Cond, condensed section.

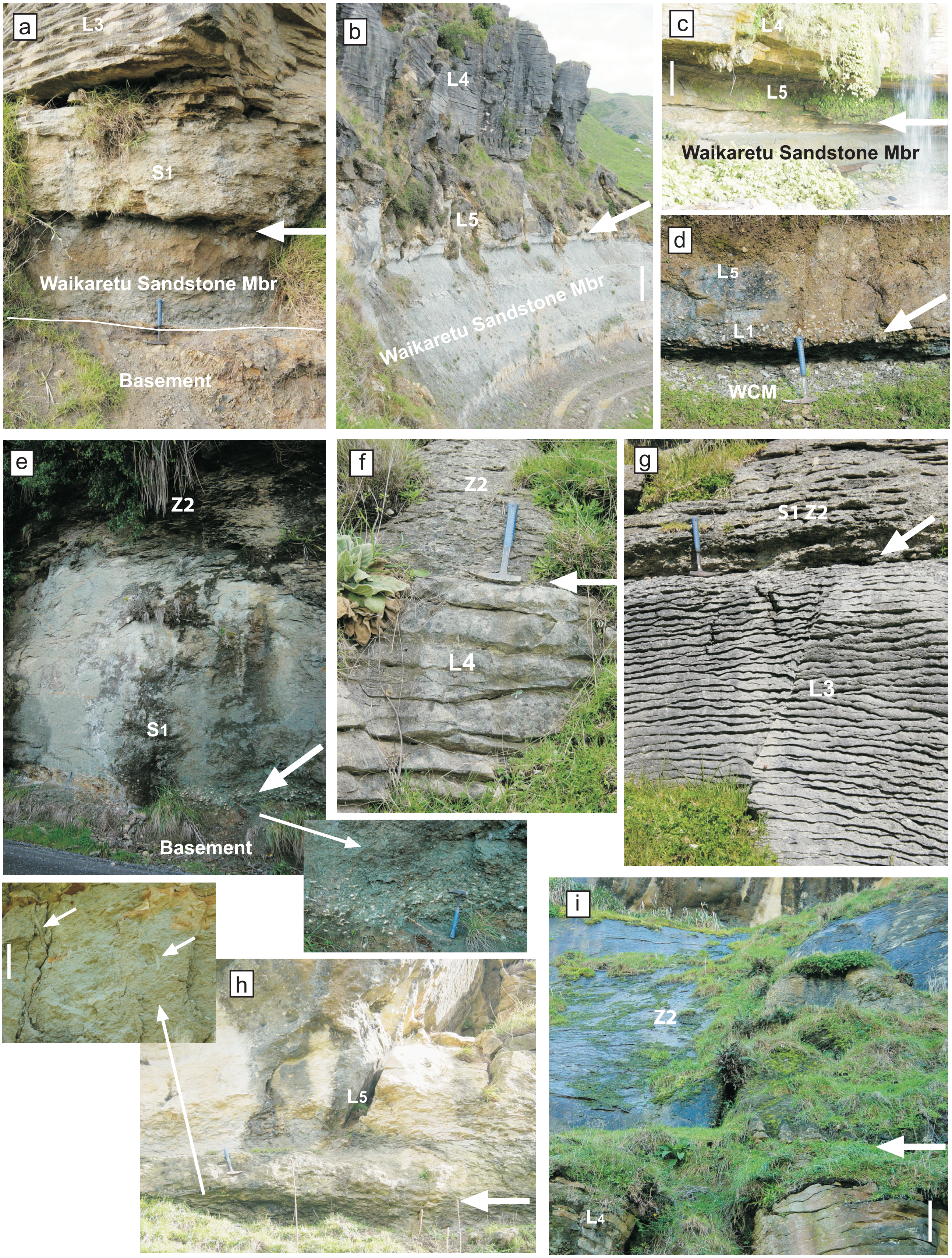

a
L3
S1
Waikaretu Sandstone Mbr
Basement
b
L4
L5
Waikaretu Sandstone Mbr
c
L4
L5
Waikaretu Sandstone Mbr
d
L5
L1
WCM
e
Z2
S1
Basement
f
Z2
L4
g
S1 Z2
L3
h
L5
i
Z2
L4

Fig. 18: (*facing page*) Photographs of outcrop expression of stratal surfaces. (a) A transgressive surface of erosion (arrow) at the contact between Waikaretu Sandstone Member, Mangakotuku Formation, and Elgood Limestone Member near Waikawau Stream bridge, Port Waikato-Waikaretu Road (PW-2). Hammer for scale. (b) A flooding surface (sequence boundary) marked by firmground (arrow) development at the contact between Waikaretu Sandstone Member and Elgood Limestone Member. Bar for scale is 2 m high. Photo location: Waikoha Road (AK-6), Te Pahu-Karamu. (c) Transgressive surface of erosion (arrow) between Waikaretu Sandstone Member and Elgood Limestone Member. Location: near Waikaretu walkway (PW-9). Bar for scale is 30 cm long. (d) An example of transgressive lag deposits (arrow) comprising abundant rounded-subrounded pebbles associated with a wave-planed surface (superposed on the sequence boundary) at the contact between Elgood Limestone Member and Waikato Coal Measure (WCM), near Mangaotaki (C-145), west of Piopio. Hammer for scale. (e) Transgressive lag deposits comprising lithofacies S1 with occasional bivalve shell fragments and rhodoliths in contact with basement, near Ruaweke Point (AK-7), on the eastern shore of Aotea Harbour. Close-up shows rhodolith conglomerate immediately above the sequence boundary. Hammer for scale. (f) Top of Elgood Limestone Member (lithofacies L4) (arrow) marks a maximum flooding surface (or DLS) overlain by HST Massive calcareous siltstone lithofacies (Z2) of Dunphail Siltstone Member. Hammer for scale. Photo location: near Waikaretu walkway (PW-9). (g) Downlap surface (arrow) at the contact between Elgood Limestone (lithofacies L3) and overlying highstand glaucontic siltstone with abundant rounded and subrounded pebbles and granules (S1) passing upward into massive calcareous siltstone (Z2). Hammer for scale. Photo location: Waiteika (AK-8), inland of Aotea Harbour. (h) Flooding surface inferred to be a sequence boundary (arrow) at the contact between Elgood Limestone Member (lithofacies L5) and underlying Waikaretu Sandstone Member at Quarry Road (AK-15), Te Pahu-Karamu. The substrate immediately beneath the flooding surface is extensively burrowed and there is no lag deposit or evidence of scouring. Hammer for scale. Close-up: large tubular burrows (*Planolites*). Bar for scale is 10 cm. (i) Downlap surface (DLS) at the conformable contact between Elgood Limestone Member TST (L4) and overlying highstand Dunphail Siltstone member (lithofacies Z2) at Shea Road (AK-4). Bar for scale is 30 cm.

(MFS), which represents the point of maximum transgression of the shoreline and may comprise condensed sediment such as greensand (e.g. Carter et al. 1998). The MFS is a conceptual surface, except where condensed deposits are formed, whereas the DLS commonly has physical expression in mixed carbonate-siliciclastic successions as the stratigraphic appearance of fine-grained terrigenous sediment over carbonate beds (Naish & Kamp 1997). Hence the DLS separates retrograding strata below from prograding strata above, and the DLS starts to form when accommodation is no longer formed at the shoreline and sediment being supplied across the shoreline has to be moved basinward (Posamentier et al. 1988; Van Wagoner et al. 1988; Galloway 1989). In effect, the DLS marks the top of a TST and the maximum rise of relative sea level, as described by Catuneanu (2006).

The field expression of the DLS is marked in the Glen Massey Formation by the occurrence of greensand (style 1, 4, 8, 12, Fig. 17) and by a sharp transition from limestone facies (Elgood Limestone Member) to siltstone facies (Dunphail Siltstone Formation), typically exemplified by styles 1, 2 and 5 (Figs. 17 & 18f, g & i). However, this surface is more of a zone in certain localities, such as represented by style 3 (Fig. 17). In this case, the transition between the TST and HST is marked by interbedded calcareous siltstone and sandy limestone (lithofacies Z1). Consequently it is difficult to pinpoint a single surface as the DLS, but the approach adopted has been to place it at the base of the first siltstone bed greater than 10 cm thick. In rare instances as in style 10 (Fig. 17), the DLS is marked by an abrupt transition from Cross-bedded grainstone (L3) into Calcareous silty sandstone with abundant scattered glauconite pellets, pebbles and granules (S1), with some pebbles showing glauconite coating (Fig. 18g). In stratigraphic sections located farther offshore, such as over much of the Huntly Coalfield, the DLS lies at the top of the regionally extensive greensand, which formed when the shoreline reached its maximum landward position.

Transgressive systems tract

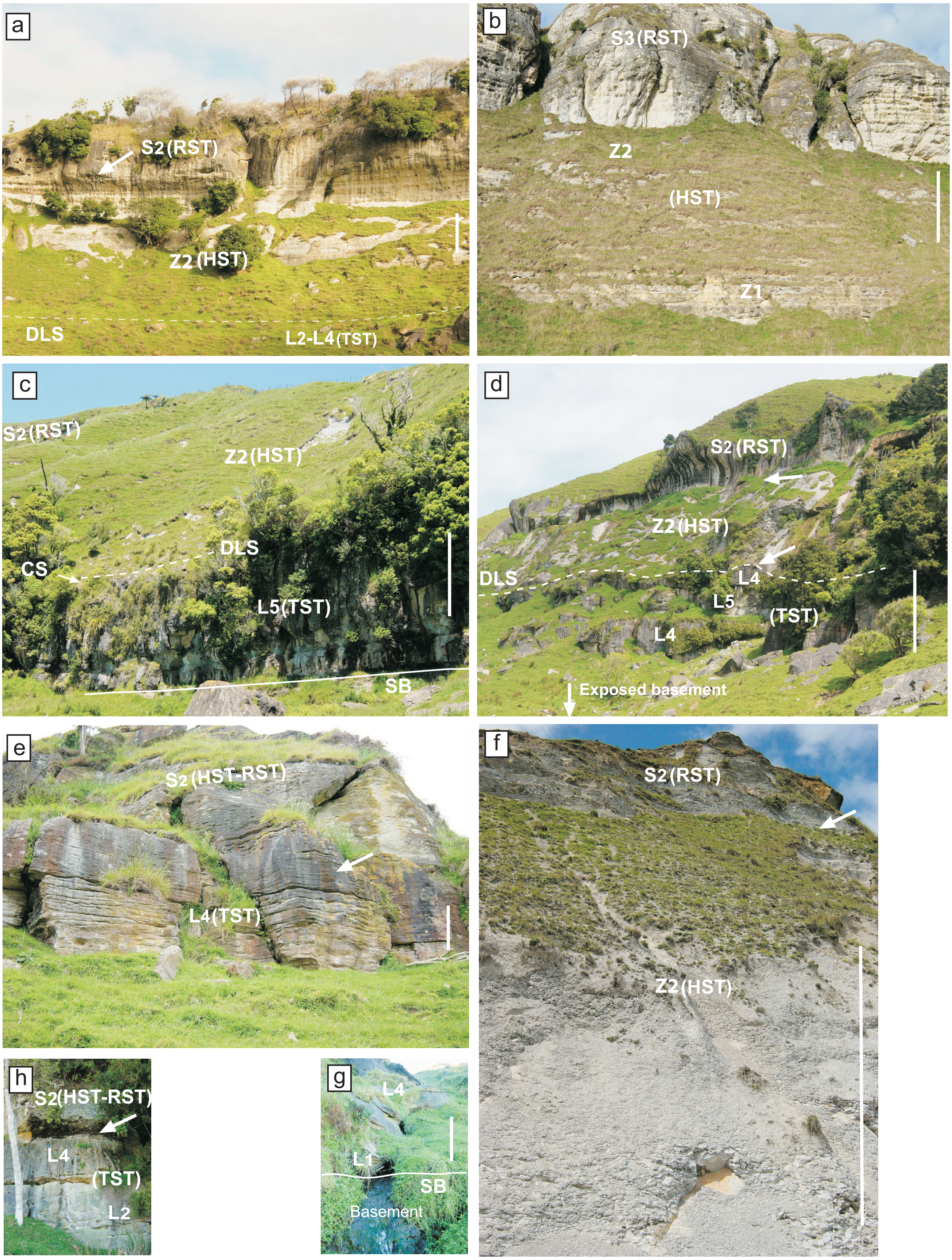
The base of a transgressive systems tract (TST) is bounded by either a sequence boundary or a transgressive surface of erosion (TSE), or by a correlative conformity. The downlap surface bounds the top of a TST. A TST forms during relative sea-level rise when the rate of rise outpaces the rate of sediment accumulation and the shoreline tracks landward. TSTs are recognised from a diagnostic retrogradational (back-stepping) stacking pattern, which results in overall deepening-upwards and commonly fining-upwards profiles.

In the western part of the basin, a well developed TST formed, represented by sequence styles 1-6 (Figs 17 & 19a, c, d & e). Relative sea-level rise during transgression is known to trap siliciclastics along shorelines in back-stepping wedges, essentially starving the offshore inner-mid shelf of terrigenous sediment supply, allowing carbonate sediments to accumulate there (e.g. Gillespie & Nelson 1997). The carbonate facies in the Elgood Limestone facies display broadly similar characteristics to shellbeds in Wanganui Basin cyclothems interpreted as TSTs (Abbott & Carter 1994; Naish & Kamp 1997).

The average $CaCO_3$ content (88%) in the Elgood Limestone Member is highest in the Port Waikato-Raglan region. Terrigenous sediment was evidently not being supplied to this part of the basin in any quantity or it was being bypassed. In stratigraphic sections in the southern part of the basin the proportion of carbonate is about 50 - 85% (Fig. 11) and there was a higher flux of terrigenous sediment.

Compositional analysis of the limestone facies in the Elgood Limestone Member indicates that lower parts are composed of bryozoans, echinoderms, benthic foraminifera (especially *Amphistegina* and *Lepidocyclina*), calcareous algae (commonly large coralline red algal fragments, rhodoliths, and occasionally open algal frameworks), with varying amounts of bivalves (micro-bores infilled with limonite), gastropods and barnacles (Fig. 11). Upper parts are composed of bivalve fragments and planktic foraminifera with a decrease in red algae, benthic foraminifera and echinoderm content compared with lower down in the member (Fig. 12). These compositional trends support an increase in

Fig. 19 (*facing page*): Photographs illustrating facies associations and significant stratigraphic surfaces within Glen Massey sequence along the western margin. (a) A typical facies association starts with limestone lithofacies (L2 and L4) (lower sequence boundary not in view), downlap surface (DLS) marking a sharp but conformable contact with massive calcareous siltstone (lithofacies Z2) that grades upwards into prograding calcareous sandstone (S2), inferred to be a regressive systems tract (RST). Note the occurrence of large-scale trough cross-bedding (pointed by arrow). Bar for scale is 4 m high. Location: Waikawau Stream bridge on Port Waikato-Waikaretu Road (PW-2). (b) Thick (c. 25 m) HST comprising Interbedded calcareous siltstone and sandy limestone (lithofacies Z1) passing into Massive calcareous siltstone (lithofacies Z2), which coarsens upwards into bluff-forming regressive calcareous silty fine sandstone and interbedded siltstone (lithofacies S3). Bar for scale is 10 m high. Location: Bothwell Road (PW-8). (c) Well developed limestone lithofacies (L5) TST capped by Glauconitic silty packstone (lithofacies C3), which passes into Massive calcareous siltstone (lithofacies Z2) suggesting an abrupt increase in water depth. The DLS marks a conformable but abruptly gradational contact. Lithofacies Z2, interpreted as HST, coarsens upward into regressive Calcareous silty fine sandstone (lithofacies S2). Location: Awamarino (C-51). (d) Three members of the Glen Massey Formation/sequence are separated by 'conformable' facies boundaries (pointed by arrows). The TST consists of lower Pebbly grainstone (lithofacies L1) that directly overlies the sequence boundary (shown in photo g), which grades upward into Horizontally bedded grainstone (lithofacies L4) with intervening Moderately to massive bedded grainstone/packstone (lithofacies L5). The end of transgression is marked by an abrupt shift to calcareous siltstone (HST). The HST-RST succession displays a characteristic break in slope indicative of coarsening-upwards and regression (RST). Bar for scale is 5 m long. Location: Shea Road (AK-4). (e) An example of a nearshore position of Glen Massey sequence development where the typical highstand siltstone deposits are missing. This results in an abruptly gradational contact between the transgressive carbonate deposits (lithofacies L4) and undifferentiated highstand-regressive sandstone (lithofacies S2). Location: Waikorea Valley Road (TA-2). Bar for scale is 1 m high. Close-up in photo (h) shows an abrupt aggradation from TST to HST/RST. Hammer for scale. Location: Waikorea (TA-2). (f) Massive highstand calcareous siltstone (lithofacies Z1) grades upward into regressive Calcareous silty fine sandstone (lithofacies S2). This facies contact (pointed by arrow) is probably diachronous, younging in a basinward direction. Bar for scale is 10 m high. Location: Orotangi Cliff (AK-5).


a
S2(RST)
Z2(HST)
DLS
L2-L4(TST)
b
S3(RST)
Z2
(HST)
Z1
c
S2(RST)
Z2(HST)
DLS
CS
L5(TST)
SB
d
S2(RST)
Z2(HST)
DLS
L4
L5
(TST)
L4
Exposed basement
e
S2(HST-RST)
L4(TST)
f
S2(RST)
Z2(HST)
h
S2(HST-RST)
L4
(TST)
L2
g
L4
L1
SB
Basement

water depth up-section within the TST.

The overall thickness of the TST decreases basinwards. In deeper water areas where the DLS almost converges with the sequence boundary, a thin sediment starved TST is represented by a shellbed (lithofacies L2), best exemplified by style 11 (Fig. 17) and/or by a condensed deposit as illustrated in style 14 (Fig. 17). Thin shellbeds representing sediment-starved TSTs in more offshore shelf settings are equivalent to the "compound shellbed" described by Naish & Kamp (1997) in Wanganui Basin Pliocene-Pleistocene cyclothems.

The end of carbonate accumulation at the top of the TST (Elgood Limestone) could have two explanations. One is drowning of the carbonate factory as a result of sea-level rise, thereby cutting off the carbonate supply (e.g. Simone & Carannante 1988). The other option is burial of the carbonate factory and areas of carbonate accumulation through the deposition of siliciclastic siltstone, representing a transition to the HST (Naish & Kamp 1997; Gillespie & Nelson 1997).

Highstand systems tract

A highstand systems tract (HST) forms during the late stage of relative sea-level rise, stillstand, and early fall of sea level (Vail 1987; Posamentier et al. 1988). Consequently, depositional trends and stacking patterns are dominated by a combination of aggradation and progradation (Catuneanu 2006). In the Glen Massey sequence, the base of the HST is marked by a downlap surface overlain by a progradational siltstone and/or sandstone. The HST in the Glen Massey sequence usually comprises 8 - 30 m of massive, sparsely fossiliferous, variably calcareous siltstone (lithofacies Z1 to Z2) (Fig. 19b & f). In a few of the stratigraphic sections (e.g. PW-9, Fig. 9b) along the western basin margin, the highstand siltstone can be thin, as exemplified by architectural style 6 (Fig. 17), or siltstone facies may be absent altogether due to non-deposition (Fig. 19e & h). In these nearshore positions it is difficult to differentiate HST deposits from overlying regressive deposits (cross section B-B', Fig. 9) as both have a sandy texture, emphasising that the HST-RST boundary is a facies transition and not an isochronous surface.

In more basinward locations where significant paleobathymetry had developed at the end of the TST, there is thick development of HST siltstone, as illustrated in architectural style 4 (Figs. 17 & 19b)

Regressive systems tract

The regressive systems tract (RST), as defined by Embry (1995), includes all deposits that accumulated during shoreline regression, which may include the upper part of HST deposits. As originally defined, the RST (Embry 1993; Naish & Kamp 1997) or FSST (Falling Stage Systems Tract) includes regressive deposits that accumulated during the interval of rapid fall in relative sea level, and this is the concept adopted here. The RST is characterised by a progradational stacking pattern formed fundamentally due to a loss of accommodation space. Within the inner to mid-shelf portions of the basin, the RST in the Glen Massey sequence is easily identified by a relatively thick coarsening-upward silty calcareous sandstone facies (lithofacies S2, S3, S4) overlying HST siltstone. The RST displays a gradational contact with the underlying HST marked by a progressive increase in sandstone content over approximately 2-5 m of vertical section (Figs 19a, b, d & 20c). Naish & Kamp (1997) have described similar regressive systems tracts from Pliocene-Pleistocene cyclothems in Wanganui Basin. These are distinguished from forced regressive systems tracts (Hunt & Tucker 1992; Walker & Wiseman 1995), which are defined as having an erosional contact with the underlying HST. This character has not been observed in Glen Massey Formation.

The RST in the Glen Massey sequence is usually thick (up to 100 m), but in rare instances a 1-2 m-thick fossiliferous greensand, representing undifferentiated HST-RST deposits, occurs, for example at the Waitetuna Estuary section (style 12 in Fig. 17). This thin glauconitic sandstone sharply overlies a 5 m-thick variably calcareous sandstone, and is then abruptly overlain by massive calcareous siltstone of the next sequence (Whaingaroa Formation).

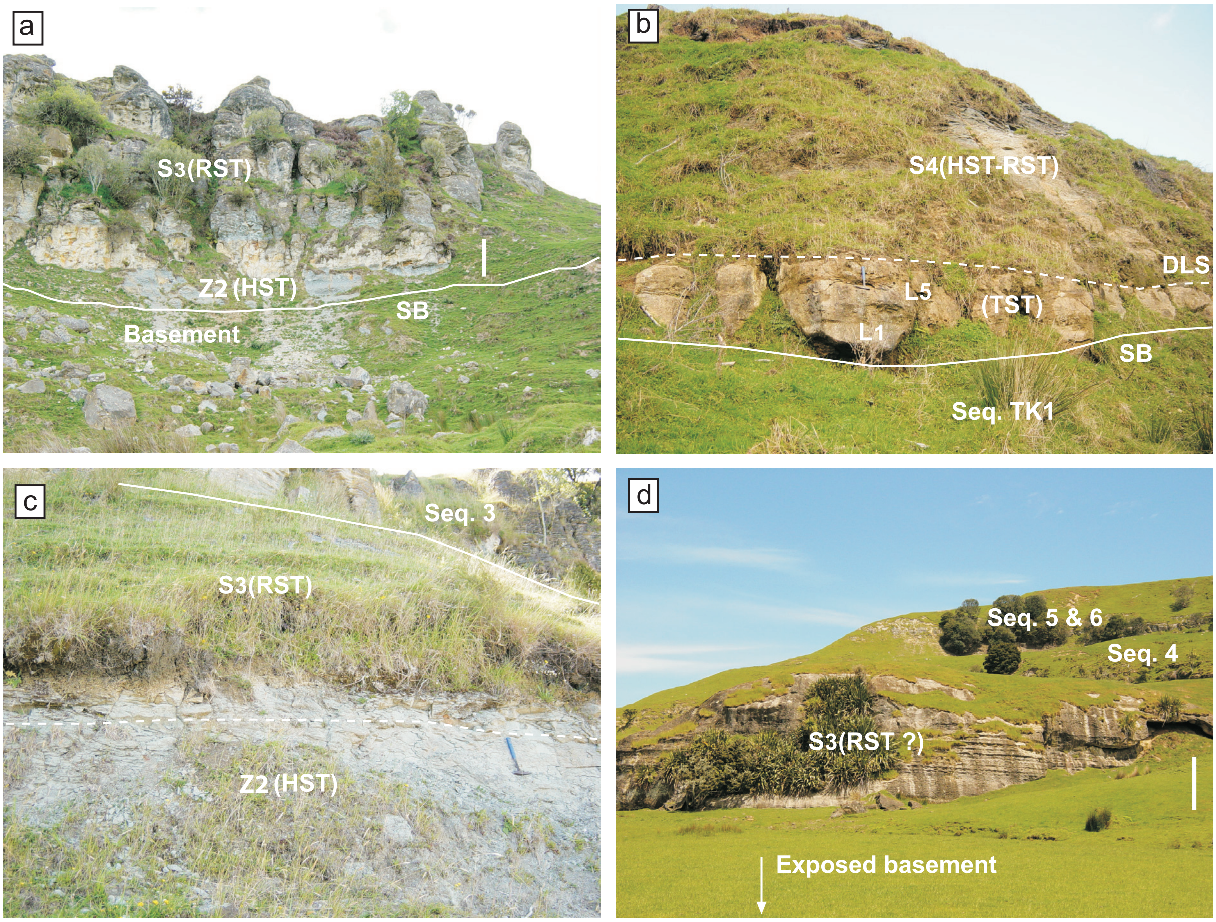


Fig. 20: (a) An outcrop example of the non-development of TST limestone facies in Glen Massey Formation. Calcareous siltstone (lithofacies Z2) typical of the HST directly overlies the sequence boundary. Limestone facies, which are common along the basin margin, are absent at this location probably due to high rates of fine terrigenous influx during transgression. Bar for scale is 2 m long. Location: Te Kotuku Creek (TA-12), north of Raglan Harbour. (b) Photograph illustrates sediment 'starved' Glen Massey sequence that overlies Waikato Coal Measures. The transgressive facies directly overlying the sequence boundary comprises thin pebbly and shelly Moderately glauconitic grainstone (lithofacies L1-L2), which passes into Massive to moderately bedded grainstone-packstone (lithofacies L5). The top of the limestone marks a downlap surface, and is overlain by HST-RST Massive muddy sandstone (lithofacies S4). Thin sequence development may represent a distal position from the sediment supply. Hammer for scale. Location: Ngapaenga (C-68). (c) Outcrop example of a subtle transition between highstand siltstone (lithofacies Z2) and regressive sandstone (lithofacies S3). The dashed line marks the top of the aggradation and the change to progradation. Hammer for scale. Location: Hautapu Hill (C-4). (d) Outcrop example where transgressive and highstand facies cannot be separated. The entire succession is represented by Alternating fine silty sandstone and siltstone (lithofacies S3) typical of RSTs directly overlying the sequence boundary (not visible in photo). Bar for scale is 5 m high. Location: Te Akau (TA-8).

The $CaCO_3$ content in the regressive sandstone (Ahirau Sandstone) ranges from 42 - 58%. The highly burrowed nature of the sandstone and the presence of variable amounts of glauconite suggest slow rates of accumulation. The siliciclastic component was probably sourced from a Murihiku basement ridge exposed to the west, as the thickness of RST sandstone increases in that direction (Fig. 5). The slow rate of RST accumulation suggests a slow rate of relative sea-level fall. This is particularly the case for the areas south of Aotea Harbour where regressive sandstone deposits are poorly developed (Fig. 20b).

The top of the RST at Waikawau Beach is comprised of a thin bed of intensely burrowed, moderately glauconitic and rarely phosphatic nodules (lithofacies C1), which displays the characteristics of a marine firmground/hardground, suggesting a degree of hiatus.

Condensed section

Condensed sections are inferred to be the product of extremely low carbonate and/or siliciclastic sediment accumulation during times of either rapid rise or still-stand of sea-level (Loutit et al. 1988; Amorosi 1995). Condensed facies can often be distinguished from overlying and underlying deposits by high concentrations of glauconite.

Although glauconite is ubiquitously scattered throughout the Glen Massey sequence, specific stratigraphic levels have a high glauconite content, for example at the top of the TST and in the lower parts of HST in western areas, where it can comprise up to 15% of bed composition, and in thin TST deposits on sediment-starved portions of the offshore shelf.

The Waikoha Road (Fig. 16c) and Awamarino sections (style 4, Fig. 17) are good examples where the top of the TST is marked by firmground development with a high concentration of authigenic glauconite and pyrite mineralisation. These beds are intensely burrowed and highly fossiliferous and are interpreted to correspond to periods of very low sedimentation or even non-deposition during rapid relative sea-level rise to maximum water depth (e.g. Van Wagoner et al. 1988). The lack of clastic input allows glauconite formation and concentration, intense sea-floor burrowing and increased cohesiveness of the substrate (e.g. Ghibaudo et al. 1996). In drill holes 9151 and 1773 near Maramarua (style 14, Fig. 17), glauconite-rich thin TST development (C2, C3) reflects sediment starvation in the more offshore shelf to upper bathyal setting.

In condensed sections observed in Glen Massey sequence, glauconite occurs as pellets and infills and includes both autochthonous and allochthonous (detrital) types, and is typically associated with pyrite grains, abundant fossils, and intense burrowing. Variable amounts of glauconite are also generally present at the sequence boundary, marking the base of the overlying TST, illustrated in architectural styles 7 and 8 (Fig. 17). This may be attributed to the remobilisation of glauconite in shallow-marine settings by wave action and currents during storms (e.g. Amorosi 1995).

A model Glen Massey sequence

Despite good local continuity of outcrop section, it is not possible within the Glen Massey sequence to trace facies changes laterally from nearshore to offshore parts of the paleoshelf because the more basinward parts have mostly been eroded through post-depositional uplift and erosion. Cross-sections constructed using outcrop and drillhole data showing the distribution of the main facies and systems tracts are illustrated in Fig. 9a-e. Fourteen distinctive 'styles' of Glen Massey sequence architecture are depicted in Fig. 17. These illustrate the architecture at different positions across the paleoshelf. Analysis of all of the fourteen styles shows that broadly similar facies recur up-section. By integrating the characteristics of all fourteen 'styles', an idealised sequence stratigraphic model has been developed that provides a simplified two-dimensional representation of the key surfaces and systems tracts (Fig. 21).

The model illustrates an idealised depositional profile from basin margin to deeper parts of the basin, all probably of shelf to upper bathyal depth. In the more landward positions, the vertical facies succession includes shelfal bioclastic limestone (TST) overlain by thin marine calcareous siltstone (HST), passing up into variably calcareous fine sandstone and silty sandstone (RST), represented by hypothetical column location 1 in Fig. 21a. In middle shelf positions, the vertical succession includes relatively thick, variably sandy-silty limestone (TST), overlain by coarsening-upward siliciclastic sandstone (HST-RST), represented by hypothetical column 2 in Fig. 21a. In more distal portions of the shelf represented by hypothetical column 3, the limestone facies (TST) are capped by a condensed section, overlain by thick highstand siltstone and relatively thin regressive sandstone. In the more basinward locations represented by hypothetical column 4 (Fig. 21a), the vertical facies succession is dominated by variably calcareous glauconite-rich sandstone and siltstone representing stratigraphic condensation.

Fig. 21b illustrates the position and timing of the key sequence stratigraphic surfaces and systems tracts in relation to a relative sea-level curve. A hypothetical chronostratigraphic panel in Fig. 21c depicts the lateral changes in the facies pattern across the paleoshelf through accumulation of the sequence. This emphasises how different depositional processes occurred at different points in time. Note that sediment starvation reached it's most landward position at nearly the maximum time of relative sea-level rise (t4, green area in Fig. 21c), however sediment starvation in

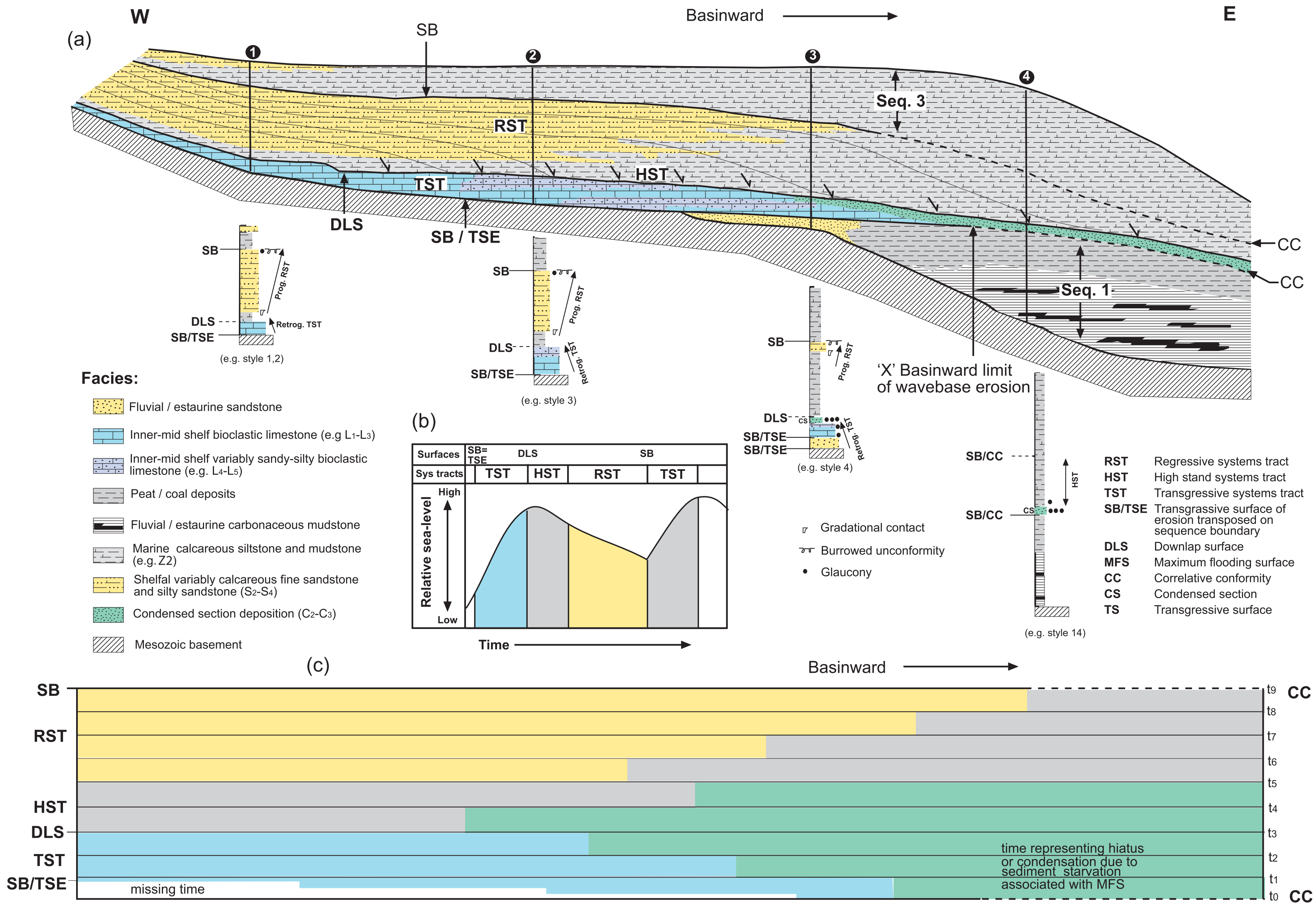


Fig. 21: (a) Shelf-normal section through the Glen Massey sequence in the northern region, drawn to depict the distribution of inner shelf to upper bathyal facies of the Glen Massey Formation. The section represents a distance of approximately 35 km. (b) Key surfaces and systems tracts associated with a theoretical relative sea-level curve. (c) A hypothetical chronostratigraphic diagram showing the time (t0-t9) represented by the systems tracts, condensed sections and maximum flooding surface.

more basinward areas continued for longer than in more landward areas of the shelf.

Summary

Analysis of closely spaced and detailed measured outcrop sections has led to the identification of fourteen lithofacies that can be grouped into four lithofacies associations. The associations are named Limestone, Mixed carbonate-siliciclastic sandstone, Mixed carbonate-siliciclastic siltstone and Chemogenic, after their dominant lithology. The Limestone lithofacies comprise skeletal-rich grainstone-packstone that accumulated close to a shoreline along the western margin of the basin, as well as upon isolated basement paleo-highs. These carbonate-rich lithofacies typically pass upwards into mainly Mixed carbonate-siliciclastic siltstone lithofacies, which form the bulk of the Glen Massey Formation thickness towards the east and northeast, and in southern parts of the basin. The Mixed carbonate-siliciclastic siltstone lithofacies grade and coarsen upward into sandstone lithofacies, which form bluffs especially in the western and northwestern parts of the basin. The chemogenic lithofacies are least common and are mostly restricted to more offshore parts of the paleo-shelf.

A Vail-type Glen Massey sequence has a basal unconformable sequence boundary formed by wave planation (transgressive surface of erosion) or a correlative conformity; a variably thick (<1-30 m) transgressive systems tract (TST) composed of limestone (lithofacies L1-L5); a maximum flooding surface (MFS) closely associated with a downlap surface (DLS); a highstand systems tract (HST) 1-40 m thick that typically constitutes an aggradational interval of calcareous siltstone (lithofacies Z2); and upward gradation of the Z2 siltstone into a regressive systems tract (RST) from 2-80 m thick dominated by progradational calcareous silty sandstone (lithofacies S2-S4).

Fourteen distinctive 'styles' illustrating the architecture of Glen Massey sequence across the paleoshelf have been identified. By integrating the characteristics of all fourteen 'styles', an idealised sequence stratigraphic model has been developed that provides a simplified two-dimensional representation of the key sequence stratigraphic surfaces and systems tracts in the Glen Massey Formation. While these 'styles' share similar characteristics and show broadly similar facies changes upsection, they result from a unique interplay of relative sea-level change, sedimentation rate, and position on the shelf profile.

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