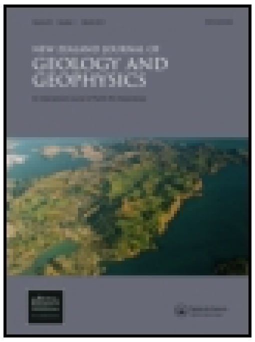


Taylor & Francis
Taylor & Francis Group

New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzg20

Stratigraphy of the Castlecliffian type section: 10 mid-Pleistocene sequences from the Wanganui coast, New Zealand

S. T. Abbott & R. M. Carter

New Zealand Journal of Geology & Geophysics, 1999, Vol. 42: 91–111
0028–8306/4201–0091 $7.00/0

Stratigraphy of the Castlecliffian type section: 10 mid-Pleistocene sequences from the Wanganui coast, New Zealand

S. T. ABBOTT
R. M. CARTER
School of Earth Sciences
James Cook University
Townsville, Queensland 4811
Australia

email: steve.abbott@jcn.edu.au
bob.carter@jcu.edu.au

Abstract The 160 m thick Castlecliff coast section was deposited during the middle Pleistocene (c. 1.07–0.35 Ma) and comprises 10 disconformity-bound cyclothems or sequences. A typical sequence has three parts: (1) a basal suite of shoreface and inner shelf sediments with intertidal and shallow subtidal molluscan faunas, and cross-bedded, pebbly shell gravels (type A shellbeds); (2) a mid-cycle shellbed, which contains *in situ* offshore molluscs in a matrix of muddy fine sandstone or fine sandy siltstone (type B shellbeds); and (3) an upper unit of terrigenous siltstone, either bedded and barren of fossils, or bioturbated and with a sparsely scattered *in situ* fauna similar to that of the subjacent shellbed. The three parts of each sequence correspond respectively to the transgressive systems tract, mid-cycle shellbed, and highstand systems tract of the sequence stratigraphic model. Sequence 7 (Kupe Formation, Upper Kai-Iwi Shellbed, Upper Kai-Iwi Siltstone) is designated as the type example of the **Castlecliff motif**. A detailed measured section is presented of the Castlecliff section, with 30 formations designated which correspond to the most significant lithostratigraphic units and to the inferred systems tract interpretation. Where possible, the formational nomenclature follows that of Fleming (21 formations, six with adjusted boundaries). However, three formations represent newly observed units (**Mowhanau Formation, Lower Kai-Iwi Shellbed, Lower Castlecliff Siltstone**), and seven other formations are erected on the basis of previously described beds, members or informal units (**Rolled Concretion Conglomerate, *Tiostrea-Dosina* Bed, *Ophiomorpha* Sand, Lower Westmere Shellbed, Kaikokopu Formation, Upper Westmere Shellbed, Upper Kai-Iwi Shellbed**). The lithofacies and macrofaunal and microfaunal associations are documented across the section in terms of this lithostratigraphic framework.

Keywords Pleistocene; Wanganui Basin; sequence; cyclothem; sea level; new stratigraphic names

G97048
Received 16 July 1997; accepted 21 September 1998

INTRODUCTION

The little deformed and richly fossiliferous mid-Pleistocene sediments of the Wanganui coast section (Fig. 1, 2) have been renowned since the start of European settlement in New Zealand. For instance, exquisitely preserved molluscs from Wanganui feature amongst the earliest illustrations of invertebrate fossils from New Zealand (Mantell 1850) and in the more comprehensive catalogue of Tertiary Mollusca prepared by Hutton (1873). The coastal section assumed even more importance after Thomson (1916) nominated it as the type section for the New Zealand Castlecliffian Stage and with Fleming's (1947, 1953) detailed description of its geology and fossil faunas. The descriptive lithological units used by these previous workers are summarised in Tables 1 and 2.

In a remarkable analysis, based primarily on the repetitive vertical variation of fossil content, Fleming (1953) demonstrated that the Castlecliff sediments were deposited under the influence of both tectonics and eustatic sea-level variation, recognising that "the (Pleistocene) cyclothems are typically separated by disconformities representing periods when the sea advanced and carved wave-cut platforms". Fleming's work, together with that of Emiliani (1955), and similarly ignored by the wider geological community at the time, showed that Earth's most recent climatic history had involved a multiplicity of glacial and interglacial episodes which far exceeded in number the four climatic cycles then recognised by Quaternary geologists studying continental deposits. With the confirmation of Emiliani's work by Shackleton & Opdyke (1973), the international research community finally came to accept the reality of multiple Pliocene-Pleistocene glaciations, thus allowing Beu & Edwards (1984) to correlate the Wanganui section to the international oxygen isotope scale. Most recently, Abbott et al. (1989) and Abbott & Carter (1994) have interpreted the Castlecliff section in terms of sequence stratigraphy, and deciphered the cyclothemic motif which marks each sea-level rise and fall.

By the early 1990s the Castlecliff coastal section was firmly established as one of the world's outstanding examples of the interplay between eustasy, tectonics and sedimentation, as a Southern Hemisphere reference section for the middle Pleistocene, and as a potential international stratotype for the Lower–Middle Pleistocene boundary (Pillans et al. 1991, 1994). To aid further study of the Castlecliff section, we present annotated photographs of some parts of the coast (see Fig. 3), the detailed measured section of Abbott (1994) (see Fig. 4), and summaries of the sedimentary facies and fossil assemblages (see Table 3, Fig. 5–8). We also take the opportunity here to adjust some details of the formal lithostratigraphic nomenclature to fit better with modern interpretations (cf. Table 2). The paper includes modified versions of a small number of diagrams

Table 1 Historical summary of the lithostratigraphic nomenclature applied to sedimentary units of the Castlecliff coastal section.

Hochstetter 1864 Buchanan 1870 Hutton 1873	Hutton 1886	Park 1887, 1905	Fleming 1947		Fleming 1953 Groups	Fleming 1953 Formations
Upper Wanganui Beds ("Pleistocene")	*Wanganui System (Upper Wanganui Beds)*	Wanganui Beds	CU-8	Estuarine Sands	Shakespeare	Mosstown Sand
			CU-7	Tawera Silts		Karaka Siltstone
			CU-6	Upper Castlecliff Shellbed		Upper Castlecliff Shellbed
		Sandy Beds	CU-5	Zethalia-Amphidesma Sands		Shakespeare Cliff Sand
Wanganui Series ("Pliocene")	Shakespeare Cliff Blue Clay	Shakespeare Cliff Blue Clay	CU-4	Stiracolpus Silts		Shakespeare Cliff Siltstone
	Wanganui System (Wanganui Series)		CU-3	Tainui Shellbed		Tainui Shellbed
			CU-2	Antisolarium Sands		Pinnacle Sand
			CU-2	Antisolarium Sands (basal shellbed)		Lower Castlecliff Shellbed
			CU-1	Basal Upper Castlecliff Sands		Seafield Sand
		Kai-iwi Blue Clays	CL-11	Upper Kai-iwi Blue Silts	Kai-iwi	Upper Kai-iwi Siltstone
			CL-10	Kupe Formation		Kupe Formation
			CL-9	Upper Westmere Silts		Upper Westmere Siltstone
			CL-8	Lower Westmere Silts		Lower Westmere Siltstone
			CL-7	Buccinulum caudatum Shellbed		Omapu Shellbed
			CL-6	Lower Kai-iwi Blue Siltstone		Lower Kai-iwi Siltstone
	Kaimatera beds	Kaimatera Beds	CL-5	Mowhanau Pumice Sands		Kaimatira Pumice Sand
		Okehu Beds, No. 5	CL-4	Upper Okehu Silts	Okehu	Upper Okehu Siltstone
		Okehu Beds, No. 6	CL-3	Okehu Shell Grit		Okehu Shell Grit
		Okehu Beds, No. 7	CL-2	Lower Okehu Siltstone		Lower Okehu Siltstone
		Okehu Beds, No. 8	CL-1	Ototoka Shell Conglomerate		Butlers Shell Conglomerate

first published elsewhere, so that it may serve as a stand-alone descriptive reference for the Castlecliff section.

HISTORY OF STRATIGRAPHIC SUBDIVISION

Mantell (1848), Hochstetter (1864), Buchanan (1870), Hutton (1873), and Park (1887, 1905) variously used the term Wanganui Beds, Series, Formation or System to describe the "fossiliferous blue-clays" which crop out along the Castlecliff coast. Hutton (1886) distinguished a conspicuously tuffaceous sand towards the base of the succession as the Kaimatera (sic) Beds, and Park (1887) recognised the Okehu, Kai-Iwi, and Wanganui Beds as subdivisions of his Wanganui Series. However, it was not until publication of the results of stratigraphic investigations by the New Zealand Geological Survey (Fleming 1947, 1953) that a proper lithostratigraphic framework was provided for detailed sedimentologic and faunal studies (cf. Table 1). In parallel studies, Thomson (1916), Fleming (1947, 1953), and Finlay & Marwick (1947) described the biostratigraphy of the Castlecliffian Stage, for which the coastal section at Wanganui was designated the type section.

RELATIONSHIP BETWEEN LITHOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY

Abbott & Carter (1994) showed that the coastal Castlecliff section comprised 10 discrete sequences. Eight sequences are characterised by three lithological subdivisions punctuated by three intra-cycle surfaces (Fig. 4), in descending order:

(6) a massive and fossiliferous, or bedded and unfossiliferous, sandy siltstone (highstand systems tract)

(5) an abruptly gradational contact (downlap surface)

(4) an *in situ* (type B) shellbed, indicative of terrigenous sediment starvation (mid-cycle condensed shellbed)

(3) an abrupt, often burrowed or bioturbated surface of deepening (local flooding surface)

(2) an interval of current-deposited, shallow marine sediment including reworked (type A) shellbeds, well sorted sand, and heterolithic sandstone and mudstone (transgressive systems tract)

(1) a basal marine-cut surface of erosion (ravinement surface, superposed upon the sequence boundary).

A ninth sequence (cycle 1) is top-truncated and comprises a sequence boundary and overlying transgressive systems tract only (=Butlers Shell Conglomerate and Ototoka Siltstone). The tenth sequence (cycle 4) contains an additional element at its top (the Omapu Shellbed of Fleming 1953), which probably indicates shallowing.

We here nominate cycle 7 (as described below, and in Fig. 4, 6) as the type example of the **Castlecliff motif** sequence, the major elements of which can be recognised in all 10 Castlecliff sequences. The relative thinness of the Castlecliff sequences which display this motif, compared with their equivalents in the basin axis, indicates that they were deposited in a low-subsidence region on the western margin of the basin.

The systems tracts recognised at Castlecliff by Abbott & Carter (1994) correspond closely to the conventional lithostratigraphic units (mostly formations, members and beds) introduced by Fleming (1953). Given the occurrence of eight three-part sequences, one two-part sequence, and one four-part sequence, a total of 30 stratigraphic units are required to describe the Castlecliff section fully (Table 2), as follows:

15 units formations recognised by Fleming (1953)

6 units formations redefined slightly from Fleming (1953)

6 units formations recognised as beds, members, or informal units by Fleming (1953)

3 units formations introduced by Abbott & Carter (1994).

An increasing number of new datasets are being collected for the Castlecliff section, for example, magnetostratigraphy (Turner & Kamp 1990), oxygen isotope stratigraphy (L. Mitchell unpubl. data), and beryllium isotope stratigraphy (Graham et al. 1998). For ease of comparison and correlation,

Table 2 Detailed lithostratigraphic subdivision of the Castlecliff coastal section after Fleming (1953), and as modified in this paper.

Fleming (1953, 1955)		This Paper		
			Abbott & Carter (1994)	
FORMATION	MEMBER or INFORMAL UNIT	Code	FORMATION	Status
Karaka Siltstone		10.3	Karaka Siltstone	U
	Tawera lenticles			
Upper Castlecliff Shellbed		10.2	Upper Castlecliff Shellbed	U
Shakespeare Cliff Sand*		10.1	Shakespeare Cliff Sand	U
	Basal shellbed (Amphidesma -rich)			
Shakespeare Cliff Siltstone *		9.3	Shakespeare Cliff Siltstone	U
Tainui Shellbed		9.2	Tainui Shellbed	U
Pinnacle Sand		9.1	Pinnacle Sand	U
(unrecognised by CAF)		8.3	Lower Castlecliff Siltstone	NU, NN
Lower Castlecliff Shellbed		8.2	Lower Castlecliff Shellbed	U
Seafield Sand		8.1	Seafield Sand	U
	Toms Conglomerate**			
Upper Kai-Iwi Siltstone		7.3	Upper Kai-Iwi Siltstone	U
Kupe Formation	Pecten layer			
	Pelecypod shellbed member	7.2	Upper Kai-Iwi Shellbed	NN, UP
	Mactra tristis layer			
	Gastropod shellbed member	7.1	Kupe Formation	TBA
	Cross-bedded sand member			
Upper Westmere Siltstone		6.3	Upper Westmere Siltstone	BBA
	Fossiliferous siltstone member	6.2	Upper Westmere Shellbed	NN, UP
			Kaikokopu Formation	TBA, UP
	Kaikokopu Shell Grit***	6.1		
Lower Westmere Siltstone		5.3	Lower Westmere Siltstone	BBA
	Fossiliferous silt member	5.2	Lower Westmere Shellbed	NN, UP
	Fossiliferous free sand member	5.1	Ophiomorpha Sand	NN, UP
Omapu Shellbed		4.4	Omapu Shellbed	U
Lower Kai-Iwi Siltstone		4.3	Lower Kai-Iwi Siltstone	BBA
(unrecognised by CAF)		4.2	Lower Kai-Iwi Shellbed	NU, NN
Kaimatira Pumice Sand****	Units a-c	4.1	Kaimatira Pumice Sand	U
Upper Okehu Siltstone		3.3	Upper Okehu Siltstone	BBA
	Basal fossiliferous conglomerate	3.2	Tiostrea-Dosina Bed	NN, UP
Okehu Shell Grit		3.1	Okehu Shell Grit	U
Lower Okehu Siltstone		2.3	Lower Okehu Siltstone	BBA
	Rolled Concretion Conglomerate	2.2	Rolled Concretion Conglomerate	NN, UP
(unrecognised by CAF)		2.1	Mowhanau Formation	NU, NN
Butlers Shell Conglomerate	Ototoka Siltstone tongue	1.1b	Ototoka Siltstone	U
	Conglomerate member	1.1a	Butlers Shell Conglomerate	U

Key for status column, with respect to Fleming (1953): U = unchanged; BBA = bottom boundary adjusted; TBA = top boundary adjusted; NU = new unit; NN; = new name; UP = upgraded to formation status.
*Unit described from Shakespeare Cliff, Wanganui City by Fleming (1953); ** Unit described from the Rangitikei Valley by Te Punga (1952); *** Unit described from Kaikokopu Road by Fleming (1953); ****Unit described from Kaimatira Bluff, Wanganui City by Fleming (1953).

it is important that such datasets are referred to a common stratigraphic column. We present such a reference column in Fig. 4, and discuss below the redefined terms and new units which are necessary to completely describe the section in formational lithostratigraphic terms. The other 20 lithostratigraphic units, 5 of which have adjusted lower boundaries, are otherwise essentially unchanged from the definitions of Fleming (1953).

Though Fleming (1953) mostly used groups (the Okehu, Kai-Iwi, and Shakespeare Cliff Groups) for his mapping of the Wanganui Subdivision, he showed that, despite poor outcrop, many constituent formations could also be recognised inland. Subsequently, Abbott (1992, 1994) demonstrated that both the sequences and the individual formations of the Kai-Iwi Group (oxygen isotope stages 25–17) can be traced 50 km across the basin as far as the

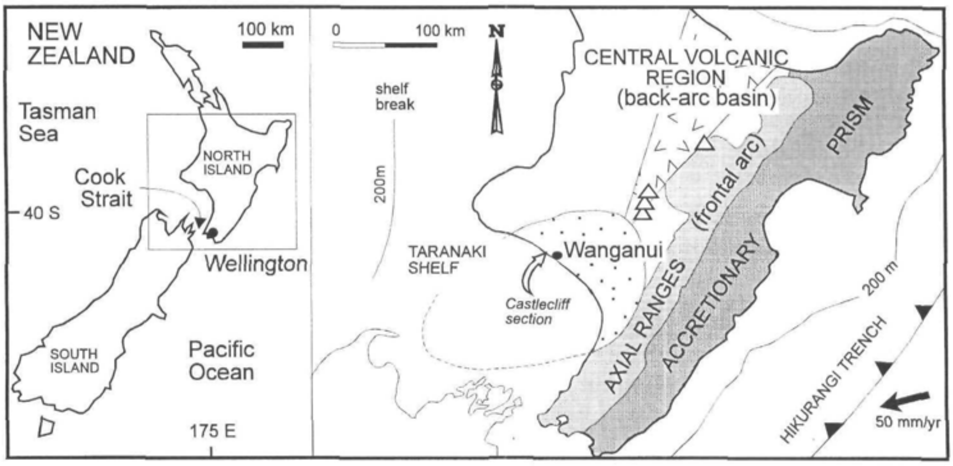


Fig. 1 Locality map of Wanganui Basin, showing the *tectonic setting and the location of* the Castlecliff coastal section.

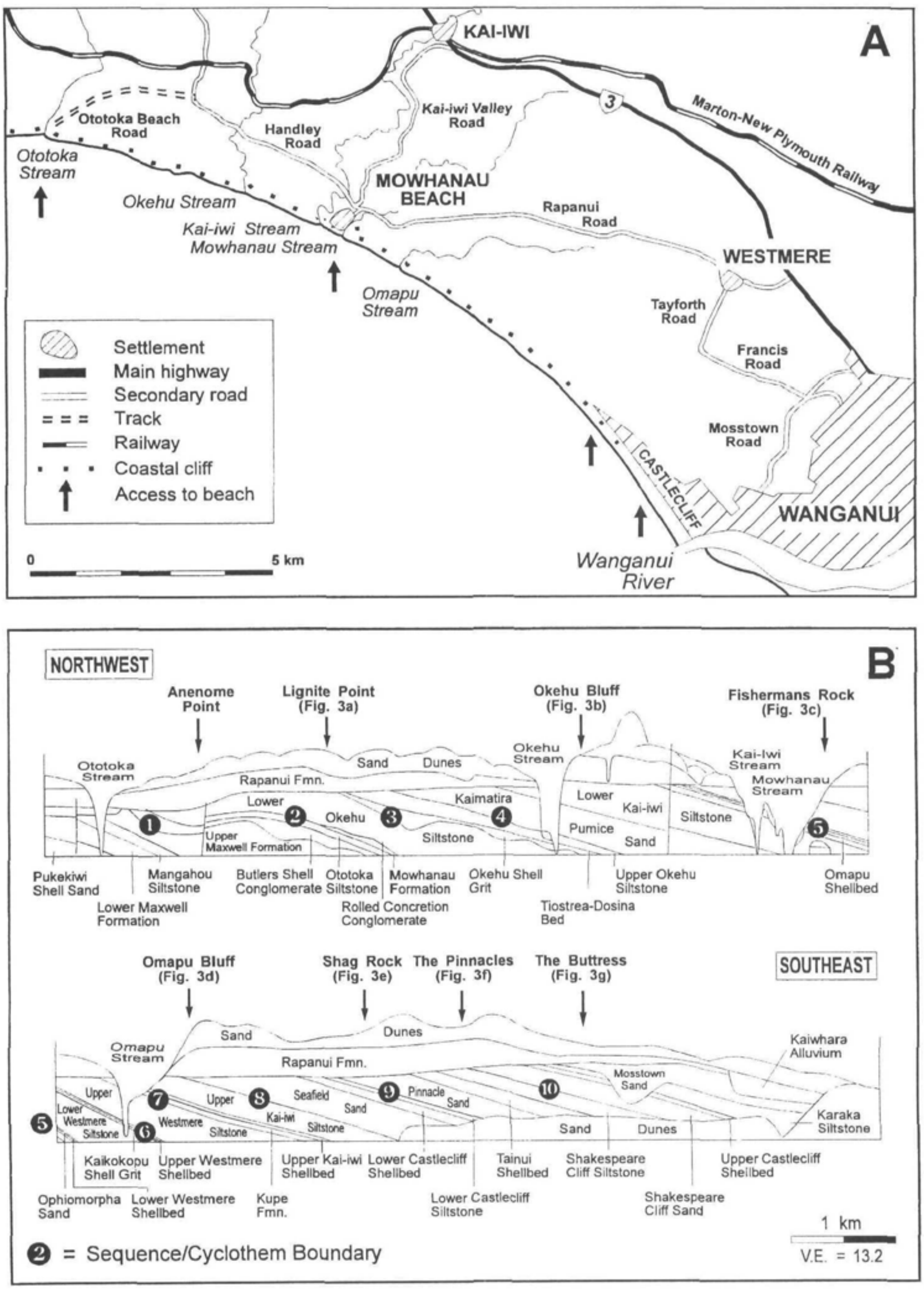


Fig. 2 **A**, Sketch map of access to the Castlecliff section. **B**, Cross-section along the Castlecliff coastal section from northwest (left) to southeast (right) (after Fleming 1953), with locations indicated for the coast photographs reproduced in Fig. 3.

Table 3 Sedimentary facies represented in the Castlecliff coast succession. The preliminary sedimentary facies scheme used by Abbott & Carter (1994) is shown for ease of comparison with the scheme of Abbbott (1994), which is followed here.

FACIES		A&C 1994	DESCRIPTION	TYPICAL UNIT	INTERPRETATION
(Massive) SILTSTONES	MZ-2	Zm-2	Massive siltstone, barren to sparsely fossiliferous	Shakespeare Cliff Siltstone	Inner to middle shelf
	MZ-1	Zm-1	Massive, fine-sandy siltstone; sparsely fossiliferous	Lower Kai-Iwi Siltstone (lower)	Inner to middle shelf
(Laminated)	BZ-2	Zl-2	Cm-dm-interbedded, streaky laminated & bioturbated siltstone; rare fossils	Lower Westmere Siltstone (upper	Inner shelf
	BZ-1	Zl-1	Massive, fine-sandy siltstone with thin streaky laminated zones; some fossils	Lower Westmere Siltstone (lower)	Inner shelf
CONDENSED SHELLBEDS	#CS-5	Sz-6	Parallel-bedded shell conglomerate; muddy sand matrix	Kupe Formation	Palimpsest; innermost shelf
	#CS-4	Zm-3	Tiostrea-Chlamys bands, clumps and scattered shells, in bioturbated siltstone	Tainui Shellbed	Starved inner shelf
	CS-3	Sz-5	Clumps, bands and abundant, scattered shells in gritty, sandy siltstone	Lower Castlecliff Shellbed (upper)	Starved inner shelf
	#CS-2	Sz-4	Close-packed shells in a very gritty, silty sandstone	Lower Castlecliff Shellbed (lower)	Starved inner shelf
	#CS-1	Sz-3	Disarticulated, obliquely aligned shells in bioturbated, gritty fine sand	Lower Westmere Shellbed	Starved inner shelf
HETEROLITHIC	HE-3	He-3	Small-scale heterolithic facies dominated by fine sand to coarse silt; parallel or ripple cross laminated, with flaser bedding	Kaimatira Pumice Sand (upper)	Tide/storm dominated, muddy, innnermost shelf
	HE-2	He-2	Small-scale heterolithic facies dominated by mud; streaky-laminated, lenticular-bedded and massive siltstone; rare fossils	Kaimatira Pumice Sand (lower)	Tide/storm dominated, muddy, innnermost shelf
	*HE-1	He-1	Metre-scale cross-bedded shell-pebble conglomerate with coarse sand matrix and mud drapes. Sets divided into foreset, bottomset and swale subfacies	Butlers Shell Conglomerate	Tide/storm dominated, muddy, innnermost shelf
(Silty)	ZS-2	Sz-2	Massive silty fine sandstone with abundant scattered fossils	Omapu Shellbed	Shoreface-shelf transition
	ZS-1	Sz-1	Massive bioturbated muddy fine sandstone scattered shells in small lags	Pinnacle Sand (lower)	Lower shoreface
SANDSTONES	WS-3	Sw-3	Intensely burrowed and bioturbated, shelly, slightly silty fine sand	Shakespeare Cliff Sand (middle)	Wave-dominated shoreface
(Well sorted)	WS-2	Sw-2	Parallel-laminated, trough cross-bedded, shelly, well-sorted fine sand	Shakespeare Cliff Sand (upper)	Wave-dominated shoreface
	*WS-1	Sw-1	As for HE-1, but no mud-drapes or pebbles	Shakespeare Cliff Sand (lower)	Tide/storm dominated, innermost shelf

*Type A shellbed facies (base of cycle); #Type B shellbed facies (mid-cycle).

Rangitikei River. Most recently, Carter et al. (1996) and Saul et al. (1999) have traced the Pliocene-Pleistocene sequences which represent oxygen isotope stages 100–11 a similar distance from the axis to the western flank of the Wanganui Basin.

SYSTEMATIC LITHOSTRATIGRAPHY

The Castlecliff mid-Pleistocene coastal succession contains 10 sedimentary sequences, which we subdivide into 30 formations, as described below and summarised in Table 2. All formations recognised are mappable, at least in a local sense, and each is chosen to correspond also to an inferred systems tract or mid-cycle shellbed. Inspection of Table 2 shows that some formations correspond exactly to original formations of Fleming (1953) (e.g., the Pinnacle Sand), and that other formations are equivalent to, but upgraded from, informal or member units of Fleming (e.g., the *Ophiomorpha* Sand). A few of the newly systematised formations contain minor lithological subdivisions named by Fleming, but which we interpret as variations within a systems tract (e.g., the Cross-bedded Sand and Gastropod Shellbed Members within the Kupe Formation). Such member names have been left standing.

Classifications of the sedimentary facies, and of the microfaunal and macrofaunal assemblages which occur in the section, are presented in Tables 2 and 3, and Fig. 4–8. Figure 4—a detailed measured section for the Wanganui coastal succession—summarises the available data, expanded detail for which is contained in Fig. 5–8 and Table 3. Figures 5–8 and Table 3 therefore act as a key for the shorthand terms for sedimentary facies and faunal assemblages which are used on Fig. 4 and throughout the text. Also, the sedimentary facies scheme adopted by Abbott (1994), and followed here (Table 3), is changed in some details from the preliminary scheme used by Abbott & Carter (1994). Detailed accounts of the sequence stratigraphy, sedimentology, macrofauna, and microfauna are given by Abbott (1997a, b; 1998) and Abbott & Carter (1997). A full historical discussion of the lithostratigraphy, including formation synonymies, is presented by Fleming (1947, 1953, 1955) and is therefore not repeated here. The cited grid references represent the locations of outcrop of the base of each unit.

Sequence 1

1.1a Butlers Shell Conglomerate (amended after Park 1887)

Type locality, mouth of Ototoka Stream, Castlecliff coast section (Fleming 1953, p. 171). Grid reference R22/667473. Thickness, 0.1–12 m. Sedimentary facies HE-1 (type), macrofossil assemblages Ma-6 (penetrating the basal unconformity), Ma-2 and Ma-7; microfossil assemblage Fo-B.

Cross-bedded worn-shell and pebble gravel, with foreset mud drapes, and inter-dune swales filled with laminated (cm-bedded) siltstone.

Interpreted as a type A shellbed, and the lower transgressive systems tract of cycle 1, by Abbott & Carter (1994).

1.1b Ototoka Siltstone (amended after Fleming 1953, p. 176)

Type locality, Castlecliff coast section southeast of Ototoka Stream mouth. Grid reference R22/688465. Treated by Fleming (1955) as a member of the Butlers Shell Conglomerate, and upgraded here to a formation. Thickness, up to 8.0 m. Sedimentary facies HE-2 and HE-3. Generally barren of fossils, apart from microfossil assemblages Fo-C (lower part) and Fo-F (upper part).

Lenticular-bedded, flaser-bedded, and streaky-laminated sandstone and siltstone with rare scattered pebbles, burrows, and rare fossils. Similar to the swale facies within the Butlers Shell Conglomerate, with which the Ototoka Siltstone interdigitates laterally and vertically.

Interpreted by Abbott & Carter (1994) as the upper part of the transgressive systems tract of cycle 1. Alternatively, the Ototoka Siltstone could represent a thin highstand systems tract, but the facies present, their interdigitation with the Butlers Shell Conglomerate, and the apparent absence of a mid-cycle shellbed or condensed section at its base, all militate against this.

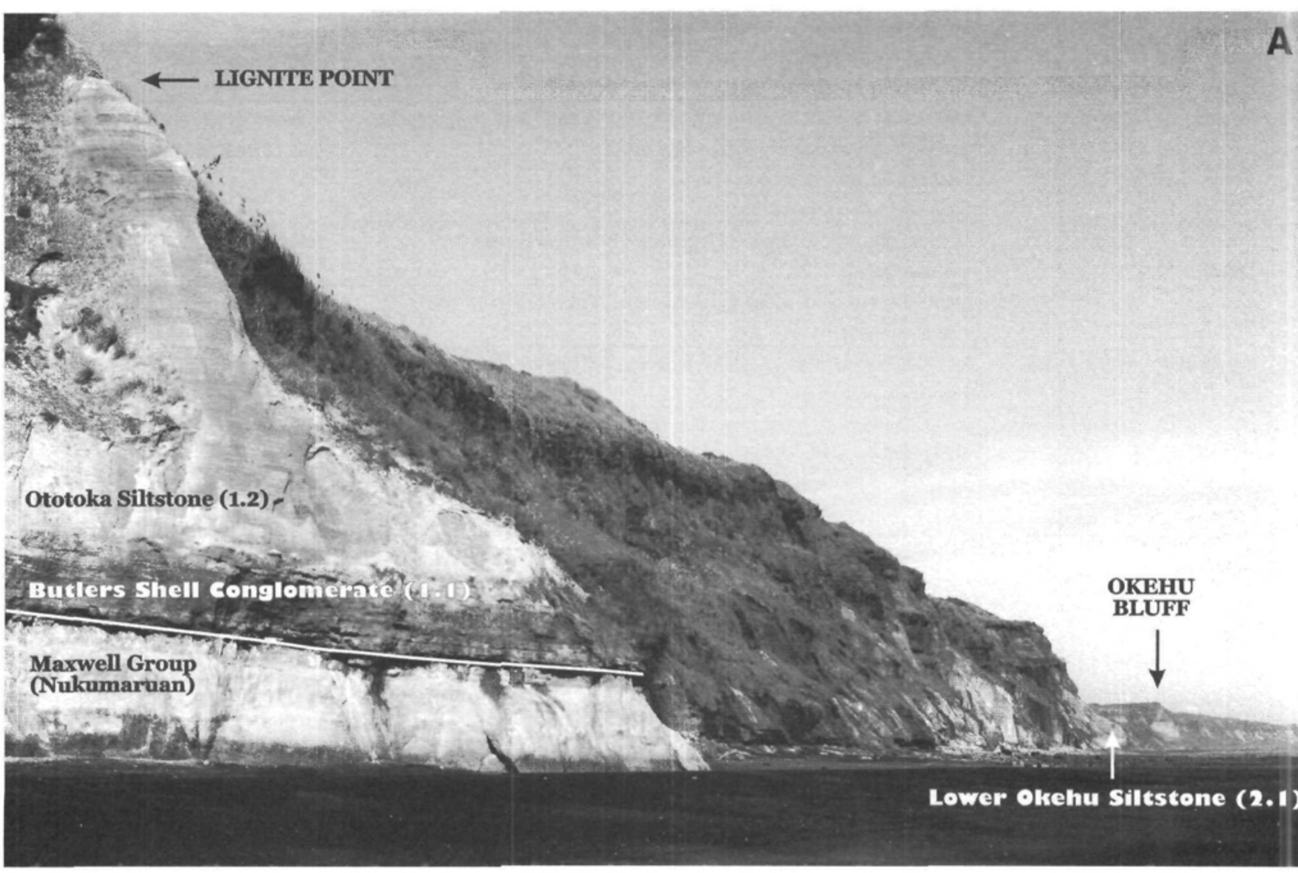
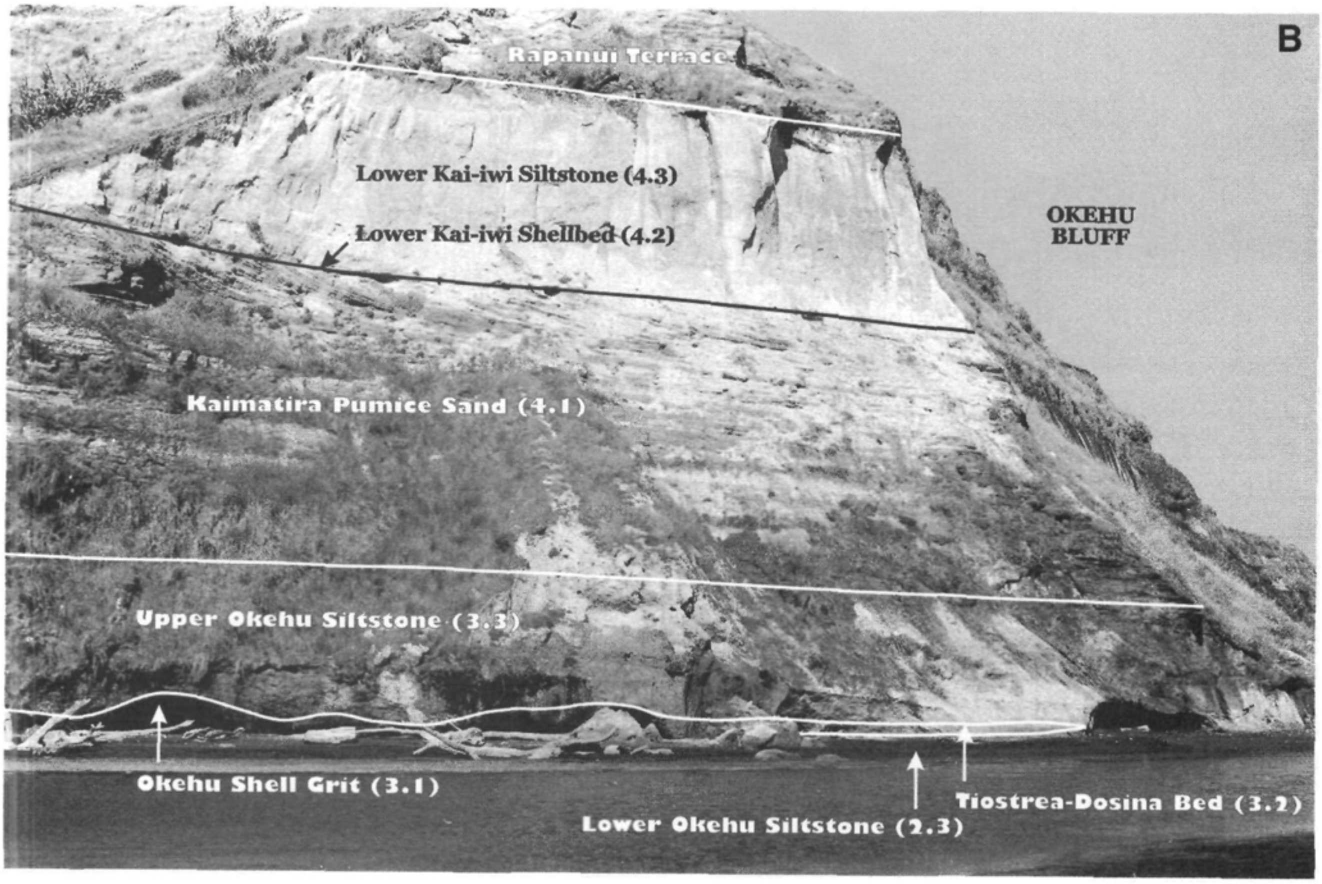


Fig. 3 A–G Annotated panoramic photographs of selected parts of the mid-Pleistocene coastal section between Lignite Point and Castlecliff. The beds dip gently southeast, and in all cases the top part of the cliffs comprises flat-lying Late Pleistocene terrace deposits of the Rapanui Formation (= oxygen isotope stage 5e; Pillans 1983). **A**, Lignite Point, Sequence 1, and view to the southeast of coastal section to Okehu Bluff (R22/687465). **B**, Okehu Bluff (southeast side of Okehu Stream mouth), Sequences 3 and 4 (R22/707458). **C**, Bay southeast of Fishermans Rock, Sequences 4, 5 and 6 (R22/729446). **D**, Cliff southeast of Omapu Creek, Sequences 6 and 7 (R22/738441). **E**, Spur a short distance southeast of the Pinnacles, Sequences 8 and 9 (R22/762423). **F**, Shag Rock Point, Sequences 7 (upper) and 8 (R22/756427). **G**, View southeast past the Buttress, Sequences 9 and 10 (R22/770415).



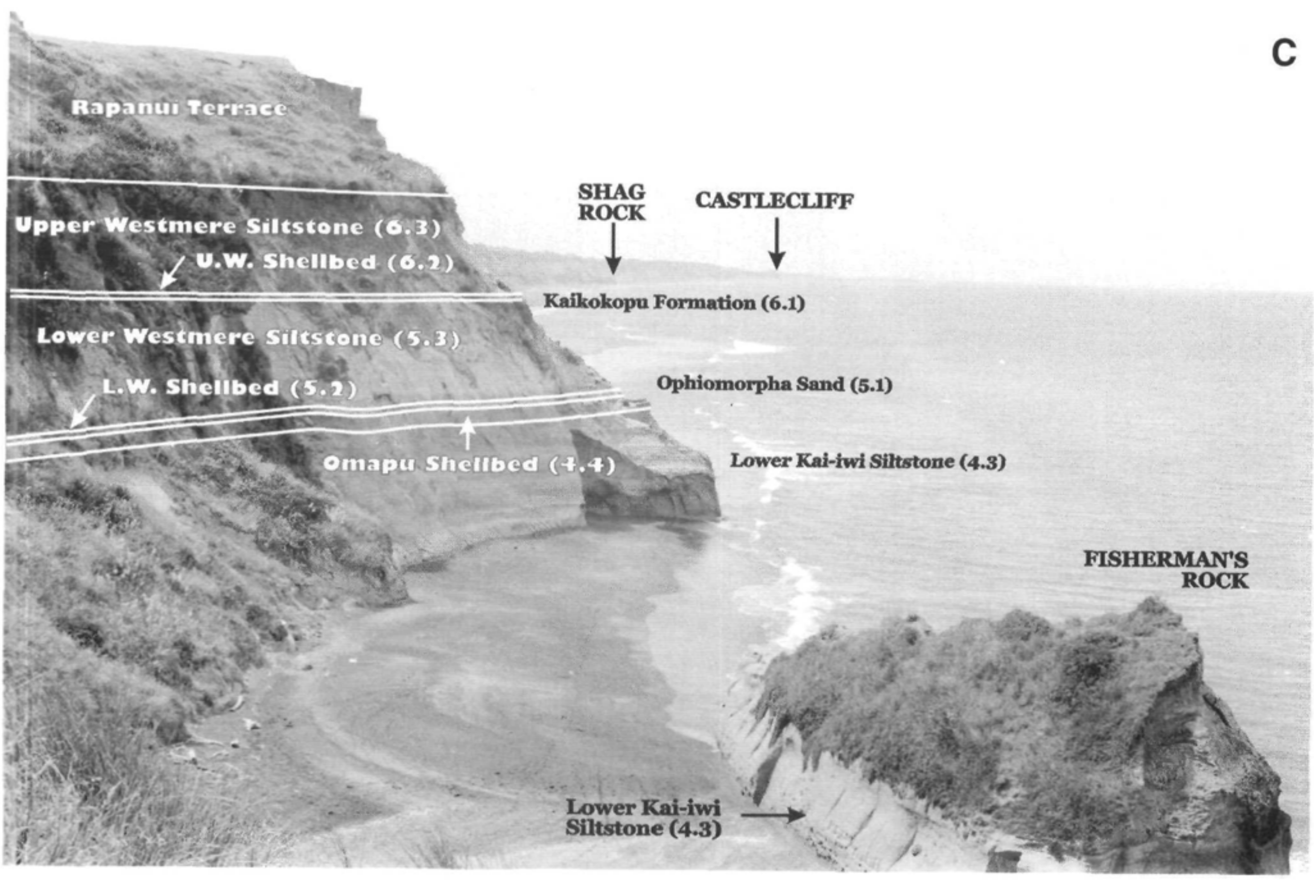
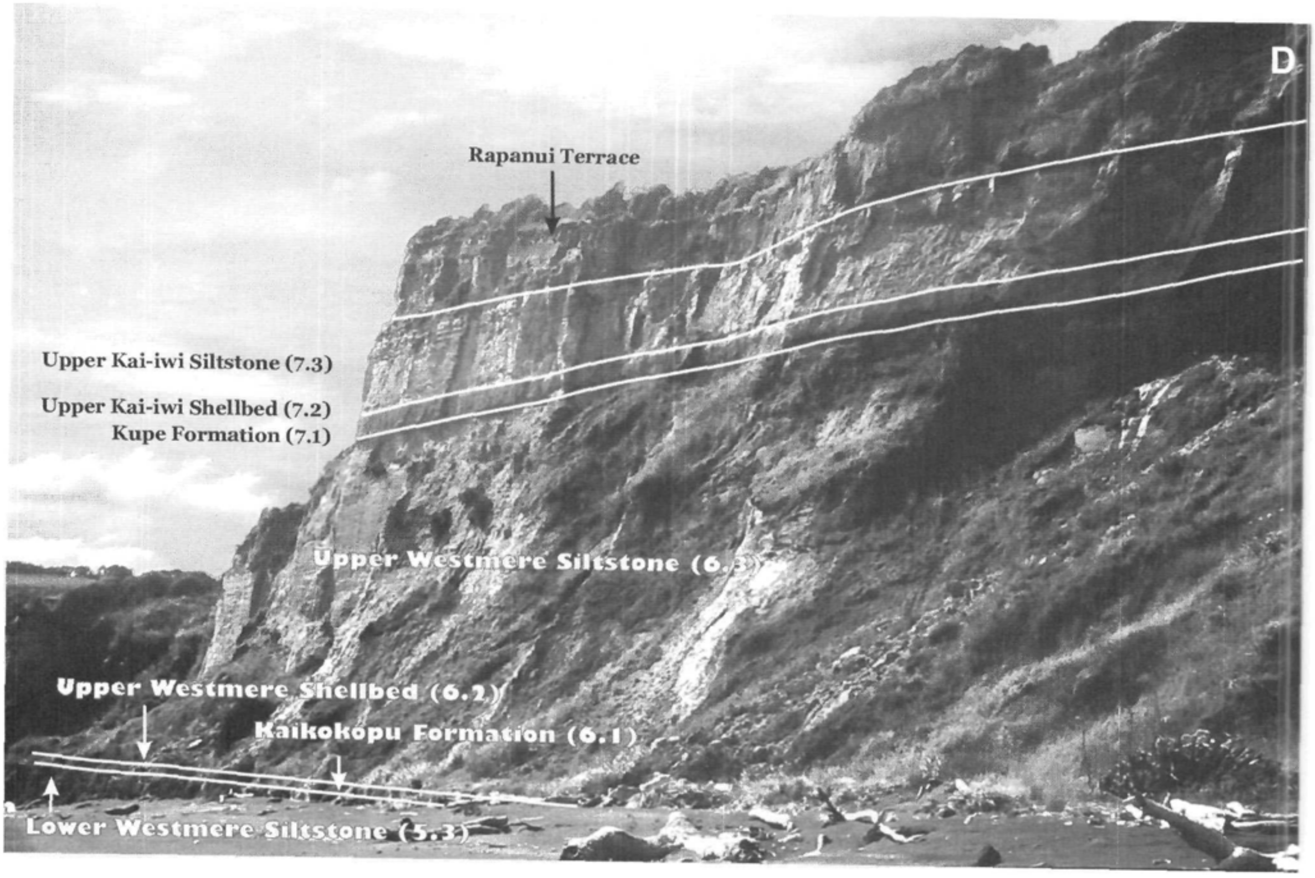


Fig. 3 B, C (*Caption on page 96*)



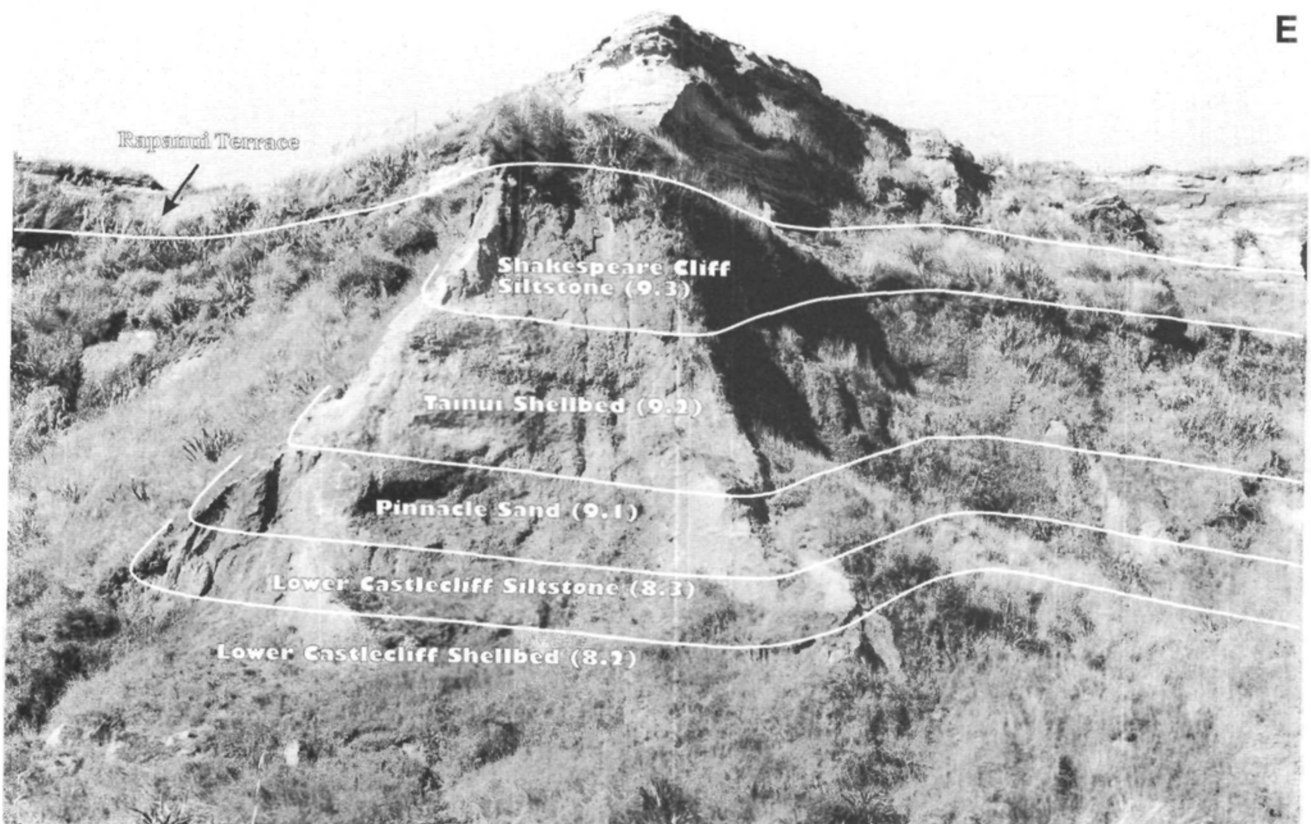
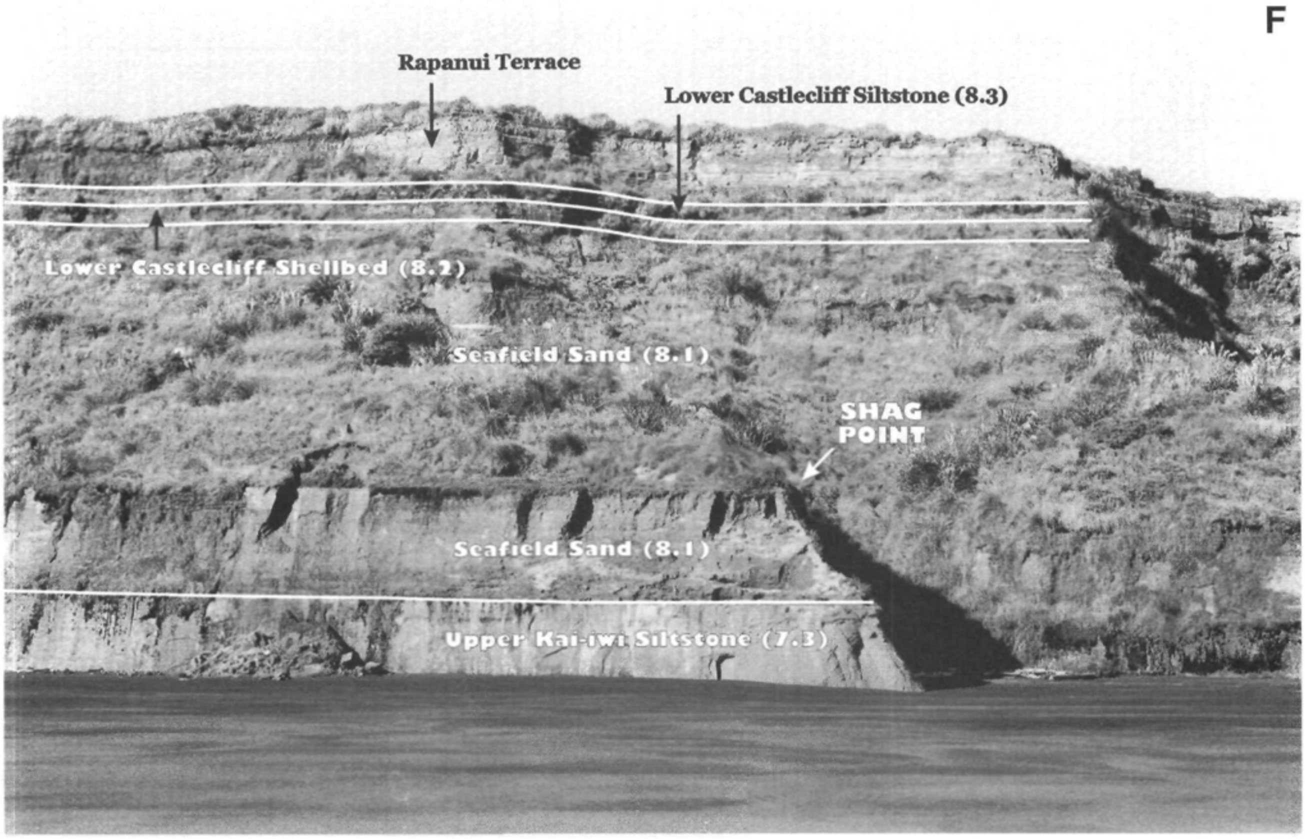


Fig. 3 D, E *(Caption on page 96)*



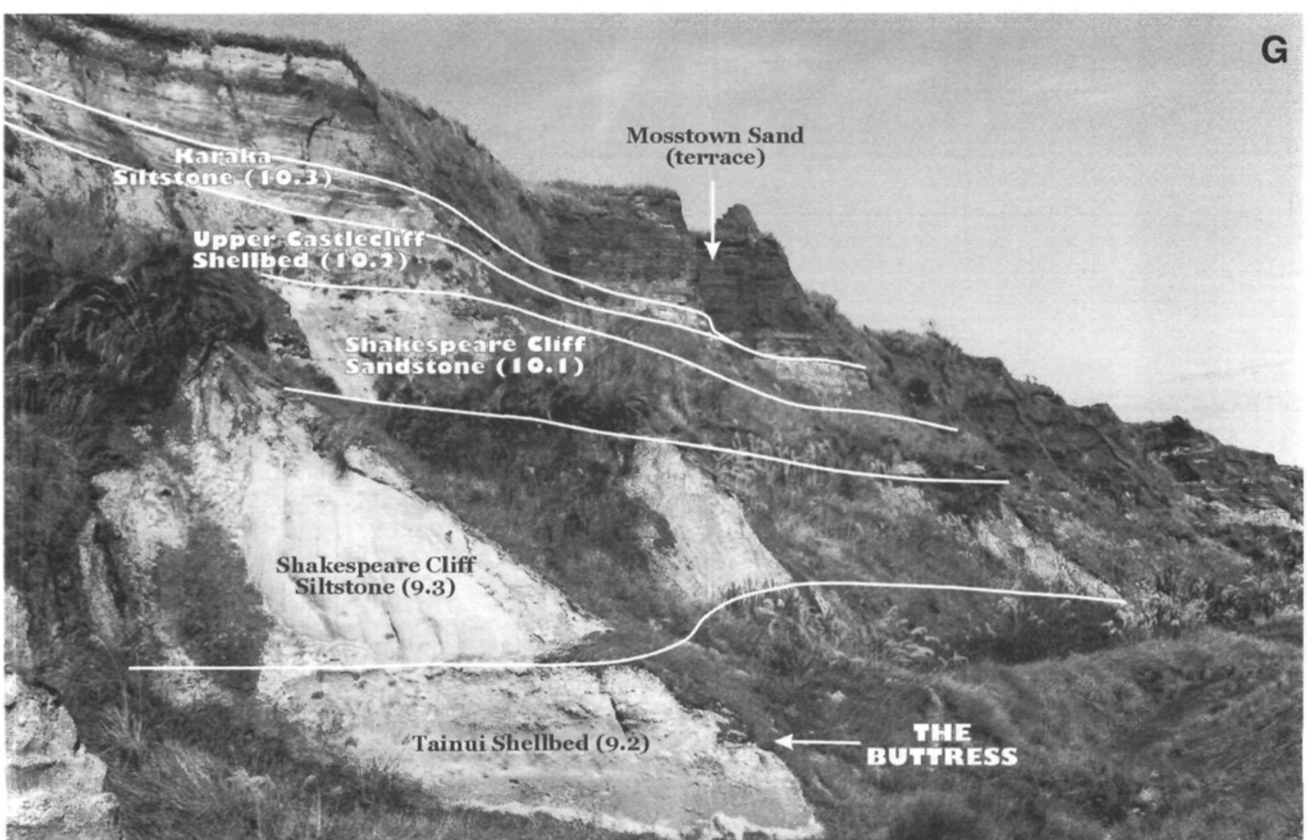


Fig. 3 F, G (*Caption on page 96)*

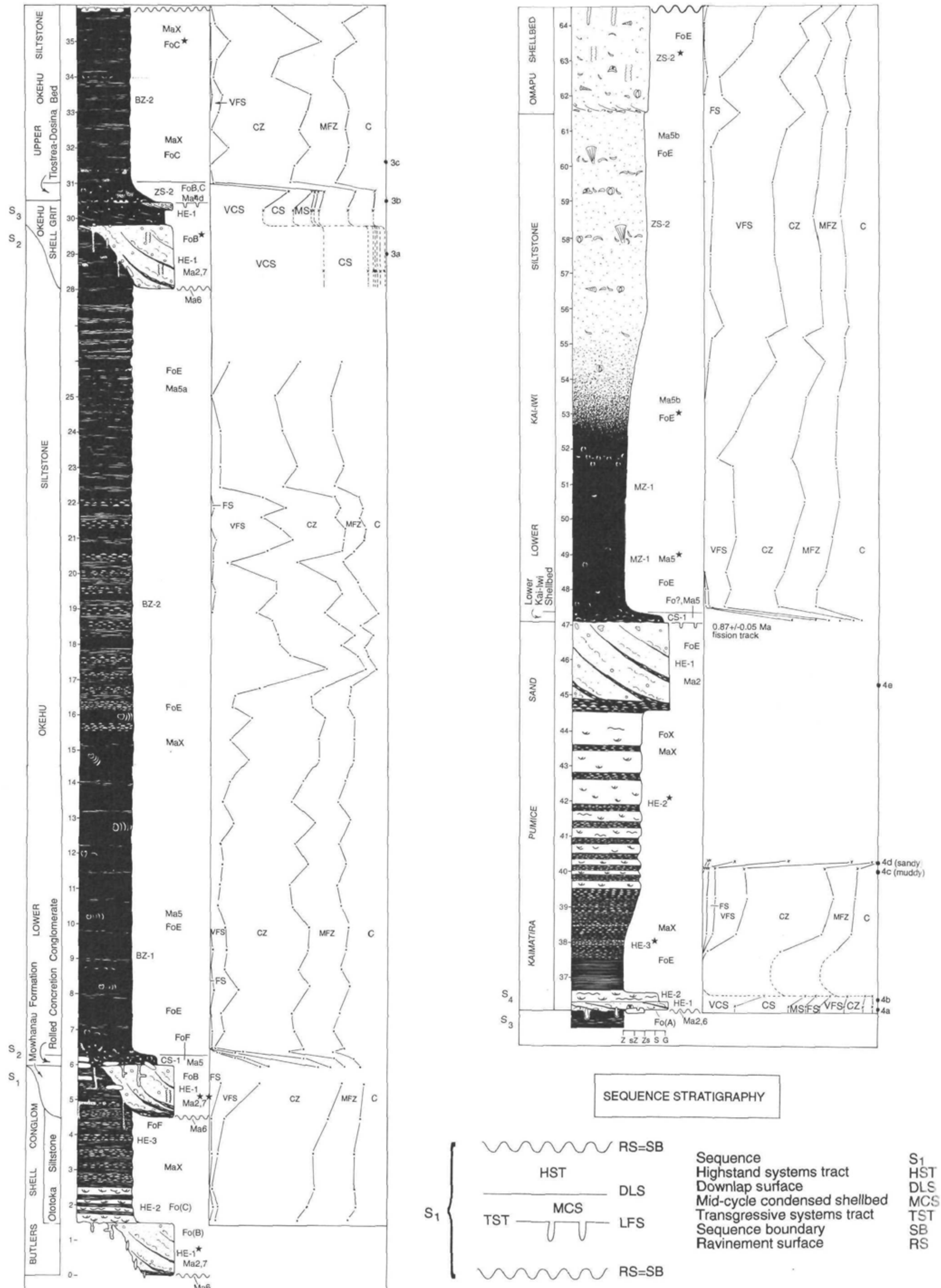


Fig. 4 (*Caption on page 102*)

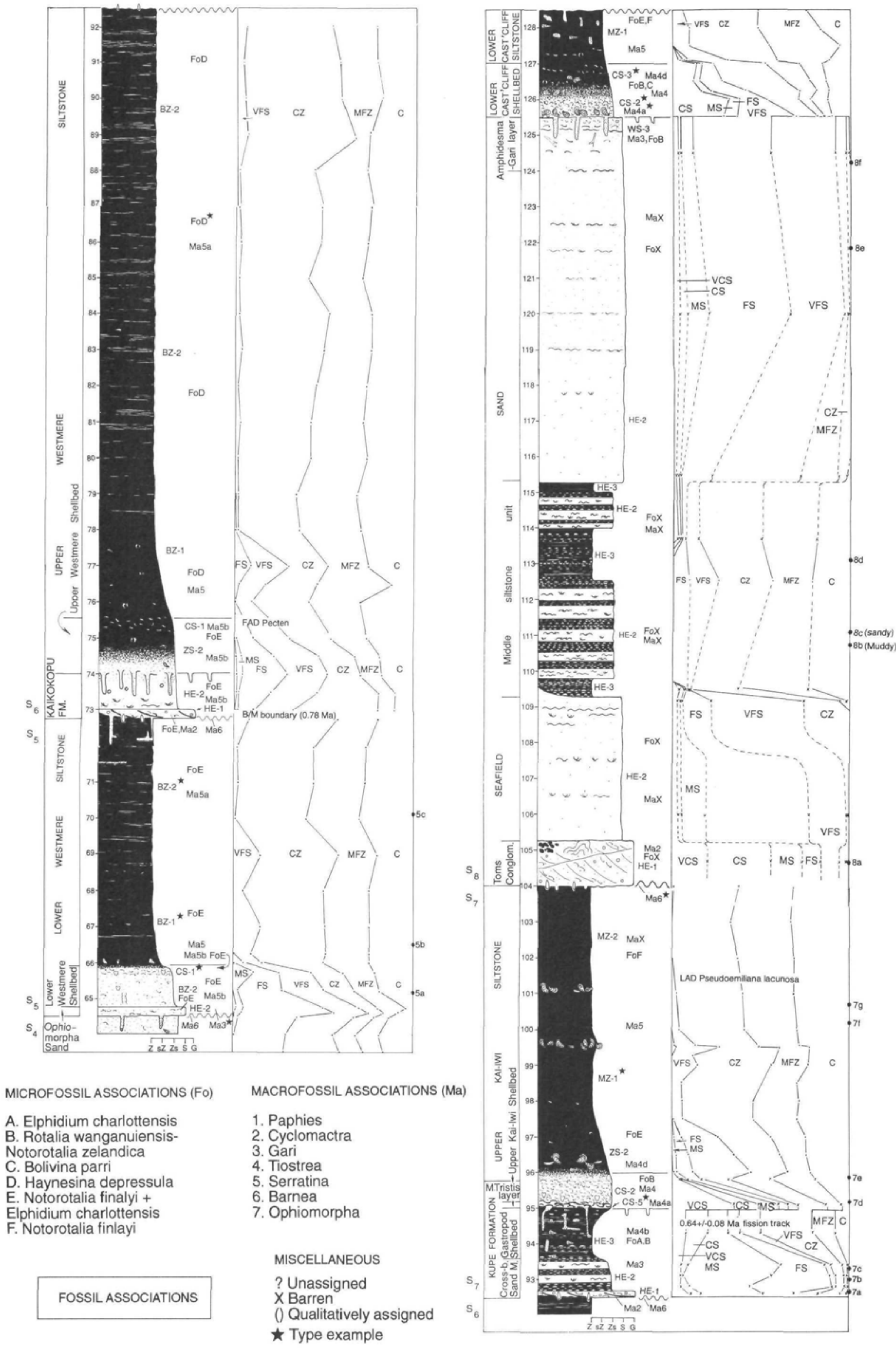


Fig. 4 (*Caption on page 102*)

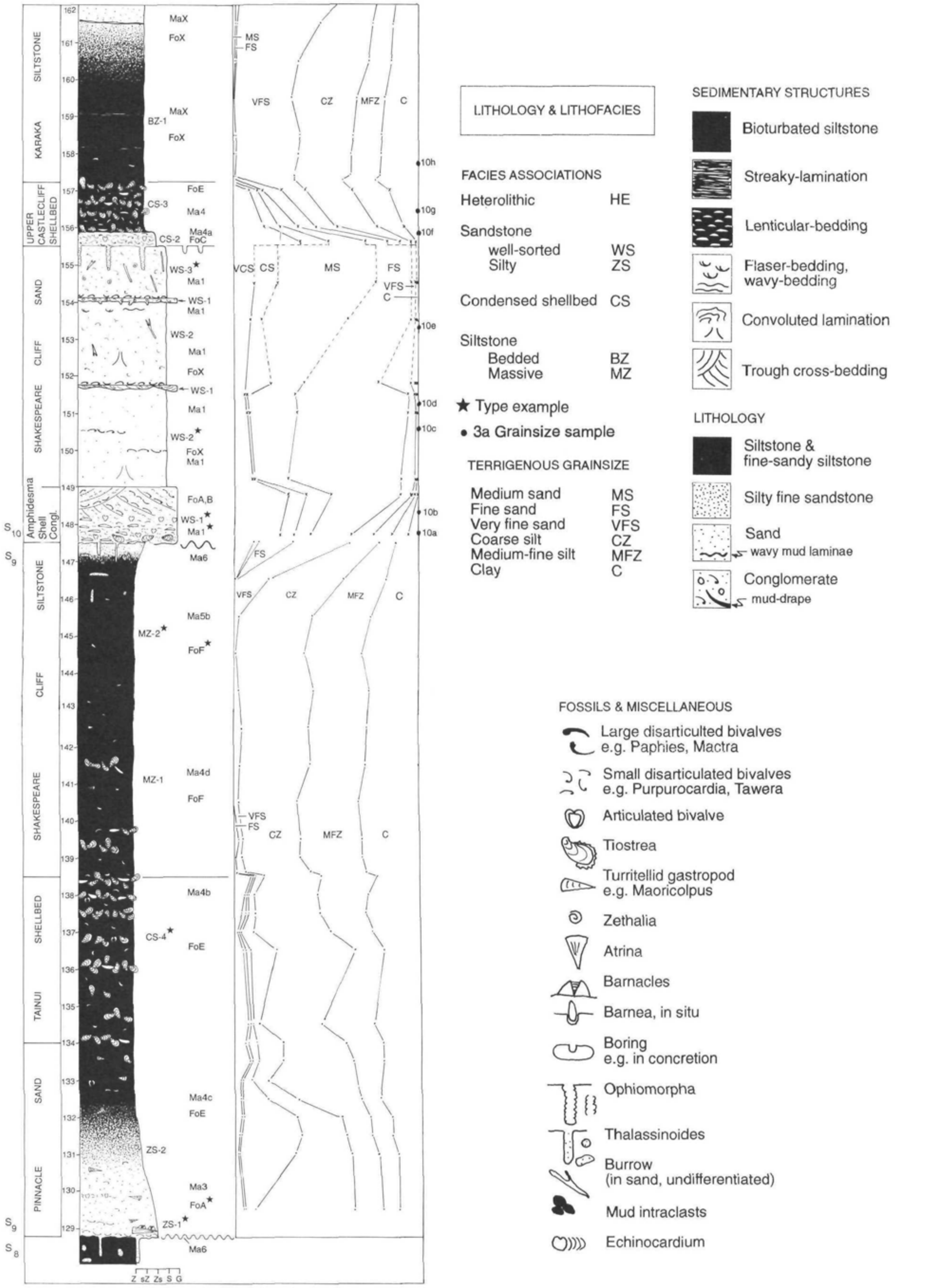


Fig. 4 Sedimentary log of the Castlecliff coastal section, between the base of the Butlers Shell Conglomerate (TST, cycle 1) and the top of the Karaka Siltstone (HST, cycle 10). [For explanation of sedimentary facies see Table 3; for typical grainsize distributions see Fig. 5; for macrofaunal assemblages see Fig. 6A, 7; and for microfaunal assemblages see Fig. 6B, 8.] Asterisks indicate the designated type horizon for the lithofacies and faunal assemblages. Radiometric dates after Shane et al. (1996).

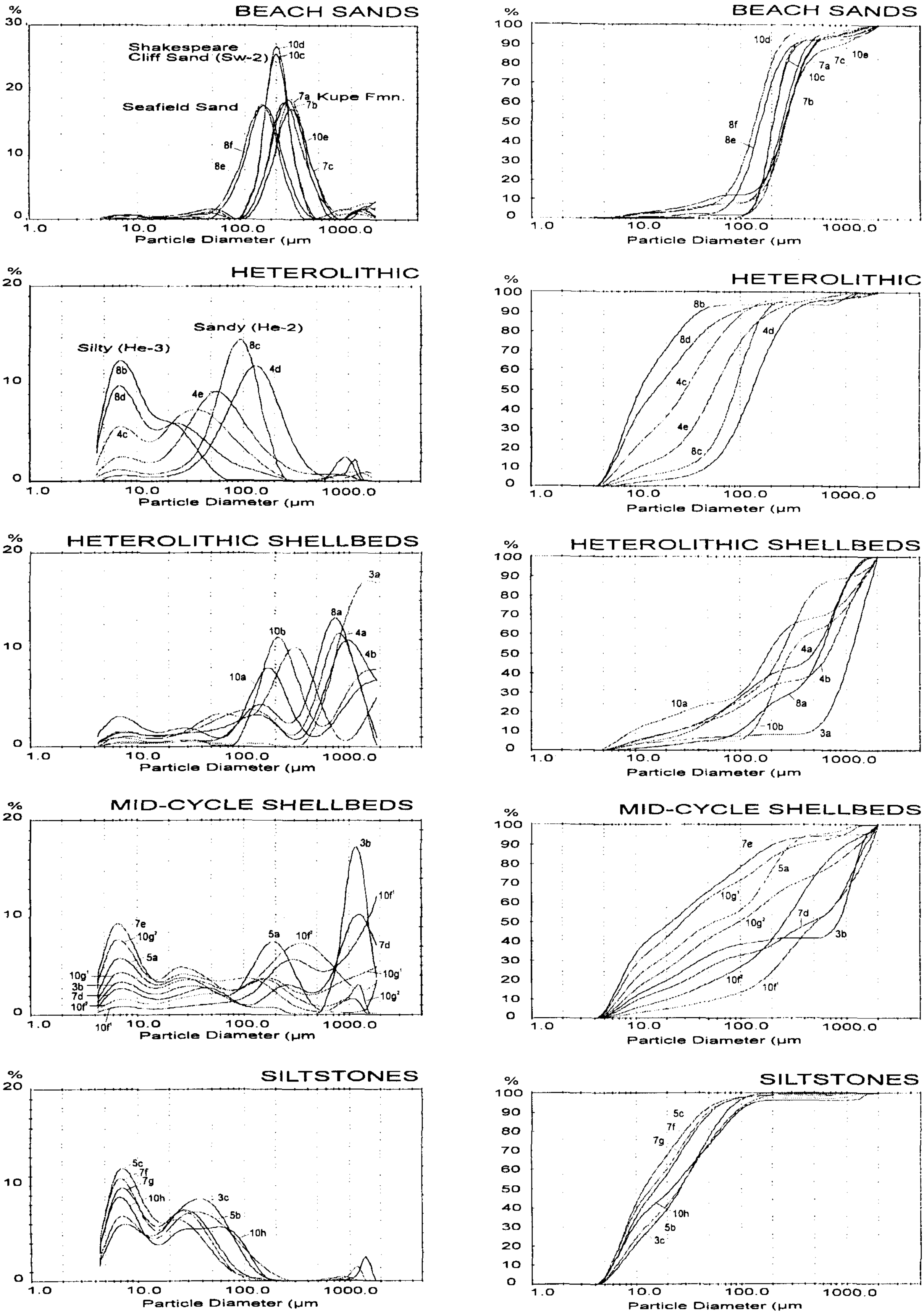
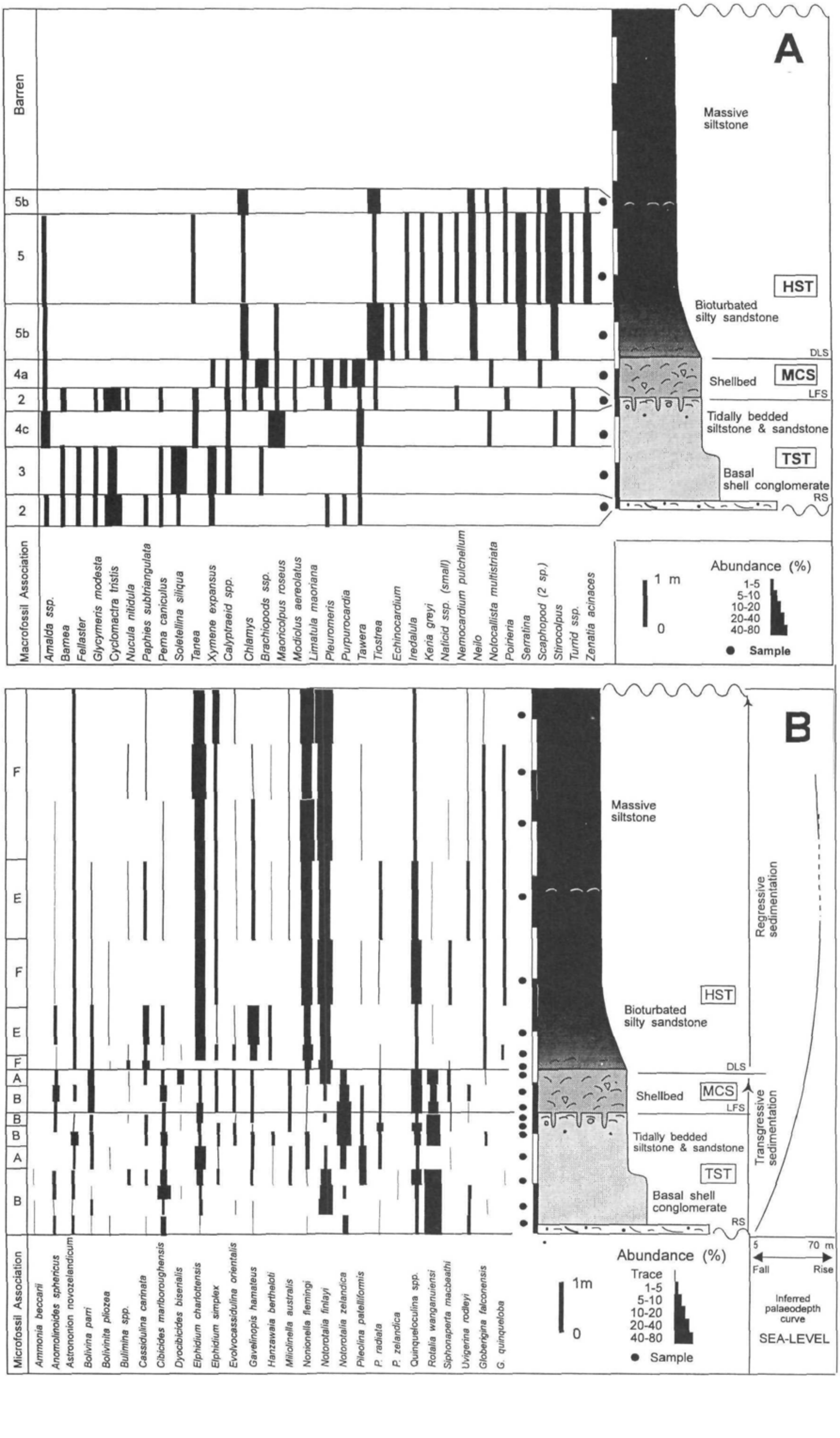


Fig. 5 Grainsize frequency histograms (left) and cumulative curves (right) for the major facies represented in the Castlecliff section in transgressive systems tracts (beach sands, heterolithic, heterolithic shellbeds), mid-cycle shellbeds, and highstand systems tracts (siltstones). Note the distinctive nature of the grainsize distribution for each major facies assemblage. Analyses of the 1–2000 µm size fractions were performed using a Malvern laser diffraction particle analyser. The positions of samples are shown on the detailed section, Fig. 4.


A
Barren
5b
5
5b
4a
2
4c
3
2
Macrofossil Association
Amalda ssp.
Barnea
Fellaster
Glycymeris modesta
Cyclomactra tristis
Nucula nitidula
Paphies subtriangulata
Perna canaliculus
Soletellina siliqua
Tanea
Xymene expansus
Calyptraeid spp.
Chlamys
Brachiopods ssp.
Maoricolpus roseus
Modiolus aereolatus
Limatula maoriana
Pleuromeris
Purpurocardia
Tawera
Tiostrea
Echinocardium
Iredalula
Kena greyi
Naticid ssp. (small)
Nemocardium pulchellum
Neilo
Notocallista multistriata
Poirieria
Serratina
Scaphopod (2 sp.)
Stirocolpus
Turrid ssp.
Zenatia acinaces
Massive siltstone
HST
Bioturbated silty sandstone
DLS
Shellbed
MCS
LFS
Tidally bedded siltstone & sandstone
TST
Basal shell conglomerate
RS
1 m
0
Abundance (%)
1-5
5-10
10-20
20-40
40-80
Sample
B
F
E
F
E
F
A
B
B
B
A
B
Microfossil Association
Ammonia beccarii
Anomalinoides sphericus
Astrononion novozealandicum
Bolivina parri
Bolivinita pliozea
Bulimina spp.
Cassidulina carinata
Cibicides marlboroughensis
Dyocibicides biserialis
Elphidium charlottensis
Elphidium simplex
Evolvocassidulina orientalis
Gavelinopsis hamateus
Hanzawaia bertheloti
Miliolinella australis
Nonionella flemingi
Notorotalia finlayi
Notorotalia zelandica
Pileolina patelliformis
P. radiata
P. zelandica
Quinqueloculina spp.
Rotalia wanganuiensi
Siphonaperta macbeathi
Uvigerina rodleyi
Globerigina falconensis
G. quinqueloba
Massive siltstone
HST
Bioturbated silty sandstone
DLS
Shellbed
MCS
LFS
Tidally bedded siltstone & sandstone
TST
Basal shell conglomerate
RS
Regressive sedimentation
Transgressive sedimentation
5
70 m
Fall
Rise
Inferred palaeodepth curve
SEA-LEVEL
1m
0
Abundance (%)
Trace
1-5
5-10
10-20
20-40
40-80
Sample

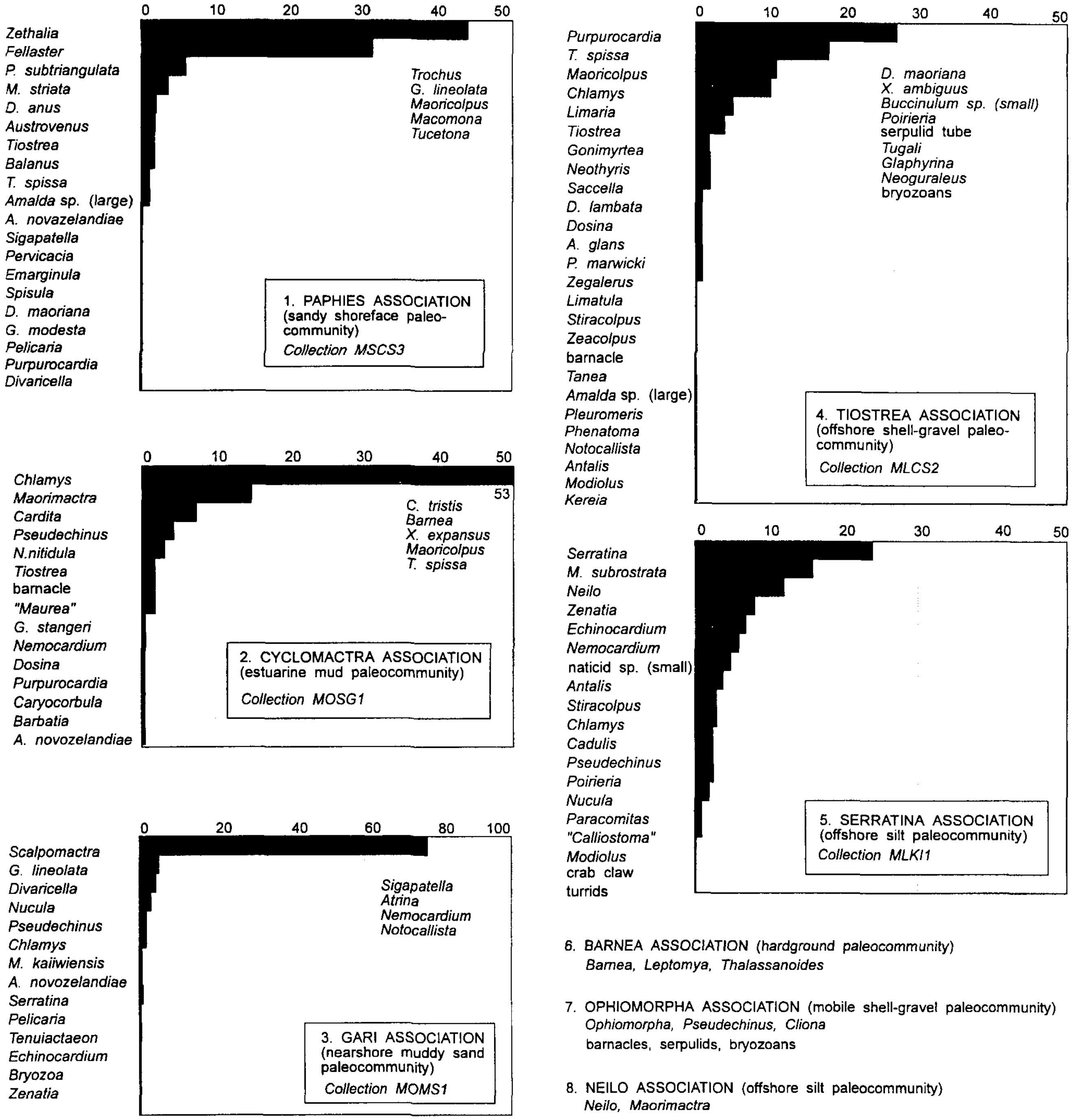


Fig. 7 Macrofaunal assemblages characteristic of the Castlecliff coastal succession (after Abbott 1994; Abbott & Carter 1997, fig. 4).

Sequence 2

2.1 Mowhanau Formation (Abbott & Carter 1994, p. 371)

Type locality, Castlecliff coast section southeast of Ototoka Stream mouth and near beach level. Grid reference R22/690464. Intermittently exposed, because of slips, and therefore not described by Fleming (1953). The term Mowhanau Pumice Sands was used by Fleming (1947, p. 317) in description of beds later reclassified as the Kaimatira Pumice Sand (Fleming 1953) and is now obsolete. Thickness laterally variable but up to 2.0 m. Sedimentary facies HE-1, macrofaunal assemblages Ma-6 (penetrating the basal unconformity), Ma-2 and Ma-7, microfaunal assemblage Fo-B.

Lithology and characteristics similar to those of the Butlers Shell Conglomerate (q.v.).

Interpreted by Abbott & Carter (1994) as a type A shellbed, and the transgressive systems tract of cycle 2.

◄ **Fig. 6** Detailed macrofaunal analysis (**A**) and microfaunal analysis (**B**) through the sediments of cycle 7, the type Castlecliff motif cyclothem (B after Abbott & Carter 1997, fig. 14). Species listed from left to right in general order of the increasing water depth preferred by their modern counterparts.

2.2 Rolled Concretion Conglomerate (amended after Fleming 1953)

Type locality, Castlecliff coast section between Ototoka and Okehu Stream mouths. Grid reference R22/694464. Thickness, 0.25 m.

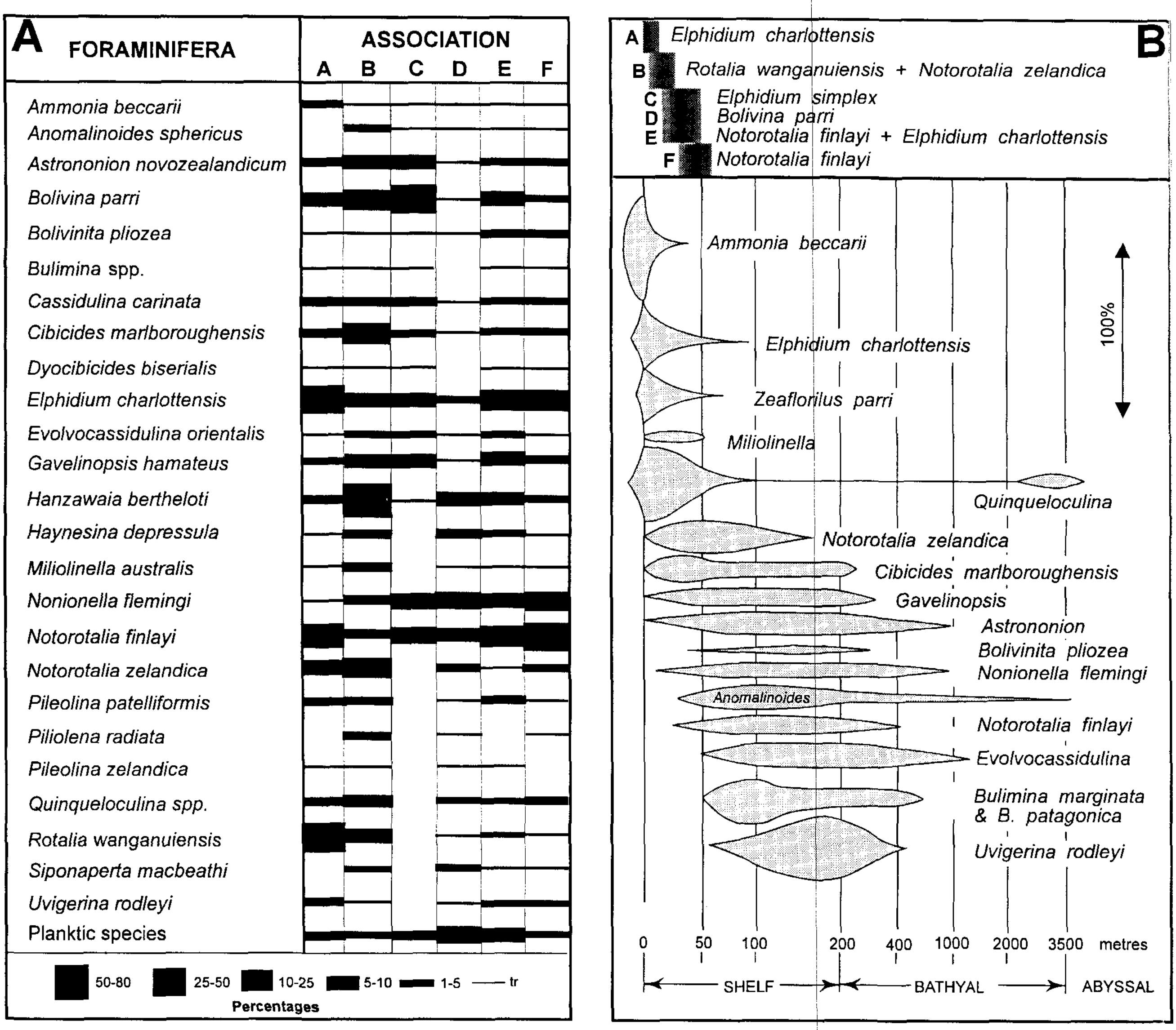


Fig. 8 Microfaunal assemblages characteristic of the Castlecliff coastal succession (after Abbott 1994, 1997b fig. 6, 9). **A**, Percentage abundance of individual species within different microfaunal assemblages. **B**, Changing relative abundance with inferred depth of the dominant species which contribute to foraminiferal assemblages A through F.

Sedimentary facies CS-1, macrofaunal assemblage Ma-5a, microfossil assemblage Fo-F. Recognised by Fleming (1953, p. 178) as the basal rolled concretion conglomerate member of the Lower Okehu Siltstone, and by Abbott & Carter (1994) as a separate unit of formation status.

Conglomerate of reworked, tabular, glauconite-rimmed, carbonate-cemented concretions (up to 0.5 m long), with a matrix of pebbly, shelly, muddy sand.

Interpreted by Abbott & Carter (1994) as the mid-cycle condensed interval of cycle 2.

2.3 Lower Okehu Siltstone *(amended after Fleming 1953, p. 178)*

Type locality, Castlecliff coast section between Lignite Point (R22/687465) and the mouth of Okehu Stream (R22/705459). Thickness, 20 m. Sedimentary facies BZ-1 and BZ-2, macrofaunal assemblage Ma-5a near base (otherwise mostly barren of macrofossils), microfaunal assemblage Fo-E throughout. Corresponding with the recognition of the Rolled Concretion Conglomerate as a formation, we move the base of the Lower Okehu Siltstone up so that it corresponds with the top of the Rolled Concretion Conglomerate.

Bioturbated siltstone, grading up into bedded siltstone and lenticular-bedded silty fine sandstone, becoming sandier upwards through the formation; common *Echinocardium* burrows.

Interpreted by Abbott & Carter (1994) as the highstand systems tract of cycle 2.

Sequence 3

3.1 Okehu Shell Grit *(Fleming 1953, p. 179)*

Type locality, Castlecliff coast section at beach level, immediately southeast of the mouth of Okehu Stream. Grid reference R22/707458. Thickness variable, 0–1.8 m. Sedimentary facies HE-1, and macrofaunal assemblages Ma-6 (penetrating the basal unconformity), Ma-2 and Ma-7; microfossil assemblage Fo-B.

Lithology and characteristics similar to those of the Butlers Shell Conglomerate and Mowhanau Formation (q.v.), though with fewer lithic pebbles.

Interpreted by Abbott & Carter (1994) as a type A shellbed, and as representing the transgressive systems tract of cycle 3.

3.2 **Tiostrea-Dosina** ***Bed*** *(Abbott & Carter 1994, p. 371)*

Type locality, Castlecliff coast section at beach level, c. 50 m southeast of the mouth of Okehu Stream. Grid reference R22/707458. Thickness, 0.5 m. Sedimentary facies ZS-2, macrofaunal assemblage Ma-4d, microfaunal assemblages Fo-B and Fo-C. The name ***Tiostrea-Dosina*** **Bed** was introduced by Abbott & Carter (1994) for the "basal conglomerate member" of the Upper Okehu Siltstone of Fleming (1953, p. 182), and is here treated as a formation.

Bioturbated fine sandy siltstone with scattered molluscan shells.

Interpreted by Abbott & Carter (1994) as a type B shellbed, the mid-cycle shellbed of cycle 3, and as typical of the shell-rich facies which accumulate "at the feather edge of any shore-connected sediment body and at depths within the reach of wave and tidal currents". Such shell-rich facies correspond to the backlap shellbeds of Kidwell (1991) and Naish & Kamp (1997).

3.3 ***Upper Okehu Siltstone*** *(amended after Fleming 1953, p. 182)*

Type locality, Castlecliff coast section a little above beach level and southeast of the mouth of Okehu Stream. Grid reference R22/707458. Thickness, 5.0 m. Sedimentary facies BZ-2, barren of macrofossils, microfossil assemblage Fo-C. Corresponding with the recognition of Fleming's (1955) basal conglomerate member as a discrete formation (=*Tiostrea-Dosina* Bed), we move the base of the Upper Okehu Siltstone up to correspond to the top of the *Tiostrea-Dosina* Bed.

Interbedded, streaky-laminated and bioturbated siltstone.

Interpreted by Abbott & Carter (1994) as the highstand systems tract of cycle 3.

Sequence 4

4.1 ***Kaimatira Pumice Sand*** *(amended after Hutton 1886)*

Type locality, roadcut at Kaimatira Bluff, on the southeast side of the Wanganui River at R22/888433 (Fleming 1953, p. 185). Reference section, Castlecliff coast between Okehu and Kai-Iwi Streams. Grid reference R22/707458. Thickness, 11.0 m. Sedimentary facies HE-1, HE-2 (type), and HE-3 (type). Fossils are not common in the formation at Okehu Bluff, except for macrofossil assemblage Ma-6 penetrating the basal unconformity. A *Mactra*-dominated shelly lag overlies the basal disconformity; microfossil assemblages Fo-A and Fo-E occur in the lower 4 m of the formation; and a 1.5 m thick *Paphies*-shellbed (Ma-2/HE-1) lies at the top.

Flaser-bedded, wavy-bedded and laminated sands, and lenticular to streaky-laminated siltstone.

Interpreted by Abbott & Carter (1994) as the transgressive systems tract of cycle 4. The unusual thickness compared with most other Castlecliff transgressive systems tracts is associated with an influx of volcaniclastic material into the basin. As at the type section at Kaimatira Bluff, the new outcrops at the coast make it clear that facies HE-2 and HE-3 represent swale and interdune muds which accumulated above and between facies HE-1 sand-shell gravel waves. The seafloor represented by the Kaimatira Formation was therefore both hydraulically active and supplied with copious volcanogenic sediment.

4.2 ***Lower Kai-Iwi Shellbed*** *(Abbott & Carter 1994, p. 371)*

Type locality, shore-platform at mouth of Kai-Iwi Stream, Castlecliff coast section (only exposed after beach erosion). Grid reference R22/726448. Thickness, up to 0.5 m. Sedimentary facies CS-1, macrofossil assemblage Ma-5. This unit is exposed but difficult to access in the higher parts of the coastal cliffs northwest of Kai-Iwi Stream, and is only intermittently exposed on the beach at Mowhanau, for example, after heavy storms. The limited and difficult outcrop probably explains why the shellbed was only recognised by Fleming (1953) as a "gradation" between the Kaimatira Pumice Sand and the Lower Kai-Iwi Siltstone.

Similar to the *Tiostrea-Dosina* Bed (q.v.), but of slightly deeper water aspect, including molluscan epifaunal elements.

Interpreted by Abbott & Carter (1994) as a thin but typical type B shellbed, which represents the mid-cycle shellbed of cycle 4.

4.3 ***Lower Kai-Iwi Siltstone*** *(amended after Park 1887)*

Type locality, Castlecliff coast section southeast of Mowhanau Stream (Fleming 1953, p. 189). Grid reference R22/726448–729448. Thickness, 14.5 m. Sedimentary facies MZ-1 (type) and ZS-2, macrofaunal assemblages Ma-5a (type) and Ma-5b, microfaunal assemblage Fo-E throughout.

Pervasively bioturbated siltstone grading upward into silty fine sandstone, with scattered nearly *in situ* fossils, occasionally concentrated into layers, lenses, or clumps.

Interpreted by Abbott & Carter (1994) as the highstand systems tract of cycle 4.

4.4 ***Omapu Shellbed*** *(Fleming 1953, p. 193)*

Type locality, Castlecliff coast section, southeast of Mowhanau Stream. Grid reference R22/733445. Thickness, 3 m. Sedimentary facies ZS-2 (type), macrofossil assemblages Ma-5b, microfossil assemblage Fo-E.

Bioturbated silty fine sandstone similar to the upper parts of the underlying Lower Kai-Iwi Siltstone, but with a higher macrofossil and sand content.

The Omapu Shellbed is the only lithostratigraphic unit in the Castlecliff section that does not at first sight fit comfortably into the threefold subdivision of each sequence into a transgressive systems tract, mid-cycle shellbed, and highstand systems tract. Abbott & Carter (1994) interpreted the unit as representing shoaling towards the top of the highstand systems tract of cycle 4, and noted that it might correspond with the minor eustatic oscillation represented by oxygen isotope stages 24–23. Alternatively, the subtle erosion which occurs at the base of the Omapu Shellbed could be taken as evidence for interpreting it as a forced regressive systems tract (e.g., Plint 1988).

Sequence 5

5.1 **Ophiomorpha** ***Sand*** *(Abbott & Carter 1994, p. 371)*

Type locality, Castlecliff coast section, near beach level c. 1000 m southeast of Mowhanau Stream. Grid reference R22/734443. Thickness, 0.3 m. Sedimentary facies ZS-1, macrofossil assemblage Ma-3 and with abundant *Ophiomorpha* burrows, microfossil assemblage Fo-E. The formation is equivalent to the "basal fossiliferous free sand member" of Fleming (1953, p. 195).

Flaser-bedded silty fine sand with abundant double-valved molluscs of lower shoreface origin (*Divalucina*, *Scalpomactra*).

Interpreted by Abbott & Carter (1994) as the transgressive systems tract of cycle 5.

5.2 ***Lower Westmere Shellbed*** *(Abbott & Carter 1994, p. 371)*

Type locality, Castlecliff coast section, near beach level c. 1000 m southeast of Mowhanau Stream. Grid reference R22/734444. Thickness, 1.5 m. Sedimentary facies BZ-2 and CS-1, macrofossil assemblage Ma-5b, microfossil assemblage Fo-E. The formation is equivalent to the "three feet of blue muddy siltstone containing scattered mollusca" described by Fleming just above the base of his Westmere Siltstone (1953, p. 195).

Dispersed shellbed of abundant nearly *in situ* molluscs, including common double-valved bivalves, set in bioturbated silty fine sandstone.

Interpreted by Abbott & Carter (1994, p. 388) as a type B shellbed, and the mid-cycle shellbed of cycle 5.

5.3 ***Lower Westmere Siltstone*** *(amended after Fleming 1953)*

Type locality, Castlecliff coast section, south side of Omapu Stream. Grid reference R22/737442. Thickness, 7.2 m. Sedimentary facies

BZ-1 and BZ-2, macrofossil assemblage Ma-5 over the basal metre and sparse Ma-5a throughout; microfossil assemblage Fo-E. Stemming from the recognition of the *Ophiomorpha* Sand and Lower Westmere Shellbed as discrete formations, the term Lower Westmere Siltstone is restricted to the upper part of the formation as defined by Fleming (1953, p. 195).

Dark grey-brown, sparsely fossiliferous siltstone grading upward into unfossiliferous, alternating, cm-scale beds of bioturbated and streaky-laminated siltstone.

Interpreted by Abbott & Carter (1994) as the highstand systems tract of cycle 5.

Sequence 6

6.1 Kaikokopu Formation (amended after Fleming 1953)

Type locality, Castlecliff coast section, c. 300 m southeast of Omapu Stream. Grid reference R22/740440. Sedimentary facies HE-1 and HE-2. Thickness, 1.25 m at the coast (but up to several metres inland). Macrofossil assemblages Ma-6 (penetrating the basal unconformity) and Ma-2 (type), microfossil assemblage Fo-E. Fleming (1953, p. 197) recognised the Kaikokopu Shell Grit as the basal member of the Upper Westmere Siltstone. We upgrade the status to that of a formation, and include within it the lower part of the fossiliferous siltstone base of the Upper Westmere Siltstone of Fleming (1953, p. 197).

A thin unit of bedding-parallel, reworked molluscan shells (mainly *Paphies*) in a poorly sorted sand matrix, including the overlying heterolithic siltstone and mudstone attributed by Fleming (1953) to the "fossiliferous siltstone member" of the Upper Westmere Siltstone.

Interpreted by Abbott & Carter (1994) as the transgressive systems tract of cycle 6.

6.2 Upper Westmere Shellbed (Abbott & Carter 1994, p. 371)

Type locality, Castlecliff coast section, c. 1.5 km southeast of Mowhanau Stream. Grid reference R22/740440. Thickness, 1.5 m. Sedimentary facies ZS-2 and CS-1, macrofossil assemblage Ma-5b, microfossil assemblage Fo-E. Fleming (1953, p. 197) recognised "a fossiliferous blue-grey siltstone member a few feet thick" in the base of his Westmere Siltstone. We name the upper part of this unit the Upper Westmere Shellbed, and designate it as a formation.

Bioturbated, sparsely fossiliferous, silty fine sandstone similar to that of the Lower Westmere Shellbed (q.v.), and containing the first occurrence of *Pecten* s.s. in the Castlecliff section.

Interpreted by Abbott & Carter (1994) as a type B shellbed, and the mid-cycle shellbed of cycle 6.

6.3 Upper Westmere Siltstone (amended after Fleming 1953)

Type locality, Castlecliff coast section, c. 2 km southeast of Mowhanau Stream. Grid reference R22/741439. Thickness, 17 m. Sedimentary facies BZ-1 (type) and BZ-2 (type), macrofossil assemblage Ma-5 in the basal few metres and Ma-5a occasionally throughout the remainder of the formation, microfossil assemblage Fo-D. Stemming from the recognition of the Kaikokopu Formation and Upper Westmere Shellbed as discrete formations, the term Upper Westmere Siltstone is restricted to the upper part of the unit described by Fleming (1953, p. 197).

The lithology is similar to that of the Lower Westmere Siltstone (q.v.).

Interpreted by Abbott & Carter (1994) as the highstand systems tract of cycle 6.

Sequence 7

The sediments of cycle 7 represent the type Castlecliff motif sequence. Detailed analyses of the changing macrofaunas and microfaunas through cycle 7 are presented in Fig. 6 (after Abbott 1997b; Abbott & Carter 1997).

7.1 Kupe Formation (amended after Fleming 1953)

Type locality, Castlecliff coast section, c. 3 km southeast of Mowhanau Stream. Grid reference R22/750433. Thickness, 2.5 m. Sedimentary facies HE-1, HE-2 and HE-3, macrofossil assemblages Ma-6 (penetrating the basal unconformity), Ma-2, Ma-3 and Ma-4b, microfossil assemblages Fo-A and Fo-B. Fleming (1953, p. 200) recognised five members, a–e, within the Kupe Formation. We here restrict the Kupe Formation to the lower two members of Fleming, comprising the basal Cross-bedded Sand and the Gastropod Shellbed Members.

A lithologically variable suite of lenticular and flaser-bedded sands and silts above a basal shell-rich layer (type A shellbed). The detailed stratigraphy which Fleming described from the Kupe Formation applies only where the Kupe lies close to beach level, and appreciable lateral facies change occurs as the formation rises along the cliff towards the northwest. About 400 m to the north, in two small lower cliff-slope bluffs, the stratigraphy comprises a thin (200 mm) basal *Mactra tristis* bed overlain by 2 m of beach sand with rare mud flasers.

Interpreted by Abbott & Carter (1994) as the transgressive systems tract of cycle 7.

7.2 Upper Kai-Iwi Shellbed (Abbott & Carter 1994, p. 371)

Type locality, Castlecliff coast section, c. 3 km southeast of Mowhanau Stream. Grid reference R22/750433. Thickness, 0.8 m. Sedimentary facies CS-5 and CS-2, macrofossil assemblages Ma-4 and Ma-4a, microfossil assemblage Fo-B. We include the three upper members of the Kupe Formation of Fleming (1953, p. 200) in the Upper Kai-Iwi Shellbed where it outcrops at beach level, namely the *Mactra tristis* layer, the pelecypod shellbed, and the *Pecten* layer.

The shellbed comprises a basal lag of bed-parallel *Mactra tristis* (reworked from underlying strata), overlain by a unit of well-preserved, closely packed, and often double-valved molluscs (*Purpurocardia*, *Dosina*, *Tawera*, *Zemysia*) and brachiopods (*Waltonia*, *Magasella*, *Neothyris*) set in a muddy sand matrix.

Interpreted by Abbott & Carter (1994) as the mid-cycle shellbed of cycle 7. The basal shell layer of *Mactra tristis* reflects rapid transgression and deepening at the base of the shellbed, after which the characteristic shell-ground conditions of a type B shellbed (starved shelf) became established. Thus, the Upper Kai-Iwi Shellbed is a compound shellbed in the terminology of Naish & Kamp (1997).

7.3 Upper Kai-Iwi Siltstone (Fleming 1953, p. 206)

Type locality, Castlecliff coast section, starting c. 3 km southeast of Mowhanau Stream. Grid reference R22/750433–756427 (Shag Rock Point). Thickness, 8 m. Sedimentary facies ZS-2, MZ-1 and MZ-2, macrofossil assemblages Ma-4d and Ma-5, microfossil assemblages Fo-E (lower) and Fo-F (upper).

Fossiliferous, fine sandy siltstone grading upward into barren bioturbated siltstone.

Interpreted by Abbott & Carter (1994) as the highstand systems tract of cycle 7.

Sequence 8

8.1 Seafield Sand (Fleming 1953, p. 212)

Type locality, Castlecliff coast section, c. 4 km southeast of Mowhanau Stream. Grid reference R22/756427. Thickness, 22.0 m. Sedimentary facies HE-1, HE-2, HE-3, WS-1 and WS-2, macrofossil assemblages Ma-6 (penetrating the basal unconformity), Ma-2 (basal conglomerate) and Ma-3, and microfossil assemblage Fo-B (shoreface sand at top of formation), but mainly barren of fossils.

1.25 m of basal, cross-bedded, shelly, sandy conglomerate (equivalent to the Toms Conglomerate Member mapped in the Rangitikei valley; Te Punga 1952), overlain by 4.5 m of well-sorted sand, a 5.5 m thick succession of lenticular and flaser-bedded sand and silt (middle siltstone member), and 10.25 m of well-sorted fine–medium sand in which the uppermost 1.5 m contains *in situ*, double-valved, shoreface bivalves (*Gari lineolata, Nucula nitidula, Pecten*). Seafield Sand, at 21.5 m thick, is the thickest transgressive systems tract in the Castlecliff section, and, unlike the Kaimatira Pumice Sand, it does not coincide with an influx of volcaniclastic material into the basin. Abbott & Carter (1994) therefore interpreted Seafield Sand as a small progradational paracycle, which was deposited during a pause (or minor fall) in the sea-level rise which marked the isotope stage 16–15 transgression.

Interpreted by Abbott & Carter (1994) as the transgressive systems tract of cycle 8.

8.2 Lower Castlecliff Shellbed *(Fleming 1953, p. 215)*

Type locality, Castlecliff coast section, c. 4 km southeast of Mowhanau Stream. Grid reference R22/762427. Thickness, 1.5 m. Sedimentary facies CS-2 (type) and CS-3 (type), macrofossil assemblages Ma-4 and Ma-4a (type), microfossil assemblages Fo-C and Fo-B.

Similar to the Upper Kai-Iwi Shellbed (q.v.). A packed assemblage of well-preserved molluscs, including double-valved bivalves (*Purpurocardia*), set in muddy sand matrix. The basal part of the shellbed contains abundant double-valved *Tiostrea*.

Interpreted by Abbott & Carter (1994) as a type B shellbed, and the mid-cycle shellbed of cycle 8.

8.3 Lower Castlecliff Siltstone *(Abbott & Carter 1994, p. 371)*

Type locality, Castlecliff coast section, c. 4 km southeast of Mowhanau Stream, on a cliff spur southeast of the former Pinnacles locality (now overgrown). Grid reference R22/756423. Thickness, 1.25 m. Sedimentary facies MZ-1, macrofossil assemblages Ma-4d and Ma-5, microfossil assemblages Fo-E and Fo-F. A thin but typical siltstone unit, which was not recorded by previous observers, perhaps because it is often obscured by slumping.

Bioturbated grey siltstone with scattered fossils including *Maoricolpus* and *Amalda*.

Interpreted by Abbott & Carter (1994) as the highstand systems tract of cycle 8.

Sequence 9

9.1 Pinnacle Sand *(Fleming 1953, p. 222)*

Type locality, Castlecliff coast section, c. 4.5 km southeast of Mowhanau Stream, on a cliff spur southeast of the former Pinnacles locality (now overgrown). Grid reference R22/762423. Thickness, 5.25 m. Sedimentary facies ZS-1 (type) and ZS-2, macrofossil assemblages Ma-6 (penetrating the basal unconformity), Ma-3 and Ma-4c, microfossil assemblages Fo-A and Fo-E.

Bioturbated, micaceous medium sand with abundant *Antisolarium* and other shoreface molluscs. Increasingly silty and more sparsely fossiliferous upwards.

Interpreted by Abbott & Carter (1994) as the transgressive systems tract of cycle 9. Cycle 9 is unusual both in the thickness of its mid-cycle shellbed and in the lack of a distinct local flooding surface at the shellbed base. Nonetheless, the fining-upward nature of the Pinnacle Sand, and accompanying faunal changes, make it clear that deepening, and therefore seafloor drowning, occurred during late Pinnacle Sand time, creating the sediment-starved seafloor conditions suitable for shellbed development.

9.2 Tainui Shellbed *(Fleming 1947, p. 322; 1953, p. 224)*

Type locality, Castlecliff coast section at the "Buttress", c. 5 km southeast of Mowhanau Stream. Grid reference R22/770415. Thickness, 4.5 m. Sedimentary facies CS-4 (type), macrofaunal assemblages Ma-4b and Ma-4c, microfaunal assemblage Fo-E.

Grey siltstone containing clumps and layers of oysters and encrusting bryozoans, with associated epifaunal and infaunal molluscs.

Interpreted by Abbott & Carter (1994) as a type B shellbed, and as the mid-cycle shellbed of cycle 9.

9.3 Shakespeare Cliff Siltstone *(amended after Hutton 1886)*

Type locality, Shakespeare Cliff, Wanganui City. Reference locality, Castlecliff coast section at the "Buttress", c. 5 km southeast of Mowhanau Stream (Fleming 1953, p. 231). Grid reference R22/770415. Thickness, 9 m. Sedimentary facies MZ-1 and MZ-2 (type), macrofossil assemblages Ma-4d and Ma-5b, microfossil assemblage Fo-F.

The lithology is similar to that of the Lower and Upper Kai-Iwi Siltstones (q.v.).

Interpreted by Abbott & Carter (1994) as the highstand systems tract of cycle 9.

Sequence 10

10.1 Shakespeare Cliff Sand *(Fleming 1953, p. 232)*

Type locality, Shakespeare Cliff, Wanganui City. Reference section, Castlecliff coast c. 6 km southeast of Mowhanau Stream. Grid reference R22/773413. Thickness, 7.5 m. Sedimentary facies WS-1 (type), WS-2 (type) and WS-3 (type), macrofossil assemblages Ma-6 (penetrating the basal unconformity) and Ma-1, microfossil assemblages Fo-A and Fo-B.

Basal cross-bedded *Paphies* shellbed 1.5 m thick, overlain by 6.0 m of well-sorted fine sand with scattered shoreface molluscan shells and shell layers. The highest shellbed, 150 mm thick and 0.95 m below the base of the Upper Castlecliff Shellbed, contains a rich variety of shallow-water taxa (*Paphies, Austrovenus, Gari, Zethalia, Fellaster*). Together with the overlying massive sand, it may have been formed by unmixing of the top of the Shakespeare Cliff Sand.

Intepreted by Abbott & Carter (1994) as the transgressive systems tract of cycle 10. Above the basal type A shellbed, the sediments represent a sandy beach-shoreface succession.

10.2 Upper Castlecliff Shellbed *(Fleming 1947, p. 323; 1953, p. 237)*

Type locality, Shakespeare Cliff, Wanganui City. Reference section, Castlecliff coast c. 6 km southeast of Kai-Iwi Stream. Grid reference R22/773413. Thickness, 1.75 m. Sedimentary facies CS-2 and CS-3, macrofaunal assemblages Ma-4 and Ma-4a, microfossil assemblages Fo-C and Fo-E.

The shellbed is composite. The lower 0.5 m comprises closely packed, well preserved, double-valved bivalves (including *Pecten* s.s.) and other molluscs in a poorly sorted silty sandstone matrix. Above a gradational contact, the upper 1.25 m is similar to the upper parts of the Tainui Shellbed (q.v.), and comprises clumps of epifauna (especially *Tiostrea* and brachiopods) in a sandy siltstone matrix.

Interpreted by Abbott & Carter (1994) as representing the mid-cycle shellbed of cycle 10.

10.3 Karaka Siltstone *(Fleming 1953, p. 240)*

Type locality, Castlecliff coast section, c. 6 km southeast of Kai-Iwi Stream. Grid reference R22/773413. Thickness, 7.25 m. Sedimentary facies BZ-1, barren of fossils.

Similar to the Lower Westmere Siltstone (q.v.).

Interpreted by Abbott & Carter (1994) as the highstand systems tract of cycle 10.

CONCLUSIONS

1. As initially shown by Fleming (1953), matching formal lithostratigraphic units with the cyclostratigraphic sedimentary subdivisions of a typical sea-level cycle is an extremely powerful tool for understanding sequences deposited under the influence of repetitive eustasy. Such description and matching enabled Abbott et al. (1989) and Abbott & Carter (1994) to formulate their basic

model for the deposition of a "Castlecliff motif" cyclothem, and also to test the sequence stratigraphic model of Vail et al. (1991).

2. Sediments of Castlecliff cycle 7 are nominated as the type example of the Castlecliff motif sequence. The sequence consists of three parts, in ascending order: (1) 2.5 m of lenticular and flaser-bedded sandstone and siltstone, and a shallow marine molluscan fauna (transgressive systems tract); (2) a compound shellbed, comprising a bed-parallel basal lag of estuarine *Mactra tristis*, overlain by a packed assemblage of well preserved, double valved, inner-middle shelf, shell-ground fossils in a poorly sorted muddy sand matrix (mid-cycle shellbed); and (3) 8 m of bioturbated, massive siltstone with scattered inner-middle shelf molluscs (highstand systems tract). The basal and upper contacts of the cycle are sharp, eroded surfaces on highstand siltstone of cycles 6 and 8, respectively, and both are penetrated by beds of the intertidal boring pholad *Barnea similis*.

3. The Castlecliff sequence model is powerful because of the predictive insight it offers into unconformity formation, sediment deposition, and faunal variation, under conditions of changing sea level. Application of the model allows part cycles (e.g., Castlecliff sequence 1, which consists of two transgressive systems tract formations only), and cycles with an "extra" subdivision (e.g., the Omapu Shellbed in Castlecliff sequence 4), to be identified and understood.

4. Recognition and definition of all 30 formational units in the Castlecliff section, as presented here, is an important prerequisite for examining alternative explanations of those units, and for questioning the favoured model of a Castlecliff motif sequence.

Formal lithostratigraphic classification does not of itself lead to a unique interpretation of either the sequence motif, or of the overall succession. For example, an inverse interpretation of the Castlecliff section is possible, whereby some or all of the sequence boundaries recognised by Abbott & Carter (1994) are reinterpreted as surfaces of forced regression, and the "transgressive systems tracts" above them reclassified as "regressive systems tracts" (cf. Naish & Kamp 1997). We considered such alternatives before arriving at the preferred sequence stratigraphic interpretation presented in Abbott & Carter (1994) and repeated in this paper. Time will tell which interpretation is more useful. Meanwhile, we provide this updated lithostratigraphic description of the section as the fundamental basis against which all alternative interpretations can be assessed.

ACKNOWLEDGMENTS

We thank the late Bill Cox, Audrey Cox and Glenys Wilson of Mowhanau Beach for their help and hospitality during fieldwork. This work has been supported by Special Research Grants from James Cook University, and by the Australian Research Council. We thank Alan Beu (Institute of Geological & Nuclear Sciences) for help and advice on Castlecliff stratigraphy and, together with Tim Naish, Brad Pillans and Tony Edwards, for making improvements to the draft manuscript.

REFERENCES

Abbott, S. T. 1992: The mid-Pleistocene Waiomio Shellbed (c. 500–600 ky), Wanganui Basin, New Zealand. *Alcheringa 16*: 171–180.

Abbott, S. T. 1994: Sedimentology of mid-Pleistocene cyclothems from Wanganui, New Zealand. Unpublished PhD thesis, James Cook University, Townsville, Australia.

Abbott, S. T. 1997a: Mid-cycle condensed shellbeds from mid-Pleistocene cyclothems, New Zealand: implications for sequence architecture. *Sedimentology 44*: 805–824.

Abbott, S. T. 1997b: Foraminiferal paleobathymetry and mid-cycle architecture of mid-Pleistocene depositional sequences, Wanganui Basin, New Zealand. *Palaios 12*: 267–281.

Abbott, S. T. 1998: Transgressive systems tracts and onlap shellbeds from mid-Pleistocene sequences, Wanganui Basin, New Zealand. *Journal of Sedimentary Research 68*: 253–268.

Abbott, S. T.; Carter, R. M. 1994: The sequence architecture of mid-Pleistocene (0.35–0.95 Ma) cyclothems from New Zealand: facies development during a period of known orbital control on sea-level cyclicity. *In*: de Boer, P. L.; Smith, D. G. *ed*. Orbital forcing and cyclic sequences. *International Association of Sedimentologists Special Publication 19*: 367–394.

Abbott, S. T.; Carter, R. M. 1997: Macrofossil associations from mid-Pleistocene cyclothems, Castlecliff, New Zealand: implications for sequence stratigraphy. *Palaios 12*: 188–210.

Abbott, S. T.; Haywick, D. W.; Carter, R. M.; Henderson, R. A. 1989: Facies signature of late Neogene eustatic sea-level fluctuations exemplified in Plio-Pleistocene cyclothems, North Island New Zealand. 28th International Geological Congress, Washington DC, abstracts. Pp. 2–3.

Beu, A. G.; Edwards, A. R. 1984: New Zealand Pleistocene and Late Pliocene glacio-eustatic cycles. *Palaeogeography, Palaeoclimatology, Palaeoecology 46*: 119–142.

Buchanan, J. 1870: On the Wanganui Beds (upper Tertiary). *Transactions of the New Zealand Institute 2*: 163–166.

Carter, R. M.; Abbott, S. T.; Naish, T.; Saul, G. 1996: Basin analysis of the cyclothemic record of oxygen-isotope stages 5–10, Wanganui Basin, western North Island, N.Z. *Transactions of the American Geophysical Union (EOS) 77 (46)*: F328 (abstract).

Emiliani, C. 1955: Pleistocene temperatures. *Journal of Geology 63*: 538–578.

Finlay, H. J.; Marwick, J. 1947: New divisions of the Upper Cretaceous and Tertiary in New Zealand. *New Zealand Journal of Science & Technology B28*: 228–236.

Fleming, C. A. 1947: Standard sections and subdivisions of the Castlecliffian and Nukumaruan Stages in the New Zealand Pliocene. *Tansactions of the Royal Society of New Zealand 76*: 300–326.

Fleming, C. A. 1953: The geology of the Wanganui Subdivision, Waverley and Wanganui sheet districts (N137 & N138). *New Zealand Geological Survey Bulletin 52*: 362 p.

Fleming, C. A. *ed*. 1955: Océania, Fasc. 4, New-Zealand. *In*: Lexique Stratigraphique International. Vol. VI. Paris, Centre National de la Recherche Scientifique. 527 p.

Graham, I. J.; Ditchburn, R. G.; Whitehead, N. E. 1998: ^{10}Be spikes in Plio-Pleistocene cyclothems, Wanganui Basin, New Zealand: identification of the local flooding surface (LFS). *In*: Carter, R. M. et al. *ed*. Sequence stratigraphy in the Plio-Pleistocene. *Sedimentary Geology 122*: 193–215.

Hochstetter, F. von 1864: Geologie von Neu-Seeland. Beitrage zur Geologie der Provinzen Auckland und Nelson. *Novara Expedition, Geol. Theil. 1 (1)*. 274 p.

Hutton, F. W. 1873: Catalogue of the Tertiary Mollusca and Echinodermata of New Zealand in the collection of the Colonial Museum. Wellington, Government Printer. 48 p.

Hutton, F. W. 1886: The Wanganui System. *Transactions of the New Zealand Institute 18*: 336–337.

Kidwell, S. M. 1991: The stratigraphy of shell concentrations. *In*: Allison, P. A.; Briggs, D. E. G. *ed.* Taphonomy: releasing the data locked in the fossil record. New York, Plenum Press. Pp. 211–290.

Mantell, G. A. 1850: Notice of the remains of *Dinornis* and other birds, and of fossil and rock-specimens, recently collected by Mr Walter Mantell in the Middle Island of New Zealand, with additional notes on Northern Island. *Quarterly Journal of the Geological Society of London 6*: 319–342.

Naish, T. R.; Kamp, P. J. J. 1997: Sequence stratigraphy of sixth-order (41 k.y.) Pliocene-Pleistocene cyclothems, Wanganui Basin, New Zealand: a case for the regressive systems tract. *Geological Society of America Bulletin 109*: 978–999.

Park, J. 1887: On the geology of the western part of Wellington Provincial District and part of Taranaki. *Reports of the geological explorations of the New Zealand Geological Survey (1886–87) 18*: 24–73.

Park, J. 1905: On the marine Tertiaries of Otago and Canterbury, with special reference to the relations existing between the Pareora and Oamaru Series. *Transactions of the New Zealand Institute 37*: 489–551.

Pillans, B. 1983: Upper Quaternary marine terrace chronology and deformation, south Taranaki, New Zealand. *Geology 11*: 292–297.

Pillans, B.; Abbott, S. T.; Beu, A. G.; Carter, R. M. 1991: A possible Lower/Middle Pleistocene boundary stratotype in Wanganui Basin, New Zealand. Abstracts, INQUA Conference, China.

Pillans, B. J.; Roberts, A. P.; Wilson, G. S.; Abbott, S. T.; Alloway, B. V. 1994: Magnetostratigraphic, lithostratigraphic and tephrostratigraphic constraints on Lower and Middle Pleistocene sea-level changes. *Earth & Planetary Science Letters 121*: 81–98.

Plint, A. G. 1988: Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: their relationship to relative changes in sea-level. *In*: Wilgus, C. K. et al. *ed.* Sea-level changes: an integrated approach. *Society of Economic Paleontologists and Mineralogists Special Publication 42*: 357–370.

Saul, G.; Naish, T. R.; Abbott, S. T.; Carter, R. M. 1999: Sedimentary cyclicity in the marine Plio-Pleistocene of Wanganui Basin (N.Z.): sequence stratigraphic motifs characteristic of the last 2.5 Ma. *Geological Society of America Bulletin 111 (4)*: in press.

Shackleton, N. J.; Opdyke, N. D. 1973: Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperatures and ice volumes in a 10^5 and 10^6 year scale. *Quaternary Research 3*: 39–55.

Shane, P. A. R.; Black, T. M.; Alloway, B. V.; Westgate, J. A. 1996: Early to middle Pleistocene tephrochronology of North Island, New Zealand: implications for volcanism, tectonism, and paleoenvironments. *Geological Society of America Bulletin 108*: 915–925.

Te Punga, M. T. 1952: The geology of Rangitikei Valley. *New Zealand Geological Survey Memoir 8*. 44 p.

Thomson, J. A. 1916: On stage names applicable to the divisions of the Tertiary in New Zealand. *Transactions of the New Zealand Institute 48*: 28–40.

Turner, G. M.; Kamp, P. J. J. 1990: Palaeomagnetic location of the Jaramillo Subchron and the Matuyama-Brunhes transition in the Castlecliffian stratotype section, Wanganui Basin, New Zealand. *Earth & Planetary Science Letters 100*: 42–50.

Vail, P. R.; Audemard, F.; Bowman, S. A.; Eisner, P. N.; Perez-Cruz, C. 1991: The stratigraphic signatures of tectonics, eustasy and sedimentology—an overview. *In*: Einsele, G.; Ricken, W.; Seilacher, A. *ed.* Cycles and events in stratigraphy. Springer-Verlag. Pp. 617–659.