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Title **Lithofacies, paleoenvironments and elements of sequence architecture, Late Oligocene - earliest Miocene Castle Craig Subgroup (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 Late Oligocene Castle Craig Subgroup (Orahiri Formation and Otorohanga Limestone) within the Late Eocene – Earliest Miocene Te Kuiti Group in the Waikato-King Country Basin in central-western North Island, New Zealand. Detailed field investigations have identified 12 lithofacies within the Castle Craig Subgroup, which have been grouped into three lithofacies associations named limestone, mixed carbonate-siliciclastic sandstone, and siliciclastic sandstone after the dominant lithologies. In areas south of Aotea Harbour the subgroup comprises a wide variety of limestone types with variable siliciclastic content, dominated by coarse skeletal rudstone/grainstone, with aggregate stratigraphic thicknesses of up to 100 m. These sediments accumulated at shelf depths in a moderate to high-energy tidal seaway. Around Raglan Harbour and in areas to the north, the subgroup comprises predominantly planktic foraminiferal-rich packstone to wackestone and calcareous siltstone/marl that accumulated mainly in slope/upper bathyal settings.

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Introduction

The Castle Craig Subgroup contains the main limestone formations within the Te Kuiti Group, which is a late Eocene – earliest Miocene mixed carbonate-siliciclastic non-marine to shelf marine succession that accumulated in the Waikato - King Country Basin in central-western North Island, adjacent to Taranaki Basin (Figs 1 and 2). The limestone units within the Castle Craig Subgroup are amongst the most spectacular limestone occurrences within the New Zealand Cenozoic record and are an important economic resource as well as being of importance for tourism and recreation in the region. The characteristics and composition of these limestone units played a large part in the development of a global model for non-tropical or cool-water shelf carbonate sediments (Nelson 1978a, b, 1988).

The purpose of this report is to document the stratigraphy and lithofacies of the Castle Craig Subgroup, as well as elements of the sequence stratigraphic and paleogeographic development of this upper part of the Te Kuiti Group. In the first part of the report a lithofacies scheme is developed for the subgroup, which is followed by their systematic description and interpretation in terms of related depositional environments. Particular emphasis is given to the horizontal and vertical distribution of the lithofacies, and from them, determination of the broad stratal patterns. An important feature of the subgroup is the occurrence of an extensive unconformity (sequence boundary) at the base of the Castle Craig Subgroup. The sedimentary evolution of the Castle Craig Subgroup has been relatively complex, but can be divided into two main phases of development. In the first phase the sedimentation patterns were characterised by shelf progradation to the north and east; in the second there is a regional transition to aggradation followed by retrogradation towards the south but with continuing progradation to the east, reflecting a rise in relative sea-level, probably driven mainly by tectonic subsidence. The prior stratigraphic distinctions between the Orahiri Formation and Otorohanga Limestone are reviewed and new insights are presented

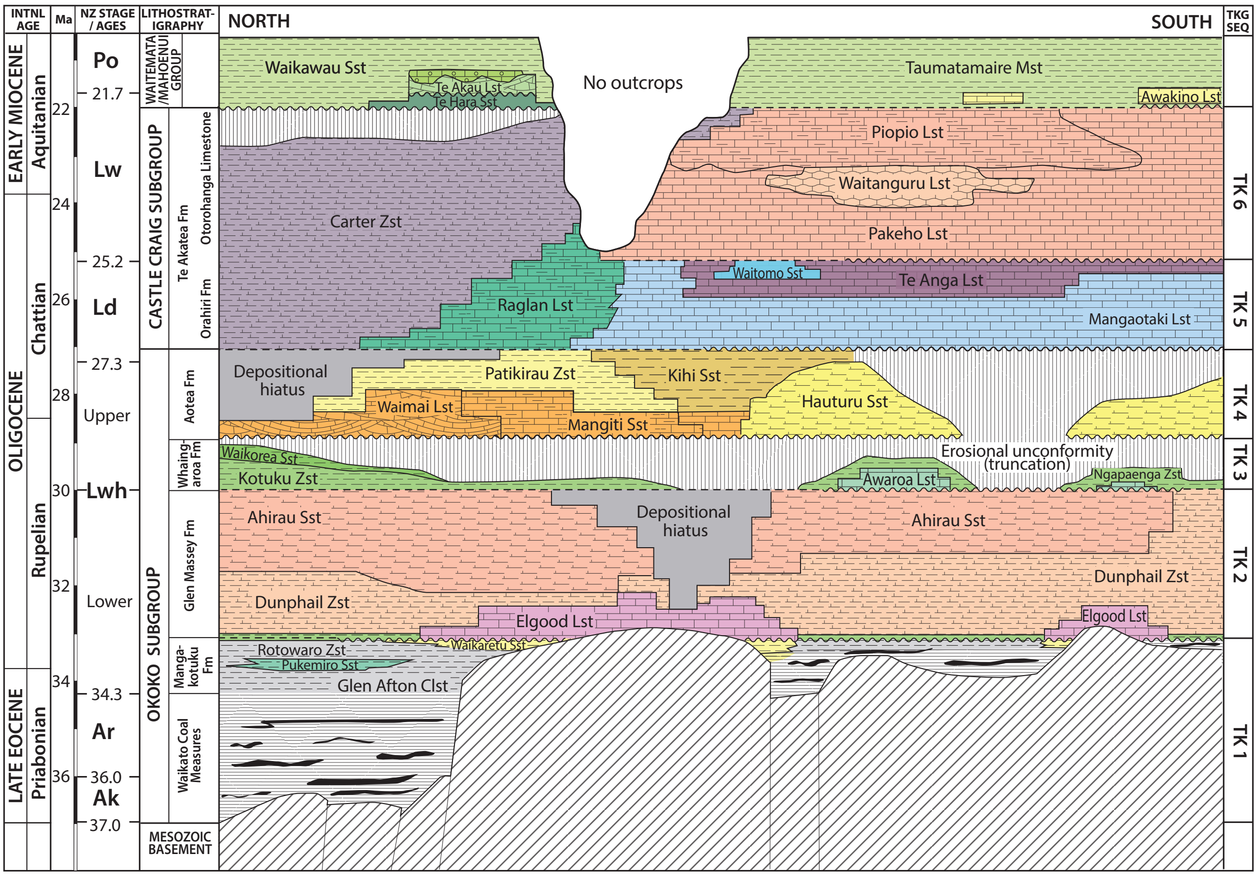


Fig. 1: A new chronostratigraphic scheme for the Te Kuiti Group and the transition up into the Waitemata and Mahoenui groups. Note the occurrence of six unconformity-bound sequences (TK 1 – TK6). Figure from Tripathi et al. (2008) based on biostratigraphy in Kamp et al. (2014c).

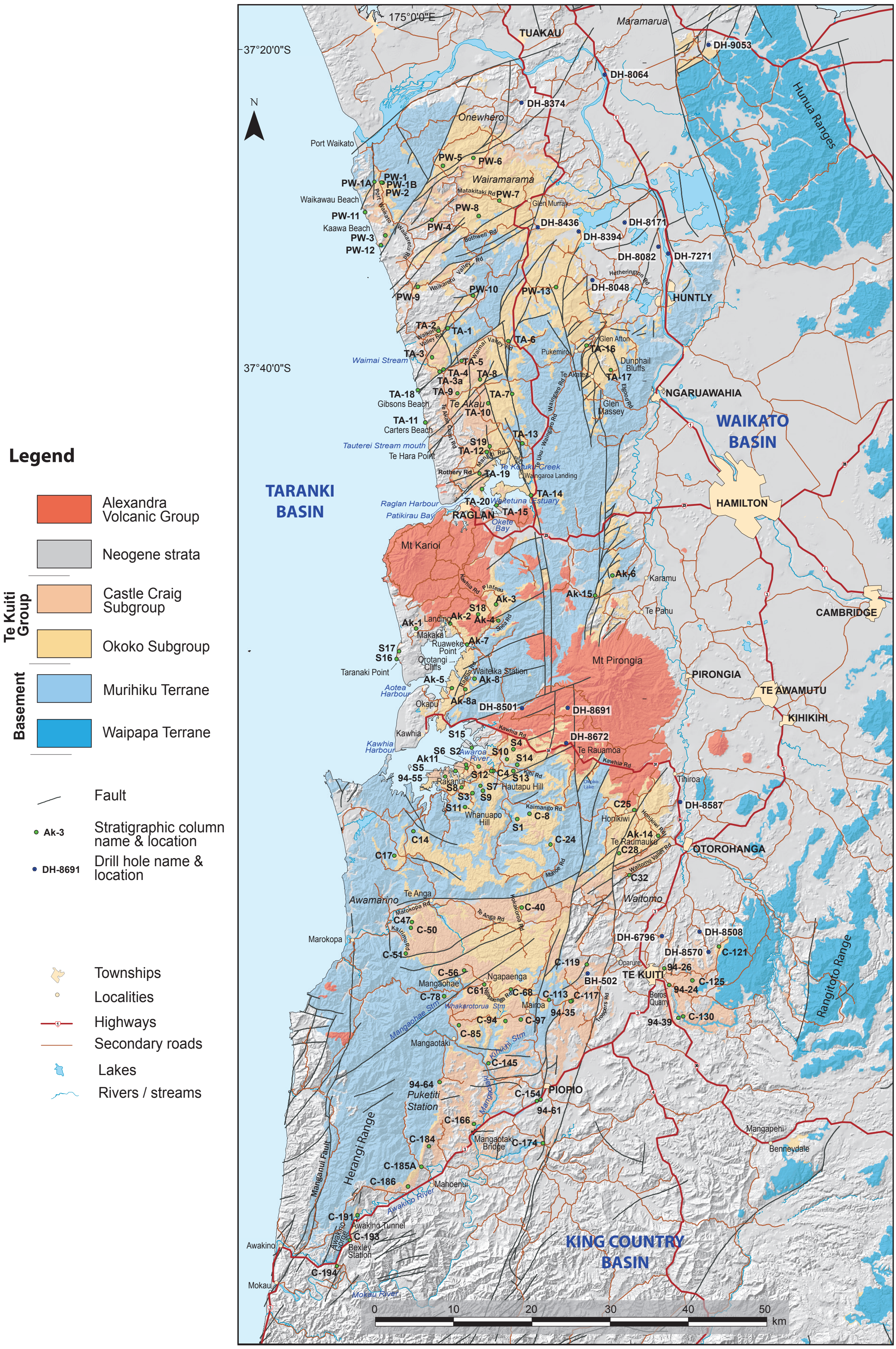


Fig. 2: Map of central-western North Island showing the distribution of the Te Kuiti Group and other units. Note the location of key stratigraphic columns.

about how the various limestone facies are related across (east-west) and along (north-south) the basin.

Thick limestone accumulations in the upper parts of the Te Kuiti Group have been interpreted in the past as the result of southward-directed marine inundation of a basement high, and considered to reflect tectonically quiescent conditions. This transgressive phase was regarded as part of New Zealand-wide submergence and marine inundation (Fleming 1979; Nelson & Hume 1987). However, here we regard syndepositional tectonism (reverse faulting and uplift of the Herangi basement high) as the main driving force behind prolific limestone accumulation in the Castle Craig Subgroup. This report aims to develop a better understanding of the role of tectonism, relative sea-level change, and sediment supply on accumulation of the subgroup.

Lithofacies analysis

The Castle Craig Subgroup contains a broadly transgressive sedimentary record of Duntroonian (Late Oligocene, 27.3 – 25.2 Ma) to Waitakian (latest Oligocene - earliest Miocene, 25.2 – 21.7 Ma) age, overlain by a thick (up to 1300 m) Early Miocene (Otaian, 21.7-18.7 Ma) terrigenous succession comprising the Waitemata Group in the north and the Mahoenui Group in the south (Fig. 1). The Castle Craig Subgroup comprises three major lithostratigraphic units: the Te Akatea Formation, the Orahiri Formation and the Otorohanga Limestone (Fig. 1). These formations unconformably, or conformably in deeper water settings, overlie largely terrigenous facies of the Aotea Formation, except in southeastern parts of the basin where they progressively onlap the Piopio High (basement). The southern and central regions contain a spectrum of shelf carbonate lithofacies represented by the Orahiri Formation and Otorohanga Limestone (Figs 3 and 4). The northern region contains the Te Akatea Formation, a sequence of predominantly deep-water (outer shelf to upper bathyal) marl and marly limestone, with rare sandy siltstone beds. The transition between the shelfal Orahiri Formation and/or Otorohanga Limestone and the basinal Te Akatea Formation is largely concealed by Pliocene-Early Pleistocene volcanics of the Alexandra Volcanic Group (Fig.2) or has been removed by modern erosion, although a few isolated outcrop windows do occur in the inland parts of the Aotea-Kawhia area.

In the areas east and south of Kawhia Harbour, the rocks belonging to the Castle Craig Subgroup form ‘flaggy’ to massive nearly vertical limestone cliffs up to 80 m high with karst topography. Earlier investigations of these skeletal limestone successions have established facies classification schemes for them (e.g. Barrett 1967; Hopkins 1970; Nelson 1973, 1978a, b). Nelson (1973, 1978a) in particular developed a lithofacies scheme for the limestone formations, which has been used as a basis for this study. Paleocurrent and associated lithofacies analysis carried out by Anastas (1997) has also proved to be useful in the analysis undertaken here. In the northern region (Raglan-Te Akau), earlier work has established two broad facies for the Te Akatea Formation, the lower part being dominated by marly limestone (Raglan Limestone Member), and middle to upper parts by calcareous siltstone/marl (Carter Siltstone Member) (Kear 1987; White & Waterhouse 1993). In the northernmost areas (Port Waikato), the formation is comprised entirely of calcareous siltstone/marl with localised occurrences of bioturbated glauconitic and phosphatic nodule deposits.

Twelve lithofacies are described here for the Castle Craig Subgroup. These are grouped into three lithofacies associations on the basis of sedimentological and faunal features. The associations are named limestone, mixed carbonate-siliciclastic sandstone, and mixed carbonate-siliciclastic siltstone after the dominant lithologies. Typical expressions of the limestone lithofacies in the field are illustrated in Figs 5 to 7 and related photomicrographs in Fig. 8. The typical field expression of the mixed carbonate-siliciclastic lithofacies is shown in Fig. 9. Their character reflects accumulation on different parts of a shelf to upper slope ramp that deepened northwards along central-western North Island. The diagnostic characteristics of each lithofacies and inferred environments of deposition are summarised in Table 1 and their broad distribution within formations is summarised in Table 2. Detailed descriptions of

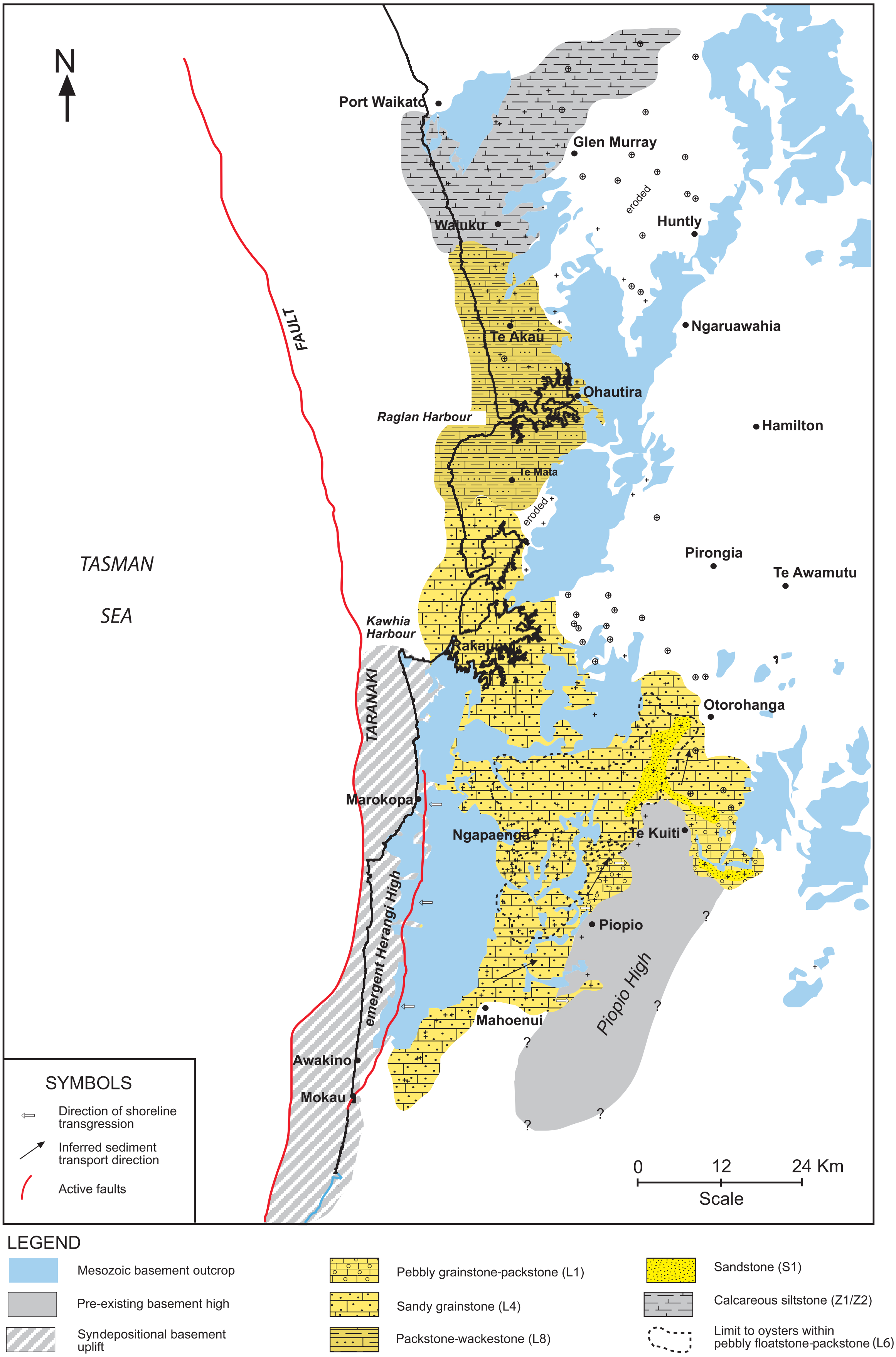


Fig. 3: Distribution of main lithofacies in the lower Castle Craig Subgroup in relation to major paleogeographic elements. The lithofacies distribution depicted between Kawhia and Raglan Harbours is partly inferred because of poor exposures.

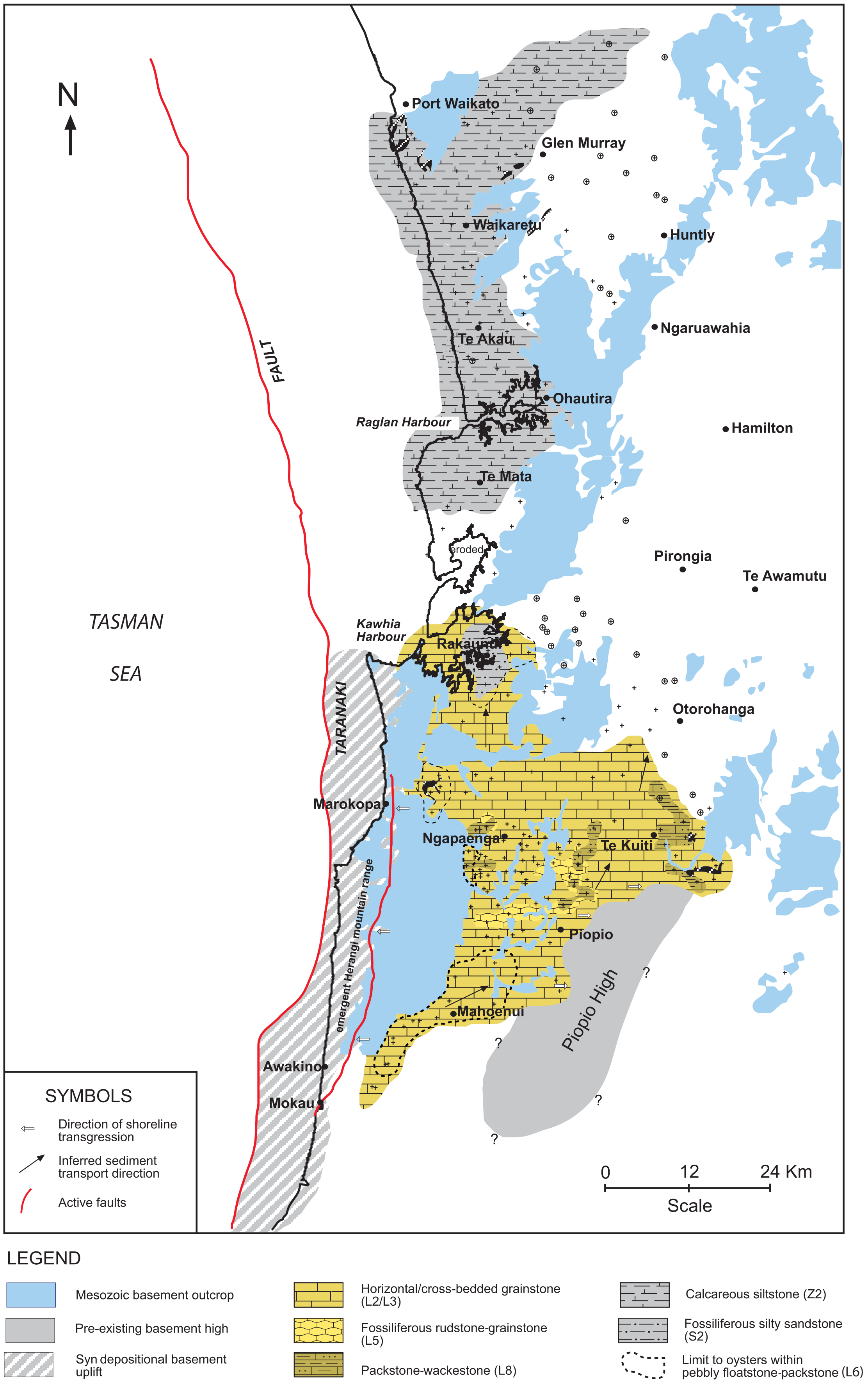


Fig. 4: Distribution of main lithofacies in the upper Castle Craig Subgroup in relation to major paleogeographic elements. The lithofacies distribution depicted between Kawhia and Raglan Harbours is partly inferred because of poor exposures.

these lithofacies and their inferred depositional paleoenvironments are given in the following sections. The vertical and horizontal relationships between the various lithofacies are depicted in north-south and east-west transects in Figs 10 to 15.

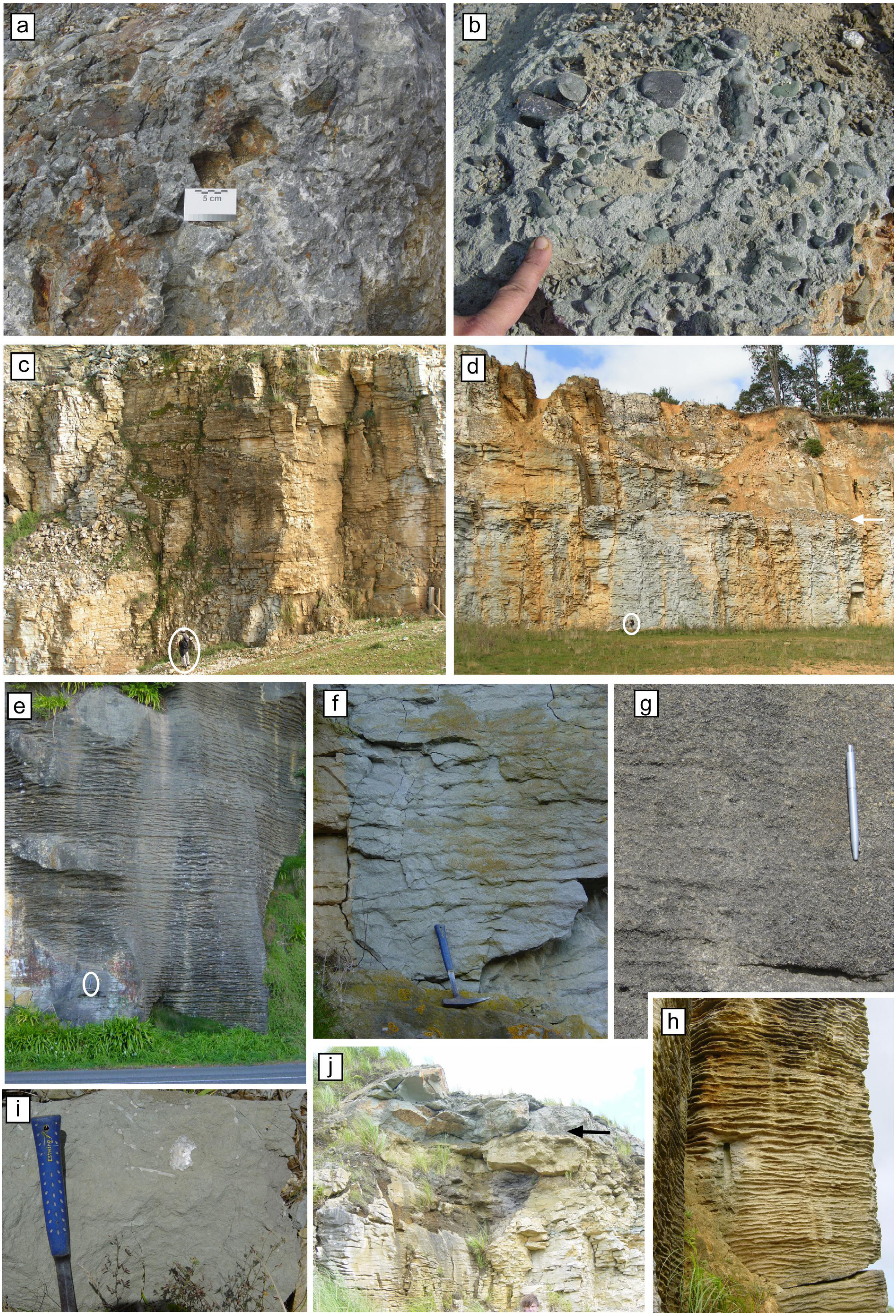
Fig. 5: (facing page) Outcrop photographs illustrating typical field expression of lithofacies identified within the Castle Craig Subgroup across the southern central region of the study area. (a) Basal Pebbly grainstone-packstone (L1) unit located near the lower contact with basement. This conglomeratic unit is up to 1 m thick comprised of subangular to subrounded clasts mainly supported by calcareous matrix that includes calcareous red algae and rare rhodoliths. Serpentine Quarry (R17/859934), Aria. (b) Pebbly grainstone-packstone (L1) unit marking the lower contact of Castle Craig Subgroup with the Aotea Formation. Note various rounded and subrounded basement pebbles and occasional cobbles supported by glauconitic sandy grainstone matrix. Mangaotaki Bridge section (C-166). (c) Tabular cross-bed sets of grainstone (L2). Person for scale. Limestone quarry at Waitomo Valley Road (C-32). (d) Cross-bedded grainstone (L2) overlain by horizontally bedded grainstone (L3). Person for scale. Limestone quarry at Waitomo Valley Road (C-32). (e) Thinly bedded sandy grainstone-packstone (L4) succession. Hammer for scale. SH 3, near Mangaotaki Bridge (C-166). (f) Freshly exposed surface exhibiting massive to irregularly bedded sandy grainstone-packstone (L4) with siliciclastic-rich seams. SH3 near Mangaotaki Bridge (C-166). (g) Massive sandy grainstone-packstone (L4) with abundant medium to coarse quartz sand grains exposed at the surface (C-51). Awamarino. (h) Horizontal to low-angle cross-beds defined by preferential weathering of siliciclastic-rich seams in sandy grainstone-packstone lithofacies (L4). Limestone quarry, Raukanui Peninsula (AK-11). (i) Fossiliferous silty sandstone (S2) with abundant bivalve fragments in a muddy matrix. Limestone quarry, Raukanui Peninsula (AK-11). (j) Sharp vertical transition (arrow) between irregularly bedded Pebbly oyster floatstone-packstone (L6) and overlying Fossiliferous silty sandstone (S2) unit. Limestone quarry, Raukanui Peninsula (AK-11).

Limestone association (L1 - L8)

The carbonate-dominated lithofacies in the Castle Craig Subgroup comprise the bulk of the thickness of stratigraphic sections in the central and southern regions of central-western North Island. In particular, they comprise the major part of the Orahiri Formation and all of the Otorohanga Limestone, with a combined thickness of up to 100 m. In both the Orahiri Formation and Otorohanga Limestone the limestone facies association is characterised by a wide variety of limestone types, ranging from massive to moderately bedded sandy and pebbly limestone through to cross-bedded and pure skeletal flaggy limestone. The limestone association also constitutes the Raglan Limestone Member of the Te Akatea Formation in the Raglan Harbour area that grades laterally into the thinly-bedded to massive calcareous siltstone/marl of the Carter Siltstone Member farther to the north. The Raglan Limestone Member is a packstone to wackestone rich in planktic and benthic foraminifera, echinoderm and occasional bivalve fragments. The limestone facies comprising the Orahiri Formation and Otorohanga Limestone are typically skeletal calcarenite or calcirudite composed predominantly of fragmental bryozoan and echinoderm remains, benthic (rarely planktic) foraminifera and epifaunal bivalves, with lesser contributions from calcareous red algae, brachiopods and barnacles. An exception is planktic foraminiferal-rich packstone/wackestone occurring in the uppermost part of the Otorohanga Limestone in parts of the southern region (Nelson 1973, 1978a).

L1. Pebbly grainstone-packstone

The Pebbly grainstone-packstone lithofacies (L1), ranging from 0.5 to 1.5 m in thickness, is limited to the southern region, particularly where Orahiri Formation or Otorohanga Limestone onlaps basement. This facies is characterised by moderate to poorly sorted, rounded-subrounded pebbles and cobbles (Fig. 5a, b), with common calcareous red algae, oysters, pectinids and other coarse bivalve skeletal hash. Other common biota includes echinoderm and bryozoan fragments, and large benthic foraminifera such as *Amphistegina* sp. This facies occurs in a stratigraphic position similar to that occupied by Basal Beds (OrA1)/(OtA1) at the base of Orahiri/Otorohanga Limestone, as described and logged by Nelson (1973, 1977, 1978a) near Te Kuiti (e.g. C-114, C-124, C-130) and Piopio (e.g. C-104, C-174). The distribution of this facies at the contact with basement is illustrated in Fig. 3.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j

The L1 facies has also been recorded at the sharp broadly undulatory erosional contact with the underlying Aotea Formation at localities C-32 (Fig. 13), BH-502 (Fig. 14), C-191, C-166 (Fig. 15), and with Glen Massey Formation at localities C-50 (Fig. 12) and C-47 (Fig. 13). At these sites the facies comprises abundant subrounded to well rounded pebbles and cobbles derived mainly from basement, infilling scours up to 30 cm deep. Also commonly associated are vertical to subvertical burrows extending down from the contact and coarse bioclastic lag (commonly pectinid, oyster and echinoderm fragments).

Interpretation: The pebbly grainstone-packstone lithofacies (L1) overlying basement is similar to the Pebbly grainstone (L1) lithofacies of the Aotea Formation, inferred to have been deposited during coastal onlap (Kamp et al. 2014b). Coralline algae, large benthic foraminifera (*Amphistegina*) and other biogenic components in this facies suggest a high energy inner shelf environment (e.g. Nelson et al. 1988a; James et al. 1992).

L2. Cross-stratified grainstone

Cross-stratified grainstone (L2) packages are 0.3 - 4.5 m thick and usually interbedded with horizontally bedded and/or sandy grainstone (Lithofacies L3, L4). Much of the observed cross-stratification occurs in the Mangaotaki Limestone Member (Orahiri Formation) and in Otorohanga Limestone (Fig. 5c, d) in the area between Kawhia Harbour and Awakino (localities C-50, AK-11, AK-12 in Fig. 12; C-32 in Fig. 13). This facies is similar to Cross-stratified grainstone Lithofacies L2 described in the Waimai Limestone Member of Aotea Formation in the northern region (Kamp et al. 2014b). However, this facies in Orahiri Formation and Otorohanga Limestone differs from the Waimai Limestone in that cross-bedded units are lenticular bodies surrounded by horizontally bedded units, whereas L2 in Waimai Limestone comprises laterally continuous tabular cross-bedded units (Anastas 1997). The cross-stratification contains complex horizontal and inclined surfaces that define the bedding planes and set boundary surfaces, often having relatively high concentrations of siliciclastic material and glauconite. These rocks are generally coarse calcarenite dominated by bryozoans, echinoderms and benthic foraminifera with lesser amounts of bivalve, barnacle and coralline red algal material (Fig. 8b) (Nelson 1973; Anastas 1997; Anastas et al. 1997).

Interpretation: The wide distribution of largely unidirectional cross-stratified lenticular units in Orahiri Formation and Otorohanga Limestone suggest that they were produced by the migration of subaqueous megadunes and sand waves within a sea-way between basement highs. These bedforms are inferred to have developed in response to strong seaway-parallel tidal and bottom currents (ENE in the southern region to NNE in the central region (Anastas 1997)) guided by rugged topography. The presence of benthic foraminifera (*Amphistegina*) and coralline red algae in many of the units implies inner to mid shelf depths (e.g. Nelson et al. 1988a; James et al. 1992).

L3. Horizontally bedded grainstone

The Horizontally bedded grainstone lithofacies (L3) forms units up to tens of metres thick and constitutes much of the upper part of Orahiri Formation and most of Otorohanga Limestone (e.g. C-50 and AK-11 in Fig. 12; C-47, C-40, DH-6796 in Fig. 13; BH-502, C-126 in Fig. 14). The horizontally bedded limestone is locally intercalated with Cross-stratified grainstone (L2) and/or Sandy grainstone-packstone (L4) (Fig. 5d). The distribution of lithofacies L3 and L2 is shown in Fig. 4. Moderately to well developed flagginess is characteristic of this facies, and individual flag thicknesses range from 2 - 25 cm. Bedding surfaces (1 - 1.5 cm thick) are enriched in siliciclastic minerals and exhibit gradational transitions into flags. Apart from the rare occurrence of *Scolicia* and *Thalassinoides* burrows, flagstones internally are massive. This facies is similar to the Flaggy Limestone Beds (OrB1), Lower Flaggy Limestone Beds (OtA2) and Upper Flaggy Limestone Beds (OtC1) of the Orahiri Formation and Otorohanga Limestone described by Nelson (1978a). The rocks are mainly coarse-grained and compositionally comprise bryozoans, echinoderms, benthic foraminifera, and occasional bivalves and calcareous red algae, with variable quantities of glauconite and quartz (Nelson 1973).

Interpretation: The horizontally bedded grainstone (Lithofacies L3) reflects deposition in a wave and tide swept inner to mid shelf setting. Intercalations with cross-bedded limestone lithofacies (L2) suggest conditions fluctuated from wave to current-dominated on the shelf, and its lateral transition into L2 indicates that the setting varied locally due to complex topography (Anastas 1997).

L4. Sandy grainstone-packstone

The Sandy grainstone-packstone lithofacies (L4) occurs in the lower part of Orahiri Formation and comprises the majority of Mangaotaki Limestone Member (Orahiri A of Nelson 1978a). Lithofacies L4 comprises much of the spectacular cliff-forming unit in western parts of the basin, ranging in thickness from 4 to 60 m (e.g. AK-12, AK-11 in Fig. 12; C-47, C-40 in Fig. 13; C-56, C-61, C-68, C-126 in Fig. 14; C-185A, C-166 in Fig.15). This facies is similar in character to the Massive Sandy Limestone Beds (OrA3)/(OrB4), Upper Banded Sandstone Beds (OrA4) and Bimodal-sandy Limestone Beds (OrA5) of the Orahiri Limestone, described by Nelson (1978a). The distribution within the basin of the Sandy grainstone-packstone lithofacies is shown in Fig. 3. Lithofacies L4 exhibits similarity to the Sandy-silty grainstone lithofacies (L4) described previously in the Aotea Formation (Kamp et al. 2014b), however unlike that facies, there is a lack of discrete sandstone beds. The Sandy grainstone-packstone lithofacies L4 is typified by massive or irregular to tabular bedded units up to 2.5 m thick. Contacts between the beds tend to be diffuse. In places, resistant beds ("flags") and recessive seams ("interflags") are common, giving the rocks a layered to wavy flagged appearance (Fig. 5e - h). Compositionally, Lithofacies L4 is skeletal dominated, with variable quantities (5-50%) of fine to coarse quartz sand. The terrigenous grain size distribution can be bimodal with fine to medium and coarse sand. Bioclasts include co-dominant bryozoans and echinoderms, and large benthic foraminifera (*Amphistegina*), with minor proportions of calcareous red algae and bivalves (Fig. 8a, d- f) (Nelson 1973, 1978a).

Interpretation: This facies is inferred to have accumulated on a moderate to high energy wave dominated inner to mid shelf. The presence of large Amphistegina and calcareous red algae, coupled with an appreciable quartz sand component, are supportive of a nearshore shallow marine depositional setting (e.g. Nelson et al. 1988a; James et al. 1992).

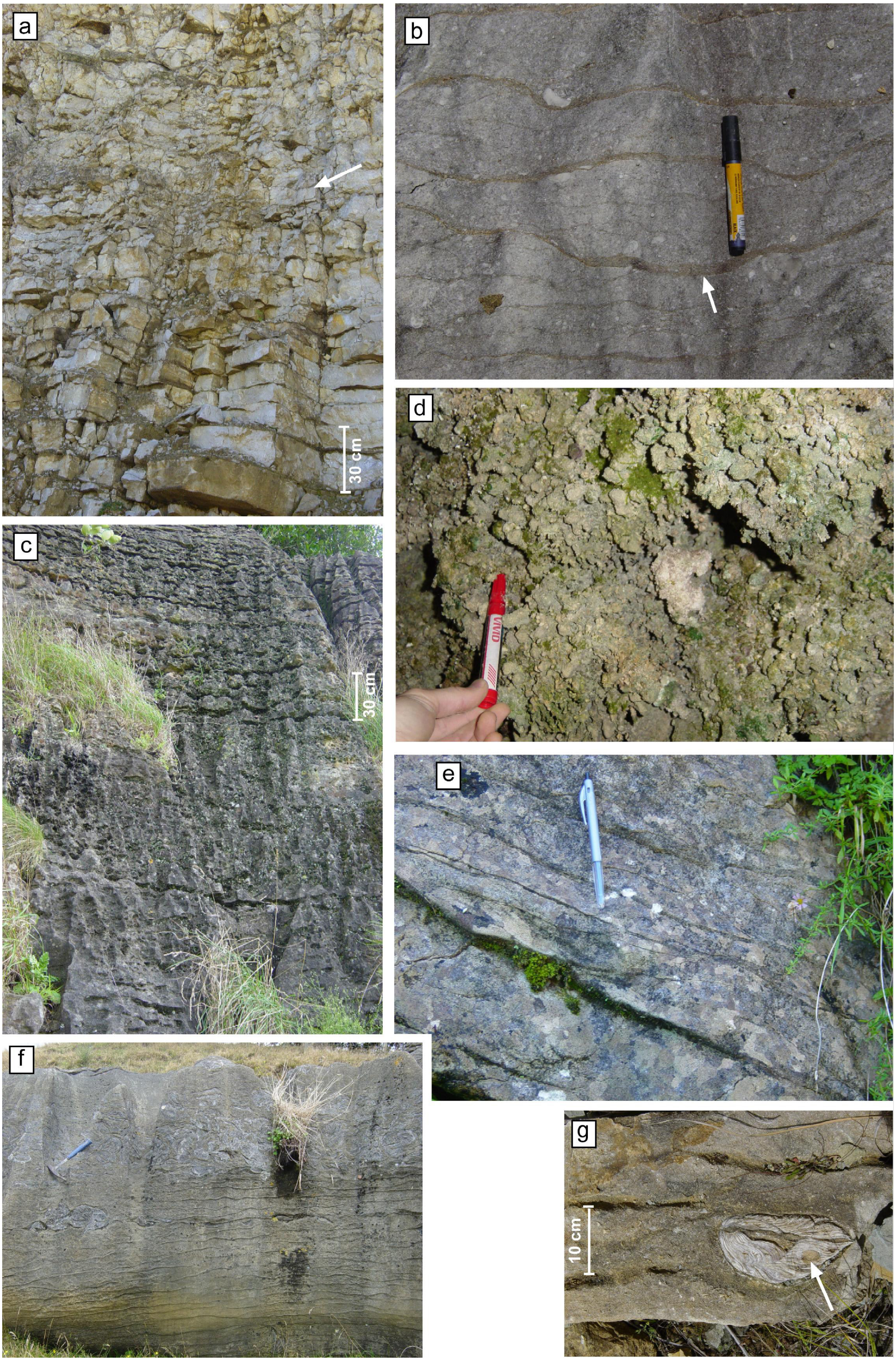
L5. Massive to irregularly bedded fossiliferous rudstone-grainstone

The Massive to irregularly bedded, fossiliferous rudstone-grainstone lithofacies L5 forms isolated 0.2-12 m thick units (e.g. C-56, BH-502 in Fig. 14) and comprises much of the Waitanguru Limestone Member (Otorohanga B; Nelson 1978a). Lithofacies L5 is similar to the Blocky Limestone Beds (OtB1), Packed Knobbly Limestone Beds (OtB2) and Open Knobbly Beds (OtB3) of the Otorohanga Limestone described by Nelson (1978a). The distribution of L5 facies is shown in Fig. 4. It is characterised by a peculiar blocky to irregularly bedded "knobbly" weathering appearance, although in places massive to honeycombed weathered units with no obvious bedding have also been observed (Fig. 6a-d). The rocks are typified by light blue to white, coarse to very coarse spar cemented skeletal-rich grainstone with whole or fragmented bivalves (including oysters and pectinids) and bryozoan colonies. Large benthic foraminifera, echinoderm fragments, occasional calcareous red algae, and gastropods form minor components (Nelson 1978a; Anastas 1997).

Interpretation: This lithofacies accumulated in a high energy shelf setting with substantial wave and/or current agitation indicated by the presence of isopachous sea floor cements (Nelson & James 2000). Large *Amphistegina* and calcareous red algae, coupled with the coarse to very coarse texture, also indicate shallow shelf depositional conditions (e.g. James et al. 1992).

L6. Pebbly oyster floatstone-packstone

The Pebbly oyster floatstone-packstone lithofacies (L6) occurs mainly within Te Anga Limestone Member (OrB; Nelson 1978a). This facies is often interbedded with horizontally bedded grainstone (L3) and/or sandy grainstone-packstone (L4) (e.g. C-40 in Fig. 13; C-56, C-61, C-68 in Fig. 14; C-185A, C-166 in Fig. 15), and forms units up to 9 m thick. The distribution of Lithofacies L6 is noted in Figs 3 and 4. It is similar



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c
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e
f
g
30 cm
30 cm
10 cm

Fig. 6: *(facing page)* Field examples of lithofacies within Castle Craig Subgroup from the south-central region. (a) Cavernous weathering (pointed by arrow) characterises an Irregularly bedded rudstone-grainstone (L5) unit overlying prominent Flaggy grainstone (L3). Oparure Limestone quarry (C-119). (b) Irregularly bedded, fossiliferous rudstone-grainstone (L5). Arrow points to slightly recessed siliciclastic-rich bedding plane layer defining the flag geometry. Mangaohae Stream section (C-56). (c) Massive to medium bedded, fossiliferous rudstone-grainstone (L5). Cavernous/ honeycombed appearance is due to the preferential weathering of skeletal components. Waipuna Road, Kawhia Harbour (R15/728419). (d) Massive bryozoan grainstone (L5) showing open grain fabric with conspicuous visual intergranular porosity. Bexley Station tunnel, Awakino Gorge (C-193). (e) Conglomeratic limestone (L7) with abundant highly irregular, angular to subangular limestone and basement clasts (dark grey), ranging in size from 1-6 cm. Clasts are chaotically orientated suggesting transport by debris flow. Near Awakino Tunnel SH-3 (C-191). (f) Hammer rests on Pebbly oyster floatstone-packstone bed (L6) overlying Massive to irregularly bedded sandy grainstone (L4). Mairoa (C-97). (g) Irregularly bedded pebbly oyster floatstone-packstone (L6) unit showing close-up of oyster shell with tubular boring (pointed by arrow) infilled with host limestone. Limestone quarry, Raukanui Peninsula (AK-11).

to the Oyster Beds (OrB2) and Fossil-hash Beds (OrB5) of Orahiri Formation described by Nelson (1978a). The presence of large articulated and disarticulated oysters (>10 cm wide and up to 25 cm long), randomly scattered or clustered in laterally discontinuous beds commonly 30-100 cm thick, is the diagnostic feature of this lithofacies (Fig. 6f). Oyster shells are commonly bored (Fig. 6g). Coarse skeletal fragments, especially of oysters, pectinids and to a lesser extent bryozoans and echinoderms, are commonly associated with this facies (Fig. 8c). It generally consists of abundant interstitial micrite matrix. Subangular to subrounded pebbles are commonly scattered throughout the rock or occur as discrete bands. The uppermost parts of Pebbly oyster floatstone-packstone units in the Te Anga Limestone at Te Anga, Ngapaenga and Awakino are capped by beds with distinct large fragmented oysters, pectinids and shell hash with occasional *Flabellum* and shark's teeth, and common limonitised pebbles. This facies occurs in association with a sharp upper erosional surface with local relief of tens of centimetres (e.g. C-40 in Fig.13; C-56, C-68 in Fig. 14; C-191 in Fig. 15).

Interpretation: Lithofacies L6 with its oyster biostromes/banks and abundant pebble lags accumulated in a current-swept inner to mid shelf depositional paleoenvironment (Nelson 1978b; Nelson et al. 1983). The disarticulated and random orientation of oysters, a matrix-supported fabric, and the presence of pebbles suggest periodic reworking, probably as a result of storm currents (Anastas 1997). The presence of micrite matrix may appear anomalous to the high-energy environment for this facies but it is a result of entrapment within the oyster banks. The oyster banks in Foveaux Strait between South Island and Stewart Island (Fleming 1952) may be an analogue for the oyster banks in Lithofacies L6 (Nelson et al. 1983).

L7. Limestone conglomerate

The Limestone conglomerate lithofacies (L7) occurs mainly in the upper part of the Orahiri Formation at Awakino Tunnel (e.g. C-191 in Fig. 15). This lithofacies is the same as the Limestone-in-Limestone Beds (OrB6) described by Nelson (1978a) and Nelson et al. (1994). They range from 0.5 – 3 m thick, are interbedded with sandy irregularly flaggy grainstone Lithofacies L4, and are overlain by Pebbly-oyster floatstone-packstone Lithofacies L6. Facies L7 is characterised by the presence of 1-10 cm-size irregularly shaped calcareous sandstone and limestone intraclasts, and rounded subrounded pebbles derived from basement (Fig. 6e). The sandstone and limestone clasts are commonly encrusted by calcareous red algae and are frequently pholad bored and have been infilled with micritic to coarse sparry calcite cement. Texturally the rocks are coarse to very coarse grainstones. Bioclasts are dominated by coarse bryozoan fragments, benthic foraminifera, echinoderms and minor proportions of calcareous red algae (Nelson 1973, 1978a; Nelson et al. 1994).

Interpretation: This lithofacies results from the deposition of high-energy gravity flows triggered by basement uplift and tilting about the Manganui Fault, and was emplaced across a carbonate shelf producing an interbedded succession of limestone conglomerate (L7) and sandy limestone lithofacies (L4) (Nelson et al. 1994).

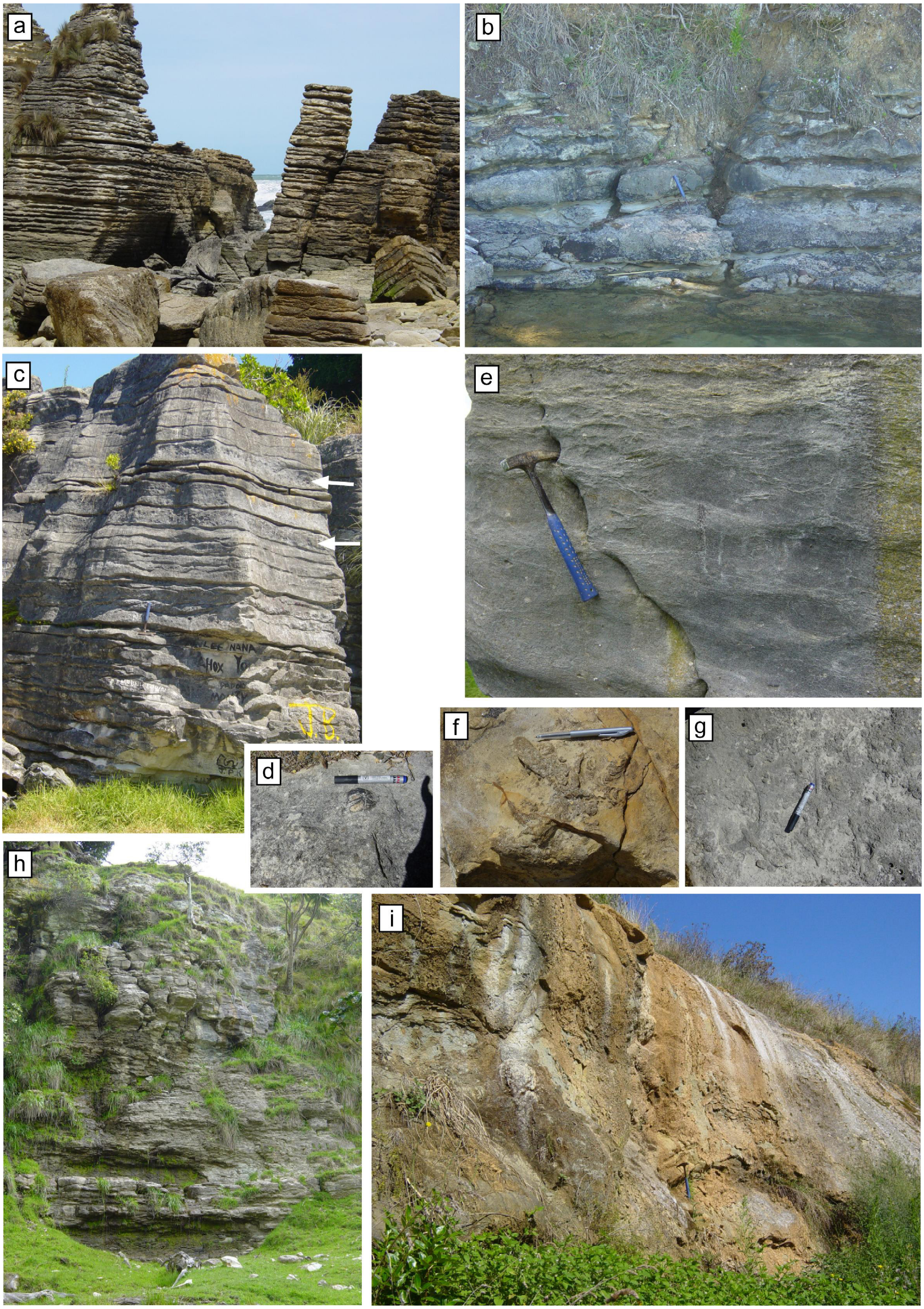
L8. Massive to horizontally bedded skeletal packstone-wackestone

The Massive to horizontally bedded skeletal packstone to wackestone lithofacies (L8) comprises the lower part of the Te Akatea Formation in the Raglan Harbour to Te Akau outcrop belt (e.g. TA-19, TA-12, TA-11, TA-9, TA-3 in Fig. 11; TA-15 in Fig. 12). These massive to bedded limestone units up to 22 m thick are distinguished as Raglan Limestone Member. The distribution of Lithofacies L8 is shown in Figs 3 and 4. In the vicinity of Raglan Harbour (e.g. TA-19, TA-12, TA-11 in Fig. 11), the lithofacies is characterised by well bedded (4 - 18 cm) fine bioclastic packstone (av. 80% $CaCO_3$), frequently with thin silty bioturbated interbeds, especially in the lower and upper parts of the member. Most beds have sharp flat bases but slightly diffuse to irregular tops owing to extensive bioturbation (Fig. 7). Resistant beds (flags) and recessive interbeds (interflags) give this limestone a strongly layered appearance in weathered outcrops. However, in places, these rocks have massive appearance with the rare presence of wavy bedding (Fig. 7e). Beds are often rich in echinoderm (occasionally whole) plates and spines, sponge spicules, gastropods (*Cirsotrema lyrata*), bivalves (*Lentipecten huttoni, Chlamys williamsoni),* brackiopods *(Terebratulina suessi*) and abundant planktic foraminifera (Fig. 8h-l). The more northern sections (e.g. TA-9, TA-3 in Fig. 11) exhibit an increase in terrigenous clastic content (av. 72% $CaCO_3$) with lithofacies characterised by moderately to well bedded calcareous siltstone intercalated with massive packstone-wackestone. The rocks in general lack the presence of macrofauna, except for rare fish teeth and calcareous nannofossils. Farther north, this lithofacies intergrades with Thin-bedded calcareous siltstone lithofacies Z1 (e.g. PW-9 in Fig. 11).

Lithofacies L8 exhibits much similarity with the Argillaceous Limestone Beds (OtC2) described by Nelson (1978a), occurring at the very top of the Otorohanga Limestone, mainly in the vicinity of Te Kuiti (e.g. DH 6796 in Fig. 13; C-126 in Fig. 14). There lithofacies L8 is comprised of planktic foraminiferal, bioturbated, argillaceous limestone with thin shaley interbeds (Nelson 1978a) and it passes rapidly upward into bathyal mudstone (Mahoenui Group, Taumatamaire Formation).

***Fig. 7:** (facing page)* Photographs (a-h) illustrating typical field character of Massive to bedded skeletal packstone and wackestone lithofacies L8 (Raglan Limestone Member) across the northern region of the study area. (a) Strongly bedded fine-grained packstone-wackestone with thin silty bioturbated interbeds. Note subparallel bedding typical of this facies. Exposure is approximately 8 m high. Photo location: Carters Beach (TA-11). (b) Alternation of hard carbonate-rich beds and recessively weathered carbonate-deficient silty wackestone interbeds. Note beds have sharp bases. Raglan Harbour (R14/745774). (c) Arrows pointing to highly burrowed layers in the Raglan Limestone Member at Raglan Harbour (R14/745774). (d) Whole delicate spatangoid tests are common in Raglan Limestone Member indicative of minimum transport and relatively deep, quiet water environments. Raglan Harbour. (e) Remnant traces of wavy bed forms apparent in Raglan Limestone Member, Te Kotuku Trig., Mangiti Road (TA-12). (f) View along a bedding plane showing large *Scolicia* burrows, Carters Beach (TA-11). (g) Bedding plane illustrating extensive *Scolicia* burrows. Raglan Harbour (R14/745774). (h) Thinly interbedded silty packstone and wackestone grading upwards into more resistant beds in the top half of the photograph. Exposure is approximately 20 m high. Waimai Valley (TA-3). (i) Massive glauconitic muddy sandstone (S1) comprises Waitomo Sandstone Member of the Orahiri Formation. The moderately cemented fine sandstone is variably glauconitic and exhibits extensive bioturbation in places. Near C-32, Waitomo Valley.

Interpretation: The massive to horizontally bedded lithofacies (L8) displays numerous features indicative of deposition under different levels of storminess, possibly due to different cyclic marine climate conditions. At times silty interbeds with abundant *Scolicia* burrows accumulated, testimony to the presence of infaunal deposit feeders. Burrowers may have been unable to homogenise sediments where the interval between storms was short. Highly burrowed beds may reflect longer durations between storms, or periods when the density of infaunal taxa was high. Consequently, all gradations from little burrowed, to burrow homogenised limestone beds are present. The common occurrence of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highly fragmented skeletal debris intermixed with planktic foraminifera probably resulted from storm-induced currents originating on the shelf with redeposition into outer shelf-upper bathyal depths. In most modern cool-water carbonate systems, the carbonate mud and marl accumulation occurs only at depths greater than 200 m (Nelson et al. 1988a; James et al. 1992; Boreen et al. 1993). The content of mud of carbonate or terrigenous origin has been shown to consistently increase with increasing water depth on modern cool-water carbonate shelves and slopes (Gillespie & Nelson 1997; James et al. 1999; James et al. 2001). The abundance of planktic foraminifera-dominated carbonate mud, the intensity of bioturbation, and the occasional occurrence of whole (commonly spatangoid) preserved delicate skeletal components support relatively deep, quiet water environments (e.g. Boreen & James 1995).

Mixed carbonate-siliciclastic sandstone association (S1, S2)

The sandstone lithofacies are the least common of the three lithofacies associations identified in the Castle Craig Subgroup. Two sandstone lithofacies have been defined in this study, and their details are summarised in Table 1. Beds with sandstone lithofacies are usually up to 15 m thick, and typically overlie limestone lithofacies (e.g. L3, L6). The sandstone lithofacies vary from sparsely fossiliferous to highly fossiliferous, with a diverse range of macrofaunal taxa. They are either overlain by horizontally to cross-stratified grainstone or occur at the very top of the thick limestone succession, possibly associated with an increase in water depth.

S1. Massive glauconitic muddy sandstone

The Massive glauconitic muddy sandstone lithofacies (S1) occurs mainly within the vicinity of Waitomo (e.g. C-32 in Fig. 13), but also forms isolated lensoidal bodies within Orahiri Formation and Otorohanga Limestone in exposures east of Te Kuiti. This lithofacies is essentially the Waitomo Sandstone described by Nelson (1978a) from the type Waitomo locality (Fig. 7i). A distinctive outcrop feature is its massive appearance with a smooth weathering profile. It generally consists of poorly to moderately cemented muddy fine sandstone with a variable detrital glauconite content ranging from 3 - 20%. Macrofossils are sparse, although thin-sections indicate the presence of variable amounts of bryozoan and echinoderm fragments (Nelson 1973). Bioturbation structures are common throughout the facies. Microfaunal components include benthic foraminifera with rare planktic foraminifera (Nelson 1973).

Interpretation: The massive fine-grained character of this lithofacies suggests moderate energy in the environment of deposition. Bioturbation was able to continuously keep pace with the slow rate of sediment accumulation, leading to the massive and homogenised character of the facies. The restricted occurrence of facies S1 may be the result of locally increased terrigenous sediment input, possibly associated with active faulting in the vicinity. It may also represent localised subsidence associated with fault movement or changes in the hydrodynamic regime.

S2. Fossiliferous silty sandstone and sandy siltstone

The Fossiliferous silty sandstone and sandy siltstone lithofacies (S2) occurs in the upper part of the Otorohanga Limestone in sections inland of Kawhia Harbour (e.g. AK-12, AK-11 in Fig. 12). It gives rise to a rounded weathering profile capping near vertical limestone cliffs (Fig. 5i, j). Approximately 15 m of this lithofacies is exposed at Whenuaupo Hill (TA-12), but the true thickness is unknown because of its eroded top. Lithofacies S2 resembles the Massive glauconitic muddy sandstone lithofacies S1 described above, as it is chiefly composed of massive to crudely bedded, moderately calcareous, fine-grained glauconitic sandstone and sandy siltstone. However, unlike lithofacies S1, it is rich in a diverse range of macrofaunal taxa, especially whole and disarticulated oysters, either scattered or clustered within beds. Other bivalve species include *Athlopecten athleta, Panopea* sp., *Lentipecten hochstetteri*, common brachiopoda (*Rhyzothyris* sp.) and occasional echinoderm fragments (Fergusson 1986). The lithofacies probably constitutes the uppermost 8-10 m of the Te Akatea Formation at Carters Beach (e.g. TA-11 in Fig. 11), reflecting retrogradation of the facies belt. This unit contains well cemented, massive to faintly bedded, sandy siltstone with scattered articulated and disarticulated oysters, with a sharp erosional contact with the overlying Waitemata Group (Fig. 9f - h).

Interpretation: Lithofacies S2 is characterised by the presence of a wide range of bivalves and coarse fossil allochems mixed into a fine silty sandstone matrix, suggesting deposition in a storm-influenced shelf setting. Strong currents may have remobilised oyster shells and other shell debris into a protected, muddy, probably deeper water environment that was subsequently colonised by infaunal bivalves.

Mixed carbonate-siliciclastic siltstone association (Z1, Z2)

A siltstone lithofacies association makes up the majority of the thickness of units in the Te Akatea Formation in the northern part of the basin, and occurs mainly within the Carter Siltstone Member. This association overlies the Massive to horizontally bedded skeletal packstone-wackestone (L8) in the outcrop belt between Raglan Harbour and Te Akau. In the more northern sections, the Calcareous siltstone lithofacies conformably overlies the condensed Patikirau Siltstone Member of Aotea Formation. The preserved thickness of this facies is up to 80 m and it is best exposed in cliffs along the coast between Raglan Harbour and Waikawau Beach (Port Waikato), and areas immediately inland. The lithofacies association is predominantly comprised of light grey marl with diverse planktic and benthic foraminiferal assemblages indicating accumulation in open marine environments. The siliciclastic marl is inferred to have accumulated as an extensive blanket over much of the northern region; however the present day eastern extent of the Carter Siltstone Member is limited by post-depositional uplift and erosion. This member has been intercepted in a few of the Coal Resources Survey drill holes in eastern parts of northern Waikato (Edbrooke 1984). Along the western areas of the northern region, a wave-planed surface at the top of the Carter Siltstone separates it from overlying diversified basal facies of the Waitemata Group. Two siltstone lithofacies have been defined in this study, and are summarised in Table 1.

Z1. Medium bedded calcareous siltstone

The Medium bedded calcareous siltstone lithofacies (Z1) occurs mainly within the lower part of the Carter Siltstone Member (e.g. PW-1, PW-11, PW-3a, PW-9, TA-11 in Fig. 11). This lithofacies is distinguished by 10-50 cm-thick light grey to creamy-white calcareous siltstone beds with occasional thin discrete glauconitic sandy siltstone interbeds (15 - 20 cm), particularly noticeable in the Port Waikato area (Fig. 9a-d). Contacts between the beds are diffuse and commonly exhibit a blocky or "frittery" surface weathering profile. The carbonate content ranges from 41 - 75 wt% (av. 55%). In thin sections, the observed siliciclastic content accounts for at least one-quarter of the whole rock composition and typically comprises clay to silt-sized material with minute proportions of fine to very fine sand-size quartz and feldspar grains. Glauconite and pyrite are common authigenic minerals within this facies. Glauconite occurs as scattered pellets as well as infills of foraminiferal tests, and is abundant in thin interbeds, especially as burrow infills. Bioclasts constitute 51-63% of samples, and are dominated by planktic foraminifera with subequal amounts of benthic foraminifera, fragments of echinoderms and bivalves, and traces of ostrocods (Fig. 8g) (Khandarosa 1989).

Interpretation: The Medium bedded calcareous siltstone lithofacies (Z1) represents deposition in outer shelf to upper bathyal environments. Bedding development is attributed to variations in storminess, possibly due to cyclic variations in marine climate. On the modern south Australian temperate carbonate shelf, large storms produce offshore-directed storm currents that have the potential to rework sediments to depths of 250 m (Schahinger 1987; Collins 1988). The sporadic occurrence of thin glauconitic beds within this facies in Carter Siltstone represents condensed sedimentation, possibly paraconformity development.

Z2. Massive calcareous siltstone

Lithofacies Z2 comprises the bulk of the Carter Siltstone Member with a thickness of about 70 m, best exposed in cliffs along the west coast between Raglan Harbour and Port Waikato. It both overlies and grades laterally into medium

Table 1: Lithofacies of the Castle Craig Subgroup.

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Texture size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence/ Figure examples	Interpretation
Limestone association						
L1. Pebbly grainstone-packstone	Common to abundant subrounded pebbles and cobbles occur as pebble bands; or fabric supported by bioclastic silty fine sandstone; usually massive	50-60%	Medium to coarse grainstone-rudstone; occasional large shell fragments, poorly to moderately sorted; very abraded	Fragmented pectinids, oysters, echinoderms; clasts occasionally encrusted by calcareous red algae	Common near the lower contact with basement, and/or mark erosional contact with underlying formation; up to tens of centimetres thick Fig. 5a, b	Nearshore to inner shelf adjacent to rocky shoreline
L2. Cross-stratified grainstone	Tabular cross-beds are low (<10^0) to moderate angle (10^0-25^0); occur in 0.3-4.5 m thick sets; cross-beds are generally 2-15 cm thick	91-96%	Medium to very coarse grainstone, rare small pebbles and granules; siliciclastic particles in bedding planes are fine sandstone to siltstone	Bryozoans, echinoderms, benthic foraminifera, some bivalves, coralline red algae, rare planktic foraminifera	Developed locally in the lower, mid and upper parts of Orahiri Formation and Otorohanga Limestone Fig. 5c, d	High energy inner to mid shelf, dominated by strong offshore-directed storm and tidal currents
L3. Horizontally bedded grainstone	Beds/flags typically well developed, averaging 2-10 cm thick	81-99%	Medium to very coarse grainstone; abraded and poorly to moderately sorted	Bryozoans, echinoderms, bethic foraminifera, and occasional bivalves, calcareous red algae; planktic foraminifera rare or absent	Comprises most of the Orahiri Formation and Otorohanga Limestone- Fig. 5d	Inner to mid wave-dominated shelf
L4. Sandy grainstone-packstone	Commonly varying from massive to tabular bedded units; bedding surfaces (0.1-1.5 cm) rich in siliciclastic material	42-87%	Coarse to very coarse grainstone; common medium to coarse quartz sand grains, abraded, and poorly to moderately sorted	Echinoderms, large benthic foraminifera (*Amphistegina*), bryozoans, occasional bivalves, calcareous red algae; planktic foraminifera rare or absent	Comprises most of the Mangaotaki Limestone; mainly in western areas Fig. 5e-h	Inner to mid shelf
L5. Massive to irregularly bedded, fossiliferous rudstone-grainstone	Massive to irregularly bedded, occasionally well bedded, 20-100 cm thick beds; commonly develops “knobbly” to blocky weathering feature	98-100%	Medium to coarse grainstone; common large skeletal fragments, abraded, poorly to moderately sorted	Bryozoans (up to 80%), echinoderms, benthic foraminifera, common bivalves and gastropod moulds, and occasional calcareous red algae	Comprises most of the Waitanguru Limestone Member Fig. 6a-d	Bryozoan mound buildup indicating high energy inner-mid shelf depths

L6. Pebbly oyster float-stone-packstone	Massive to irregularly bedded, beds tens of centimetres thick; beds laterally traceable for few metres	77-97%	Medium to very coarse with pebbles (<2 cm) matrix supported; poorly sorted	Articulated/disarticulated, randomly orientated oysters (*Flemingostrea* sp.); bryozoans, echinoderms, benthic foraminifera, bivalves and occasional calcareous red algae and solitary corals (*Flabellum*)	Comprises most of the Te Anga Limestone Member Fig. 6f, g	Oyster reefs commonly associated with sandy grainstone–packstone; high energy tide-swept inner-mid shelf
L7. Conglomeratic limestone	Bedded units 0.5-3 m thick with abundant clasts of limestone, calcareous sandstone and rounded basement pebbles; often profusely bored	Moderate to high	Coarse to very coarse sparry grainstone with 1-10 cm size clasts; poorly sorted	Bryozoans, echinoderms, benthic foraminifera, oysters and occasional calcareous red algae encrusting basement pebbles	Occurs as conspicuous unit within Orahiri Formation in the vicinity of Awakino Tunnel Fig. 6e	Interpreted as carbonate debrite/ mass-emplaced unit deposited at shelf depths in response to basin margin tilting
L8. Massive to horizontally bedded skeletal packstone-wackestone	Massive to well bedded (beds 2-25 cm) with prominent subhorizontal to bifurcating thin (0.5 -1.5 cm) silty interbeds	59-89%	Predominantly micritic with scattered whole and fragmented bivalves (pectinids) and echinoderms; poorly to moderately sorted	Moderate to abundant planktic foraminifera with subequal proportions of echinoderms, benthic foraminifera and bivalve fragments; occasional whole well preserved echinoderms; rare bryozoans and calcareous red algae	Comprises most of Raglan Limestone in the northern region; also occurs as a transition facies near the upper contact with Mahoenui Group Fig. 7a-h	Outer shelf to slope
Mixed carbonate-siliciclastic sandstone association						
S1. Massive glauconitic muddy sandstone	Typically massive with smooth weathering profile; poorly to moderately cemented; bioturbated	20-60%	Fine to very fine sandstone, poorly sorted	Echinoderms, bryozoans and benthic foraminifera with rare presence of calcareous red algae and bivalves	Most common in the Waitomo Valley area Fig. 7i	Mid to outer shelf
S2. Fossiliferous silty sandstone and sandy siltstone	Massive, dull brownish grey, moderately cemented; occasional hard concretionary glauconitic sandstone bands; bioturbated	38-62%	Fine silty sandstone with scattered large bivalve and skeletal fragments; poorly sorted	Oysters (*Flemingostrea* sp.), *Athlopecten athleta, Lentipecten hochstetteri, Panopea worthingtoni, Dosinia* sp., solitary corals (*Flabellum* sp.), abundant pectinid fragments and benthic foraminifera	Mostly forms the top part of Orahiri Formation/ Otorohanga Limestone at inland Kawhia Harbour area Fig. 5i, j	Mid-outer shelf above storm wave base

Table continues on to next page

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Texture size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence/ Figure examples	Interpretation
Mixed carbonate-siliciclastic siltstone association						
Z1. Medium bedded calcareous siltstone	Light grey to creamy yellow, moderately to well bedded (10-50 cm), occasional glauconite infilled burrowed horizons (10-30 cm)	51-75%	Medium to coarse siltstone, occasional whole bivalves, gastropods and echinoderms; poorly to moderately sorted	Dominated by planktic foraminifera with variable proportions of benthic foraminifera, echinoderms, bivalves and bryozoans	Common in the lower part of Carter Siltstone Fig. 9	Outer shelf to upper bathyal
Z2. Massive calcareous siltstone	Massive, light blue grey to brownish grey, characteristic conchoidal fracture when fresh, weathers into a finely frittered surface	24-73%	Medium to coarse siltstone, with fine to very fine sand locally; planktic foraminifera common	Bioclasts dominated by planktic foraminifera with minor proportion of benthic foraminifera, echinoderms and bivalves	Widespread in the northern region forming most of Carter Siltstone Fig. 9	Outer shelf to upper bathyal

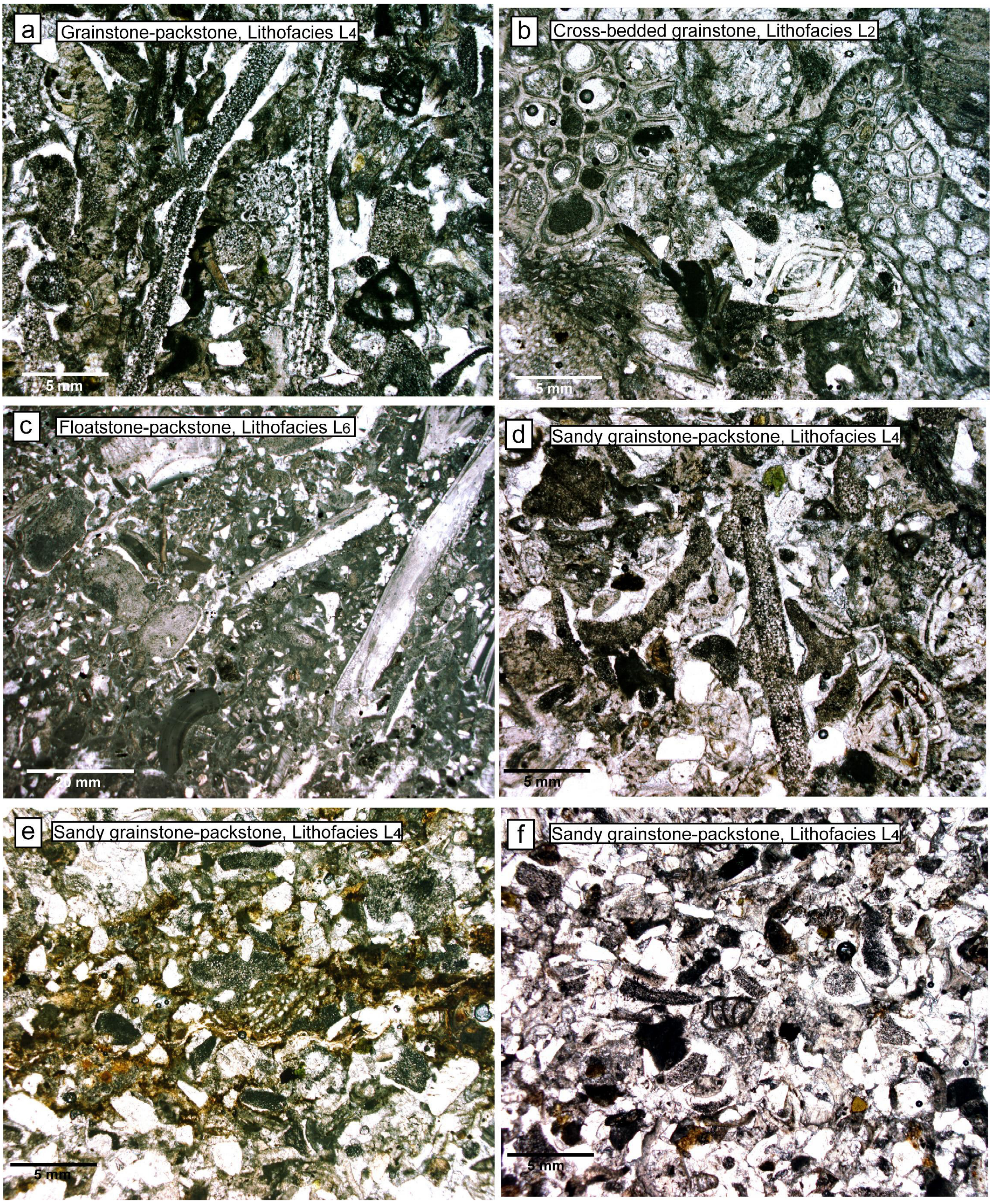

Fig. 8 (i): Photomicrographs of representative samples from the Castle Craig Subgroup carbonate lithofacies from the central region. (a) Echinoderm/benthic foraminifera-rich sandy grainstone-packstone (Lithofacies L4). Note syntaxial overgrowth cement around echinoid plates. Limestone Quarry, Rakaunui Peninsula (AK-11), Sample 367. (b) Bryozoan-dominated cross-bedded grainstone (Lithofacies L2) with common benthic foraminifera (*Amphistegina*). Limestone Quarry, Rakaunui Peninsula (AK-11), Sample 368. (c) Pebbly oyster floatstone-packstone (Lithofacies L6) showing large bivalve fragments in coarse bryozoan/benthic foraminiferal-rich matrix. Limestone Quarry, Rakaunui Peninsula (AK-11), Sample 369. (d) Echinoderm/benthic foraminiferal/bryozoan sandy grainstone-packstone (Lithofacies L4). Whanuapo Hill (S-11), Sample 391. (e) Echinoderm-rich/benthic foraminiferal/bryozoan/calcareous red algal grainstone-packstone (Lithofacies L4). Whanuapo Hill (S-11), Sample 392. (f) Benthic foraminiferal/echinoderm /bryozoan/calcareous red algal sandy grainstone-packstone (Lithofacies L4). Whanuapo Hill (S-11), Sample 395.

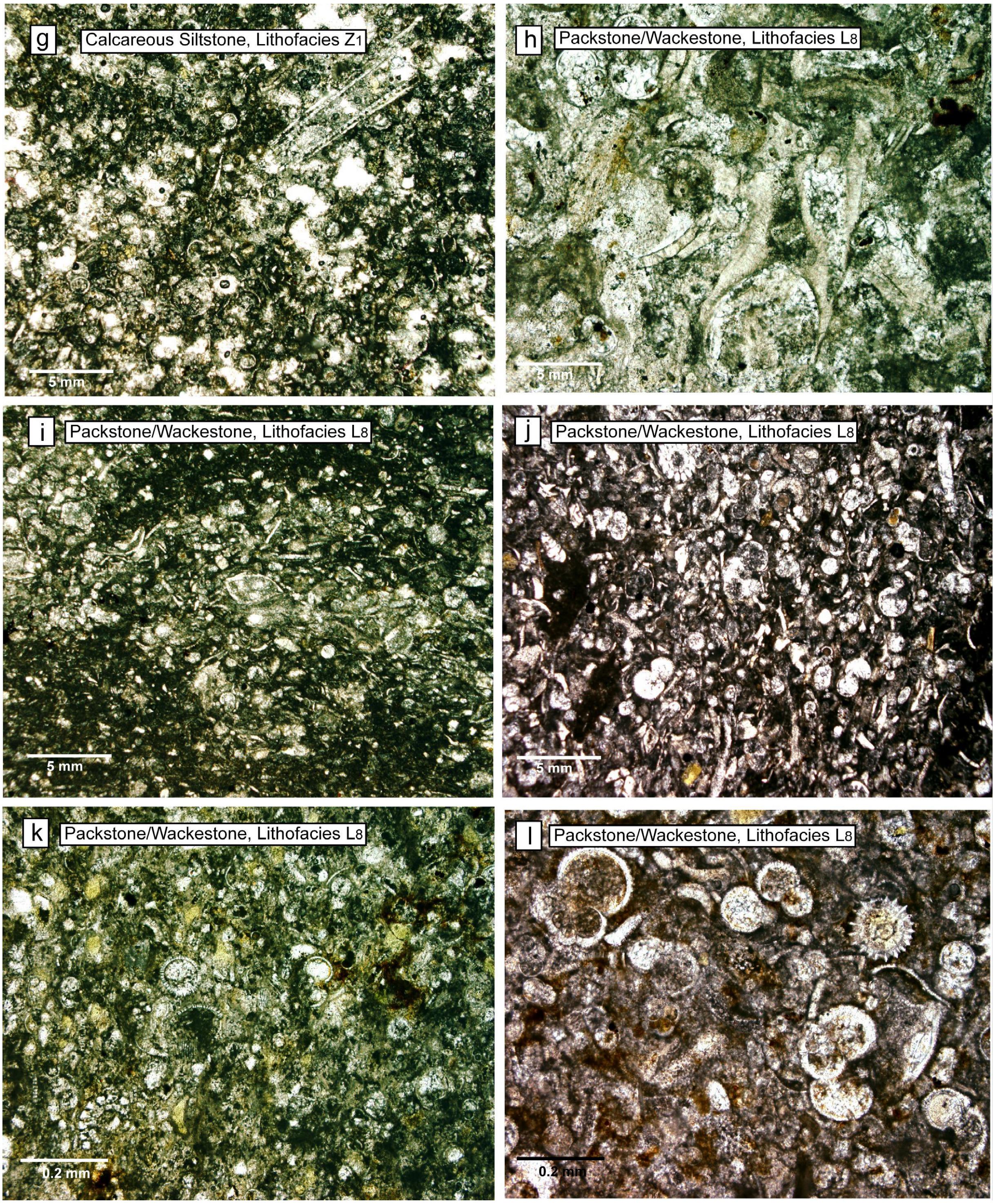

Fig. 8 (ii): Photomicrographs of representative samples from the Castle Craig Subgroup carbonate lithofacies from the northern region. (g) Planktic foraminifera-dominated medium bedded calcareous siltstone (Lithofacies Z1). Note echinoid spine in the surrounding planktic foraminiferal-rich micritic matrix. Waikawau Beach, Port Waikato (PW-11), Sample 133. (h) Bivalve and echinoderm fragments in a planktic foraminiferal-rich packstone/wackestone (Lithofacies L8), Rothery Road (TA-19), Sample 276. (i) Planktic foraminifera-dominated wackestone (Lithofacies L8) with abundant micritic matrix. Carters Beach (TA-11), Sample 280. (j) Planktic foraminiferal-rich/bivalve/echinoderm packstone-wackestone (Lithofacies L8), north of Te Akau (TA-3), Sample 185. (k) Planktic foraminiferal-rich/bivalve/echinoderm/benthic foraminiferal assemblage in a packstone-wackestone (Lithofacies L8). Carters Beach (TA-11), Sample 281. (l) Planktic foraminiferal-rich/echinoderm packstone/wackestone (Lithofacies L8). Mangiti Road (TA-12), Sample 234.

bedded calcareous siltstone lithofacies Z1, as at localities TA-11, PW-9, PW-3a and PW-11 (Fig. 11). The distribution of Massive calcareous siltstone lithofacies (Z2) is shown in Figs 3 and 4. In outcrop, this facies exhibits peculiar weathering characteristics, which include conchoidal fracture when rocks are freshly exposed and a "fine frittery" appearance (crumbles into 4 - 20 mm polygonal pieces) after prolonged exposure. Lithofacies Z2 comprises primarily homogenous, light grey, variably calcareous siltstone, but locally may include thin (<20-30 cm) sandy siltstone beds containing concentrations of glauconite and/or pyrite. Facies Z2 is similar to Lithofacies Z1 just described, however it has less carbonate, varying from 25% to 65%, with mud content much higher than sand content. Bedding is only discernible from occasional resistant sandy siltstone beds and is more obvious from a distance than up close. Common trace fossils include *Zoophycus* and occasional inclined and subhorizontal (up to 15 cm) tubular burrows. In general, bioturbation is commonly so extensive that individual trace fossils cannot be identified (Fig. 9e). Macrofossils are rare and are generally dominated by *Lentipecten hochstetteri*, *Chlamys williamsoni, Flabellum* sp. and *Dentalium* sp. In thin-section bioclasts constitute an average 59% of the whole rock composition and are dominated by planktic foraminifera (av. 33%), echinoderm and bivalve fragments, benthic foraminifera, and ostrocods (Khandarosa 1989).

Interpretation: The Massive calcareous siltstone lithofacies Z2 accumulated in outer shelf to upper bathyal water depths. The abundant bioturbation including *Zoophycus* is generally indicative of a quiet-water, poorly oxygenated sea floor below storm-wave base, where suspension sedimentation dominates (Seilacher 1967; Ekdale et al. 1984). However, the siliciclastic marl implies significant ongoing siliciclastic influx. The skeletal component is dominated by planktic foraminifera, such as common *Globoquadrina dehiscens* and *Globigerina brazieri* (R14/f6739-6743), and various benthic foraminifera (*Cibicides, Karreriella, Notorotalia, Sphaeroidina*) as reported by earlier workers (e.g. Khandarosa 1989; Waterhouse & White 1994). The microfauna are indicative of outer shelf-upper bathyal water depths (e.g. Hayward 1986; Hayward et al. 1989). The presence of rare benthic foraminifera *Amphistegina*, which are intermixed with the outer shelf to upper bathyal fauna, suggests seaward reworking of these shallow shelfal fauna. Clear physical evidence of mass-emplacement is lacking. Bottom currents probably introduced the allochthonous components. Overall, deposition was dominated by hemipelagic settling of background sedimentation.

Lithofacies distribution and paleo-environmental implications

The lithologically diverse facies in the Castle Craig Subgroup, ranging from coarse sparry rudstone-grainstone through to fine packstone-wackestone to calcareous siltstone and marl, represents a wide paleobathymetric span from shallow shelf to upper bathyal water depths. The vertical and lateral facies relationships are depicted in selected stratigraphic columns along a series of north - south and east-west transects (Figs 10 - 15). Although lithofacies transitions occurring in the Aotea-Harbour area are sketchy due to a lack of outcrop, isolated outcrop windows do provide some indications of the stratigraphic development of the Castle Craig Subgroup to the south and north of this area. The distribution of the lithofacies within the various formations and members (Fig. 1) are summarised in Table 2.

The geographic extent of the main lithofacies within the subgroup and key paleogeographic elements that are inferred to have had a major influence on depositional environments and processes are illustrated in Figs 3 and 4.

The onset of deposition of the Castle Craig Subgroup in the southern region is marked by an extensive unconformity at the base of Orahiri Formation formed by subaerial erosion and subsequent wave planation of Aotea Formation during coastal onlap. The basal facies of Orahiri Formation resting on this unconformity in southern areas is a Pebbly grainstone-packstone (L1), which is up to tens of centimetres thick. It commonly passes upward into Sandy grainstone-packstone (L4), which makes up a major part of Orahiri Formation in sections located between Kawhia Harbour and Awakino in the western belt (Fig. 3). Facies L4 is locally intercalated with

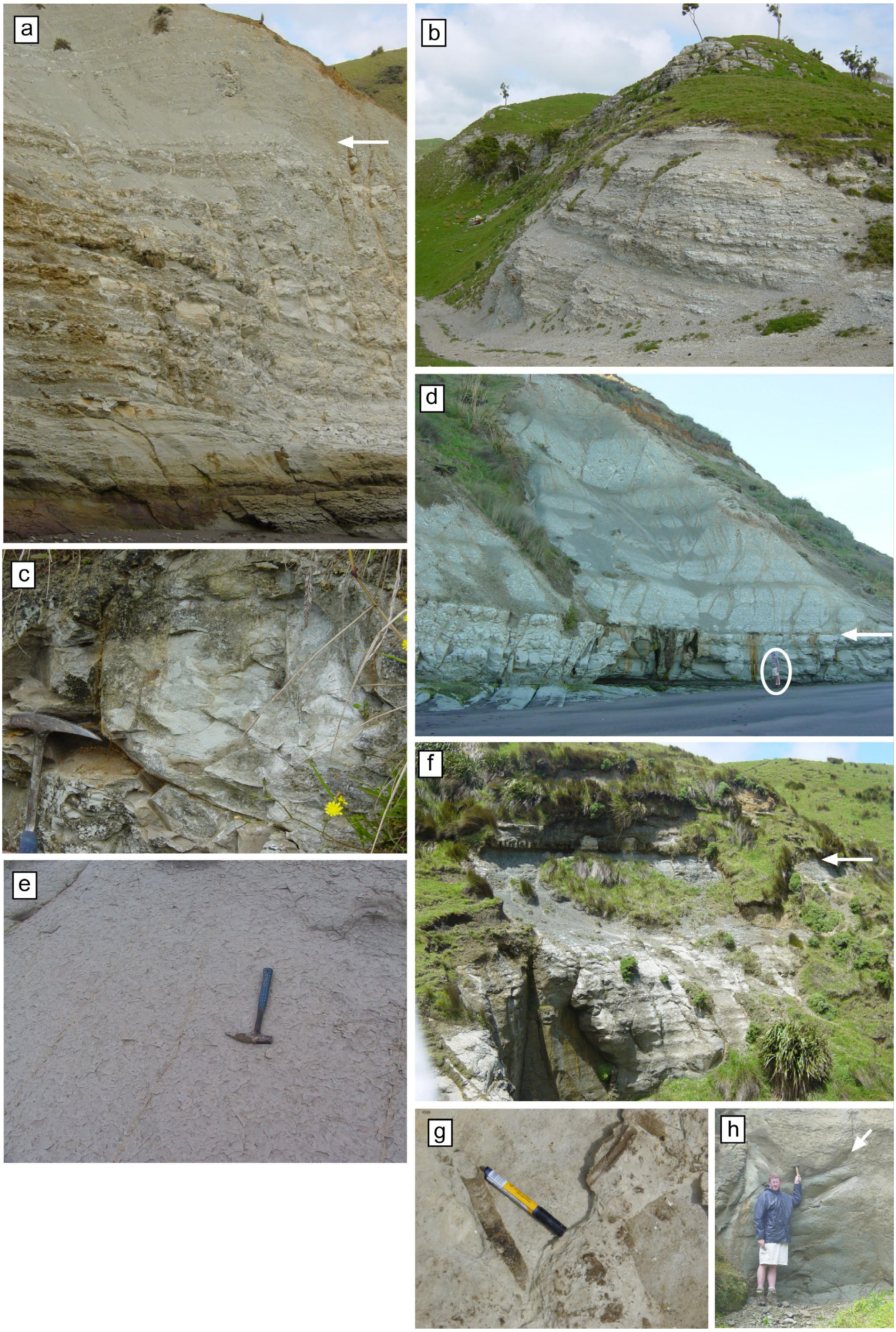
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Fig. 9: (facing page) Photographs of the typical field expression of lithofacies within the Te Akatea Formation (Carter Siltstone Member) across the northern region. (a) Medium bedded calcareous siltstone lithofacies (Z1). Arrow marks the gradual upward transition into Massive calcareous siltstone lithofacies (Z2). Cliff is approximately 20 m high. Waikawau Beach, Port Waikato (PW-11). (b) Thinly bedded calcareous siltstone lithofacies (Z1) forming the lower part of the Carter Siltstone. Exposure is approximately 30 m high. Bedding is interpreted to be the result of storm-current driven depositional processes. Waikorea Valley Road (TA-2). (c) Extensively burrowed calcareous siltstone interval with abundant glauconitic siltstone-filled *Thalassinoides* burrows in the lower part of medium bedded calcareous siltstone (Z1), indicating a period of non-deposition to very slow deposition. Photo location: Port Waikato-Waikaretu Road, near Waikaretu Limestone Quarry (PW-9). (d) Arrow marks the rapid upward facies transition between Medium bedded (Z1) and Massive calcareous siltstone (Z2) lithofacies. North of Kaawa Beach (PW-12). Person for scale. (e) Massive calcareous siltstone (Z2) showing extensive bioturbation is a common feature in this lithofacies. Raglan Harbour. (f) Fossiliferous sandy siltstone (S2) occurring at the top of the Carter Siltstone. Arrow points at erosional unconformity with overlying distinctly bedded sandstone of Waitemata Group. Exposure is approximately 15 m high. Carters Beach, north of Raglan Harbour (TA-11). (g) Close-up view of large tubular burrows occurring in Fossiliferous sandy siltstone (S2) unit shown in photo f. (h) Hammer and arrow pointing to scattered whole oysters within Fossiliferous sandy siltstone (S2) unit shown in photo f.

Cross-bedded grainstone (L2) and Horizontally bedded grainstone (L3). The widespread occurrence of L4 lithofacies (i.e. Mangaotaki Limestone), typically comprising fine to coarse quartzitic sand in variable proportions (up to 50% by volume) along with medium to coarse skeletal fragments (bryozoans, echinoderms and large benthic foraminifera), accumulated as calcareous sand sheets under moderate to high energy in a seaway at inner to mid shelf depths along the eastern margin of the Herangi High. Only in one locality (C-191 (Awakino Tunnel), Fig. 15) is facies L4 interbedded with Conglomeratic limestone (L7), indicating syn-depositional tilting and eastward reworking of shelf-derived carbonate lithoclasts (Nelson et al. 1994; King & Thrasher 1996).

The Sandy grainstone-packstone (L4) is commonly overlain by Pebbly floatstone-packstone facies (L6) with laterally discontinuous oyster beds, forming most of the Te Anga Limestone in the south-central area (Fig. 3). The facies contact between L4 and L6 is generally conformable, however in the vicinity of Ngapaenga (e.g. C-56, C-61, C-68 in Fig. 14) a sharp erosional surface of local extent marks this contact. Lithofacies L6 contains up to metre-thick oyster biostromes/banks and other common large bivalves (mainly pectinids) generally associated with pebble lags and abundant micrite matrix, indicating accumulation in a mid shelf current-swept seaway (Nelson et al. 1983). Although the oyster-bearing L6 lithofacies is a useful stratigraphic marker of the Te Anga Limestone in south-central areas, this facies occurs sporadically in the lower parts of Orahiri Formation (C-

Table 2: Broad lithofacies distribution within Castle Craig Subgroup.

South			North		
Formation	**Member**	**Facies**	**Formation**	**Member**	**Facies**
Otorohanga Limestone	Piopio Limestone	L1, L3-L4, L8	Te Akatea	Carter Siltstone	Z1-Z2, S2
	Waitanguru Limestone	L5			
	Pakeho Limestone	L1-L4			
Orahiri	Waitomo Sandstone	S1		Raglan Limestone	L8, Z1
	Te Anga Limestone	L1, L3-L6			
	Mangaotaki Limestone	L1-L4, L7			

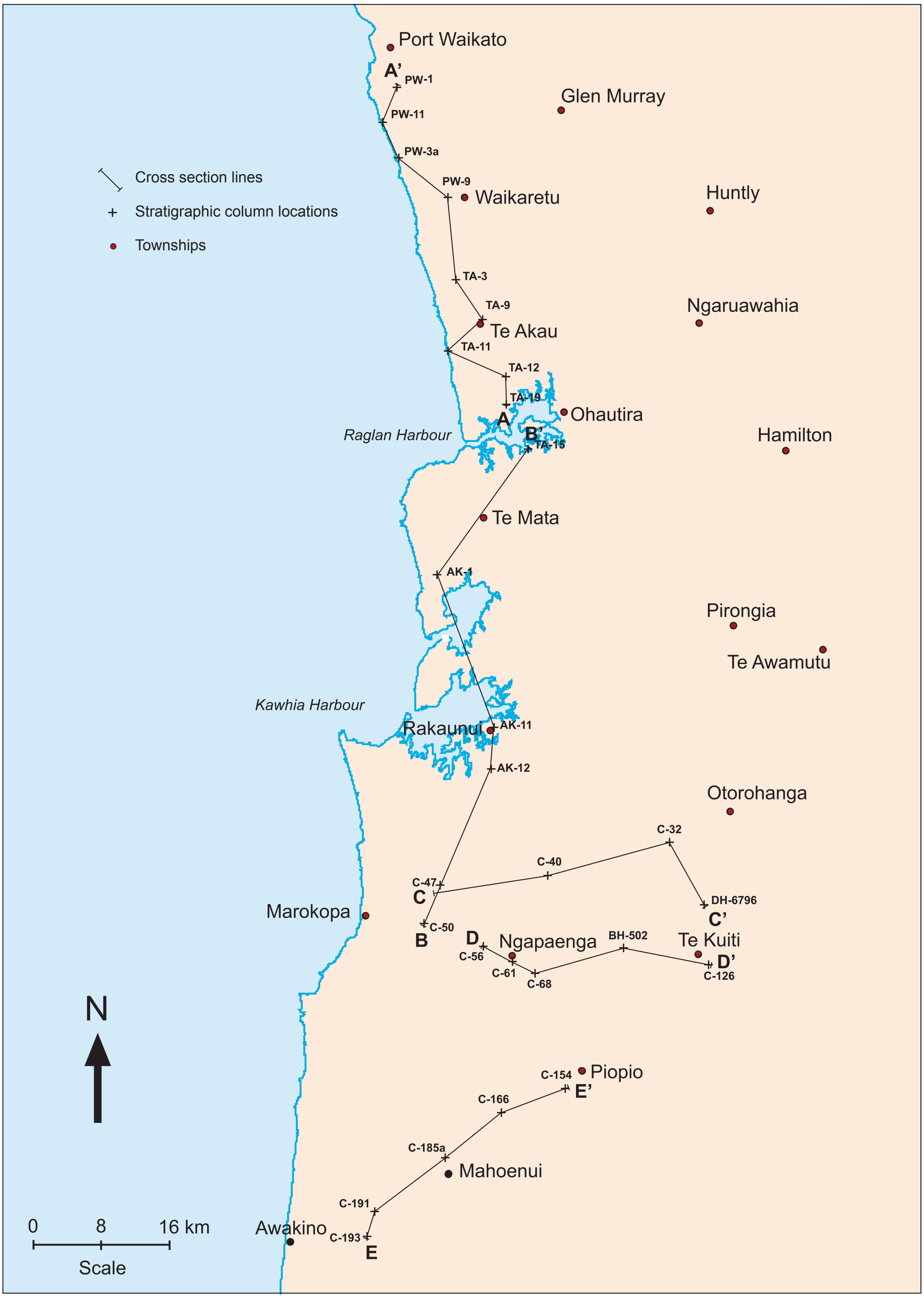


Fig. 10: Map showing location of columns and cross-sections illustrated in Figs 11 to 15.

32, Fig. 13), as well as in the upper 4 - 5 m of undifferentiated Orahiri Formation/Otorohanga Limestone (AK-11, Fig. 12; C-166, Fig. 15). In the vicinity of Waitomo, facies L6 grades upward into moderately glauconitic muddy fine sandstone (Waitomo Sandstone Member/Lithofacies S1), which generally appears massive throughout (C-32, Figs 7i, 13). Thin sandstone units of similar lithofacies affinity and with variable amounts of glauconite and calcareous content also occur sporadically within the limestone to the east and northeast of Te Kuiti (Nelson 1973, 1978a). Their occurrence is difficult to explain other than having been locally sourced from basement.

In southwestern areas (e.g. Ngapaenga, west of Piopio), a sharp erosional surface with associated basement-derived pebbles, fragmented bivalves and occasional iron-oxide mineralisation separates Lithofacies L6 (Te Anga Limestone) from overlying well flagged Lithofacies L3, locally interstratified with cross-bedded L2 units with relatively higher $CaCO_3$ (av. 90%) content. Both facies are assigned to Otorohanga Limestone (e.g. C-56, C-61, C-68 in Fig. 14). In places they also include a limestone unit (Waitanguru Limestone Member, Lithofacies L5) with an unusual field weathering character including massive, irregularly or “knobbly” to “blocky” appearance, containing close to 100% $CaCO_3$ content (Nelson 1973). Facies L5 is best developed in areas west of Piopio and near Mangaohae River sections (e.g. C-56, Fig. 14). The geographical extent of Lithofacies L5 is shown in Fig. 4. These early marine cemented limestone units comprise organic mounds constructed by bryozoans and may also include large shell fragments mainly of oysters and/or pectinids. They are inferred to be associated with relatively high-energy settings caused by local base level fluctuations (Nelson & James 2000). They commonly grade through Horizontally bedded grainstone (L3) into planktic foraminifera-rich, bioturbated packstone and wackestone (Lithofacies L8). In the south, lithofacies L8 grades into terrigenous mudstone of Mahoenui Group. Facies L8 reflects increasing water depths in the upper part of Otorohanga Limestone, reflecting a retrogradational stratal pattern. In the vicinity of Te Kuiti, interbedded foraminiferal limestone (L8) and calcareous siltstone mark this transition as well (e.g. C-126, Fig. 14) (Nelson 1973; Anastas 1997).

The distribution of Otorohanga Limestone extends to the east and southeast of Te Kuiti, and also in the vicinity of Piopio and Aria, where it accumulated directly on basement and represents flooding of the Piopio High. The basal onlap facies (L1) mark the contact with basement on the northern and eastern low-lying fringes of this structural high (Fig. 3).

In the central Aotea-Kawhia Harbour region, the vertical succession of lithofacies within the subgroup is somewhat different compared to the south and south-central areas discussed above. Three parts can broadly be identified. The lower two-thirds of the subgroup is composed of either Sandy grainstone-packstone (L4) or low angle Cross-bedded grainstone (L2) (Fig. 12). The upper part of the subgroup is composed of relatively pure limestone comprising mainly Horizontal bedded grainstone (L3), passing upward into Oyster floatstone-packstone (L6), which in turn grades into Fossiliferous silty sandstone and sandy siltstone (S2) with scattered oysters and other common bivalves (*Athlopecten athleta, Lentipecten, Panopea*). The present day extent of exposure of this lithofacies is limited by erosion, but is tentatively identified as the uppermost-eroded top of the C-50 section (Fig. 12) in the south, and at a similar stratigraphic position in inland sections east of Kawhia Harbour and north of Aotea Harbour.

In the northern region, the base of Castle Craig Subgroup corresponds to a major paraconformity, which contains extensively burrowed and fossiliferous siltstone and sandy siltstone with high concentrations of glauconite. It grades into Massive to horizontally bedded skeletal packstone-wackestone (L8) of Raglan Limestone, or medium bedded calcareous siltstone (Z1) of Carter Siltstone in more northern localities (Fig. 11). The distribution of this deep-water micritic and foraminiferal limestone (L8) is recorded in stratigraphic sections in an area extending from Te Akau to Raglan Harbour (i.e. from TA-3 to TA-19 in Fig. 12), and probably also extends south of Raglan Harbour (Fig. 4). Raglan Limestone is absent over much of the northernmost sections (Port Waikato-Waikaretu,

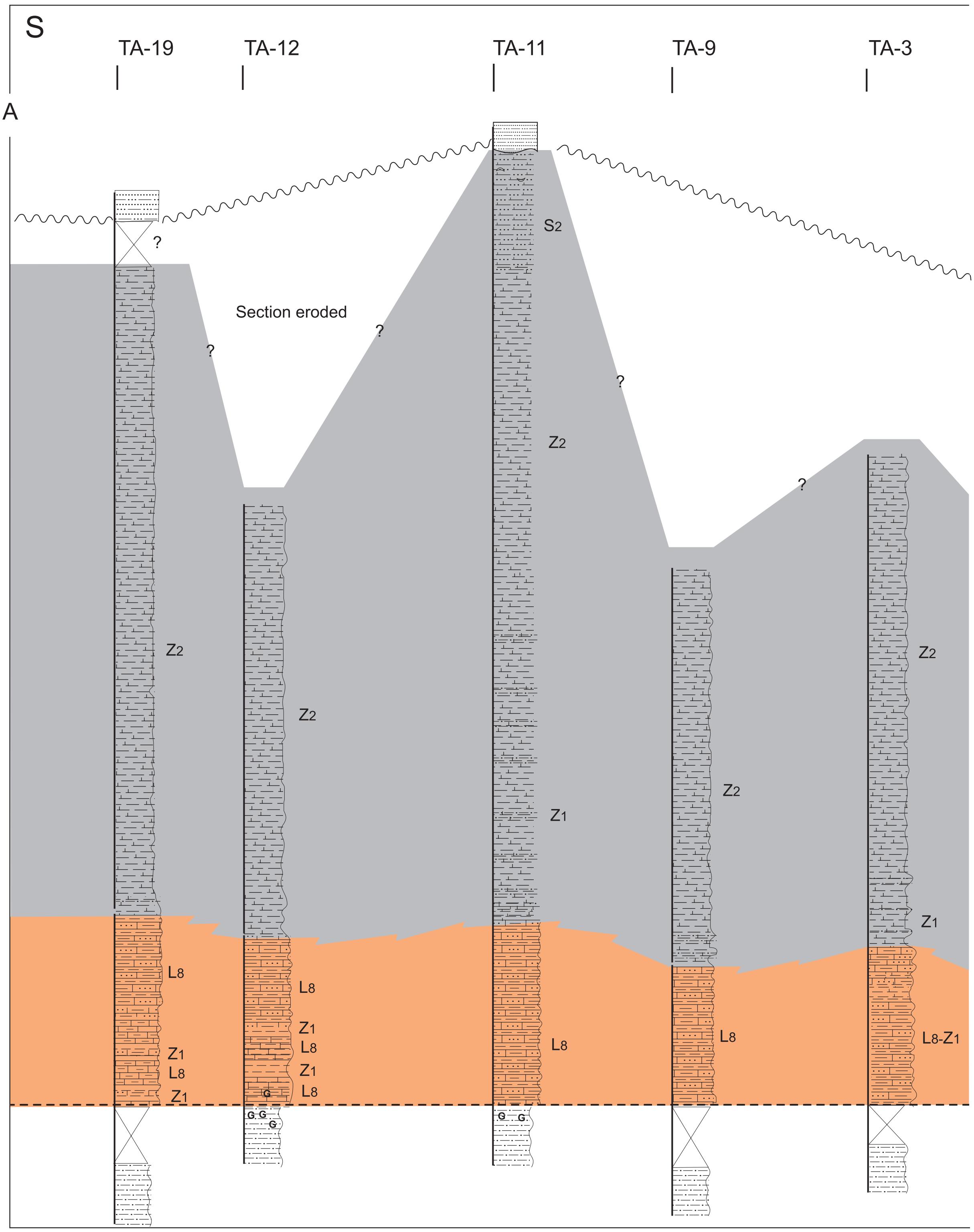
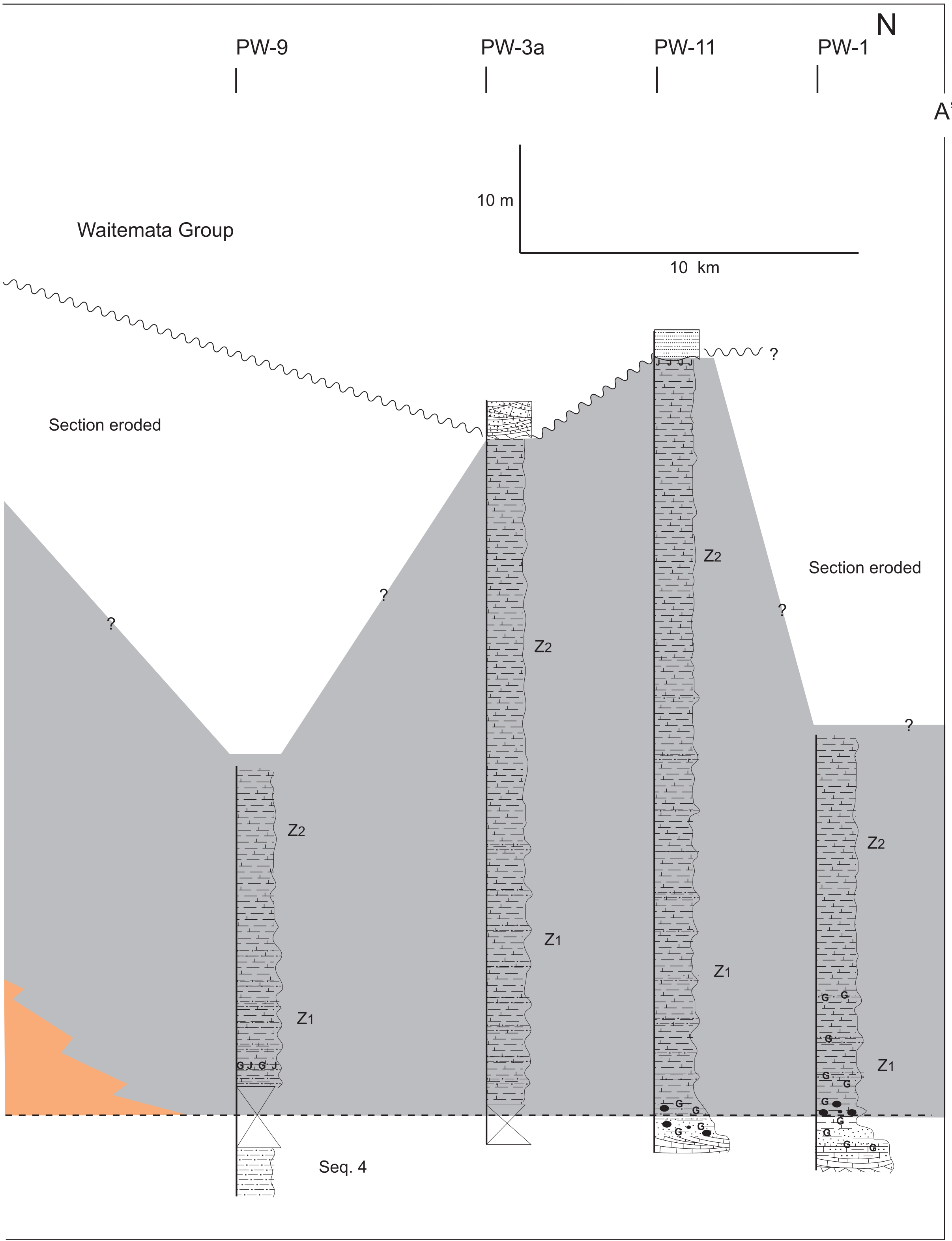


Fig. 11: (*two-page spread*) South (Raglan Harbour) to north (Port Waikato) correlation panel for Te Akatea Formation and distribution of lithofacies within it. Also shown is its lower sequence boundary (dashed line, Aotea Formation-Te Akatea Formation contact) and unconformity (wavy line) with the overlying Waitemata Group. Orange colour indicates limestone lithofacies (i.e. Raglan Limestone Member) and grey colour indicates mixed carbonate-siliciclastic lithofacies (i.e. Carter Siltstone Member). See Fig. 10 for cross section and stratigraphic column locations.



N
PW-9
PW-3a
PW-11
PW-1
A'
10 m
10 km
Waitemata Group
Section eroded
Section eroded
?
?
?
?
?
Z2
Z2
Z2
Z2
Z1
Z1
Z1
Z1
Seq. 4

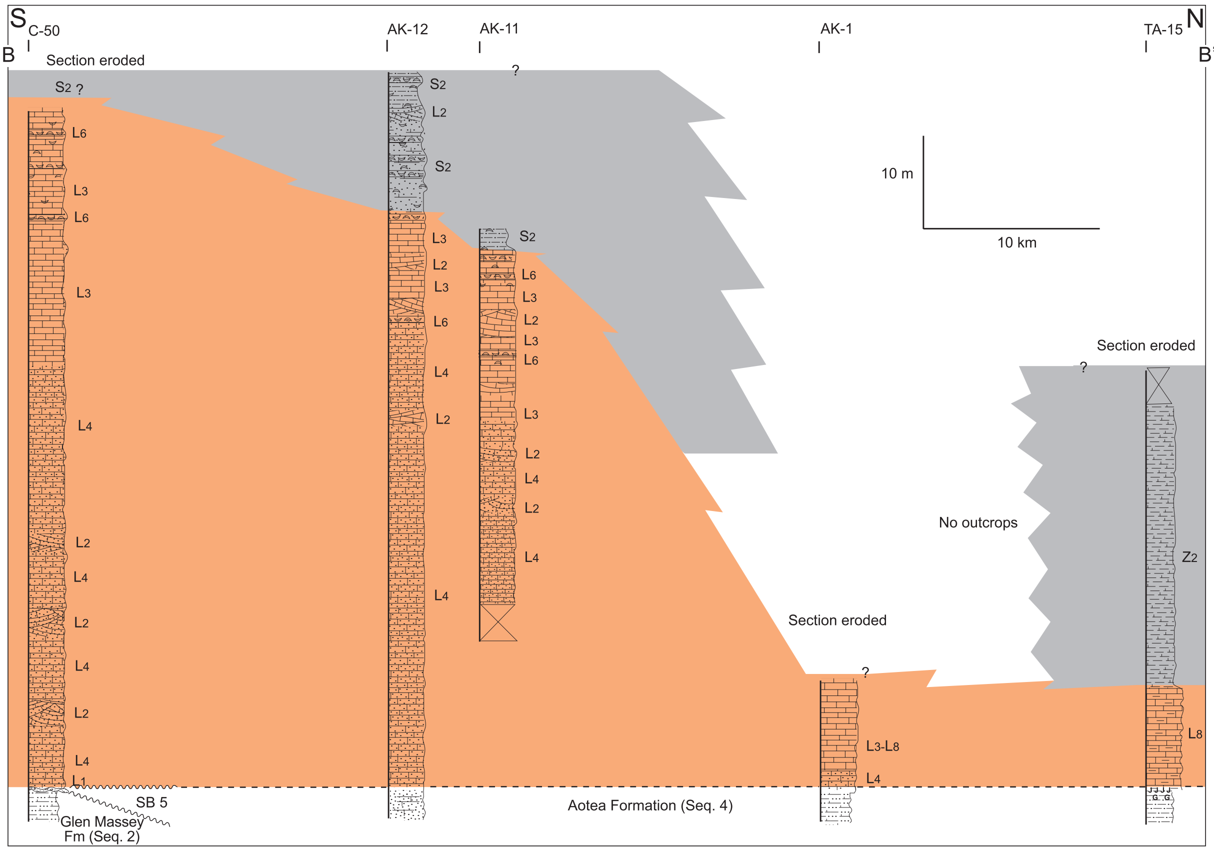


Fig. 12: South (Awamarino) to north (Raglan Harbour) correlation of Castle Craig Subgroup and distribution of lithofacies and significant facies transition. The sequence boundary at the base of the subgroup at Awamarino (C-50) is an erosional unconformity (wavy line), but in the north (TA-15) it is a correlative conformity. In the Aotea-Kawhia area (AK-12, AK-11 and AK-1) the contact between Aotea Formation and Castle Craig Subgroup is apparently conformable. Orange colour indicates limestone lithofacies and grey colour indicates mixed carbonate-siliciclastic lithofacies. See Fig. 10 for cross section and column locations.

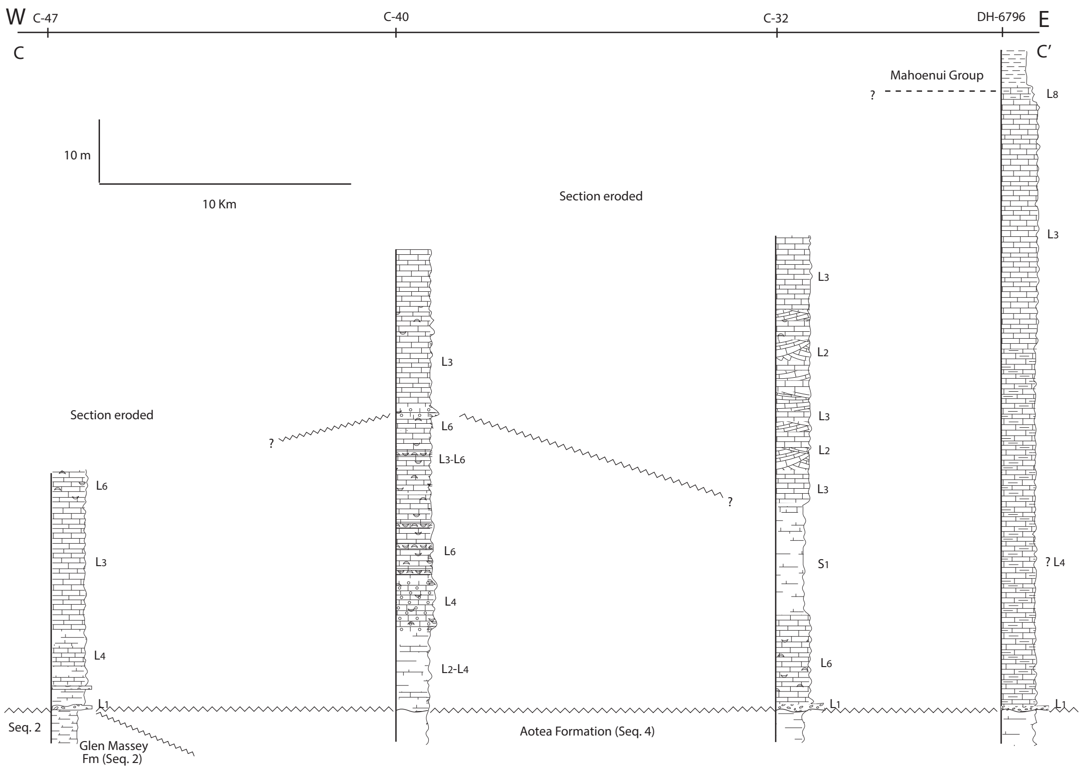


Fig. 13: West (Awamarino) to east (Te Kuiti) correlation of Orahiri Formation and Otorohanga Limestone units, and distribution of lithofacies. The lower boundary of Castle Craig Subgroup is an erosional unconformity (wavy line) with Glen Massey Formation at Awamarino (C-47) and with Aotea Formation in the eastern localities (C-40, C-32 and DH-6796). There is a conformable contact with the overlying Mahoenui Group in DH-6796. See Fig. 10 for cross section and column locations.

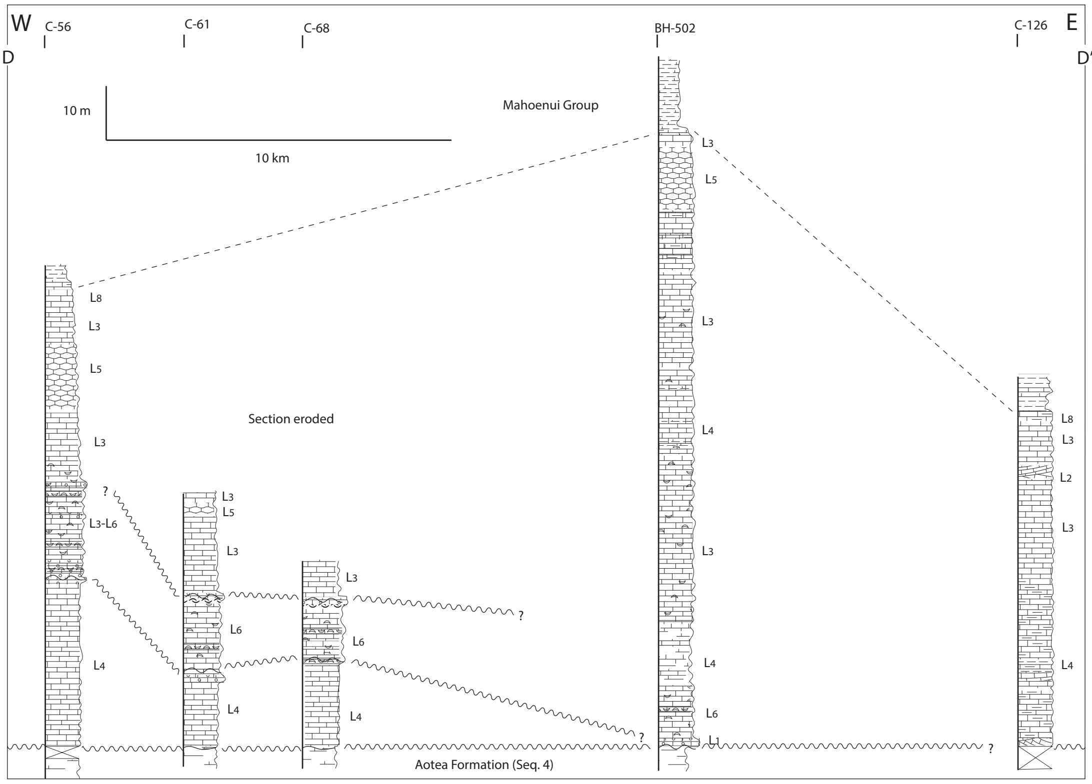


Fig. 14: West (Ngapaenga) to east (Te Kuiti) correlation of Orahiri Formation and Otorohanga Limestone units, and distribution of lithofacies association. The boundary of Castle Craig Subgroup is an erosional unconformity (lowermost wavy line). Prominent intra-formational unconformities of localised extent occur through the middle of the columns at C-56, C-61 and C-68 but are not obvious in more easterly localities e.g. BH-502 and C-126. The topmost unconformity defines the contact between Orahiri Formation and Otorohanga Limestone at C-61 and C-68. There is a conformable contact with the overlying Mahoenui Group at C-56, BH-502 and C-126 (dashed line). See Fig. 10 for cross section and column locations.

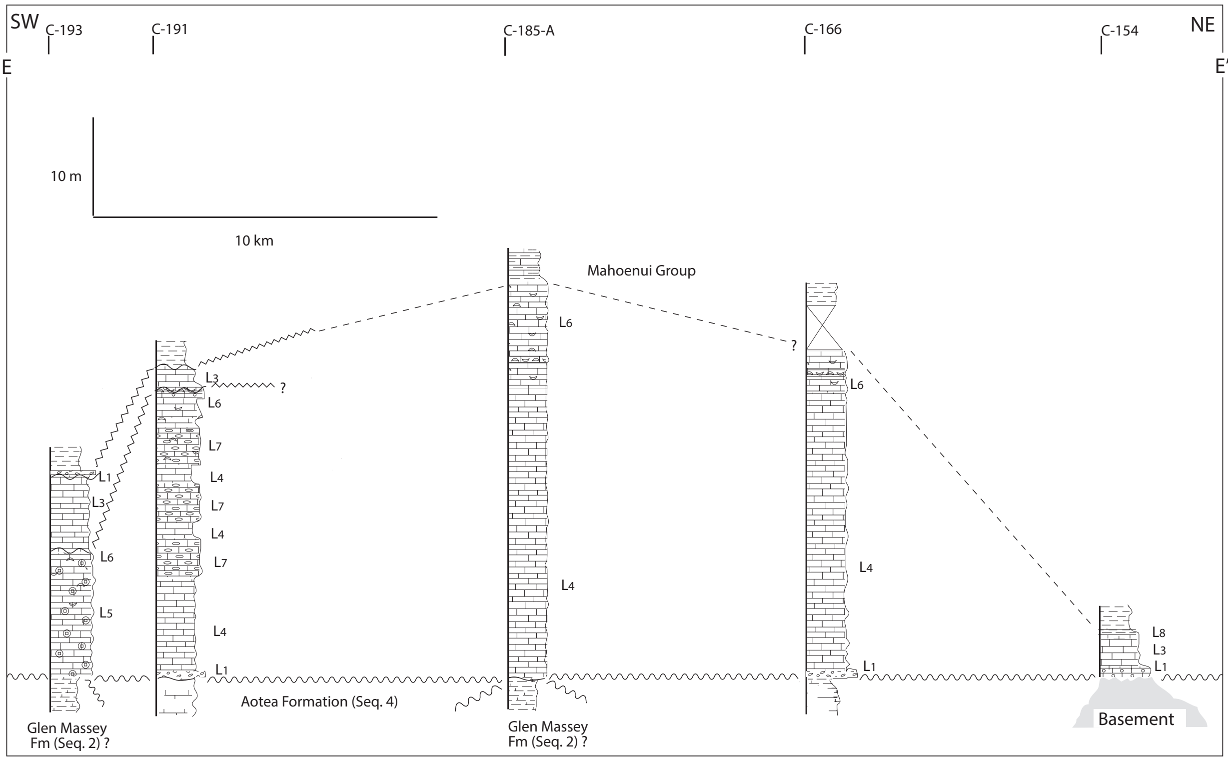


Fig. 15: Southwest (Awakino Gorge) to northeast (Piopio) correlation of Orahiri Formation and Otorohanga Limestone units, and distribution of lithofacies. Lower boundary of Castle Craig Subgroup is an erosional unconformity with Glen Massey Formation at C-193 and C-185A, and with Aotea Formation at C-191 and C-166. The middle unconformity (wavy line) defines the contact between Orahiri Formation and Otorohanga Limestone of Nelson (1973, 1978a). There is an erosional unconformity between the subgroup and overlying Mahoenui Group at C-193 and C-191, whereas it is a conformable contact at more eastern localities. See Fig. 10 for cross section and column locations.

localities PW-1 to PW-9 in Fig. 11) and areas farther to the east where it laterally grades into Medium bedded calcareous siltstone lithofacies (Z1) of Carter Siltstone. Lithofacies Z1 in the Port Waikato-Waikaretu area often contains thin (<50 cm), extensively burrowed, glauconitic and phosphatic horizons, probably reflecting sediment starvation in more distal parts of the basin. Raglan Limestone in effect represents a transition between shelf carbonates (L1-L7) to the south of Aotea Harbour and outer shelf to upper bathyal marls (Z1-Z2) to the north. Alternation of more and less stormy conditions resulted in the strongly bedded character of deposits. Raglan Limestone (Lithofacies L8) displays a silting upwards trend before transitioning into Medium bedded to Massive calcareous siltstone (Z1/Z2) of Carter Siltstone. In a few sections located to the north of Raglan Harbour (e.g. TA-11, Fig. 11) where the top of Carter Siltstone is well preserved, Z2 lithofacies grades into an 8 - 10 m-thick extensively burrowed calcareous sandy siltstone with scattered oysters and occasional large bivalves having a similar lithofacies affinity to S2. The top of this calcareous sandy siltstone unit is truncated as a result of uplift and erosion that preceded deposition of Waitemata Group.

Sedimentary evolution of the carbonate succession in Castle Craig Subgroup

Overview

The spatial and vertical facies distribution within Castle Craig Subgroup provide the descriptive and interpretative basis to consider the evolution of its depositional system. From the facies associations it is clear that the Orahiri Formation and Otorohanga Limestone accumulated in shoreline and shelf marine paleoenvironments under strong wave and tidal influence (Nelson 1973, 1978a; Anastas 1997). In contrast, the mixed carbonate-siliciclastic facies of the contemporaneous Te Akatea Formation accumulated in an open marine setting, probably at outer shelf to upper bathyal water depths, in the northern part of the basin. The transition between the carbonate shelf and upper bathyal environments lies in the vicinity of Raglan Harbour and it can be characterised as a ramp setting rather than a classical shelf-slope break margin.

The following section describes the nature of the sequence boundary at the base of the Castle Craig Subgroup, and two stages in the evolution of the overlying shelf to slope depositional system.

Sequence boundary

The base of the Castle Craig Subgroup corresponds to a widespread unconformity, which has different origins in different parts of the basin. The unconformity south of Kawhia Harbour may have involved subaerial exposure, involving the southwestern part of the basin adjacent to the Herangi High. For example, at Awakino Tunnel the unconformity is an irregular surface with scours up to 40 cm deep (Fig. 16a, b). In the Mangaotaki Bridge, Waitomo Valley Road and Honikiwi sections (Fig. 16), there is a sharp undulatory contact between Kihi Sandstone and Orahiri Formation overlain by polished pebbles, glauconite pellets and shell hash concentrations. This unconformity is interpreted to be a transgressive surface of erosion (TSE) (e.g. Nummendal & Swift 1987) that formed through wave planation during coastal onlap.

In some locations the base of the Orahuri Formation appears to be gradational. For example, in the Aotea-Kawhia Harbour area, the contact is not a surface but rather an abruptly gradational transition from Hauturu Sandstone or Kihi Sandstone into sandy limestone of Orahiri Formation, commonly marked by a gradual increase in the flaggy character reflecting an increasing carbonate content upsection (Fig. 17).

In the northern region, the base of the Castle Craig Subgroup is a paraconformity between Aotea Formation members and Te Akatea Formation. In the vicinity of Raglan Harbour it occurs at the base of Raglan Limestone and is marked by a high concentration of glauconite and a dense network of *Thalassinoides* and/or *Scolicia* burrows, characteristics of firmground to hardground development (Fig. 18). In the vicinity of Port Waikato the paraconformity comprises a glauconitic and phosphatic burrowed horizon about 30 cm thick. In sections to the east of

Port Waikato (e.g. Glen Murray) the formation boundary is marked by a change from siliciclastic Patikirau Siltstone to calcareous siltstone (Carter Siltstone Member) without much evidence for condensation.

In sequence stratigraphic terms the burrowed omission zone qualifies as a correlative conformity and is inferred to merge with the erosional unconformity at the base of Orahiri Formation in the southern part of the basin (Fig. 1).

Stages in evolution of Castle Craig Subgroup

Evolution of the shelf to slope depositional system during accumulation of the Castle Craig Subgroup is inferred from stratal patterns reconstructed between the southern and northern parts of the basin.

Stage A: progradation

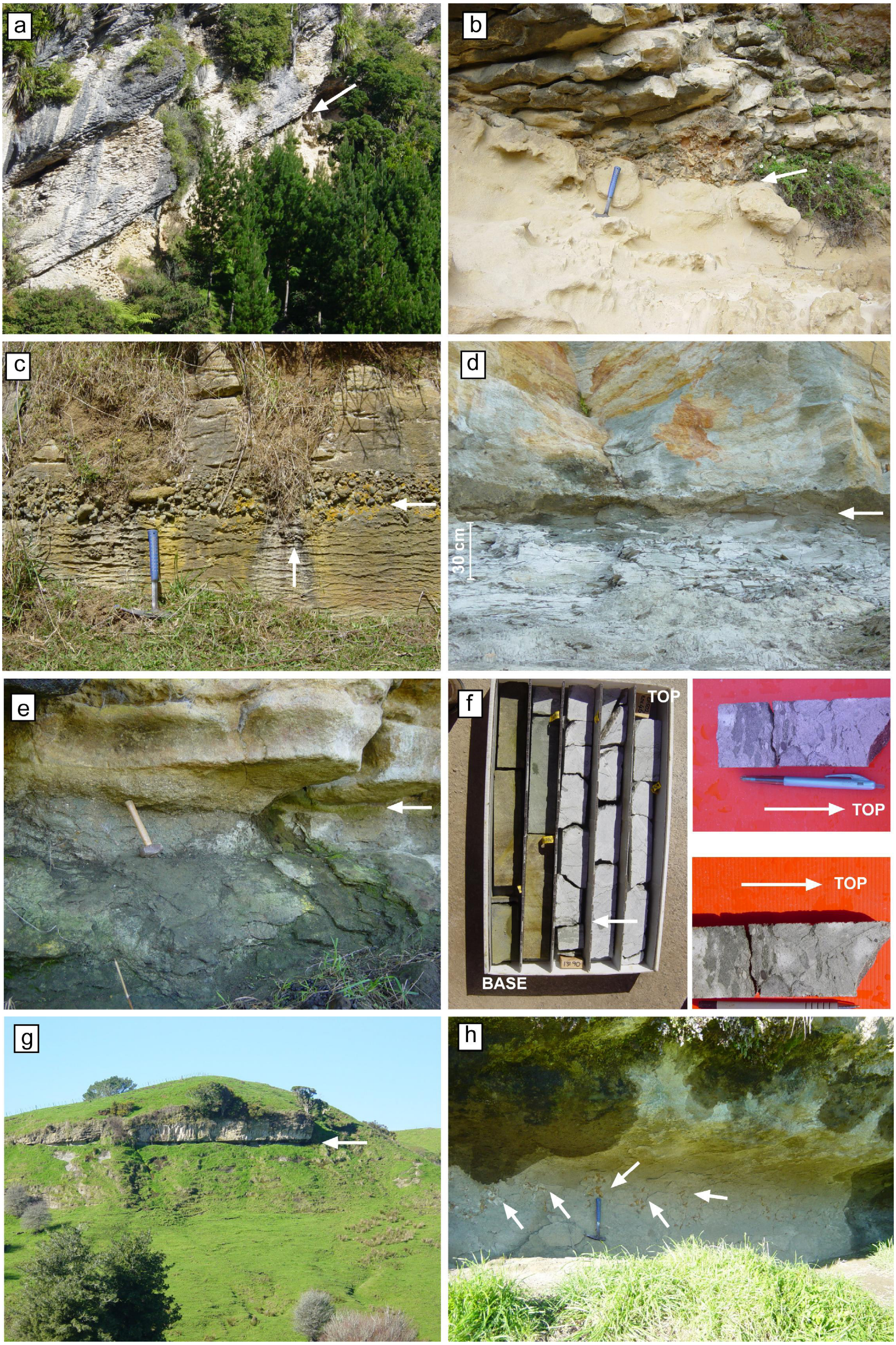
The main paleogeographic elements inferred during deposition of Orahiri Formation and the lower units of Te Akatea Formation include the Herangi High, a broad shelf between the Herangi High and the Piopio High (Fig. 3), and a gentle north and northeast sloping ramp (av. ~1-2° angle) between Kawhia Harbour and Port Waikato (a distance of 150 km). The lack of obvious turbidites, slump structures or other types of mass emplacement within Te Akatea Formation highlights the gentle gradient of the shelf to slope transition and the absence of a marked shelf-slope break.

The overall depositional system in the lower part of the Castle Craig Subgroup (Orahiri Formation and Raglan Limestone Member) is envisaged to be mildly progradational, controlled mainly by the relatively high flux of sediment. This depositional model envisages a rocky shoreline along the eastern side of the Herangi High that provided ideal conditions for the growth of skeletal carbonate fauna and flora. The high terrigenous sandstone content (up to 50%) within the lower part of the Orahiri Formation (Mangaotaki Limestone, Lithofacies L4) adjacent to Herangi High implies recycling of eroded material from Hauturu Sandstone back into the basin. This is supported by the accumulation of Conglomeratic limestone facies (L7) in Orahiri Formation in the Awakino Tunnel area upon an actively tilting shelf (Nelson et al. 1994). The widespread occurrence of horizontally and cross-bedded grainstone (Lithofacies L2 and L3) within Orahiri Limestone suggests that the carbonate accumulated in a wave and tidal current swept seaway (Nelson 1978a) (Fig. 19). The cross-beds (Lithofacies L2) formed from the migration of large (1-5 km long) dune fields within this seaway in water depths of about 40-60 m depth. Much of the energy to entrain sediments and move dunes probably came from tidal currents strengthened by irregular topography. It is inferred that the skeletal carbonate sediment supply and current strengths were sufficient to prograde the carbonate shelf eastwards to onlap the flanks of Piopio High and to form a carbonate ramp to the north (Fig. 20).

The predominantly calcarenitic nature of the shelf limestone accumulation in the southern part of the basin, and hence the degree of fragmentation of the original flora and fauna that must have occurred, implies the production of large volumes of carbonate mud (micrite) (Nelson 1978b). Much of this micrite was transported beyond the shelf area to accumulate as part of Te Akatea Formation. Raglan Limestone in Raglan Harbour sections has carbonate contents as high as 89% and represents part of this load; the remainder became mixed with planktic foraminifera and background terrigenous mud and accumulated in Carter Siltstone. Even within Raglan Limestone facies the carbonate content decreases, being 72% at Te Akau. This gradual decrease in carbonate content to the north is reflected in the lateral facies transition from Lithofacies L8 (Raglan Limestone) to Lithofacies Z1 and/or Z2 in Carter Siltstone, the transition lying midway between Raglan Harbour and Port Waikato.

Stage B: retrogradation

The second stage in the accumulation of Castle Craig Subgroup involved a long term relative rise in sea level that increased accommodation on the shelf and terminated the earlier northward progradation of the carbonate shelf. This is


a
b
c
d
30 cm
e
f
TOP
BASE
TOP
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g
h

Fig. 16: *(facing page)* Photographs illustrating typical field expression of sequence boundaries (TSE) in the Castle Craig Subgroup across the south-central region of the study area. (a) Massive to thin bedded, variably calcareous fine sandstone (Hauturu Sandstone Member) is truncated (pointed by arrow) and overlain by sandy grainstone-packstone (L4) of the Orahiri Formation. The Orahiri Formation dips 31°E. Exposure is approximately 30 m high at Awakino Tunnel (C-191). (b) Close-up of contact shown in photo a. Arrow points at the scoured contact infilled with rounded basement cobbles and pebbles. (c) Horizontal arrow points at erosional unconformity surface overlain by cobbles and pebbles (transgressive lag deposits). This unconformity separates the highly calcareous sandstone (Ahirau Sandstone Member) from the overlying sandy grainstone-packstone unit (Orahiri Formation). Note the pebble-filled scour pockets associated with transgressive erosion (vertical arrows). Awamarino (C-50). (d) Wave-ravinement surface truncates the top of muddy sandstone unit of the Kihi Sandstone Member overlain by sandy grainstone-packstone of the Orahiri Formation. Note the presence of a thin pebble band with high concentration of glauconite pellets (transgressive lag deposit) at the base of the overlying sandy grainstone-packstone unit. Mangaotaki Bridge (C-166) (e) A bioturbated glauconitic sandstone unit (Kihi Sandstone Member) is truncated at the top by a wave-planed surface (arrow), overlain by slightly sandy grainstone (Orahiri Formation) with a thin basal pebble grit and containing abundant skeletal fragments (transgressive lag deposit). Waitomo Valley Road (C-32). (f) Slightly irregular scoured contact (arrow) between dark greenish-grey muddy glauconitic sandstone (Kihi Sandstone Member) and overlying sandy grainstone-packstone (Orahiri Formation). Two insets show close-ups of this contact. Note the glauconitic, burrowed mottled texture of the sandstone below the contact and rounded pebbles in the overlying glauconitic grainstone-packstone unit. Photograph of core from BH-502, Oparure Limestone Quarry. C-119. (g) Sharp and broadly undulatory contact (arrow) between bioturbated muddy sandstone (Kihi Sandstone Member) and overlying low-angle cross-bedded grainstone (Orahiri Formation). Outcrop is approximately 20 m high. Honikiwi (C-25). (h) Close-up of the contact shown in photo g. Arrows point to *Thalassinoides* burrows that penetrate downwards into the sandstone from the erosional unconformity. The burrows are infilled with carbonate sand from the overlying Orahiri Formation.

expressed in the northern part of the basin by accumulation of Carter Siltstone over Raglan Limestone. This transition from L8 into Z1 and/ or Z2 facies is interpreted as a retrogradational shift in the facies belts. A similar vertical facies transition from dominantly carbonate (Lithofacies L2 - L6; Otorohanga Limestone) to sandy siltstone (Lithofacies S2; Carter Siltstone) is apparent in the Kawhia area (Localities AK-11, AK-12 in Fig. 12; and Fig. 1).

In the south-central region, Otorohanga Limestone overlies Orahiri Formation, which in general marks a change to more pure carbonate sedimentation with terrigenous content rarely exceeding 10% (Nelson 1973, 1978a). The minimal siliciclastic input during the accumulation of Otorohanga Limestone probably reflects a more productive carbonate factory than earlier and possibly a lower siliciclastic flux to the basin. An overall deepening trend within Otorohanga Limestone has been inferred from variations in bryozoan growth forms (Nelson et al. 1988b; Anastas 1997). However, the occurrence of Massive to irregularly bedded fossiliferous rudstone-grainstone (L5) forming most of the Waitanguru Limestone Member (Fig. 1) indicates a high energy depositional environment, possibly related to periodic lowering of relative sea level (Nelson 1973; Nelson et al. 1988b; Nelson & James 2000).

The Otorohanga Limestone succession rests directly on basement in the vicinity of Piopio and Aria, implying enough carbonate sediment supply from the west to enable progradation of the carbonate shelf across the Piopio High. The start of the retrogradational phase in the southern region is marked by the accumulation of Lithofacies L8 in the upper part of Piopio Limestone Member. Previous estimates of paleobathymetry based on textural and paleontological evidence suggested a gradual increase in water depth within the upper part of Otorohanga Limestone (Nelson 1973, 1978a). The upper parts of Otorohanga Limestone become progressively richer in terrigenous silt before grading into Mahoenui Group, usually via interbedded packstone-wackestone (Lithofacies L8), reflecting an increase in water depth.

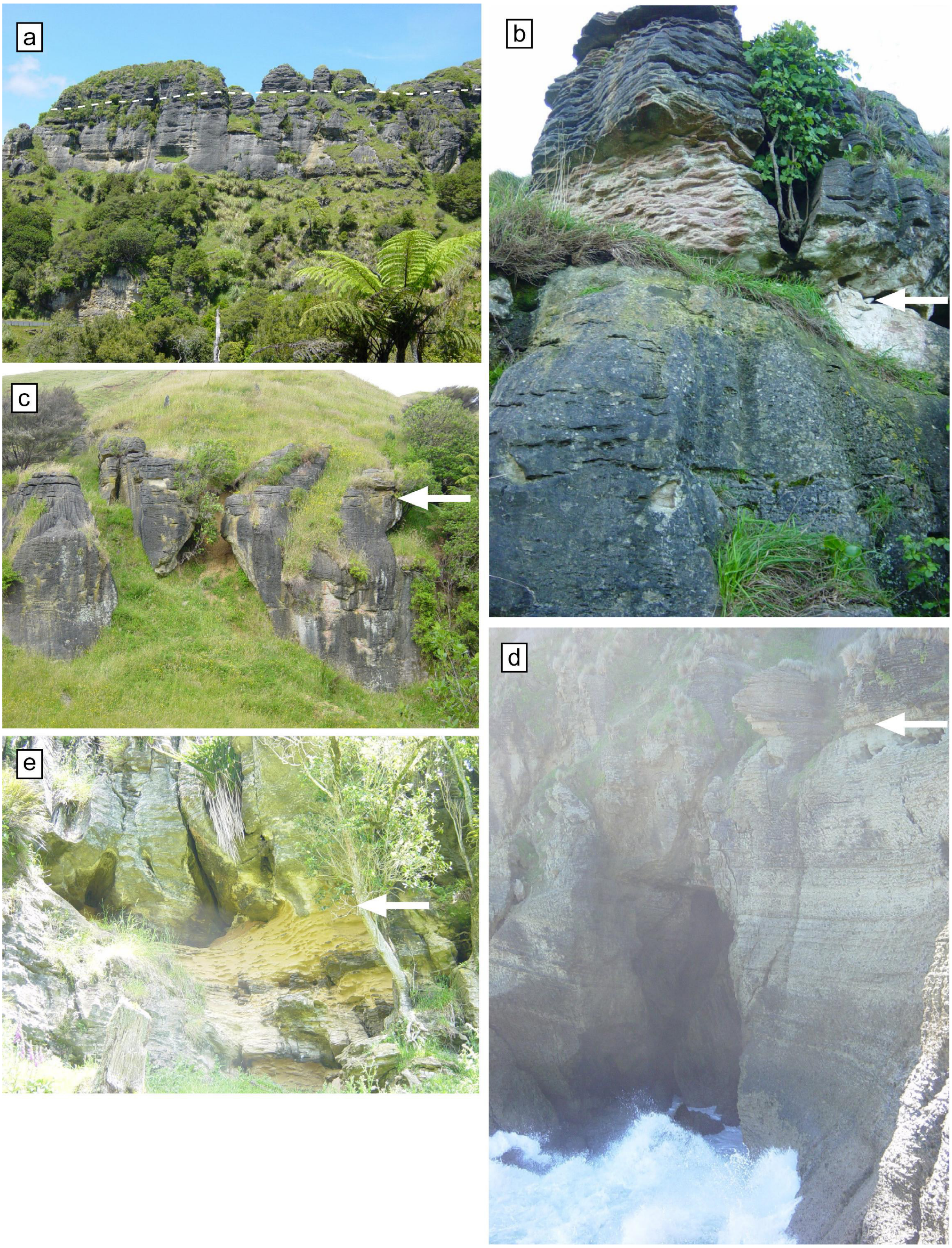
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Fig. 17: *(facing page)* Photographs illustrating typical field expression of conformable contact between Aotea Formation and overlying Castle Craig Subgroup across the central Aotea-Kawhia area. (a) Contact between Kihi Sandstone Member and overlying Sandy grainstone-packstone (L4) of Orahiri Formation (dashed line). Exposure is about 50 m high. Hautapu Hill (AK-10). (b) Arrow points to abruptly gradational contact between Kihi Sandstone Member and overlying Horizontally bedded grainstone (L3) of Orahiri Formation. Note change in increased carbonate content is reflected in flagginess of the overlying unit. Exposure is about 6 m high. Makaka, north of Aotea Harbour (AK-1). (c) Arrow points to conformable contact between Kihi Sandstone Member and overlying Sandy grainstone-packstone (L4) of Orahiri Formation at Pakoka Landing, north of Aotea Harbour (R15/726621). Exposure is about 5 m high. (d) Abruptly gradational contact between Hauturu Sandstone and Sandy grainstone-packstone (L4) of Orahiri Formation (arrow) at Taranaki Point (S16, Fig 2). Sea cliff is about 50 m high. (e) Gradationa.l contact between Hauturu Sandstone Member and overlying Sandy grainstone-packstone (L4) of Orahiri Formation at Whanuapo Hill, Toi Road, south of Kawhia Harbour (R16/755379).

Overview of vertical facies succession and the definition of Orahiri Formation and Otorohanga Limestone

The Castle Craig Subgroup in the south-central region of the basin has a complex mosaic of facies. Nelson (1978a) used a terminology of OrA, OrB, Wt, OtA, OtB, and OtC to describe individual depositional units within what is named here the Castle Craig Subgroup, and constructed east-west correlation panels showing facies relationships between the eastern and western parts of Waitomo District (Figs 31, 32 in Nelson 1978a). The inferred facies relationships in those cross-sections indicate multiple stacked units consisting mainly of OrA, OrB, OtA, OtB and OtC along the western sector, progressively pinching out to the east against a topographic high. The limestone succession overlying the basement high (Piopio High) was shown to consist of OtA and OtC units, implying that the entire eastern sector was emergent during the deposition of OrA and OrB units. The inferred absence of OtA, OtB and OtC rock units in many localities lying in the western sector was explained by non-deposition and/or erosion as a result of basin margin inversion and tilting (Nelson et al. 1994).

To determine more fully the implied relationship between Orahiri Formation and Otorohanga Limestone, additional east-west cross-sections were constructed in this investigation (Figs 22, 23), focusing on the stratigraphic location of oyster beds used by Nelson (1978a) as a marker to differentiate Orahiri Formation (OrB) from Otorohanga Limestone. The significance of unconformities and associated marine-cemented units within the limestone succession, used by previous workers to differentiate the Orahiri and Otorohanga depositional units, are also discussed below.

Location of oyster beds

The spatial extent of oyster beds (L6) within the limestone succession is shown in Figs 2 and 3, and their stratigraphic positions are shown in three E-W transects (Figs 22b, 23). In cross-section A-A' (Fig. 22b), oyster beds at C-166 occur at the top of the limestone succession, whereas at C-184 they occur mainly in the lower and middle parts of Castle Craig Subgroup. Sandy grainstone (L4), which is a commonly occurring facies in Mangaotaki Limestone, forms the bulk of stratigraphic thickness at these localities. Oyster beds are absent in sections located farther to the east (e.g. C-174). In all three localities, the Castle Craig Subgroup is overlain by Mahoenui Group with apparent conformity, which implies that there is no missing limestone interval from the top of the subgroup. In cross-section B-B' (Fig. 23a), the oyster beds are present near the base of the limestone at localities C-117, C-99/C-100 and C-80, but they are also absent in the nearby section C-82 located to the west. Oyster beds are also absent in the east at C-126. In cross-section C-C' (Fig. 23c), oyster beds occupy stratigraphic positions high in the limestone, such as at locality C-51, and progressively lower positions northeastward into C-32. The schematic west-east cross-section X-X' in Fig. 19b also shows a similar trend of oyster beds occurring at the lower levels of the limestone in the east.

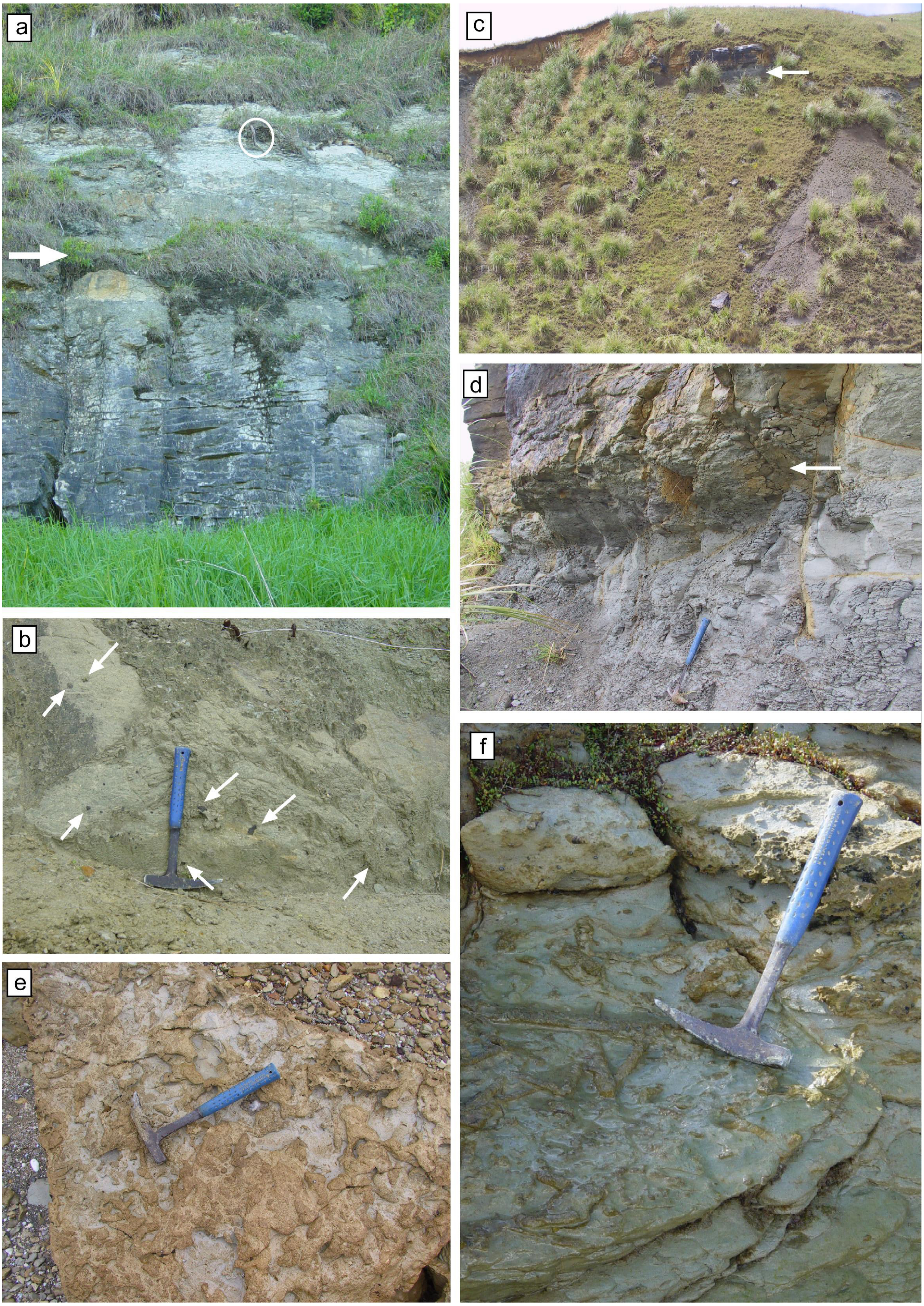
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Fig. 18: *(facing page)* Photographs illustrating typical field expressions of sequence boundaries of the Castle Craig Subgroup across the northern region of the basin. (a) The Waimai Limestone Member passes into massive calcareous siltstone (Z1/Carter Siltstone Member) through a highly fossiliferous greensand (condensed Patikirau Siltstone Member of Aotea Formation) pointed to by arrow. This facies contact is inferred to be a sequence boundary (correlative conformity) at the base of the Te Akatea Formation in the Port Waikato area. Hammer for scale. Photo location: Port Waikato-Waikaretu Road section (PW-2). (b) Arrows point to scattered phosphate nodules near the conformable contact between the greensand (condensed Patikirau Siltstone of Aotea Formation) and overlying massive calcareous siltstone (Z2/Carter Siltstone Member). Waikawau Beach (PW-11). (c) Arrow points to a sharp but conformable facies contact (an inferred sequence boundary) between massive sandy siltstone (Patikirau Siltstone) and the overlying highly bioturbated packstone-wackestone (L8/ Raglan Limestone). Cliff is approximately 30 m high. Patikirau Bay, Raglan Harbour (TA-20). (d) Close-up view of the conformable facies contact shown in photo c. Note extensively bioturbated base (pointed to by arrow) of the packstone-wackestone unit (L8, Raglan Limestone). Locally conspicuous glauconite pellets are also observed at this contact. (e) Close-up of burrowed hardground surface exposed in one of the fallen blocks from the contact shown in photo c. (f) Abundant *Scolicia* and *Thalassinoides* burrows marking an inferred sequence boundary between sandy siltstone (Patikirau Siltstone) and Silty packstone-wackestone (L8, Raglan Limestone). Okete Bay, Raglan Harbour (TA-15).

All of the sedimentological evidence noted previously suggests that the oyster facies (Lithofacies L6) were deposited in a current swept inner to mid shelf environment (Nelson et al. 1983). It is likely that the environmental conditions favourable for oysters to thrive, such as strong currents and elevated nutrient supply, existed at various times across the southern part of the basin. Favourable environmental conditions for oyster growth seem to have migrated from east to west and to the southwest (Awakino) with time (Nelson 1973). The absence of oysters in the thick limestone succession (Otorohanga Limestone) in the vicinity of Te Kuiti (e.g. C-126) probably indicates that favourable conditions for oyster growth were not present at that time at that place. It is therefore suggested that the occurrence or otherwise of oyster beds as a basis to distinguish Orahiri Formation from Otorohanga Limestone is not robust.

Regional significance of unconformities and associated marine-cemented units

The Castle Craig Subgroup over the south-central area is punctuated by several unconformities. In the vicinity of Ngapaenga and west of Piopio, past workers (Hopkins 1966; Nelson 1973, 1978a) have mapped or correlated several unconformities which generally mark abrupt facies transitions. Nelson & James (2000) observed that many of these unconformities are associated with marine-cemented units, either below, or sometimes immediately above the unconformity surfaces. In outcrop, these unconformities are typically marked by irregular, sharp, erosion surfaces, and may include scattered basement-derived pebbles, occasional limestone clasts and conspicuous fragments of pectinids, oysters and bryozoan colonies concentrated below the surface and also immediately above it (Fig. 24). Erosion surfaces superimposed on a submarine hardground locally exhibit rusty-brown iron oxide colouration, phosphatic mineralisation, and concentrations of glauconite pellets and/or glauconitised clasts and shell fragments. Collectively, these features along with marine cementation were associated with stratigraphic condensation and relatively high-energy sediment reworking at this surface during periods of relative lowstand (Nelson & James 2000). One of the more prominent unconformities is used by Nelson (1978a) to delineate the boundary between Orahiri Formation and Otorohanga Limestone (Tripathi et al. 2008). A significant shoaling of the water depth has been suggested below this contact based on variation in bryozoan growth-form trends (Nelson et al. 1988b).

However, these unconformities and their associated features are only recognisable locally in the south-central area lying to the west of Waipa Fault (Fig. 19b). This is also evident from the distribution of the associated facies belts. The unconformities probably have a local origin related to uplift of Herangi High to the west, resulting in relative sea-level fall, rather than necessarily indicating a regional base-level change. Definite physical evidence for subaerial exposure at these surfaces is elusive except at the few localities in the vicinity of Ngapaenga where red iron oxide coating on pebbles occurs on the unconformity

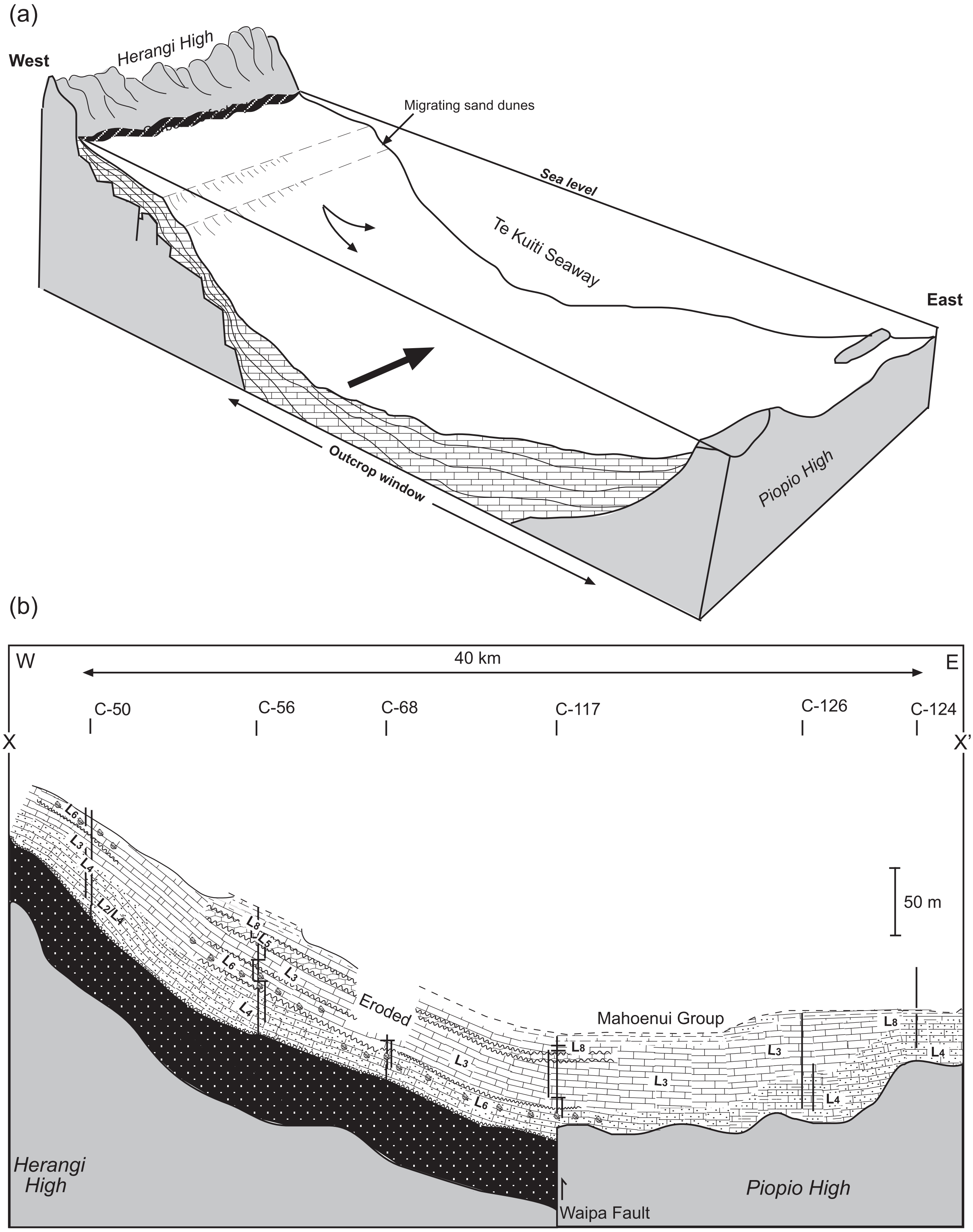

Fig. 19: (a) Idealised paleogeographic reconstruction for the southern region showing the high-energy, clastic carbonate seaway (not to scale) that produced a mosaic of lithofacies in the Castle Craig Subgroup (refer text for details). (b) Schematic cross-section showing main facies relationships from westerly localities and more distal eastern localities (see Fig. 22 for column locations). Stratigraphic thicknesses shown against the columns are approximate. Note the oyster-bearing limestone facies (L6) in C-117 occurs at a lower level whereas they occur at higher levels in the more western located columns (C-50). Wavy lines indicate unconformities, including the prominent erosional unconformity that marks the contact between Okoko Subgroup and overlying Castle Craig Subgroup. Other unconformities occur in the limestone succession west of Waipa Fault, but are not obvious in the east. These unconformities are probably of tectonic origin and may have developed in response to local fault movement. Piopio High was probably tectonically stable during limestone accumulation. No vertical scale implied.

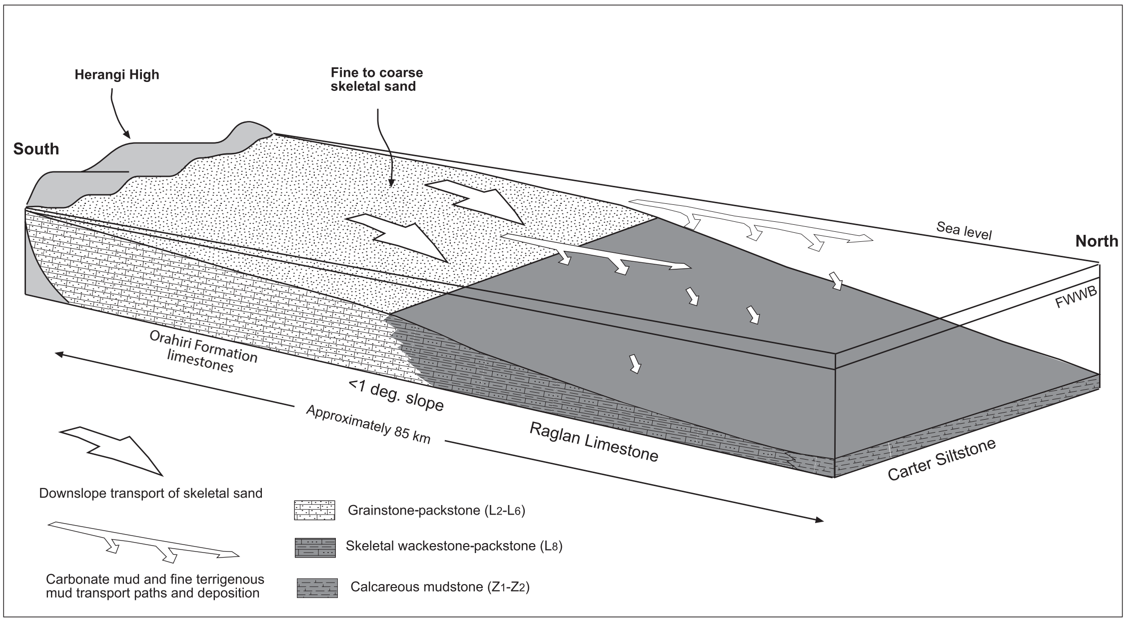

Fig. 20: Conceptual model illustrating carbonate shelf to slope transition via a gentle northward sloping ramp from Marokopa (south of Kawhia Harbour) to Port Waikato in the western sector of the central northern region. No scale or specific correlation is implied. Broad lateral facies transition along this transect reflects hydrodynamic conditions. Well developed Medium to coarse sandy grainstone-packstone (L2-L5) in the south is derived mainly from skeletal sands produced by wave abrasion processes on the rocky shoreline of the Herangi High, which were transported down the ramp by storm and/or tidal currents. The carbonate mud and fine terrigenous fraction was flushed out and swept farther into the outer shelf-upper bathyal environment and accumulated by suspension fallout. This fine carbonate material forms the Raglan Limestone in the northern part of this transect (Massive to horizontally bedded skeletal packstone-wackestone facies, L8). The Raglan Limestone Member (L8) grades laterally into Carter Siltstone Member (Z1-Z2) farther north, where it was partly diluted by background terrigenous mud.

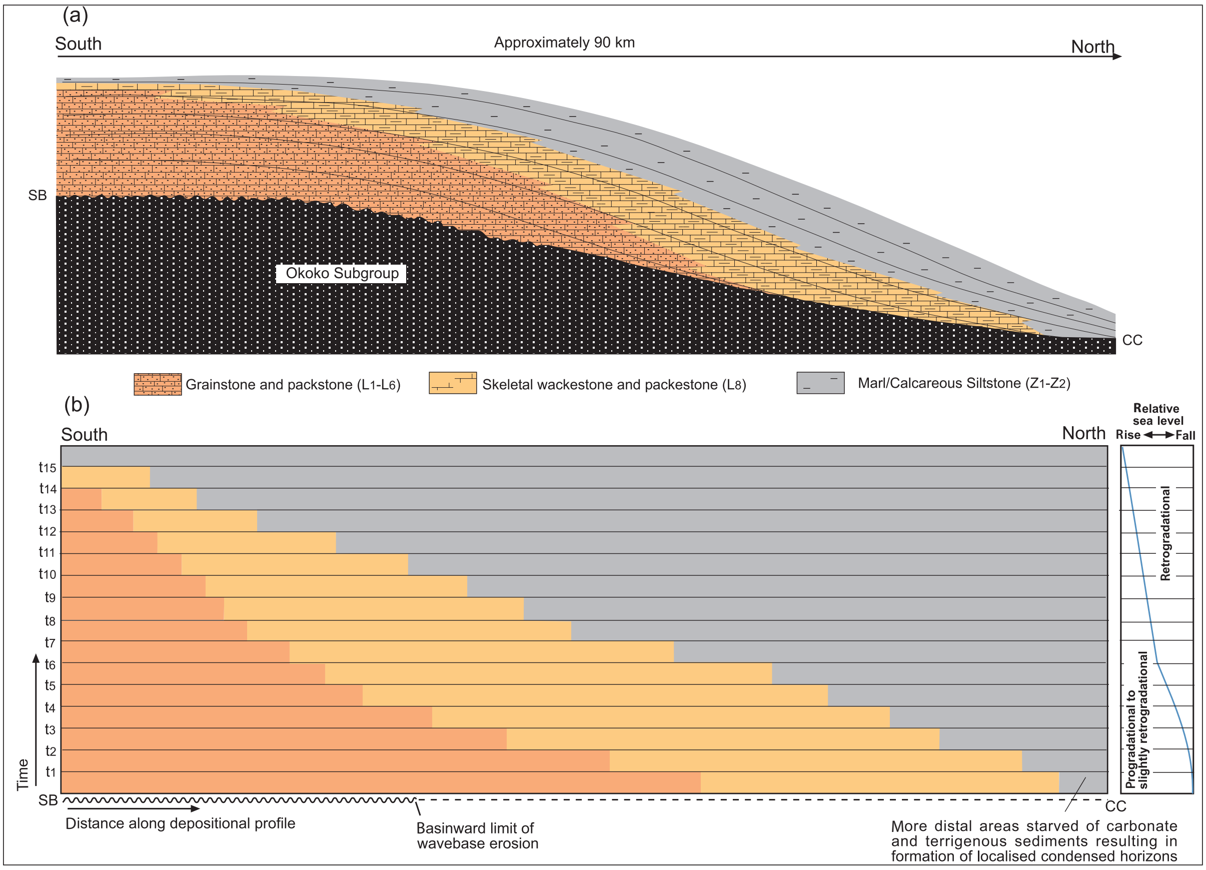

Fig. 21: (a) Schematic depositional model and (b) chronostratigraphic panel showing the inferred distribution of the main lithofacies in the Castle Craig Subgroup along a north-south profile. In the lower part of the model the carbonate shelf and slope are mildly progradational, as shown by the occurrence of Raglan Limestone (L8), sourced from the south. Subsequently the system became retrogradational, and a southward migration of the facies belts is inferred with mixed carbonate and siliciclastic siltstone (Z1-Z2) progressively accumulating over the carbonate lithofacies.

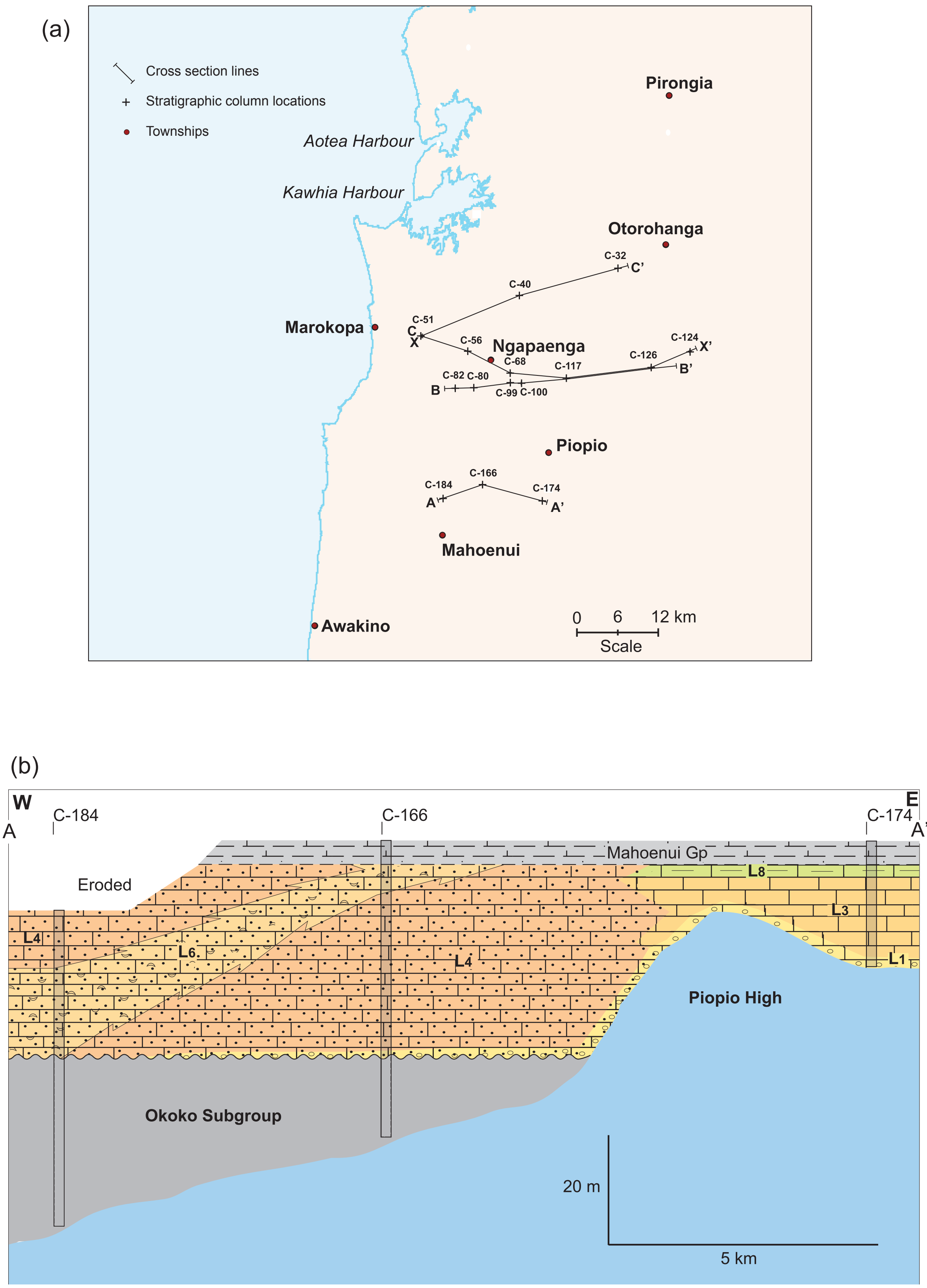

Fig. 22: (a) Map showing the location of cross-sections illustrated in Figs 19b, 22b and 23. (b) West to east stratigraphic correlation of lithofacies through the Orahiri Formation/Otorohanga Limestone. The datum is the basal erosional unconformity with the Okoko Subgroup.

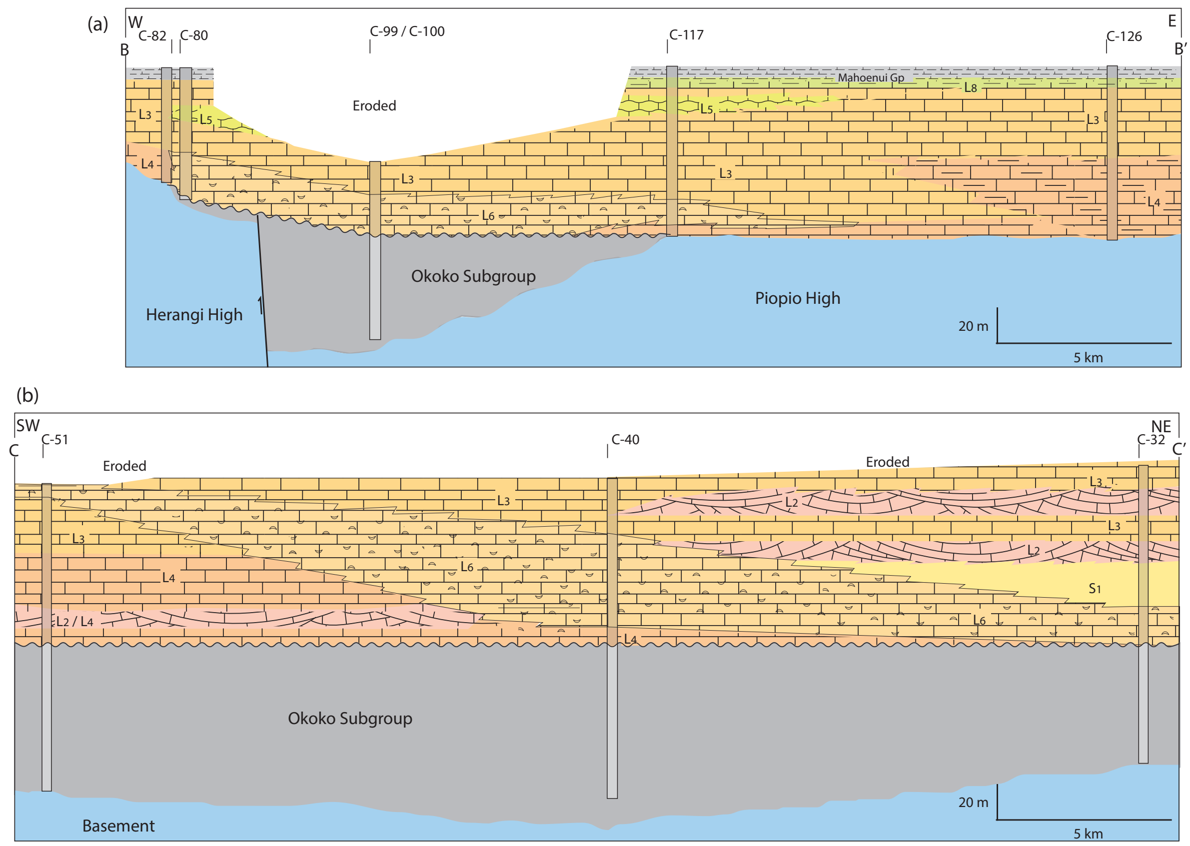

Fig.23: (a) West to east stratigraphic correlation of lithofacies through the Orahiri Formation/Otorohanga Limestone. The datum is the erosional unconformity with the Okoko Subgroup. (b) Southwest to northeast stratigraphic correlation of lithofacies through the Orahiri Formation/Otorohanga Limestone. The datum is the erosional unconformity with the Okoko Subgroup. See Fig. 22 (a) for cross-section and column locations.

surface. This implies that in the majority of cases the hardgrounds were not developed in the subaerial environment but rather by shoaling into an inner shelf zone of marine erosion. The development of unconformities and marine-cemented limestone units is not evident in areas east of Waipa Fault. In that eastern depocentre subsidence and accumulation of limestone seems to have continued relatively uninterruptedly.

Summary

Detailed field investigations have identified twelve lithofacies within the Castle Craig Subgroup, which have been grouped into three lithofacies associations named limestone, mixed carbonate-siliciclastic sandstone, and mixed carbonate-siliciclastic siltstone after their dominant lithologies. In areas south of Aotea Harbour the subgroup comprises a wide variety of limestone types with variable siliciclastic content, dominated by coarse skeletal rudstone-grainstone (L1-L7), comprising mainly fragmental bryozoans, echinoderms, benthic foraminifera and epifaunal bivalve shells. The subgroup in these areas has an aggregate thickness of up to 100 m. The carbonate sediments accumulated at shelf depths in a moderate to high-energy tidal seaway. Around Raglan Harbour and in areas to the north, the subgroup comprises predominantly planktic foraminiferal-rich packstone to wackestone (L8) and calcareous siltstone/marl (Z1, Z2) that accumulated mainly in slope/upper bathyal settings. Pliocene and Pleistocene Alexandra Volcanic Group and Okete Volcanic Group bury the transition between the shelf carbonate facies of the Orahiri Formation and Otorohanga Limestone south of Aotea Harbour and the upper bathyal mixed carbonate-siliciclastic facies of Te Akatea Formation north of Raglan Harbour.

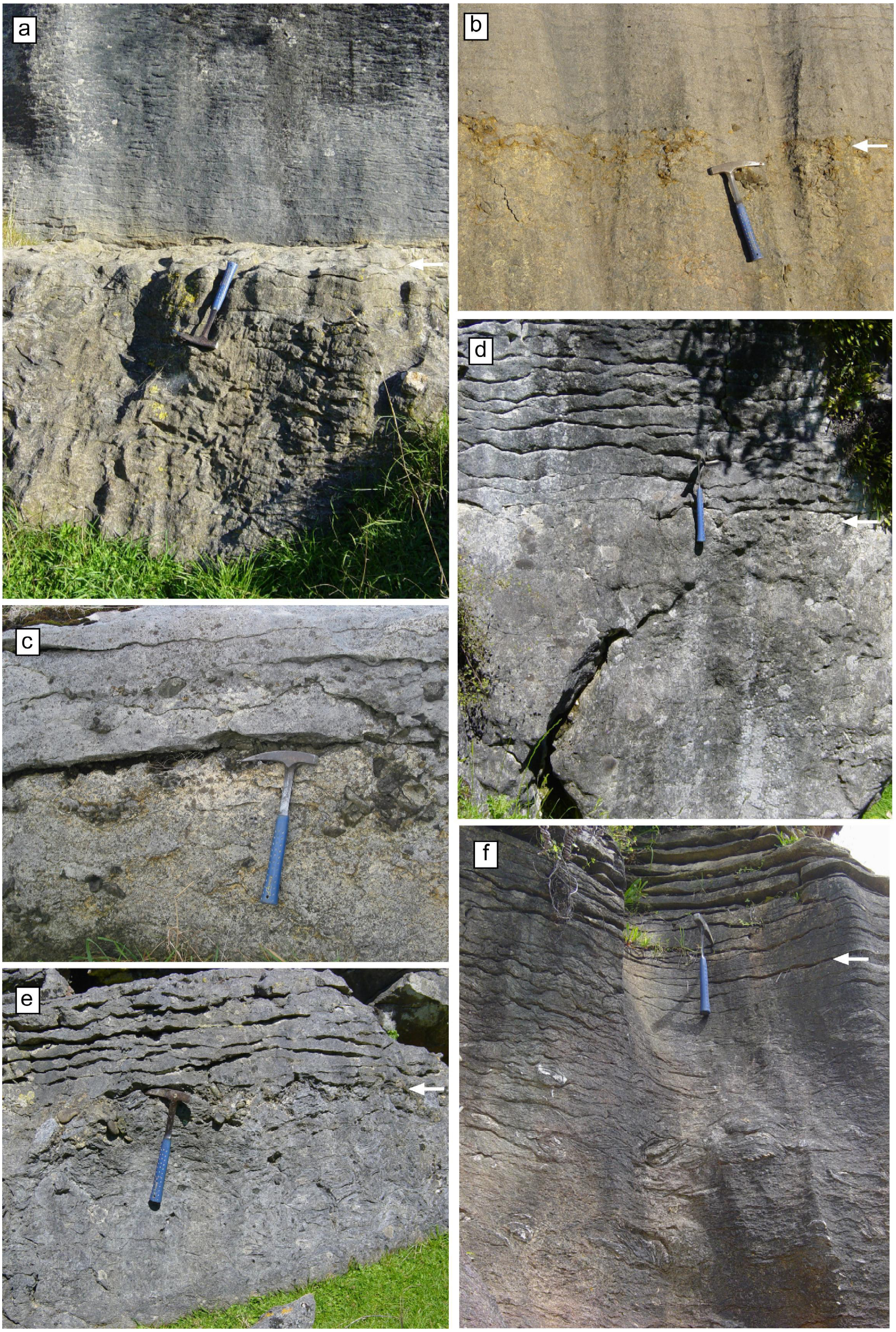
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Fig. 24: *(facing page)* Typical field expression of unconformities and marine-cemented limestone units in the southern region of the study area. (a) Arrow points at the erosional contact between Pebbly oyster-bearing floatstone-packstone (L6, Te Anga Limestone Member) and overlying Horizontally bedded grainstone (L3, Pakeho Limestone Member). Mangaohae Stream section (C-56). (b) The arrow points at the slightly irregular nature of the erosional surface between marine-cemented micritic Oyster floatstone-packstone (L6, Te Anga Limestone Member) and overlying Horizontally bedded grainstone (L3, Pakeho Limestone Member). Note light rusty brown colouration on clasts and skeletons indicating iron oxide staining. Ngapaenga (C-68). (c) The hammer lies across the sharp erosional contact between Pebbly oyster-bearing floatstone-packstone (L6, Te Anga Limestone Member) and overlying Irregularly bedded grainstone (L3, Pakeho Limestone Member). Note scattered subangular to rounded basement clasts occurring both below and above the contact surface. Ngapaenga (C-68). (d) Sharp vertical facies transition (arrow) between Massive fossiliferous rudstone-grainstone (L5) with scattered oysters and Irregularly bedded grainstone (L3). Mangaotaki (C-145). (e) Hammer head rests at irregular, sharp contact between Pebbly oyster-bearing floatstone-packstone (L6) and Low-angle cross-bedded grainstone (L2). Note abundant basement clasts near the contact surface. Mangapohue Natural Bridge. (f) Arrow points at vertical facies transition between Oyster-bearing floatstone-packstone (L6, Te Anga Limestone Member) and Horizontally bedded grainstone (L3, Pakeho Limestone Member). Mangaohae Stream section (C-56).

The base of Castle Craig Subgroup corresponds to a widespread unconformity, which is erosional in sections south of Kawhia Harbour, whereas it is a paraconformity in sections around Raglan Harbour and north to Port Waikato. The sedimentary evolution of the subgroup has been relatively complex, but can be subdivided into two major phases. In the first phase, sedimentation patterns were characterised by shelf progradation to the east and north (Raglan Limestone Member). The second phase involves a change to aggradation, followed by south-directed retrogradation, represented by deposition of Carter Siltstone Member over Raglan Limestone Member. In the south around Kawhia Harbour, retrogradation in response to marked subsidence is recorded by the accumulation of argillacious limestone (L8) at the top of Otorohanga Limestone (Fig.1; Table 2), but in general subsidence east of the Herangi High was less than the carbonate sediment flux forcing eastward progradation of the carbonate shelf, east of Piopio High, as well as to the south in the vicinity of the Awakino Gorge.

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References

Anastas, A.S. 1997: Physical sedimentology of the Cenozoic Te Kuiti Group limestones, North Island, New Zealand. PhD thesis, lodged in the Library, Queen's University, Ontario, Canada.

Anastas, A.S.; Dalyrymple, R.W.; James, N.P.; Nelson, C.S. 1997: Cross-stratified calcarenites from New Zealand: subaqueous dunes in a cool-water, Oligo-Miocene seaway. Sedimentology 44: 869-891.

Barrett, P.J. 1967: Te Kuiti Group in the Waitomo-Te Anga area. New Zealand Journal of Geology and Geophysics 10: 1009-1026.

Boreen, T.; James, N.P. 1995: Stratigraphic sedimentology of Tertiary cool-water limestones, SE Australia. Journal of Sedimentary Research 65: 142-159.

Boreen, T.; James, N.P.; Wilson, C.; Heggie, D. 1993: Surficial cool-water carbonate sediments shelf: Otway, southern Australia. Journal of Sedimentary Research 63: 574-588.

Collins, L.B. 1988: Sediments and history of the Rottnest Shelf, southwestAustralia: a swell-dominated, non-tropical carbonate margin. Sedimentary Geology 60: 15-49.

Edbrooke, S.W. 1984: Pukekawa Coalfield; Assessment of coal resources survey exploration, New Zealand Geological Survey. Coal Report Series CR 1317, Ministry of Economic Development, Wellington, New Zealand.

Ekdale, A.A.; Bromley, R.G.; Pemberton, S.G. 1984: Ichnology: the use of trace fossils in sedimentology and stratigraphy. Society of Ecomomic Paleontologists and Mineralogist (SEPM), Short Course Notes Number 15: 317 p.

Fergusson, D.A. 1986: Geology of inland Kawhia: emphasis on Te Kuiti Group stratigraphy and sedimentation. Unpublished MSc thesis, lodged in the Library, University of Waikato, Hamilton, New Zealand.

Fleming, C. A. 1952: A Foveaux Strait oyster-bed. New Zealand Journal of Science and Technology B34: 73-85.

Fleming, C.A. 1979: The geological history of New Zealand and its life. New Zealand, Auckland University Press.

Gillespie, J.L.; Nelson, C.S. 1997: Mixed siliciclastic-skeletal carbonate facies on Wanganui shelf, New Zealand: A contribution to the temperate carbonate model. In: Cool water carbonates (Ed. James N.P.; Clarke, J.A.D.). SEPM (Society for Sedimentary Geology) Special Publication 56: 127-140.

Hayward, B.W. 1986: A guide to paleoenvironmental assessment using New Zealand Cenozoic foraminiferal faunas. New Zealand Geological Survey Report Paleontology 109.

Hayward, B.W.; Brook, F.J.; Isaac, M.J. 1989: Cretaceous to middle Tertiary stratigraphy, paleogeography and tectonic history of Northland, New Zealand. In Sporli, K.B.; Kear, D. (eds): Geology of Northland: accretion, allochthons and arcs at the edge of the New Zealand micro-continent. Royal Society of New Zealand Bulletin 26: 47-63.

Hopkins, J.C. 1966: The Te Kuiti Group in the West Piopio area. Unpublished MSc thesis, lodged in the Library, University of Auckland, Auckland, New Zealand.

Hopkins, J.C. 1970: Stratigraphy, petrography and origin of the Te Kuiti Group in the west Piopio area. Transactions of the Royal Society of New Zealand, Earth Sciences 8: 1-26.

James, N.P.; Bone, Y.; von der Borch, C.C.; Gostin, V.A. 1992: Modern carbonates and terrigenous clastic sediments on a cool-water, high energy, mid-latitude shelf; Lacepede, southern Australia. Sedimentology 39: 877-903.

James, N.P.; Collins, L.B.; Bone, Y.; Hallock, P. 1999: Sub-tropical carbonates in a temperate realm: modern sediments on the southwest Australian Shelf. Journal of Sedimentary Research 69: 1297-1321.

James, N.P.; Bone, Y.; Collins, L.B.; Kyser, T.K. 2001: Surficial sediments of the Great Australian Bight: facies dynamics and oceanography on a vast cool water carbonate shelf. Journal of Sedimentary Research 71: 549-567.

King, P.R.; Thrasher, G.P. 1996: Cretaceous-Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. Institute of Geological and Nuclear Sciences (IGNS) Monograph 13: 244 p.

Kamp, P.J.J., Tripathi, A.R.P.; Nelson, C.S. 2014a: Paleogeography of the Late Eocene to earliest Miocene Te Kuiti Group, central-western North Island, New Zealand. New Zealand Journal of Geology and Geophysics, *DOI:10.1080/00288306.2014.904384*.

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

Kamp, P.J.J., Tripathi A.R.P., Nelson, C.S and Hendy, A.J.W. 2014c: Biostratigraphy, Sr isotope chronology and chronostratigraphy of the Late Eocene – earliest Miocene Te Kuiti Group, Waikato – King Country Basin, New Zealand. Ministry of Business, Innovation and Employment, New Zealand, unpublished Petroleum Report PR4878, 31 p.

Kear, D. 1987: Te Akau. Notes on the geological map of New Zealand 1:63,360. Sheet N55. New Zealand Geological Survey Record 17: 44 p.

Khandarosa, W. 1989: Sedimentology-stratigraphy of the Te Akatea Formation, Port Waikato to Raglan District, South Auckland, New Zealand. Unpublished MSc thesis, lodged in the Library, University of Auckland, Auckland, New Zealand.

Nelson, C.S. 1973: Stratigraphy and sedimentology of the Te Kuiti Group in Waitomo County, South Auckland. Unpublished PhD thesis, lodged in the Library, University of Auckland, Auckland, New Zealand.

Nelson, C.S. 1977: Stratigraphic columns of the Oligocene Te Kuiti Group in Waitomo County, North Island, New Zealand. University of Waikato Department of Earth Sciences Occasional Report 2: 138 p.

Nelson, C.S. 1978a: Stratigraphy and paleontology of the Oligocene Te Kuiti Group, Waitomo County, South Auckland, New Zealand. New Zealand Journal of Geology and Geophysics 21: 553-594.

Nelson, C.S. 1978b: Temperate shelf carbonate sediments in the Cenozoic of New Zealand. Sedimentology 25: 737-771.

Nelson, C.S. 1988: An introductory perspective on non-tropical shelf carbonates. Sedimentary Geology 60: 3-12.

Nelson, C.S.; Burns, D.A.; Rodgers, K.A. 1983: The taxonomic status and isotope evidence for paleoenvironments of giant oysters from the Oligocene Te Kuiti Group. New Zealand Journal of Geology and Geophysics 26: 289-299.

Nelson, C.S.; Hume, T.M. 1987: Paleoenvironmental controls on mineral assemblages in a shelf sequence: Te Kuiti Group, South Auckland, New Zealnd. New Zealand Journal of Geology and Geophysics 30: 343-362.

Nelson, C.S.; Keane, S.L.; Head, P.S. 1988a: Non-tropical carbonate deposits on the modern New Zealand shelf. Sedimentary Geology 60: 71-94.

Nelson, C.S.; Hyden, F.M.; Keane, S.L.; Leask, W.L.; Gordon, D.P. 1988b: Application of bryozoan zoarial growth-form studies in facies analysis of non-tropical carbonate deposits in New Zealand. Sedimentary Geology 60: 301-322.

Nelson, C.S.; Kamp, P.J.J.; Young, H.R. 1994: Sedimentology and petrography of mass-emplaced limestone (Orahiri Limestone) on a Late Oligocene shelf, western North Island, and tectonic implications for eastern margin development of Taranaki Basin. New Zealand Journal of Geology and Geophysics 37: 269-285.

Nelson, C.S.; James, N.P. 2000: Marine cements in mid-Tertiary cool-water shelf limestones of New Zealand and southern Australia. Sedimentology 47: 609-629.

Nummedal, D.; Swift, D.J.P. 1987: Transgressive stratigraphy at sequence-bounding unconformities: Some principles derived from Holocene and Cretaceous examples. In: Sea-level fluctuation and coastal evolution (Ed. Nummedal, D.; Pilkey, O.H.; Howard, J.D.), Society of Economic Paleontologists and Mineralogists Special Publication (SEPM) 41: 241-259.

Schahinger, R.B. 1987: Structure of coastal upwelling events observed off the south-east coast of South Australia during February 1983-April 1984. Australian Journal of Marine and Freshwater Research 38: 439-459.

Seilacher, A. 1967: Bathymetry of trace fossils. Marine Geology 5: 413-428.

Tripathi, A.R.P., Kamp, P.J.J.; Nelson, C.S. 2008: Te Kuiti Group (Late Eocene – Oligocene) lithostratigraphy east of Taranaki Basin in central-western North Island, New Zealand. Ministry of Economic Development, New Zealand, unpublished Petroleum Report PR3900, 70 p.

Waterhouse, B.C.; White, P.J. 1994: Geology of the Raglan-Kawhia area. Scale 1:50 000. Institute of Geological & Nuclear Sciences geological map 13. 48 p, 1 sheet. Institute of Geological & Nuclear Sciences Lower Hutt, New Zealand.

White, P.J.; Waterhouse, B.C. 1993: Lithostratigraphy of the Te Kuiti Group: a revision. New Zealand Journal of Geology and Geophysics 36: 255-266.