New Zealand Journal of Geology & Geophysics, 2009, Vol. 52: 73–93
0028–8306/09/5202–0073 © The Royal Society of New Zealand 2009

Mangarara Formation: exhumed remnants of a middle Miocene, temperate carbonate, submarine channel-fan system on the eastern margin of Taranaki Basin, New Zealand

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Abstract The middle Miocene Mangarara Formation is a thin (1–60 m), laterally discontinuous unit of moderately to highly calcareous (40–90%) facies of sandy to pure limestone, bioclastic sandstone, and conglomerate that crops out in a few valleys in North Taranaki across the transition from King Country Basin into offshore Taranaki Basin. The unit occurs within hemipelagic (slope) mudstone of Manganui Formation, is stratigraphically associated with redeposited sandstone of Moki Formation, and is overlain by redeposited volcaniclastic sandstone of Mohakatino Formation. The calcareous facies of the Mangarara Formation are interpreted to be mainly mass-emplaced deposits having channelised and sheet-like geometries, sedimentary structures supportive of redeposition, mixed environment fossil associations, and stratigraphic enclosure within bathyal mudrocks and flysch. The carbonate component of the deposits consists mainly of bivalves, larger benthic foraminifers (especially *Amphistegina*), coralline red algae including rhodoliths (*Lithothamnion* and *Mesophyllum*), and bryozoans, a warm-temperate, shallow marine skeletal association. While sediment derivation was partly from an eastern contemporary shelf, the bulk of the skeletal carbonate is inferred to have been sourced from shoal carbonate factories around and upon isolated basement highs (Patea-Tongaporutu High) to the south. The Mangarara sediments were redeposited within slope gullies and broad open submarine channels and lobes in the vicinity of the channel-lobe transition zone of a submarine fan system. Different phases of sediment transport and deposition (lateral-accretion and aggradation stages) are identified in the channel infilling. Dual fan systems likely co-existed, one dominating and predominantly siliciclastic in nature (Moki Formation), and the other infrequent and involving the temperate calcareous deposits of Mangarara Formation. The Mangarara Formation is an outcrop analogue for middle Miocene-age carbonate slope-fan deposits elsewhere in subsurface Taranaki Basin, New Zealand.

Keywords submarine channel; temperate carbonates; sediment gravity flows; middle Miocene; Mangarara Formation; Taranaki Basin

INTRODUCTION

Sediment gravity flow deposits are an integral part of submarine channel and fan systems on both passive and active continental margins worldwide (e.g., Normark et al. 1998; Curray et al. 2003; Pirmez & Imran 2003; Posamentier & Kolla 2003; Bonnel et al. 2005; Ó Cofaigh et al. 2006). In the main they are constructed of siliciclastic sediment sourced originally from erosion on the adjacent continental landmass and subsequently redeposited into slope and basin settings. Carbonate-dominated fan systems are numerically and volumetrically much less common (e.g., Ruíz-Ortíz 1983; Wright & Wilson 1984; Watts 1988; Savary & Ferry 2004; Payros et al. 2007), and many of these are constructed of heterozoan skeletal material which is typical of, but not restricted to, temperate-latitude carbonate facies (James 1997). Because of their general lack of early cementation, shallow-marine temperate skeletal sediments are readily prone to reworking and redeposition (Nelson et al. 1982, 1988), so that remobilised temperate carbonates behave similarly to their siliciclastic counterparts (e.g., Martín et al. 1996, 2004; Anastas et al. 1997; Betzler et al. 1997a; Braga et al. 2001; Puga-Bernabéu et al. 2007). A few ancient examples of deep-water mass-emplaced temperate carbonate systems have been described from eastern Mediterranean localities (Braga et al. 2001; Vigorito et al. 2005; Puga-Bernabéu et al. 2008), where submarine channels have cut temperate carbonate platforms at shallow depths, funnelling bioclastic shelf carbonate basinwards onto submarine fans.

The Miocene sedimentary fill of Taranaki Basin (Fig. 1) involves a 3 km thick, mainly subsurface succession of hemipelagic and mass-emplaced siliciclastic sediments deposited across a range of mainly bathyal depths (200–4000 m) in slope, submarine fan, and basin floor settings (Fig. 2) (Nodder 1987; Nodder et al. 1990; King et al. 1993; King & Thrasher 1996). An outcrop window into this succession is exposed in coastal onshore areas of easternmost Taranaki Basin and the adjoining King Country Basin (Fig. 1) (Kamp et al. 2004). Within it is a middle Miocene unit named the Mangarara Formation, involving redeposited mixed siliciclastic and carbonate sediments, which is unique compared to the bulk of the Miocene deposits because of its prominently calcareous nature, ranging from a few tens to near 100% $CaCO_3$. Moreover, the carbonate fraction

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G08020; Online publication date 3 June 2009
Received 10 July 2008; accepted 11 May 2009

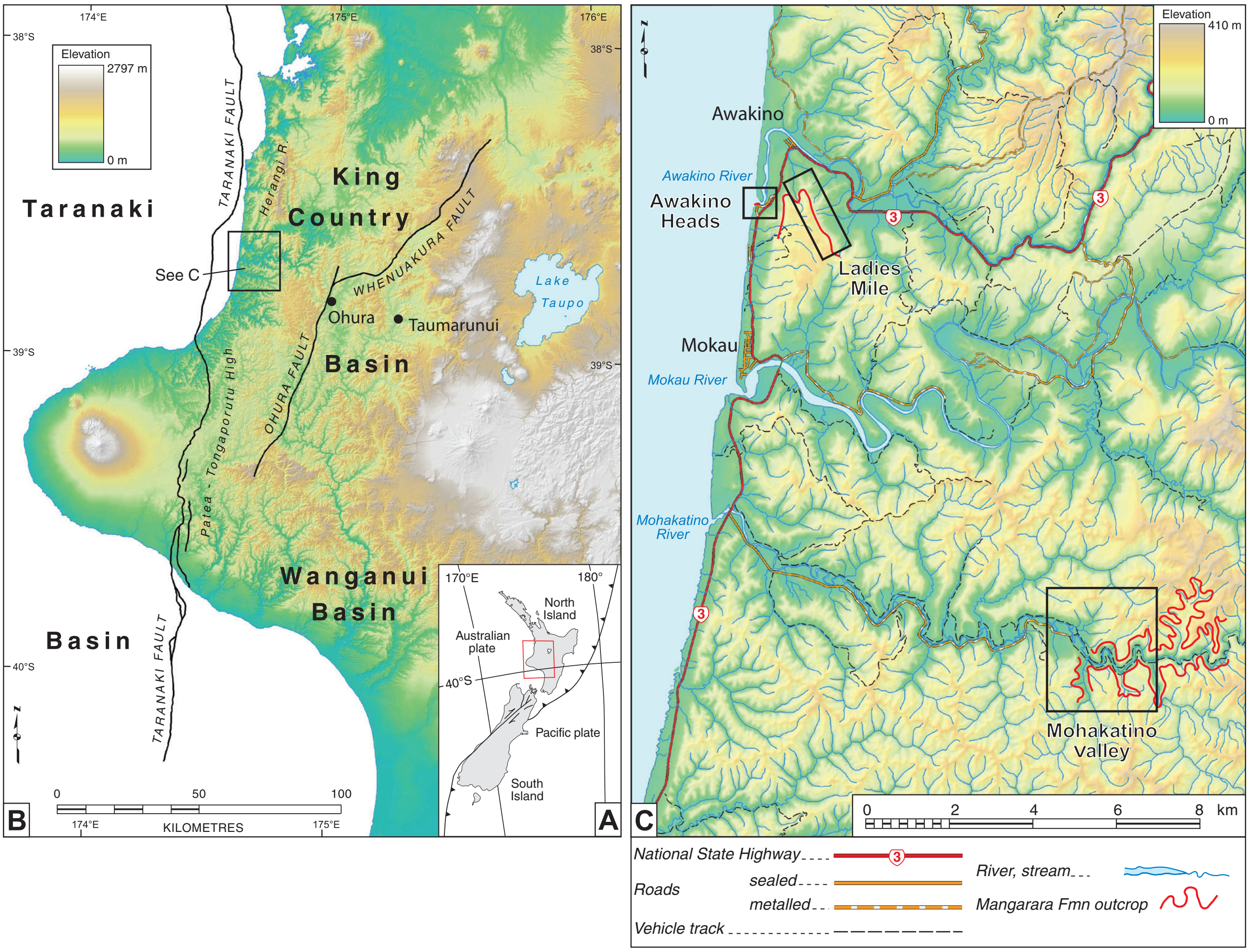


Fig. 1 Locality maps. **A**, Modern plate tectonic setting of New Zealand. **B**, Named Cenozoic sedimentary basins in western North Island, including some structural elements and faults. **C**, Enlargement of box in (B) showing the three main study sites (Ladies Mile, Awakino Heads, and Mohakatino valley) and the outcrop distribution of Mangarara Formation.

comprises whole and fragmented skeletons typical of the shallow-water heterozoan skeletal association developed at temperate latitudes (James 1997).

To date, no detailed sedimentary interpretation of the channelised and redeposited temperate carbonates of the Mangarara Formation has been reported. We do so here, expanding upon the sedimentary spectra of channelised and submarine fan deposits in temperate-latitude settings, as well as providing some additional insight into the paleogeography of the eastern margin of Taranaki Basin in the western North Island of New Zealand during middle Miocene time.

GEOLOGICAL SETTING

Taranaki Basin is a long-lived basin developed off the west coast of the North Island of New Zealand with multiple tectonic origins, including foreland basin development during the late Oligocene and early Miocene (Fig. 1) (King & Thrasher 1996). The basin occupies an area of c. 100 000 km^2 and includes a Late Cretaceous–Recent fill up to 7 km thick (King & Thrasher 1996). Most of this fill is offshore in the subsurface, but an exhumed window of the Neogene succession is exposed onland in eastern Taranaki Peninsula and the King Country region (Kamp et al. 2004). Basement rocks are Paleozoic and Mesozoic granite and schist west of Taranaki Fault and Triassic–Jurassic sandstone and mudstone, typically greywacke and argillite, east of it (Mortimer 1995; Briggs et al. 2004).

The Oligocene and Neogene sedimentary successions on land in central-western North Island, common to eastern parts of Taranaki Basin and King Country Basin, comprise five second-order sequences or groups separated by unconformities (Fig. 2) (Kamp et al. 2004): Te Kuiti Group (late Eocene to earliest Miocene), Mahoenui Group (early Miocene), Mokau Group (late early–middle Miocene), Whangamomona Group (middle Miocene to early Pliocene), and Rangitikei Group (Pliocene–Pleistocene). The relationships between these groups and the lithostratigraphy for northern Taranaki Basin (King & Thrasher 1996) are not fully established, and are shown schematically for the early and middle Miocene in Fig. 2. Complications in lithostratigraphic correlations between the successions in the two basins arise because of (1) the more basin margin setting (and diversified lithofacies) in the King Country Basin compared with the generally more distal setting of Taranaki Basin, and (2) the application of

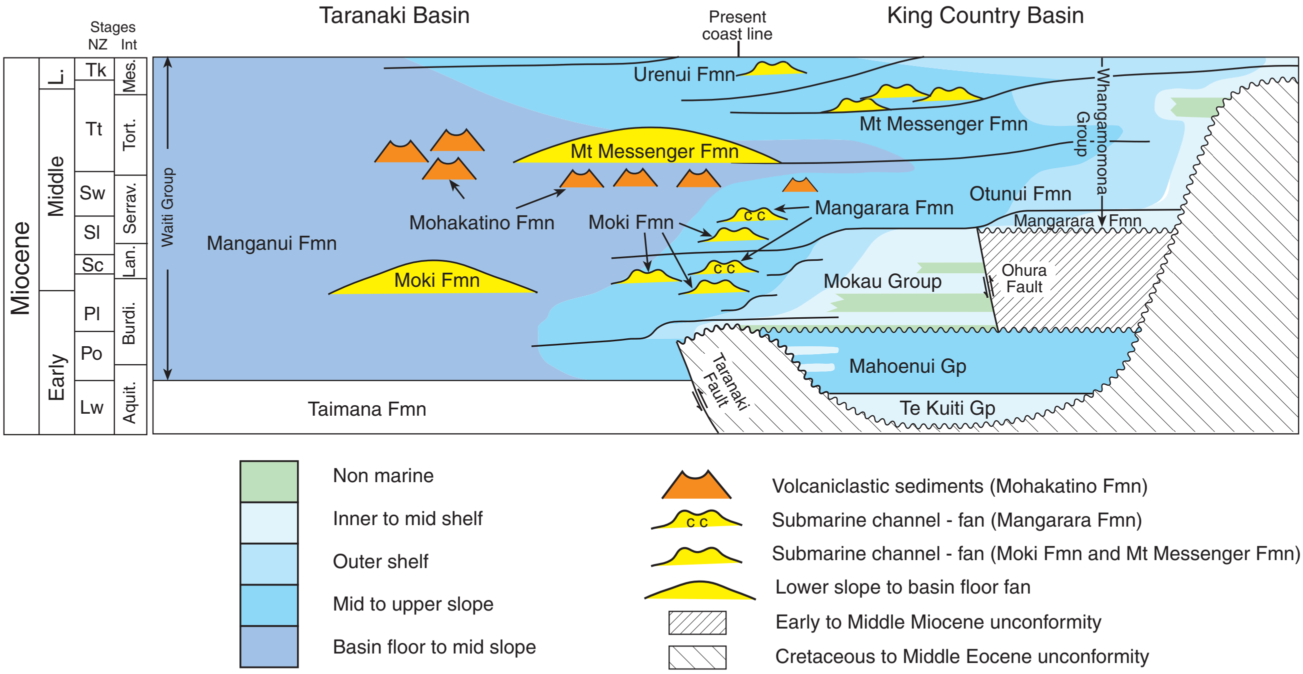


Fig. 2 Time-space stratigraphic panel for early–middle Miocene deposits and their inferred depositional settings in a roughly west (Taranaki Basin) to east (King Country Basin) section across the western North Island coastline (modified from Vonk & Kamp 2006). L., Late; NZ Stages, New Zealand Stages; Tk, Kapitean; Tt, Tongaporutuan; Sw, Waiauan; Sl, Lillburnian; Sc, Clifdenian; Pl, Altonian; Po, Otaian; Lw, Waitakian; Int Stages, International Stages; Mes., Messinian; Tort., Tortonian; Serrav., Serravallian; Lan., Langhian; Burdi., Burdigalian; Aquit., Aquitanian; Fmn, Formation; Gp, Group.

conventional mapping in the former, versus the definition of units from electric logs in petroleum boreholes in the latter (i.e., well to well correlations in subcrop versus the mapping of formation and group contacts in outcrop). For example, in King Country Basin, Mangarara Formation of late Lillburnian (early Serravallian) age and comprising shelf facies occurs at the base of the Whangamomona Group east of Ohura Fault, whereas isolated lenses of slope facies of this formation, both of older and younger age, occur within Manganui Formation in Taranaki Basin, and are associated with Moki Formation. Moki Formation can be mapped onland in valleys (e.g., Mohakatino, Okau, and Mangatawa) east of the North Taranaki coast as a conventional siliciclastic formation containing flysch facies (and tongues of Mangarara Formation characterised by calcareous facies), whereas in Taranaki Basin its stratigraphic extent has historically been limited to sandy facies interpreted as submarine fan deposits (Fig. 2) (King & Thrasher 1996). Here, we view the Mangarara Formation as a name applying to distinctive calcareous sandstone and carbonate lenses of middle Miocene age, whether exposed onland or in the subcrop of Taranaki Basin. This paper is not specifically about Moki Formation, but we (AJV and PJJK) have mapped it onland as a conventional formation enclosing and underlying Mangarara Formation, and as a correlative of the upper part of the Mokau Group and the lower part of the Otunui Formation; we appreciate this is a different approach to its application in Taranaki Basin as a name more or less restricted to submarine channel and fan sandstone facies.

During the late Oligocene and earliest Miocene (Duntroonian–Otaian), westerly directed overthrusting of basement rocks took place along the Taranaki Fault and other major faults (Fig. 1) (King et al. 1993; Stagpoole & Nicol 2008; Tripathi & Kamp 2008). As a consequence, topographic highs involving basement blocks (the Herangi High and Patea-Tongaporutu High) developed along eastern Taranaki Basin (Fig. 1, 2). During the late early Miocene (Altonian) the Herangi High subsided with accumulation of transgressive shoreface sediments (Bexley Sandstone; Vonk 1999) above it, followed by shelf to slope facies (Kamp et al. 2004), while farther east in King Country Basin reverse movement on the Ohura Fault segmented the basin into the Whangamomona (western and subsided) and Taumarunui (eastern and uplifted) blocks (Hunt 1980; Vonk 1999). The Mokau Group comprising fluviatile, coastal, and shallow-marine facies, and its slope and basinal equivalents—the Manganui and Moki Formations—formed at this time over what had formerly been a basement structural high (Fig. 2). East of this high, the contemporary shelf was very narrow (c. 10 km), with a shoreline located on, or just to the east of, the Ohura Fault (Kamp et al. 2004).

During the middle Miocene (late Lillburnian), regional subsidence led to marked marine transgression across the Whangamomona block in the King Country with accumulation of an inner neritic shellbed (Mangarara Formation) followed by siliciclastic shelf and upper bathyal facies of the Otunui Formation. Redeposited carbonate facies also named Mangarara Formation and of early middle Miocene age, some predating the shellbed facies to the east, accumulated within Manganui Formation to the west (Kamp et al. 2004; Vonk & Kamp 2006) and form the main focus of this investigation. The overlying Mohakatino Formation is composed of redeposited, deep-marine volcaniclastic mudstone and sandstone up to 80 m thick in onland coastal sections (Nodder et al. 1990; King & Thrasher 1996). The volcaniclastic sediment was derived from a chain of now-buried andesitic volcanoes (Mohakatino Volcanic Centre) located to the west of this region in offshore northern Taranaki Basin (Bergman et al. 1990, 1992; Nodder et al. 1990). The Mt Messenger Formation, comprising sandstone and mudstone deposited in basin floor fan and slope fan environments (King & Thrasher 1996), overlies Otunui Formation in the King Country and interfingers with Mohakatino Formation in coastal North Taranaki sections (Fig. 2).

MANGARARA FORMATION

Stratigraphic nomenclature, setting, and age

The middle Miocene Mangarara Formation was defined originally during regional geological mapping in central western North Island by Hay (1967). Subsequently the formation has been described in several MSc theses documenting the Tertiary sedimentary successions in this region (e.g., Happy 1971; Wilson 1994; Vonk 1999; Ngatai 2004). Of particular interest has been the interpretation of the stratigraphic position of the Mangarara Formation in relation to the surrounding Miocene units (e.g., King et al. 1993). Vonk (1999) and Ngatai (2004) presented a historical review of the Mangarara Formation nomenclature. The Mangarara Formation has been previously called Mangarara Sandstone Formation (Hay 1967), Mangarara Sandstone (Happy 1971), Mangarara (Sandstone) Member (King et al. 1993), and Pongahuru Limestone Member (Gerritsen 1994). The present name Mangarara Formation was proposed by Vonk (1999) so as to avoid the use of any lithological descriptor because the unit actually involves a wide variety of mixed siliciclastic and carbonate lithologies. We follow Vonk's definition of Mangarara Formation as comprising all deposits with a significant carbonate content of middle Miocene age that occur onland. This is a more restricted use than Hay (1967), which included sandstone facies that we now regard as part of the Moki Formation onland.

Western outcrops of Mangarara Formation are sporadic and discontinuous, occurring mainly in the vicinity of the lower reaches of the Awakino, Mokau, and Mohakatino river valleys near the modern coastline (Fig. 1) (Wilson 1994; Ngatai 2004). Specifically, the most significant and complete sections of the Mangarara Formation beds occur at Ladies Mile, Awakino Heads, and Mohakatino River valley (Fig. 1C). Here they consist mainly of redeposited carbonate and mixed siliciclastic-carbonate sediments (Fig. 2). These occurrences are unlikely to have accumulated concurrently; rather, they represent a middle Miocene phase of carbonate accumulation on a west-facing continental slope. Broadly correlative *in situ* shallow-marine facies of the Mangarara Formation locally occur farther inland to the south of Ohura and Taumarunui townships (Armstrong 1987; Gerritsen 1994; Vonk 1999; Vonk & Kamp 2006).

While overall the Mangarara Formation is middle Miocene in age (Fig. 2), in terms of the more refined New Zealand stages based on foraminiferal biostratigraphy, the ages vary between outcrop localities (King et al. 1993; King & Thrasher 1996; Ngatai 2004). Thus, a late Altonian (earliest Langhian) to Clifdenian (Langhian) age range is recorded at Ladies Mile and Awakino Heads (i.e., early middle Miocene), but from Clifdenian to Waiauan (Langhian–Serravallian) at the Mohakatino valley (late middle Miocene), where age constraint comes from samples of the enclosing Moki Formation (Ngatai 2004). Likely correlative beds assigned to the Tirua Formation by Nodder et al. (1990) on the coast north of Awakino Heads yield an exclusively Waiauan age (late Serravallian).

Sedimentary facies

In the study area, five main sedimentary facies have been established for the Mangarara Formation (Facies A–E), as well as two subordinate ones (Facies F and G) which are, however, more common in the associated Moki Formation. The facies are defined primarily on the basis of field properties, supported by examination of 50 thin sections under a petrographic microscope to identify grain and matrix/cement types. The distinguishing characteristics of these facies are summarised in Table 1 and each is briefly described below.

Facies A

Facies A involves tabular or channelised bodies constructed of massive to well stratified, sometimes low-angle cross-stratified, parallel laminated, decimetre-thick beds of brownish medium-grained packstone/grainstone to fine-grained (granule-size) floatstone/rudstone rich in *Amphistegina* tests and fragmented coralline algae (Fig. 3A,B). Accessory skeletal remains include bryozoans, bivalves, gastropods, echinoderms (mainly spines), rhodoliths, solitary corals, and other foraminifers (e.g., *Lepidocyclina*). Dispersed mudstone and sandstone clasts occur in some beds. Fine-grained (mud) terrigenous material is negligible.

Facies B

Sheet-like units up to 50 cm thick of greyish rudstone and floatstone comprise abundant robust bivalve shells (*Cucullaea*, *Glycymeris*, *Glycymerita*, *Tucetona*, *Ostreinae*) in a fine–medium calcarenite matrix rich in *Amphistegina* and coralline algae (Fig. 3C,D). Valves are variably fragmented, disarticulated, 2–3 cm in average size (up to 7 cm for some oyster fragments), and densely packed (*sensu* Kidwell & Holland 1991). Shells are stacked (concave-up and -down) and are oriented parallel to the base of beds. Other large bioclasts present are solitary corals (*Trunctoflabellum*). Some pebbles of cemented mudstone are dispersed through the beds.

Facies C

This facies involves channelised to sheet-like, massive, rarely inversely graded conglomerate composed of rounded, well cemented, green to blue-green mudstone pebbles and boulders (Fig. 3E). Clasts are elongated ellipsoidal and spherical, and packing ranges from clast- to matrix-supported. Facies C can be divided into two subfacies according to the geometry, nature of the matrix, and bioclast content:

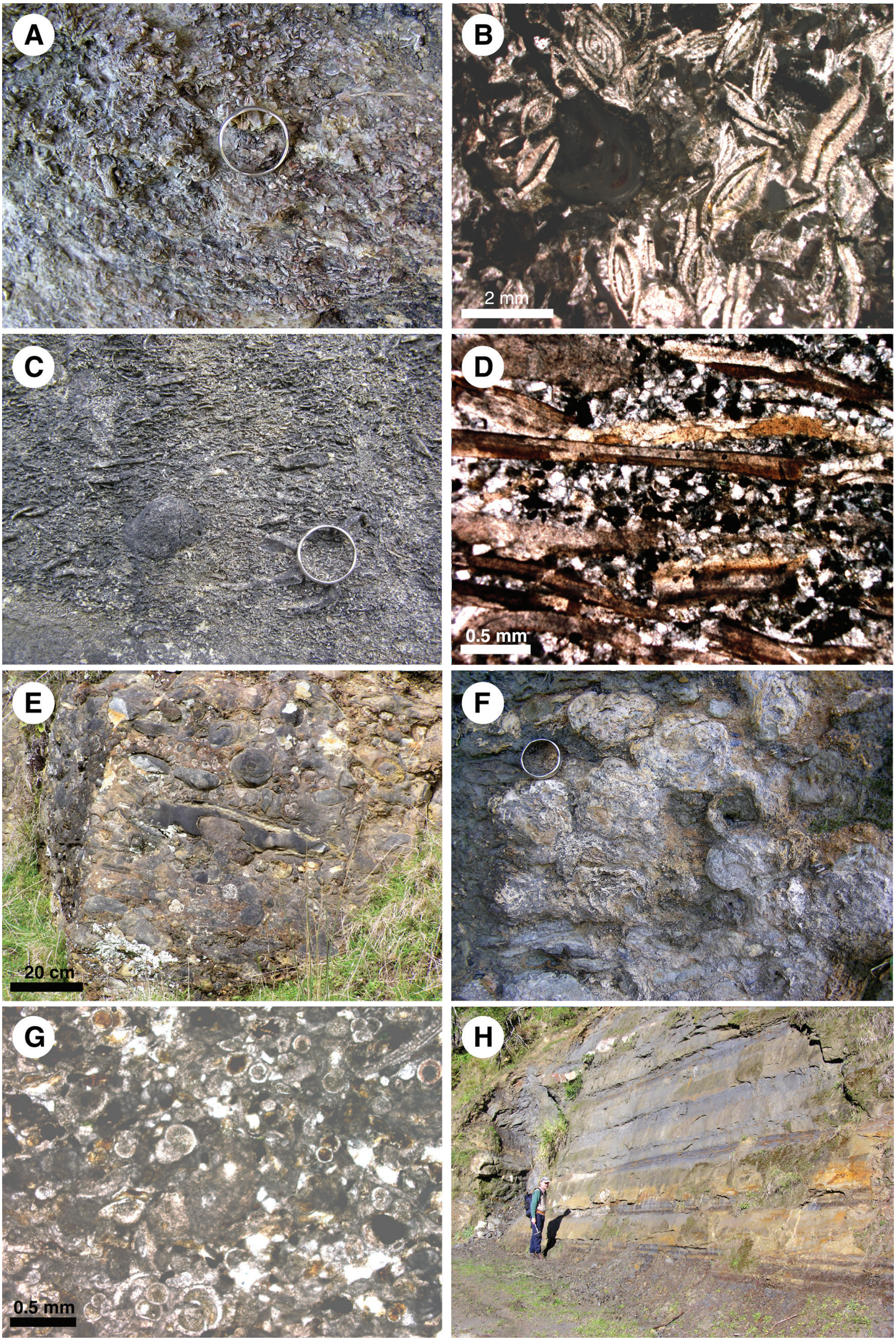
Facies C_1: occurs at the base of channelised bodies, has a muddy bioclastic matrix, and the main bioclasts are rhodoliths and minor bivalves. Some clasts are bioeroded by *Gastrochaenolites* (*Lithophaga* borings).

Facies C_2: normally exhibits sheet-like geometry with planar limits, but locally has an irregular base. Matrix is bioclast-rich with abundant coralline algal and *Amphistegina* remains. Large bioclasts (rhodoliths and bivalves) are common. Solitary corals and gastropods are also present. Mudstone and sandstone clasts can be locally abundant.

Table 1 Summary of facies attributes for the Mangarara Formation (A–E) and associated Moki Formation (F, G).

Facies	Site (ab)	Geometry and thickness	Sedimentary structures	Lithology	Main components	Other components	Other characteristics
A	LM (a) AH (r) MV (a)	Channelised, tabular Up to 63 m Individual beds are decimetres thick	Massive, well- to rough-bedded, low-angle cross-bedded, parallel lamination	*Amphistegina*-rich calcarenite and calcirudite (packstone, grainstone, floatstone, rudstone)	*Amphistegina*, coralline algae (variable proportions)	Bryozoans, bivalves, gastropods, echinoderms, rhodoliths, solitary corals, foraminifers	*Lepidocyclina* present Glauconitised bioclasts and matrix, minor glauconite grains Rhodoliths locally important/abundant at bottom of beds Dispersed mud (loose and cemented) and sandstone clasts can be present
B	MV (p)	Sheet-like 8–50 cm	Crude parallel lamination, concave-up and-down bioclast stacking	Bivalve rudstone/floatstone with a calcarenite matrix rich in coralline algae and *Amphistegina*	Bivalves	*Amphistegina*, coralline algae, solitary corals	Disarticulated shells Oysters up to 10 cm Dispersed cemented mudstone pebbles
C_1	LM (p) AH (r)	Channelised 0–60 cm	Massive, rare inverse grading	Conglomerate (pebble–boulder) in a bioclastic muddy packstone	Well-cemented mudstone concretions. Rhodoliths 2–3 cm in average size (up to 10 cm)	Bivalves, bryozoans	Some mudstone clasts are bored by *Lithophaga* Some greywacke pebbles present
C_2	MV (c)	Sheet-like, channelised base locally 25–130 cm	Massive, rough bedded	Conglomerate pebble–cobble-size (minor boulders) with large bioclasts in a calcarenite/calcirudite matrix rich in coralline algae and *Amphistegina*	Well-cemented mudstones Rhodoliths and bivalves in variable proportions	Mud and sandstone clasts Gastropods, solitary corals	Bivalves occur as shells and moulds Pebbles encrusted by thin rhodolith crusts
D	MV (c)	Sheet-like 15–65 cm	Massive	Rhodolith rudstone/floatstone with a calcarenite/calcirudite matrix rich in coralline algae and *Amphistegina*	Rhodoliths 3–5 cm in average size (up to 10 cm), coralline algae, *Amphistegina*	Mud and sandstone clasts Bivalve shells, gastropods, bryozoans (matrix), echinoderms (matrix), benthic foraminifers (matrix)	Rhodoliths are spheroidal to ellipsoidal and are composed of warty to laminar plants (mainly *Lithothamnion*) Intergrown with bryozoans and vermetids
E	LM (a) AH (p)	Channelised, tabular 220–600 cm (individual beds are decimetre thick)	Massive, well- to rough-bedded, parallel lamination, local normal graded, locally burrowed	Bioclastic sandstone with variable amounts of mud and bioclasts	Bivalves, bryozoans (branching and unilaminar), planktic foraminifers	Dispersed cemented mudstone clasts (up to pebble-size) Gastropods, solitary corals, echinoderms, *Amphistegina*, benthic forams	Glauconitised bioclasts and matrix Granule–pebble-sized glauconite grains locally abundant Limonitised shell moulds common
F	AH (r) MV (a)	Channelised, sheet-like, lenticular 2–70 cm	Massive, locally burrowed	Mudstone with variable amounts of dispersed small bioclast fragments	Bivalves, bryozoans, planktic foraminifers	Benthic forams, echinoderms, gastropods, coralline red algae, *Amphistegina*	Glauconitised bioclasts and rare glauconite grains Small bioclastic pockets occur in some beds
G	MV (a)	Wedge, sheet-like Up to 80 m Individual beds are centimetre–decimetre thick	Massive, horizontally bedded, parallel lamination, cross-lamination, bioturbation traces locally	Very fine to fine sandstone	–	–	Bed amalgamation occurs Some dispersed clasts and bioclastic pockets locally present

ab = Relative abundance (a = abundant; c = common; p = present; r = rare) at site specified: LM = Ladies Mile; AH = Awakino Heads; MV = Mohakatino valley.


A
B
2 mm
C
D
0.5 mm
E
20 cm
F
G
0.5 mm
H

◀ **Fig. 3** Examples of facies types (Table 1) in the Mangarara (and Moki) Formation. **A**, Close-up of Facies A showing well-preserved *Amphistegina* tests. Ring 2 cm in diameter. **B**, Photomicrograph showing the main components of Facies A: *Amphistegina* and coralline algae. **C**, Bivalve-dominated rudstone of Facies B. Ring 2 cm in diameter. **D**, Photomicrograph of Facies B showing bivalve shells within a silty matrix. **E**, Outcrop view of Facies C (subfacies C_2). Most of the coarse-grained components are cemented mudstone clasts (dark) and rhodoliths (white). Sandstone clasts (yellow) are also present. **F**, Close-up of Facies D showing the spherical to ellipsoidal centimetre-sized rhodoliths. Ring 2 cm in diameter. **G**, Photomicrograph of Facies E showing the abundance of planktic foraminifers (some glauconitised) in a packstone matrix. **H**, Outcrop view of the siliciclastic-dominated facies in the Moki Formation. In this view, beds of Facies F are slightly recessive while Facies G strata protrude from the outcrop.

Facies D

Massive sheet-like units, up to several decimetres thick, of rhodolith rudstone/floatstone are composed of conspicuous spherical and ellipsoidal rhodoliths up to 10 cm in size (av. 3–5 cm) (Fig. 3F). Rhodoliths are formed mainly by warty and laminar thalli of *Lithothamnion* and occasional *Mesophyllum*. Matrix consists of a packstone-floatstone dominated by coralline algal fragments and subordinate *Amphistegina* tests. Bivalves (important locally), bryozoans, and gastropods are accessory components, and echinoderms and small benthic foraminifers also occur mainly within the matrix. Pebbles and cobbles of cemented mudstone and friable sandstone are also present.

Facies E

Facies E involves tabular or channelised bodies up to 6 m thick of massive to well stratified, parallel laminated, and often burrowed bioclastic sandstone (locally calcarenite and calcirudite) with variable amounts of mud (silt) and bioclasts. Granules and pebbles of cemented mudstone occur dispersed. Macrobioclasts (>0.5 cm) are mainly of bivalves and bryozoans (branching and unilaminar). Bivalve shells commonly occur as fragmented small remains, with minor disarticulated, pebble-sized valves. Some limonitised internal shell moulds are also present. Other skeletons are of gastropods, *Amphistegina*, solitary corals, and echinoderm spines. Planktic foraminifers are abundant in the matrix (Fig. 3G). Bioclasts (especially planktic foraminifers) and matrix are commonly glauconitised.

Facies F

This facies comprises channelised, sheet-like, or lenticular bodies of greenish grey massive mudstone (Fig. 3H) with a bioclast content ranging from negligible to c. 10–15%. Bivalves (especially *Lima colorata*), bryozoans, planktic and benthic foraminifers including *Amphistegina*, gastropods, coralline algae, and echinoderms are present. Bioclasts occur mainly as fragmented remains, although some whole shells are also preserved. Burrowing is locally abundant, and small bioclastic pockets or nests (typically up to a few centimetres in size) are scattered throughout Facies F. Bioclasts are partially glauconitised.

Facies G

Fine to very fine yellowish sandstone makes up this facies (Fig. 3H), abundant only at the Mohakatino River valley site. Several types of sedimentary structures occur (Table 1). Bioclasts are present only in small bioturbation pockets that occur locally. Dispersed granule–pebble-size clasts occur in some beds.

Ladies Mile section

Ladies Mile section is a 1.7 km long cliff face, extending roughly northwest–southeast, located 2 km southeast of the coastal settlement of Awakino (from grid reference R17/522808 to R18/528798 on NZMS 260 Series 1:50 000 topographic maps) (Fig. 1, 4). In the steep exposures of Ladies Mile, the mixed siliciclastic-carbonate sediments of the Mangarara Formation overlie thick (up to 125 m) grey siliciclastic mudstone and intercalated sandstone beds of the Manganui Formation (King et al. 1993). In turn, the Mangarara Formation at this locality is overlain by volcaniclastic sediments of the Mohakatino Formation, capped by Mt Messenger Formation (Fig. 4).

Description

The panoramic view of Ladies Mile outcrop highlights distinctive channel complexes in the Mangarara Formation at a large scale (Fig. 4). Channelised beds as a whole show an erosive and/or a sharp planar base on the underlying sediments (Manganui Formation). Individual channels within the channel complex have low to very low angle margins and a high width/height ratio. They range 25–120 m across and up to 3–15 m thick at their axes, and appear to be directed towards the NNW, more or less perpendicular to the outcrop face. Nested small-scale channels are present at different positions cutting the underlying major channel (Fig. 5). Small-scale cut-and-fill structures are also identified in some large channel-fills.

Channel-fill normally consists of decimetre-thick beds conforming to the underlying surface. Asymmetric infilling is also present in some channels (Fig. 5). Beds are well to crudely stratified, have diffuse to planar limits, and are mostly massive and moderately to poorly sorted. Only a few beds show parallel lamination. Normal grading occurs locally. Average grain size ranges from medium sand to granule, with some coarser grains occurring dispersed at the base of beds.

Facies A, C_1, and E (Table 1) compose the channel infilling at Ladies Mile. Facies A dominates the fill of the stratigraphically higher channels at the site. Beds of this facies are commonly well cemented and amalgamated with some intercalations of less cemented, finer grained intervals. Facies E occurs in the lower-channel fill and separates two superimposed channels filled with Facies A. These two facies types contain dispersed pebbles at different positions of the infilling, usually in the basal beds. Facies C_1 is located at the base of some of the channels, irrespective of their position (Fig. 4).

Interpretation

Channelised bodies at the Ladies Mile section are mainly characterised by broad channel-structures (i.e., high width/height ratios). Sediment fill conforms to the channel base and flattens up, building tabular beds that partially extend over the channel margins (Fig. 5). Within a submarine channel-fan

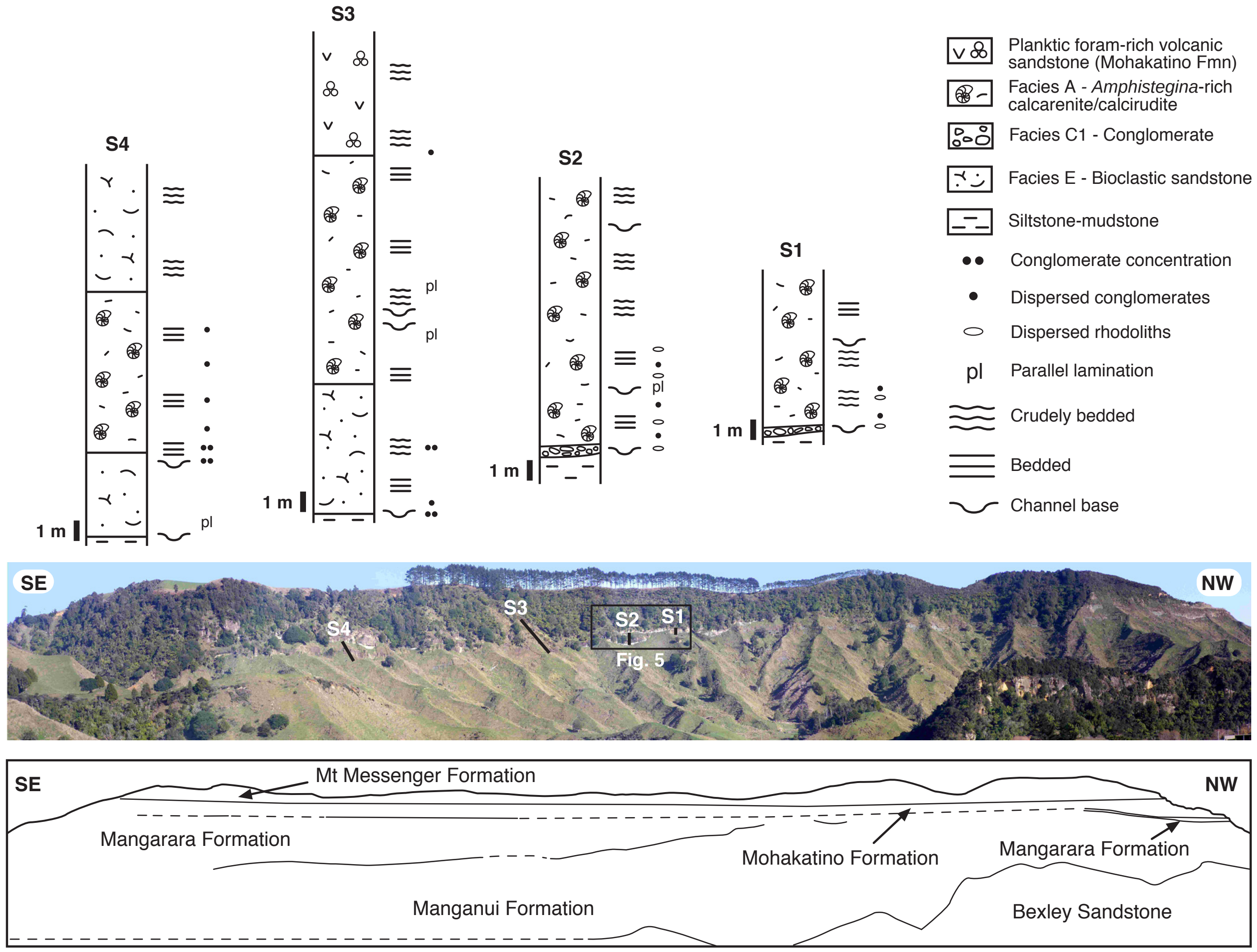


Fig. 4 Panoramic view of the Ladies Mile section. Inset shows the location of Fig. 5, and black lines S1–S4 mark the position of the logged sections and their facies, shown above. Interpreted geological boundaries among the different units are shown in the lower part of the figure.

system, channels at Ladies Mile are interpreted to lie in the proximity of the channel-lobe transition, where channels of the middle fan-system merge into outer-fan lobes (cf. Reading & Richards 1994), or in the transition from the leveed channel to frontal splay (nomenclature of Posamentier & Kolla 2003).

Low-angle structures that downlap the bases of some channels (Fig. 5) are interpreted as lateral-accretion structures. This suggests a sinuous meandering morphology of the channel system and indicates that deposition was contemporaneous with lateral and downdip channel migration. Two different phases in the channel infilling are identified (Fig. 5): (1) lateral-accretion stage in which flows through the channel erode the outer meander margin and deposit sediment in lateral-accretion packages or lateral bars on the inner meander margin; and (2) aggradation-stage during which the channel-infilling accretes vertically. During the aggradation phase, sediment backfill processes fill the channel to capacity until a point where the channel avulses and is overlain by overbank or spillover deposits from subsequent channels (Fig. 6A). After channel avulsion, channels are abandoned and the channel-lobe zone shifts position (composite channel). In fact, the channelised and redeposited carbonates at Ladies Mile show a large-scale channelised geometry (channel complex) (Fig. 4) composed of channel-fills and spillover deposits (Fig. 6A).

Cut-and-fill structures observed in the infilling of some large channels probably relate to small-scale channel development within major channels at certain times.

We consider that lateral accretion occurred during sustained-flow conditions. During such periods, concentrated density flows probably deposited structureless layers on the lateral bar. This steady flow was not prolonged for long periods but there was sufficient time to enable minor longitudinal flow transformation to occur. Subsequently, no differentiation of sedimentary structures occurred and the final result is a massive and poorly sorted deposit. Flow partially decelerated when it climbed up the lateral bar (secondary helicoidal flow), and shear velocity decreased and coarser sediment was deposited. This explains the presence of dispersed clasts accumulated preferentially at the base of the beds conforming to the lateral-accretion structures. Parallel laminated beds that occur locally may also be related to flow deceleration.

Flow behaviour in the lower channel-lobe zone, where Facies E dominates, is poorly understood as sand, bioclasts, and

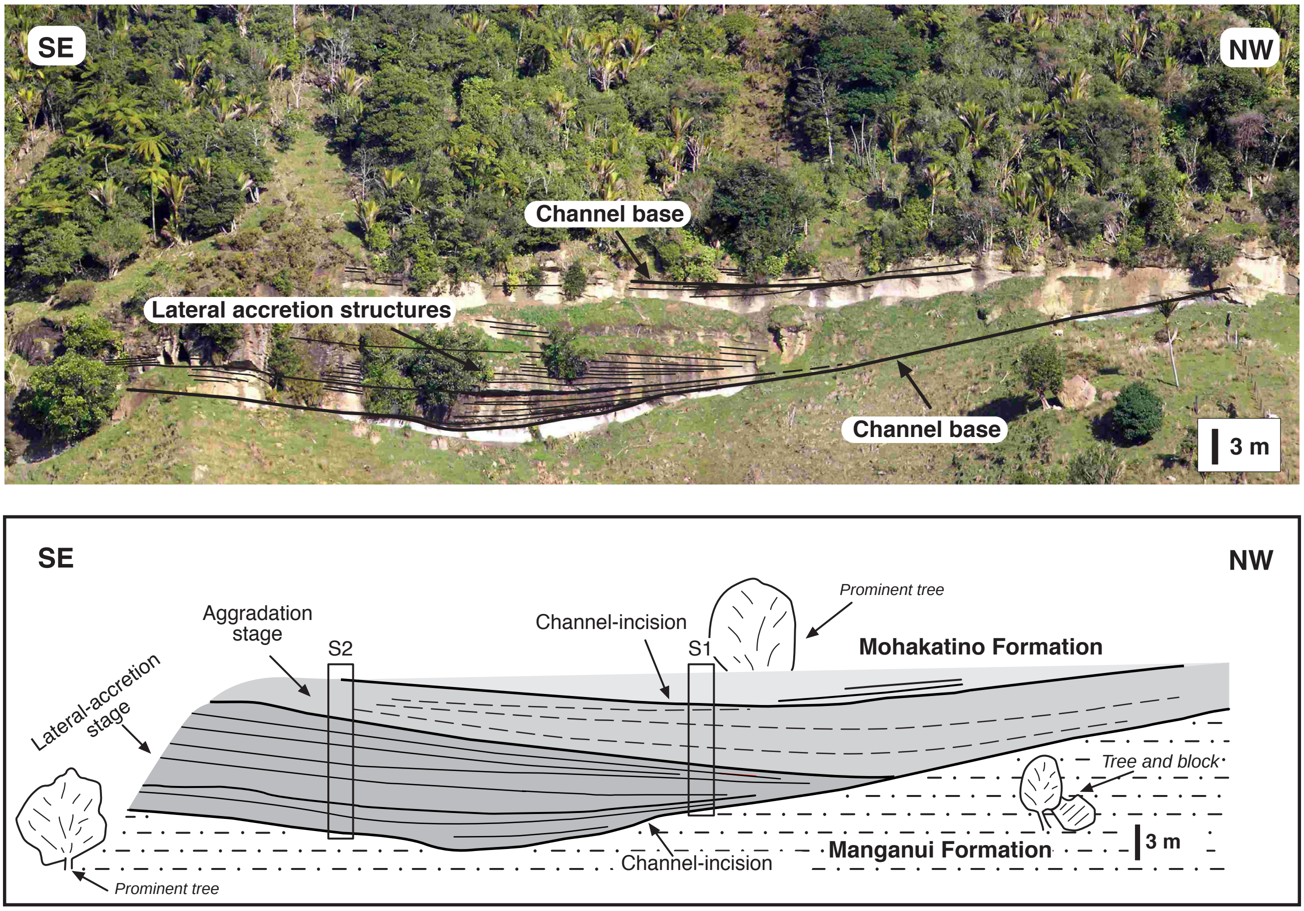


Fig. 5 Channels in the Ladies Mile section (see Fig. 4). Outcrop view shows the shape of a large channel and a small nested channel on top. Low-angle cross-bedding is interpreted as lateral-accretion structures. Interpreted diagram below indicates the different stages of the channel fill. Lateral-accretion stage developed after channel incision. In this stage, lateral bars were deposited on the inner meander side during active sediment transport through the channel. Channel infilling occurred during the aggradation stage. The shift of the channel-lobe position after channel avulsion produced another channel incision.

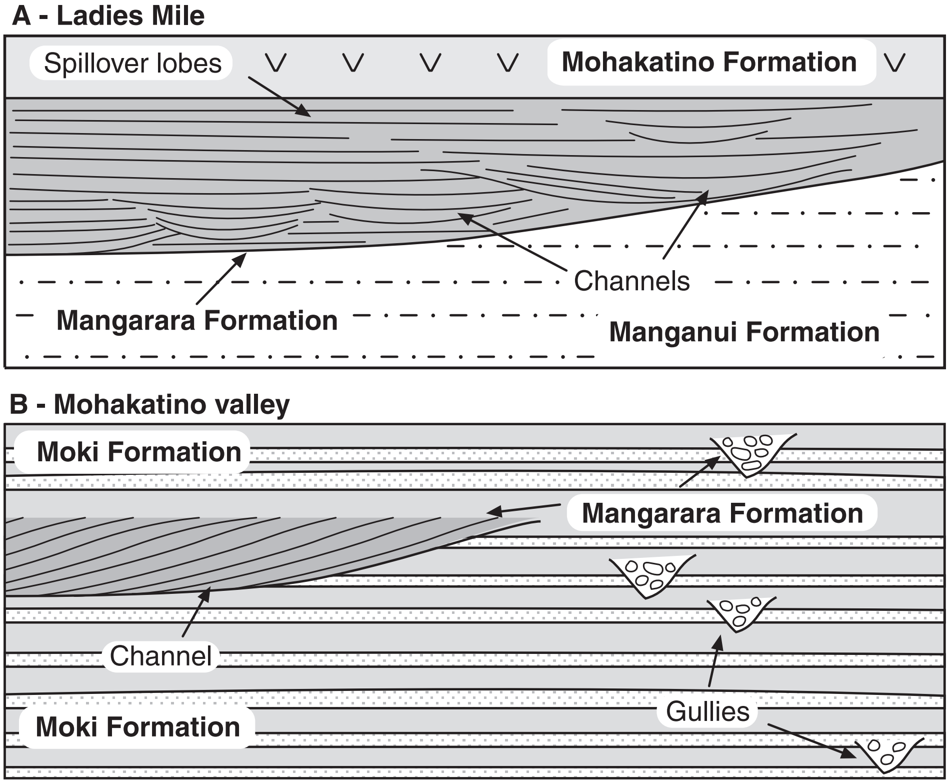


Fig. 6 Schematic diagrams illustrating the main structural elements of the Mangarara Formation submarine-fan system in (**A**) Ladies Mile section and (**B**) Mohakatino valley section (not to scale). The Mangarara Formation is composed of channel-fill and backfill (lobe) deposits at the Ladies Mile section. At the Mohakatino valley section, the Mangarara Formation consists of channel-fills and gullies cutting the underlying sediments of the Moki Formation.

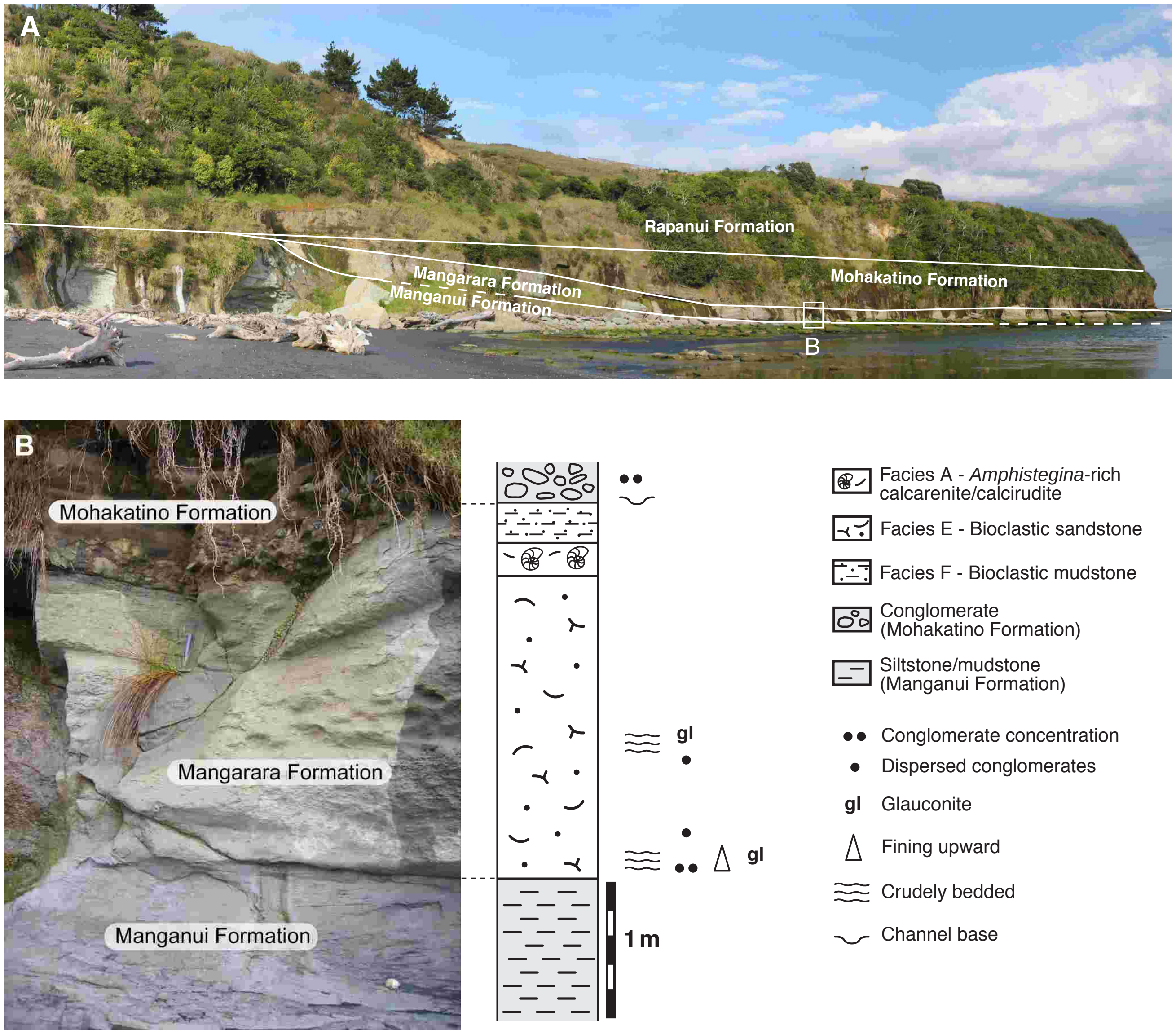


Fig. 7 **A**, Field view looking south at the Awakino Heads section showing boundaries of the different geological units. Note channel margin geometry in the Mangarara Formation. Channel axis is located towards the seaward end (northwest) of the section, and is usually sand covered. Inset shows the position of B. **B**, Close-up of Mangarara Formation, with associated stratigraphic column and facies. Burrowed and glauconite-rich sediment of Facies E composes most of the channel infilling.

mud occur in different proportions in massive or locally parallel laminated beds. Mud flows, concentrated debris flows (steady and waning flows), and turbidity flows may produce these sorts of deposits (Ghibaudo 1992; Clark & Pickering 1996).

Coarse conglomerates of Facies C_1 at the base of some channels are interpreted as residual lag deposits during sediment-bypass phases along the channel.

Awakino Heads section

Small outcrops of the channelised Mangarara Formation, accessible mainly during low tide, occur at the mouth of Awakino River (R17/511808) (Fig. 1). Here the Mangarara Formation unconformably overlies the Manganui Formation, whose top is of middle Miocene (Langhian or late Altonian) age (King et al. 1993), and is in turn unconformably overlain by the distinctly volcaniclastic sandstones of the Mohakatino Formation (Fig. 7).

Description

A channelised geometry (channel margin) is evident for the Mangarara Formation (Fig. 7A). However, precise determination of the channel geometry is not possible because of the seaward dip of beds, the erosive contact with the overlying Mohakatino Formation and late Pleistocene terrace deposits (Rapanui Formation), and burial by modern coastal sand deposits at the Awakino River mouth. There is no ambiguity surrounding the channel margin at the inland end of the outcrop even though Mangarara Formation is erosionally truncated by unconformities at the base of Mohakatino Formation and Rapanui Formation.

Channel-fill is almost 3 m thick, with sediment ranging from crudely bedded to mainly massive. At the base, a 10 cm thick, normally graded interval (Facies C_1) occurs. Facies E, here thoroughly burrowed throughout, composes most of the logged section with some decimetre-thick beds of Facies A

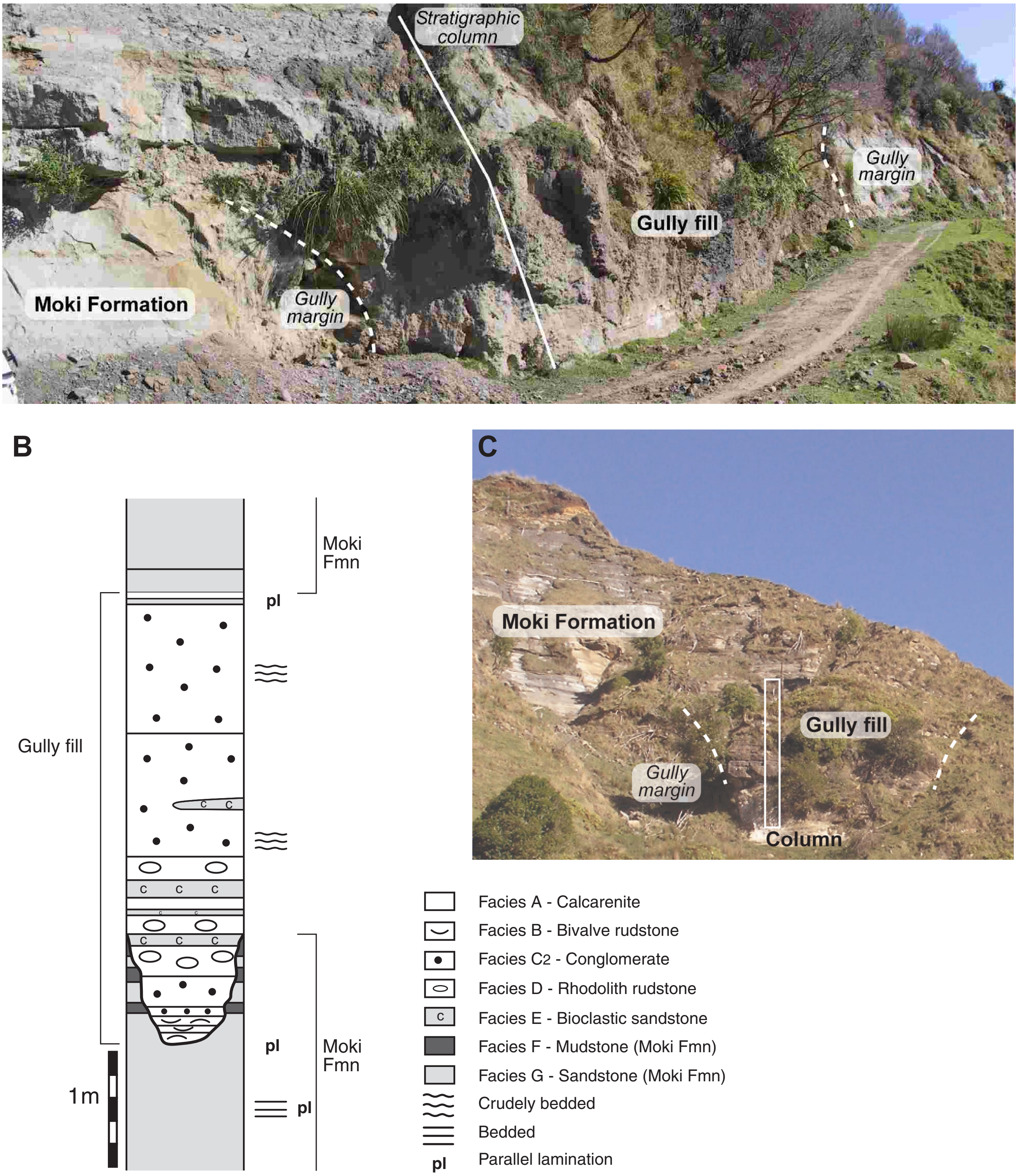


Fig. 8 **A**, Small poorly defined channel or gully filled by coarse-grained debrites of Mangarara Formation facies (conglomerate and rhodolith rudstone) within the Moki Formation on farm track beyond the end of the road in the Mohakatino valley (R18/593697). **B**, **C**, Stratigraphic log (B) and field exposure (C) of another gully fill of Mangarara Formation composed mostly of coarse-grained debrites (bivalve and rhodolith rudstone and conglomerate) enclosed by the Moki Formation on the hillside (R18/595698) above the Mohakatino River, near beyond locality A.

and F in the upper part (Fig. 7). Pebbles and cobbles of bored concretionary mudstone occur in channelled depressions at the base of the section at the seaward end of the outcrop, but are exposed only when modern sand has been scoured from the river mouth. Comparable smaller fragments are dispersed throughout the Facies E fill, along with common glauconitic and/or glauconitised grains or mud clasts, often concentrated in small, centimetre-sized pockets. A prominent

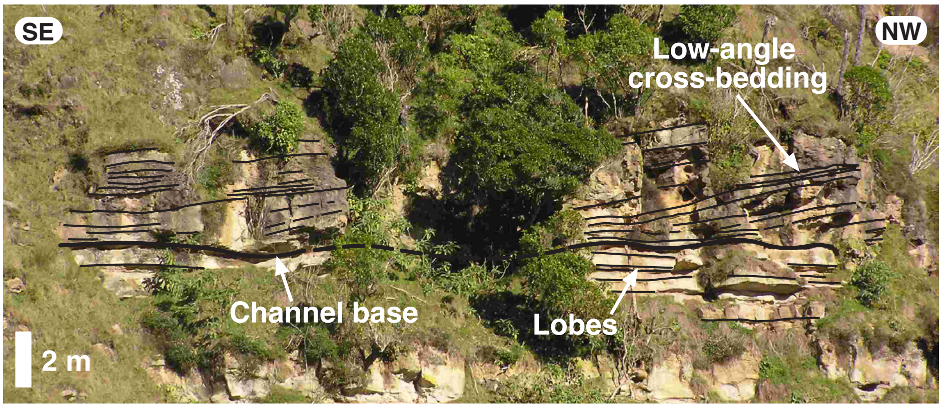


Fig. 9 Sedimentary structures within a well-defined channel at the Mohakatino valley section. Low-angle cross-bedded calcirudites/calcarenites of Facies A (*Amphistegina*/coralline algal-dominated facies) interpreted as lateral bars.

conglomerate bed on top is similar to Facies C_1 but it does not contain bioclasts and its matrix is volcaniclastic sandstone (Fig. 7B). Consequently, it is assigned to the basal Mohakatino Formation.

Interpretation

The sediments of the Mangarara Formation at Awakino Heads were deposited in a submarine channel. As noted previously for the Ladies Mile section, different types of flows could generate the mixed sand-mud-bioclastic fill of the channel. The presence of highly burrowed intervals precludes a definitive flow interpretation as indicative sedimentary structures have been destroyed. Tentatively, we consider this channel to be located near the channel-lobe transition zone. The localised conglomeratic deposits in basal depressions at the seaward end of the section are likely lag deposits, while the muddy interval of Facies F at the top of the channel infill indicates channel abandonment and deposition of hemipelagic sediment, although we are mindful that an unknown amount of the upper part of the fill may have been removed during formation of the overlying unconformity surface.

The concretionary cobble conglomerate at the base of the overlying Mohakatino Formation is interpreted to be residual lag from subsequent erosive channel-cutting events and deposition from debris flows on the contemporary slope. The disconformity that spans this upper contact is of c. 4.5 m.y. duration based on the reported early Clifdenian age (c. 15.5–15.9 Ma) for the Mangarara Formation compared with the latest Waiauan age (c. 11 Ma) for the overlying Mohakatino Formation (King et al. 1993). This local disconformity suggests that continued erosive events, possibly interspersed with depositional phases, occurred on parts of the contemporary slope throughout this interval until the latest Waiauan, when the Mohakatino volcaniclastic sediments were deposited from a combination of sediment gravity flows and submarine ash fallout (e.g., Nodder et al. 1990).

Mohakatino valley section

The Moki Formation crops out within the Mohakatino River valley (Fig. 1) (Ngatai 2004) and the Tongaporutu River valley to the south. About 10 km upstream from the Mohakatino River mouth (R18/585704–605698), this siliciclastic unit contains mixed siliciclastic-carbonate and carbonate deposits of the Mangarara Formation. Here, Moki Formation comprises decimetre-scale interbedded sandstone (Facies G) and mudstone (Facies F) (Fig. 3H, 8), which in the next major river valley (Tongaporutu) to the south involves distinctive flysch facies (turbidites). The sandstone is typically fine to very fine grained, moderately well sorted, locally bioturbated, and has sharp bases and sharp to abruptly gradational tops. These sandstone beds are interpreted to be sandy debris flow deposits (debrites). The mudstone beds in Moki Formation are massive and locally thoroughly bioturbated and can contain bivalves, gastropods, scaphopods, and solitary corals, including *Lima colorata*, *Lentipecten hochstetteri*, *Limopsis lawsi*, *Amalda* sp., *Austrofusus* sp., *Penion crawfordi*, *Falsicolus* sp., *Alcithoe* aff. *bathgati*, *Austrotoma nevosa*, *Zemacies elatior*, *Sigapatella* sp., *Dentalium otamaringaense*, and *Trunctoflabellum spenodeum* (Ngatai 2004). This mix of neritic and bathyal species in the Moki Formation is consistent with reworking and redeposition of shelf taxa downslope.

Description

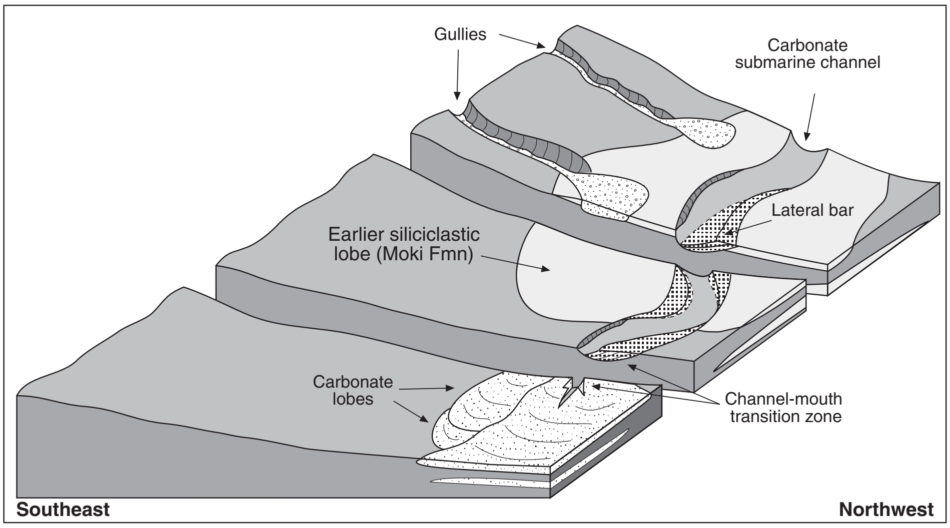
The geometry of the mixed siliciclastic-carbonate bodies of the Mangarara Formation at this site can be assigned to narrow channels, broad channels, or sheet-like beds.

Narrow channels: These channels have steep margins. In many channels the cross-section geometry is indicated by the lateral extent of cemented beds compared with softer surrounding sediments, rather than from well-defined margins, commonly obscured by lack of outcrop. Where measurable, their orientation appears to be directed mainly towards the north–northwest. Channel widths range 25–50 m and channel thickness 2–5 m. Individual beds within channels are from a few centimetres to 1.5 m thick. Most bed bottoms are planar and sharp, but erosive bases are also present.

A coarse-grained fill, rich in carbonates with some intercalated siliciclastic beds, helps to characterise narrow channels (Fig. 8). Coarse-grained beds (Facies B, C_2, and D) are crudely bedded, while parallel and cross-lamination occur in some finer grained beds (Facies A and E). Intraclasts (rip-up clasts) of Facies F (mudstone) and G (sandstone) from the enclosing Moki Formation are common in the coarse-grained beds.

Broad channels: Broad, well-defined channels are up to 200 m wide with infillings up to 15 m thick. Channel-fill consists of amalgamated beds, mainly of Facies A and minor D, separated by thin mud layers (Facies F). Low-angle cross-bedded to sigmoidal beds occur locally (Fig. 9). The dips of these beds range 3–13°. Channel axes align northeast–southwest, but no other paleocurrent indicators have been observed. Steep

Fig. 10 Integrated depositional model in a slope to basin floor setting for middle Miocene redeposited carbonates in eastern Taranaki Basin (not to scale). Mangarara Formation comprises lateral-accreting confined channel (Mohakatino valley section), moving downslope into a channel-lobe transition zone and lobes (Ladies Mile and Awakino Heads sections). This carbonate channel-fan system cut across the siliciclastic lobes (frontal-splay complex) of the Moki Formation. Slope gullies funnelled coarse-grained mixed carbonate-siliciclastic sediments into the basin floor that cut across the lobes of the Moki Formation.



walls of the outcrops and dense vegetation preclude thorough examination of many of these channels.

Sheet-like beds: These beds are up to 70 cm thick, have sheet-like geometry, and extend laterally >400 m. They are located beneath the main set of well-defined channel deposits and intercalated between sandstone and mudstone beds of Moki Formation. These latter deposits are also sheet-like. Tabular carbonate beds are made up of Facies A, mainly grainstone or calcareous sandstone. A crude parallel lamination, associated with the alignment of *Amphistegina* tests, is evident in some beds.

Interpretation

The narrow channels are interpreted as the remnants of submarine gullies that cut the slope from the shelf-edge and funnelled coarse sediment downslope. Supporting evidence includes: (1) these channels intersect and are overlain by redeposited sediments of the Moki Formation, interpreted as submarine lobes in a submarine-fan system or frontal-splay complex (*sensu* Posamentier & Kolla 2003) (Fig. 8); (2) no evidence exists for channel migration, avulsion, or appearance of related levees, overbank splays, sediment waves, or frontal-splay complexes/lobes; and (3) the emplacement mechanism for these sediment bodies suggests erosion and simultaneous sediment deposition rather than sediment transport and redeposition along a channel.

Although several facies types may infill the narrow channels, they can be broadly grouped as coarse-grained (Facies B, C_2, and D) and fine-grained (Facies A, F, and G) varieties. The coarse-grained sediments were deposited in submarine gullies by debris flows. Rip-up clasts (of Facies F and G) were eroded from the underlying siliciclastic lobe sediments and incorporated into the flow. Fine-grained sediments were funnelled through the gullies by turbidity currents and concentrated debris flows.

The broad channels are similar to those described at the Ladies Mile section. Cross-beds to sigmoidal beds (Fig. 9) are interpreted to result from the migration of lateral bars in sinuous submarine channels. However, in contrast to those at Ladies Mile, the lateral bars in these channels accreted over larger distances. Consequently, the lateral-accretion stage and migration activity of the channels were more important at the Mohakatino valley site than at Ladies Mile. This probably relates to a more proximal position in the submarine channel-fan system for the Mohakatino valley section compared with the Ladies Mile position. Outcrop quality precludes a more detailed interpretation and an aggradational phase is not clearly identified at Mohakatino valley.

As interpreted for Ladies Mile, lateral bar migration was produced under steady flow conditions. Flow was partially decelerated during the helicoidal movement over the bar. Resulting deposits are massive and only locally did large rhodoliths accumulate as a lag deposit at the base of beds. Thin caps of mud were deposited during periods of quiescence.

Sheet-like beds are interpreted to represent submarine lobe deposits generated down-dip of channel mouths when flows became unconfined. The flow deceleration produced by this unconfinement is reflected in the crude but common parallel lamination in these beds compared with those in the more confined channel setting. Carbonate beds are intercalated within redeposited sandstone and mudstone beds, which suggests that the channel systems could be shared by both carbonate- and siliciclastic-dominant density flows, producing a crosscutting of two deep-water submarine sediment transport systems, namely the Mangarara and Moki systems (Fig. 10). The lobe deposits are overlain by channel deposits, reflecting channel migration over the lobes.

DISCUSSION

Position of outcrop occurrences within a channel-fan system

The channelised and redeposited carbonates and mixed siliciclastic-carbonate sediments composing the Mangarara Formation in onshore eastern Taranaki Basin are here interpreted to have accumulated within the channel-lobe transition zone in one or more submarine channel-fan systems (Fig. 10). Another element of slope settings, submarine gullies, is also recognised.

One of the shelf-to-basin transport paths was via submarine gullies distributed along the contemporary paleoslope. Such slope gullies are morphological features of modern continental margins and are conduits for channelising coarse-grained sediment into deep water from the shelf-break (e.g., Ricketts & Evenchick 1999; Spinelli & Field 2001). Spinelli & Field (2001) describe ancient submarine gullies up to 100 m wide and 1–3 m deep that extended 10–15 km across the slope in the northern California Continental Borderland. These gullies are of the same order of magnitude as the fossil occurrences at the Mohakatino valley site. We envisage for eastern Taranaki Basin that submarine gullies funnelled coarse-grained carbonate sediment from shallow shelf regions out onto the basin floor, via debris flows and other density flows, where they cut into siliciclastic lobe and basinal sediments (Fig. 10). In some literature examples, gullies act as tributary channels that merge into large channels and submarine canyons (e.g., Hunt & Tucker 1993; Vigorito et al. 2005; García et al. 2006; Payros & Pujalte 2008). In our examples, seemingly no physical connection existed between the gullies and channels, although outcrop exposure is limited.

The main paths of sediment remobilisation to the basin floor were via broad channels. Lateral-accretion structures suggest the channels had a sinuous geometry (Fig. 10). Active sediment transport and deposition occurred during the migration of these channels (lateral-accretion stage) that were later filled up (aggradation stage) and eventually smothered with overbank deposits. Similar stages of channel drift have been recognised in other submarine sinuous channel systems (Peakall et al. 2000; Lien et al. 2003). In the final stage, spillover deposits overtop the channel levees (Piper & Normark 1983). In the Mangarara case, no evidence for levees has been observed. This is probably a consequence of the coarseness of the channel-fill sediment and the behaviour of the associated flows. The broad nature of some of the channels relates to their proximity to the channel-lobe transition zone, where sediment flows become unconfined, decelerate, and deposit the transported sediment.

The most downslope element in the system recognised here are lobes that spread over the basin floor from a channel mouth. The lobes identified from facies analysis in the field are, however, parts of the Moki Formation, albeit that some of the sandstone beds may be calcareous or even carbonate (limestone). Channel migration over the lobes, and changes in the position of the channel-lobe transition, reflect the dynamic activity of these channels.

We resist suggesting that the various occurrences of Mangarara Formation described here formed one particular channel-fan system, as this cannot be demonstrated by mapping or other forms of correlation. It is likely that the various sites described are parts of several channel-fan systems, all of them near the channel-lobe transition zone.

Comparison with established calciclastic submarine fan models

Carbonate (calciclastic) slope systems are divided into slope apron and base-of-slope apron systems (Mullins & Cook 1986) and carbonate submarine channel-fan systems. The latter have been traditionally interpreted based on siliciclastic submarine fan models (see Payros & Pujalte 2008) because no specific carbonate submarine fan equivalent existed. However, most recently, Payros & Pujalte (2008) have proposed some general facies models for calciclastic submarine fans (CSF), grouping them into three categories: coarse-grained, small-sized CSF; medium-grained, medium-sized CSF; and fine-grained, large-sized CSF.

Following this scheme, we propose a sedimentary model for the Mangarara carbonate submarine channel-fan system (Fig. 10) of a medium-grained, medium-sized CSF based on sediment texture (dominantly calcarenite) and system scale (within the range of 10–35 km in length). This facies model includes an upper slope cut by tributary gullies, a channelised feeder system with braided axis, unconfined lobes/sheets, and a fan fringe (Payros & Pujalte 2008). Architectural elements recognised in the Mangarara channel-system are comparable to the channel-levee system and unconfined lobes, although the Mangarara system shows also some distinctive features. The lateral-accreting confined-channel system (i.e., Mohakatino area) (Fig. 10) is considered to be a sinuous submarine channel with well-developed lateral bars at the channel margins. This contrasts with the presence of braided feeder channels in the Payros & Pujalte (2008) model. In this regard, the Mangarara carbonate channel-fan system more closely resembles siliciclastic systems, which develop long feeder channels (Abreu et al. 2003; Posamentier & Kolla 2003; Posamentier & Walker 2006; Wynn et al. 2007). This shared feature may relate to very gentle slope gradients (0.1–0.5°) (Wynn et al. 2007) compared to most calciclastic systems where slope gradients are usually slightly greater (Payros & Pujalte 2008). Submarine channels in the channel-lobe transition zone (Ladies Mile area) (Fig. 10) can be considered equivalent to the radially diverging and branching distributary channels in the lobe/sheet zone of Payros & Pujalte (2008) in terms of their geometry, facies, and sedimentary processes.

The submarine gullies identified in the Mangarara Formation differ from those in the general facies model of Payros & Pujalte (2008) by seemingly not being linked to the confined-channel but still acting as sediment conduits from shallow to deep-water settings (Fig. 10). However, the presence of tributary feeder gullies of the lateral accreting confined channel cannot be discarded because of the relatively poor exposure of outcrop. The fan fringe in the Payros & Pujalte (2008) model is not recognised for the Mangarara system.

Depositional processes in mixed siliciclastic-carbonate fan systems

The architectural elements of the carbonate channelised system described above are present in many siliciclastic systems (e.g., Spinelli & Field 2001; Gardner et al. 2003; Posamentier & Kolla 2003; Klaucke et al. 2004; Ó Cofaigh et al. 2006), as well as in some carbonate deep-water systems (e.g., Braga et al. 2001; Vigorito et al. 2005, 2006; Payros et al. 2007). Subaqueous sediment gravity flows are responsible for the transport and deposition of sediment in deep-water settings. However, much controversy remains concerning the flow-type, flow-behaviour, and the nature of the individual layers and bed sets that build the different architectural elements (e.g., Lowe 1982; Shanmugam 1996, 2000; Lowe & Guy 2000; Mulder & Alexander 2001; Keevil et al. 2006). Complexity derives from the fact that density flows are vertically graded (Kneller & Buckee 2000; Peakall et al. 2000; Gladstone & Sparks 2002) and undergo transformation in time (surge, steady, waning, and waxing flows) and space (longitudinal) (Kneller & McCaffrey 2003). Flow behaviour depends also on multiple physical factors, among which sediment concentration seems to be the most important conditioning the final deposit (Mulder & Alexander 2001; Gani 2004).

For redeposited carbonates the problem can be even more complicated. Carbonate particles have shapes, densities, and provenances different from siliciclastic particles, being platform-produced in the case of coarse-grained carbonates versus continent-derived for most siliciclastics. Size, shape, and density first determine the hydrodynamic behaviour (sediment-support mechanism) of component grains, which can be highly variable amongst different skeletal particle types (Nelson & Hancock 1984), and second the structure of the resulting deposit. Similar kinds of hydrodynamic variability may characterise volcaniclastic submarine materials which, like redeposited deep-water carbonates, are usually poorly sorted and mud-scarce (Gladstone & Sparks 2002). Carbonates are also commonly mixed with siliciclastic material. For example, a massive decimetre-thick bed of poorly sorted, coarse carbonate sediment (coarse sand to granule) may be deposited by hyperconcentrated and concentrated density flows (*sensu* Mulder & Alexander 2001), either as a surge-type or steady-type flow (Kneller & McCaffrey 2003). Although some nexus between sediment concentration and longitudinal flow transformation can be proposed for explaining redeposition of these carbonates, further investigations are needed. Thus, in deep-water systems involving redeposited carbonates, to avoid misuse of otherwise widely used complex density-flow terminology (e.g., Lowe 1982; Shanmugan 1996; Mulder & Alexander 2001), we recommend following Gani's (2004) simplified terminology. Gani's classification divides gravites, a general term for deposits of any kind of sediment gravity flow, into turbidites (deposit from Newtonian fluid), densites (deposit from partly non-Newtonian fluid and partly Newtonian fluid), or debrites (deposit from non-Newtonian dilatant fluid and Bingham plastic). In this scheme, most of the Mangarara deposits would be densites (channel fill) and debrites (gully fill).

Warm-temperate carbonate affiliation

Oligocene temperate or cool-water limestones are widespread in New Zealand (Nelson 1978). Tectonic upheavals associated with propagation of the Australian-Pacific convergent plate boundary through the New Zealand subcontinent at the start of the Miocene saw these temperate limestones largely replaced in the early Miocene by siliciclastic, commonly redeposited, sediments (Kamp 1986). Accompanying climatic amelioration involved increasingly warm subtropical conditions throughout the early Miocene in New Zealand, indicated by widespread warm-water molluscs (Beu & Maxwell 1990), a variety of larger foraminifers (Chaproniere 1984), and even isolated heads of reef corals in northern New Zealand (Hayward 1977). The climax of Neogene warmth occurred near the early–middle Miocene boundary (Hornibrook 1992).

The ensuing middle Miocene, when the Mangarara Formation was being deposited, saw the start of long-term climatic deterioration in New Zealand that was to continue throughout the remainder of the Cenozoic (Nelson & Cooke 2001). Central western North Island lay at about 45°S latitude in the middle Miocene, certainly well outside tropical latitudes, and was under the influence of warm temperate oceanic circulation patterns (Nelson & Cooke 2001). The carbonates in the Mangarara Formation contain an exclusively heterozoan skeletal assemblage including the remains of bryozoans, echinoderms, bivalves, benthic foraminifers, and coralline algae (Hayton et al. 1995; James 1997). However, unlike most other New Zealand temperate limestone occurrences where bryozoans in particular, but also echinoderms, bivalves, and barnacles, are usually the major skeletal contributors (e.g., Nelson 1978; Hayton et al. 1995; Hood et al. 2003; Nelson et al. 2003), the Mangarara redeposited carbonates are dominated by robust, large, benthic foraminifers and coralline algae.

The benthic foraminifers include predominantly *Amphistegina* as well as less common larger foraminifers like *Lepidocyclina*, and possibly *Heterostegina* and *Cycloclypeus*. The coralline algae comprise both fragmented material and subspherical rhodoliths from a few centimetres up to 10 cm size. The algal genera involved in the rhodoliths include mainly *Lithothamnion* and some *Mesophyllum*. Today in the Pacific, the 20°C mean annual sea surface isotherm roughly corresponds to the southern limit of the distribution of *Amphistegina* (Hornibrook 1968), which, together with the sporadic larger foraminifers and the coralline red algae, supports the contention that the main carbonate factories for the Mangarara Formation were sited in warm, photic, very shallow marine platform settings. These settings lay very much toward the warm end of the spectrum of cool-water or temperate shelf carbonate facies, closely analogous to the warm-temperate carbonate realm discussed by Betzler et al. (1997b) and others (e.g., Halfar & Ingle 2003). Larger foraminifers became extinct in New Zealand by the end of the middle Miocene, as did *Amphistegina* during the Pliocene (Hornibrook 1992), despite the existence of appropriate facies for preservation, so their ultimate disappearance reflects continued long-term cooling of marine temperatures through the late Cenozoic (Nelson & Cooke 2001).

Paleogeography and skeletal carbonate sources

The heterozoan skeletal components in the channelised and redeposited carbonate sediments of the Mangarara Formation must have been sourced from nearby warm-temperate shallow-marine shelves or platforms. A possible provenance is the shellbed facies that accumulated to the ESE in the vicinity of Taumarunui and Ohura following transgressive flooding in the early middle Miocene (late Lillburnian) (Kamp et al. 2004) (Fig. 11). The transgressive shellbed consists mainly of bivalve-rich sandstone and mudstone, along with some local limestone (Armstrong 1987; Gerritsen 1994; Vonk 1999). The bivalves are variably fragmented and small amounts of *Amphistegina* and coralline algae may occur in the matrix sediment. Other bioclasts include solitary corals, gastropods, and echinoderms. However, the upper channels at Ladies Mile and Mohakatino valley are completely dominated by coralline algae and *Amphistegina*, which are otherwise minor components in the transgressive shellbed. Moreover, the late Lillburnian age of the transgressive shellbed would discount them as the source of older (Altonian to early Lillburnian) redeposited Mangarara Formation sediments in contemporary slope deposits to the west. Thus, some other carbonate source must be involved.

Because the basin deepened to the north and west, provenance from a northerly or westerly direction is unlikely. Instead, a source from the south is most likely, associated with the Patea-Tongaporutu High (Fig. 11). Several petroleum exploration wells drilled on the margin of this high (numbered in Fig. 11) indicate that thick (up to 80+ m) middle Miocene-age limestones, rich in *Amphistegina* and coralline algae, occur within Manganui Formation or lie stratigraphically above basement (Table 2). Despite being assigned different names in the different petroleum reports (Table 2), these middle Miocene limestones are considered to be correlatives of the Mangarara Formation.

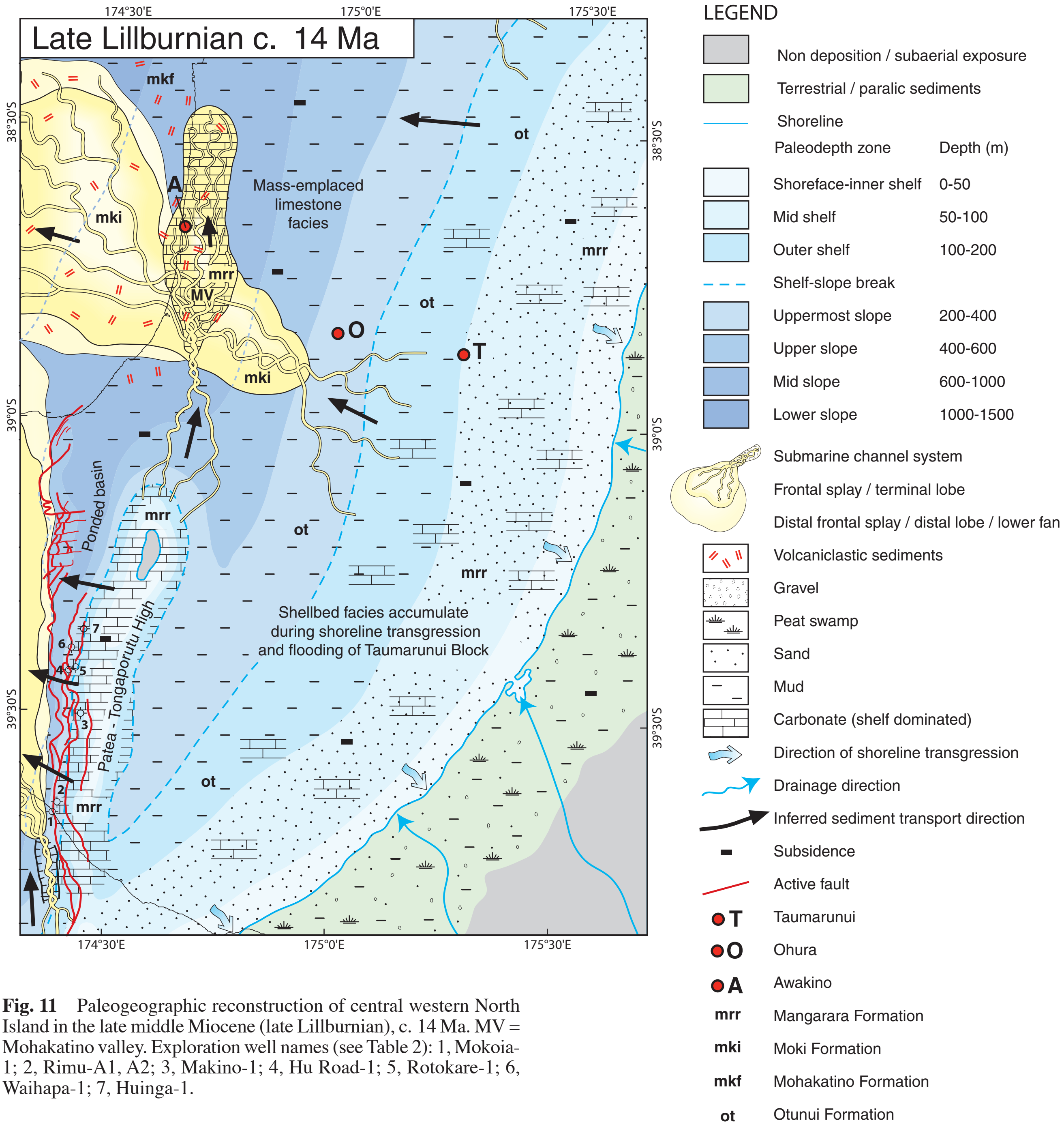


Fig. 11 Paleogeographic reconstruction of central western North Island in the late middle Miocene (late Lillburnian), c. 14 Ma. MV = Mohakatino valley. Exploration well names (see Table 2): 1, Mokoia-1; 2, Rimu-A1, A2; 3, Makino-1; 4, Hu Road-1; 5, Rotokare-1; 6, Waihapa-1; 7, Huinga-1.

As previously emphasised for the Mohakatino valley and Awakino areas, a close interaction existed between the carbonate submarine system and a siliciclastic submarine system (Fig. 10). The main source area for the siliciclastic system (Moki Formation) was located to the southeast where shoreface sandstone occurs in the Mokau Group and there was a narrow shelf to the west leading to contemporary slope environments (Manganui and Moki Formations) (Fig. 2). The terrigenous influence probably precluded the widespread development of neritic carbonates in that area. However, to the south upon the Patea-Tongaporutu High, terrigenous input was less significant because of positive submarine relief, and the warm-temperate shallow seas over the high supported extensive carbonate production involving coralline algae and associated *Amphistegina* benthic foraminifera that were periodically redeposited down-slope to the west and north into the Mangarara Formation (Fig. 11).

In Fig. 11, for one time interval (late Lillburnian or early Serravallian), we show a carbonate-sourced channel-fan complex shedding northwards off the contemporary Patea-Tongaporutu High, but at different times such systems could have been directed anywhere between north and west. There will be complexities around the particular down-slope direction for channel-fan complexes along this part of the

Table 2 Middle Miocene-aged limestone-bearing units (from open-file petroleum exploration wells) from onshore eastern Taranaki Basin that are here suggested as correlatives of the Mangarara Formation.

Well	Report no.	Author (year)	Lithostratigraphic name in report	Age	Thickness (m)	Upper contact	Lower contact	Description (from composite log and report)
Rimu-A1	PR 2447	Harris et al. (1999)	Awakino Limestone	Middle Miocene	76	Manganui Formation	Manganui Formation	Limestone, light grey to white, argillaceous grading to calcareous claystone, embedded with minor volcanics
Rimu-A2	PR 2614	Harris et al. (2001)	Awakino Limestone	Early–middle Miocene	324	Manganui Formation	Lower Manganui Formation	Mottled, weathered argillaceous limestone horizons, interbedded and intermixed with sandstones, siltstones, claystones, and metasediments. Overthickened nature and weathered appearance suggest possible faulting
Mokoia-1	PR 1679	New Zealand Oil & Gas Ltd (1990)	Awakino Limestone	Clifdenian (Sc)	56	Manganui Formation	Lower Manganui Formation	White, light grey to light brown mottled limestone, fine pebble-sized shell fragments, forams, algae, hard siltstone and sandstone pebbles with ?chlorite. Glauconite, calcite cemented
Makino-1	PR 2649	Marabella Enterprises Ltd (2001)	Awakino Limestone	Clifdenian (Sc) to Waiauan (Sw)	22	Manganui Formation	Murihuku Terrane basement	Crystalline limestone with common lithic clasts. White to off-white, yellowish grey to pale yellowish brown, hard or very soft to soft, crushed recrystallised with trace algal fragments. Trace well rounded granular dark grey siltstone lithics
Rotokare-1	PR 1680	New Zealand Oil & Gas Ltd (1988)	Awakino Limestone	Clifdenian (Sc)	35	Manganui Formation	Syntectonic unit	Light olive-grey clay rich carbonates and arenaceous limestone
Hu Road-1	PR 1825	New Zealand Oil & Gas Ltd (1991)	Awakino Member (Manganui Formation)	Late Altonian (Pl) to Clifdenian (Sc)	194	Manganui Formation	Manganui Formation	Calcareous claystone with interbeds of bioclastic limestone and occasional stringers of siltstone. Bioclastic limestone is off-white to pale brown to buff, calcilutitic, 30–40% bioclastic material, especially *Amphistegina* foraminifera tests, abraded bivalve and echinoid debris; coarse to very coarse crystalline calcite cement with trace silt and in places pyrite and glauconite
Waihapa-1	PR1825	New Zealand Oil & Gas Ltd (1991)	Waihapa Member	Late Altonian (Pl) to Clifdenian (Sc) by correlation with Hu Road-1	80	Mahoenui/ Manganui	Mahoenui/ Manganui	No description, only correlation to Awakino Member in Hu Road-1 in PR 1825 Enclosure 1
Huinga-1/1A	PR 2440	MacFarlan et al. (1999)	Slope debris unit	Altonian (Pl)	49	Manganui Formation	Murihiku Supergroup basement	Claystone interbedded with siltstone, lithic sandy limestone, and calcite-cemented conglomerate

eastern Taranaki Basin margin during the middle Miocene, but we envisage a local northerly paleoslope off the northern end of the contemporary Patea-Tongaporutu High interfering with a regional west–northwest-facing paleoslope, which would allow for interfingering of separate Moki and Mangarara channel-fan systems, distinguished amongst other features by the predominantly siliciclastic versus carbonate content of the respective deposits.

CONCLUSIONS

1. The middle Miocene Mangarara Formation is unique amongst the otherwise siliciclastic-dominated Neogene deposits of eastern Taranaki Basin because of its significant (typically 40–90%) carbonate content. In the vicinity of Awakino and Mohakatino valley, these Mangarara carbonate and mixed siliciclastic-carbonate sediments are interpreted as mass-emplaced densites and debrites deposited at slope depths within different parts of a submarine channel-fan system.
2. The recognised parts of this system include distal portions of lateral-accreting confined-channel complexes, channel-lobe transition zones, and lobes (frontal-splays). Lateral-accretion structures interpreted as lateral bars are the best represented architectural element in the channel-fan system. Phases of active sediment transport and deposition (lateral-accretion stage) and filling (aggradation stage) are identified within channel infillings, which are dominated by densites.
3. Submarine slope gullies, which appear not to be connected with submarine channels or canyons, are also identified. Gullies are filled with coarse-grained mixed carbonate-siliciclastic sediments (debrites) and were cut into siliciclastic lobes of the coeval Moki Formation.
4. Dual fan systems likely co-existed, one dominating and predominantly siliciclastic in nature (Moki Formation), and the other infrequent and involving temperate calcareous deposits of the Mangarara Formation sourced mainly from shoal carbonate factories around and upon isolated basement highs (Patea-Tongaporutu High) to the south.
5. The redeposited skeletal carbonate material forming the Mangarara deposits consists mainly of coralline algae and larger benthic foraminifers (especially *Amphistegina*), together with bivalves and bryozoans. Such a heterozoan skeletal association is indicative of the warmest conditions of the temperate-carbonate realm, consistent with development soon after the Neogene climatic optimum in New Zealand near the early–middle Miocene boundary.
6. The Mangarara Formation is an outcrop analogue for middle Miocene-age carbonate slope-fan deposits elsewhere in subsurface Taranaki Basin.

ACKNOWLEDGMENTS

Fieldwork was carried out while the first author was on a short-stay leave at the University of Waikato. A. Puga-Bernabéu was funded by a doctoral contract (MECD-UGR) awarded by “Ministerio de Educación y Ciencia” (Spain). He thanks the Department of Earth and Ocean Sciences for logistical support during his stay in Hamilton. Additional research funding support for this study came from the New Zealand Foundation for Research, Science and Technology (FRST contract UOWX0301) to the University of Waikato. We acknowledge the contribution made to documenting the geology of the north Taranaki region by several past MSc thesis students (A. Happy, B. Wilson, S. Gerritsen, M. Ngatai). The constructive comments of J. M. Martín, J. C. Braga, and two anonymous reviewers on versions of this manuscript are much appreciated.

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