

Chapter 18

Ancient New Zealand Seep Limestones



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18.1 Introduction

The East Coast Basin of eastern North Island, New Zealand, is one of a few places in the world that offers the opportunity to reconstruct a spatiotemporal record of long-lived (ca. 25 Myr duration from Neogene to the Recent) hydrocarbon seepage for both onshore, exhumed accretionary prism and forearc rocks and their adjacent, offshore, modern convergent tectonic settings (Campbell et al. 2008). Comparable settings, with analogous ancient and modern seeps, are found elsewhere on the Pacific Rim and include Japan, northwestern USA, and western South America (e.g., Olsson 1931; Goedert and Squires 1990; Kanie et al. 1992a, b; Asami et al. 1995; Goedert and Campbell 1995; Hattori et al. 1995; Naganuma et al. 1995a, b; Squires and Goedert 1995; Goedert and Kaler 1996; Kanie and Sakai 1997; Peckmann et al. 2002; Goedert et al. 2003; Majima et al. 2005; Campbell 2006; Kiel and Peckmann 2007; Kaim et al. 2014). The basin is also host to much older, Late Cretaceous allochthonous seep deposits, which are less numerous than the Miocene

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seeps, and not as widely studied, but are similar lithologically and also contain rich faunal assemblages (Kiel et al. 2013).

18.2 Miocene New Zealand Seep Sites

18.2.1 *Distribution*

At least 16 geographically isolated Miocene hydrocarbon seep deposits occur as discrete pods or lenses of authigenic carbonate enclosed within thick siliciclastic bathyal mudstone deposits along a 300 km tract of the East Coast Basin, eastern North Island (Fig. 18.1 and Table 18.1; Campbell et al. 2008). They occur in two distinct areas—the northern (Gisborne) and southern (Dannevirke) sites—separated by approximately 200 km through the Hawke’s Bay region (Fig. 18.1). By far, the largest of these deposits, at least in exposure, is at Rocky Knob in the Raukumara Peninsula, which also harbors the widest diversity of seep taxa and characteristic seep geological features such as tubular conduit concretions (e.g., Nelson et al. 2019). There is also evidence for other potential late Miocene seepage from the presence of tubular conduit concretions without associated development of seafloor seep carbonate at other sites in East Coast Basin (e.g., Nyman et al. 2010; Nelson et al. 2017), as well as in Taranaki Basin on the west coast of North Island (Nyman and Nelson 2011).

18.2.2 *Geotectonic Setting*

The East Coast Basin formed as the result of regional tectonism that has been ongoing since the Miocene (New Zealand Waitakian Stage; e.g., Ballance 1976; Barnes et al. 2002, 2010). Extending roughly 650 km north to south, the East Coast Basin varies in width from 60 to 110 km, bounded to the west by NNE–SSW trending axial mountain ranges and extending offshore to its eastern boundary along similarly trending troughs. It represents an exhumed forearc, its sediments having been generated during a period of oblique convergence along the Hikurangi subduction zone (HSZ, Fig. 18.1) throughout the late Cenozoic (e.g., Ballance 1976; Barnes et al. 2002), in correspondence with the onset of intense deformation, the appearance of andesitic volcanism, and abrupt changes in sedimentation rate and character (Rait et al. 1991).

Today, the margin constitutes the southern extremity of the Tonga–Kermadec–Hikurangi seismic zone, a west-facing subduction zone running roughly parallel to the east coast of North Island, along which the thick and bathymetrically elevated

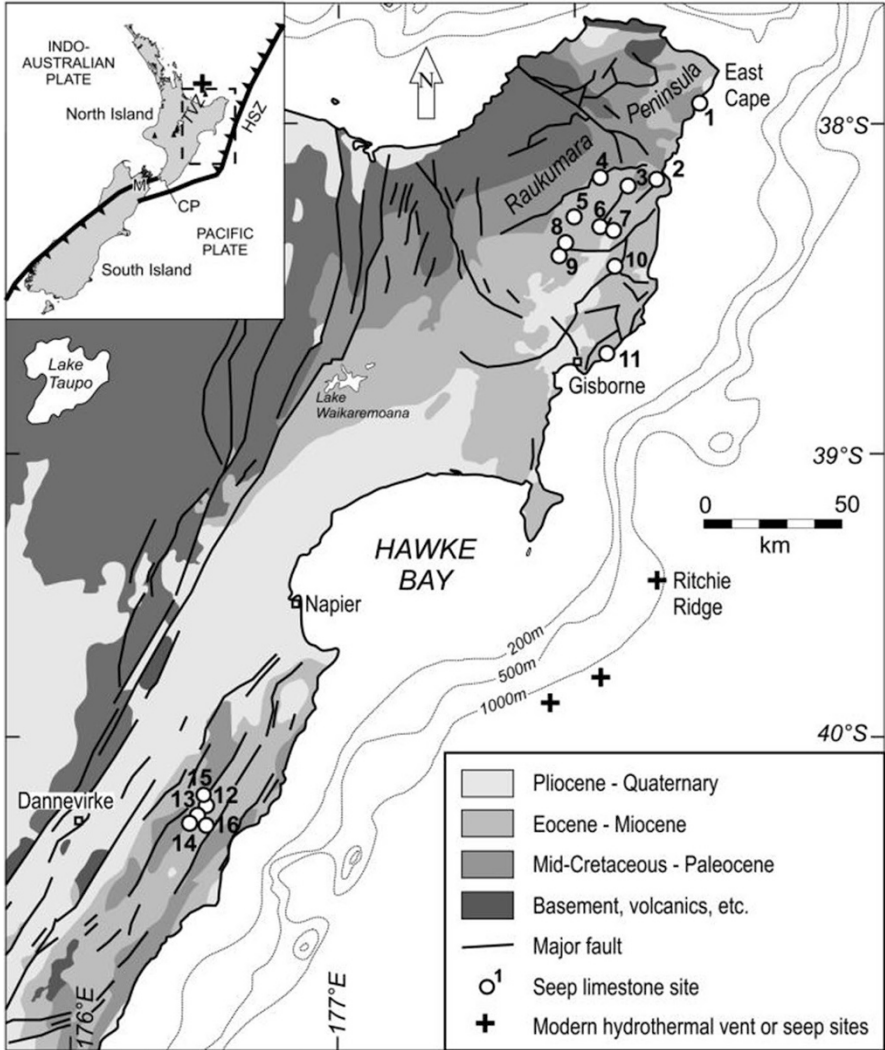


Fig. 18.1 Overview of the East Coast Basin in the Hawke's Bay area, east coast of North Island, showing the approximate locations of the majority of the known Miocene carbonate seep sites (see also Table 17.1). Numbers 1–11 correspond to the northern sites: 1 = Waiapu; 2 = Waipiro; 3 = Karikarihuata; 4 = Bexhaven; 5 = Tauwhareparae; 6 = Puketawa; 7 = Totaranui; 8 = Moonlight North; 9 = Rocky Knob; 10 = Waikairo; 11 = Turihaua. Numbers 12–16 correspond to the southern sites: 12 = Wanstead; 13 = Ugly Hill; 14 = Haunui; 15 = Ngawaka; 16 = Wilder. Also shown are some of the modern offshore hydrocarbon seep and hydrothermal vent sites on the Hikurangi margin. Inset shows the Hikurangi subduction zone (HSZ) as part of the transpressive boundary between the Indo-Australian and Pacific plates. CP = Cape Palliser; TVZ = Taupo Volcanic Zone. (Image modified from Campbell et al. 2008)

Table 18.1 Locality and age information for the main onshore Miocene seep limestone occurrences in East Coast Basin, North Island, New Zealand, arranged in roughly north to south order (see Fig. 18.1)

No.	Name	Approx. NZ Map Grid (NZMG) reference ^a	NZ stage	International epoch
1	Waiapu	Z15/917654	Tongaporutuan	Late Miocene
2	Waipiro	Z16/763394 and nearby	Otaian–Altonian	Early Miocene
3	Karikarihuata	Y16/657351	Lillburnian– Waiauian	Middle Miocene
4	Bexhaven	Y16/558332	Lillburnian	Middle Miocene
5	Tauwhareparae	Y16/463242	Lillburnian	Middle Miocene
6	Puketawa	Y16/557206	Clifdenian– Lillburnian	Middle Miocene
7	Totaranui	Y16/606192	Lillburnian	Middle Miocene
8	Moonlight North	Y16/433141	Waiauian	Middle Miocene
9	Rocky Knob	Y16/412103	Lillburnian	Middle Miocene
10	Waikairo	Y17/600065	Lillburnian	Middle Miocene
11	Turihaua	Y18/581745	Tongaporutuan	Late Miocene
12	Wanstead	V23/130107	Waitakian–Otaian	Early Miocene
13	Ugly Hill	U23/095076 and nearby	Waitakian	Early Miocene
14	Haunui	U23/072044-092070	Waitakian	Early Miocene
15	Ngawaka	U23/040075-044072	Waitakian– Clifdenian	Early to middle Miocene
16	Wilder	U23/063027	?	Miocene

^aBased on existing series of NZMS260 1:50,000 topographic map sheets

oceanic Hikurangi Plateau (Pacific Plate) is subducting northwestward underneath the overriding Indo-Australian Plate (e.g., Ansell and Bannister 1996; Barnes et al. 2010). Along the Hikurangi margin, subduction occurs at a gentle dip angle of ca. 3° before steepening south of the North Island (Henry et al. 2006) and at variable rates, from ~50 mMa⁻¹ at the Kermadec Trench (northwest of North Island), decreasing southward to ~38 mMa⁻¹ at the southern tip of the Hikurangi Trough (Beanland et al. 1998; Barnes et al. 2002).

The present forearc system can be divided into three major east–west components (Lewis and Pettinga 1993): an inner forearc located mostly onshore; an imbricated, frontal accretionary wedge lying mainly offshore; and a zone of trench slope sediments formed via offshore frontal accretion. West of the forearc lies a backstop, the axial ranges, of Mesozoic metasedimentary basement that comprises Torlesse terrane dominated by graywackes (Barnes et al. 2002), with older (Mid-Cretaceous to Paleogene) passive margin sediments underlying the Miocene section, some of which are known organic-rich (gas and oil) source rocks (Field et al. 1997).

18.2.3 Localities

18.2.3.1 Northern (Gisborne) Sites

Waiapu A fossil-poor limestone described by McKay (1877) from near the mouth of the Waiapu River, probably on the south bank, contains a few poorly preserved, undescribed bivalves similar to those in the Waipiro locality (see below). It is hosted in a small outlier of Miocene mudstone, probably mid-upper Miocene (New Zealand Tongaporutuan Stage), but the age is uncertain.

Waipiro This site is a collection of several sublocalities, in the form of large, often slumped, boulders (~2 × 4 m) of moderately fossiliferous limestone, within a 1 km area on either side of the Waipiro Stream. Boulders of the same material can be found downstream. McKay (1877, p. 138) described "... a very peculiar yellow semi-crystalline limestone. This contains some fossils, which, from what I can make out, I believe to be the same as those that are found in the limestones near the mouth of the Waiapu River, and in coral beds in the cliff behind ... Great quantities of this limestone, in large blocks, are found in the bed of the creek further up, ..." This early Miocene (New Zealand Otaian–Altonian Stage) locality is set in a structurally complex, partly faulted Miocene outlier surrounded by Cretaceous–Eocene strata. The area is also affected by severe hillside slumping, which is locally more significant than faulting.

Karikarihuata The Karikarihuata site and surroundings are cyclically covered by pine forest that can make access difficult, but access is possible using a track south from Ihungia Road for about 2 km and then walking or, alternatively, traversing along Karikarihuata Stream (Fig. 18.2c). The main limestone is 4–8-m thick and pure (97% CaCO₃), with thick mudstone below and thin-bedded flysch above, all part of the Ihungia Formation (Mazengarb et al. 1991). Outcrops occur on both sides of the Karikarihuata Stream, extending in a north–south direction for up to 300 m along strike. The site is structurally set in a middle Miocene (New Zealand Lillburnian–Waiuan Stage), generally west-dipping sequence measured at 28° and 44° below and above the limestone, respectively. The base of the underlying thick mudstone is faulted against the Whangai Formation to the east, while a short distance up-section the flysch is faulted against Altonian Stage (early Miocene) strata to the west.

Bexhaven This site was mapped by Mazengarb et al. (1991), close to, and named for the nearby Bexhaven Farm. The deposit is up to 4 m thick in places and extends laterally for about 150 m above the road, but is concealed in part by slope colluvium (Fig. 18.2b). The rocks are probably middle Miocene (New Zealand Lillburnian Stage) in age and sit on the northwest limb of the Tutamoe Syncline, about 3 km southeast of a major normal fault terminating the Miocene strata.

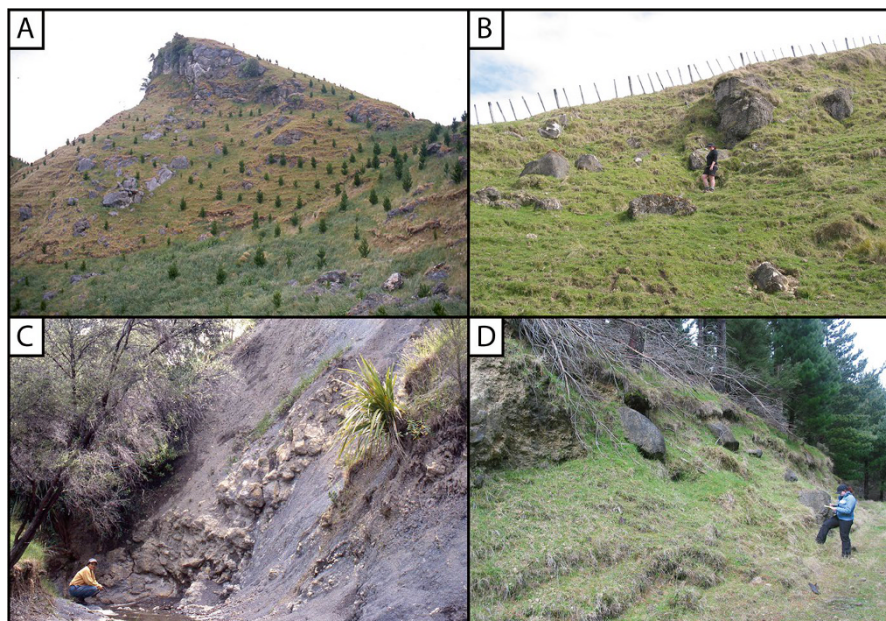


Fig. 18.2 Some of the larger northern (Gisborne) Miocene sites. (a) Rocky Knob, young trees (ca. 1 m tall) for scale; (b) Bexhaven, person for scale; (c) Karikarihuata, person for scale; (d) Moonlight North, person for scale. (Photographs taken on various field trips from 1997 to 2009 by the authors, Andrea C. Alfaro and Mike Collins)

Tauwhareparae This site is an abandoned (1985) limestone quarry site, named for the nearby Tauwhareparae Road. It is underlain by 2.5 km or more of middle Miocene (New Zealand Otaian–Lillburnian Stage) strata from a fault contact to the west, probably mostly mudstone, but this is uncertain. Overlying to the southwest are ca. 800 m of middle–late Miocene (New Zealand Lillburnian–Tongaporutuan Stage) strata, including ca. 500 m of shallow-facies late Miocene sandstone. It is probably a part of the Ihungia Formation, lying in the axis of the extensive north-east–southwest Tutamoe Syncline.

Puketawa This site is upstream of the Totaranui locality (see below) near the Upper Waiau River. It is a single large slumped limestone boulder in a creek bed, up to 1.8-m thick across bedding, with a 0.6-m-thick richly fossiliferous unit at one end. A strong fetid smell (as at Totaranui) is evident upon striking the rock. The surrounding geology consists of middle Miocene mudstone, so is dated to the middle Miocene (New Zealand Clifdenian Stage). Structurally, it is set near the axis of the Matanui Anticline, which plunges southward locally.

Totaranui The Totaranui locality comprises limestone boulders (the largest about 2-m thick through bedding) located ca. 800 m west of and named for Totaranui outstation, near a spur track 500 m north and 150 m above the Waiau River. It is

accessible via a forestry track down to the river, from where it is possible to drive further upstream, and is notable for a somewhat fetid sulfur smell, and radially recrystallized tubes, ca. 8-mm diameter and up to 100 mm long, which are worm tubes (Georgieva et al. 2019). Analysis indicates about 88% CaCO₃ content. It is situated within a fault-bounded segment of Miocene strata and is probably middle Miocene (New Zealand Lillburnian) in age.

Moonlight North This site consists of a single ca. 2-m-thick bed of richly fossiliferous limestone that crops out for about 200 m along strike that is located in a high tributary of the Waingaromia River, just east of a watershed created with Mangaorongo Stream (a tributary of the Waipaoa River), and south of the high escarpment forming the Tutamoe Plateau (Fig. 18.2d). Moonlight North is underlain by thick (>2 km) Miocene mudstone to the north of the Atarau Fault, and overlain by some 700 m of mudstone and flysch that is unconformably topped by late Miocene fossiliferous sandstone. Access is via Moonlight Station and farm or forestry tracks. The site includes the presence of tubular concretionary plumbing features observable in road cuts, and float blocks that occur in a nearby paddock which is under forestry management and cyclically covered in pine plantations. Probably middle Miocene (New Zealand Waiuan Stage) in age, the deposits at Moonlight North dip 28° NNE, within a north–northeast-dipping sequence north of the east–west trending Atarau Fault.

Rocky Knob The name “Moonlight Limestone” was first used informally by Kamp and Nelson (1988) for this locality. The name “Moonlight Limestone” was then formalized by Mazengarb et al. (1991) for an older, lithologically different limestone nearby, and the name “Bexhaven Limestone” was applied to the locality originally mentioned by Kamp and Nelson (1988). It is a large (roughly 15 × 200 m) and prominent fossiliferous limestone outcrop forming a minor north–northeast trending spur in the headwaters of an unnamed tributary of Tawa Stream, in turn a tributary of the Waingaromia River, at the end of a subsidiary track of Moonlight Station (Fig. 18.2a). The outcrop is currently within a pine plantation, but sporadic good exposures remain. Up to 15-m thick, Rocky Knob extends 200 m in strike direction. Part of the deposit has been quarried, and an oily odor is evident on freshly broken samples. A mudstone-dominant section to the south (about 1.5-km thick) underlies down to a ca. 100 m sandier phase near an unconformity at the base of the Miocene. It is overlain by about 500 m of mudstone followed by a sharp erosional unconformity by a late Miocene (Tongaporutuan Stage) sandstone to the north. Argillaceous sandstone blocks can be found in the adjacent stream (Adams 1910), containing abundant macrofossils. Rocky Knob is middle Miocene (New Zealand Lillburnian) in age and structurally dips at 20–25° WNW, with local complexities. It is situated 2 to 3 km from the northern end of Waitangi High (with its modern active oil and gas seeps), 2.5 km east of the northern faulted extension of this high, and 1.8 km south of the east–west trending Atarau Fault (e.g., Campbell et al. 2006; Nelson et al. 2017).

Waikairo This site consists of a single, large, spheroidal block ($\sim 0.8 \times 1$ m) of limestone located within Waikairo Stream, a tributary of Mangaheia River, that can be accessed through a plantation forest. It bears signatures typical of other seep limestones, such as a micritic lithology, yellow-orange weathering, and reports of a few mussels. It is situated within probable middle Miocene (New Zealand Lillburnian Stage) mudstone with some interbedded sandstone on the steeply dipping northern flank of a faulted anticline.

Turihaua Sometimes referred to as *Idasola* Limestone, Turihaua is a slumped site extending ca. 150 m laterally on the northeast side of Turihaua Stream on both sides of a farm access track, altitude ca. 80–100 m. With a thickness of 2 to 4 m, the lateral extent is difficult to assess due to slumping; it was probably originally less than 50 m. This broken outcrop extends over 150 m due to slumping. There are active modern gas seeps in the area, and notable features of the limestone include a mussel-dominated coquina, clotted microbialite, and anastomosing calcite veins. It is late Miocene (New Zealand Tongaporutuan Stage) in age, based on foraminiferal data from the surrounding mudstone, and situated in the axis of a syncline trending and plunging gently east–southeast.

18.2.3.2 Southern (Dannevirke) Sites

Wanstead First described by Lillie (1953), the Wanstead locality is a suite of brecciated limestones comprising several boulders in a field, close to nearby Manley Stream, which affords a variant name sometimes used for the site (Fig. 18.3d). The boulders are early Miocene (New Zealand Waitakian–Otaian Stage) in age and are situated on the west flank of Akitio Syncline, adjacent to the faulted margin of Whangai Range.

Ugly Hill The Ugly Hill locality contains moderately coherent small outcrops and/or boulders on the north and south sides of Ugly Hill Road (and, therefore, sometimes separated into North and South Ugly Hill localities), near to Epae Road. The main outcrop is the northern one, with localized common fossil horizons, occurring about 500 m north of the owner's house, across a small valley from a sheep graveyard, accessible by walking downhill through the owner's garden to the left, past a stable, through two gates, then bearing right over a ridge (Fig. 18.3c). Directly south across Ugly Hill Road from the northern deposits, entering through a roadside gate, involves a different landowner and consists of several isolated, small seep boulders and probably in situ outcrops. They occur within a few 100 m of the road and protrude through some of the knolls in the grassy paddocks; a small disused and overgrown quarry occurs in the limestone over the fence line in a bounding pine plantation. The site is early Miocene (New Zealand Otaian–Altonian, possibly Waitakian Stage) in age, sitting on the west flank of the Akitio Syncline, adjacent to the faulted margin of the Whangai Range.

Haunui Named for nearby Haunui Farm, this is a relatively extensive set of outcrops of fossiliferous limestone, covering a moderately sized, sparsely forested hill (an ancient pā site), approximately 300 m south of the farmhouse at the end of the farm entrance road, north of Mangawhero Stream and northeast of Motuotaraia Stream (Fig. 18.3a). With permission, the hill site is accessible on tracks across the farmland, by foot, or 4-wheel drive vehicle. Outcrops occur at the base, on the sides, and all over the summit, spanning approximately 200 × 100 × 30 m. The summit area is the site of a now disused, shallow quarry. Late early Miocene (New Zealand Altonian–Clifdenian Stage) in age, the site, like Ugly Hill, is situated on the west flank of the Akitio Syncline, adjacent to the faulted margin of the Whangai Range.

Ngawaka This locality comprises several outcrops across four paddocks on the eastern side of Ngawaka Road, yielding its name. To the west of the site are a few probably in situ outcrops in paddocks as well as the largest uninterrupted seep carbonate outcrop in southern Hawke's Bay, some 15 m long by 8 m high, composed of brecciated and veined limestone (Fig. 18.3b). Access is through a roadside gate on the east side of the road near the farm owner's house (on the west side of road) and then walk down the fence line to the main outcrop. Several 100 m southeast of these western deposits, and walkable from it, are float boulders of sparsely fossiliferous limestone ranging from small to large (>5 m) and exposed over a few 100 m of grassy hillside, from about 20 m above the edge of a small lake all the way up to the summit a few 100 m away, with the occasional cabbage tree interspersed between the rocks. Access, if not from the west of the site, is over a roadside fence across a barren strip of muddy ground that may have been a plantation but had no growth at the time of the last visit (July 2007), about a 50 m walk. The rocks are in general strongly veined, often in reticulate fashion and sometimes anastomosing, and a strong hydrocarbon odor is detectable upon striking them. The age of the site is probably early to middle Miocene (New Zealand Waitakian–Clifdenian Stage).

Wilder This site consists of about five separate outcrops found in the middle of a large complex of fields used for grazing sheep, located approximately 2 km down a farm track off Wilder Road (entrance at Gate No. 164), just past the cottage of the farmer who owns the land. This track can be quite treacherous and best navigated in a four-wheel-drive vehicle, then walking back downhill. Go through a significant dip in the track, and about a further 500 m as it trends to the right, and turn left through a gate then follow this straight, even track down a further 300–400 m. There is a large pond which will be unseen at this point out to the right, another 200 or so m into the field, with some nearby trees. No fossil material was observed, and its specific age (other than Miocene) is unknown.

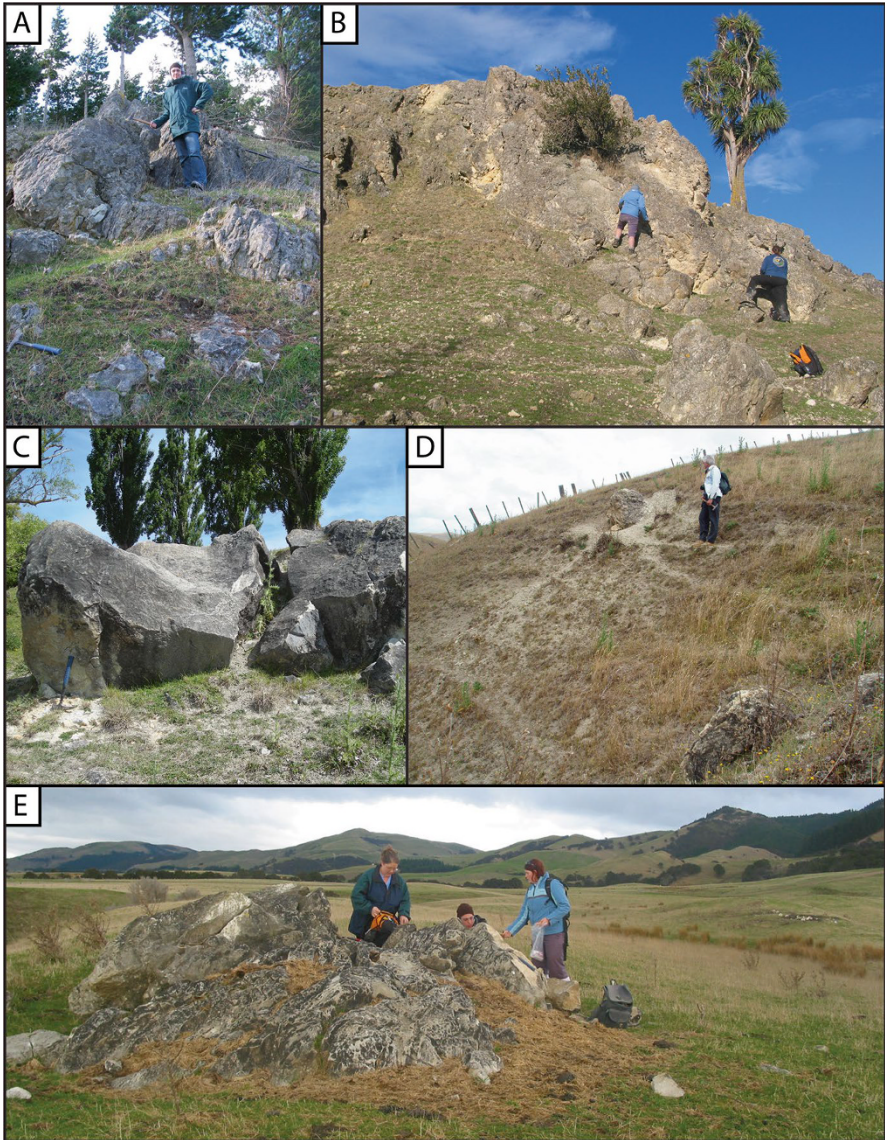


Fig. 18.3 Some of the larger southern (Dannevirke) Miocene sites. (a) Haunui, person for scale; (b) Ngawaka, people for scale; (c) Ugly Hill, geological hammer for scale; (d) Wanstead, person for scale. (All photographs taken on a 2008 field trip with CSN, KPS, Stephanie L. Nyman, Sarah M. Ewen, and Susan Nyman)

18.2.4 Fauna

For his PhD thesis, Saether (2011) identified numerous taxa at northern Miocene New Zealand hydrocarbon seep deposits (Table 18.2) and ranked this fauna among the most diverse known globally compared to other ancient fossil seeps. He observed around 39 taxa in at least 28 families (some of which are identified at suprafamilial levels but cannot be confamilial with any other New Zealand seep taxa), in nine classes, belonging to six phyla, not including ichnotaxa, microtaxa, and identifications of uncertain nature. However, further, more detailed work for formal completion of the taxonomy of these deposits is required, and therefore for the purposes of this chapter only, those reports from primary literature are recorded.

18.3 Cretaceous New Zealand Seep Sites

18.3.1 Distribution

Kiel et al. (2013) separated the Cretaceous (late Albian–middle Cenomanian) seep limestone concretions into three localities, namely the coastal Port Awanui and Waipiro Bay sites situated within the East Coast Allochthon (see Sect. 18.3.2), and a third locality located roughly 20 km inland, in situ and informally named “Owhena Stream” (Fig. 18.4). “Owhena Stream” represents a single deposit apparently devoid of macrofossils but was identified through isotopic and petrographic analyses as of seep origin. Port Awanui is identified as three distinct deposits, each of which is represented by shore-platform boulders almost certainly eroded from a well-exposed, calcareous mudstone unit that forms the onshore platform at this point (Kiel et al. 2013). Two of these boulders can be observed today, and a third was recognized as most likely a similar boulder based on literature study (see McKay 1887; Ongley and Macpherson 1928). The Waipiro Bay locality comprises two deposits which, as at Port Awanui, are represented by boulders found on the beach, and inferred to have been sourced from a mélange that formed in association with emplacement of the East Coast Allochthon (Kiel et al. 2013; Zwicker et al. 2021).

18.3.2 Geotectonic Setting

Adding to the complexity of the geology of the Raukumara Peninsula mentioned earlier (Sect. 18.2.1), there is also a significant Cretaceous–Paleogene allochthon that separates the Miocene strata (and hence, the Miocene seep deposits) into its northern and southern components (Figs. 18.1 and 18.6). This allochthon, called the East Coast Allochthon, is characterized by a succession of thrust sheets and folds and was emplaced in response to the development of the East Coast Basin in the

Table 18.2 Fossil distribution of Miocene New Zealand seep deposits

Taxon	Locality distribution	Reference
Bivalvia		
<i>Bathymodiolus heretaunga</i>	3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 14, 15	Saether et al. (2010b)
<i>Gigantidas coseli</i>	6, 8, 9, 11	Saether et al. (2010b)
<i>Pliocardia</i> sp.	8	Amano et al. (2014)
<i>Notocalyptogenia neozelandica</i>	13	Amano et al. (2014)
<i>Thyasira (Thyasira) beui</i>	4, 8	Amano et al. (2015)
Protobranchia indet.	4	Saether et al. (2016)
Solemyidae indet.	8	Saether et al. (2016)
Cf. <i>Pulvinites</i> sp.	8	Saether et al. (2016)
<i>Acesta</i> cf. <i>saginata</i>	9	Saether et al. (2016)
<i>Parvamussium</i> cf. <i>maorium</i>	8	Saether et al. (2016)
<i>Pratulium quinarium</i>	4, 5, 7, 8	Saether et al. (2016)
<i>Semeloidea</i> (s.l.) <i>bexhavenensis</i>	4, 8	Saether et al. (2016)
<i>Meganodontia haunuiensis</i>	12, 13, 14, 15	Amano et al. (2018)
<i>Elliptiolucina neozelandica</i>	8	Amano et al. (2018)
<i>Lucinoma saetheri</i>	4, 8, 9, 13, 14	Amano et al. (2018)
<i>Lamellinucula</i> sp.	8	Amano et al. (2018)
<i>Nuculana</i> sp.	8	Amano et al. (2018)
<i>Leptomya</i> sp.	14	Amano et al. (2018)
Gastropoda		
Buccinidae indet.	5	Campbell et al. (2008)
<i>Provanna marshalli</i>	6, 9, 13	Saether et al. (2010a)
<i>Bathyacmaea kimberleyae</i>	6, 7, 9	Saether et al. (2012) (as <i>Serradonta</i>)
<i>Homalopoma</i>	8	Amano et al. (2018)
Naticidae indet.	8	Amano et al. (2018)
<i>Mitrella</i> sp.	8, 9	Amano et al. (2018)
Other body fossils		
Vestimentiferan worm tubes	3, 4, 5, 7, 8, 9, 13	Campbell et al. (2008)
Decapod fragments	4, 9	Campbell et al. (2008)
Terebratulidae indet. (×3, including <i>Liothyrella</i>)	4, 8, 9	Campbell et al. (2008)
Cf. <i>Goniocorella</i> sp.	5, 8, 9, 12, 13, 15	Campbell et al. (2008)
Trace fossils		
<i>Thalassinoides</i>	4, 5, 9	Campbell et al. (2008)
<i>Gastrochaenolites</i>	15	Campbell et al. (2008)
Small circular borings	9	Campbell et al. (2008)

See Fig. 18.1 for locality key, and Figs. 18.4 and 18.5 for image of representative taxa

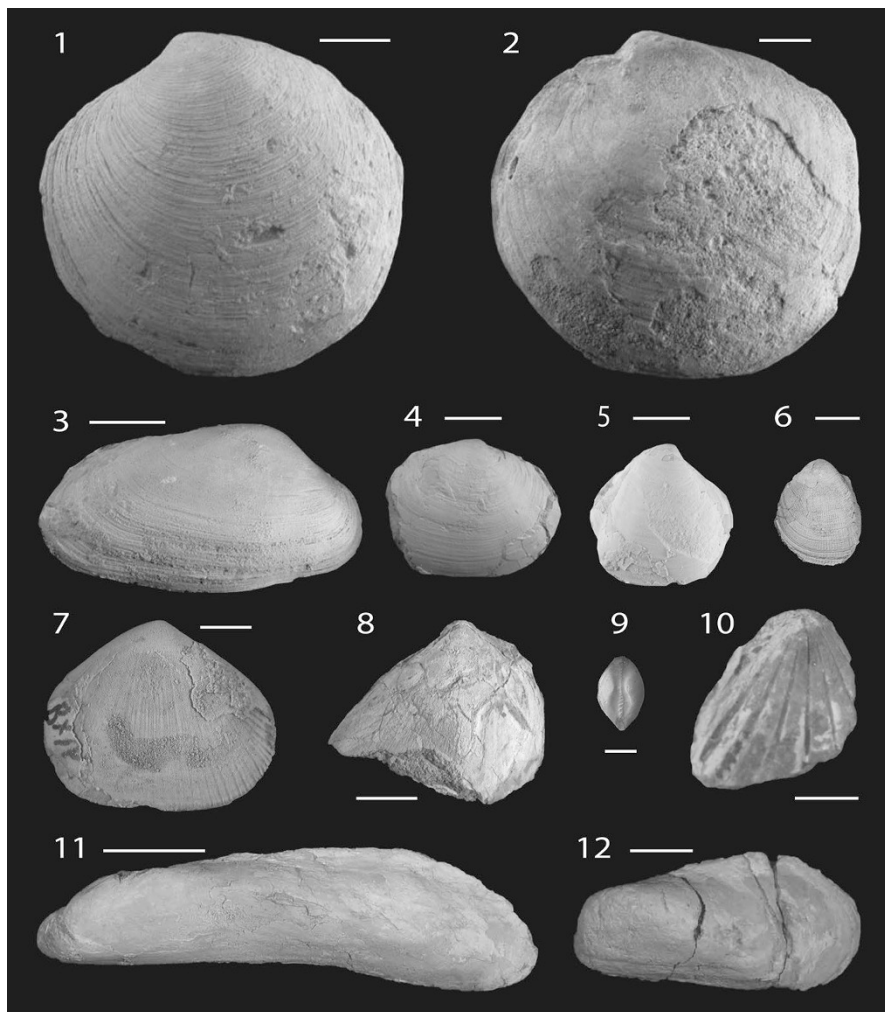


Fig. 18.4 Miocene bivalves from New Zealand ancient seep sites. 1. *Lucinoma saetheri* Amano et al., 2018, 2. *Meganodontia haunuiensis* Amano et al., 2018, 3. *Notocalyptogena neozelandica* Amano et al., 2014, 4. *Elliptiolucina neozelandica* Amano et al., 2018; 5. *Thyasira beui* Amano et al. 2015; 6. *Pratulium quinarium* (Marwick, 1944), 7. *Semeloidea bexhavenensis* Saether et al., 2016, 8. *Acesta* cf. *saginata* Marshall, 2001, 9. protobranch bivalve indet., 10. *Parvamussium* cf. *maorium* Dell, 1956, 11. *Gigantidas coseli* Saether et al., 2010, 12. *Bathymodiolus heretaunga* Saether et al., 2010. For 6–10, see Saether et al. 2016; for 11–12, see Saether et al. 2010b. Scale bars: 1, 2, 8, 11, 12 are 10 mm; 3 and 4 are 5 mm; 5 and 7 are 3 mm; 6 and 10 are 2 mm; 9 is 0.5 mm

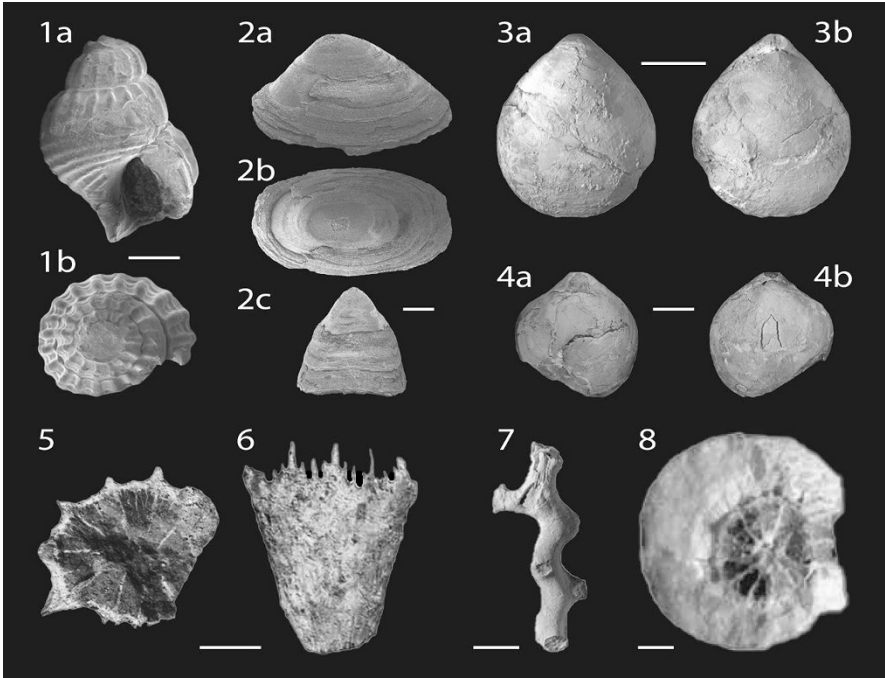


Fig. 18.5 Miocene fossils from New Zealand ancient seep sites. 1. *Provanna marshalli* Saether et al., 2010a, 2. *Bathyacmaea kimberleyae* (Saether et al., 2012), 3. *Liothyrella* sp. A, 4. *Liothyrella* sp. B, 5–6. *Caryophyllia clavus* Scacchi, 1835, 7–8. *Madrepora oculata* Linnaeus, 1758. All corals are from Moonlight North. *Liothyrella* sp. A is from Rocky Knob and *Liothyrella* sp. B is from Tauwhareparae. Scale bars: 1 is 2 mm; 2 is 1 mm; 3 is 20 mm; 4 is 10 mm; 5, 6 are 5 mm; 7 is 4 mm; 8 is 0.5 mm

early Miocene (Kiel et al. 2013). The allochthon strata are similar to the Miocene deposits (Sect. 18.2) in that thinly interbedded mudstones and sandstones can be found within vast successions of bathyal mudstone (Field et al. 1997), and are likely displaced by at least a few 10s of kilometers from their original position (Mazengarb and Speden 2000; Kiel et al. 2013). To the south and west of the East Coast Allochthon lie autochthonous Cretaceous strata that were deposited on the passive paleo-Pacific margin of New Zealand during early thermal subsidence following the separation of the New Zealand crustal block from Gondwanaland (Crampton et al. 2006; Kiel et al. 2013).

18.3.3 Localities

Owhena Stream Kiel et al. (2013) described a conspicuous concretionary mudstone exposed within the river bed at the mouth of Owhena Stream. Because of the nature of its occurrence, it is periodically covered by riverine gravelly deposits, but

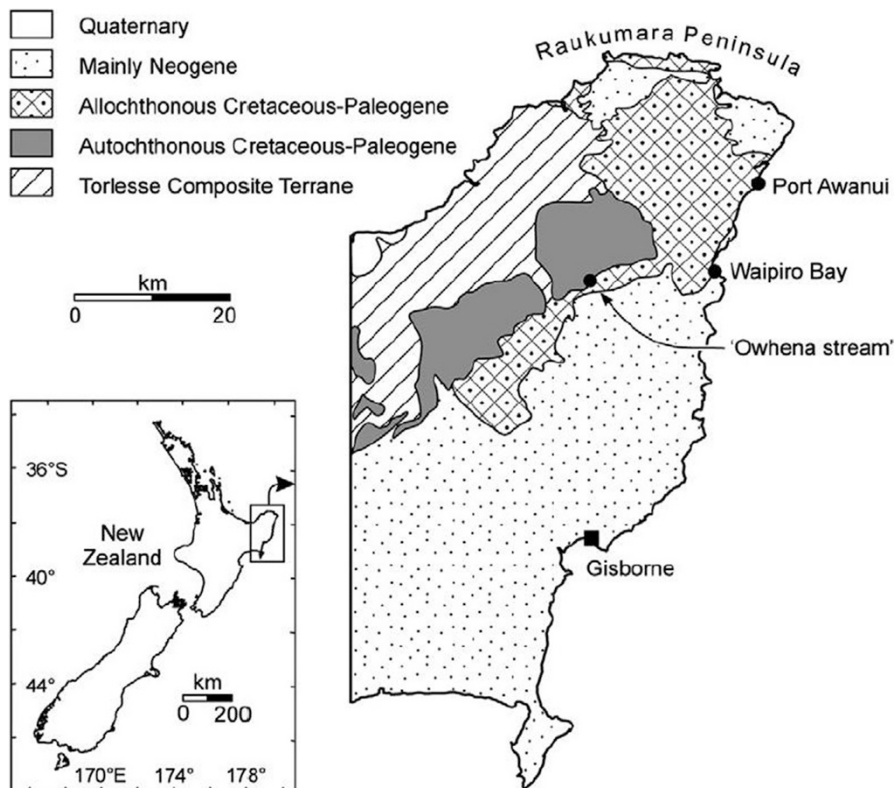


Fig. 18.6 Map of the Raukumara Peninsula (East Coast Basin) showing the locations of the three Cretaceous New Zealand seep localities. (Image modified from Kiel et al. 2013)

up to 2 m of laminated, concretionary sandy mudstone can occasionally be exposed. Distinctive pipe-like concretions extend at least 15 m up into the base of the overlying Whangai Formation. Owhena Stream remains the only known in situ Cretaceous seep locality in New Zealand, and Schiøler et al. (2000) established a middle Campanian (New Zealand early Haumurian) age for the site. Moore et al. (1988) placed a gradational contact between the Owhena and overlying Whangai formations at the level of the concretionary mudstone.

Port Awanui McKay (1877) first described this coastal locality, at the mouth of Waiotautu Stream, East Cape, as concretionary black shales with some Cretaceous fossils. Crampton (1998) noted that the geology to the south is entirely of Eocene age and shows a common trend of northward younging, but that the area is characterized by intensive faulting which may have juxtaposed the strata and locally reversed this trend, or else this could be an olisthostrome deposit. Kiel et al. (2013) identified three separate sites that they named Awanui I, Awanui II, and GS 688, all

Table 18.3 Locality and age information for the main onshore Cretaceous seep limestone occurrences in East Coast Basin, North Island, New Zealand, arranged in roughly north to south order (see Fig. 18.6)

No.	Name	Approx. NZ Map Grid (NZMG) reference ^a	NZ stage	International epoch
1	Port Awanui	Z15/f82–63, 7485	Motuan–Ngaterian	Late Albian–middle Cenomanian
2	Waipiro Bay	Z16/f83–84	Haumurian	Middle Campanian
3	Owhena Stream	Y16/f945	Early Haumurian	Middle Campanian

^aBased on existing series of NZMS260 1:50,000 topographic map sheets

hard, medium gray, calcareous mudstone eroded from a well-exposed shore platform unit close to the headland of Whakariki Point and of late Albian–middle Cenomanian (New Zealand Motuan–Ngaterian) age.

Waipiro Bay Not to be confused with the Miocene Waipiro locality described earlier, which lies inland, Kiel et al. (2013) identified two loose boulders, designated Waipiro I and Waipiro III, on the beach at Pokurakura Point, immediately south of Waikawa Stream. The boulders comprise hard, medium gray, calcareous mudstone sourced from adjacent outcrops of undifferentiated *mélange* mentioned above in Sect. 18.3.1. They aged the boulders to the middle Campanian (New Zealand Haumurian Stage) (Table 18.3).

18.3.4 Fauna

The fauna of the Cretaceous New Zealand seep sites (Fig. 18.7 and Table 18.4) is similar to that of the Miocene sites in terms of being dominated by bivalves and gastropods. It is slightly less diverse among its bivalve content but perhaps more diverse among the gastropods, although many of the taxa are still in open nomenclature and require further study. This is particularly true of the gastropods many of which are still left in open nomenclature (e.g., Campbell et al. 2008; Kiel et al. 2013) with only two formally described species from the Miocene seep deposits and one from the Cretaceous sites (Saether et al. 2010b; Saether et al. 2012; Kaim et al. 2014). Coral and decapod fragments are present from both Miocene and Cretaceous deposits, and the Miocene deposits also contain at least two brachiopod species, and worm tubes that are well represented in number but also require further future work.

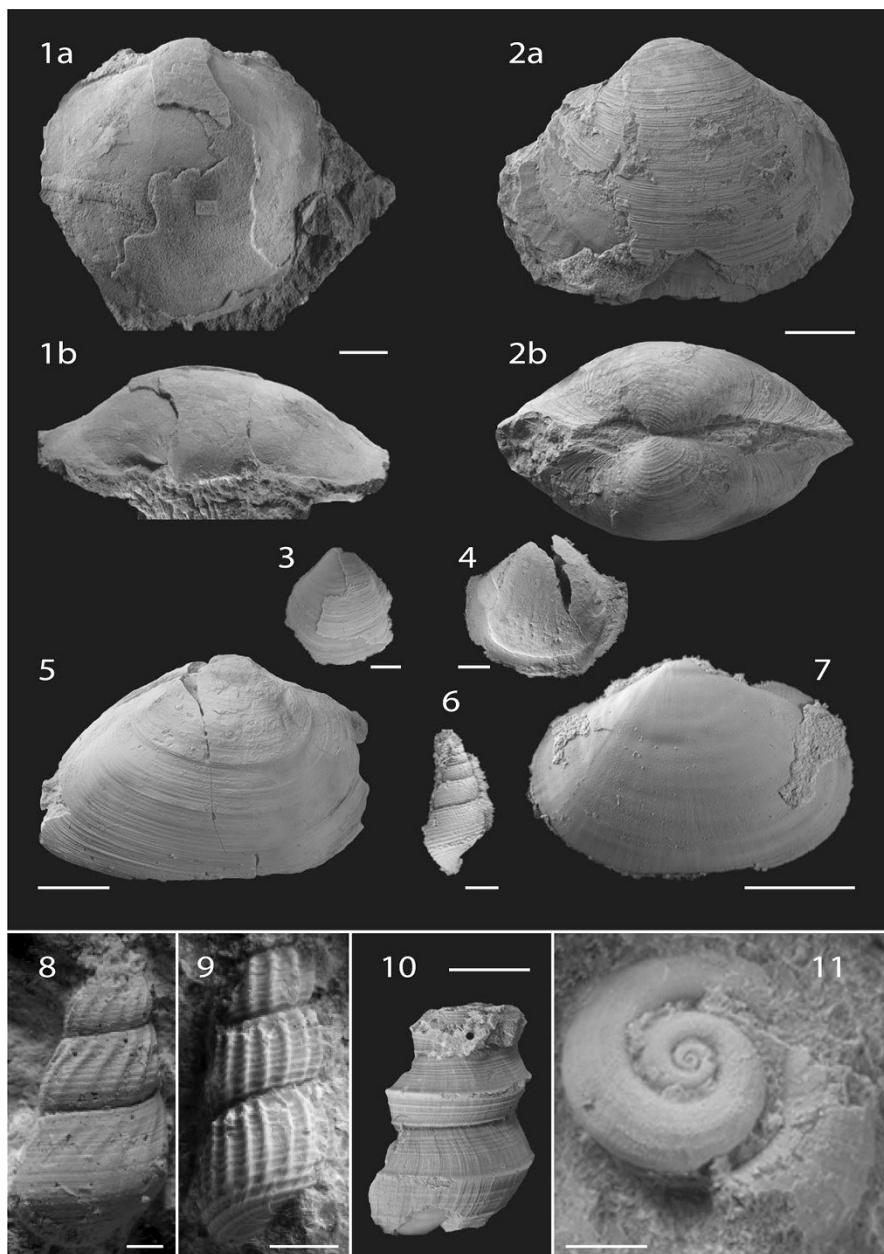


Fig. 18.7 Selected molluscs from the Cretaceous deposits. 1, *Amanocina raukumara* Kiel, 2013, from Port Awanui: 1a: Lateral view of right valve. 1b: Dorsal view. Scale bar is 10 mm. 2, *Ezolucina* sp. "Awanui": 2a: Lateral view of left valve. 2b: Dorsal view. Scale bar is 10 mm. 3, *Thyasirid* from Awanui II, lateral view of left valve. Scale bar is 2 mm. 4, *Ezolucina* "tall" from Awanui I, lateral view of right valve. Scale bar is 5 mm. 5, *Ezolucina* sp. "Waipiro" from Waipiro I, lateral view of right valve. Scale bar is 5 mm. 6, *Ezolucina* sp. "Waipiro" from Waipiro I, dorsal view of right valve. Scale bar is 5 mm. 7, *Ezolucina* sp. "Waipiro" from Waipiro I, lateral view of left valve. Scale bar is 5 mm. 8, *Thyasirid* from Awanui II, lateral view of left valve. Scale bar is 2 mm. 9, *Thyasirid* from Awanui II, lateral view of right valve. Scale bar is 2 mm. 10, *Thyasirid* from Awanui II, lateral view of left valve. Scale bar is 2 mm. 11, *Thyasirid* from Awanui II, dorsal view. Scale bar is 2 mm.

(continued)

right valve. Scale bar is 25 mm. 6. Fusiform gastropod from Awanui I, abapertural view. Scale bar is 1 mm. 7. Heterodont bivalve from Awanui I, lateral view of left valve. Scale bar is 5 mm. 8. *Abyssomelania cramptoni* Kaim et al., 2014, from Waipiro III, apertural view. Scale bar is 5 mm. 9. *Hokkaidoconcha* sp. 1 from Awanui GS 688, apertural view. Scale bar is 2 mm. 10. Aporrhaid gastropod from Awanui GS 688, lateral (abapertural) view. Scale bar is 3 mm. 11. *Aucellina* aff. *euglypha* Woods, 1917 from Awanui GS 688, lateral view of right valve. Scale bar is 5 mm. All specimens are illustrated by Kiel (2013), Kiel et al. (2013) and Kaim et al. (2014). Photographs courtesy of Steffen Kiel (Stockholm, Sweden). All specimens housed at GNS Sciences, Lower Hutt, New Zealand

Table 18.4 Fossil distribution of Cretaceous New Zealand seep deposits

Taxon	Locality distribution	Reference
Bivalvia		
Solemyidae indet.	AWII, WPIII	Kiel et al. (2013)
<i>Nucinella</i> sp.	AWI, AWII	Kiel et al. (2013)
Nuculanidae indet.	AWI, AWII, WPIII	Kiel et al. (2013)
Thyasiridae indet.	AWII, GS 688, WPIII	Kiel et al. (2013)
Inoceramidae indet.	AWI, AWII, GS 688	Kiel et al. (2013)
<i>Aucellina</i> aff. <i>euglypha</i>	GS 688	Kiel et al. (2013)
Carditiidae indet.	AWI	Kiel et al. (2013)
<i>Caspiconcha</i> sp.	AWII, GS 688	Kiel et al. (2013)
Veneridae indet.	AWI	Kiel et al. (2013)
<i>Cubatea awanuiensis</i>	AWII, GS 688	Kiel (2013)
<i>Ezolucina</i> sp. “ridge”	GS 688	Kiel et al. (2013)
<i>Ezolucina</i> sp. “Waipiro”	WPI	Kiel et al. (2013)
<i>Ezolucina</i> sp. “tall”	AWI	Kiel et al. (2013)
<i>Amanocina raukumara</i>	GS 688	Kiel (2013)
Gastropoda		
<i>Bathyacmaea</i> sp.	WPIII	Kiel et al. (2013) (as <i>Serradonta</i>)
<i>Retiskenea</i> sp.	GS 688	Kiel et al. (2013)
<i>Hokkaidoconcha</i> sp. 1	AWII	Kiel et al. (2013)
<i>Hokkaidoconcha</i> sp. 2	GS 688, WPIII	Kiel et al. (2013)
Fusiform gastropod	AWI	Kiel et al. (2013)
Low spired gastropod	AWII	Kiel et al. (2013)
Small globular gastropod	AWII	Kiel et al. (2013)
Aporrhaidae indet.	GS 688	Kiel et al. (2013)
Naticidae indet.	WPIII	Kiel et al. (2013)
<i>Abyssomelania cramptoni</i>	WPIII	Kaim et al. (2014)
Other		
<i>Callianassa</i> spp.	AWII, WPIII	Kiel et al. (2013)
Solitary coral	GS 688	Kiel et al. (2013)
Fish scales	AWI	Kiel et al. (2013)
Argentinid otolith	AWII	Kiel et al. (2013)

Localities are after Kiel et al. (2013). None are reported from “Owhena Stream,” which is devoid of macrofossils

Awanui localities: AWI = Awanui I; AWII = Awanui II; GS 688. Waipiro Bay localities: WPI = Waipiro I; WPIII = Waipiro III

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References

- Adams JH (1910) The geology of the Whatatutu Subdivision, Raukumara Division, Poverty Bay. New Zealand Geological Survey Bulletin, no. 9. MacKay, Wellington
- Amano K, Saether KP, Little CTS et al (2014) Fossil vesicomyid bivalves from Miocene hydrocarbon seep sites, North Island, New Zealand. *Acta Palaeontol Pol* 59(2):421–428
- Amano K, Little CTS, Campbell KA et al (2015) Paleocene and Miocene *Thyasira* sensu stricto (Bivalvia: Thyasiridae) from chemosynthetic communities from Japan and New Zealand. *Nautilus* 129(2):43–53
- Amano A, Little CTS, Campbell KA (2018) Lucinid bivalves from Miocene hydrocarbon seep sites of eastern North Island, New Zealand, with comments on Miocene New Zealand seep faunas. *Acta Palaeontol Pol* 63(2):371–382
- Ansell JH, Bannister SC (1996) Shallow morphology of the subducted Pacific plate along the Hikurangi margin, New Zealand. *Phys Earth Planet Inter* 93:3–20
- Asami S, Kanie Y, Takei H (1995) Chemosynthetic fossil communities discovered from fractured stones of the Miocene Hayama Group in the Miura Peninsula. *Rep Cult Nat Treas Yokosuka City* 29:19–22. (in Japanese)
- Ballance PF (1976) Evolution of the Upper Cenozoic magmatic arc and plate boundary in northern New Zealand. *Earth Planet Sci Lett* 28:356–370
- Barnes PM, Nicol A, Harrison T (2002) Late Cenozoic evolution and earthquake potential of an active listric thrust complex above the Hikurangi subduction zone, New Zealand. *Geol Soc Am Bull* 114:1379–1405
- Barnes PM, Lamarche G, Bialas J et al (2010) Tectonic and geological framework for gas hydrates and cold seeps on the Hikurangi subduction margin, New Zealand. *Mar Geol Spec Issue* 272:26–48
- Beanland S, Melhuish A, Nicol A et al (1998) Structure and deformational history of the inner forearc region, Hikurangi subduction margin, New Zealand. *N Z J Geol Geophys* 41:325–342
- Campbell KA (2006) Hydrocarbon seep and hydrothermal vent palaeoenvironments: past developments and future research directions. *Palaeogeog Palaeoclimat Palaeoecol* 232:362–407
- Campbell KA, Francis DA, Collins M et al (2008) Hydrocarbon seep-carbonates of a Miocene forearc (East Coast Basin), North Island, New Zealand. *Sediment Geol* 204:83–105
- Crampton JS, Schiøler P, Roncaglia L (2006) Detection of Late Cretaceous eustatic signatures using quantitative biostratigraphy. *Geol Soc Am Bull* 118:975–990
- Cuvier G (1797–1798) *Tableau élémentaire de l’histoire naturelle des animaux*. Baudouin, Paris
- Dell RK (1956) The archibenthal Mollusca of New Zealand. *Bull Dominion Mus Wellington* 18:1–235

- Field BD, Uruski CI, Beu AG et al (1997) Cretaceous–Cenozoic geology and petroleum systems of the East Coast region, New Zealand. *Inst Geol Nucl Sci Monogr* 19:1–301
- Georgieva MN, Paull CK, Little CTS et al (2019) Discovery of an extensive deep-sea fossil serpulid reef associated with a cold seep, Santa Monica Basin, California. *Front Mar Sci* 6:115. <https://doi.org/10.3389/fmars.2019.00115>
- Goedert JL, Campbell KA (1995) An Early Oligocene chemosynthetic community from the Makah Formation, northwestern Olympic Peninsula, Washington. *Veliger* 38:22–29
- Goedert, JL, Squires, RL (1990) Eocene deep-sea communities in localized limestones formed by subduction-related methane seeps, southwestern Washington. *Geology (Boulder)*, 18:1182–1186
- Goedert JL, Kaler KL (1996) A new species of *Abyssochrysos* (Gastropoda: Loxonematoidea) from a middle Eocene cold-seep carbonate in the Humptulips Formation, western Washington. *Veliger* 39:65–70
- Goedert JL, Thiel V, Schmale O et al (2003) The late Eocene ‘Whiskey Creek’ methane-seep deposit (western Washington State) Part I: Geology, palaeontology, and molecular geobiology. *Facies* 48:223–240
- Hattori M, Kanie Y, Oba T (1995) Carbonates and chemosynthetic fossil community from the Miocene Hayama Group, central Miura Peninsula. *Rep Cult Nat Treas Yokosuka City* 29:89–96. (in Japanese)
- Henrys S, Reyners M, Pecher I et al (2006) Kinking of the subducting slab by escaloator normal faulting beneath the North Island of New Zealand. *Geology* 34:777–780
- Kaim A, Jenkins RG, Tanabe K et al (2014) Mollusks from late Mesozoic seep deposits, chiefly in California. *Zootaxa* 3861:401–440
- Kamp PJJ, Nelson CS (1988) Nature and occurrence of modern and Neogene active margin limestones in New Zealand. *N Z J Geol Geophys* 31:1–20
- Kanie Y, Sakai T (1997) Chemosynthetic thraacid bivalve *Nipponothracia*, gen. nov. from the Lower Cretaceous and middle Miocene mudstones in Japan. *Venus* 56:205–220
- Kanie Y, Asami S, Okada H et al (1992a) White clam community discovered from fractured claystone of the Miocene Hayama Group, Miura Peninsula, south-central Japan. *Sci Rep Yokosuka City Mus* 40:31–35. (in Japanese)
- Kanie Y, Hattori M, Sasahara Y (1992b) Two types of white clam communities in Sagami Bay, central Japan: geologic settings and the Tertiary records in the Miura and Boso peninsulas. *Sci Rep Yokosuka City Mus* 40:37–43
- Kiel S (2013) Lucinid bivalves from ancient methane seeps. *J Molluscan Stud* 79:346–363
- Kiel S, Peckmann J (2007) Chemosymbiotic bivalves and stable carbon isotopes indicate hydrocarbon seepage at four unusual Cenozoic fossil localities. *Lethaia* 40:345–357
- Kiel S, Birgel D, Campbell KA et al (2013) Cretaceous methane seep deposits from New Zealand and their fauna. *Palaeogeog Palaeoclimat Palaeoecol* 390:17–34
- Lewis KB, Pettinga JR (1993) The emerging, imbricate frontal wedge of the Hikurangi margin. In: Ballance PF (ed) *Sedimentary basins of the world 3: basins of the South West Pacific*. Elsevier Science, Amsterdam, pp 225–250
- Lillie AR (1953) The geology of the Dannevirke subdivision. *N Z Geol Surv Bull* 46:1–156
- Linnaeus C (1758) *Systema naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis*, 10th edn. Salvius, Stockholm
- Majima R, Nobuhara T, Kitazaki T (2005) Review of fossil chemosynthetic assemblages in Japan. *Palaeogeog Palaeoclimat Palaeoecol* 227:86–123
- Marshall BA (2001) The genus *Acesta* H. and A. Adams, 1858 in the south-west Pacific (Bivalvia: Limidae). In: Bouchet P, Marshall BA (eds) *Tropical deep-sea benthos*, vol 22. *Mém Mus Natl Hist Nat* 185, pp 97–109
- Marwick J (1944) New Zealand fossil and Recent Cardiidae (Mollusca). *Trans R Soc N Z* 74:255–272

- Mazengarb C, Speden IG (2000) Geology of the Raukumara area. Institute of Geological and Nuclear Sciences 1:250 000. Geological Map 6
- Mazengarb C, Francis DA, Moore PR (1991) Sheet Y16 Tauwhareparae. Geological Map of New Zealand 1:50 000. DSIR, Wellington
- McKay A (1887) On the geology of East Auckland and the northern district of Hawke's Bay. *N Z Geol Surv Rep Geol Explor* 18:182–219
- Moore PR (1988) Stratigraphy, composition and environment of deposition of the Whangai Formation and associated Late Cretaceous–Paleocene rocks, eastern North Island, New Zealand. *N Z Geol Surv Bull* 100:1–82
- Naganuma T, Hattori M, Kanie Y (1995a) Worm tubes from the Miocene Hayama Group, central Miura Peninsula. *Rep Cult Nat Treas Yokosuka City* 29:77–87. (in Japanese)
- Naganuma T, Okayama Y, Hattori M et al (1995b) Fossil worm tubes from the presumed cold-seep carbonates of the Miocene Hayama Group, central Miura Peninsula, Japan. *Island Arc* 4:199–208
- Nelson CS, Nyman SL, Campbell KA et al (2017) Influence of faulting on the distribution and development of cold seep-related dolomitic conduit concretions at East Cape, New Zealand. *N Z J Geol Geophys* 60:478–496. <https://doi.org/10.1080/00288306.2017.1372489>
- Nelson CS, Campbell KA, Nyman SL et al (2019) Genetic link between Miocene seafloor methane seep limestones and underlying carbonate conduit concretions at Rocky Knob, Gisborne, New Zealand. *N Z J Geol Geophys* 62(3):318–340. <https://doi.org/10.1080/00288306.2018.1561474>
- Nyman SL, Nelson CS (2011) The place of tubular concretions in hydrocarbon cold seep systems: late Miocene Urenui Formation, Taranaki Basin, New Zealand. *Am Assoc Pet Geol Bull* 95:1495–1524
- Nyman SL, Nelson CS, Campbell KA (2010) Miocene tubular concretions in East Coast Basin, New Zealand: analogue for the subsurface plumbing of cold seeps. *Mar Geol* 272:319–336. <https://doi.org/10.1016/j.margeo.2009.03.021>
- Olsson AA (1931) Contributions to the Tertiary paleontology of northern Peru: part 4, the Peruvian Oligocene. *Bull Am Paleontol* 17:97–264
- Ongley M, Macpherson EO (1928) The geology of the Waiapu Subdivision, Raukumara Division. *N Z Geol Surv Bull* 30:1–79
- Peckmann J, Goedert JL, Thiel V et al (2002) A comprehensive approach to the study of methane-seep deposits from the Lincoln Creek Formation, western Washington State, USA. *Sedimentology* 49:855–873
- Rait G, Chanier F, Waters DW (1991) Landward and seaward-directed thrusting accompanying the onset of subduction beneath New Zealand. *Geology* 19:230–233
- Saether KP (2011) A taxonomic and palaeobiogeographic study of the fossil fauna of Miocene hydrocarbon seep deposits, North Island, New Zealand. Dissertation, University of Auckland
- Saether KP, Little CTS, Campbell KA (2010a) A new fossil provannid gastropod from Miocene hydrocarbon seep deposits, East Coast Basin, North Island, New Zealand. *Acta Palaeontol Pol* 55:507–517
- Saether KP, Little CTS, Campbell KA et al (2010b) New fossil mussels (Bivalvia: Mytilidae) from Miocene hydrocarbon seep deposits, North Island, New Zealand, with general remarks on vent and seep mussels. *Zootaxa* 2577:1–45
- Saether KP, Little CTS, Marshall BA et al (2012) Systematics and palaeoecology of a new fossil limpet (Patellogastropoda: Pectinodontidae) from Miocene hydrocarbon seeps deposits, East Coast Basin, North Island, New Zealand with an overview of known fossil seep pectinodontids. *Molluscan Res* 32:1–15
- Saether KP, Sha J, Little CTS et al (2016) New records and a new species of bivalve (Mollusca: Bivalvia) from Miocene hydrocarbon seep deposits, North Island, New Zealand. *Zootaxa* 4154:1–26

- Schiøler P, Crampton JS, King P (2000) Palynostratigraphic analysis of a measured section through the Karekare, Owheana and Whangai formations (Upper Cretaceous) at Waitahaia River-‘Owheana Stream’ (Raukumara Peninsula). *Inst Geol Nucl Sci Rep* 31:1–24
- Squires RL, Goedert JL (1995) An extant species of *Leptochiton* (Mollusca: Polyplacophora) in Eocene and Oligocene cold-seep limestones, Olympic Peninsula, Washington. *Veliger* 38:47–53
- Woods H (1917) The Cretaceous faunas of the north-eastern part of the South Island of New Zealand. *N Z Geol Surv Paleontol Bull* 4:1–41
- Zwicker J, Smrzka D, Steindl F et al (2021) Mineral authigenesis within chemosynthetic microbial mats: coated grain formation and phosphogenesis at a Cretaceous hydrocarbon seep, New Zealand. *Depos Rec* 7:294–310