

Hydrocarbon seep-carbonates of a Miocene forearc (East Coast Basin), North Island, New Zealand

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Abstract

An ancient hydrocarbon seep province of 14 isolated, authigenic carbonate deposits has been identified in fine-grained, deep-marine siliciclastic strata of the Miocene East Coast Basin, North Island, New Zealand. These forearc sediments have been uplifted and complexly deformed into accretionary ridges, adjacent to the still-active Hikurangi convergent margin. Older active and passive margin strata (mid-Cretaceous to Oligocene in age) underlie the Neogene sequence, and contain oil- and gas-prone source rocks. Older Mesozoic meta-sedimentary rocks constitute the backstop against which the current phase of subduction-related sedimentation has accumulated (~24 Ma–present). The seep-carbonates (up to 10 m thick, 200 m across) archive methane signatures in their depleted carbon isotopes (to $\delta^{13}\text{C} -51.7\text{‰}$ PDB), and contain chemosynthesis-based paleocommunities (e.g. worm tubes, bathymodioline mussels, and vesicomylid, lucinid and thyasirid bivalves) typical of other Cenozoic and modern seeps. Northern and southern sites are geographically separated, and exhibit distinct lithological and faunal differences. Structural settings are variable. Seep-associated lithologies also are varied, and suggest carbonate development in sub-seafloor, seafloor and physically reworked (diapiric expansion, gas explosion, gravity slide or debris flow) settings, similar to Italian Apennine seep deposits of overlapping ages.

Peculiar attributes of the New Zealand Miocene seep deposits are several, including digitate thrombolites of clotted microbial micrite encased in thick, isopachous horizons and botryoids of aragonite. Seep plumbing features are also well-exposed at some sites, displaying probable gas-explosion breccias filled with aragonite, tubular concretions (fluid conduits), and carbonate-cemented, thin sandstone beds and burrows within otherwise impermeable mudstones. A few seeps were large enough to develop talus-debris piles on their flanks, which were populated by lucinid bivalves and terebratulid brachiopods. Firmgrounds and hardgrounds were common, as evidenced by trace fossil associations or caryophyllid coral thickets atop some seep-carbonate deposits. Thus, the New Zealand examples show strong evidence of formation in sediments at or just beneath the seafloor, but some were clearly exhumed by erosion to sustain later non-seep, epifaunal and boring paleocommunities.

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1. Introduction

Modern and ancient convergent margins of temperate regions are typified by voluminous terrigenous sedimentation, which generally limits limestone deposition to geographically restricted occurrences atop isolated banks, seamounts and structural highs (e.g. Dickinson and Seely, 1979; Sliter, 1984;

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Kamp and Nelson, 1988; Whidden, 1994). Fine-grained carbonate concretions are common in these settings, formed during shallow burial and early diagenesis of organic matter *via* microbial processes (cf. Irwin et al., 1977; Nelson and Smith,

1996; Cope and Curtis, 2000). Another type of authigenic carbonate deposit related to hydrocarbon seepage is now known to be quite common in fluid over-pressured, marine sedimentary basins worldwide, especially in compressive tectonic regimes

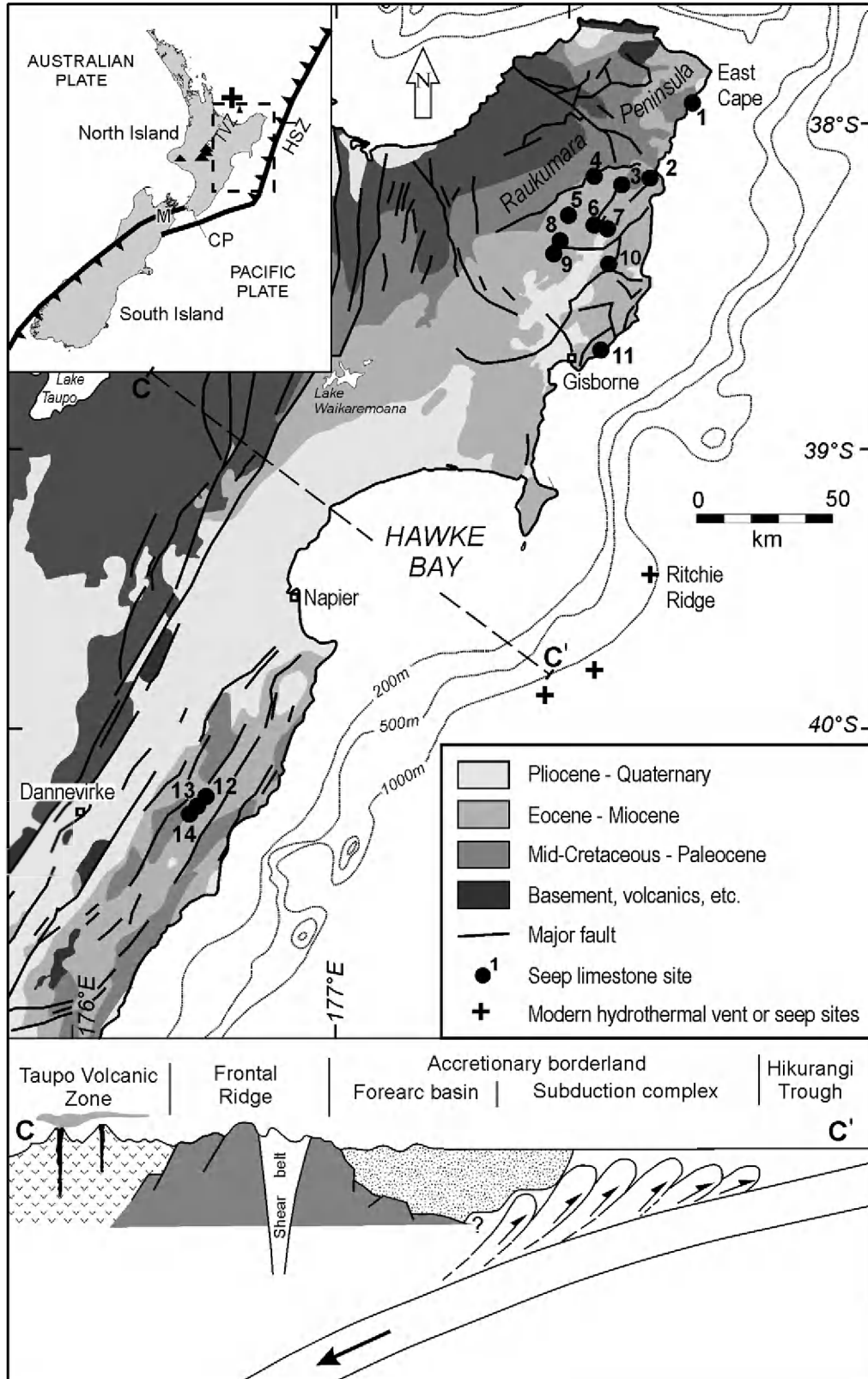




Fig. 2. Field views of stratigraphically isolated, deep-water, seep-carbonate deposits, Miocene East Coast Basin. (A) Rocky Knob (site 9 of Fig. 1; circled person for scale), (B) Karikarihuata Stream (site 3 of Fig. 1), and (C) Tauwharepare (site 5 of Fig. 1). Star in (C) indicates paleotopographic upper surface of the seep deposit, where caryophyllid coral “thickets” occur (cf. Fig. 7F).

(Moore and Vrolijk, 1992; Conti and Fontana, 1999; Campbell, 2006 and references therein). These seep-carbonates often are isotopically depleted in carbonate-carbon, and form as a product of sulfate-dependent, archaeal, anaerobic oxidation of methane

(AOM) (e.g. Ritger et al., 1987; Aharon, 2000; Han et al., 2004 and references therein). In these settings, associated chemosynthesis-based communities oxidize dissolved H_2S and CH_4 to provide energy for a food web flourishing in harsh physico-chemical conditions, similar to the biota of submarine hydrothermal vents and whale/wood-falls worldwide (Van Dover, 2000; Distel et al., 2002; Baco and Smith, 2003). Thus, seep-carbonates demarcate the transient passage of hydrocarbon-charged fluids through continental margin sediments and, in passing, can leave an archive of their effects on the biota and seafloor environments.

Only along a few marine continental margins worldwide do opportunities exist to reconstruct the four-dimensional (spatio-temporal) record of long-lived hydrocarbon seepage for both onshore, exhumed accretionary prism and forearc rocks and their adjacent, offshore, modern convergent tectonic settings. These regions include Japan, the Pacific Northwest of the U.S.A., western South America, and New Zealand (cf. Majima et al., 2005; Campbell, 2006 and references therein). Based on reconnaissance investigations to date, this paper gives a first account of more than a dozen Miocene seep-carbonate sites in the uplifted East Coast forearc of New Zealand’s eastern North Island (Fig. 1). The East Coast Basin lies onshore and westward of its modern analog, the presently active Hikurangi convergent margin, where the Pacific Plate subducts beneath the Indo-Australian Plate (Fig. 1; Cole and Lewis, 1981; Davey et al., 1986). Currently, the margin hosts numerous onshore oil and gas seeps, and offshore seismic surveys and sampling have revealed submarine seeps, mud diapirs and gas hydrates (Ridd, 1970; Katz, 1982; Kvenvolden and Pettinga, 1989; Giggenbach et al., 1993; Lewis and Marshall, 1996; Francis and Murray, 1997; Henrys et al., 2003, in press; Pecher et al., 2004, 2005).

In thick bathyal mudstones of the Miocene East Coast forearc, minor but extensive isolated pods and lenses of carbonate (Figs. 1 and 2) have been known since the earliest days of geological exploration of the region (McKay, 1877a,b). However, their origin remained obscured for more than a century (Campbell and Francis, 1998; Campbell et al., 1999). This study is the first to analyze the stratigraphic, structural, lithologic, stable isotopic and paleoecologic character of the deposits. The data show that these distinctive carbonates formed *via* AOM at seafloor seeps during the Early to Late Miocene (22–6 Ma, Otaian to Tongaporutuan New Zealand Stages). Regional differences in northern and southern localities are evident. These New Zealand carbonates share many similarities with other modern and ancient seep-carbonates worldwide. They also display several unusual attributes compared to other such deposits, including well-exposed fluid-plumbing features, distinctive flank facies in larger deposits, an associated whale

Fig. 1. Locality map of Miocene seep-carbonates (black circles) in East Coast Basin forearc mudstones of North Island, New Zealand. Circles and numbers indicate field localities, as follows: northern sites — 1) Waiapu, 2) Waipiro Stream, 3) Karikarihuata Stream, 4) Bexhaven, 5) Tauwharepare, 6) Upper Waiau River at Puketawa, 7) Upper Waiau River at Totaranui, 8) Moonlight North, 9) Rocky Knob (Moonlight South), 10) Waikairo Stream, 11) Turihaua; southern sites — 12) Wanstead, 13) Ugly Hill, 14) Haunui. Map also shows simplified geology of Cretaceous through Neogene rocks across eastern North Island, a simplified cross-section of the margin from offshore Hawke Bay to Taupo (modified from Cole and Lewis, 1981), and locations of some modern offshore hydrothermal vent or seep sites (plusses) of the northern and eastern North Island (cf. Lewis and Marshall, 1996). Inset shows the complex transpressive boundary between the Australian and Pacific Plates, position of the Hikurangi subduction zone (HSZ) and arc volcanoes (black triangles) of the Taupo Volcanic Zone (TVZ). CP, Cape Palliser; M, Marlborough.

fall, microbial structures encased in fibrous aragonite, and well-developed seafloor firmgrounds and hardgrounds.

2. Geological and historical setting

2.1. Modern and Neogene convergent margin, eastern North Island

The East Coast Basin extends 650 km in a NNE–SSW direction from East Cape to Cape Palliser in the eastern North Island, and also includes Marlborough, in the northeastern South Island, New Zealand (Fig. 1). The basin varies in width between 60 and 110 km, and about half of it is offshore (Field et al., 1997). Onshore, the rocks represent an exhumed forearc, related to a period of Neogene convergence along the Hikurangi Subduction Zone that has been on-going for ~24 m.y. (Spörli, 1987; Ballance, 1993; Lewis and Pettinga, 1993). The present-day convergent margin embodies the southern part of the 3000-km-long, Tonga–Kermadec–Hikurangi system (Lewis and Pettinga, 1993), subducting westward at a rate of about 43 mm/year (azimuth 263°, latitude 39°50' S at southern Hawke Bay; De Mets et al., 1990). Plate motion is partitioned into both transcurrent and convergent components, causing substantial surface deformation along the plate margin (Cutten, 1991). Early Miocene onset of subduction was marked by initiation of andesitic volcanism in northern New Zealand, abrupt changes in sedimentation style, and accompanying deformation signatures in forearc strata (e.g. van der Lingen, 1982; Spörli, 1987). Plate reconstructions and paleomagnetic studies suggest that the margin underwent considerable clockwise rotation, from an original NW-trending

subduction system north of New Zealand to its present orientation along eastern North Island (Fig. 1; Cole and Lewis, 1981; reviewed in Field et al., 1997). Large dextral movements of East Coast structures also have been suggested (Cutten, 1991).

The present forearc system can be divided into three components: (1) an inner forearc located mostly onshore; (2) an imbricated, frontal accretionary wedge lying mainly offshore; and (3) a zone of offshore frontal accretion, i.e. trench-slope sediments (Lewis and Pettinga, 1993). West of the forearc, and oriented in a NE–SW direction, lies a backstop of Mesozoic meta-sedimentary basement. Older passive margin sediments (mid-Cretaceous to Paleogene in age), some of which are known organic-rich source rocks (Fig. 3), underlie the Miocene–Pliocene section, which attains thicknesses of 4–11 km (Francis et al., 2004). These strata have been thrust faulted and back tilted during the past 25 m.y. of convergence along the plate boundary (Lewis and Pettinga, 1993). Further west, a line of subduction-related, calc-alkaline arc volcanism is situated within the Taupo Volcanic Zone (Cole and Lewis, 1981; van der Lingen, 1982; Spörli, 1987; Fig. 1 inset).

The 14 geographically isolated carbonate deposits of this study are found in Miocene, deep-water, terrigenous forearc strata to the north of Gisborne or east of Dannevirke (Fig. 1). In the northern part of the East Coast, structuring is complex. Major, long-active, low-angle normal faults predominate in some parts, including the area with the most known seep-carbonates; whereas, east or SE-verging reverse faults dominate structure elsewhere (Mazengarb et al., 1991; Francis et al., 2004). In the southern areas where these carbonates occur, linear coastal ranges were formed by rapid uplift (Lewis and Pettinga, 1993).

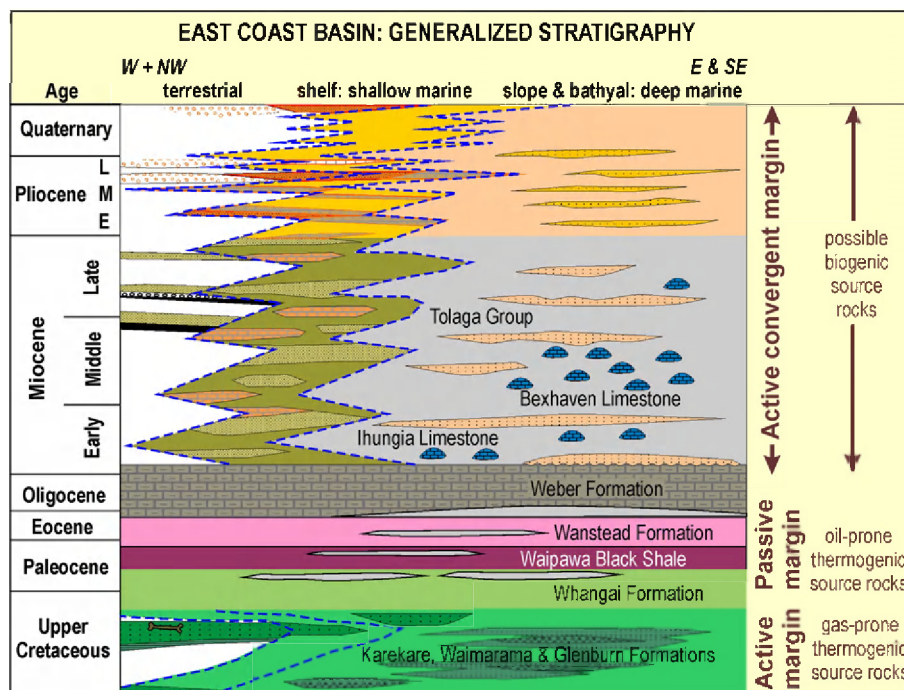


Fig. 3. Stratigraphic panel (Upper Cretaceous–Quaternary) for the East Coast region showing some of the formations in the Cretaceous and Paleogene section, which include hydrocarbon source rocks, and broad depositional settings for the thick Neogene strata. Seep-carbonates (blue mounds with brick symbols) are distributed in Lower to Upper Miocene bathyal mudstones of the active convergent margin.

2.2. Manifestations of fluid expulsion along the modern Hikurangi margin

A subduction complex, 100–150 km wide, has formed along the leading edge of the Indo-Australian Plate, with muds accumulating in the ancestral Hikurangi Trench (Cole and Lewis, 1981). In general, terrigenous sediments incorporated into accretionary prisms are ideal places to generate hydrocarbons by biogenic processes, as they accumulate rapidly, contain marine and terrestrial organic matter, and incorporate large volumes of pore waters. Pore waters are released during the subduction process *via* sediment compaction and compression linked to dewatering along faults, fractures and high-permeability horizons (e.g. Lewis and Cochrane, 1990; Shipley et al., 1990; Moore and Vrolijk, 1992). Along the Hikurangi margin, trench-fill turbidites store ~25–38% pore waters, and are undergoing frontal accretion at a rate of 12 ± 3 mm/year (Barnes and Mercier de Lepinay, 1997). Fluid over-pressuring is enhanced by both low-permeability mudrocks in the forearc, and containment of over-pressures in a compressional thrust-fault regime (Sibson and Rowland, 2003). Sibson and Rowland (2003) estimated an annual fluid expulsion rate of $>2 \times 10^6$ m³ per 100 km along the strike length of the margin.

At outer shelf to mid-slope depths along the modern Hikurangi margin (Fig. 1), fishing boats have recorded hydroacoustic anomalies in the water column, or dredged up distinctive carbonates and typical seep-associated organisms (e.g., tube worms, bathymodioline, thyasirid and vesicomid bivalves, gastropod *Provanna*; Lewis, 1991; Lewis and Marshall, 1996; von Cosel and Marshall, 2003). One $\delta^{13}\text{C}$ measurement (–39‰ PDB), from sedimentary fill within a *Calypptogena* shell collected at Ritchie Ridge (Fig. 1; 39°26.39' S, 178°23.56' E; Lewis and Marshall, 1996), implies derivation from methane sources (cf. Schoell, 1983; Suess and Whiticar, 1989). Hydroacoustic anomalies caused by methane bubbles rising over 250 m above the seabed have been reported from three sites offshore the East Coast (Lewis and Marshall, 1996). During a cruise in July 2006, all three sites were found to be still active, and geochemical water analyses proved that methane is released to the water column (GNS Science, unpublished data). In addition, a gas hydrate province of 50,000 km² has been revealed by seismic data (Katz, 1982), with an estimated 7% of Hikurangi margin sediments storing these deposits (Henrys et al., 2003, *in press*). Furthermore, over 380 active oil and gas seeps are recorded from the onshore East Coast Basin, which have been analyzed for their kerogen kinetics, and biomarker and stable isotopic characteristics (Murray et al., 1994; Francis and Murray, 1997). Collectively these modern onshore and offshore seeps and hydrates indicate substantial discharge of hydrocarbon-rich fluids landward of the current deformation front of the subduction zone.

The discovery of ancient seep signatures in isolated carbonates scattered throughout Miocene mudrocks of the northern and southern Hawke's Bay area (Fig. 1; Campbell and Francis, 1998; Campbell et al., 1999) extends the recorded history of hydrocarbon-rich fluid expulsion back to a time (~22 Ma) just after the initiation of the current phase of subduction in the region.

2.3. Historical references to Miocene carbonates of the East Coast Basin

Cool-water carbonate deposits are significant geographic and stratigraphic constituents of Neogene strata on the New Zealand subcontinent (Beu et al., 1980; Kamp and Nelson, 1988; Nelson and Smith, 1996). They have formed in different tectonic sectors of the plate boundary (e.g., forearc, continental transform, arc, backarc), and can be distinguished by geometry, thickness, skeletal composition, hosting clastic lithologies, and carbonate-to-clastic ratios (Kamp and Nelson, 1988). Some are laterally extensive (Beu et al., 1980) while others, like the forearc seep-carbonates of this study, occur in isolated pods or lenses enclosed by thousands of meters of bathyal mudstones (Figs. 2 and 3). In particular, the Miocene seep-carbonates detailed herein are quite different in lithologic and faunal character (see Sections 3 and 4) from the well-known, cool-water "Te Aute Facies" limestones in the same area, which dominate the landscape and topographical ridge-lines from south of Dannevirke to north of Gisborne (Beu et al., 1980; Nelson et al., 2003). The latter are Pliocene–Early Pleistocene in age, generally well-bedded and locally cross-bedded, and accumulated in shallow waters around the margins of a restricted, forearc basin seaway, inboard of today's convergent Australia/Pacific plate boundary (Caron et al., 2004). The central axis of this Wanganui–Hawkes Bay seaway contains a thick sequence of mudstones that are considered a hydrocarbon prospect, and which may hold buried Plio-Pleistocene seep deposits not yet uplifted/exposed along the Hikurangi margin.

McKay (1877a,b) was the first to describe the isolated, deep-water Miocene carbonates of eastern North Island. At Waipiro in the northern Raukumara Peninsula (Fig. 1), he noted "... a very peculiar yellow semi-crystalline limestone....Great quantities of this limestone, in large blocks, are found in the bed of the [Waipiro] creek further up, and seem to be almost entirely made up of the remains of the particular shell [mussels] which I have mentioned." Another long-known, large deposit exposed ~40 km north of Gisborne (Fig. 2A), is herein termed Rocky Knob after a local farm track, and was recorded as "Limestone Stream" during early geological mapping (Adams, 1910; Henderson and Ongley, 1920). Ongley and MacPherson (1928) coined the name "*Modiolus* limestone" for northern deposits at Bexhaven, Tauwharepara (Fig. 2C) and Waipiro Stream, after the abundant mytilid mussels embedded in the carbonate pods and lenses. In an overview of limestones on the Neogene plate margin of New Zealand, Kamp and Nelson (1988) informally designated the deposits at Rocky Knob as the "Moonlight limestone," named after a nearby sheep station. Beu and Maxwell (1990, p.174) noted that the Moonlight deposits display an "...unusual lithology, a white or pale grey, massive limestone, at many localities with vague to obvious tubular structures and scattered molluscs, [occurring] widely in the East Coast of the North Island, always as small pods, from 10 m to 100 m across, within thick Lillburnian [Middle Miocene] mudstone sequences." They mentioned several distinctive fossils associated with the carbonates, including deep-water mytilids, lucinid bivalves, trochid gastropods, and lepetellid limpets (Beu and Maxwell, 1990). In a detailed geological map

of part of the northern East Coast Basin, Mazengarb et al. (1991) elevated the scattered Moonlight/*Modiolus* limestones to formation status, describing them collectively as the Bexhaven Limestone. Sites specified in that study, and evaluated herein, included the Bexhaven, Karikarihuata Stream (Fig. 2B), Upper Waiau River (Totaranui), Upper Waiau River (Puketawa), and Moonlight North localities. This new designation eliminated any possible confusion with the same name (Moonlight) already given to lower Miocene, shallow-water, bioclastic limestones of the upper Waipaoa valley. The Bexhaven Limestone lenses occur in deep-water, massive mudstones of the Tolaga Group (Early to Late Miocene), which also includes alternating mudstones with thin-bedded, fine-grained sandstones (Fig. 3; Mazengarb and Speden, 2000). Subsequently Neef and Bottrill (1992) recognized Bexhaven Limestone at Turihaua, 10 km northeast of Gisborne, and the small Waikairo Stream occurrence was found more recently by Francis (unpublished). Southern localities at Wanstead, Ugly Hill and Haunui were mapped as the basal Ihungia Limestone by Lillie (1953; Fig. 3), who described conglomeratic limestones as “a subordinate formation attaining a thickness of several hundred feet”.

To date, no systematic, integrated survey of these eastern North Island carbonate deposits has been undertaken, of which at least 14 are currently known to occur onshore along 300 km of the exhumed forearc, from East Cape to Dannevirke (Fig. 1).

3. Miocene East Coast seep-carbonates: an overview

The stratigraphic and structural settings of the 14 studied carbonate occurrences of eastern North Island are outlined here, along with other key, fluid-related features of this frontier petroleum system (Section 3.1), as preserved in the 22 m.y. history of convergence and uplift along the Hikurangi Margin. We also examine the sedimentologic, paleontologic, and stable isotopic signatures of seafloor-associated seep-carbonates (Sections 3.2 and 3.3), which display geographic differences north and south. Moreover, some deposits exhibit clear indications of firmground and hardground development on the seafloor (Section 3.4), owing to either a hiatus in post-seepage sedimentation or later exhumation. Finally, some deposits are affiliated with sub-seabed plumbing features or post-depositional reworking events (Section 3.5), with unique lithological characteristics that differentiate them from the *in situ*, fossil-rich, seafloor seep-carbonates.

3.1. Stratigraphic, structural and associated petroleum migration features of the East Coast Basin carbonates

Broadly, the overall tectono-stratigraphic framework of the East Coast region is presently conducive to both biogenic and thermogenic hydrocarbon generation and migration (Fig. 3; Francis, 1992, 1995; Field et al., 1997). Late Cretaceous and Paleocene marine source rocks accumulated on a passive margin, and convergence was initiated at the end of Oligocene time (~24 Ma). Rapid and voluminous terrigenous sedimentation and compaction, and compressive deformation drove release of hydrocarbons throughout the Miocene, along the

length and breadth of the basin (Figs. 1 and 3). The seep-carbonates of this study occur in differing stratigraphic and structural settings, and some are close to present-day oil or gas seeps.

In the northern part of the East Coast Basin (Fig. 1), almost all of the Miocene-aged strata belong to the Tolaga Group, with the Bexhaven Limestone comprising a volumetrically minor formation at different stratigraphic levels within this Group (Fig. 3). Data from Lillie (1953), Mazengarb et al. (1991), Mazengarb and Speden (2000) and Francis (unpublished) indicate that these northern seep-carbonates are situated in a variety of structural settings, with four positioned within monoclinical sequences, three on or near synclinal axes, two on or near anticlinal axes, and two in uncertain structural settings. Some are not far from normal faults with substantial displacement, but this may be coincidental given the predominance of normal faulting in the region. Differing sedimentary thicknesses across these faults indicate movement extending as far back as the later part of Middle Miocene, and several of these normal faults demonstrate Late Quaternary activity. All of the northern carbonates are underlain by substantial thicknesses of mudstone-dominant Miocene strata (between 1500 and 3500 m), and none is situated close to a conspicuous basal Miocene unconformity in the area. Age-diagnostic foraminifera within enclosing mudstones indicate a Middle Miocene age for the northern carbonates except at Waipiro and Turihaua, which have Early Miocene and Late Miocene ages, respectively.

Seep-carbonate occurrences in the southern East Coast Basin (Fig. 1) are situated along strike, and within 8 km of one another, on the moderately- to steeply-dipping western limb of a major syncline (Akitio Syncline). The southernmost site is 500 m east of the reverse-faulted margin of a structural high in the Whangai Formation. Broadly, these southern seep-carbonate sites occur at or near the basal unconformity of the Ihungia Formation (equivalent to the lower part of Tolaga Group), which overlies the Oligocene Weber Formation (Fig. 3). All are of Early Miocene age. In places, they occur as a series of fossiliferous carbonate beds up to 100 m above the unconformity, and are associated with sandstone and conglomerate. Pebble-sized clasts are derived from Upper Cretaceous to Oligocene formations, as exposed down section. Therefore, these southern deposits differ markedly in stratigraphic and structural setting from the northern sites, in that they overlie a relatively thin Miocene section, are close to a major unconformity, and are associated with coarser clastic lithologies.

With respect to the types and distributions of hydrocarbon indications in the study area, present-day gas seeps are found over most of the onshore East Coast Basin, with compositions that vary from methane with significant higher hydrocarbons (C2 to C5), through to almost solely methane. Their origins range from entirely thermogenic through mixed thermogenic–biogenic, to entirely biogenic (marine) (Lyon et al., 1992; Lowry et al., 1998). Most of these gas seeps are associated with cold saline water, and two in the northern East Coast Basin are associated with warm or hot saline water. Oil seeps and stains also occur in various parts of the onshore basin, and have been linked by biomarkers to known Late Cretaceous or Paleocene marine source rocks (Fig. 3).

Several of the Miocene seep-carbonates in the East Coast Basin are relatively close to (within 2 km) presently active gas seeps. It is uncertain whether this geographic association is

coincidental, given the large number of gas seeps in the basin, or whether there is a direct association with long-active seeps affiliated with fundamental tectonic boundaries. For example, in

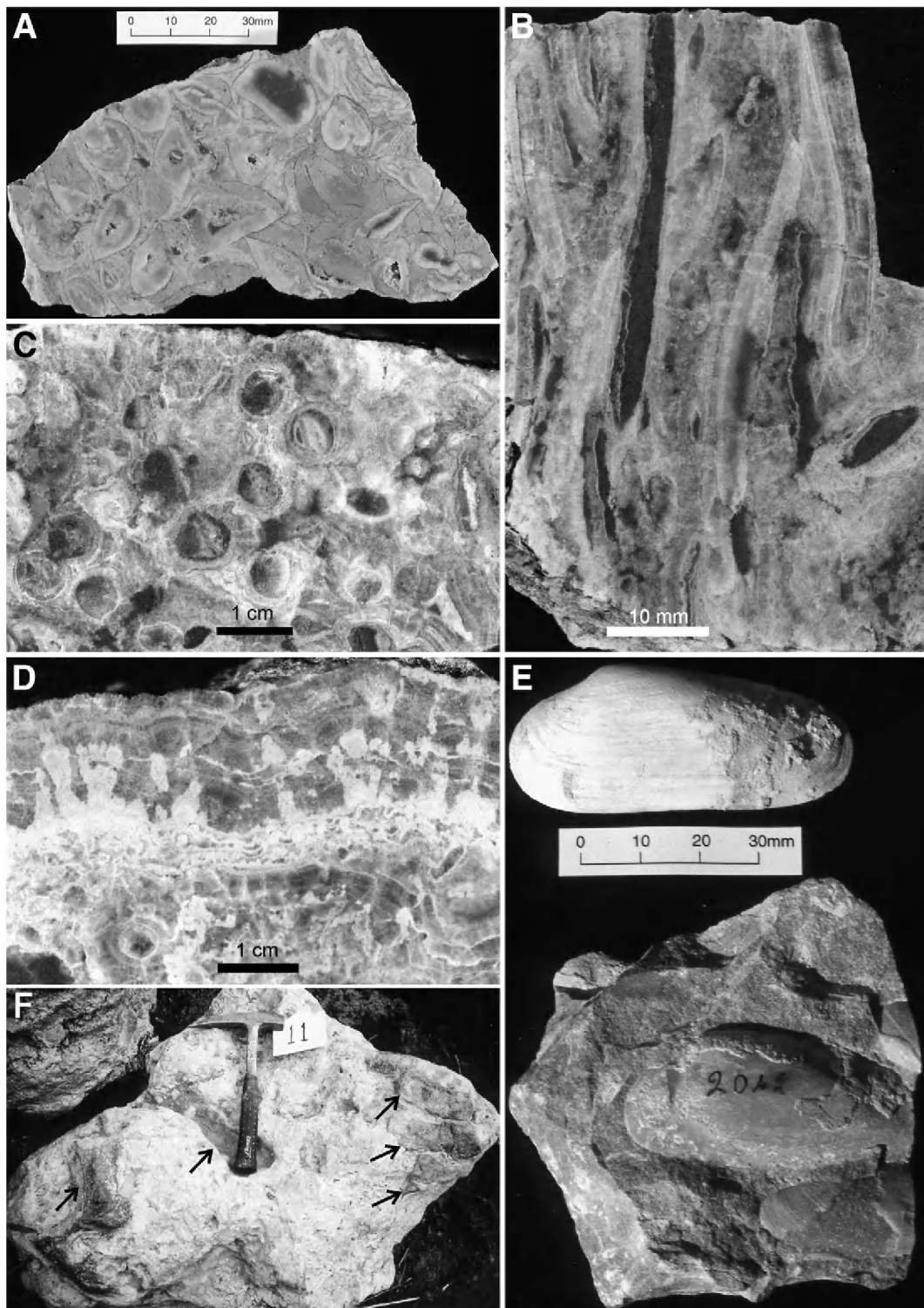


Fig. 4. Seafloor affiliated, seep-carbonate fossils, East Coast Miocene deposits. (A) Polished block of varied cements and densely packed mussels at Turihaua (site #11), typical of many seep localities in northern regions. (B) Longitudinal view of calcareous worm tubes in dense patches from Rocky Knob (site #9; NE circular knoll, see Fig. 12) displaying complex cement stratigraphy. (C) Worm tube cross-sections from the circular knoll, Rocky Knob. (D) Micritic oatmeal fabric within digitate, thrombolitic microbial structures, encased in thick layers of fibrous aragonite at Rocky Knob. (E) Vesicomyid bivalves typify Wanstead sandy micrites (lower fossil, site #12), similar to those found offshore at modern Hikurangi margin seeps (upper white shell, Ritchie Ridge). (F) Cluster of whale bones (arrows) associated with abundant mussels in a float block from Karikarihuata (site #3).

the northern part of the basin, the Waipiro Stream locality is less than 2 km from Te Puia Springs, where hot and cool saline waters associated with thermogenic hydrocarbon gas issue from numerous sites over an area exceeding 2 km² (Macpherson, 1945; Francis et al., 1991).

Carbonate from the Rocky Knob locality has a strong petroliferous odor when crushed or cut. Rocky Knob is presently 5 km from the highly active oil seeps on the Waitangi High. It is uncertain whether hydrocarbons in the carbonate are the result of late Neogene generation and migration into natural rock porosity, or have been generated from organic material contained within the limestone, or occur as a remnant of liquid hydrocarbons produced on the seabed along with the original methane. Because this large carbonate deposit is close to a subsidiary anticline, it is likely that a pathway for liquid migration of oil during the late Neogene could have existed.

The three studied seep-carbonate deposits in the southern East Coast Basin are close to and along trend with several relatively minor gas and saline water seeps (Lillie, 1953). The basal Miocene unconformity may be the common controlling factor in the distribution of both the Early Miocene seep-carbonates and the modern, onshore hydrocarbon seeps in this area.

Overall, the onshore and offshore presence of methane-derived seep-carbonates, and extensive modern oil and gas seeps, are indicators of a relatively long period (Miocene to present-day) of hydrocarbon generation and expulsion along the Hikurangi Margin. Further work is needed to determine the characteristics of the hydrocarbons within the seep-carbonates (G. Logan and J. Peckmann, in progress), and studies are also underway on offshore samples from a recent research cruise (Greinert and SO191 Participants, 2007).

3.2. Lithologic and paleontologic characteristics of fossiliferous, seafloor seep-carbonates

Seafloor affiliated carbonates of this study are distinguishable from the inferred basal plumbing features (Section 3.5) in that they typically form relatively large lenses and pods roughly parallel to bedding, contain abundant megafossils (some inferred as chemosymbiotic), and commonly display a relatively complex sequence of cement phases. For example, one recurring paragenetic sequence from a Turihaua sample (Fig. 4A) comprises: (1) greenish-gray, early diagenetic micrite packed with fossil mussels, followed by (2) isopachous fibrous aragonite, (3) buff, clotted “oatmeal” fabric, and finally (4) a pore-fill of late-stage, dark gray, silty micrite. Calcareous worm tubes also are found in dense patches (Fig. 4B), with the clotted oatmeal fabric encrusting tube surfaces (Fig. 4C). Close spatial associations between worm tubes and mussels are not common, although nearly monospecific groupings of one or the other fossil type are known from different horizons at the same sites (see Section 4.2). In places, the micritic oatmeal fabric has also developed into digitate, thrombolitic macrostructures, encased by thick layers of fibrous aragonite (Fig. 4D), comparable to other fossil microbialites (e.g. Kennard and James, 1986; von Bitter et al., 1990). The lipid biomarker signature of one aragonite–

thrombolite sample yielded some of the key markers for AOM, including pentamethyleicosane (PMI) and crocetane/phytane (J. Peckmann, pers. comm., 2006). Northern localities contain recurring seep taxa, such as fossil mussels, worm tubes and lucinids; whereas, sandy carbonates of southern localities are typified by vesicomid and lucinid bivalves, akin to those found offshore in seep environments today (Fig. 4E). Finally, a cluster of whale bones (Fig. 4F) was found in seep-carbonates at the Karikarihuata Stream locality. Further study is warranted to determine if any invertebrate taxa were spatially associated with the whale fall, which may have produced localized seepage of sulfide from bacterial decay of bone-oil (cf. Baco and Smith, 2003; Amano and Little, 2005; Nesbitt, 2005).

Table 1

Preliminary mega-invertebrate fossil checklist for East Coast Miocene seep-carbonate deposits

Megafossil taxa	East Coast Miocene seep-carbonate sites
Bivalvia	
Bathymodioline mussels	2, 3, 4, 5, 6, 7, 8, 9, 11
(3 morphotypes)	
<i>Modiolus</i> cf. <i>M. areolatus</i> *	5, 9
<i>Xenostrobus</i> cf. <i>X. altijugatus</i> *	11
<i>Thyasira</i> sp.	7, 8, 11
<i>Lucinoma</i> aff. <i>L. taylori</i>	9
<i>Calypptogena</i> sp.	12, 14
<i>Parvamussium</i> sp.	4
<i>Diplodonta</i> ? sp.	5
Vesicomids	6, 12, 14
Venerid indet.	5, 6
Lucinid, small	4, 7
Teredinid	2, 5
Nuculid	3
Gastropoda	
<i>Lepetella</i> ? sp.	5, 7, 9
3 naticids (2 <i>Polinices</i> sp., 1 <i>Friginatica</i> ? sp.)	2, 8, 12
Turrid	9
Buccinid	6
Mitrid	9
Trochid	4
Polychaeta	
Vestimentiferan worm tubes	3, 4, 5, 6, 7, 11
Crustacea	
Decapod fragments	4
Brachiopoda	
3 terebratulides (<i>Liothyrella</i> ?, others)	5, 9
Cnidaria	
cf. <i>Goniocorella</i>	2, 5, 8
Trace fossils	
Large, irregular, 3D-branching (<i>Thalassinoides</i> ?)	3, 4, 8
Roughly cylindrical to clavate borings	2, 4, 5, 7, 9, 11
(<i>Gastrochaenolites</i> ?, to 1 cm) with dark brown fill	
Small circular borings (~1 mm) with dark brown fill, in neat rows and clusters	9

Fossil-bearing field locations (cf. Fig. 1) include: Waipiro Stream (2), Karikarihuata (3), Bexhaven (4), Tauwharaepare (5), Upper Waiiau River at Puketawa (6) and Totaranui (7), Moonlight North (8), Rocky Knob (9), Turihaua (site 11), Wanstead (12), and Haunui (14). Asterisks (*) indicate fossil mussels identified in Beu and Maxwell (1990) that are likely to be bathymodioline (B. Marshall, pers. comm., 2007). List compiled from Beu and Maxwell (1990), GNS Science paleontology collections, and new University of Auckland field collections of this study.

A preliminary megafossil checklist for all known East Coast ancient seep sites is compiled in Table 1 from Beu and Maxwell (1990), former New Zealand Geological Survey fossil collections (now housed at GNS Science, Avalon), and our own field studies. Several of the taxonomic groups have been reported from other seep deposits of Cretaceous to Recent age elsewhere, and are here considered seep-related. These include the bathymodioline mussels (Collins, 1999), *Thyasira*, *Lucinoma*, and *Calyptogena*, and lepetellid limpets commonly associated with fossil worm tubes. The tubes originally were identified as ? *Hyalinoceia* by Beu and Maxwell (1990), but on-going study suggests they are likely vestimentiferans (C. Little, pers. comm.

2006). Beu and Maxwell (1990, p. 174) did not assign a name to the abundant fossil mussels in the Bexhaven carbonates, noting that “a deep-water, byssally attached mytilid closely resembling *Idasola* is present at almost all localities.” In a biometric study of fossil mytilids from East Coast seep-carbonate sites, Collins (1999) differentiated distinct morphotypes that he suggested fall within the deep-water subfamily Bathymodioline, whose members occupy modern hydrothermal vent and hydrocarbon seep environments (e.g. Van Dover, 2000; von Cosel and Marshall, 2003). These include a large, curved, elongate fossil form (Fig. 5A and B) similar to *Gigantidas* (von Cosel and Marshall, 2003), and a smaller, stouter, flared variety that

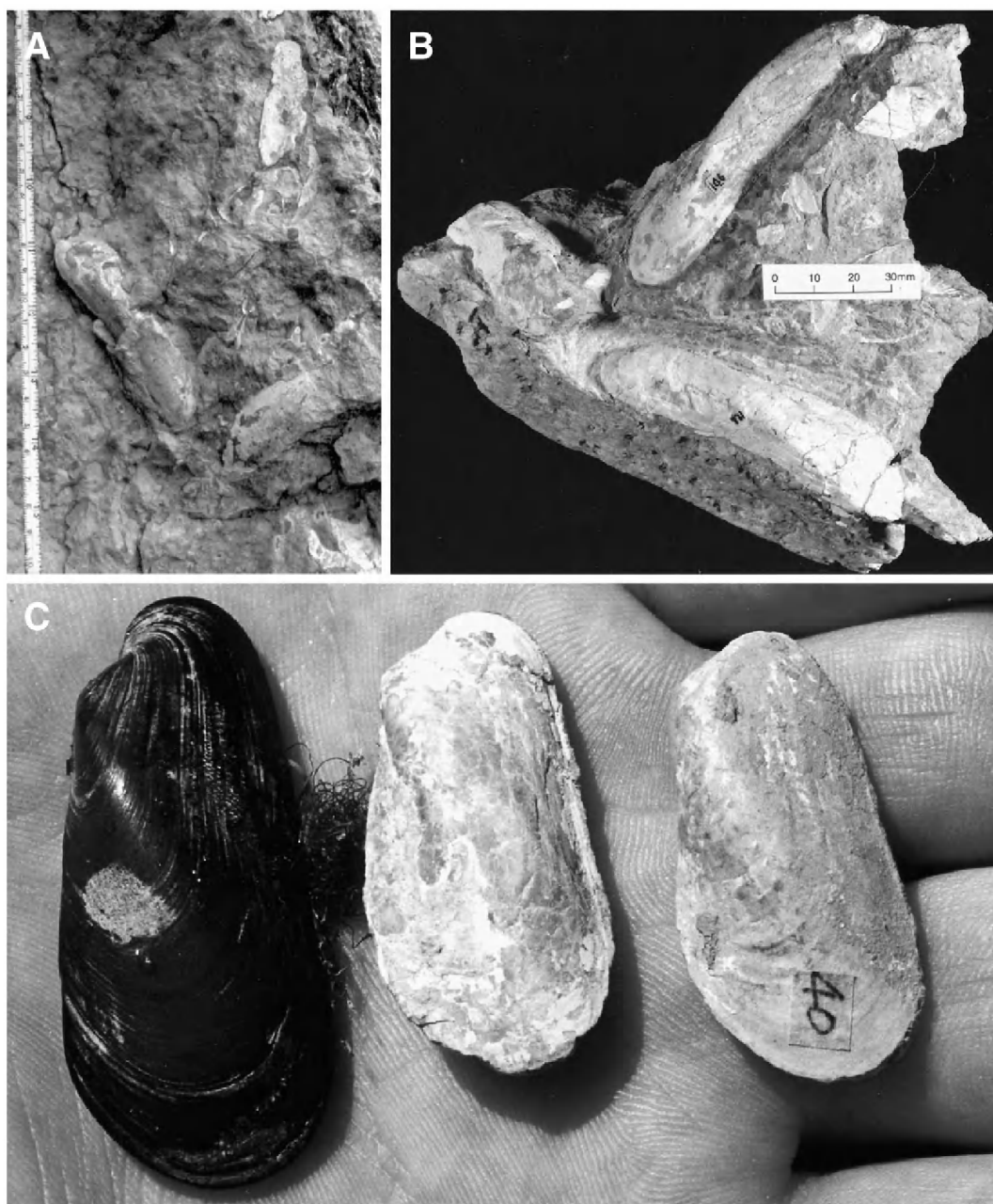


Fig. 5. Bathymodioline mussels of East Coast Miocene seep-carbonates (cf. Collins, 1999). A large elongate form in A and B, similar to *Gigantidas* (von Cosel and Marshall, 2003), and a smaller, stouter, flared variety in C (the two light colored fossils on right) that resembles the living Japanese hydrothermal vent mussel, *Bathymodiolus adulooides* (the dark brown shell with byssus threads at left in C).

resembles the living Japanese hydrothermal vent mussel, *Bathymodiolus aduloides* (e.g. Fig. 5C, cf. Hashimoto and Okutani, 1994). The modern New Zealand hydrothermal vent-affiliated *Gigantidas gladius* is anatomically closest to small, wood-fall affiliated species of *Idas* (von Cosel and Marshall, 2003). In addition, both *Modiolus* cf. *areolatus* and *Xenostrobus* cf. *altijugatus* listed in Beu and Maxwell (1990) are likely to also be fossil bathymodiolines, as all living vent and seep mussels in New Zealand's Exclusive Economic Zone are members of this subfamily (B. Marshall, pers. comm., 2007). Hence, opportunities exist to compare living and fossil deep-sea mussel taxa in both Miocene onshore and modern offshore, chemosynthesis-based settings around New Zealand and the Pacific Rim (K. Campbell and others, work in progress). Nonetheless, mussel taxonomy can be complex, as habitat reversals (hydrothermal vent to cold seep and *vice versa*) are well-known among living bathymodiolines (Jones et al., 2006; Samadi et al., 2007), and genetic heterogeneity is high among modern New Zealand species from hydrothermal vents of the Kermadec Arc (Fig. 1 inset; Smith et al., 2004).

Other noteworthy taxa (Table 1) associated with these Miocene seep deposits include various scavenging and predatory

gastropods, and several terebratulid brachiopods. Brachiopods are common in Paleozoic and Mesozoic seeps, rare in Cenozoic seeps and almost absent from modern vent-seep settings (Campbell and Bottjer, 1995; Campbell, 2006). Where found at modern sites, they appear to be exploiting the carbonates as hardgrounds for attachment while they filter bacterio-plankton from the water column, since no living brachiopods are known to be chemosymbiotic (reviewed in Campbell, 2006). New Zealand has a remarkably rich and diverse, Cenozoic (>100 species) and modern brachiopod fauna (e.g. Dawson, 1990; Morton, 2004) that is dominated by terebratulid, rhynchonellid, and inarticulated brachiopods. Hence, compared to elsewhere in the world, the presence of fossil brachiopods in the Miocene East Coast seep-carbonates may reflect the relict nature of brachiopods in New Zealand in general. As far as we know, there are no brachiopods associated with the modern seep fauna offshore.

3.3. Stable isotopic characteristics of the Miocene seafloor seep-carbonates

Many of the fossil-rich seep-carbonates exhibit depleted $\delta^{13}\text{C}$ signatures indicative of their formation as a by-product of

Table 2
Stable isotopic measurements of carbon and oxygen for various Miocene seep-carbonate lithologies, East Coast, North Island, New Zealand

Sample number	Description	$\delta^{13}\text{C}$ (‰, PDB)	$\delta^{18}\text{O}$ (‰, PDB)
<i>East Coast Miocene seep-carbonates</i>			
BXH-1-1 (4)	Light green-brown micrite matrix	-43.3	+0.2
BXH-1-2 (4)	Late, clear blocky calcite spar	-42.5	-5.1
BXH-2-1A (4)	Dark gray micrite fill of firmground burrows	-34.0	-5.0
BXH-2-1B (4)	Light green-brown micrite matrix	-48.5	+1.2
TWP-1-1A (5)	Bioturbated micrite	-44.3	+1.2
TWP-100-1 (5)	Fibrous aragonite	-48.8	+2.2
UWP-1 (6)	Mixed micrite, fibrous cement	-51.7	+2.2
UWT-2-1A (7)	Botryoidal aragonite filling vugs, veins	-45.0	+0.7
UWT-2-1B (7)	Dark gray micrite filling void	-31.5	-2.0
MN1-1-1 (8)	Bioturbated micrite	-31.1	+1.2
MN1-2-1 (8)	Dark gray internal micrite	-29.9	-3.6
RK-4-1A (9)	Blue-gray micrite matrix; brecciated	-43.9	-0.7
RK-4-1B (9)	Dark gray-brown sinuous firmground	-31.2	-1.8
RK-12-1A1 (9)	Botryoidal aragonite filling vugs, veins	-48.3	+2.0
RK-12-1F (9)	Dark gray micrite	-36.2	-1.3
RK-12-1F2 (9)	Clotted buff micrite	-44.6	+2.4
RK-6-1A (9)	Lucinid shell calcite	-10.9	+1.6
TRH-3-1 (11)	Green micrite	-49.2	+1.5
TRH-4-1 (11)	Fibrous aragonite	-49.0	+2.7
WAN-1 (12)	Sandy micrite	-22.9	-4.0
WAN-2 (12)	Clotted buff micrite	-21.8	+1.0
HAU-1 (14)	Buff micrite	-11.1	-1.3
<i>Modern hydrocarbon seep site at Ritchie Ridge, offshore eastern North Island, Hikurangi convergent margin. Site 1 of Lewis and Marshall (1996).</i>			
	<i>Calypptogena</i> shell	-0.34	nd
	"Cement" fill inside	-39.16	nd
<i>Onshore active hydrocarbon seeps, East Coast Basin (Lowry et al., 1998)</i>			
	Exploration wells, natural gas seeps	~-35 to -68	na

Numbers in parentheses refer to locality numbers of Fig. 1. Also shown are comparative carbon isotopic data from modern Hikurangi margin shell (chemosymbiotic bivalve, *Calypptogena*), shell-fill carbonate, and oil and gas seeps. Powdered samples of ~2 mg were reacted with anhydrous H_3PO_4 at 25 °C. The evolved CO_2 gas was separated from the uncondensable gases and purified using cryogenic techniques in a vacuum extraction line according to the method of McCreath (1950). The liberated CO_2 was analyzed on a multiple collector gas-source IRMS at the Alabama Stable Isotope Laboratory following standard procedures. Based on multiple analyses of the NBS-19 standard and repeats of about 20% of the samples, the overall reproducibility of the chemistry and mass spectrometry combined is estimated to be $\pm 0.1\%$ for both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ determinations. nd, not determined; na, not applicable.

AOM in the zone of sulfate reduction ($\delta^{13}\text{C} < -30\text{‰}$ PDB), although several factors have contributed to the wider range of carbonate-carbon values reported for Phanerozoic seep deposits worldwide (discussed in Campbell, 2006). Table 2 and Fig. 6 illustrate a suite of carbon and oxygen stable isotopic measurements for several East Coast carbonate samples, revealing that AOM contributed to carbonate precipitation for most cement types. The $\delta^{13}\text{C}$ signatures of the authigenic carbonates range from -11.1 to -51.7‰ PDB, and $\delta^{18}\text{O}$ values show a spread from -5.1 to $+2.7\text{‰}$ PDB (Table 2, Fig. 6). Only a few stable isotopic measurements from the vesicomid-dominated, sandy carbonates south of Hawke Bay have been evaluated in this pilot study, but they appear to indicate higher $\delta^{13}\text{C}$ values and negative $\delta^{18}\text{O}$ values compared to northern seep sites. These and other lithologic and faunal differences between northern and southern seep-carbonates are under further study in a basin context. Overall, the $\delta^{13}\text{C}$ values herein suggest that the methane expelled in seeps throughout the Miocene was probably biogenic, although their range indicates that mixing with thermogenic methane and/or seawater bicarbonate are other possible sources for the more enriched signatures in some cements.

Table 2 also lists the $\delta^{13}\text{C}$ value of a (?sub)Recent chemosymbiotic bivalve (*Calypptogena*) shell and its internal carbonate fill, dredged from an offshore seep at Ritchie Ridge, Hikurangi

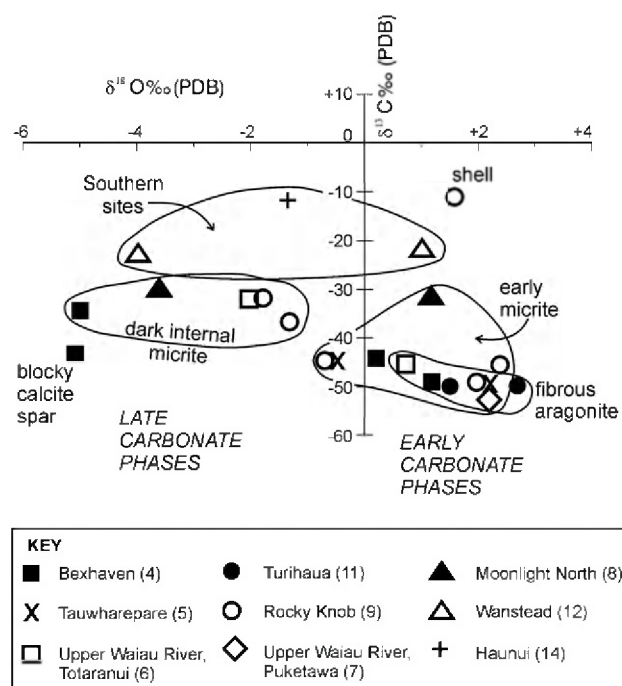


Fig. 6. Cross-plot of stable carbon versus oxygen isotopic measurements from nine East Coast Miocene seep-carbonate sites (numbers in parentheses in the key refer to site numbers listed in Fig. 1). Six fields are suggested from these preliminary results, grouped by carbonate type. Northern sites contain carbonate with complex early and late diagenetic carbonate phases, including: shell carbonate, early micrite, early fibrous aragonite, late calcite spar, and late, dark internal micrite. The southern localities cluster in a relatively carbonate-carbon enriched region of the plot, a grouping also supported by additional data collected from the same localities (J. Greinert, unpublished). See Section 3.3 for details.

margin (Fig. 1; Lewis and Marshall, 1996). Lewis and Marshall (1996) interpreted these measured carbon isotopic values to be indicative of a thermogenic methane source. However, recent pore water sampling at Ritchie Ridge did not show this to be the case, although thermogenically derived methane has been assumed from geophysical studies (Pecher et al., 2004; Faure et al., 2006). Finally, the range of reported methane-carbon isotopic values from onshore exploration wells and natural gas seeps across the region (Lowry et al., 1998; Lyon et al., 1992) are shown in Table 2 for comparison with the modern and fossil submarine seep data.

In detail, early diagenetic cements and shell carbonate from northern East Coast localities are generally enriched in ^{18}O compared to northern, late diagenetic cements, and to carbonates from southern sites (Fig. 6, Table 2). Fibrous to botryoidal aragonite cements from northern deposits yielded strongly negative $\delta^{13}\text{C}$ values (-45 to -51.7‰ PDB) and positive oxygen signatures ($\delta^{18}\text{O} +0.7$ to $+2.7\text{‰}$ PDB), similar to measurements reported for fibrous cements from other seep settings (e.g. Bohrmann et al., 1998; Greinert et al., 2001). Fibrous cements are considered an early seafloor diagenetic phase in ancient seep examples (e.g. Beauchamp and Savard, 1992; Campbell et al., 2002; Peckmann et al., 2007). Moreover, some modern fibrous aragonites form in close spatial association with gas hydrates (Bohrmann et al., 1998), a seep lithotype recently termed clathrite (Teichert et al., 2005). The Miocene East Coast fibrous cements overlap in their stable isotopic signals with early micrite matrix samples and microbial fabrics of the northern localities, with the micrites showing a greater spread in both the carbon and oxygen isotopic values (Fig. 6). By contrast, the single shell measurement from a Rocky Knob lucinid yielded an unusual isotopic signature of depleted carbon ($\delta^{13}\text{C} -10.9\text{‰}$ PDB) with respect to shells of modern seep sites (e.g. Greinert et al., 2001, 2002). However, the oxygen isotopic value implies a shell grown in reasonably cold bottom water ($\delta^{18}\text{O} +1.6\text{‰}$ PDB) and does not indicate any late burial diagenetic overprinting. The Rocky Knob shell is similar to both the stable oxygen and carbon isotopic values measured for unaltered bivalve shells (lucinids, solemyids) and well-preserved foraminiferal tests in Neogene seep deposits of the U.S. Pacific Northwest (Martin et al., 2005, 2007).

Isotopic analysis of late diagenetic carbonate phases from northern localities includes samples from a distinctive, dark-colored micrite that typically fills pores, including marine borings, and a single measurement from a translucent, blocky calcite spar (Fig. 6, Table 2). Despite sampling from four different sites, the dark micrites all show remarkably similar carbon isotopic signatures (mean $\delta^{13}\text{C} -33\text{‰}$ PDB), and a relatively narrow spread in $\delta^{18}\text{O}$ values from -1 to -5‰ PDB. The dark micrites that fill borings are important (see also Section 3.4) because they indicate continued methane-associated carbonate production after the deposits had been exposed, from exhumation or lack of burial, in seafloor environments before renewed sedimentation. Additional geochemical, mineralogic and petrographic studies of all micritic carbonates are underway, as there are many varieties evident in the Miocene East Coast deposits (cf. Section 4.1), and they

occur in varying stratigraphic positions within and between sites.

3.4. Seep-carbonates as seafloor firmgrounds and hardgrounds

The biogenic structures of seep-carbonates give clear indications of substrate consistency and help to establish when benthic organisms were active in seafloor settings before, during and after fluid-seepage events. Gradients of increasing

lithification of the seabed through continuing carbonate cementation can be recognized in modern and ancient seep deposits by evaluating preserved trace fossil characteristics. For example, tubular concretions from modern seeps offshore eastern North Island are commonly bored (Fig. 7A), suggesting focused fluid-flow in the subsurface, followed by erosional exhumation and exposure on the seafloor. In the geologic record, diffuse bioturbation has been reported in softgrounds from western North American seep-carbonates (Campbell et al.,

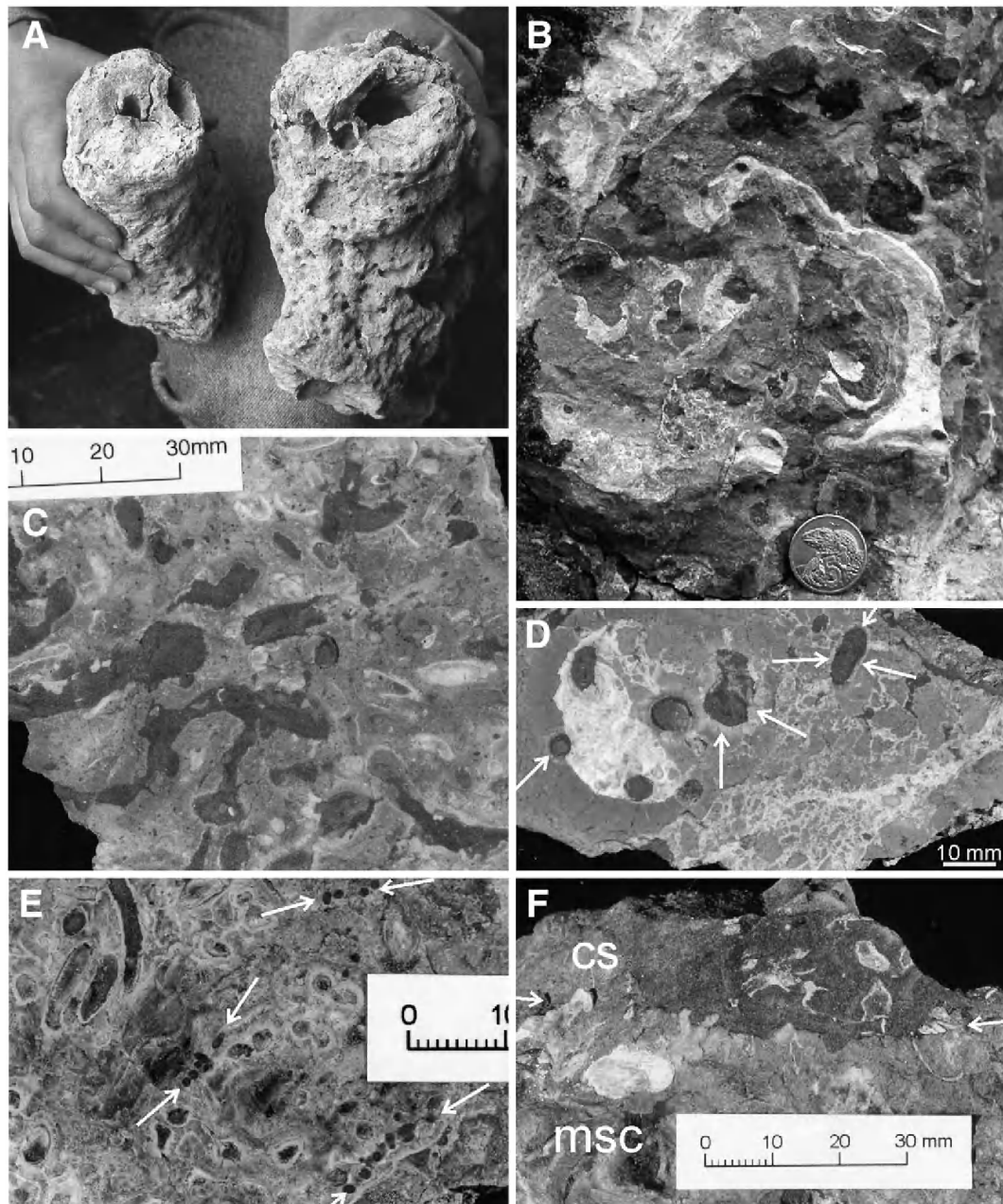


Fig. 7. Firmground and hardground trace fossils from eastern North Island seep-carbonates. (A) Tubular concretions dredged from the Hikurangi margin today are usually infested by boring and encrusting organisms. From the National Institute of Water and Atmosphere collections, Wellington. (B, C) Marble cake fabric caused by firmground burrowing (?*Thalassinoides*) into light-colored, fossiliferous micrites; burrows later filled with dark, late-stage micrite. Margins of these large (up to 1 cm diameter), branching, three-dimensional burrows are irregular and sinuous. Bexhaven (site #4). (D, E) Hardground borings represented by subspherical to clavate structures with sharp boundaries, and are of two sizes: (D) spatially scattered and large (arrowed, to ~1 cm diameter, ?*Gastrochaenolites*) at Rocky Knob (site #9); or (E) small (~1 mm diameter), in neat rows and clusters (paired arrows) at Rocky Knob. (F) Caryophyllid coral thickets (cs) atop mussel-rich seep-carbonate (msc) at Tauwharepare (site #5). The two horizons are separated by an irregular surface (arrows), possibly formed by corrosive seep fluids (cf. Campbell et al., 2002).

2002, Fig. 7B; cf. Campbell and Nesbitt, 2004; Campbell et al., 2006, Fig. 10B–D). By contrast, firmground and hardground development in the Miocene East Coast seep-carbonates of this study are indicated by various traces with more strongly demarcated boundaries. For instance, a swirly “marble cake” fabric is common in some deposits (Fig. 7B), caused by firmground burrowing into light-colored, fossiliferous micrites, and subsequent fill of these burrows by a darker, pore-filling, late-stage silty micrite (Fig. 7C). Margins of these large (up to 1 cm diameter), branching, three-dimensional burrows (?*Thalassinoides*) are irregular and sinuous. In comparison, hardground borings are manifest as subspherical to clavate structures (vase-shaped ?*Gastrochaenolites*) with sharp boundaries. They occur in two sizes and shapes: large and scattered (up to 1 cm diameter, Fig. 7D), or as small rows and clusters (up to 1 mm diameter, Fig. 7E). Both types are filled with the same late diagenetic, dark internal micrite.

A typical paragenetic sequence associated with the large borings suggests a complex and recurring series of events that also probably involved fluid-flow through the borings. For a typical sample (RK-4, Fig. 7D), a light-brown, detrital micrite matrix formed during diffuse seepage through seafloor sediments, and became indurated early in diagenesis. Nonetheless, fluid pressures subsequently built up from continuing seepage, eventually causing brecciation of the light-brown micrite, and filling of the breccia cavities with white, isopachous fibrous aragonite. During or shortly following this event, the substrate became lithified, because large clavate borings sharply cross-cut both the early micrite and fibrous aragonite. Regardless, continuing minor seepage is signaled by thin rims of white, isopachous aragonite lining some borings. Finally, a dark brown, pore-associated, silty micrite filled the borings, as well as any remaining fractures that had not earlier been cemented by aragonite. This cement-brecciation-boring-fill sequence (Fig. 7D) recurs at several locales, and implies that organisms were exploiting seep-carbonate surfaces before, during and after seepage, in physically and chemically dynamic environments.

The crests of some Miocene East Coast seep deposits are encrusted with caryophylliid coral thickets (Figs. 2C and 7F). These fossil corals, cf. *Goniocorella*, likely occupied seep-carbonate hardgrounds exposed above the muddy sediment–water interface. *Goniocorella* is known today from offshore New Zealand oceanic banks at water depths of 300–400 m (Cairns, 1995). Analogous modern deep-water corals associated with hydrocarbon seepage have been reported from offshore Norway

(cf. Hovland et al., 1998; Hovland and Risk, 2003), and from Eocene and Oligocene seep paleoenvironments in western Washington and Oregon, U.S.A. (Goedert and Peckmann, 2005).

3.5. Basal plumbing features and reworked seep-carbonates

Directly beneath some fossiliferous East Coast carbonate outcrops, various types of subsurface fluid “plumbing” structures are evident. For example, micritic nodules and irregular slabs

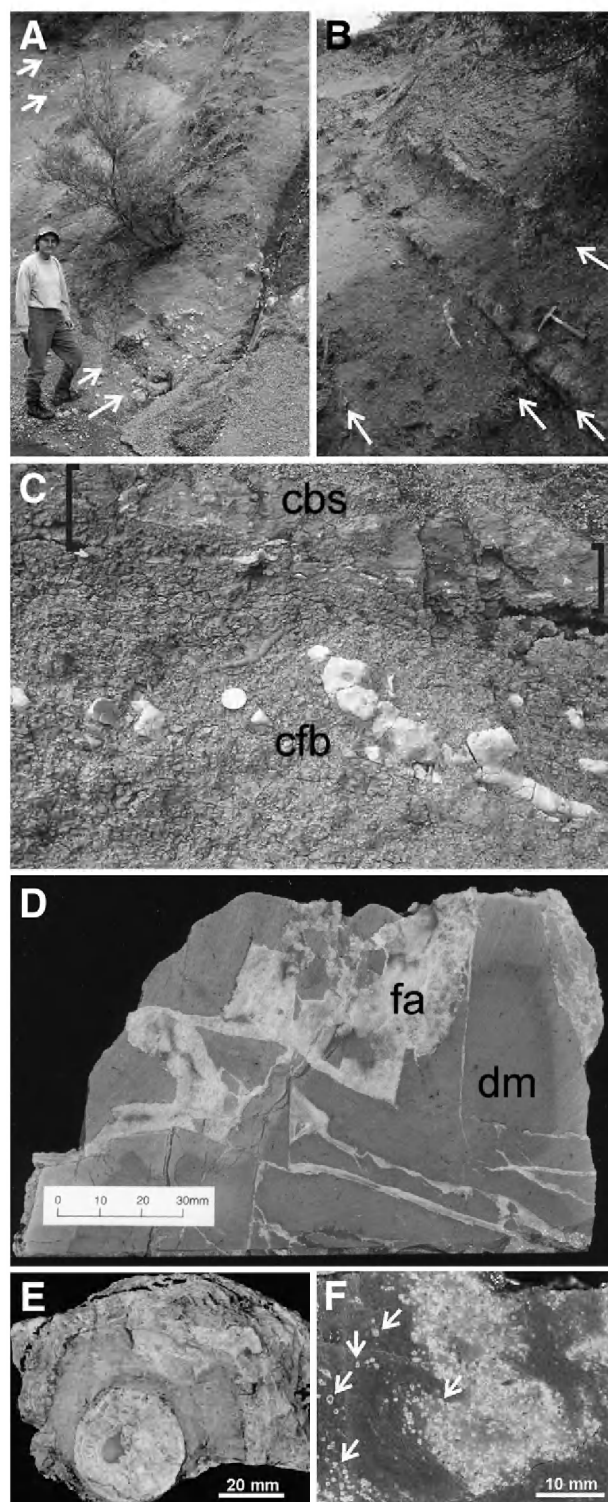


Fig. 8. Examples of inferred sub-seafloor seep-plumbing features, East Coast Miocene carbonate deposits. (A) Nodules and irregular beds of micrite precipitated in voluminous mudstones, in places following joints, at Karikarihuata; bedding arrowed. (B, C) Thin sandstone beds and burrows at Karikarihuata provided fluid pathways for migrating, hydrocarbon-infused fluids in otherwise impermeable muds, to deposit carbonate blebs in sandstone (cbs), or carbonate fill in burrows (cfb). (D) Breccias formed during fluid overpressuring to break through indurated micrite (dm), with cavities filling with pinkish-white, botryoidal or banded fibrous aragonite (fa) at Rocky Knob. (E) Some pinkish-white, fibrous aragonites fill circular vent conduits within micrites at Rocky Knob. (F) In places, mudstones at Karikarihuata are infused with diffuse, lighter-colored micrite that contain once-hollow, 100–1000 μm diameter micritic spheres (e.g. arrowed).

developed within thick mudstones, along bedding or in joints (Fig. 8A). Migrating fluids also deposited carbonate “blebs” (fine-grained carbonate with diffuse boundaries) within coarse sandstone horizons, or filled once-open burrows with micrite (Fig. 8B and C). Both the sandstones and burrows served as relatively permeable fluid pathways through otherwise tight mudstones. Thick bands of fibrous to botryoidal aragonite broke through indurated micrite to form vein breccias (Fig. 8D), or

circular conduits (Fig. 8E) within muddy sediments. In a few places, hollow micritic spheres occur (100–1000 μm diameter; Fig. 8F), possibly indicating the preserved remains of calcifying bubbles of methane forming in and/or moving through sediments (cf. Bohrmann et al., 1998). Near-vertical micritic pipes (Fig. 9A) are present at many sites beneath the main fossiliferous pods and lenses (the latter herein inferred as seafloor-associated; see Section 3.2). Some pipes, also described as tubular concretions

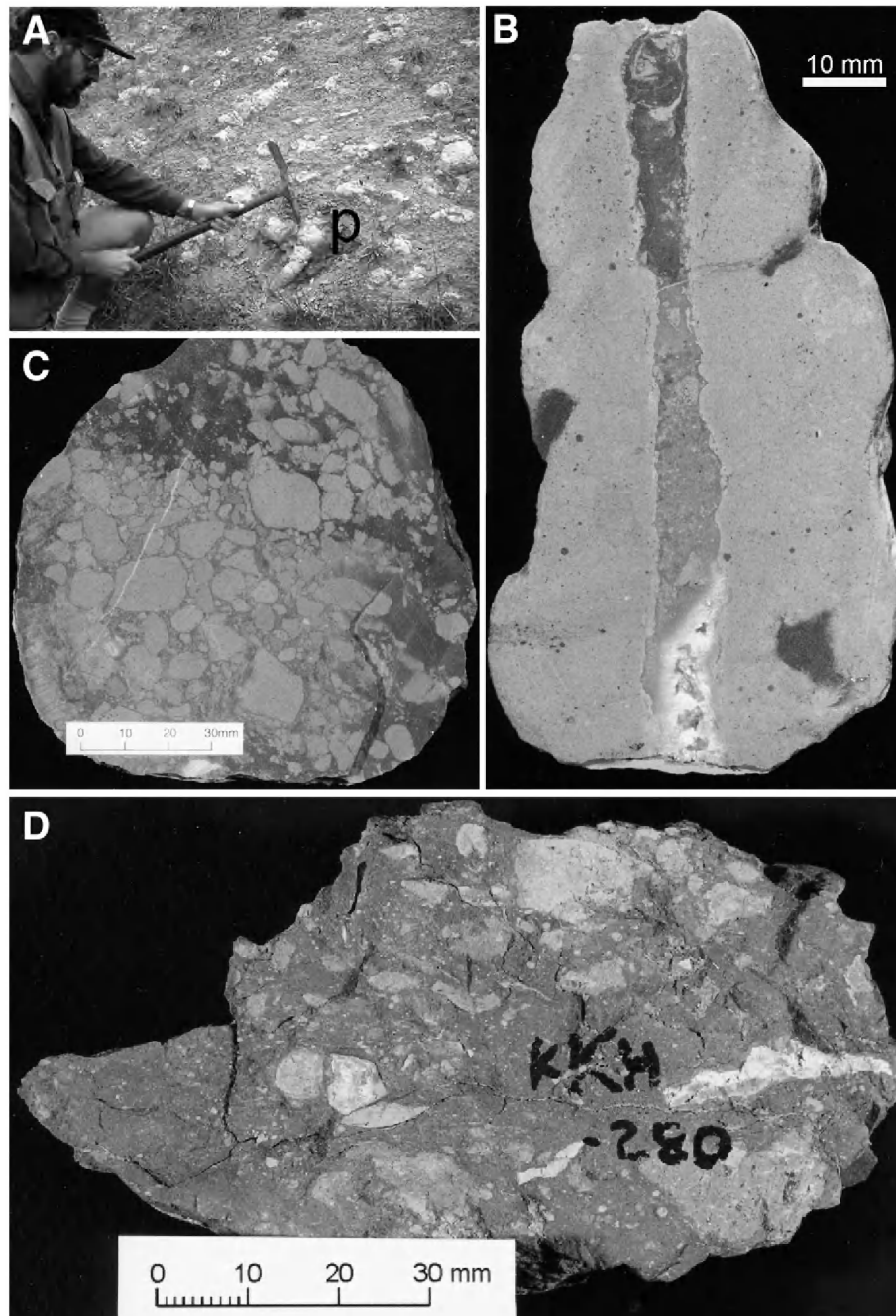


Fig. 9. Subvertical pipes and reworked carbonate clasts from mudstones directly beneath large pods and lenses of fossil-rich carbonate. These underlying beds are inferred herein as sub-seafloor features or reworked and redeposited by erosion or multi-phase venting episodes. (A) Near-vertical micritic pipes (“paramoudra”) and nodular micrite in mudstones, ranging from 3–10 m beneath fossil-rich, seafloor carbonates at Rocky Knob. (B) Some pipes contain central shafts filled with material of a different lithology, here from Karikarihuata. (C) Micrite breccia of subrounded clasts, with later cementation by additional micrite, perhaps formed by explosive release of gas (cf. pockmark formation), diapiric expansion, or by transport in slump debris at Karikarihuata. (D) Broken shells and stretched carbonate clasts at Karikarihuata, probably caught up in a physical reworking event before they were fully lithified.

from other areas of the North Island (cf. Nelson et al., 2004; Nyman et al., 2005), contain central shafts filled with material of a different lithology (Fig. 9B). They have been referred to as “paramoudra,” and interpreted as either cement-encrusted, tubular trace fossils (Mazengarb and Francis, 1985), or more recently as abiogenic fluid conduits (Campbell et al., 1999). Typically, these various plumbing features consist of detrital-rich micrite, are stratigraphically concentrated at the base of or in the mudstones beneath the larger pods of fossil-rich carbonates, and are devoid of megafossils. These inferred subsurface carbonates often weather to a distinctive light buff-color in outcrop (e.g. Figs. 2C and 9A). By contrast, the fossil-rich seafloor seep-carbonates (Section 3.2) generally weather to a darker, blue-gray or brownish green color. The seep-affiliated tubular concretions

are undergoing more detailed petrographic, mineralogic and geochemical study (Nyman et al., 2005; Nelson et al., 2007).

Both the subsurface and seafloor-associated carbonates are physically disturbed in places, probably by *in situ* gas explosion, diapiric expansion, erosional exhumation and/or submarine gravity sliding, because reworked micrite clasts are relatively common. Some hard carbonate substrates were ripped-up, with clasts extensively rounded during transport, before being redeposited and cemented into a micritic groundmass of somewhat different character (Fig. 9C). Thus, more than one phase of fluid seepage was archived. Other clasts are more stretched in appearance, possibly caught up in physical disturbance before they were fully indurated (Fig. 9D). Similar reworked seep-related carbonates have been reported from

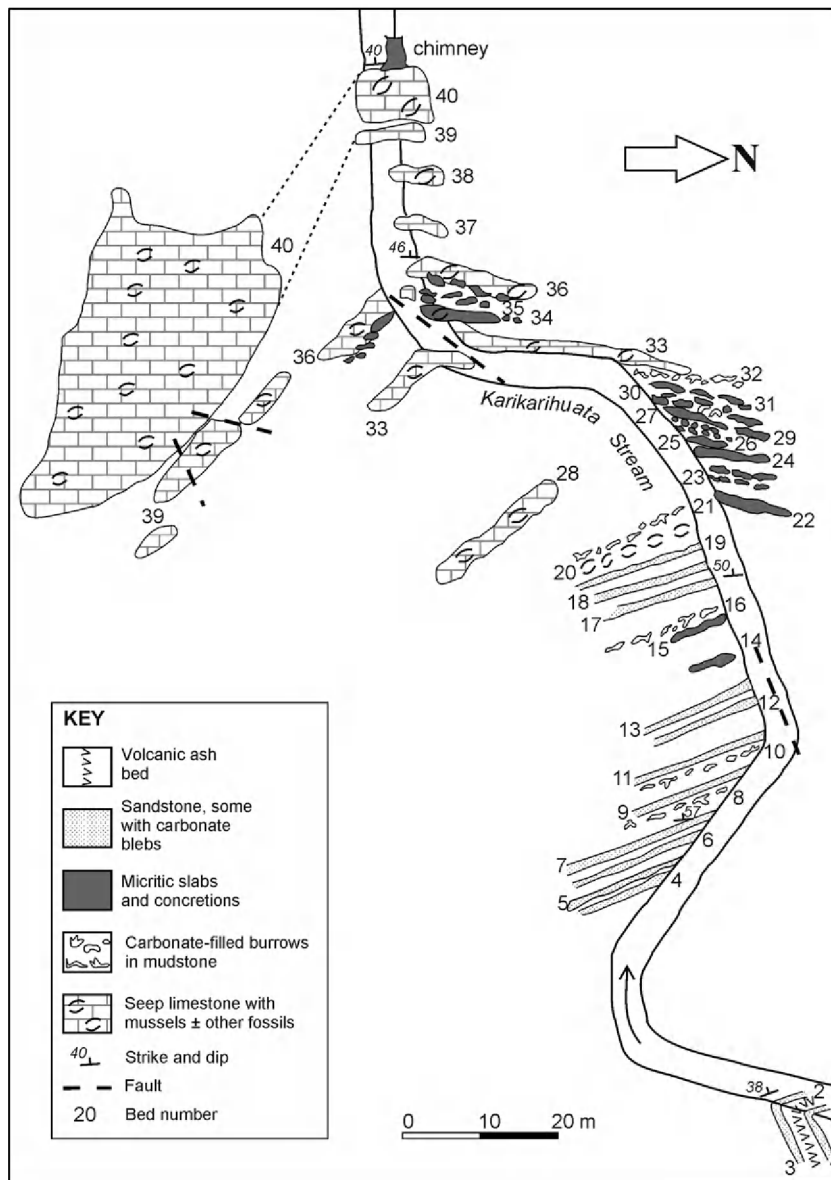


Fig. 10. Karikarihuata Stream outcrop pattern of mudstone, sandstone and carbonate bedding (site #3). Thin sandstone and variably thick carbonate beds are numbered sequentially up-section (beds 1–40), dipping westward downstream through the stream exposures. Seven distinct lithologies are present (see Fig. 11), from siliciclastic to mixed carbonate-siliciclastic to carbonate in composition. Total measured thickness of the section is 120 m.

Miocene mudrocks of the Italian Apennines (cf. Berti et al., 1994; Conti and Fontana, 1999, 2002, 2005; Conti et al., 2004; Lucente and Taviani, 2005), and are discussed further in Section 5.4 with respect to New Zealand examples.

4. Stratigraphic development of seep deposits: two case studies

Two well-exposed Miocene East Coast seep-carbonate sites north of Gisborne illustrate the internal anatomy of linked plumbing-surface seep features, as well as facies distributions of carbonates and faunas. Several distinctive lithologies allow differentiation among those seep-carbonates that developed in seafloor, sub-bottom and physically reworked paleoenvironments. These site analyses also revealed more in-depth spatial distributions of fossils across outcrops, illuminating recurring biofacies as well as showing clear paleoecological differences within sites.

4.1. Karikarihuata Stream locality

The Karikarihuata Stream seep-carbonates (Fig. 10) are surrounded by Middle to Upper Miocene mudstones (G.H. Scott, New Zealand Fossil Record File data). They lie between the northeast-trending Waihua and Waipapa faults, 800 m east of the junction with the Ihungia River, near the top of a generally west-dipping sequence of Early to Middle Miocene age that is terminated westward by the Waipapa Fault (Mazengarb et al., 1991). Although strata underlying the carbonate are predominantly mudstones, the overlying mid-Miocene section up to the Waipapa Fault consists of thin-bedded turbidite sandstones. In the study area, thin sandstone and carbonate beds of variable thickness dip westward, and are numbered sequentially on a map of the stream exposures (Fig. 10). The exposed section (beds 1–40) measures 120 m in thickness. The Karikarihuata Stream valley intersects lithologically varied strata, which collectively display a relatively uninterrupted stratigraphic history of fluid migration pathways and seep-carbonate formation at the site. Lithotype changes across the transition from subsurface plumbing to seafloor seeps are illustrated for a portion of the uppermost stratigraphic sequence (Fig. 11).

Seven lithologies are present (Figs. 10 and 11), of siliciclastic, mixed carbonate-siliciclastic, and carbonate makeup, in three stratigraphic zones. The lower sequence (horizons 1–19, 65 m thick) comprises mostly mudstone (lithology 1) that lacks megafossils. The mudrocks are punctuated by thin, planar sandstone beds (3–30 cm) with conspicuous, small (~1–4 cm diameter), scattered carbonate blebs along their bases (lithology 2, e.g. Fig. 8B and C). Micritic carbonate fills *Thalassinoides*-like burrows along some mudstone horizons subjacent to thin sands (e.g. Fig. 8B and C).

The middle sequence (horizons 20–32, 20 m thick; Fig. 10) exhibits more competent carbonates, namely irregular to bedding-parallel bands of cemented micritic nodules and slabs (to 1 m thick, 15 m across), with few to no fossils (lithology 3). It also contains intraformational breccias of variably cemented, matrix-supported, micrite-intraclasts (to 1.5 cm diameter) and some broken shell material, in indurated blocks up to 40 cm across (lithology 4). The breccias probably formed from fracturing by fluid over-pressuring

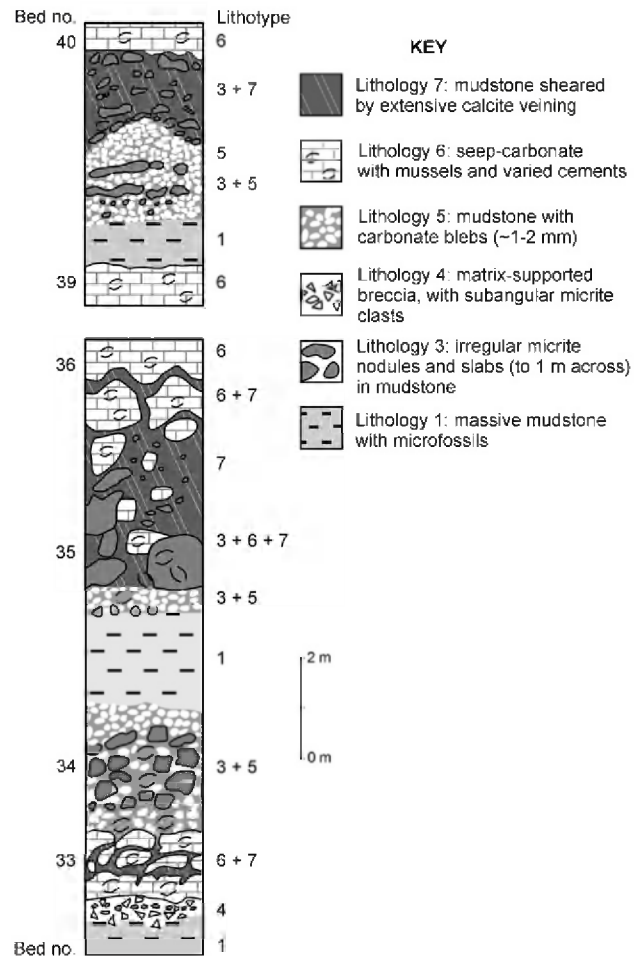


Fig. 11. Details of stratigraphic transition from sub-seafloor plumbing structures to fossiliferous seafloor seep-carbonates, uppermost section at Karikarihuata Stream (beds 33–36 and 39–40, cf. Fig. 10). Six of seven lithologies are represented; not shown are thin sandstone horizons (lithology 2), as these occur only in the lowermost part of the sequence. See Section 4.1 for details.

and/or sediment slumping. In the lower part of the middle sequence, a few horizons of somewhat more cemented mudstone occur, characterized by 1–10 mm accumulations of micrite with swirly, diffuse boundaries (lithology 5; e.g. Fig. 8F). Moreover, fossiliferous seep-carbonates were first encountered in the middle sequence, occurring in a few small lenses (*in situ*, to 2 m thick) or blocks (allochthonous), with mussels, nuculid bivalves, naticid gastropods, and calcareous tubes (lithology 6).

The upper sequence (horizons 33–40, at least 35 m thick; Fig. 10) is typified by thick (1–14 m), lens- and mound-like carbonates of lithology 6, typified by abundant megafossils and a range of carbonate cement types (e.g. micrite, fibrous aragonite veins and layers, pore-fill blocky calcite). Directly beneath most of these “classic” seep-carbonates (cf. Campbell, 2006), and illustrated in Fig. 11, the mudstones contain recurring bands of lithology 3 or 5, and/or are sheared extensively by calcite veining (lithology 7). Thus, lithologies 1 and 6 are inferred to have accumulated in bathyal seafloor environments; whereas, lithologies 2–5 and 7 are interpreted as sub-seafloor or physically reworked in origin. The intraformational carbonate breccias of lithology 4 require further investigation, in order to separate

subsurface auto-clastic features from potential gravity flows/slides that could have incorporated sediments from both seafloor and subsurface environments. The varied cements of lithology 6 indicate that carbonate formation was episodic, involved changing pore-fluid geochemistry, and continued for some time during the burial phase of the sediment pile (cf. Campbell et al., 2002; Peckmann et al., 2003; Conti et al., 2004).

Overall, there is an up-section trend of sub-seafloor micrite nodules (lithology 3) becoming larger and more common beneath each lens of fossiliferous seep-carbonate (lithology 6; cf. Fig. 11). The nodules gradually increase in size until they coalesce into larger slabs and form relatively continuous, irregular lenses. The fossil-rich, seafloor seep-carbonates also increase in size up to the uppermost outcrop (50 m × 30 m, 14 m thick; Fig. 2B), which exhibits at least two convex, mound-like features amalgamating upward, and a chimney-like fluid-escape structure emerging from its upper surface (Fig. 10).

4.2. Rocky Knob locality

The Rocky Knob seep-carbonate site (Fig. 2A) is located about 80 km north of Gisborne, where several promontories are

exposed above Limestone Stream (Adams, 1910), a tributary of the Waingaromia River. The carbonate deposit is Middle Miocene in age, based on microfossils in enclosing deep-water mudstone of the Tolaga Group (Mazengarb et al., 1991; Francis unpublished data). There is a larger triangular body (175 × 50 m in plan view), with steep headscarps that dip ~25°WNW, and a smaller, semi-circular knoll located at the northeast corner of the deposit, dipping ~28°NNW (Fig. 12). The carbonate has been partially quarried for use as a road aggregate, so that its original geometry is uncertain. Sub-seafloor “plumbing” features, in particular buff-colored tubular concretions and nodular micrite (e.g. Fig. 9A), occur in mudstones stratigraphically beneath the main, dark blue-gray colored, fossil-rich carbonate outcrops. The basal portions of the overlying main carbonate bodies consist of massive micrite (1–3 m thick) brecciated by fibrous aragonite veins, commonly oriented in three directions (Fig. 8D). Anastomosing firm-ground trace fossils with a dark micrite infill were contemporaneous with and post-date the vein aragonite. Thick, seafloor seep-carbonates with complex cement sequences and abundant megafossils lie directly above the massive micrite. Many outcrops are dominated by mussel beds, both *in situ* and para-

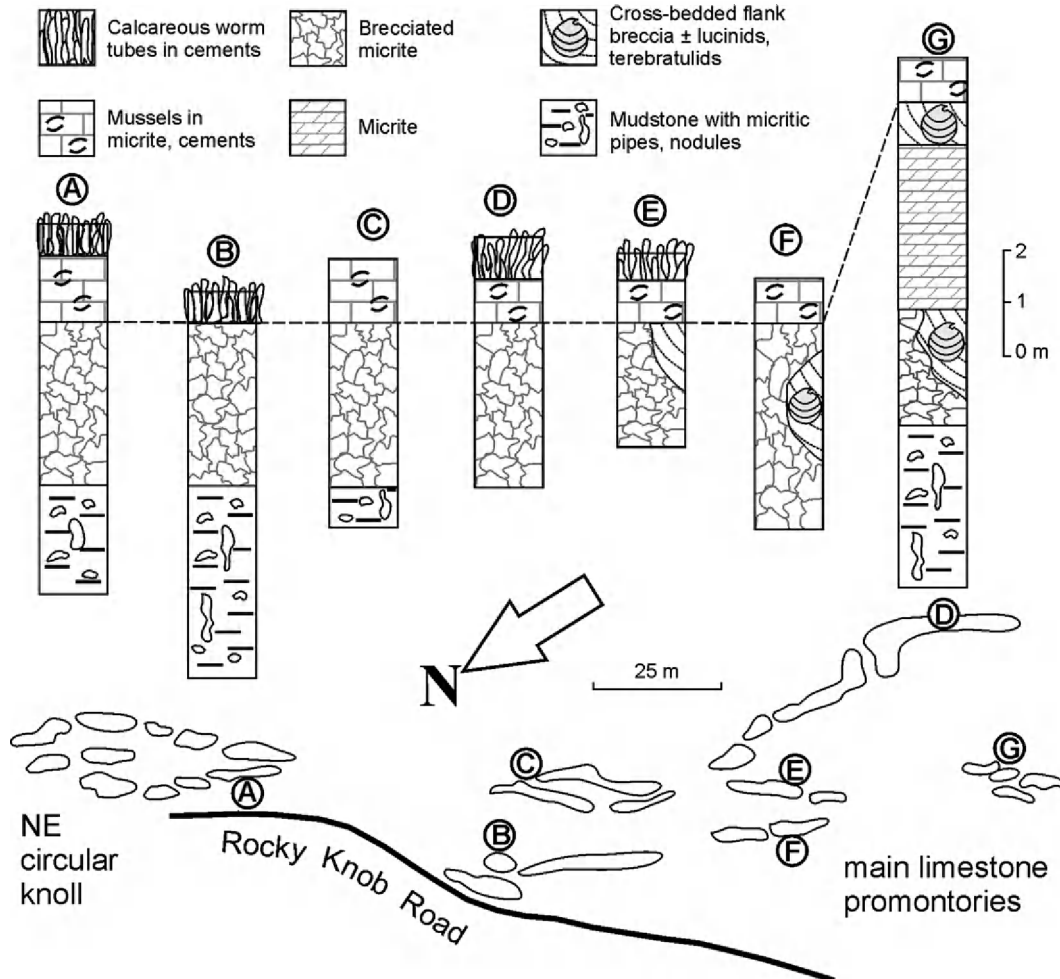


Fig. 12. Plan view sketch of seep-carbonate outcrops at Rocky Knob (site #3, lower drawing), which consist of a large triangular body (175 × 50 m in area) dipping 25°WNW (sites B–G inclusive), and a smaller, semi-circular knoll, located at the NE corner of the deposit and dipping 28°NNW (site A). Simplified stratigraphic columns (A–G, upper drawing) from around the Rocky Knob locality illustrate the gross progression of lithologies and fossil biota.

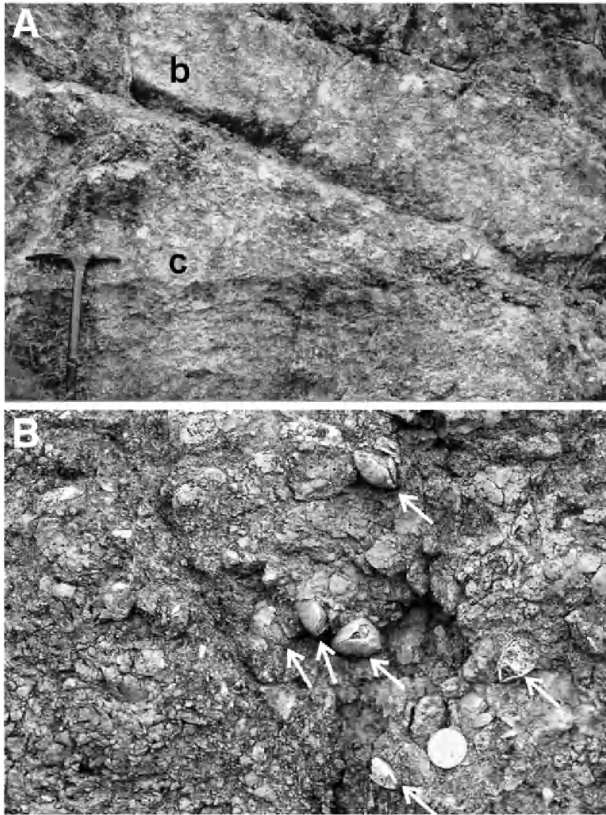


Fig. 13. Cross-bedded coarse breccia at Rocky Knob, with broken and entire shells of the distinctive flank facies association. (A) Large-scale cross-bedding (c) in a typical flank facies deposit; bedding (b). (B) Detail from a sedimentary breccia site that displays different carbonate clast sizes and shapes, and broken fragments of mussels and other fossils. The coarse breccia was populated by gregarious associations of lucinid bivalves (arrows pointing to some articulated shells).

autochthonous, with associated limpets and naticid gastropods. The mussel beds are commonly overlain by thickets of calcareous tubes (e.g. Fig. 4B and C). Simplified stratigraphic columns from around the Rocky Knob locality illustrate the gross distributions of lithologies and fossil biota (Fig. 12).

Another type of breccia found in several places around the margin of the main carbonate body at Rocky Knob is a cross-bedded flank facies deposit (Fig. 13A). Different subrounded to angular carbonate clasts (to 4 cm diameter) are incorporated into the slumped material, as are broken fragments of mussels and other fossils. The coarse sedimentary breccia was populated by lucinids, now preserved as gregarious clusters of articulated individuals among the carbonate clasts (Fig. 13B). Articulated brachiopods also occur in these coarse flank facies, whereas finer grained breccias (to 3 mm clast diameters) were inhabited by small gastropods.

5. Discussion

Several aspects of the East Coast Miocene seep-carbonates are noteworthy, such as the distinctive biotic zonation patterns within sites, and geographic differences in carbonate-organism distributions from north to south. The carbonates also contain abundant evidence for borings into exposed/exhumed substrates on the

seabed, a feature common at modern seeps but not generally reported from other ancient hydrocarbon seeps. Moreover, well-exposed stratigraphic transitions occur at some localities, from subsurface to near-seafloor carbonate formation. Stable isotopic compositions of seafloor seep-carbonates also cluster according to cement type and/or geographic location, and indicate fluid mixing and diagenetic trends. Finally, the New Zealand examples are strikingly similar to Miocene seeps of the Italian Apennines with respect to lithology, setting and isotopic composition.

5.1. Carbonate-organism distribution patterns: within-site zonation and geographic differentiation

At northern locales, distinct biotic zonation patterns can be recognized from vents to more distal areas of seepage. Specifically, microbialites (i.e. buff-colored micrite with clotted to digitate thrombolitic macrotextures) are best preserved where fibrous to botryoidal aragonite occurs in thick isopachous layers and circular radiating features (cf. Fig. 4D). Similar aragonitic textures at modern seeps are interpreted to have formed rapidly near vent fluid-conduit areas, typified by vigorous hydrocarbon fluid flow and/or decomposition of ancient gas hydrates (cf. Greinert et al., 2001). Pinkish aragonite or calcite veins are also found in sheared micrite or mudstone beneath some fossil-rich carbonate pods and lenses (Figs. 8D and 11). These veins represent near-subsurface, advective plumbing that fed ancient seafloor seep sites (cf. Burton, 1993; Schwartz et al., 2003). Worm tubes and mussels are also common at northern sites. Whereas the tubes tend to be associated with fibrous cement precipitation, suggestive of advective flow, the mussels are embedded in detrital micrite, indicative of relatively diffuse fluid flow through seafloor sediments (cf. Ritger et al., 1987; Campbell et al., 2002). At the large Rocky Knob deposit, lucinid bivalves and terebratulid brachiopods are affiliated with the cross-bedded, flank facies breccias (Fig. 12), presumably representing submarine talus piles distal to central vent areas. Hence faunal and lithological zonations, likely controlled by differential fluid fluxes, are evident in the northern East Coast seep-carbonate deposits.

Similar distributions have been reported from modern gas hydrate regions of the Cascadia convergent margin, whereby decreasing sulfide-flux through sediments causes biotic zonation from *Beggiatoa* microbial mats at vents, to *Calyptogena* clusters, to finally solemyid bivalve (*Acharax*) associations at outer seep areas (Sahling et al., 2002). Other ancient seeps also show analogous, lateral mega-faunal zonations away from main seepage areas (e.g. Nesbitt and Campbell, 2004; Jenkins et al., 2007).

Southern Miocene East Coast seep-carbonates are less well-known compared to northern sites, but clear lithological and faunal patterns have been identified in this reconnaissance study. In particular, paragenesis appears to have been less complex in the south, with most known deposits exhibiting sandy to conglomeratic lithologies, and few carbonate cements. Common taxa at southern sites include vesicomylid and lucinid bivalve fossils, rather than the dominance of mussels and worm tubes seen at northern sites. The lithological–faunal association

observed in Miocene southern seep-carbonates has been documented from dredge samples at modern seeps offshore. Sandy micrites with abundant vesicomyids are known from Ritchie Ridge off Gisborne (1000–1202 m; 39°26.39'S, 178°23.56'E), and Groomes Hill on Puysegur Bank (950–970 m; 46°57.64'S, 165°25.21'E). As southern and northern Miocene seep-carbonates display different lithologies, fauna and stable isotopic signatures (see also Section 5.2), fluid sources were also likely to have been different.

5.2. Stable isotopic patterns

The stable isotopic patterns from the New Zealand Miocene seep pilot data (Fig. 6) fall within the range reported for Cenozoic to modern seep-carbonates worldwide (Campbell, 2006, Group II, Fig. 9A), especially for the early diagenetic carbonate phases sampled. The presence of methane at the New Zealand sites caused the isotopically depleted carbonate-carbon signatures. Positive oxygen isotopic data from the early diagenetic cements suggest precipitation in equilibrium with cold bottom water (few degrees C; Greinert et al., 2001) and no recrystallization during diagenesis, perhaps with input from meteoric waters (cf. Nelson and Smith, 1996). The negative shift in $\delta^{18}\text{O}$ values to -5% PDB for the late-stage carbonates is consistent with other seep deposits elsewhere, with diagenetically driven changes in the oxygen isotopic composition due to recrystallization at higher burial temperatures and/or a meteoric water influence (Campbell, 2006, Fig. 9A).

At least two aspects of this reconnaissance isotopic study require further investigation. First, the origin and significance of the late-stage, pore-filling, dark, silty micrite needs elucidation, especially since borings filled with this phase (e.g. Fig. 7D) imply increasing substrate lithification and exhumation of the carbonate. Borings are common in modern seep-carbonates exposed on the seafloor, but only rarely have been mentioned from ancient seep deposits (e.g. Campbell et al., 2002; Conti and Fontana, 2005, Fig. 11). Second, the paleoenvironmental implications of the enriched carbonate-carbon from the few southern sites sampled needs further study, with more field and laboratory work already underway (Greinert and others, unpublished). The southern samples of this study were taken from archived national collections, and show clear sedimentologic and faunal differences compared to northern sites. Isotopic mixing between bicarbonate produced during diffuse methane seepage and that generated by breakdown of organic matter in marine sediments (cf. Nelson and Smith, 1996) is one possible explanation for the less negative carbonate-carbon values from the south. Such mixing might have been more easily facilitated by the relatively more porous (sandy) sediments associated with these particular seeps.

5.3. Ages of seeps and their distributions with respect to sedimentary basin history

The seep-carbonates in the East Coast Basin occur predominantly in very thick mudstone-dominated sequences that were deposited in deep-water (outer shelf to upper bathyal).

Their ages range from Early, perhaps basal Miocene (in the southern localities and also at Waipiro Stream in the north), through Middle Miocene (most of the northern localities) to Late Miocene (Turihau). There are no known seep-carbonates in Paleogene sequences (including Waipawa, Wanstead, and Weber formations; see Fig. 3) and, as yet, none are known in exposed Pliocene strata. Although thick mudstone-dominant sequences of deep-water facies suitable to develop seep-carbonates occur in the Pliocene section, these are not well-exposed except in the northern basin. The deep-water Pliocene section is known mainly through petroleum well intersections in the southern onshore part of the basin (especially in central Hawke's Bay), and also in limited offshore wells. Some tubular concretions that probably originated through methane seepage are known in deep-water mudstone of Early Pliocene age in the northern basin (Mazengarb and Francis, 1985).

Beginning at about earliest Miocene and continuing through the whole of the Neogene, the East Coast Basin has been subjected to the initiation and continued tectonism on the Australian/Pacific boundary. Intense transpression along this subduction margin resulted in the development of a series of mainly east-verging reverse faults and thrusts, major normal growth faults, and numerous elongate sub-basins and highs of differing dimensions. Rapid sedimentation resulting from nearby arc volcanism and erosion of the uplifted foreland, and significant burial of underlying Paleogene and Cretaceous formations, have combined to produce a scenario conducive to expulsion of large volumes of fluids from forearc sediments during the Miocene.

5.4. Comparisons with Miocene seep settings of the Italian Apennines

The Middle to Late Miocene seep-carbonates of New Zealand's East Coast Basin share many similarities with ancient seep deposits of the Italian Apennines. In particular, they are of overlapping age, and many developed in foredeeps where fluid-flow was driven by convergence. Their structural and stratigraphic settings are also similarly varied. Moreover, the two ancient hydrocarbon seep provinces are rich in chemosynthesis-based fossil assemblages, and exhibit similar lithologies, paragenesis and spread in measured stable isotopic values. The Italian examples are scattered throughout fine-grained siliciclastic and marly sequences associated with closure of the Ligurian–Piedmont Ocean (Tethys) and collision of the European plate and Adriatic microplate, causing thrusting and compressional deformation in foredeep, satellite and other basins (Ricci Luchi and Vai, 1994; Conti and Fontana, 1999; Conti et al., 2004). Various lithotypes of the Italian seep-carbonates are strikingly akin to the New Zealand examples described herein. These include thick fibrous aragonite bands; micrites \pm lucinids or mussels; extensive calcite veins and/or carbonate pipes; and several types of carbonate breccias (Clari et al., 1988; Conti et al., 2004; Conti and Fontana, 2005). The Italian examples have been compared to modern hydrocarbon seep-carbonates from the North Sea, Oregon (Cascadia) accretionary prism and northern Gulf of Mexico (Taviani, 1994; Terzi et al., 1994; Conti and Fontana, 2002).

Sedimentary structures and stratigraphic relationships of the Italian carbonates and their enclosing strata indicate excessive pore-fluid pressures, diapirism and sediment instability that were likely triggered by continuing methane seepage and possibly also gas hydrate dissociation during the Miocene (cf. Berti et al., 1994; Clari et al., 1994; Conti and Fontana, 1999, 2002; Conti et al., 2004). The intrinsic mobility of the developing orogenic belt caused the dynamic gas-related fracturing of older rocks, collapsing and squeezing of basal muds, and lateral/vertical migration of methane from previously confined source areas (Ricci Luchi and Vai, 1994). Fewer lithotypes have been identified in this New Zealand reconnaissance study, as compared to the detailed assessments made during intensive research in the Apennines over the past decade (e.g. Conti and Fontana, 2005; Conti et al., 2007). However, the geologic complexities suggested by the New Zealand seep deposits, as currently known, are likely to more fully emerge with further study of the relationships between these unusual carbonates and the stratigraphy and structure of the East Coast region.

6. Conclusions

A 22 million year record of hydrocarbon seepage is recorded in seep-carbonates of the Miocene East Coast Basin forearc and the modern offshore Hikurangi convergent margin, eastern North Island, New Zealand. The exhumed onshore seep-carbonates (14 studied) are enclosed in voluminous, deep-water mudstones and alternating, thinly bedded mudstones and fine sandstones. The geographically isolated carbonates are isotopically depleted in carbonate-carbon, and contain fossils typical of chemosynthesis-related communities. Within-site faunal zonation is evident at some sites. These isolated pods and lenses of authigenic carbonate also show regional differences in lithologic, stable isotopic and paleontological content that require further investigation. The rocks share many similarities with seep-carbonates of the same age in the Italian Apennines, including representative lithologies that formed in sub-bottom, seafloor and physically reworked depositional settings. The New Zealand deposits are unique in exposing plumbing features, a whale fall, firmgrounds, hardgrounds, fossil coral thickets, and extensive thrombolites in several deposits. Their faunas indicate associated seep and non-seep invertebrate taxa, some of which may have affinities to modern hydrothermal vents or hydrocarbon seeps elsewhere on the Pacific Rim.

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