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Ichnology and sequence stratigraphy of the early permian pebbley beach formation and snapper point formation in the southern Sydney basin

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ICHNOLOGY AND SEQUENCE STRATIGRAPHY
OF THE
EARLY PERMIAN
PEBBLEY BEACH FORMATION
AND
SNAPPER POINT FORMATION
IN THE
SOUTHERN SYDNEY BASIN.

A thesis submitted in fulfillment of
requirements for the degree of

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by

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Except where otherwise acknowledged, this thesis represents the author's original research, which has not previously been submitted to any institution in partial or complete fulfillment of another degree.

K. L. BANN
August 1998
ABSTRACT

The Early Permian sequences of the Pebbley Beach and Snapper Point Formations in the southern Sydney Basin are interpreted as a complex of wave-dominated, aggradational, siliclastic shoreline parasequences deposited during a period of thermal basin sag. An ichnotaxonomic list containing 43 species from 29 genera is provided for these strata and four new ichnospecies are defined; *Cylindrichnus eccentricus*, *Teichichnus sinuosus*, *Taenidium synyphes* and *Rosselia motivus*. A previously unsubstantiated link between *Asterosoma*, *Rosselia* and *Cylindrichnus*, which also contains *Teichichnus* as an intergradational end member, is clearly established.

Roughly one third of the Pebbley Beach Formation consists of a wave-dominated, microtidal barrier island complex. Alternating changes in trace fossil assemblage diversity and ichnofabric complexity throughout the sequence provide evidence for variation in bathymetry and energy levels. Stratification of a low diversity, opportunistic, restricted Cruziana ichnofacies with a higher diversity opportunistic Arenicolites ichnofacies, reflects the storm-washover of marine sands into a brackish backbarrier environment.

Sedimentary facies ranging from lower offshore to foreshore occur in the remainder of the Pebbley Beach and Snapper Point Formations; these facies can be readily defined through the integration of ichnofacies, ichnofabric and sedimentological characters. Analysis of ichnofabrics and ichnofacies has allowed subdivision of the offshore and lower shoreface facies into sub-facies on the basis of degree of storm influence. Each sedimentary facies contains characteristic ichnofabrics and ichnofacies.

Four distinct ichnofacies are recognized in the study area, the Skolithos, Cruziana, Arenicolites ichnofacies and Glossifungites ichnofacies. The Cruziana ichnofacies is subdivided here into four categories, proximal, diverse, and distal open marine subfacies and restricted brackish water subfacies. The Glossifungites ichnofacies occurs along transgressive surfaces of erosion in the Pebbley Beach Formation and at the base of the Snapper Point Formation.

Lower offshore facies in the Pebbley Beach and Snapper Point Formations are storm influenced to strongly storm-dominated and characteristically contain complex ichnofabrics comprising a fairweather distal Cruziana ichnofacies assemblage with an associated opportunistic Arenicolites ichnofacies assemblage in storm-deposited units.

Upper offshore and offshore transition facies in the study area are storm influenced to strongly storm-dominated and tempestites comprise a high proportion of the facies. Consequently ichnofabrics
are composite and comprise complex mixtures of proximal or diverse Cruziana ichnofacies, reflecting fairweather conditions, and Arenicolites ichnofacies reflecting opportunistic colonization of storm beds.

Lower shoreface facies are characteristically storm-dominated in the Pebbley Beach and Snapper Point Formations. They contain composite ichnofabrics produced by an Arenicolites ichnofacies, which reflects storm deposition, and a proximal Cruziana ichnofacies reflecting fairweather conditions. A glacially influenced deposit in the Pebbley Beach Formation containing a mixed distal Cruziana / Glossifungites ichnofacies is also interpreted as lower shoreface facies affected by alternating perennial and seasonal ice cover.

Upper and middle shoreface facies are wave-dominated and characteristically contain a Skolithos ichnofacies with rare resilient proximal Cruziana ichnofacies. Tide-dominated foreshore facies occur at the top of the Snapper Point Formation and are exclusively inhabited by a Skolithos ichnofacies reflecting ongoing high levels of hydrodynamic energy.

The Pebbley Beach and Snapper Point Formations consist of parasequences combined to form parasequence sets. The Pebbley Beach Formation contains four parasequences which display an overall basinward facies shift and occur as regressive half sequences separated by thin transgressive deposits. The lower Snapper Point Formation contains nine parasequences that have thick transgressive half sequences reflecting rapid creation of accommodation space balanced by a very high rate of sediment supply. The upper Snapper Point Formation marks an environmental change to a tide-dominated constricted seaway and parasequences become progradational. This latter change resulted from the emergence or near emergence above sea level of the developing Curranong orogen to the east. The overall aggradational pattern of the Pebbley Beach and Snapper Point Formations reflects a sediment supply that balanced the creation rate of accommodation space.

Fourth and fifth order Milankovitch cyclicity recognised in this succession is attributed to eustatic (commonly glacio-eustatic) change. The Pebbley Beach and Snapper Point Formations are a part of a larger third order cycle, which was controlled by combined tectonic and glacial eustacy.

The overall transgression represented by the Pebbley Beach and Snapper Point Formations is marked by the *Eurydesma* fauna. This transgression corresponds to the Tastubian Transgression that affected most other Permian Gondwanan Basins. The maximum flooding surface in the overlying Wandrawandian Siltstone marks the onset of the Sterlitamakian regressive phase which is attributed here, and throughout the Permian Gondwanan Basins, to tectonically induced eustacy.
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CHAPTER 1: INTRODUCTION

The study area comprises the Early Permian Pebbley Beach and Snapper Point Formations that form a part of the southernmost Sydney Basin. The Sydney Basin forms part of the larger Permian to Triassic Sydney-Bowen Basin system (Fig. 1.1). The ichno-sedimentology and cyclostratigraphy of all Permian strata along the coast between Jervis Bay and Point Upright (Fig. 1.2) were comprehensively examined in order to explain the depositional history, palaeogeographical development and relationship of the depositional system to other Permian basins along the Panthalassan margin of Gondwana.

1.1 ICHNOLOGY:

Ichnology is the study of biologically produced sedimentary structures, or of animal-sediment relationships (Pemberton 1992). Trace fossils record fossil behaviour and are often difficult to identify and classify phylogenetically. Most can however, be allocated to a behavioural, preservational and environmental category. Trace fossils are environmentally sensitive to bathymetry, energy levels, aeration, rate of deposition, food abundance, substrate stability and salinity and, therefore, hold enormous potential for sequence stratigraphic studies. Variations in the nature of trace fossil assemblages, even when the strata contain a single ichnofacies, can reflect palaeoenvironmental changes that are predicted in the sequence stratigraphic paradigm to occur in response to sea level dynamics (Savrda 1991).

Despite its potential utility, ichnological analysis has received very little attention in sequence stratigraphic studies in Australia.

A systematic study of the ichnological variability within depositional cycles of the Pebbley Beach and Snapper Point Formations (as a function of lithology, depositional environment and absolute water depth) demonstrates that ichnological analysis can greatly increase the resolution of a sequence stratigraphic interpretation. The degree of bioturbation, general ichnofabrics, and assemblages of discrete trace fossils vary throughout the two formations and principally reflect changes in physical environmental energy, substrate consistency, sedimentation rate and bottom- and/or pore-water chemistry that are consistent with the phases and magnitude of associated sea-level fluctuations.
1.2 THE SYDNEY BASIN

1.2.1 Tectonic Development of the Sydney Basin

The Sydney-Gunnedah-Bowen Basin (Fig. 1.1) is related to the major Permian to Triassic Pangean basins along the Panthalassan margin of Gondwana. This major system occurs in eastern Australia, Antarctica, South Africa, South America and India. Pre-Permian eastern Australia had a complex tectonic history, a detailed discussion can be found in Murray et al. (1987) and Fergusson & Leitch (1993).

During the Late Carboniferous, collision between a mid-ocean ridge and a trench system resulted in a change from a convergent plate margin to a dextral transform margin (Murray et al. 1987, Fergusson & Leitch 1993) and caused cessation of convergent tectonics along the eastern Australian margin. Basin development was related to transtension associated with the rotation and heat release within Pangea (Veevers et al. 1994a). The Permian to Triassic history of the basin was divided into seven stages by Veevers et al. (1994b). These stages are in agreement with those outlined by Baker et al. (1993, Fig 1.4).

During the Early Permian (290-268 Ma), a convergent tectonic regime was re-established and extension and volcanism was initiated. Sedimentation was restricted to sub-basins that developed as a result of rifting (stage A, Veevers et al. 1994b). Stage B consists of a general sag over the entire platform which resulted in marine conditions and the initiation of an embryonic magmatic arc and foreland basin between 268-258 Ma. The magmatic arc is represented by the present position of the New England Fold Belt in eastern Australia. After 258 ma (the approximate age of the Hunter Bowen Orogeny), The Sydney-Bowen Basin had developed into a mature foreland basin (stages C-F). The foreland stage continued until rifting of the orogen occurred during stage G in the late Triassic.

1.2.2 Early Permian Stratigraphy of the Sydney Basin

The Pebbley Beach and Snapper Point Formations comprise a part of the Sakmarian to Artinskian Shoalhaven Group which, along with the older (Sakmarian) Talaterang Group, forms the basal part of the Sydney Basin succession at its southernmost onshore extremity. The Sydney Basin comprises part of the larger, north-south trending, elongate Sydney-Gunnedah-Bowen Basin, which has a complex tectonic history. Rifting was initiated in the Late Carboniferous to Early Permian, possibly within a backarc environment (Scheibner 1974,
Battersby 1981, Murray 1990, Fielding et al. 1990). A phase of passive thermal subsidence followed the rifting stage (Tye et al. 1996) and in the Late Permian the basin became a foredeep or retro-arc foreland basin of the New England Fold Belt (Scheibner 1993), flanked to the west by the Lachlan Fold Belt and to the east by a resurgent and emergent volcanic arc (Tye et al. 1996). In the southern part of the Sydney Basin, the Permian sedimentary deposits overlie highly deformed Ordovician, Silurian and Devonian rocks of the Lachlan Fold Belt.

In the most southeastern extremity of the Sydney Basin, between Myrtle Beach and Wasp Head (near Batemans Bay), the Wasp Head Formation unconformably overlies the folded deep-marine shale and chert of the Ordovician Wagonga Beds. The Wasp Head Formation consists of two upward-deepening sequences of upper shoreface to transition offshore facies (interbedded sandstone and siltstone) with numerous large dropstones (Tye et al. 1996). At the base of the formation, large breccia beds represent debris flow deposits locally derived from a north-trending tectonic slope (Tye et al. 1996) representing a graben or half graben margin. The Wasp Head Formation is laterally equivalent to the Clyde Coal Measures and the alluvial and overbank facies of the Pigeon House Creek Siltstone (Tye et al. 1996) both of which occur in the southwestern part of the lower Sydney Basin. These three sedimentary successions comprise the Talaterang Group.

The Shoalhaven Group disconformably and erosionally overlies the Talaterang Group and comprises a series of stratigraphic units interpreted by Tye et al. (1996) as being of marine shelf to coastal-plain origin, together with coarse-clastic high-energy alluvial facies of the Yadboro and Tallong Conglomerates. Where the Talaterang Group is absent the Yadboro and Tallong Conglomerates unconformably overlie Ordovician basement. These two conglomerate facies were originally assigned to the Talaterang Group by Gostin and Herbert (1973) but Tye et al. (1996) argued that the setting and lateral facies relationships, with the coarse-grained units passing laterally into Pebbley Beach and Snapper Point Formations, are such that they should be considered part of the Shoalhaven Group. This revised lithostratigraphy for the southern Sydney Basin is seen in Figure 1.3.

The Pebbley Beach Formation unconformably overlies the Wasp Head Formation in the Durras region. The contact is visible on Wasp Island where it is erosional and represents a hiatus. Pebbley Beach Formation outcrop extends along the coast from Point Upright to Clear Point and a small section is present at South Island Beach where the contact with the overlying Snapper Point Formation is visible beneath a coarse sandstone bed with an associated Glossifungites ichnofacies. The sandy marine facies found near the base of the Sydney Basin sequence in all of the Elcom Clyde River drillcores shows no silt-dominated facies typical of the
Pebbley Beach Formation and the latter is, therefore, restricted to the southeastern extremity of the basin, south of Termeil (Tye et al. 1996). The Pebbley Beach Formation is laterally equivalent to the Yarrunga Coal Measures which represents a coastal plain succession overlying and laterally adjacent to the Tallong and Yadboro Conglomerates (Tye et al. 1996).

The Snapper Point Formation conformably overlies the Pebbley Beach Formation. It is dominated by shallow marine facies and displays a broad sheet-like architecture. In the west it interdigitates with, and then overlies the upper Tallong and Yadboro Conglomerates and, where present, the Yurrunga Coal Measures (Tye et al 1996). It unconformably overlies basement where all older non-marine Permian units are absent. Where the Snapper Point Formation interdigitates with the Yadboro and Tallong Conglomerates there is local evidence of fluvial deposition. These fluvial deposits were referred to as the Jindelara fluvial facies by Evans et al. (1983) but included within the Snapper Point Formation by Tye et al. (1996) as they are lithologically equivalent and do not constitute a distinct and mappable lithology. Above the Yadboro Conglomerate fluvial intervals were probably deposited on a braidplain delta, as defined by McPherson et al. (1987) and Orton (1988), and represent a series of progradational river facies from the Yadboro Conglomerate deposited into a wave-dominated marine environment (Tye et al. 1996).

The Permian units above the Snapper Point Formation also display a sheet-like architecture (Herbert 1980). The Wandrawandian Siltstone overlies the Snapper Point Formation and represents fine-grained offshore facies, deposited following a major transgression. This is overlain by the Nowra Sandstone which was deposited in a middle to upper shoreface environment under the influence of north-directed longshore currents (LeRoux & Jones 1994). Another fine-grained offshore facies, the Berry Siltstone, deposited after a major transgressive event, overlies the Nowra Sandstone. The uppermost unit of the Shoalhaven Group, the Broughton Formation, marks the onset of a major phase of shoshonitic volcanism and reorganization of sediment provenance and dispersal (Tye et al. 1996) which was influenced by north-directed tidal currents (Bull & Cas 1989).

1.2.3 Previous Work in the Southern Sydney Basin

Some of the earliest stratigraphic studies of the southern Sydney Basin were carried out by David & Stonier (1891) and Harper (1915). McElroy & Rose (1962) proposed the first comprehensive stratigraphic model of the area that was later modified by Gostin & Herbert (1973) and Herbert (1980). Tye (1995) and Tye et al. (1996) carried out an extensive study of
the southern Sydney Basin which included a sequence stratigraphic interpretation based on coastal and inland outcrop, drillcore and pre-existing data, and presented a revised lithostratigraphic model which is consistent with the tectonic development of the basin (Fig. 1.3).

Gostin (1968) undertook the first detailed study of the coastal exposures of the southern Sydney Basin. This study was extended by Carey (1978), Ramli and Crook (1978), McCarthy (1979), Runnegar (1980), Stutchbury (1989), Bann (1990), Mifsud (1990), Straub (1993) and Tye (1995).

Authors such as Carey (1978), McCarthy (1979) and Runnegar (1980) provided limited ichnological interpretations.

Eyles et al. (1997) and Eyles et al. (1998) provided depositional and environmental interpretations of the lower Shoalhaven Group focussing on glacial influences but these studies were significantly flawed by a number of erroneous ichnological and environmental interpretations.

1.3 AIMS

To date there has been no detailed and comprehensive ichno-sedimentological study of the southern Sydney Basin. The tectonic context and the controlling mechanisms of sedimentation have been extensively addressed by Tye (1995) and Tye et al. (1996) but ichnological information that has the potential to yield high resolution sedimentological, palaeoenvironmental and cyclo-stratigraphic interpretations has not been adequately assessed. This study will attempt to redress these inadequacies through detailed ichnological and sedimentological analysis. The central focus of this study will be the ichnology and sedimentology of the upper Pebbley Beach Formation and the exposed eastern part of the Snapper Point Formation which comprise the lower part of the Shoalhaven Group. Individual trace fossil species (chapter 2) and combined ichnofacies and ichnofabric data (chapter 3) will be examined and the information gained will be used in association with sedimentological data in an attempt to construct a detailed environmental history (chapter 4) of the sequence. Finally a detailed cyclostratigraphic and eustatic history will attempt to relate these units to the rest of the Sydney Bowen Basin and to the other glacially influenced Permian basins along the Panthalassan margin of Gondwana.

Specific questions that form the focus of this study of the Pebbley Beach and Snapper Point Formations are:
1. Are existing ichnofaunal lists adequate?

2. What kind of environmental information can be extrapolated from interpretation of the individual ichnospecies?

3. In what sedimentary environments were the facies deposited?

4. Can the ichnofacies model be employed to recognise broad palaeoenvironmental gradients that, in turn, can be linked to spatial or temporal changes in bathymetry?

5. Can ichnofacies and ichnofabric analyses result in a high resolution cyclostratigraphic interpretation and assist in the general recognition of important bounding surfaces (such as transgressive surfaces of erosion, maximum flooding surfaces and regressive surfaces of erosion) by registering vertical bathymetric change across these surfaces?

6. What are the implications of the data in terms of the broader Sydney-Bowen Basin System?

7. How does the cyclicity relate to other documented Permian successions along the Panthalassan margin of Gondwana?
CHAPTER 2: TAXONOMY

2.1 SYSTEMATIC ICHNOLOGY

Ichnotaxa are arranged alphabetically, rather than in any formal morphological or behavioral groupings, for ease of reference. Due to sampling difficulties, some specimens are only figured from field photographs and can, therefore, not be formalised as new taxa. All type and mentioned specimens have been lodged with the University of Wollongong School of Geosciences (UWSG). In the interest of saving space, synonymies are set out in full only when there are two or more specific names recorded. Only examples relevant to the present study have been included in the synonymy lists.

Difficulties With Generic Separation: In the Pebbley Beach and Snapper Point Formations, the consistent definition of, and discrimination between, *Cylindrichnus*, *Rosselia*, *Asterosoma* and *Teichichnus* is difficult due to the recognizable inter-relationship between the trace fossil types. A variety of individual forms are common, but specimens that clearly show transitional forms containing two connected structures belonging to different species are present in many beds (e.g. Fig. 2.1a, Pl.2.11a, 2.12c, 3.1j, 3.2f,g, 3.4e, 3.7b); the most common examples are *Asterosoma-Teichichnus* and *Rosselia-Teichichnus*, the *Cylindrichnus-Rosselia* and *Rosselia-Asterosoma* associations being less common. The end members have been separated and described here as separate ichnotaxa because excessive lumping tends to mask important relationships among intergradational taxa (Frey & Howard 1982). Each structure represents a discrete behavioural function and should be emphasized as such (Pemberton & Frey 1982).

Intergradational forms have been suggested in the literature (e.g. Frey & Howard 1970, Howard 1972), but to date no direct evidence has been published.

Ichnogeneric and ichnospecific separation has been made according to dominant features of the funnels and tubes within individual beds (Fig. 2.1a).

Traces exhibiting intergradational characteristics occur in sandstone beds with bioturbation indices (BI, Goldring & Taylor 1991, Chapter 3 this study) ranging from 2-6. Retrusive *Teichichnus* is the most common structure in beds with a high BI and commonly overprints associated funnel structures.

*Cylindrichnus*: In the study area *Cylindrichnus* is rarely a distinct, isolated structure. It often passes down into a simple walled basal structure identical with *Skolithos*. Most commonly it is
associated with or connected to a variety of forms that range from bulbous, concentrically lined structures (Rosselia socialis), through back-filled funnel structures (Rosselia rotatus) to large, flaring, complex funnel-shaped structures that have been interpreted as Asterosoma. A new ichnospecies, with an eccentric rather than concentric wall lining, is here ascribed to Cylindrichnus.

**Rosselia-Asterosoma-Teichichnus:** This association is the most abundant trace fossil in the study area and it commonly dominates an ichnofabric. The overlap in morphology seen in the Rosselia-type structures presents a potential problem in differentiating these trace fossils both at ichnogeneric and ichnospecific level. Frey & Howard (1985) considered the traces from a strict ethological point of view and maintained that Rosselia should be retained as a separate ichnogeneric concept due to its distinction from the stellate configuration of Asterosoma (Müller 1971) - although that ichnogenus is essentially a radial collection of individual specimens of Rosselia socialis. It is also apparent that Rosselia is unlike isolated specimens of Cylindrichnus.

In the Pebbley Beach Formation the Rosselia-Teichichnus association is most common and larger Asterosoma funnels are rare. In the Snapper Point Formation large floral Asterosoma funnels and concentrically lined Rosselia socialis are abundant. Rosselia rotatus (an intermediate form) and Rosselia motivus (a form with lateral spreiten) are also common in both formations. The robust development and conical flair of Rosselia distinguish it from Cylindrichnus.

A branching form is present in the top 5 m of the Pebbley Beach Formation and, although this also displays a range of funnel shapes, it has been interpreted as Polycylindrichnus. Structures with a radiating, stellate form are interpreted as Asterosoma.

**Teichichnus:** Retrusive Teichichnus-like tubes connected to the base of funnel structures are very common and add to the difficulty in ichnogeneric separation. In some instances the basal Teichichnus portion of the trace dominates and funnel structures are rare. Retrusive tubular structures have been interpreted as Teichichnus.

**Discussion:** The presence of traces containing transitional characteristics of two or more separate genera may suggest that the trace fossils, although representing different behavior, were produced by the same or similar animals. The lower, Teichichnus portion of the structure may have been produced after deposition of storm deposits by an animal mining the sediment
for deposited organic material. The funnel structures may have been produced during fairweather periods when the animal was able to adopt a different mode of feeding.

**Systematic Descriptions:**

Ichnogenus *Arenicolites* Salter, 1857

**Type Ichnospecies:** *Arenicola carbonaria* Binney, 1852, p. 192, designated by Richter (1924, p. 137).

1994 *Arenicolites*; Droser *et al.*, p. 279, fig. 4e-f.

**Diagnosis:** Vertical U-tubes without spreiten (Fürsich 1974b).

**Discussion:** Differentiation of isolated vertical arms of *Arenicolites* (where no definite U-shaped structure is preserved) from individual *Skolithos* and *Polykladichnus* is often impossible.

*Arenicolites statheri* Bather, 1925

Figure 2.1b; Plate 2.1a

**Synonymy:** *A. statheri*; Bather 1925, p. 198, pl. 14-16; Fürsich 1974b, p. 9, figs 5a, 6.

**Diagnosis:** Straight, symmetrical *Arenicolites* (Fürsich 1974b).

**Description:** Simple, vertical U-tubes. Tube diameter ranges from 10-15 mm and the distance between the two arms varies from 2-5 cm. U-tubes are always filled with coarse-grained sandstone from the overlying bed, and reach a length of 15 cm (Fig. 2.1b, Pl. 2.1a). Burrow-fill is commonly reworked by the basal portions of *Cylindrichnus errans*. No lining is evident on the tube.

**Comparisons:** The Late Jurassic example of *A. statheri* described and figured by Fürsich (1974b) is very similar to Snapper Point Formation examples, except that the former has a thick lining and it is not as long. This lining difference is interpreted as resulting from the difference
in cohesive properties of the containing sediment. The loose, uncohesive, sandy limestone with immature ooliths into which the Late Jurassic burrows were constructed probably influenced the lining thickness and burrow length.

MacEachern et al. (1992b) figured a species of Arenicolites very similar to this example and referred it to the Glossifungites ichnofacies.

**Occurrence:** Such traces are only observed in vertical section beneath a transgressive surface of erosion at South Island Beach (Chapter 5.2). The structures are preserved in full relief and protrude beneath a 20 cm pebbly sandstone bed, 15 cm into a 2.5 m thick, bioturbated, fine-grained sandstone (Fig. 2.1b, Pl. 2.1a, 4.11d).

**Interpretation:** The pebbly sandstone bed above the Arenicolites layer is interpreted as the basal unit of a thin transgressive deposit. The distinct burrow outline, the absence of a lining and the passive nature of the burrow-fill suggest that it acted as a dwelling for a suspension feeding organism in partially compacted sediment. The trace is, therefore, interpreted as part of the Glossifungites ichnofacies. Removal of the upper, soft-ground portion of the bioturbated, fine-grained sandstone bed probably occurred during erosion and exhumation of dewatered backbarrier sediments during transgression. A community of opportunistic organisms then occupied the substrate.

The presence of the Arenicolites structures suggests that the erosional exhumation of the substrate was not immediately followed by preserved depositional cover. Rather, the plastic nature of the sediment allowed the burrows to remain open after the trace maker had vacated and the structures were passively filled during the deposition of the next unit (MacEachern et al. 1992b).

The Arenicolites burrow-fill has been reworked by Phycosiphon incertum from the overlying coarse-grained sandstone. This suggests that A. statheri was the pioneer opportunistic organism and occupation by the P. incertum organism occurred as a second phase opportunistic colonization following deposition of the coarse-grained sandstone.
**Arenicolites isp. 1**

Plate 2.1b

**Description:** Paired holes on bedding planes, 0.5-10 cm apart (Pl. 2.1b). Rarely, the base of a U-tube is poorly preserved. The U-tube is lined with 0.5-3 mm of silt surrounding a central sand fill 1-3 mm wide. Sand within the fill is usually the same as the surrounding bed.

**Occurrence:** Arenicolites isp. 1 is abundant in fine- to coarse-grained sandstone, most commonly in HCS sandstone in transitional offshore facies, particularly at Termeil Point. Associated ichnogenera include Skolithos, Polykladichnus, Macaronichnus and Phycosiphon.

**Interpretation:** The inhabitant of Arenicolites isp. 1 was able to inhabit high-energy environments lacking in fine-grained material attractive to deposit feeding animals, and is thus interpreted as the domicile of a suspension feeder. The silt lining suggests that the burrow acted as a permanent domicile.

**Arenicolites isp. 2**

Figure 2.2; Plate 2.1c

**Description:** Arenicolites isp. 2 is present on bedding planes as pairs of weathered-out holes lacking a silt lining. Tube thickness reaches a maximum of 6 mm. The distance between tube openings ranges from 2-10 cm. Arenicolites isp. 2 often displays parallel alignment (Fig. 2.2; Pl. 2.1c).

**Occurrence:** It is common in wave-rippled granule-rich sandstone in the Snapper Point Formation north of Bannisters Point.

**Discussion:** Arenicolites isp. 1 and Arenicolites isp. 2 are very similar in tube diameter but differ in that the latter lacks a lining and is less common in coarse-grained and granule-rich sandstone.
Interpretation: The lack of lining and the scattered distribution of *Arenicolites* isp. 2 suggests that it acted as a shelter for only a short period and not a permanent domicile. The inhabitant of the U-tube is interpreted as a suspension feeder that adapted itself to a well-aerated, high-energy environment of considerable physical instability.

The orientation of the traces perpendicular to the crests of large-scale wave-ripples is a result of the organisms' response to water currents (Fürsich 1975). Alignment of the U-tube parallel to currents aids in the process of bringing nutrients into one end of the tube and removing waste through the other end, which is achieved by active pumping of water through the burrow (Barnes 1980).

Ichnogenus *Asteriacites* von Schlotheim, 1820

Type ichnospecies: *Asteriacites lumbricalis* von Schlotheim, 1820.


Diagnosis: Impressions in the form of asteroids or ophiuroids (Häntschel 1975).

*Asteriacites* isp.

Plate 2.1i

Description: The single float specimen consists of a starfish-shaped trace with five incomplete rays tapering distally. The rays are 10 mm (maximum) in diameter and the distal portions have been broken away leaving 2-3 cm of arm length. Central to the arms is a 3 cm wide pentagonal area containing a single hole situated at the base of each ray and a centrally positioned hole (Pl. 2.1i). The trace occurs with abundant *Skolithos*.

Occurrence: The trace fossil is preserved on the surface of a large piece of clean, medium-grained sandstone that is believed to have fallen from middle shoreface facies on the south side of Snapper Point.
Interpretation: This trace was probably produced by an immobile asteroid where the centrally positioned hole probably represents the mouth. It is a significant record because the skeletal fossil record of the Asterozoa is not very well known due to disintegration of the skeleton after death (Sprinkle & Kier 1987). The occurrence of the trace, on a thick bed of clean medium-grained sandstone with *Skolithos* indicates a high energy environment typical of the middle shoreface. The preservation of the trace undoubtedly occurred due to rapid burial.

Ichnogenus *Asterosoma* von Otto, 1854

Type Ichnospecies: *Asterosoma radiciforme* von Otto, 1854.

Diagnosis: Fan to star-shaped structures with bulbous, outward tapering rays extending from a central shaft (modified from Saunders & Pemberton 1986).

*Asterosoma* isp.

Figures 2.1a, 2.3; Plates 2.1d-g, 3.2f, 3.4a, e, g, 3.5a-b, 3.7b

1978 Zoophycos? sp; Carey, p. 449, figs 25d, 26c.
cf 1986 *Asterosoma* sp; Saunders & Pemberton, p. 55, pl. 5, figs 4, 6, 7.
cf 1988a *Asterosoma*; Vossler & Pemberton, p. 250.

Description: Fan-shaped traces consisting of numerous (3->10), horizontal to vertical, elements radiating from a common, central shaft. The central shaft ranges from horizontal to vertical and is lined with one or more layers of black silt. The shaft measures 3-10 mm in diameter and the inner sand fill commonly contains faecal pellets and *Phycosiphon incertum*. Retrusive spreiten up to 15 cm in depth are common at the base of the shaft (Fig. 2.3b, Pl. 3.4e, 3.7b). The retrusive spreiten are often pervasive, overprinting almost all evidence of the associated funnel structures (Pl. 3.4d).

The radial elements consist of horizontal to vertical, sand-filled tubes with concentric, black, silt lining (Fig. 2.3b). The individual radial tubes may be few and bulbous or numerous, fine and linear.

Commonly U-tube tops are truncated (Pl. 3.7b).
**Occurrence:** In the Pebbley Beach Formation large *Asterosoma* funnels are rare. In the Snapper Point Formation large floral *Asterosoma* funnels are abundant, especially on Pretty Beach and Snapper Point.

**Interpretation:** The tubular nature of the galleries and the central tube suggests that these trace fossils represent a feeding-dwelling structure formed by a vermiform organism. The inhabitant systematically probed the sediment to enlarge the burrow and exploit more and more of the substrate vertically and laterally (Chamberlain 1971, Fig. 2.3a).

The species appears to have had a wide environmental tolerance and, although it was temporarily replaced by opportunists after sudden environmental changes such as storms, it was capable of re-establishing itself and dominating the ichnofauna.

**Ichnogenus Calycraterion** Karaszewski, 1971

**Type Ichnospecies:** *Calycraterion samsonowiczi* Karaszewski, 1971.

**Diagnosis:** Smooth, symmetrical, calyx-shaped structures possessing up to three smaller knobs or depressions on the apex (Pemberton *et al.* 1988).

*Calycraterion samsonowiczi* Karaszewski, 1971

Figure 2.4; Plates 2.1h, 2.2d-e

**Synonymy:** *C. samsonowiczi* Karaszewski 1971, p. 104; Häntzschel 1975, p. 48, fig. 2a-b; Pemberton *et al.* 1988, p. 886; Fillion & Pickerill 1990, p. 22, pl. 1, figs 14, 15, 18.

**Diagnosis:** Smooth, usually symmetrical *Calycraterion* possessing up to three outlets (compiled from Karaszewski 1971, Pemberton *et al.* 1988, Fillion & Pickerill 1990).

**Description:** Smooth, slightly irregular mounds with a smaller, single apical depression or knob. Calyx diameter ranges from 6-20 mm and outlet diameter is typically 1-3 mm. Calyx depth may reach 15 mm.
On bedding planes, the structures are commonly crowded and may be situated directly next to each other but do not appear to overlap.

**Occurrence:** All three occurrences in the Snapper Point Formation exist in clean, medium- to coarse-grained sandstone, often with primary sedimentary structures essentially unaltered on Snapper Point and Termeil Point.

**Interpretation:** The calyx is believed to represent the top of a vertical burrow with the smaller outlet reflecting the tube outlet (Fig. 2.4). The zoological affinities of this form are difficult to determine but the absence of radial symmetry and the presence of a tube connected to the calyx suggest a suspension feeding vermiform animal.

**Ichnogenus** *Conostichus* Lesquereux, 1876

**Type Ichnospecies:** *Conostichus ornatus* Lesquereux, 1876.

1971 *Conostichus*; Chamberlain, p. 220, fig. 4A-D.
1971 *C. broadheadi*; Pfefferkorn, p. 888-892.
1976 *Conostichus*; Hakes, p. 24, pl. 5, fig. 2a-b, pl. 6, fig. 1a-c.
1988 *Conostichus*; Pemberton et al., p. 871, figs 2A-C, 3A-D, 4A-D.
1990 *Conostichus*; Fillion & Pickerill, p. 23, pl. 2, figs 4-5.

**Diagnosis:** Variable but mainly vertical, conical to sub-conical trace fossils most of which display a duodecimal symmetry on the apex and sides. Burrow walls are commonly fluted by longitudinal ridges and furrows and transverse constrictions. Burrow-fills display concentric conical laminae or may be structureless (after Pemberton et al. 1988).

**Discussion:** Pemberton et al. (1988) revised the taxonomy of *Conostichus* and found that, due to the complexity and preservational history of the large number of specimens examined, every specimen was, in some way, unique; this renders ichnospecific designation difficult. Detailed analysis of burrow geometry by Pemberton et al. (1988) indicated that several distinctions between burrow forms could be recognized, based primarily on overall burrow geometry and characteristics of the apical disc. Specimens examined in this study were only available in
vertical section on outcrop where the characteristics of the apical disc are impossible to
determine. Consequently no ichnospecific interpretation is possible.

*Conostichus* isp.

Plate 2.2a-c

**Description:** Vertical, endogenic structures. In vertical section *Conostichus* isp. is preserved as
a sub-conical structure with or without a well developed apical disc (Pl. 2.2a-b).

Burrows are commonly truncated but it is evident that the depth is greater than 1.5
times the burrow width. Burrow diameter ranges from 6-10 cm and depths reach 13 cm.

Burrow-fill consists either of a sub-cylindrical core surrounded by concentric conical
laminae of massive sand that is coarser than the host sediment, or of chaotic laminae.

The top of the structure flares out and overlaps the surrounding sediment surface.

No external surfaces are exposed rendering identification of surface features impossible.

**Comparisons:** Chamberlain (1971) described and figured *Conostichus* that perfectly reflects
the lithology and ethological interpretation of these specimens. Many other authors have
described *Conostichus* and provided interpretations of its affinities, including an alga
(Lesquereux 1876), a sponge (Lesquereux 1880), an aquatic plant (Stout 1956),
scyphomedusans (Branson 1960, 1961, 1962), feeding cones of *Arenicola*-like worms (Barthel
& Barth 1972) and dwelling burrows of actinians (Chamberlain 1971). A full revision was
given by Pemberton *et al.* (1988).

**Occurrence:** *Conostichus* was identified from the upper Pebbley Beach Formation and in the
lower Snapper Point Formation. The sand-filled burrows are common in a 2 m thick,
biogenically reworked HCS bed on the north side of Mill Point where they occur in association
with abundant *Diplocraterion habichi* and *Rosselia motivus* (Pl. 2.2b). The structures are also
common in a 4 m thick flaser and lenticular-bedded sandstone and siltstone on the south side of
South Island Beach. The latter represents tidal flat deposits of the upper Pebbley Beach
Formation. One other possible occurrence of the trace is in an interbedded siltstone and
sandstone layer in an amalgamated storm-deposited unit on south Snapper Point (Pl. 2.2c).

*Phycosiphon* is common in the burrow-fill and surrounding host sediment.
Interpretation: *Conostichus* may be interpreted as the product of burrowing anemones (see Chamberlain 1971, for a detailed description of anemone behavior). The concentric burrow-fill suggests that the animal migrated slowly upwards in order to keep pace with the local sedimentation rate. The truncation of burrows probably occurred during the fluctuating energy conditions responsible for the deposition of the flaser and lenticular-bedded sandstone and siltstone. The slightly chaotic internal structure may have resulted from the animals' attempt to avoid burial during periods of rapid sedimentation.

Ichnogenus *Cylindrichnus* Toots in Howard, 1966

Type Ichnospecies: *Cylindrichnus* was introduced in an unpublished thesis by Toots (1962), who proposed *C. concentricus* as type ichnospecies. These concepts were later published by Howard (1966); however, no type specimens were designated formally until Frey & Howard (1985) deposited specimens in the palaeontological collections of the University of Wyoming.

Diagnosis: Long, vertical to horizontal, straight to gently curved, subcylindrical to subconical trace fossils that are rarely branched and have multiple, concentrically or eccentrically layered walls (modified from Frey & Howard 1985 to include eccentrically layered burrows).

*Cylindrichnus concentricus* Toots in Howard, 1966

Figures 2.1a, 2.5; Plate 2.2k

Synonymy: *C. concentricus* McCarthy 1979, p. 361, pl. 1.8; Howard & Frey 1984, p. 203, fig. 8a; Pemberton & Frey 1984a, p. 289, fig. 12b.

Diagnosis: Concentrically lined *Cylindrichnus* (modified after Pemberton & Frey 1984a).

Description: Vertical to inclined, subconical, slightly curved unbranched trace fossils. Crossovers and interpenetrations are common in the lower half of the structures. Tubes range from 3-8 mm in diameter with maximum length of 25 cm. The trace fossil consists of a central fill containing the same sediment as the surrounding host material, with a concentrically layered silt and sand lining (Fig. 2.5).
**Occurrence:** *C. concentricus* is common throughout the study area in fine- to medium-grained, storm deposited sandstone units. Commonly the *C. concentricus* structures are the only ichnospecies evident.

**Interpretation:** These trace fossils are interpreted as the domicinia of suspension-feeding vermiform organisms. The burrow wall served to stabilize the structure in an unstable substrate, with the concentric lining possibly representing burrow maintenance (Frey 1990).

*Cylindrichnus eccentricus* ichnosp. nov.

Figures 2.1a, 2.6; Plates 2.2g-j, 3.8e

**Paratypes:** UWF 3801-3806.

**Etymology:** The name refers to the eccentric position of the sand tube within the structure.

**Diagnosis:** Long, subcylindrical to subconical, straight to gently curved, predominantly vertical *Cylindrichnus* having an eccentrically positioned sand-filled tube and eccentrically layered walls.

**Description:** *C. eccentricus* structures are preserved as very long (up to 50 cm), predominantly vertical, eccentrically lined trace fossils (Fig. 2.1a). The lower portion of the structure consists of a long, vertical to inclined sand tube that reaches 8 mm in thickness and 30 cm in length. A thick silt lining is preserved on unweathered examples but, where weathering has occurred, only cylindrical holes remain. The silt lining reaches 3 mm in thickness and the tube infill consists of loosely packed sand that is either the same as the surrounding host sediment or slightly finer-grained.

Above the tube the structure widens gradually to an eccentrically lined, long, slender funnel that commonly tapers inwards at the top (Fig. 2.6a, Pl. 2.2h) and may reach 20 cm in length and 6 cm in diameter. Funnels consist of an eccentrically positioned sand tube (Fig. 2.6a, Pl. 2.2g-h), surrounded by alternating layers of grey siltstone and sandstone.

Most specimens have a slight angle of taper that increases in the basal region of the funnel. The trace fossils are either preserved as closely spaced individuals or as clusters of funnels that curve around each other to avoid collision (Fig. 2.6b). The lower portion of the
sand tubes commonly cut across each other. Funnel tops are commonly truncated by overlying beds.

**Occurrence:** These long, thickly-lined structures are only preserved in two 2 m thick sandstone units at Bannisters Point near the top of the Snapper Point Formation. The units consist of amalgamated, low angle cross-bedded to parallel-bedded, medium-grained, clean sandstone to granule conglomerate. *C. eccentricus* dominates the ichnofauna and the only other ichnofossil preserved is rare *Diplocraterion parallelum*.

**Discussion:** This ichnospecies differs from *C. concentricus* in that the sand tube is always eccentrically positioned within the funnel and the funnel-fill is eccentric rather than concentric as it is in *C. concentricus*. Rare funnels have a degree of bulbousity that may be more characteristic of *Rosselia* (Pl. 2.2g) but predominantly the amount of taper compared to the length of the structure is low and thus the structures have been attributed to *Cylindrichnus*.

**Interpretation:** These structures indicate a high energy environment, where there would probably have been insufficient fine-grained material to support deposit feeding organisms. The thick silt lining, the passive nature of the tube fill and the vertical nature of the traces suggests that they acted as a permanent domicile for a suspension feeding animal. The shape of the sand tube suggests that the inhabitant was a long vermiciform animal. The long thickly lined tubes reflect the unstable conditions within the sea floor sediment.

Physical reworking appears to have been common, as indicated by erosive horizons and truncated burrows. Frey (1990) interpreted the wall lining in *C. concentricus* as representing burrow maintenance. This may also be the case with the present specimens or it is possible that the increase in wall lining at the top of the structure may have increased the stability of the tube top.

The crowded burrows indicate that there was competition for living space within the substrate. The fact that they do not intersect at funnel height shows that the gregarious animal was able to thrive in an unstable, high energy environment.

*Cylindrichnus errans* D'Alessandro & Bromley, 1986.

Figure 2.7; Plate 2.2f

1974b  *C. concentricus*; Fürsich, p. 31, figs 26, 27a-c.
Diagnosis: Long, unbranched, vertical or subvertical Cylindrichnus with lateral, randomly oriented, limited displacement of the causative shaft, producing vertical and lateral spreiten. Shafts may be joined together to form bundles (D'Alessandro & Bromley 1986).

Description: Vertical to sub-vertical, cylindrical structures up to 20 cm in length. The overall burrow morphology is identical to that of C. concentricus, but with the addition of well developed lateral spreiten. The top of the structure reaches a maximum diameter of 15 mm with the tube tapering down to 3-5 mm. The top of the structure is thickly lined with 1-3 mm of silt. The bottom portion of the trace fossil is lined with a single layer of grey silt and is identical to Skolithos. The upper conical part of the structure consists of concentric layers of grey silt. The central sand fill is 3 mm wide and contains material that is finer than the host sediment. Lateral displacement of the burrow is more extensive in the lower portion of the structure and reaches a maximum distance of 5 cm (Fig. 2.7). The spreiten consist of the same silt that defines the burrow lining and concentric fill. No bundles of tubes were observed.

Occurrence: Cylindrichnus errans occurs in fine- to medium-grained sandstone at South Island Beach in the Snapper Point Formation where it post-dates a Glossifungites ichnofacies. Associated trace fossils include Phycosiphon, Skolithos and Diplocraterion habichi.

Interpretation: C. errans represents the dwelling structure of a suspension feeding animal that was able to tolerate the instability of a high energy environment. The thick lining of the burrow indicates that it served as a permanent domicile. The lateral movement of the burrow may represent the inhabitant's response to a shifting substrate. The concentric layering mainly represents burrow maintenance (Frey 1990), which may also be a result of a shifting substrate.

Comparisons: The specimens described here are shorter and display less lateral shift than the type specimen (D'Alessandro & Bromley 1986) but are, however, identical in all other morphological aspects. Within the strata of the lower Sydney Basin Cylindrichnus errans is very similar to Rosselia motivus but the more robust, bulbous nature of the upper portion of the
Rosselia motivus burrow distinguishes the two. The two burrow types also indicate different feeding habits, with Cylindrichnus representing the burrow of a suspension feeding organism and Rosselia representing the feeding and dwelling structure of a detritus feeder.

Ichnogenus Diplocraterion Torell, 1870

Type Ichnospecies: Diplocraterion parallelum Torell 1870, p. 13 (designated by Richter 1926, p. 214).


Diagnosis: Vertical U-shaped spreiten burrows (Fürsich 1974a).

Discussion: Two distinct types of Diplocraterion are present in the study area (Fig. 2.8b) Diplocraterion habichi Lisson 1904 and Diplocraterion parallelum Torell 1870. Phycosiphon may be abundant within the sand tube and spreite of D. parallelum (Pl. 2.3i), somewhat resembling faecal material.

Diplocraterion morphology and terminology is illustrated in Fig. 2.8a.

Catenichnus McCarthy (1979) and Diplocraterion are here considered to be synonymous.

Diplocraterion habichi Lisson, 1904

Figures 2.8b, 2.9, 4.15, 4.16
Plates 2.3a-h, 3.1g-i, 3.2c, d, h, 3.3a-b, 3.6a-b, 3.8d

1904 Tigillites habichi Lisson, p. 31, figs 11-18, 21.
1974a D. habichi; Fürsich, p. 960.
1974b D. habichi; Fürsich, p. 11, figs 8-9.
1978 Diplocraterion sp.; Carey, p. 449, fig. 19a-b.
1979 D. parallelum Torell; McCarthy, p. 356, fig. 6a-e.
1979 Diplocraterion Torell; Runnegar, p. 277, fig. 14.
1984 D. habichi; Heinberg & Birkelund, p. 363, figs 4h, 5.
1986 D. habichi; Cornish, p. 491, figs 4d, 10.
Diagnosis: Diplocraterion with a small diameter in which the arms of the U-tube diverge upward (Fürsich 1974a).

Description: The Pebbley Beach Formation and Snapper Point Formation examples of D. habichi range in width from 9-30 mm (average 15 mm). Sand tube diameter ranges from 1-5 mm (average 3 mm). Usually only the parallel arms of the U-tube are preserved but two, well preserved examples of the diverging tube top, were observed. Some burrows show pinching of upper limbs of the U-tube.

Between the arms of the U-tube are silty spreiten formed by retrusive, protrusive or more commonly both (retro-protrusive) burrowing (Fig. 2.9a-b). Burrow depths, inclusive of spreiten, commonly exceed 50 cm, with the structures protruding through several beds; the maximum depth measured was 100 cm.

Tube walls are smooth and unornamented and are usually lined with silt. Examples of unlined burrows are uncommon. Burrows have been passively filled from above with sediment that is either the same as the surrounding bed (Pl. 2.3e), or coarser (Pl. 2.3b-c, f, 3.1g-h).

The traces may be extensively reworked by Phycosiphon. In plan view the two sand tubes are surrounded by silty material (Fig. 2.9b, Pl. 2.3a, g, 3.2d, 3.6a) and in rare examples there may be a raised rim surrounding the paired openings (Pl. 2.3h).

The burrows often exist in dense clusters (Pl. 2.3a, c). One trace displayed lateral disturbance (Fig. 2.9c).

Remarks: Two, unambiguous, well-preserved examples of the diverging tube arms were observed, resulting in identification of this form as D. habichi rather than D. parallelum.
Comparisons: These long slender U-tubes closely resemble *D. habichi* described by Heinberg & Birkelund (1984) from Middle Jurassic sandstone of central East Greenland. They stated that, despite the length of the structure being much greater than that of the type specimen designated by Fürsich (1974a), it should still be referred to as *D. habichi*.

*D. habichi* as described by Dam (1990a) has the same dimensions as Snapper Point Formation and Pebbley Beach Formation examples.

Occurrence: This form is abundant throughout the Pebbley Beach Formation in fine flaser and lenticular sandstone, clean sandstone and silty sandstone beds. Very often a composite ichnofabric results from protrusion into underlying siltstone beds. The burrow inhabitants are largely responsible for the almost complete homogenization of thin (up to 20 cm) beds. At Clear Point and South Pebbles the burrows form part of an assemblage that represents a possible Glossifungites ichnofacies.

It also occurs abundantly in the Snapper Point Formation in siltstone and silty-sandstone beds interbedded with fine sandstone. In low angle cross-beded, fine-grained sandstone it is associated with *Arenicolites* and *Skolithos*, and it has been largely reworked by *Phycosiphon*.

Interpretation: *D. habichi* is here interpreted as the fossilised burrow of an opportunistic suspension feeder inhabiting a high energy environment. Its association with other suspension feeding burrows such as *Skolithos* and *D. parallelum* suggests an environment experiencing low supply of the fine-grained material that is attractive to deposit feeding organisms.

The upper divergence of the arms of the U-tube increases the distance between the apertures thus ensuring better separation of the inhalant and exhalant currents (Fürsich 1974b). This further suggests the domicile of a suspension feeder.

Irregular but evident spreiten are protrusive, retrusive or retro-protrusive, and support the hypothesis that the environmental conditions were unstable, fluctuating between periods of sediment deposition and erosion. The inhabitants of the burrows were under constant pressure to adjust their living depth to maintain equilibrium (see Goldring 1962, p. 244, fig. 3).

The sand within the tubes represents post-mortem fill and can usually be traced to its bed of origin, which either represents the environmental conditions responsible for the burrows (fill is the same as the surrounding sediments) or post habitation conditions (coarser sedimentary fill). The thin silt lining suggests that the structures represent simple, quickly constructed domiciles in an uncohesive substrate (Vossler & Pemberton 1988b). Those that are unlined reflect a firm substrate typical of the Glossifungites ichnofacies.
The long slender structures suggest that they provided a protective shelter against unstable conditions active at the sea floor (Heinberg & Birkelund 1984), for an obviously small animal. The high energy conditions, which may result in low sedimentation rates and frequent reworking, are believed to be responsible for the apparent lack of diverging upper limbs. Bromley (1990) stated that *D. habichi* virtually never exhibits diverging arms.

An example at North Termeil Point (Pl. 2.3h) displays paired openings accentuated by a raised rim of more weather-resistant sediment. The rim may be the result of early cementation of the sediment by mucoid binding substances secreted by the inhabitant in order to strengthen the walls of the burrow (Fürsich 1974b). Animals establishing their burrows in sand are known to drench the immediately adjacent sediment with mucus to ensure that the burrow walls will be self-supporting (Bromley 1990). An example with lateral disturbance structures is interpreted as an escape structure (Fig. 2.9c).

The low diversity association of *D. habichi* within storm-deposited beds suggests that the burrows were produced over a short period of time in an environment that most other organisms found inhospitable.

A number of authors have described *D. habichi* from the Glossifungites ichnofacies (e.g. Frey & Pemberton 1984a, Bradley & Pemberton 1992, MacEachern *et al.* 1992a, MacEachern *et al.* 1992b, Raychaudhuri *et al.* 1992). The trace fossils at Clear Point and South Pebbles with no silt lining and coarse-grained passive infill appear to display the typical characteristics of this ichnofacies (see Ch. 5.1.2, 5.1.5, 5.2.1).

*Diplocraterion parallelum* Torell, 1870.

Figure 2.8b, Plates 2.3i-k, 2.4a-g, 3.1c, 3.3f, 3.5a, 3.6c-f, 3.7b, f, h

**Diagnosis:** *Diplocraterion* with parallel burrow walls and unidirectional spreiten (Fürsich 1974a).

1974a  *D. parallelum*; Fürsich, p. 958, figs 2, 5.
1978  *Arenicolites*; Carey, p. 449, fig. 16a-b.
1979  *Catenichnus contentus*; McCarthy, p. 357, figs 9-10, pl. 1, figs 4-6.
1990  *C. contentus*; Bann, p. 81, figs 4.4, 4.9-10.
1990  *C. contentus*; Mifsud, p. 117, fig. 4.11.
Description: Burrows are symmetrical U-tubes with parallel arms commonly removed (Pl. 2.3j, 2.4b). The structure is 10-30 mm in diameter and is most commonly elliptical or circular. The width ranges from 10-35 cm (average 20 cm). Most tubes have a 0.5-2 mm thick lining of black to dark grey silt. Burrow walls are generally thin and smooth but, where the lining has been removed by weathering and the sand infill has been exposed and partly eroded, the surface often displays a distinctive knobbly texture.

The burrow-fill consists of sediment from the bed in which the top of the burrow was situated during the last operational stage. Commonly the sand-filled tubes are the only remaining evidence of coarser sand lenses that have been biogenically homogenized or eroded.

Burrow bases are commonly crowded on an exposed bedding plane, and may cross or lie parallel to each other.

Spreiten are most commonly retrusive and well-defined by dark silty material (Pl. 2.4d, f, g, 3.6e). Retruso-protrusive forms are much less common and protrusive forms are rare (Pl. 2.3k). In vertical section spreiten are unidirectional. Many examples display minor gradual lateral displacement of the tube with the formation of each spreite. Depth of spreiten is usually less than 5 cm but may reach a maximum of 15 cm (Pl. 2.4g). Distance between successive spreite is most commonly less than 2 mm, rarely up to 10 mm.

In plan view, some burrow fills are reworked by smaller silt-lined sand tubes parallel to the long direction of the \textit{D. parallelum} tube (Pl. 3.3f).

Occurrence: \textit{D. parallelum} is locally common in fine- to coarse-grained sandstone, being sparse in the Pebbley Beach Formation and abundant in the Snapper Point Formation.

Associated trace types include \textit{Phycosiphon}, \textit{Skolithos}, large \textit{Rhizocorallium jenense}, \textit{Thalassinoideas}, \textit{Palaeophycus}, \textit{Psammichnites}, \textit{Macaronichnus}, \textit{Cylindrichnus eccentricus}, \textit{Taenidium synyphes}, \textit{Diplocraterion habichi} and escape structures. In composite ichnofabrics it is overprinted most commonly by \textit{Asterosoma} and \textit{Phycosiphon}, and occasionally by \textit{Rhizocorallium irregulare}.

Discussion: McCarthy (1979) was the first to diagnose formally and name this species in the southern Sydney Basin as \textit{Catenichnus contentus}. He described it 'as being always strongly divergent at the openings of the tube', giving this as the feature that distinguished it from other U-shaped structures such as \textit{Diplocraterion}, \textit{Arenicolites} and \textit{Corophoides}. In his paper on
Diplocraterion Torell and the significance of morphological features in spreiten-bearing U-shaped burrows, Fürsich (1974a) outlined the significant features of Diplocraterion as:

(a) the vertical U-tube; and
(b) the presence of spreiten.

After careful examination of over 500 specimens in the field, it is obvious to the writer that the parallel arms in this species have commonly been removed by penecontemporaneous erosion. Parallel arms were rarely observed in place (Pl. 2.3j, 2.4a, c). It seems, therefore, that the feature used by McCarthy (1979) to separate Catenichnus from Diplocraterion (i.e., the divergence of the arms towards the depositional surface) is a preservational accessory feature of the structure and should not be used to differentiate the two ichnogenera, especially since the two significant features of Diplocraterion are present (the U-tube and the vertical spreiten).

Another feature used by McCarthy (1979) to separate Catenichnus from other U-shaped burrows was its larger size. Burrow size is not a relevant feature for generic classification (Bromley 1990). Additionally McCarthy (1979) used the mainly retrusive nature of the spreiten as a significant feature for ichnogeneric separation. Fürsich (1974a) gave a detailed description of the formation of spreiten in vertical U-tubes, and concluded that it was the product of the organism's response to sedimentation or erosion. He concluded that protrusive and retrusive spreiten reflect the same behavior with the animal reacting to different conditions. Spreiten direction is classified by Fürsich (1974a) as an accessory feature and, therefore, represents a taxonomic criterion unavailable for the separation of ichnogenus or ichnospecies. It is inappropriate to construct a new genus and species for this structure and it is considered to be synonymous with D. parallelum Torell.

**Interpretation:** The presence of mainly retrusive spreiten is evidence that the inhabitant was constantly attempting to maintain functional equilibrium in an environment that was experiencing gradual aggradation. Depths at which infaunal animals live within the substrate are usually critical to their survival (Bromley 1990).

The consistent occurrence of burrows in sandstone displaying sedimentary structures (SCS and large-scale wave-ripples) formed in high energy environments is evidence that the burrowing organism was able to thrive in a high energy aggradational environment. Slight lateral shift of the burrow with each vertical adjustment may also be the result of rapid sedimentation (Fürsich 1974a) in a high energy environment. Fürsich (1974a) stated that lateral deviation from the vertical plane has only been described in retrusive burrows. He also suggested that lateral shift of a U-tube may be the result of obstacles within the sediment (see
Fürsich 1974a, fig. 4c-d, p. 956, & 1974b, fig. 13c, p. 17). The lateral shift may also be a response to the changing position of the migrating wave ripples.

It is most likely that the inhabitant of these large structures constructed the U-tube as a permanent dwelling, as suggested by the thick silt lining. In addition, the passive structure-fill representing sediment from overlying beds suggests that the tube was an open dwelling structure.

This interpretation agrees with McCarthy (1979) who suggested that it probably functioned as the domicile of a suspension feeder that was able to actively pump seawater through its tube.

The lack of parallel arms and the fact that U-tube bases are often present in composite ichnofabrics, suggests that the sandstone infill represents a forced filling of a subsurface burrow (tubular tempestite Wanless et al. 1988, Tedesco & Wanless 1991, see Chapter 4.4.3). The parallel arms were probably eroded during the earlier part of the storm and the burrow bases filled with sand during the waning phase of the storm (Bromley 1996).

Comparisons: Ekdale & Lewis (1991) described a slightly smaller U-tube than these *D. parallelum* from a Late Quaternary fan delta complex in New Zealand. The structures (*D. parallelum* variety *arcum*) have several similarities to *D. parallelum* in the study area, including the broad open U-tube and the predominance of retrusive spreiten. Interestingly, the U-tube was commonly permeated with *Phycosiphon*, as is very common in the Permian *D. parallelum* tubes from the present study.

Fillion and Pickerill (1990) also figured substantially smaller, broad, shallow U-tubes and assigned them to *Catenichnus*. These structures do not resemble the type material of *D. parallelum* (or *Catenichnus contentus*) and are not considered congeneric.

**Ichnogenus Gordia** Emmons, 1844

**Type Ichnospecies:** *Gordia marina* Emmons, 1844.

**Synonymy:** *Gordia* Emmons 1844, p. 24; Hantzschel 1975, p. W64, fig. 39.1a-b; Narbonne 1984, p. 408, fig. 7e; Fillion & Pickerill 1990, p. 34, pl. 7, figs 13-15; pl. 8, fig. 1.

**Diagnosis:** Smooth, unbranched horizontal trails with uniform diameter. Winding but not meandering with a tendency to level crossing. Massive burrow-fill (Fillion & Pickerill 1990).
Gordia isp.

Plate 2.5d

**Description:** Small, 2-3 mm wide, horizontal trace fossils that are smooth and loosely winding, and intersect. The specimens are incomplete and have either been partially removed by erosion or overprinted by other traces. Burrow-fill is the same as the host sediment.

**Occurrence:** The small worm-like traces are preserved at two localities. At South Island Beach they occur in lenticular bedded sandstone and siltstone that represents intertidal facies of the upper Pebbley Beach Formation. In sediments of similar lithology, on O’Hara Island in the lower Snapper Point Formation, they occur in a unit that represents a possible transgressive deposit.

**Interpretation:** Gordia isp.’s probably formed by a slender vermiform deposit-feeding organism exploiting organic material in the silt lenses.

Ichnogenus **Gyrochorte** Heer, 1865

**Type Ichnospecies:** Gyrochorte comosa Heer, 1865.

**Diagnosis:** Horizontal structures having biserially arranged, obliquely aligned, transverse segments separated by a median furrow. The whole burrow system may consist of vertically repetitive, more or less identical modular units (Pemberton & Frey 1984a).

**Gyrochorte comosa** Heer, 1865

Plate 2.12h


**Diagnosis:** As for the ichnogenus.
**Description:** Unbranched, straight to sinuous, horizontal bilobed ridges with a diameter of 3 to 6 mm.

**Occurrence:** These small traces are preserved on top of a sandstone bed at Snapper Point in the Snapper Point Formation (Pl. 2.12h). The only other trace fossil present is funnel topped *Skolithos linaris*.

**Interpretation:** *G. comosa* is interpreted as the fossilised burrow of an elongate organism that moved obliquely through the sediment in search of food (Heinberg 1973). The occurrence of the structure in storm deposited sandstone with funnel topped *Skolithos*, indicates that the inhabitant was able to survive in a high energy, possibly erosive environment.

**Ichnogenus** *Gyrolithes* de Saporta, 1884

**Type Ichnospecies:** *Gyrolithes davreuxi* de Saporta, 1884 by subsequent designation (Hántzschel 1962, p. W200).

**Synonymy:** *Gyrolithes* Gernant 1972, p. 735; Bromley & Frey 1974, p. 311; Hántzschel 1975, p. 65, 67, fig. 4a-b; Powell 1977, p. 552; Crimes & Anderson 1985, p. 321; King 1987, p. 38, figs 2b, 3; Beynon et al. 1988, p. 227, fig. 6a-c & p. 288; Ranger & Pemberton 1988, p. 443, fig. 4a-b; Föllmi & Grimm 1990, p. 1069, figs 2a-b, 3c-d; Beynon & Pemberton 1992, p. 207, fig. 6a-b; Pemberton & Wightman 1992, fig. 6b-c; Ranger & Pemberton 1992, fig. 8a.

**Diagnosis:** Generally vertical structures forming a dextral or sinistral circular helix with tunnel diameter and whorl radius remaining rather constant. Burrow surface may be with or without wall structure or scratch marks (Bromley & Frey 1974).

**Gyrolithes saxonicus** Hántzschel, 1934

Plates 2.5f-h, 3.8d

1934 *G. saxonicus* Hántzschel, p. 313.

1972 *Gyrolithes*; Gernant, pl. 1, figs 1-3.
1977  *Gyrolithes*; Powell, p. 554, fig. 1.

1990  *G. saxonicus*; Fillion & Pickerill, p. 35, pl. 8, figs 2, 4-5.

**Diagnosis:** Dextral or sinistral, smooth, regularly coiled *Gyrolithes*, tunnel diameter from 0.2-0.8 cm (Fillion & Pickerill 1990).

**Description:** The traces are preserved as vertical to sub-vertical, corkscrew-shaped structures in flat-bedded, medium-grained sandstone to granule conglomerate. In vertical section they appear as a series of vertically stacked holes, with burrow depth reaching a maximum measured length of 25 cm. Commonly a burrow terminates abruptly and another slightly displaced burrow continues upwards. The connecting portions of the two burrows may overlap.

Coiling is regular within individual burrows but differs greatly between burrows. All observed burrows display dextral coiling.

Tube diameter ranges from 3-6 mm with helix diameter ranging from 10-30 mm and remaining regular and untapered upwards.

Tube cross-section is circular in granule-sized strata and elliptical in medium-grained sandstone. Wall linings composed of dark grey silt are smooth and regular. Most burrows have the fill removed by weathering but one example (Pl. 2.5f) has burrow-fill of the same sediment as the surrounding sandstone.

*Gyrolithes* is commonly overprinted by other trace fossil types (e.g. *Palaeophycus*, *Arenicolites*, *Diplocraterion habichi* and *Ophiomorpha*).

**Occurrence:** *G. saxonicus* is preserved in the upper Snapper Point Formation in medium- to coarse-grained sandstone of the middle to upper shoreface facies at Jervis Bay, Narrawallee Inlet and Bannisters Point.

**Interpretation:** This trace probably represents the dwelling structure of decapod crustaceans similar to those that constructed *Ophiomorpha* (Kilpper 1962; Keij 1965), but reflecting a particular type of behaviour (King 1987). Corkscrew-shaped structures were interpreted by Schmitt (1965) as the result of a soldier crab using the appendages on only one side of its body to dig, causing the body to rotate and produce a spiral-shaped burrow. King (1987) noted that *Gyrolithes* structures occurring in similar sediment to that in the Snapper Point Formation, exhibited a shallower depth than that of associated *Ophiomorpha*. He concluded that *Gyrolithes* appeared to be limited to the near-surface portion of the tiering profile where
sediment was less compacted, higher in water content and more easily burrowed, and that both structures may have been produced by the same organism reacting to the degree of compaction of the sediment. This kind of association is also very likely in the Snapper Point Formation where *Gyrolithes* displays overprinting by other traces and probably occupied a shallow tier position (Fig. 3.3.25).

Ichnogenus *Heimdallia* Bradshaw, 1981

**Type Ichnospecies:** *Heimdallia chatwini* Bradshaw, 1981.

**Diagnosis:** Vertical burrows that appear on bedding surfaces as straight to gently curved ribbons due to progressive lateral migration of the active burrow chamber. Internally, concavo-convex, vertical or inclined packets of sediment slope away from the concave side (Bradshaw 1981).

*Heimdallia chatwini* Bradshaw, 1981

Plate 2.5a-c

1962 "Worm traces"; Vialov, figs 7-8.
1963 "Probable burrows of shallow-water animals"; Hamilton & Hayes.
1963 "Worm casts"; Webb, fig. 8.
1981 *H. chatwini* Bradshaw, p. 641, figs 40-46.
1990 *H. chatwini*; Fillion & Pickerill, p. 36, pl. 8, figs 6-8.

**Diagnosis:** Straight to gently curved *Heimdallia* (Bradshaw 1981).

**Description:** A lateral succession of vertical or inclined, slightly irregular, unbranched cylindrical structures measuring 5-10 mm in width and descending over 15 cm into the sediment. Smooth and regular burrow walls are lined with 1-2 mm of grey silt.

Sections cut horizontally through the trace fossil display spreiten that have resulted from the lateral movement of the tube. Burrow fill commonly weathers out on bedding planes to featureless ribbons traceable for lengths of over one metre. A circular depression at the end of a
ribbon is interpreted as the final stage burrow (Pl. 2.5c). Burrow infill consists of massive sand similar to the host sediment.

Comparisons: The present material agrees in all essential features with *H. chatwini* Bradshaw (1981) and is considered conspecific. It differs slightly from the material described by Fillion & Pickerill (1990), in that the present material descends substantially deeper into the sediment, but this may be a function of bed thickness.

In the Snapper Point Formation the trace is similar to the basal *Teichichnus* tubes associated with *Asterosoma* and *Rosselia*. It differs in lacking any evidence of a funnel top and it does not depart from vertical orientation. Additionally it occurs in clean coarse-grained sandstone whereas *Teichichnus* is abundant in poorly-sorted silty-sandstone.

Interpretation: The location of this deposit-feeder in clean, coarse-grained quartzose sediment, that was most probably low in particulate organic matter, points to *Heimdallia* as a systematic miner for microbial films from the sand grains, as concluded by Bradshaw (1981) and Fillion & Pickerill (1990). Bradshaw (1981) also postulated that the inhabitant may have been a carnivorous creature preying on smaller animals within the sediment or adjacent to the mouth of the burrow.

The thick lining and the substantial depth of the structure suggests that it acted as a permanent dwelling in uncohesive sediment. *Heimdallia* is here interpreted as the fossilised dwelling burrow of an organism, possibly a crustacean, that migrated laterally through the sediment feeding on algal films around sand grains or on smaller animals within the sediment.

Ichnogenus *Macaronichnus* Clifton & Thompson, 1978

Type Ichnospecies: *Macaronichnus segregatis* Clifton & Thompson, 1978.

1978 "Finger Trails"; Carey, p. 450, fig. 17D.
1978 *Macaronichnus* Clifton & Thompson, p. 1293, figs 1-3.
1979 "Bedding interface trails"; McCarthy, p. 363, fig. 3f.
1986 *Macaronichnus*; Saunders & Pemberton, p. 46.
1992c *Macaronichnus*; Pemberton et al., p. 310, fig. 16C.
1992 *Macaronichnus*; Bradley & Pemberton, p. 396, fig. 11D.
1993 *Macaronichnus*; Pollard et al., p. 152-154, figs 4a-c.
1995  *Macaronichnus*; Goldring, p. 156, fig. 7.

**Diagnosis:** Small, circular burrows (3-5 mm in diameter) that commonly interpenetrate but do not branch. Burrows have a thin, sharp, dark boundary layer (or mantle); the fill differs from the host sediment (Clifton & Thompson 1978, Bromley 1990).

*Macaronichnus segregatis* Clifton and Thompson, 1978

Figure 2.10, Plates 2.5i-k, 3.6c, 3.7g, 4.4i,

1978  *M. segregatis* Clifton & Thompson, p. 1293, figs 1-3.
1983  *M. segregatis*; Leckie, p. 70.
1985  *M. segregatis*; Curran, p. 263, pl. 1B-D.
1986  *M. segregatis*; DeCelles, p. 14-17, fig. 16d.
1986  *M. segregatis*; Saunders & Pemberton, p. 47, pl. 10.1-10.6, 10.8, fig. 13.
1987  *Macaronichnus*; Lockley *et al*., fig. 2b.
1988  *M. segregatis*; Ranger *et al*., p. 460, fig. 6A-D.
1990  *M. segregatis*; Bromley, p. 179, 229.
1990  *M. segregatis*; Maples & Suttner, p. 870, fig. 12.1
1992  *M. segregatis*; Male, p. 40, figs 6A-C, 712C.
1992  *M. segregatis*; MacEachern & Pemberton, p. 57, 65, figs 5D-F, 6C, E-F.
1992c  *Macaronichnus*; Pemberton *et al*., p. 310, fig. 16c.
1996  *M. segregatis*; Bromley, p. 262-264, fig. 11.9a-b.

**Diagnosis:** Sinuous *Macaronichnus* that are commonly densely packed and may be preferentially oriented about a horizontal plane. Burrows are defined by mineralogical segregation within the host sediment (adapted from Clifton & Thompson 1978).

**Description:** Horizontal to inclined structures with the internal sediment similar to the host material but lighter in colour. In sandstone beds with mixed sediment, the outer burrow margin is slightly darker than the burrow-fill and the host sediment. In clean, sandstone beds the outer burrow margin is more difficult to see but it is commonly slightly more weather-resistant than the burrow-fill or the host sediment (Pl. 2.5j, 3.7g). Diameter of the trace ranges from 3-15...
Macaronichnus is commonly pervasive and has reworked the sediment into a distinctive ichnofabric. Burrows are never branched and rarely cross. More commonly they follow meandering paths and run parallel to each other for short lengths (Pl. 2.5k).

**Occurrence:** Macaronichnus is very rare in the upper Pebbly Beach Formation and was only identified in amalgamated HCS sandstone at South Pebbles. In the Snapper Point Formation it is common in the lower half of the formation and abundant in fine- to coarse-grained, cross-bedded sandstone units in the upper half. The most pervasive examples occur in clean HCS sandstone on top of Snapper Point and in a thick unit of planar and trough cross-bedded sandstone (representing foreshore facies) on top of Bannisters Point and Crampton Island. Macaronichnus is occasionally the only identifiable ichnofossil in a bed. Most commonly it is associated with Diplocraterion parallelum.

**Remarks:** Macaronichnus has been distinguished from morphologically similar structures such as Planolites and Palaeophycus on the basis of active or passive burrow-fill (Fillion & Pickerill 1990). Wall linings and the character of the burrow-fill are also used (Clifton & Thompson 1978, Pemberton & Frey 1982), but may be misleading, depending on a number of preservational criteria (see Fillion & Pickerill [1990] for a thorough discussion). Palaeophycus is passively filled and usually occurs as a lined burrow with fill identical to the host sediment. Planolites is actively filled and occurs as an unlined structure with fill of a different nature to the host sediment. Macaronichnus is also actively filled but it typically occurs with a burrow margin and has burrow-fill differing to that of the host sediment (Fig. 2.10).

**Interpretation:** M. segregatis is interpreted as the fodichnia of an active deposit feeder that sorted the sediment presumably for food. The lighter colored, cleaner sand in the burrow-fill was possibly ingested by the burrow inhabitant (Bromley 1996). The outer sediment of the Macaronichnus structure represents a mantle and not a true burrow lining or wall and was probably created by particle segregation during the process of feeding. The clean nature of the host sediment would suggest that there was an absence of organic material that deposit feeders usually utilize. It is believed that the trace-maker fed on micro-organisms that colonized the surface of sand grains (MacEachern & Pemberton 1992). The lack of interpenetrations despite the pervasive nature of the burrowing probably represents a phobotaxic behavioural response whereas the burrows that run parallel to each other for short distances before swinging off, represent a thigmotaxic behavioural response (Saunders & Pemberton 1986). These response mechanisms offset any energy expenditure losses resulting from path inter penetrations.
Planispiral patterns typical of *Macaronichnus spiralis* (Saunders & Pemberton 1986) were not observed.

**Ichnotaxonomy**

*Ichnogenus* *Margaritichnus* Bandel, 1973

**Type Ichnospecies:** *Margaritichnus reptilis* (Bandel 1967).

1967 *Cylindrichnus reptilis* Bandel, p. 6.
1975 *Margaritichnus*; Hántzschel, p. W82, fig. 51.5.
1976 *Margaritichnus*; Hakes, p. 29, pl. 8, fig. 1a-e.
1988 *Margaritichnus*; Pemberton *et al.*, p. 887, fig. 12a-b.

**Diagnosis:** Vertical, subcylindrical structures, circular to slightly elliptical in cross-section; both proximal and distal ends are enlarged and joined by a poorly defined cylindrical shaft. Walls are unornamented and burrow-fill is essentially structureless (Pemberton *et al.* 1988).

*Margaritichnus* isp.

Plate 2.5e

**Description:** Flattened, subspherical structures up to 30 mm in diameter. Burrow-fill is structureless and of the same material as the surrounding host sediment. Around the circular burrows there is commonly a margin of removed sediment (Pl. 2.5e). No linear arrangement of burrows is evident.

**Discussion:** No vertical view is exposed and the internal and lower morphology of the burrows is impossible to determine. An ichnospecific classification is therefore impossible.

**Occurrence:** These structures are only observed on the bedding plane of a fine-grained HCS sandstone at Willinga Point. Rare associated trace fossils include *Psammichnites* and *Macaronichnus*. 
Interpretation: The structures may have been the domicinia of soft-bodied organisms such as anemones (Hakes 1976). The animal was probably a suspension feeder able to survive in a silt-free, high-energy environment.

Ichnogenus *Monocraterion* Torell, 1870

**Type Ichnospecies:** *Monocraterion tentaculatum* Torell, 1870.

**Synonymy:** *Monocraterion* Torell 1870, p. 13; Häntzschel 1975, p. 82, fig. 51.4a-b; Crimes et al. 1977, p. 118, fig. 7; Singh & Rai 1983, p. 75, fig. 6, pl. VI-53; Beynon et al. 1988, p. 288; Bjerstedt & Erickson 1989, p. 221, figs 13g, 14a-b; Hoffman & Patel 1989, p. 141, fig. 2c; Droser 1990, p. 319, fig. 4; Fillion & Pickerill 1990, p. 39, pl. 9, figs 9-10; Male 1992, p. 41, fig. 6c; Pemberton & Wightman 1992, fig. 9a, c.

**Diagnosis:** Funnels or vertically stacked funnels characterized by a central downward deflection of sedimentary laminae. A centrally positioned tube that continues into the underlying sediment may be present (Crimes et al. 1977).

*Monocraterion tentaculatum* Torell, 1870.

Plates 2.6a, 3.8a

1870  *M. tentaculatum* Torell, p. 13.
1931  *M. tentaculatum*; Westergård, p. 12.
1966  *M. tentaculatum*; Hallam & Swett, p. 103, pl. 1, figs 4-6.
1974  *Monocraterion*; Goodwin & Anderson, figs 4-6.
1990  *M. tentaculatum*; Fillion & Pickerill, p. 39, pl. 9, figs 9-10.

**Diagnosis:** Sub-cylindrical, typically straight, unbranched tube that is perpendicular to the bedding plane and ends upwards in a funnel. Size and shape of funnel variable. The tube may continue through the funnel and sporadically ends upward in another funnel (Westergård 1931).

**Description:** Vertically stacked, nested, concordant and discordant funnel-shaped, downward deflected laminae that run through the depth of the bed (1.8 m). Centrally positioned, cylindrical, silt-lined sand tubes are common. Burrows are unbranched, straight or slightly
curved to moderately oblique, and are 20-50 mm apart. Funnel diameters reach 40 mm and sand tubes range from 4-8 mm. Burrow-fill is the same as the host sediment.

**Comparisons:** Male (1992) described *Monocraterion* as an escape structure. The Permian examples of *Monocraterion* studied here are not considered to be escape structures due to the presence of well-defined silt-linings on the tube walls. In contrast to mucus-lined dwelling tubes, escape structures do not normally have well defined cemented walls (Goodwin & Anderson 1974).

**Occurrence:** This species has been identified only from a 1.8 m thick low angle cross-bedded medium-grained sandstone reflecting upper shoreface deposits on south Bannisters Point.

**Interpretation:** The sedimentary structures and lithology of the host sediment reflect high energy deposition typical of an upper shoreface environment. The downward deflection of laminae surrounding the vertical tube may indicate that following the deposition of a new layer of sediment the inhabitant burrowed upward without disturbing the previously constructed funnel and established a mucus-lined dwelling structure in the fresh sediment (Goodwin & Anderson 1974). Alternatively the ascent of the organism may have led to collapse of the sedimentary matrix and downward deflection of the laminae (Crimes et al. 1977). The animal's upward movement might have occurred as a response to sediment influx or during feeding episodes (Beynon et al. 1988).

The size and shape of *Monocraterion* is suggestive of a suspension-feeding polychaete (Goodwin & Anderson 1974).

**Ichnogenus Ophiomorpha** Lundgren, 1891

**Type Ichnospecies:** *Ophiomorpha nodosa* Lundgren, 1891, p. 114-118.

**Diagnosis:** Simple to complex burrow systems distinctly lined with agglutinated pelletoidal sediment. Burrow lining more or less smooth interiorly; mammalated or nodose exteriorly. Individual pellets or pelletal masses may be discoid, ovoid, mastoid, bilobate or irregular in shape. Characteristics of the lining may vary within a single specimen (cf. Frey *et al.* 1978).

*Ophiomorpha* isp.

**Plate 2.7j-k**

**Description:** Cylindrical, mostly vertical burrow systems ranging from 7-12 mm in width. Outer surface of the structures appears to be mammilated. Burrow-fill is structureless and consists of sediment similar to that of the host bed. No obvious branching was observed.

**Discussion:** Only isolated, poorly preserved examples of *Ophiomorpha* are present in the Snapper Point Formation. The pelletal masses are poorly preserved and no specific identification is possible.

**Occurrence:** *Ophiomorpha* is only preserved in one section of flat-bededded medium- to coarse-grained sandstone in the upper Snapper Point Formation at Jervis Bay. It is associated with *Gyrolithes, Palaeophycus, Arenicolites* and *Diplocraterion habichi*.

**Interpretation:** Several authors have noted the similarities in form and environmental distribution between *Ophiomorpha* and those burrows made by modern thalassinid shrimps such as *Callianassa* (e.g. Weimer & Hoyt 1964; Frey *et al.* 1978; Saunders & Pemberton 1986). In the Snapper Point Formation *Ophiomorpha* is believed to represent the dwelling burrows of a decapod crustacean that preferred the clean, reasonably well-sorted sandstone present in the high-energy upper shoreface to foreshore environment.

Ichnogenus *Palaeophycus* Hall, 1847

**Figure 2.10**

**Type Ichnosphéries:** *Palaeophycus tubularis* Hall 1847, p. 7, 63. Subsequent designation by Bassler (1915, p. 939).

**Diagnosis:** Predominantly unbranched, distinctly lined, essentially cylindrical, horizontal to inclined trace fossil in which the sediment fill typically is of the same lithology and texture as the host material. Wall linings may be smooth or striate externally (Frey & Howard 1990).

*Palaeophycus heberti* de Saporta, 1872

Plates 2.6b-d 2

1872 *Siphonites heberti* de Saporta, p. 110, pl. 22, figs 1-2.

1982 *Palaeophycus heberti*; Pemberton & Frey, p. 861, pl. 1, figs 4, 9, pl. 4, fig. 4.

1984 *P. heberti*; Pemberton & Frey, p. 293, fig. 8b.

1985 *P. heberti*; Frey & Howard, p. 382, figs 5.5, 5.9, 12, 16.10.

1990 *P. heberti*; Bromley, p. 230, figs 12.3, 12.14, 12.15.

1990 *P. heberti*; Fillion & Pickerill, p. 45, pl. 10, figs 14, 16.


1996 *P. heberti*; Bromley, p. 263-264, figs 11.3, 11.16-17

**Diagnosis:** Smooth, unornamented, thickly lined *Palaeophycus* with variable orientation (Pemberton & Frey 1982).

**Description:** Straight, unbranched, smooth-walled cylindrical structures, 5-10 mm in diameter and up to 10 cm in length. Burrow orientation ranges from horizontal to steeply oblique. Burrow-fill is massive and identical to that of the host sediment. Burrow walls either consist of 1-2 mm of black siltstone (Pl. 2.6c) or of a 1-2 mm thick lining of light coloured, agglutinated sediment (Pl. 2.6b, d). Crushed and collapsed burrows are common.
Occurrence: *P. heberti* is abundant in reworked, storm-deposited sandstone beds in the Snapper Point Formation. It is not well preserved and is rarely exposed in plan view. The bioturbation index in the host beds is high and associated trace fossils are difficult to identify, although *Phycosiphon incertum* is a common associate (Pl. 2.6c).

*Palaeophycus tubularis* Hall, 1847

Plate 2.6e

**Synonymy:** *P. tubularis* Hall 1847, p. 7, pl. 2, figs 1-2, 4-5; Pemberton & Frey 1982, p. 856; Pemberton & Frey 1984, p. 293, fig. 8c; Frey & Howard 1985, p. 382, figs 5.10, 5.12-13, 10.6, 14; Bjerstedt & Erickson 1989, p. 221, fig. 14c; Fillion & Pickerill 1990, p. 45, pl. 11, figs 3, 6-7; Frey & Howard 1990, p. 812, figs 13.9, 20.1; Aceñolaza & Buatois 1993, p. 192, fig. 4d.

**Diagnosis:** Smooth-walled, unornamented *Palaeophycus*, thinly but distinctly lined (Pemberton & Frey 1982).

**Description:** Horizontal to oblique, subcylindrical, unbranched, thinly lined structures. Burrow diameter ranges from 5-10 mm, with burrows commonly collapsed. Wall lining is thin (< 1 mm) and consists of dark grey to black silt (Pl. 2.6e). Burrow-fill is massive and the same as the host sediment. Branching was not observed but burrows do intersect and cross.

**Occurrence:** *P. tubularis* is common throughout the study area in fine- to medium-grained sandstone. It is associated with a number of different trace fossil types, the most common being *Diplocraterion, Taenidium synyphes* and *Rhizocorallium*. In the upper Snapper Point Formation it occurs in association with *Gyrolithes*.

**Interpretation of *Palaeophycus***: *Palaeophycus* is interpreted as the domicinia of either a suspension-feeder, a surface deposit-feeder (detritus feeder) or a carnivore (Bromley 1990). Passively filled, lined burrows are typically interpreted as dwelling structures. The thick, agglutinated wall seen in *P. heberti* suggests occupation and stabilization of a permanent burrow (Bromley 1990). The passive nature of the burrow-fill suggests gravity-induced sedimentation within an open, lined burrow (Pemberton & Frey 1984a). Collapse features are
more common in \textit{P. heberti} than in \textit{P. tubularis} and suggest that some burrows were incompletely filled.

\textbf{Ichnogenus \textit{Phycosiphon} Fischer-Ooster, 1858}

\textbf{Type Ichnospecies: \textit{Phycosiphon incertum} Fischer-Ooster, 1858}

\textbf{Discussion:} Until recently (Wetzel & Bromley 1994) \textit{Anconichnus} was a common name employed for this trace fossil. However, Wetzel & Bromley (1994) re-examined material from the type locality of Fischer-Ooster (1858) and Kerns' (1978) original \textit{Anconichnus} material, plus \textit{Phycosiphon} from modern Sulu Sea sediments. They relegated \textit{Anconichnus} to the status of a subjective junior synonym of \textit{Phycosiphon}. The two monotypic ichnogenera do not differ significantly in geometry, size, sediment fill and environmental occurrence and therefore taxonomic priority has to be given to \textit{Phycosiphon} (Wetzel & Bromley 1994).

The mottled texture produced by \textit{Phycosiphon} has been recognized in a number of North Sea Basin wells by authors such as Johnson \textit{et al.} (1986) and Stewart (1986). Goldring \textit{et al.} (1991) re-examined a number of cores from the same area and assigned the small pervasive trace to \textit{A. horizontalis}. Bromley (1990) figured sections of core from the North Sea Basin and assigned the small pervasive trace to \textit{Helminthopsis horizontalis} (transferring the specific name from \textit{Anconichnus} Kern, 1978). The presence of a burrow mantle, the discontinuous faecal core, and the non-planar aspect differentiate \textit{Phycosiphon} from \textit{Helminthopsis} (Goldring \textit{et al.} 1991).

\textit{Phycosiphon incertum} Fischer-Ooster, 1858

Plates 2.6c, e-k, 3.1a, c, d, 3.3a, 3.5f, 3.6b, 3.7b

An extensive early synonymy was listed by Fu (1991).

1858 \textit{P. incertum} Fischer-Ooster, p. 59.
1978 \textit{Chondrites} sp.; Carey, p. 449, fig. 18.
1978 \textit{Anconichnus horizontalis}; Kern, p. 190, figs 4, 5a-b.
1982 back-filled burrows; Byers in McCall & Tevesz, p. 228, fig. 2.
1984 \textit{Chondrites}-like trace; Ekdale & Bromley, p. 693, fig. 11.
1984 Helminthopsis; Miller, p. 561, fig. 4g.
1988 Helminthopsis; Bjerstedt, p. 515, fig. 10.10.
1988 Helminthopsis; Keith et al., p. 324, fig. 21.
1988 Helminthopsis; Moslow & Pemberton, p. 376, fig. 2.
1988a Helminthopsis; Vossler & Pemberton, p. 352.
1990 Helminthopsis horizontalis; Bromley, p. 214, fig. 11.20, p. 226, figs 12.3, 12.4(a), p. 230, figs 12.7-12.11, p. 239, fig. 12.15.
1990 Phycosiphon; Wetzel & Wijayananda, p. 15, figs 4B, 8A-B.
1991 Anconichnus; Bockelie, p. 210, fig. 2a-b.
1991 A. horizontalis; Ekdale & Bromley, figs 5-6.
1991 A. horizontalis; Ekdale & Lewis, p. 265, fig. 2a-c.
1991 P. incertum; Fu, p. 45, figs 27-29, pl. 7a-c.
1992 Helminthopsis; Pattison, fig. 14A.
1992 A. horizontalis; Raychaudhuri & Pemberton, p. 126, figs 6F, 7C, 8B, 9J.
1992d A. horizontalis; Pemberton et al., p. 357, figs 9, 13A-D, 14A-B, 15C,E, 16E.
1992 Anconichnus; Bradley & Pemberton, p. 394, figs 9A-D, 10D.
1994 P. incertum; Wetzel & Bromley, p. 1396, figs 1-6.
1995 A. horizontalis & P. incertum; Goldring, p. 163, fig. 8.
1996 P. incertum; Bromley, p. 264-266, figs 5.14, 11.10, 12.3, 12.8-9, 12.11-12.

**Diagnosis:** Extensive, small (0.2-2 mm) spreiten structures that consist of an arcuate, twisted U-shaped faecal core, oriented at any angle and enclosing spreiten in millimetre to centimetre scale. The traces are commonly pervasive and may cross, and branch regularly or irregularly from an axial spreite. Lobes are protrusive, and are mainly parallel to bedding/seafloor (Wetzel & Bromley 1994).

**Description:** P. incertum is represented in both outcrop and slabbed sections as dark lengths, hooks, ticks and paired spots surrounded by a mantle of slightly bleached host sediment. Two distinct size classes occur: a smaller (less than 0.5 mm) class and a larger (0.8-2 mm) class (see also Kern 1978, Goldring et al. 1991). The structure has a different appearance in bedding-plane expression verses vertical section (Bromley 1996, Fig. 2.11). On bedding planes the trace rarely displays lobed spreite (Pl. 2.6g). More commonly the trace does not spread horizontally
but is tangled in three dimensions and the lobes lie in a vertical plane (Kern 1978, Wetzel & Bromley 1994).

Commonly the faecal core is more resistant to weathering, thus producing a complex network of small worm-like free-standing tubes when the host sediment is removed by weathering. In thin section the faecal core commonly darkens substantially towards the wall. Clusters of smaller faecal pellets are common.

The mantle ranges from 1/3 to 2 times the thickness of the faecal core. The faecal core is centrally positioned within the mantle. Rarely faecal core and surrounding mantle pass into a length of slightly bleached host sediment without faecal core. Sometimes the mantle may be unrecognizable (the recognition of the mantle becomes increasingly difficult as thin section thickness decreases). The presence of spreiten is difficult to detect as it has the same colour as the mantle. It is identified as the slightly lighter sediment colour between the arms of the U-structure.

The core mostly consists of very fine organic detritus, whereas the mantle contains large organic particles and sand grains. The largest sand grains appear to be mainly concentrated along the outer edge of the mantle. As Bromley (1990) noted, the mantle is indistinct in pale toned un laminated sediment.

Thin section analysis also reveals a grain-scale meniscus packing in the core that appears to continue into the mantle (Pl. 2.6f) where it represents the spreiten.

*P. incertum* is commonly preserved in the living chamber of other trace types such as *Diplocraterion* and *Rosselia*. It is also commonly cut by other traces.

**Remarks:** *P. incertum* in the Snapper Point Formation is easily identified, despite its small size, by its stark colour contrast with surrounding sediments. In the Pebbley Beach Formation the structures are less easily identified as the burrow-fill and the host sediment are of a similar colour, but the characteristic mottled texture is still very evident.

In outcrop and hand specimen, traces are difficult to discern in silt, but in thin section the structures in silt display a higher degree of preservation and the exact nature of the core/mantle relationship is very evident.

The pervasive nature of the trace forms a characteristic ichnofabric.

**Comparisons:** *P. incertum* from the Snapper Point Formation was identified by Carey (1978) as *Chondrites*. Examples figured by Kern (1974), Ekdale & Lewis (1991) and Goldring *et al.*
(1991), are conspecific with this New South Wales material. The two distinct size classes present in this material have also been noted by other authors (Kern 1978, Goldring et al. 1991).

For a detailed ichnotaxonomic and taphonomic discussion of the species see Goldring et al. (1991) and Bromley (1996).

Occurrence: P. incertum is abundant throughout both the Snapper Point Formation and the Pebbley Beach Formation. It occurs as a facies-crossing trace fossil in that it is abundant in fairweather and storm beds, siltstone to coarse sandstone, but it is absent to very rare in the very coarse-grained lithofacies.

The traces are commonly concentrated in organically defined laminations in storm re-deposited sandstone (Pl. 2.6j) and concentrated within pre-existing trace fossils.

Interpretation: The interpretation of this species by Goldring et al. (1991) as an irregular endichnial fabric of faecal strings and pellets, variably related to a lighter coloured structure, is supported here. The faecal core most likely represents the defecation of a vagile deposit feeder (Goldring et al. 1991).

Several interpretations have been suggested for the mantle:
1. Byers (1982) suggested that it represented the coarser grained material removed from the sediment by a deposit feeding animal during a process of particle size selection;
2. Goldring et al. (1991) agreed with this interpretation and added that the mantle represented the diameter of the animal that produced it, possibly a polychaete;
3. Bromley (1990) interpreted the mantle as a disturbance zone.
4. Ekdale & Lewis (1991) stated that the light-coloured mantle suggested oxidization of organic substances in the sediment immediately adjacent to the trace.
5. Tyszka (1994) confused the pale mantle with a diagenetic halo.
6. Wetzel and Bromley (1995) suggested that the rigorous manipulation of grains may represent the deposit-feeding activities of an opportunistic marine organism.
7. Bromley 1996 (Fig 2.11), proposed a constructional 'probe-and-run' model and this is believed to be the most likely mode of formation of the P. incertum in this study.

The intensity of reworking by P. incertum appears to be controlled by sedimentation rate. In storm beds the intensity of burrowing is much less than in beds deposited under conditions of slow sedimentation where bioturbation was intense and primary sedimentary
structures have often been obliterated. When present along organically defined laminae in thick storm beds, *P. incertum* may serve as an indicator of amalgamation. This suggests that it represents an opportunistic species able to colonize storm bed tops during brief breaks in storm sand deposition.

Reburrowing of pre-existing traces may represent late stage opportunistic behavior whereby the *P. incertum* organism exploited the organic material missed by the pioneer, opportunistic suite of ichnofossils. Alternatively this organism may have fed on organic material found in the wall linings of the original opportunistic assemblage (Raychaudhuri & Pemberton 1992).

Ichnogenus *Planolites* Nicholson, 1873

**Figure 2.10**

**Type Ichnospecies:** *Planolites volgaris* Nicholas & Hinde, 1874 by subsequent designation (Miller 1889, p. 520).


**Diagnosis:** Unlined, rarely branched, straight to tortuous, smooth to irregularly walled or ornamented, horizontal to slightly inclined burrows, circular to elliptical in cross-section, of variable dimensions and configurations; burrow-fill biogenic, essentially massive, differing from host rock; where present, branching is not systematic and swollen bifurcations are absent (emended by Fillion & Pickerill 1990, from Fillion & Pickerill 1984).

**Discussion:** The ichnogenus *Planolites* has been a matter of confusion since its establishment by Nicholson (1873). Detailed discussions have been outlined by Alpert (1975), Benton & Trewin (1978), Pemberton & Frey (1982) and Fillion & Pickerill (1990). The differentiation of *Planolites* from similar structures such as *Macaronichnus* and *Palaeophycus* is outlined above.
(also see Fig. 2.10). For extensive generic and specific synonymies see Pemberton & Frey (1982).

**Interpretation of Planolites:** The characteristics of *Planolites* suggest that it represents the feeding and dwelling structure produced by a mobile deposit-feeding vermiform animal. The lack of burrow lining presumably results from the thinness of the mucous film secreted by the tracemaker (Fillion & Pickerill 1990).

*Planolites beverleyensis* Billings, 1862

Plate 2.7e, f

1862 *Palaeophycus beverleyensis* Billings, p. 97.
1984a *Planolites beverleyensis*; Pemberton & Frey, p. 295, fig. 10a.
1990 *P. beverleyensis*; Fillion & Pickerill, p. 49-50, pl. 12, figs 6, 15.
1990 *P. beverleyensis*; Frey, p. 206, fig. 4b.
1996 *P. beverleyensis*; Bromley, p. 293, fig. 2.9f.

**Diagnosis:** Relatively large, smooth, straight to gently curved or undulose *Planolites* (after Pemberton & Frey 1982).

**Description:** Unlined, relatively large (3-10 mm diameter) structures with an elliptical to round cross-section. Burrow-fill is biogenic in nature, massive and differs from the host rock, either consisting of siltstone fill in a sandstone host bed or sandstone fill in a host sediment of siltstone.

**Occurrence:** These structures are most common in siltstone partings in storm deposited sandstone beds on Snapper Point.
**Planolites montanus** Richter, 1937

Plate 2.7 a-b

**Synonymy:** *Planolites montanus* Richer 1937, p. 151, figs 1-5; Pemberton & Frey 1982, p. 869-870, pls 2.4, 2.7, 3.9; Pemberton & Frey 1984a, p. 296, fig. 10b; Fillion & Pickerill 1990, p. 50, pls 12.6-12.8, 12.11, 13.1; Frey 1990, p. 206, fig. 4a.

**Diagnosis:** Relatively small, curved to contorted *Planolites* less than 5 mm in diameter (after Pemberton & Frey 1982).

**Description:** Small (< 3 mm), straight to curved structures that rarely cross and branch. Burrow-fill consists of grey siltstone that differs from the relatively clean sandstone host material.

**Occurrence:** These structures are common in storm washover deposits in the backbarrier facies association at South Clear Point in the upper Pebbley Beach Formation. They are rare in storm deposited sandstone beds on Clear Point in the lower Snapper Point Formation.

**Ichnogenus** *Polycylindrichnus* Fournier *et al.*, 1980

**Type Ichnospecies:** *Polycylindrichnus prolifer* Fournier *et al.*, 1980.

*Polycylindrichnus prolifer* Fournier *et al.*, 1980

Plates 2.7d, 3.3c, 3.3e

**Diagnosis:** Vertical to sub-vertical fossilised burrow system composed of individual elements that bud off one another to form a branching network. Elements are conical to sub-conical with oval to circular cross-sections and are curved. Burrow walls are unornamented but display concentric lining (Fournier *et al.* 1980).
Description: Vertical to inclined structures that bud off one another to form a burrow system. Budding occurs near the base of the system with up to 5 elements in any one system. No spreiten are developed between elements.

Individual elements are circular to oval in cross-section and possess a central sand fill surrounded by concentric lining of black siltstone. Elements range in diameter from 3-15 mm with the widest measurements attained at the top of the cylindrical structure. Some specimens resemble long, slender, branched *Rosselia socialis*.

Occurrence: The structures occur at only one location in a 3 m thick, silty sandstone representing lagoon sediments, directly below the base of the Snapper Point Formation at South Island Beach. There appear to be transitional forms to *Polycylindrichnus*, *Rosselia* and *Asterosoma*. The structures are associated with large *Rhizocorallium irregular*, *Phycosiphon incertum* and *Rosselia socialis*.

Comparisons: The specimens differ slightly from the type material of Fournier *et al.* in being smaller and much less robust. In all other ways, however, they are the same; further, as size is not a factor available for ichnosppecific separation (Bromley 1990), the Snapper Point Formation material has been assigned to *P.prolifer*.

Interpretation: Fournier *et al.* (1980) concluded that *Polycylindrichnus* was formed by a coelomate animal capable of suspension feeding and budding, probably an infanual tunicate, as is possible for the Snapper Point Formation examples. However, the specimens transitional to *Rosselia* and *Asterosoma* suggest formation by the same or similar animals reacting to different environmental conditions. The structure may be the fossilised dwelling and feeding burrow of a surface deposit-feeding animal. The multiple branches produced may have served to increase the surface area of the sea floor available for exploitation.

Ichnogenus *Polykladichnus* Fürsich, 1981

Type Ichnospecies: *Polykladichnus irregularis* Fürsich, 1981, p. 155

1986 *Polykladichnus* isp.; D'Alessandro & Bromley, p. 82.
1990 *Polykladichnus* isp.; Bromley, p. 206, fig. 11.15
1990 *Polykladichnus* ispp.; Bromley, p. 207, fig. 11.16a

*Polykladichnus irregularis* Fürsich, 1981

Figure 2.12; Plates 2.7c, 3.8c

1970a *Y*-shaped dwelling tube of a cerianthid anemone; Frey, p. 310, fig. 2.
1975 *feeding structures produced by Heteromastus filiformis*; Howard & Frey, figs 5A-D, 6D-E, G.
1977 *probable cerianthid anemone dwelling structure*; Curren & Frey, p. 143, pl. 1e.
1981 *Polykladichnus irregularis* Fürsich, p. 155, pl. 3.1-4, fig. 2.

**Diagnosis:** Vertical, lined tubes with *Y*-shaped bifurcations connecting to the bedding surface. Number of bifurcations variable (Fürsich 1981).

**Description:** Tubes range from 2-10 mm in diameter, with most examples between 3 mm and 5 mm. Maximum measured length was 100 cm. Most burrows appear to be as deep as the containing bed, rarely protruding down into the underlying bed. They consist of an inner, sand-fill of less than 3 mm in diameter that is lined with 1-2 mm of black silt.

The traces are vertical, with the upper half displaying a succession of *Y*-shaped branching patterns (Fig. 2.12a). This branching commonly occurs at several levels, with secondary branching also occurring in side branches. On the bedding surface, the resulting shafts are represented by holes that appear to occur in pairs (Fig 2.12b). The apertures are mostly truncated, but rarely funnel-shaped apertures are preserved.

**Occurrence:** *P. irregularis* occurs in full and negative relief in quartzose sandstone ranging from medium-grained to granular. It is most common in coarse-grained sandstone that exhibits large-scale wave ripples. It occurs in association with vertical structures such as *Skolithos* and *Cylindrichnus concentricus* as well as *Diplocraterion parallelum*, horizontal to oblique *Palaeophycus heberti* and *Macaronichnus segregatis*, and *Phycosiphon incertum*. Rarely it is the only trace type present.
Discussion: Differentiation of *Polykladichnus* from associated *Skolithos* is often difficult as the latter may represent the lower portions of *P. irregularis*. For this reason only associated vertical tubes with strikingly different features, such as size or lining characteristics, have been specifically differentiated from associated *Polykladichnus*. This is also the case with the holes, visible on the bedding plane. If the size dimensions of the holes reflects the tops of *Polykladichnus* tubes, and if no associated *Arenicolites* or *Skolithos* is evident in vertical section, holes are interpreted as reflecting the openings of the *Polykladichnus* burrows with the sediment/water interface.

Interpretation: The coarse-grained nature of the sediment and the associated sedimentary structures reflect the high energy shoreface environment of deposition. This suggests that the inhabitant was a suspension feeder, although Fürsich (1981) explains that deposit feeding polychaetes may construct a very similar burrow. The long thin nature of the structures, commonly reflecting the bed thickness, suggests that they acted as a protective shelter against unstable conditions that were active at the sea floor (Heinberg & Birkelund 1984).

The sand fill within the tube suggests that the burrows were passively filled from above. This suggests that the burrow was kept open by its producer, and had a permanent connection to the sediment/water interface (Fürsich 1981).

The lack of bulging and the acute intersection angle at Y-shaped branches, suggests that they did not function as turning points.

The diameter and length of the structure suggests that the inhabitant was a vermiform (polychaete?) organism (Fürsich 1981).

Comparisons: Burrows studied here appear to be almost identical to the type material described by Fürsich (1981). Rarely their length greatly exceeds that of Fürsich's examples but, as this aspect seems to be a function of bed thickness, it does not warrant ichnospesific separation.

The sediment containing the burrows is very similar in lithology and grain size to the material described in Fürsich (1981). From his description it seems that the lining on the burrow walls is thicker than that observed in Snapper Point Formation examples. The thicker lining may be a result of the burrows existence in a deltaic environment experiencing higher sedimentation rates and a greater degree of sediment instability.

Howard & Frey (1975), described burrows very similar to *Polykladichnus* made by the polychaete *Heteromastus filiformis*, in a present day estuary.
Polykladichnus isp. (D'Alessandro & Bromley 1986), P. isp., P. ispp. (Bromley 1990) and Polykladichnus (Raychaudhuri & Pemberton 1992) are all much narrower and shorter than P. irregularis, although they do occur in very similar ichnofacies associations. Bromley (1990) interpreted the burrows as a suspension-feeding, pioneer community of opportunists.

Ichnogenus Psammichnites Torell, 1870

Type Ichnospecies: Arenicolites gigas Torell, 1868, p. 34.


Diagnosis: Horizontal, typically gently curved burrows or trails, showing a bilobate upper surface that is divided by a median ridge or furrow (depending on type of preservation). The lobes may bear transverse to oblique striellae. Lateral margins are steep or gently sloping. Lower surface is ornamented with a median ridge or furrow and/or with transverse or longitudinal striae (Fillion & Pickerill 1990).

Psammichnites gigas Torell, 1868

Plates 2.7g-i, 3.2d

1868 Arenicolites gigas Torell, p. 34.
1979 P. gigas; McCarthy, p. 362, figs 11b-e
1989 P. gigas; Hofmann & Patel, p. 145, figs 3a-c, 4a-e, 5.
1990 P. gigas; Fillion & Pickerill, p. 51, pl. 17, figs 15-16.

Diagnosis: Large ribbon-like trails with narrow longitudinal median ridge or furrow. Convex upper surface with fine, transverse, closely spaced ridges. Lower surface shows evenly spaced transverse markings (Häntzschel 1975, Hofmann & Patel 1989).

Description: The specimens are poorly- to well-preserved, straight to curved, horizontal trails with a well-defined longitudinal median ridge and transverse markings. The trails range in width from 15-50 mm. No undersurfaces were observed.
The transverse markings may be very faint or clearly defined by alternating layers of sand and silt (Pl. 2.7g-i). In all specimens except one the transverse markings are straight.

The transverse ridge is well-defined by sand and may be raised as much as 3 mm. Walls are unlined but well-defined.

**Occurrence:** *Psammichnites* is rare throughout the Snapper Point Formation where it occurs as poorly preserved trails on bedding surfaces of HCS sandstone beds. Associated trace fossils include *Skolithos*, *Arenicolites*, *Diplocraterion parallelum*, *Macaronichnus* and *Planolites monotanus*.

In the Pebbley Beach Formation, *Psammichnites* commonly occurs as moderately to well preserved trails on the bedding planes of HCS sandstone beds at Mill Point. Trace diameters are smaller than in the Snapper Point Formation with the maximum measured diameter reaching 20 mm. The types of traces associated with *Psammichnites* in this formation are quite different, including *Rosselia rotatus*, *R. socialis*, *Diplocraterion habichi*, *Phycosiphon incertum*, *Taenidium barretti*, and *Teichichnus rectus*.

**Interpretation:** The trail producer was probably a deposit feeder extracting particulate organic material from the surface sand. Several authors have suggested that the traces represent the trails of gastropods (Glaessner 1969, Hántzschel 1975, McCarthy 1979). Backfill structures suggest that the trace was formed as the animal selectively sorted the sediment for food and packed unused material behind itself.

Regardless of the exact nature of the burrow inhabitant, it is clear from the HCS and associated trace fossils that the organism inhabited an energetic, well-oxygenated environment. It is believed to represent part of the storm-influenced opportunistic community.

Ichnogenus *Rhizocorallium* Zenker, 1836

**Type Ichnospecies:** *Rhizocorallium jenense* Zenker, 1836, p. 219.

**Synonymy:** *Rhizocorallium* Zenker 1836, p. 219; Chishlom 1970, p. 47, figs 6a, 7; Fürsich 1974b, p. 18; Fürsich 1974c, p. 16; Basen & Scott 1979, p. 12, figs 1, 4-8; D'Alessandro et al. 1986, p. 299, fig. 5a; Pemberton & Frey 1984a, p. 296; Bjerstedt 1987, p. 882, fig. 10.5; Vossler & Pemberton 1988a, p. 253.
**Diagnosis:** U-shaped spreiten burrows, parallel with or oblique to the bedding plane. Limbs are more or less parallel and distinct. Spreiten typically protrusive (Fürsich 1974c, Pemberton & Frey 1984a).

*Rhizocorallium irregulare* Mayer, 1954

**Synonymy:** *Rhizocorallium irregulare* Mayer 1954, p. 82, pls 2-3; Fürsich 1974c, p. 24, figs 1, 2, pl. 4a; Fürsich 1981, p. 158, pl. 1.4, pl. 4.1, 4.2, 4.4, figs 4-6; Pemberton & Frey 1984a, p. 296, fig. 11; D’Alessandro *et al.* 1986, p. 300.

**Diagnosis:** Long, sinuous, predominantly horizontal, U-shaped spreiten burrows, which may bifurcate or be planispiral (Fürsich 1974c).

**Description:** Sinuous, U-shaped spreiten burrows, with the entrance shafts never observed; traces may be crowded and are commonly vertically superimposed. They may be predominantly horizontal or slightly oblique to bedding. Sinuosity is evident both on bedding plane exposures and in vertical section (Fig. 2.13a & b).

In plan-view the trace fossil shape is variable. Parallel sided U-tubes are the most common form (Pl. 2.8c-d) but bell-shaped U-tubes and teardrop-shaped U-tubes were also observed (Fig. 2.13a). Only segments of the traces are visible with the longest segment measuring 30 cm. No bifurcating or planispiral examples were observed.

In vertical section preserved burrows may be singular or contain extensive retrusive spreite (Fig. 2.13b). The retrusive spreiten consist of layers of silt-lined tubular structures and these were commonly measured at lengths of over a metre. Vertically retrusive and non-retrusive forms may both be abundant within the same bed.

The trace diameter is variable both within beds and occasionally within individual burrows and ranges from 3-15 cm. U-tubes are smooth, silt-lined and filled with the same sediment as the host material. The diameter of the U-tube may range from 3-20 mm. Protrusive spreiten are clearly defined by tongue-shaped layers of siltstone and sandstone between the arms of the U-tube. Separate lamellae are 1-5 mm apart.
Occurrence: *R. irregulare* is abundant in silty sandstone and fine-grained sandstone in the upper Pebbley Beach Formation and lower Snapper Point Formation. It is associated with a large number of other traces including *Asterosoma, R. rotatus, Polycylindrichnus, D. parallelum, T. synyphes, P. incertum* and *D. habichi*. In larger examples *P. incertum* is common in the U-tube (Pl. 2.8c).

Interpretation: The inter-U-tube spreiten are interpreted as the result of a mining process and the long, sinuous nature and the predominantly horizontal orientation of the structure strongly suggest that these examples of *R. irregulare* were formed by a deposit feeding animal. The vertically retrusive nature of the structure probably acted to increase the exploitation area of the sediment. Food particles, concentrated in layers in the sediment, were mined and then the animal shifted upwards to exploit the next sedimentary layer. This shift may have been to avoid collision with an inhabited neighboring burrow or it may have simply provided the animal with a renewed source of organic material. Retrusive spreiten are usually associated with the suspension feeding *R. jenense* but the long sinuous nature of the *R. irregulare* U-tube would have made water circulation difficult and therefore suspension feeding is highly unlikely.

Vertically retrusive *R. irregulare* have not been documented previously. An example of vertically protrusive *R. irregulare* was documented by Fürsich (1981) and interpreted as the result of slight erosion at the sedimentary interface or a response to an obstacle in the sediment. The retrusive behavior of the examples in this study appear to have occurred when the animal wished to start a new burrow but was unable to move downwards due to the presence of an underlying, clean, HCS sandstone. This bed would have been devoid of the organic material attractive to the *R. irregulare* inhabitant and the animal was, therefore, forced to make an upward adjustment of the burrow. Upward movement of the burrow system may also be a function of sedimentation rate.

The very large size of many examples may indicate that the population contained an abundance of fully mature individuals existing in non-stressful conditions (Ranger et al. 1988), or it may suggest different inhabitants in the small and large traces. Examples with large outer tubes, wide spreiten, and faecal pellets may have been made by decapod crustaceans whilst those with narrow outer tubes and closely spaced spreiten were probably made by worms (Chamberlain & Baer 1973).

*R. irregulare* formed part of the fairweather resident community in environments that experienced long periods of quiescence. The association with many vertical, suspension feeding structures suggests that storms disrupted the environment but their effects were minor; the
resident community appears to have successfully re-established itself and reworked much of the storm-deposited sand.

*Rhizocorallium jenense* Zenker, 1836

**Figure 2.14**

**Synonymy:** *Rhizocorallium jenense* Zenker 1836, p. 219; McCarthy 1979, p. 360, fig. 6f, 6g; Fursich 1974b, p. 18, fig. 14a; Fursich, p. fig. 2, pl. 4b; Fursich *et al.* 1981, p. 545, figs 2, 3f-g, pl. 3, figs 1-2, 8-9; Clausen & Vilhjálmsson 1986, p. 60, pl. IIc; Saunders & Pemberton 1986, p. 58, pl. 12, figs 4, 6-8.

**Diagnosis:** Predominantly straight, short, U-shaped spreiten burrows, commonly oblique to the bedding plane and sometimes vertically retrusive (Fursich 1974c).

**Remarks:** Three distinctly different types are present (Fig. 2.14):

1. Type A traces - small, oblique structures with vertically retrusive spreiten;
2. Type B traces - large, horizontal structures with converging U-tube apertures and no vertically retrusive spreiten and;
3. Type C traces - very large, horizontal to oblique structures with vertically retrusive spreiten.

*Rhizocorallium jenense* type A.

**Figure 2.14a; Plates 2.8g-j, 3.7e**

**Description:** Obliquely oriented, short, straight *Rhizocorallium*. Some examples have short vertically retrusive spreiten (Pl. 2.8g). The structures generally range from 4-5 cm in width and up to 12 cm long, with the U-tube diameter measuring normally from 3-8 mm. No tube openings were observed but it is clear that there is an upturning of the U-tube entrances towards the sedimentary surface.

The living tube is smooth and is lined with a fine silt layer, which may be up to 2 mm thick. Tubes are filled with either the same sediment as the host material or with coarser, cleaner sandstone. One example shows evidence of collapse of the U-tube (Pl. 2.8h).
Spreiten between the arms are poorly- to well-defined and consist of tongue-shaped layers of sandstone. Silty spreiten are not always present. In one example the spreiten are defined by tongue-shaped lenses of siltstone and poorly sorted sandstone that is coarser than the host sediment.

**Occurrence:** This small form of *R. jenense* was only observed in fine- to medium-grained sandstone in a number of locations in the Snapper Point Formation. Well-preserved examples are at Snapper and Bannisters Points. Associated trace fossils include *Diplocraterion habichi*, *Diplocraterion parallelum*, *Rhizocorallium jenense* type C, *Palaeophycus tubularis*, *Teichichnus rectus* and *Rosselia rotatus*. Small *Rhizocorallium jenense* type A and very large *Rhizocorallium jenense* type C may be preserved side by side on a bedding plane (Pl. 3.7e).

**Rhizocorallium jenense** type B.

Figure 2.14b, Plates 2.8e-f, 2.9a-b

**1990** *Rhizocorallium jenense*; Mifsud, p. 106, fig. 4.4.

**Description:** Large, horizontal *R. jenense* with the arms of the U-tube converging towards the apertures. Trace diameter ranges from 10 cm at the apertural end to 20 cm at the distal end of the U-tube. Tube diameter ranges from 2-5 cm. Spreiten between the arms are poorly to moderately defined and range from 2 mm to 6 cm apart. The U-tube is lined with black silt and filled either with sediment the same as the host material or with sandstone that is considerably coarser than the host sediment. No tube apertures or vertical retrusive spreiten were evident.

**Occurrence:** *Rhizocorallium jenense* type B is only preserved in silty, fine-grained sandstone in the Pebbley Beach Formation and in the lower Snapper Point Formation. The host sediment is commonly very mottled from intense bioturbation. Identifiable associated trace fossil types include *Diplocraterion parallelum* and *Polycylindrichnus*. Glendonites are common in the bed that contains the most abundant examples of this trace fossil.
**Rhizocorallium jenense type C.**

Figure 2.14c; Plates 2.9c-h, 3.7a, 3.7e

1978 *Rhizocorallium?* sp, Carey, p. 449, fig. 20b.

**Description:** Very large, straight to slightly curved, horizontal to slightly oblique, U-shaped structures with spreiten preserved between the arms of the tube. The preserved burrows measure up to 30 cm in width and up to 70 cm in length. The U-tube is thickly lined with silt and may reach 5 cm in diameter. The apertures were not preserved in any example but the limbs of the U-tube curve upwards towards the sediment surface in several specimens.

The tube infill is usually the same material as the host sediment but is commonly less resistant to weathering. Reworking of the burrow-fill by other ichnospecies is very common. One example displays chevron backfill structures in the U-tube fill.

Spreiten are usually absent but are well preserved in some examples. The traces are commonly crowded on a bedding plane and may overlap. Vertically retrusive spreiten are present on most specimens.

**Occurrence:** These very large *Rhizocorallium* are only preserved in fine- to medium-grained sandstone beds on Snapper Point. They appear to be confined to the coquinitic sandstone that contains buried life assemblages of mollusc shells. Associated trace fossils include *Diplocraterion parallelum, Teichichnus rectus, Rosselia socialis*, and the smaller *Rhizocorallium jenense* type A. The large trace fossils pre-date all other ichnofossil types in the bed.

**Interpretation of *Rhizocorallium jenense* types A-C:** Several morphological features of the three different types of *R. jenense* indicate that the burrows were produced by suspension feeding inhabitants. The short, straight, commonly oblique burrows would have aided in water circulation. The presence of a relatively thick silt lining on the U-tube suggests that the burrow remained open at the sediment-water interface. This is also suggested by the collapsed nature of the U-tube and by the infilling of the tubes with coarser sediment. The sediment fill is the result of passive infilling of the burrow from above and supports the suggestion that the burrow was an open domicile. The short, vertically retrusive spreiten reflect the inhabitant's attempt to re-equilibrate the burrow to the new sediment-water interface after a phase of deposition.
Type A traces are interpreted as being produced by small, probably vermiform filter-feeding animals, that preferred high energy, storm and shoreface facies.

Type B traces existed in an environment that was quieter and siltier. The inhabitants may have been vermiform animals or crustaceans. The distal widening of type B traces is probably a function of the animal’s growth. The animal was filtering food material that was probably being constantly renewed by tidal currents in a back-barrier environment.

Type C traces represent an opportunistic suspension feeding community that inhabited storm-deposited sand. The animal was able to thrive in the well-aerated conditions that were probably out of equilibrium with the fairweather environment. A diverse community subsequently replaced the *Rhizocorallium* animal as conditions returned to normal and the resident community was able to re-establish itself.

**Ichnogenus Rosselia** Dahmer, 1937

**Type Ichnospecies:** *Rosselia socialis* Dahmer, 1937, p. 532.


**Diagnosis:** Horizontal to vertical, conical to irregularly bulbous, funnel-shaped structures, consisting of a central burrow with concentric, cone-in-cone laminae, spreite-like helicoid swirls surrounding a cone or crescentic backfill structures, all tapering downward to a concentrically lined, subcylindrical shaft. Downward, the apex may become a horizontal or vertical structure, or contain retrusive spreite. Burrows may exhibit lateral movement in the form of spreite (modified after Howard & Frey 1984, after Dahmer 1937, to include lateral spreiten).

**Discussion:** Two previously named species and one new species of *Rosselia* are described here. The new species *Rosselia motivus* is similar in morphology to *Rosselia socialis*; however, it contains horizontal spreiten representing lateral shift of the funnel structure. Even within individual species there is a wide variety of shapes and sizes of burrows.
*Rosselia motivus* ichnosp. n.

Figure 2.15; Plates 2.10, 3.2c

**Origin of Name:** Derived from the Latin *motivus*, moving, referring to the lateral movement of the trace.

**Holotype:** UWF. 3807, paratypes 3808-3809.

**Diagnosis:** Vertical to inclined, concentrically lined *Rosselia* with extensively developed lateral spreiten. The silt-lined central shaft is vertical to inclined and also displays extensively developed lateral and/or retrusive spreiten.

**Description:** The upper portion of the structure consists of a vertical to inclined, concentrically lined funnel that ranges from 15-150 mm in diameter. The funnel is associated with well-developed lateral spreiten that may reach 15 cm in length (Pl. 2.10a-e, Fig. 2.15).

The central sand shaft is silt-lined and contains the same sand as the surrounding host sediment. It is usually vertical in the upper portion of the burrow close to the funnel but may become sub-horizontal in the lower part. The spreiten associated with the sub-horizontal portion of the shaft are always retrusive (Pl. 2.10f) and, when seen in isolation, may be mistaken for *Teichichnus*. Traces commonly overlap and may intensively rework beds.

**Comparisons:** These structures resemble *R. socialis* in that they contain a concentrically lined, circular to elliptical funnel, but the presence of extensive lateral spreiten in *R. motivus* differentiate the two ichnospecies.

**Occurrence:** *R. motivus* was recorded from two locations in silty fine-grained sandstone in the lower Snapper Point Formation: south of South Island Beach and on north Snapper Point. One example was observed at South Pebbley Beach in the Pebbley Beach Formation. This was occurred with a number of transitional forms including *Rosselia* through to *Asterosoma*. The burrows are associated with opportunistic trace fossils such as *Phycosiphon* (Pl. 2.10b) *Diplocraterion habichi* and *Diplocraterion parallelum* but have largely reworked the sediment and overprinted all other traces.
Interpretation: *R. motivus* is interpreted as the fodiichnia of a vermiform, surface deposit-feeding animal. The spreiten associated with the funnel reflect the lateral movement of the burrow. Lateral movement greatly increases the active surface area of the animal in contact with the sea floor and aids in maximizing food-gathering activities (Bromley 1990). The retrusive spreiten associated with the lower sub-horizontal portion of the shaft may reflect the upward movement (associated with waste disposal) of the lower part of the animal during feeding or it may reflect the inhabitant's response to sediment accumulation at the sea floor.

The reworking and overprinting of opportunistic traces suggests that *R. motivus* represents the recolonization of the resident community after environmental changes such as storm deposition.

**Rosselia rotatus** McCarthy, 1979

Figure 2.16; Plates 2.11a-d, f-h, 3.2e

1979 *R. rotatus*; McCarthy, p. 361, pl. 1, figs 2-3, fig. 4a-j.

Diagnosis: *Rosselia* with the funnel composed of finer grained sediments than the surrounding host material, with intensively developed, crescentic backfill structures formed by rotary movements of the tube within the funnel (modified after McCarthy 1979).

Description: Vertical to inclined, funnel-shaped structures with a simple central shaft in the lower portion of the structure. Funnel diameter ranges from 3-10 cm with the shaft reaching a maximum of 8 mm in diameter. Funnel depths are usually less than 6 cm and funnel tops are commonly truncated.

The funnel consists of a silt-lined conical to bulbous structure containing a sand-filled tube that is associated with crescentic backfill structures and contorted sediment (Fig. 2.16, Pl. 2.11b-c, g-h). The crescentic backfill structures are commonly preserved outside the funnel and, when abundant, they may take on a *Zoophycos*-like appearance. Commonly more than one sand-filled tube is preserved within the funnel (Pl. 2.11b, h). The lower portion of the funnel contains a single sand-filled tube surrounded by concentrically layered silt and is identical to *Rosselia socialis*. 
The central shaft is concentrically lined below the base of the funnel and is identical to *Cylindrichnus concentricus*. Very commonly the tube contains preserved retrusive spreiten (Pl. 2.11a). Where retrusive tubes are very abundant and funnels are truncated or poorly preserved, the tubes are identical to *Teichichnus*.

**Occurrence:** *R. rotatus* is abundant throughout the southern Sydney Basin in silty, fine-grained to coarse-grained sandstone. It is commonly the dominant and best preserved trace fossil in a bed, usually overprinting vertical suspension-feeding burrows in storm-deposited sandstones. Because of its abundance and wide occurrence it is associated with many ichnofossil types. Intermediate forms linking simple structures such as *Cylindrichnus* to more complex forms such as *Rosselia* and *Asterosoma* are commonly closely associated. Intermediate forms between *R. rotatus* and *R. socialis* are also preserved.

**Interpretation:** *R. rotatus* is interpreted as the preserved feeding and dwelling burrow of a vermiform, surface deposit-feeding animal (detritus feeder; Bromley 1990). It is obvious that there are many intermediate forms linking *Cylindrichnus* to *R. rotatus*, *R. socialis*, *R. motivus* and *Asterosoma*. *R. rotatus* may represent the transitional form between the deposit-feeding *Asterosoma*-type structures and the circular surface deposit-feeding behavior of *R. socialis*. It is possible that all the *Rosselia* and *Asterosoma*-type structures were formed by the same or similar animals reacting to different environmental influences.

*R. rotatus* is interpreted as having been formed by backfilling of a tube that moved in a rotational pattern about an approximately central axis (McCarthy 1979). The lack of crescentic backfill in the lower portion of the funnel suggests that most of the feeding took place higher in the burrow, probably at the sediment surface. Truncation of funnel tops may also support McCarthy's (1979) suggestion that feeding was carried out at the sediment surface (as indicated by Chamberlain 1971, fig. 8c-g). Cross-cutting relationships and the fact that the structures are usually the most discrete traces in a bed, overprinting most others, suggests that they were the last traces to be formed. Overprinting of vertical, suspension-feeding structures representing an opportunistic trace fossil suite suggests that *R. rotatus* represents the resident community re-establishing after environmental changes such as storms.

The retrusive nature of the lower shaft may reflect the behavior of the animal prior to construction of the feeding funnel. Alternatively it may represent the upward movement of the lower, (longer) portion of the vermiform animal as sediment accumulated and feeding took place at the sediment water interface.
Rosselia socialis Dahmer, 1937

Figure 2.17; Plates 2.11e, i-n, 2.12a-c, 3.7a

1937  *R. socialis* Dahmer, p. 532, fig. 2; pl. 31, figs 2-4; pl. 32, fig. 1.
1971  *R. socialis*; Chamberlain, p. 239, figs 8c-g; pl. 30, figs 16-17.
1978  'siphon funnels', Carey, p. 450, fig. 29.
1982  *R. socialis*; Cooper & Romano, p. 79, fig. 4; pl. II, figs 1-6.
1984  *R. socialis*; Howard & Frey, p. 209, fig. 18.
1984a *R. socialis*; Pemberton & Frey, p. 297, fig. 12a.
1990  *R. socialis*; Fillion & Pickerill, p. 52, pl. 13, figs 6-7.
1990  *R. socialis*; Frey & Howard, p. 813, fig. 17.

**Diagnosis:** Conical to irregular, bulbous or funnel-shaped structures that are vertical to horizontal and consist of a central burrow surrounded by broad concentric laminae tapering downward to a concentrically walled stem (Pemberton & Frey 1984a).

**Description:** In the lower Sydney Basin *R. socialis* is variable in its overall shape and configuration. The shape of the structure ranges from slender to bulbous and robust.

Funnel widths expand towards the sediment surface and may reach as much as 12 cm. Funnel-fill consists of closely packed, concentric sheaths of siltstone and fine-grained silty sandstone that are commonly partially mixed in the outer portion of the funnel (Pl. 2.11i). The concentric layering is circular to elliptical and may show rare intergradations with *R. rotatus* and contain some poorly developed, backfill structure in the outer portion of the funnel. Funnels are vertical to inclined with horizontal examples rarely recorded. Lateral branching is rare but specimens commonly display vertical displacement with two funnel structures seen one on top of the other (Pl. 2.11e, 2.12b; Fig. 2.17c). Burrows are most commonly isolated structures, but one example in the Pebbley Beach Formation exhibits closely packed funnel tops (Pl. 2.11n). Paired funnel tops are common (Pl. 2.11k, m), but it is unknown if these specimens represent branched burrows. Funnels are commonly truncated (Pl. 2.12c).
The central shaft ranges from 3-10 mm in diameter and may reach over 30 cm in length. It consists of the same sand as the surrounding host sediment and is lined with up to 3 mm of silt that is concentrically layered in the upper portion. The shaft is most commonly vertical to inclined but may be horizontal. Commonly there has been upward shift of the shaft resulting in retrusive spreiten (Pl. 2.12c, Fig. 2.17b).

**Occurrence:** *R. socialis* is common throughout the study area in fine- to medium-grained silty sandstone. *Rosselia* is usually the most discrete trace fossil in an ichnofacies. They occur with many other trace fossils but are most commonly associated with vertical suspension feeders such as *Diplocraterion habichi* and *D. paralellum*, which they usually overprint.

**Interpretation:** Previous authors have suggested that *R. socialis* is the domicnicha of a suspension feeder (Frey 1990) or a deposit feeder (Bromley 1990). *R. socialis* is here interpreted as the fodinichnia of a vermiform, surface deposit-feeding animal. Chamberlain (1971, fig. 8c-g) figured the successive possible movements in the development of *R. socialis* which probably accurately represent the formation of this surface deposit feeding animal. Supporting evidence for a surface deposit-feeding mode of formation is:

1. truncation of funnel tops and the concentric morphology of the structure suggest that the burrow existed at the sediment surface and that the inhabitant collected food from the surrounding sedimentary surface in a circular motion (as seen in Chamberlain 1971, fig 8c-g);
2. the width of funnel tops is largest in sediments where there was abundant food material at the surface (such as the coquinite beds where the sea floor was probably covered with organic material resulting from the presence of abundant shells). One *R. socialis* specimen in this bed appeared to have been directly exploiting the organic material from the underside of a deceased mollusc (Pl. 2.11j);
3. the presence of retrusive spreiten on the vertical shaft; these probably formed as the animal shifted the burrow upwards to maintain its feeding position at the interface in response to sediment accumulation at the sea floor; and
4. the common occurrence of stacked funnels also suggesting a response to sediment accumulation at the sea floor, and reflecting the need of the animal to maintain the burrow top at the sedimentary interface.
Ichnogenus *Skolithos* Haldermann, 1840

**Type Ichnospecies:** *Fucoides? linearis* Haldermann, 1840, p. 3.


**Diagnosis:** Vertical to steeply inclined, cylindrical to sub-cylindrical, straight to curved, rarely branched burrows. Walls are distinct and generally smooth, fill typically structureless (Pemberton & Frey 1984a).

**Discussion:** Differentiation of *Skolithos* from other vertical shafts that serve to connect deeper structures to the surface is vital. This is difficult when ichnofabric grade is high.

*Skolithos linearis* Haldermann, 1840

Figure 2.18; Plate 2.12 d-h

1840 *Fucoides? linearis* Haldermann, p. 3.
1974 *S. linearis*; Alpert, p. 663.
1979 *Tigillites* sp; Carey, p. 449, fig. 24
1984a *S. linearis*; Pemberton & Frey, p. 299.
1990 *S. verticalis*; Bann, p. 74, fig. 4.3.
1990 *S. linearis*; Fillion & Pickerill, p. 59, pl. 15, figs 15-17.

**Diagnosis:** Cylindrical to sub-cylindrical, vertical to slightly inclined burrows. Diameter of burrow averages 3-12 mm, with lengths up to 1 m. Burrow wall distinct to indistinct, may be annulated (Alpert 1974).

**Description:** *S. linearis* are straight to slightly sinuous, vertical to slightly inclined tubes, most of which possess a thin silt lining. Variation in morphology is shown in Fig. 2.18. Diameters range from 3-15 mm, and lengths up to 50 cm were recorded. Burrows do not branch or cross. Funnel-tops are uncommon.
Rarely the tube wall is annulated. Commonly the wall is defined by sand that is slightly coarser and more weather-resistant, but tube walls are sometimes indistinct. Most commonly burrow-fill consists of sediment from above.

Some examples exhibit funnel tops (Pl. 2.12f, h).

**Occurrence:** *S. linearis* occurs throughout the study area in fine to granular sandstone beds, being most common in medium-grained sandstone beds.

It is usually associated with other vertical dwelling tubes such as *Diplocraterion* and *Arenicolites*, but also occurs with oblique and horizontal structures such as *Palaeophycus, Macaronichnus, Gyrochorte* and *Rhizocorallium*.

**Interpretation:** *Skolithos* represents the dwelling and feeding burrows of suspension-feeding organisms, being regarded by most authors as the burrow of annelids or phoronids (Alpert 1974). A number of authors have suggested possible originators for the burrow but essentially it could have been formed by a multitude of animals. In the study area it is frequently found in high-energy environments, and represents a part of the *Skolithos* ichnofacies. It is absent from opportunistic trace fossil suites that represent the *Arenicolites* ichnofacies. Funnel tops indicated removal of sediment by currents.

Ichnogenus *Taenidium* Heer, 1877.

**Figure 2.19**

**Type Ichnospecies:** *Taenidium serpentinum* Heer, 1877, p. 117.

1877 *Taenidium* Heer, 1877, p. 117.

1987 *Taenidium*; D’Alessandro & Bromley, p. 743.

1994 *Taenidium*; Keighley & Pickerill, p. 305.

**Diagnosis:** Straight to sinuous, variably oriented, unwalled, essentially cylindrical, mensicate back-filled burrows. Secondary successive branching may occur, but true branching is absent (Keighley & Pickerill 1994).
Discussion: Three distinct types are present (Fig. 2.19, Pl. 2.13);

1. *Taenidium barretti*: large (40-80 mm diameter), unbranched, unwalled *Taenidium* with meniscate backfill;
2. *Taenidium serpentinum*: Medium-sized *Taenidium* (5-10 mm diameter), with well-spaced, arcuate menisci; and
3. *Taenidium synyphes*: small *Taenidium* (2-4 mm diameter) occurring as tightly spaced, irregularly meandering, backfilled grazing burrows.

_Taenidium barretti_ Bradshaw, 1981

Figure 2.19a; Plate 2.13d-g

1968 'Scolicia'; Webby, fig. 8.
1971 *Beaconites antarcticus* Gevers et al., p. 80, pl. 18.
1975 *Beaconites antarcticus*; Hántzschel, p. W45, fig. 28.1.
1981 *Beaconites antarcticus*; Allen & Williams, p. 255.
1982 *Beaconites antarcticus*; Graham & Pollard, p. 257.
1986 'non-marine bivalve burrows'; Bridge et al., pl 1.
1990 *Beaconites* isp.; Dam & Andreasen, fig. 11b.
1990 *Beaconites barretti*; Woolfe, p. 302, fig. 3.
1992 ?*Beaconites*; Pearson, figs 3d-e.
1993 *Taenidium barretti*; Keighley & Pickerill, p. 83.
1994 *Taenidium barretti*; Keighley & Pickerill, p. 327, figs 2 & 6, pl. 1.

Diagnosis: Straight or meandering, unwalled, unbranched, meniscate back-filled burrow. Menisci may be deeply arcuate, hemispherical, tightly packed, stacked, or form non-compartmentalised back-fill or thin meniscate segments (Keighley & Pickerill 1994).

Description: Large, subhorizontal, back-filled tubular structures that are sinuous in plan and may be traced on bedding plane surface for up to 2 m. Trace diameter ranges from 40-80 mm. Horizontal sections are joined by vertical or inclined intersections that weather as projecting cylinders (Pl. 2.13d). In plan view the structures are often crowded and cross each other. The horizontal structure may run for some distance and then become vertical proximally. No burrow terminations were observed although some traces are rounded at their distal end.
Burrow infill consists of transverse crescentic meniscus back-fill of sand and silt that weathers to ridges and grooves. The distinctiveness of the menisci in the back-fill varies; occasionally part of the burrow infill consists of massive, muddy sandstone with the remainder of the trace fossil containing well developed meniscus structures. The sand-fill in the burrow commonly contains a substantially higher proportion of coarse-grained material than the surrounding matrix. This is especially evident in vertical sections.

No definite wall structure is preserved. Menisci may merge laterally at the burrow boundary to form a crude burrow lining but no true lining is developed. The burrow boundary may be distinct to crenate with individual menisci frequently laterally offset or displaced.

The silt-lined tubes of other smaller trace fossil types may exist within the burrow-fill, although more commonly the large *T. barretti* overprint other trace fossil types (Pl. 2.13f).

**Occurrence:** Only two examples of *T. barretti* are present; they occur on Mill Point; in the upper part of the Pebbley Beach Formation. The first is in an HCS sandstone, and the second is in a large float block of sandstone that has fallen from just above the tidal channel facies.

**Comparisons and Discussion:** Pebbley Beach Formation examples of *T. barretti* are conspecific with examples from the literature (e.g. Bradshaw 1981, figs 17-18; Graham & Pollard 1982, figs 3-5; Woolf 1990, fig. 3; and Keighley & Pickerill 1994, pl. 1, figs 2-6).

The 32 known occurrences of *T. barretti* (see Keighley & Pickerill 1994 for a detailed synonymy) have been recorded from Ordovician to Pleistocene, non-marine environments (see Keighley & Pickerill 1994, text-fig. 5). The specimens described here constitute the first record of this species from an offshore marine environment.

**Interpretation:** It is evident from the meniscus back-fill that the structures were formed by animals moving within the substratum redepositing sediment behind them (Woolf 1990). The separation of coarse material from finer silts suggests that a degree of sediment sorting took place, which in turn suggests that there must have been ingestion of finer material by the trace maker.

Suggestions for the identity of the trace maker of *T. barretti* include polychaete worms (Gevers et al. 1971), vertebrates or arthropods (Ridgeway 1974, Müller 1975, Pollard 1976), and escaping bivalves (Bridge et al. 1986). Probably a number of different organisms could have made these traces, and it is likely that the actual producer will never be identified as it appears to have become extinct in the Pleistocene. The lateral displacement of the menisci
suggests limited lateral locomotive flexibility of an organism with a short body length rather than smooth rectilinear locomotion of a worm-like form (Graham & Pollard 1982).

The coarse sand fill in the vertical pipes is attributable to passive infilling, suggesting that these portions of the structure were open to the surface.

*Taenidium serpentinum* Heer, 1877

Figure 2.19b; Plate 2.13c

1877  *T. serpentinum* Heer, p. 116, pls 46.3-46.4.
1974b *Muensteria* Sternberg; Fürsich, p. 34, figs 28-29a.
1987  *T. serpentinum*; D'Alessandro & Bromley, p. 752, figs 5-7.
1990  *T. serpentinum*; Dam, p. 142, fig. 11a
1994  *T. serpentinum*; Keighley & Pickerill, p. 324, fig. 2.

**Diagnosis:** Serpentiform *Taenidium* with well-spaced, arcuate menisci. The distance between the menisci is equal to or slightly less than burrow width. External moulds display annulation corresponding to menisci, or transverse wrinkling. Secondary subsequent branching and intersections occur. Burrow boundary is sharp and lacks lining (D'Alessandro & Bromley 1987).

**Description:** Curved to sinuous, horizontal, backfilled structures that range from 5-10 mm in diameter. No lining is present and sediment packages may be slightly offset from one another. Burrows very commonly cross each other and in places are very abundant on the bedding plane. Trace fossil lengths exceed 30 cm.

The back fill consists of meniscate packets of sand that is the same as the host sediment, separated by thin siltstone partings (Pl. 2.13c). The length of the mensicate packets is variable and ranges from 1-10 mm. Most menisci are approximately the same length as the trace width.

**Occurrence:** The structures are preserved in the top portion of the Pebbley Beach Formation on a silt-draped sandstone lens, within a flaser bedded unit, on the underside of north Clear Point. The structures were obviously more abundant than is now apparent, but most have been weathered away.
Interpretation: These structures represent the locomotion and feeding structures of a deposit-feeding, vermiform animal. The organism was most likely exploiting the organic-rich silty sediment deposited between the sandstone ripple beds. The sandstone menisci probably represent the non-ingested material separated by the organism during the feeding process and subsequently packed behind it. The thin siltstone partings are interpreted as coprolitic material ingested by the organism and then packed behind it.

Water conditions must have been slack for the burrows to have been preserved.

*Taenidium synyphes* n. ichnosp.

Figure 2.19c; Plate 2.13a-b

Origin of Name: From the Latin *synyphes* (woven together), referring to the resemblance of the trace to a weaving.

Holotype: UWF 3810, paratype-3811.

1978 *Taenidium* sp. Carey, p. 449, fig. 22.

Diagnosis: A species of *Taenidium* that exhibits sub-parallel, tightly spaced, irregular meanders. The backfill consists of hemispherical, meniscate packages of sand separated by thin layers of silt. Sand packet lengths are 2-5 times the thickness of the siltstone partings, and one third the width of the structure.

Description: Small, 2-4 mm wide, backfilled unlined structures. The individual trace proceeds for a length of up to 10 cm where it appears to turn and continue back directly adjacent itself. This close meandering pattern and the crescentic nature of the backfill give the appearance of a woven piece of cloth. The meandering pattern is irregular, with the structures running sub-parallel and appearing not to intersect or branch.

The backfill consists of distinctive packets of fine sandstone devoid of any fine, dark silty material. They are commonly offset to one another forming an irregular burrow boundary. Alignment of sand grains, producing internal menisci, is evident under magnification. Sandstone packets are 2-4 mm wide and 0.5-1.5 mm thick.
Between each sandstone package is a thin layer of darker material which consists of biotite and up to 40% sand. Under magnification it is clear that biotite flakes are aligned to form the menisci.

The structures are parallel to stratification with only rare examples of vertical sections or undulose portions of the burrow preserved.

**Occurrence:** *T. synyphes* is commonly preserved along siltstone partings within the upper portions of storm-deposited sandstone beds. It is common throughout both the Pebbley Beach Formation and the lower Snapper Point Formation. It occurs in association with vertical suspension-feeding burrows, such as *Skolithos* and *Diplocraterion*, and with *Palaeophycus*. It also occurs with other horizontal traces such as *Gordia* and *Planolites*.

**Interpretation:** *T. synyphes* is interpreted as the grazing (or locomotion and feeding) burrow of an infaunal, deposit-feeding vermiform animal. The regular, close meandering pattern was probably adopted by the inhabitant to maximize coverage of the organic-rich layer. The parallel alignment of the meanders suggests that the animal had a means of detecting the proximity of its previous path, possibly by the use of chemoreceptors (Carey 1978). This would have maximized feeding efficiency.

Sorting of grain sizes suggests that the inhabitant was ingesting the nutrients from the organic-rich silt and packing the waste material behind it.

The trace represents the opportunistic colonization of the upper portion of storm-deposited units. Overprinting by other traces suggests that it was an early stage colonizer that was subsequently replaced by organisms from the original pioneer fairweather community.

Ichnogenus *Taphrhelminthopsis* Sacco, 1888

**Type Ichnospecies:** *Taphrhelminthopsis auricularis* Sacco, 1888, p. 170 (Commonly incorrectly spelt *Taphrohelminthopsis*, see Bhargava & Srikantia 1982).

1888 *Taphrhelminthopsis* Sacco, p. 170.
1975 *Taphrhelminthopsis*; Häntzschel, p. W113, fig. 70.6a-b.
1975 *Taphrhelminthopsis*; Ksiazkiewicz, p. 135.
1977 *Taphrhelminthopsis*; Crimes et al., p. 125.
Diagnosis: Bilobate trails, 1-3cm wide, straight to free-winding or meandering with a distinct median furrow 3-10 mm wide. Flat lateral ridges may be transversely striated (adapted from Häntzschel 1975).

_Taphrhelminthopsis circularis_ Crimes _et al._, 1977

Plate 2.14a-b

1977  _T. circularis_ Crimes _et al._, p. 125, pl. 8a-e.

1982  _Taphrohelminthopsis circularis_; Bhargava & Srikantia, p. 406, fig. 2.


Diagnosis: Bilobate trails with well-developed central furrow and an irregularly circling habit. Transverse or oblique striations may be present (Crimes _et al._ 1977).

Description: Preservation of these bilobate trails is generally poor; unlike most other examples from the literature, they are preserved as positive features on the upper surface of the bed. Varying in width from 15-30 mm and in height from 3-8 mm. The median groove is 1-5 mm wide and is commonly enhanced by weathering. The tops of the lobes are rounded and weathered specimens display well-developed internal oblique striations (Pl. 2.14b). The trails are both horizontal and undulose to the bedding. Complete lengths of specimens are difficult to ascertain due to removal by erosion. Samples remaining are mostly short, straight lengths; however, several poorly preserved examples circle irregularly, cross and form figure 8-like patterns.

Occurrence: These bilobate trails are only preserved on the bedding planes of medium- to coarse-grained sandstone in the upper Snapper Point Formation. The best examples are on Bannisters Point. The host sediment is poorly sorted and contains shell material. Associated trace fossils include _Diplocraterion, Skolithos_ and _Macaronichnus._

Comparisons: _Taphrhelminthopsis_ is often associated with deep-water deposits (e.g. Ksiazkiewicz 1970, Crimes 1977, Roniewicz & Pienkowski 1977). However, whilst it is common in deep water sediments, it has also been widely recorded from shallow water deposits.

Crimes et al. (1992) described shallow water forms of *Taphrhelminthopsis* as tending to circle irregularly, cross and produce figure 8-like patterns, similar to Snapper Point Formation examples.

**Interpretation:** Most authors agree with Hantzschel (1975) that trails such as these were produced by gastropods grazing for food. Snapper Point Formation specimens were associated with a suspension feeding community that existed in a high energy, shallow marine environment. Only rapid burial of the *Taphrhelminthopsis* trails would have resulted in their preservation.

Ichnogenus *Teichichnus* Seilacher, 1955

**Synonymy:** *Teichichnus* Seilacher 1955, p. 378; Chisholm 1970, p. 32, figs 4, 6, pls. VI 1-6, 8-10; Häntzschel 1975, p. W114, fig. 71.4a-d; Frey & Howard 1985, p. 391; Fillion & Pickerill 1990, p. 60.

**Type Ichnospecies:** *Teichichnus rectus* Seilacher, 1955, p. 378.

**Diagnosis:** Wall-shaped structures consisting of a pile of gutter-shaped laminae (after Seilacher 1955 *trans. litt*). Rarely branched spreiten structures consisting of several closely concentric, horizontal or inclined longitudinally nested structures in osculating to simple, singular tunnels. Burrows within a given spreite are displaced upwards (retrusive), or downwards (protrusive), and are oriented at various angles with respect to bedding (Frey & Howard 1985).

*Teichichnus rectus* Seilacher, 1955

Figure 2.20a; Plate 2.14c-e

**Synonymy:** *Teichichnus rectus* Seilacher 1955, p. 378, pl. 24, fig. 1; Fürsich 1981, p. 161; Howard & Frey 1984, p. 211, fig. 21; Frey & Bromley 1985, p. 812, figs 7b, 16a-c, 18c; Frey & Howard 1985, p. 391, figs 5.15, 16.4, 19.6, 21; Fillion & Pickerill 1990, p. 61, pl. 16, figs 13, 17; Frey & Howard 1990, p. 816, fig. 26.
**Diagnosis:** Straight, unbranched *Teichichnus* with exclusively retrusive spreiten (Seilacher 1955).

**Description:** Straight, smooth, unbranched tunnel structures oriented slightly to steeply oblique to bedding. All observed specimens were incomplete.

Spreiten are always retrusive. Planes containing spreiten are essentially vertical to oblique and are rarely offset (Pl. 2.14e). Spreiten are closely spaced (from less than 1 mm to 2 mm apart), and range in depth from 1-25 cm.

Tunnel diameter ranges from 5-10 mm. Tunnel lengths are difficult to measure due to the oblique nature of the burrows, the tunnels are largely concealed by sediment (Pl. 2.14c-d). Tunnels are filled with the same material as the host sediment.

**Occurrence:** *T. rectus* is common in amalgamated, fine- to medium-grained HCS beds throughout the shallow marine deposits of the Pebbley Beach Formation. Throughout the Snapper Point Formation it is abundant in poorly sorted, silty sandstone. It is always associated with *Rosselia rotatus* and *Phycosiphon incertum, Diplocraterion habichi, Diplocraterion parallelum* and *Psammichnites.* It is commonly the most abundant trace fossil within a bed and may overprint all other traces. Although both *T. rectus* and *T. sinuosus* are seen to be directly connected to *R. rotatus* funnels, transitional forms between the two *Teichnichnus species* were not observed.

**Interpretation:** These traces are interpreted as the feeding dwelling structures of vermiform animals. The fairweather *Teichichnus* overprinted opportunistic storm traces.

*Teichichnus sinuosus* ichnosp. nov.

Figure 2.20b; Plates 2.14f-i, 3.4d-g

**Holotype:** UWF 3812.

1971  *?Teichichnus* sp. Maberry, p. 11, pl. 1, figs 4-5.
Origin of Name: From the Latin *sinuosus*, meaning full of bendings, winding; referring to the sinuous, winding nature of the trace.

Diagnosis: Long, unbranched *Teichichnus* consisting of a spreite-like body of moderately to strongly sinuous, horizontal to steeply oblique, stacked tunnels with exclusively retrusive spreiten.

Description: These structures consist of horizontal to steeply oblique tunnels that contain up to 20 cm of vertically stacked, retrusive spreiten (Pl. 2.14h-i, 3.4f). In plan view, structures are moderately to very strongly sinuous (Pl. 2.14g-i, 3.4d, g) and commonly cross.

Tunnels are silt-lined and range from 3-15 mm in diameter. The longest measured tube was 45 cm. Tube walls are smooth and the tubes are filled either with the same material as the host sediment or with coarser, cleaner sand.

The retrusive tubes are usually associated with or directly connected to *Rosselia*-type funnels (Pl. 3.4e). Inhabited beds may be intensively bioturbated by *T. sinuosus* tubes, with the *R. rotatus* funnels (if present) preserved in lenses along bed tops. Bioturbation intensity is generally much lower in funnel lenses.

Burrows are commonly aligned.

Occurrence: *T. sinuosus* is preserved in storm-deposited, silty- to medium-grained sandstone beds in the Pebbley Beach and Snapper Point Formations. Bioturbation intensity ranges from BI 3-6. Associated trace fossils include *Asterosoma, Rosselia, Phycosiphon incertum, Diplocraterion habichi* and large *Rhizocorallium*.

Interpretation: *T. sinuosus* is interpreted as the burrow of a deposit feeding animal. The occasional infilling of the tube with coarser sand suggests that at some time the tube was directly open to the sediment surface. The apparent alignment of burrows probably served to maximize the amount of feeding space that each burrow could occupy. Such alignments represent a rheotactic response by the trace maker (Frey & Bromley 1985).

Ichnogenus *Thalassinoides* Ehrenberg, 1944

Type Ichnospecies: *Thalassinoides calliassae* Ehrenberg, 1944, p. 358.
Synonymy: *Thalassinoides* Ehrenberg 1944, p. 358; Bromley & Frey 1974, p. 329; Häntzschel 1975, p. W115, figs 70.2a-b; Pemberton & Frey 1984a, p. 229; Droser *et al.* 1994, p. 279, fig. 5e.

**Diagnosis:** Large preserved burrow systems consisting of smooth walled, essentially cylindrical components. Branches are Y- to T-shaped and may be enlarged at points of bifurcation. Burrow dimensions may vary within a given system. Systems may be essentially horizontal or irregularly inclined (Pemberton & Frey 1984a).

**?Thalassinoides paradoxicus** Woodward, 1830

Fig. 4.15, Pl. 2.15a-c

1830 *T. paradoxicus*; Woodward.
1973 *Spongeliomorpha paradoxica*; Fürsich, p. 730, fig. 6.
1974b *Spongeliomorpha paradoxica*; Fürsich, p. 23-25, figs 16c, 17a.
1978 *Spongeliomorpha saxonica*; Carey, p. 449, fig.21.
1979 *T. paradoxicus*; McCarthy, p. 360-361, fig. 3g.
1985 *T. paradoxicus*; Frey & Bromley, p. 815-816, figs 4a-b, 21a.

**Diagnosis:** Sinuous to straight, cylindrical, irregularly branching burrow systems. Burrow diameters may be very variable. Burrow walls may be unlined, or have a smooth lining (Fürsich 1974b, Frey & Bromley 1985).

**Description:** The extensive systems are mainly vertical to inclined and stand out against a mudstone or siltstone host material because of the coarse nature of the burrow-fill. Burrow infill is typically more resistant to outcrop weathering than the host material. Trace fossil diameters reach 1 cm and some swollen intersections were observed. The burrow network forms an irregular boxwork that in some places is so extensive that the traces have obliterated almost all evidence of other ichnofossils. Burrow walls are smooth but linings appear to be absent. No surface connection shafts were observed.

**Interpretation:** These structures represent the remains of open burrow systems that were passively filled with sediment from above. There must have been some degree of sediment
coherence in the host mudstone and siltstone beds for the unlined burrow systems to remain open to the sedimentary surface. They are typical of structures from the Glossifungites ichnofacies. The open burrow excavation is indicative of burrows formed in the upper transition layer (Bromley 1990). The absence of surface connection shafts is probably the result of their removal by erosion during the emplacement of overlying storm deposited sandstone layers. The extensive nature of the burrow network suggests that the inhabitants were able to thrive in this firm sediment for some period of time, indicating slow sedimentation rates.

*Thalassinoides* is generally regarded as the preserved dwelling and feeding burrow of decapod crustaceans (Häntschel 1975, Pemberton & Frey 1984a) due to morphological similarities between recent and fossil burrows and rare occurrences of actual body fossils preserved inside burrow systems (e.g. Bromley & Asgaard 1972, Fürsich 1974b).

**Fugichnia (Escape Traces)**

Figure 2.9c; Plates 2.15d-f, 3.4b-c


**Description:** Escape traces vary considerably in size and shape. The most common form consists of roughly cylindrical, features up to 30 cm in length (Pl. 3.4c). The infill is either chaotically organized (Pl. 3.4b), or it may consist of downwarped, collapsed laminae. Disrupted siltstone lamina and associated faecal material is common. This variety of *Fugichnia* is only present in thick beds (> 1m) of clean, fine- to medium-grained, amalgamated HCS sandstone.

Another common form consists of vertical pouch-shaped structures up to 5 cm wide and 10 cm deep with structureless infill (Pl. 2.15e-f). Sedimentary laminae have been completely destroyed by the burrowing event but burrow boundaries are sharp and downwarping of laminae adjacent to the structures is rare. These structures are only present in interbedded siltstone and sandstone units preserved at the top of thick HCS sandstone beds. The beds commonly contain small, symmetrical, silt-draped ripples and thin siltstone partings.

A final rare type of *Fugichnia* occurs in the form of escape structures directly associated with other ichnospecies. The most notable example consists of a *Rosselia rotatus* in silty
sandstone with a connected vertical, cylindrical escape structure above it in a bed of mega-rippled fine- to medium-grained sandstone (Pl. 2.15d).

One example of a horizontal escape trace was noted in sandy siltstone. The specimen consists of a *Diplocraterion habichi* structure containing a connected lateral escape structure 8 cm long (Fig. 2.9c). The fill is preserved as a chaotic mixture of silt and sand.

**Occurrence:** *Fugichnia* are only present in storm-deposited sandstone units. Commonly they are the only trace fossils in the bed but other structures such as *Skolithos*, *Palaeophycus* and *Phycosiphon* may also be present.

**Interpretation:** Schäfer (1972) defined escape traces as 'any escape effort triggered by an external adverse cause'. The *Fugichnia* here are formed as a response to sudden (event) or rapid sedimentation associated with the deposition of storm beds. The organisms have been separated from oxygen-rich waters by rapid burial and have had to burrow out or face suffocation (Schäfer 1972). Escape structures are unusual in storm beds because commonly the thickness of the bed exceeded the escape limit of the trace makers (Frey & Goldring 1992).

The different morphology of the structures reflects the different animals responsible for their construction. Long cylindrical traces are probably the result of vermiciform animals. The presence of a similar structure connected to a *Rosselia rotatus* supports this as the inhabitant of this structure is considered to be a detritus feeding vermiciform animal. The sudden and rapid burial of the *Rosselia* burrow is evident from the clean mega-rippled nature of the overlying bed and from the truncation of this and other *Rosselia* structures.

Some of the long cylindrical *Fugichnia* may have been produce by bivalves. Rapid, sudden burial releases escape reaction in buried bivalves, which intrude foot-first upward (Bromley 1990, fig 5.8e). Bivalves attempting to escape suffocation from the deposition of the storm sand may have produced pouch-shaped *Fugichnia*.

The recorded lateral escape structure could have been produced when the *D. habichi* inhabitant attempted to avoid a predator (Bromley 1996).
2.2 CONULARIIDS

2.2.1 Introduction

The phylogenic affinities of Conulariids have been debated for more than 160 years. Resolution of the question of their affinities has been hindered by misinterpretation of preserved morphology and disagreements about morphological terminology (Babcock 1991). They have been interpreted as mollusks, worms, cnidarians, conodont animals, invertebrate chordates, vertebrates and an independent animal phylum. It is very unlikely that conulariids are an extinct molluscan group, as was commonly believed in the 1930’s, due to the absence of skeletal phosphate and rods in mollusks (Babcock 1991).

Babcock & Feldmann (1986a) proposed that conulariida are a monophyletic lineage of bilateria that have no obvious relationship to any extant phylum. Conulariids secreted an elongate, pyramidal, four-sided, bilateral, phosphatic exoskeleton strengthened by transverse thickenings called rods (Babcock 1991). The rods are slightly more resistant to decomposition than the rest of the exoskeleton. Babcock et al. (1987) suggested that although conulariids possess a weak bilateral symmetry, they might have functioned as radially symmetrical organisms.

2.2.2 Previous Work In Australia

The first reference to conulariids in Australia was by Morris (1845) when he described and figured specimens from the Illawarra district and Raymond Terrace as *Conularia levigata*.

McCoy (1847) recorded three species from Harpers Hill and Muree, *C. levigata*, *C. torta* and *C. tenuistriata*. Fletcher (1938) considered *C. torta* of doubtful validity because McCoy (1847) originally described only two specimens and they appeared to describe a pteropod shell rather than a conulariid.

Dana (1849) described *C. levigata* Morris and *C. tenuistriata*. He also erected a new species, *C. inornata*, from Permian strata at Glendon in the Hunter Valley.

De Koninck (1877) described several species; Fletcher (1938) discussed these and many other occurrences in detail.

More recent studies of conulariids in Australia have included:

- Talent (1965) on Siluro-Devonian species;
- Sherwin (1969) on Silurian conulariids from New South Wales;
Thomas (1969) proposed the erection of *Notoconularia*; and

a review of Palaeozoic conulariids from Tasmania by Parfrey (1982).

Bischoff (1973, 1978) described and figured some small phosphatic fossils from the Palaeozoic of western New South Wales and interpreted them as conulariids. Bischoff (1978) erected a suborder of conulariids, known as Ciroconulariida, but Babcock (1991) concluded that these fossils are unrelated to conulariids as they contain very few similarities.

**Occurrence:** The conulariids in this study are preserved in two beds, that crop out between 12.5-13 m above the base of the Snapper Point Formation, on the northern side of the rock-platform at South Island Beach. The lower bed is a phosphate-cemented diamictite that overlies a transgressive surface of erosion. Dropstones are common and measure up to 80 cm in diameter. Trace fossils are rare but other skeletal material is abundant and includes fenestellids, *Stenopora*, brachiopods, foraminifers, gastropods, bivalves, algae? and phosphatised plant remains. The conulariids in this bed are mostly fragmented due to transgressive winnowing.

Collophane makes up much of the phosphatic conulariid material as well as a large proportion of the spectacularly preserved wood material present in this and other directly overlying and underlying beds.

The overlying bed consists of moderately sorted, phosphate-cemented sandstone that is moderately bioturbated. Within this bed conulariids are common and appear to be the only body fossil remains.

**2.2.3 Taxonomy**


**Phylum Conulariida** Babcock & Feldmann 1986a.

**Diagnosis:** Animals with a four sided, steeply pyramidal exoskeleton; bilaterally symmetrical; integument composed of calcium phosphate and protein, multilayered, moderately flexible; exoskeletal framework of calcium phosphatic rods (or ridges) arranged transversely across each side face; adjacent rods abut or alternate at the midline of each face; rods of adjacent faces meet in a groove at the intersection of two faces; apical end commonly closed in a blunt point; apex sheathed by a phosphatic or chitinophosphatic stalk; aperture simple and open. Internal hard parts are unknown. Soft internal parts include an elongate tube extending most of the body
length, and one or more globular structures, all of uncertain function (Babcock & Feldmann 1986a).

**Remarks:** Genera are differentiated on the basis of:

1) the relative spacing of ridges;
2) the relative proportion of ridges that abut at the midline to those that alternate;
3) apical angles;
4) the presence or absence of nodes or spines; and
5) the spacing of nodes and spines (Fig. 2.21; Babcock & Feldmann 1986a).

Species are differentiated on:

1) patterns of rod articulation; and
2) rod angles.

Subfamily *Paraconulariinae* Sinclair, 1952.

**Diagnosis:** Conulariids with the corners of the shell sharply inflected; the facial ridges either stopping or alternating (modified after Sinclair 1952).

**Genus** *Notoconularia* Thomas, 1969.

**Type Species:** *Conularia inornata* Dana, 1849.

**Diagnosis:** Paraconulariinae with corner grooves divided into two furrows by a distinct longitudinal central ridge. Facial ridges smooth and interrupted at the corner groove. Interridge area smooth or may have variably developed longitudinal or oblique interridge crests. Test elongate, with a low angle of taper (less than 12°). Cross-section square, rectangular or rhombohedral (Thomas 1969).

**Discussion:** *Notoconularia* has only been recorded from the Permian of eastern Australia. Records of *N. levigata* and *N. tenuistriata* in the Salt Range (Waagen 1891), of *N. tenuistriata* in Kashmir (Diener 1899) and of *N. levigata* in Kolyma, USSR (Licharew 1934, 1939) are incorrect (Thomas 1969).
Notoconularia levigata (Morris).

Fig. 2.22

1845  Conularia levigata  Morris in Strzelecki, p. 290, pl. 18, fig. 9a-b.
1888  Conularia tasmanica  Johnston, pl. 20, fig. 1b, non fig. 1a.
1888  Conularia tenuistriata  McCoy; Johnston, pl. 20, fig. 5a.
1938  Conularia levigata  Morris; Fletcher, p. 247, p. 25, figs 10-13, non p. 26, fig. 4.
1969  Notoconularia levigata;  Thomas, p. 1287, pl. 150, figs 1-7.
1982  Notoconularia levigata;  Parfrey, p. 76, fig 8a.

Diagnosis: Large, elongate Notoconularia with an almost square cross-section. Apical angle of 3°-5°. Facial ridges spaced at 11-12 per cm (Thomas 1969).

Description of Snapper Point Formation Material: The almost square cross-section distinguishes this material from the more common Notoconularia inornata. Specimens that have undergone little compaction show the almost square cross-section with the ratio of the two faces ranging from 1:1 to 4:5. Specimens distorted by compaction are commonly compressed across a midline plane, giving the impression of a very rectangular cross-section. The midline exists as a ridge with no carina present.

No complete specimens were available. The largest cross-section measured was 30 mm and the longest (incomplete) specimen 150 mm. No specimens were well preserved enough to determine exoskeletal constrictions.

No apertures or apices were sufficiently well exposed to be described in detail. In one example, cross-sections through several small (3-5 mm), round, black, chitinous or chitinophosphatic? structures (located at the apex of a cluster of four parallel conulariids) are interpreted as possible stalks.

The four faces of the exoskeleton are planar except in slightly compressed or crushed specimens.

The integument appears to have been diagenetically compressed close to the framework, and now is mostly found on rods and midline ridges and in the corner groove. There appears to be some thickening of the integument interior to the corner groove. This is most evident in thin-section where definite layering is visible. Layers consist of collophane and thin bands of protein? or chitin?, with at least 45 layers visible under standard light microscopy.
Rods are embedded in the integument and cross each face transversely (Fig. 2.22). They are slightly irregularly spaced, with a spacing difference of up to 0.1 mm. The rods are straight to very slightly curved, paired and are commonly removed. On major faces rod pairs are offset and display left superior arrangement. On minor faces rod pairs abut at the midline. Rods on adjacent faces alternate in position along the corner groove. Rods display Gothic arch style articulation (see Babcock & Feldman 1986a, p. 354). Where the integument is removed the inter-rod area is smooth and consists of black, vitreous material. Where the integument is still preserved it is clear that the interridge area is smooth.

At the corner groove, the rods from the major and minor faces fold in towards the apex and then abruptly turn and run back towards the aperture. Each 'groove rod' abuts on the underside of the opposite rod to form a zigzag shaped longitudinal central ridge (Fig. 2.22).

The central cavity is filled with quartz sandstone cemented with phosphate. The percentage of phosphate within the central cavity is substantially higher than in the surrounding host sediment.

Commonly the conulariids occur in clusters of up to four similarly sized specimens. The individuals radiate from a point with the apices pointed in at the same angle as the angle of taper. Although the apices were not seen it appears that they all originate at the same point.

**Discussion:** *Notoconularia* is one of the few conulariine genera that have the faces supported by rods without nodes and spines. It is the only genus that displays a longitudinal ridge in the corner groove. Nodes and spines along rods are interpreted to provide a stronger framework to support the integument (Babcock & Feldmann 1986a).

### 2.2.4 Palaeoecology

Conulariids are now widely accepted as sessile, benthic organisms, with the organs in the region of the aperture probably utilized for filter feeding (Babcock & Feldmann 1986a). They lived attached by a flexible, possibly chitinous stalk that partially sheathed the apical end and had no obvious connection to the central body cavity (Babcock 1991).

Conulariids are known from Early Ordovician through Late Triassic marine deposits, and are most common in low-diversity assemblages (Babcock & Feldmann 1986b). They are rare in the Early Ordovician and in the Triassic but may be pervasive faunal elements in Middle Ordovician through Permian marine rocks (Babcock & Feldmann 1986a).
Babcock (1991) gave the following major functional arguments against the interpretation of conulariids as free-swimming medusoids or medusoid-like forms:

1) Calcium apatite (collophane), which has a specific gravity of 3.15 to 3.20 (Hulbut & Klein 1977), is too dense to form the skeleton of a large nektonic animal having a low surface area to volume ratio. Some conulariids were more than 20 cm long and probably could not have achieved neutral buoyancy unless most of their body mass was composed of lipids.

2) The long, slender, pyramidal form is hydrodynamically unstable for a nektonic organism.

It is probable that *Notoconularia levigata* existed as a sessile, benthic organism attached by a flexible, possibly chitinous stalk. The Snapper Point Formation examples appear to represent an opportunistic organism, occurring in abundance just below and associated with a transgressive surface of erosion.

Low levels of fragmentation of conulariid specimens in the sandstone unit may be a function of low biotic activity, and rapid burial. The more fragmented conulariids in the diamictite bed reflect the higher diversity fauna and are related to the rapid fragmentation of the multielement skeleton by predation, scavenging and constancy of water movement near the sediment water interface (Babcock & Feldman 1986a). Erosion and low sedimentation rates associated with the transgression rendered the conulariids more susceptible to fragmentation.

The clusters of conulariids, such as noted here, are rare in the literature but have been reported by Hall (1876, p. 28, fig. 1; 1879, p. 24, fig. 1), Slater (1907, p. 2, fig. 1), Sinclair (1944, p. 2, fig. 5) and Babcock & Feldman (1984, p. 17; 1986c, fig. 4a, c). This clustering is suggestive of a gregarious life style (Babcock 1991) and supports the suggestion that the organism was an opportunist.
ICHNOFACIES, ICHNOFABRICS AND TIERING OF BURROWS

3.1 ICHNOFACIES

In the past there have been two main styles of trace fossil analysis: (1) ichnofacies and ichnotaxa; and (2) ichnofabric. The type of analysis used has generally depended on the nature of the material, the type of project and the background of the ichnologist (Bromley 1996).

In this study, the abundance of spectacularly preserved individual trace fossils and ichnofabrics provided an extensive complementary data base and it was possible to employ both techniques and ultimately to integrate the analysis, along with sedimentological and palaeontological observations, to provide reliable, high resolution interpretations.

The concept of ichnofacies (i.e., recurring and widespread associations of trace fossils that are linked to and reflect palaeoenvironmental conditions such as bathymetry, salinity and substrate character) was introduced by Seilacher (1964). Past misuse or misconceptions of the ichnofacies concept has lead to considerable scrutiny and discussion of the concept (Byers 1982, Ekdale 1988, Frey et al. 1990, Bromley & Asgaard 1991, Pemberton et al. 1992, Pemberton & Wightman 1992, Pickerill 1992, Goldring 1993, MacNaughton & Pickerill 1995, Savrda 1995, Bromley 1996).

It appears to be generally accepted that, if employed alone, the ichnofacies concept provides limited resolution and may yield grossly overgeneralised results (Savrda 1991, Goldring 1993, Savrda 1995). Many authors also appear to agree that, when ichnofacies are used with caution and in association with other aspects of sedimentology, ichnology and palaeontology, there is a potential for high-resolution reconstructions of depth-related environmental gradients (Bromley 1996).

Four marine ichnofacies were originally established by Seilacher (1967) named after characteristic ichnogenera. In this study the eponymous ichnogenera are not italicized (following Bromley 1996), because it is a facies and not an ichnotaxon that is under discussion (this is in line with the usage of taxa in biostratigraphical zones, e.g. Bifrons zone). Several marine and non-marine ichnofacies have since been added and, although there is still considerable debate and disagreement, the number of currently defined ichnofacies stands at 11 (Bromley 1996).
Several authors have discussed the general characteristics of the presently defined ichnofacies (e.g. Bromley & Asgaard 1991, Bromley 1996) and, therefore, only those relevant to the present study have been outlined.

Four distinct ichnofacies were identified through the facies of the Pebbley Beach and Snapper Point Formations.

3.1.1 Skolithos Ichnofacies

This ichnofacies reflects high levels of hydrodynamic energy (Bromley & Asgaard 1991) and is typical of lower littoral to infralittoral environments (Frey et al. 1990). The substrate usually comprises slightly muddy to clean well-sorted, loose or shifting sediments subject to abrupt erosion or deposition (Frey et al. 1990). Physical reworking is enhanced by high energy levels, and the tiers of the endobenthic community are repeatedly obliterated (Bromley & Asgaard 1991); thus physical sedimentary structures are preferentially preserved (Pemberton et al. 1992a). The relationship between water agitation, sediment transport and animal distribution results in an ichnoassemblage that has a low diversity and is predominantly comprised of suspension-feeding organisms (Bromley 1990; Pemberton et al. 1992a). Inhabitants of this environment typically construct deeply penetrating, permanent domiciles and the resultant ichnofabric consists of a vertical fabric from deep shafts and equilibrium movements. For a detailed discussion of the development and preservation potential of the Skolithos ichnofacies see Bromley (1996).

In the Snapper Point and Pebbley Beach Formations the Skolithos ichnofacies is characterised by predominantly cylindrical or U-shaped burrows, vertical and less commonly horizontal spreiten burrows, less abundant horizontal structures and rare structures produced by mobile organisms (see Table 3.1, Fig. 3.1).

Occasionally in the lowest energy realm of the Skolithos ichnofacies in the study area, some very robust *Rosselia* burrows occur. *Rosselia* is interpreted as the dwelling structure of a detritus-feeding organism and reflects fairweather deposition in the quietest part of the ichnofacies. When this resilient ichnogenus (more typical of the Cruziana ichnofacies) occurs within the Skolithos ichnofacies, the term 'distal Skolithos ichnofacies' is used. A typical occurrence of a distal Skolithos ichnofacies occurs in the Pebbley Beach Formation at Clear Point in tidal inlet deposits (see Table 4.1, Fig. 4.5). The *Rosselia* burrows may have been
produced during low energy periods (inlet closure, channel migration etc.) and preserved by rapid burial during periods of high energy.

3.1.2 Cruziana Ichnofacies

This ichnofacies is characteristic of lower energy situations where erosion poses a rarer threat than in Skolithos environments and preservation potential of the upper tiers is substantially increased (Bromley & Asgaard 1991). Conditions range from moderate energy levels in shallow environments between fairweather and storm wave-base, to low energy levels in deeper, quieter environments (Pemberton et al. 1992a). Food supplies comprise suspended and deposited components typically resulting in a diverse assemblage of suspension and deposit-feeders, as well as mobile carnivores and scavengers.

In the study area this ichnofacies can generally be subdivided into proximal Cruziana, diverse Cruziana, distal Cruziana or restricted Cruziana ichnofacies (Table 3.2).

**Proximal** Cruziana ichnofacies assemblages (Fig. 3.2) represent the highest energy portion of the Cruziana ichnofacies. Traces are larger and more robust than usual and the assemblage is not highly diverse. Fluctuating energy levels prevailed and deposits usually consist of moderately to intensely reworked, storm-deposited sandstone beds. The ichnofacies represents the fairweather assemblage in a lower shoreface environment and comprises a resilient, equilibrium community of detritus and deposit-feeding organisms.

**Diverse** Cruziana ichnofacies assemblages (Fig. 3.3) are more mature and bioturbation is usually complete. The trophic theme is one of detritus- and deposit-feeding. High ichnodiversity and slow deposition have resulted in deposits with BI's of > 5 (see Ch. 3.1.2, Fig. 3.1).

**Distal** Cruziana ichnofacies (Fig. 3.4) typically contain a less diverse assemblage although bioturbation is still usually complete due to slow deposition rates and low energy levels in deeper, quieter water. The deepest tier structures, such as *Teichichnus rectus* and *Phycosiphon incertum* commonly dominate the ichnofabric, also reflecting very slow deposition and reworking by both deposit-feeding and grazing/foraging animals.

**Restricted** Cruziana ichnofacies (Fig. 3.5) are typically of low diversity and contain traces with reduced size compared to marine counterparts. It is characteristic of estuarine
intertidal channel and lagoon deposits and reflects a stressed ecosystem typical of brackish water conditions.

3.1.3 Arenicolites Ichnofacies

Bromley & Asgaard (1991) introduced this ichnofacies to encompass recurring, low diversity assemblages of vertical, opportunistic (Table 4.3), suspension-feeding trace fossils. It applies to short-term colonization of storm beds and other sand bodies occurring in incongruous environments (Bromley & Asgaard 1991). The Arenicolites ichnofacies differs from the Skolithos ichnofacies in that the Skolithos ichnofacies reflects communities adapted to ongoing high hydrodynamic energy and shifting sands resulting in the preservation of only deeper-tier biogenic structures. The Arenicolites ichnofacies also usually occurs in sand deposited by a raised energy event, but it represents post-event colonization and reflects tranquil conditions, allowing the preservation of all tiers including the shallowest levels (Bromley 1996). Although there has been some criticism and confusion surrounding the erection of the Arenicolites ichnofacies (Frey & Goldring 1992, Goldring 1995), in this study it proved extremely useful for differentiating storm deposited units from high energy, shallow water deposits.

In the study area the Arenicolites ichnofacies differs from the original definition (Bromley & Asgaard 1991) in that (here) it has a reasonably high diversity, possibly due to very favorable preservation potential of all tiering levels (Fig. 3.6). Characteristic traces and environments can be seen in Table 3.3. The most common trace fossil in this ichnofacies in the study area is *Diplocraterion habichi* and the intensity of bioturbation is usually high, as is characteristic of opportunistic colonization.

3.1.4 Glossifungites Ichnofacies

The Glossifungites ichnofacies is represented by a substrate-controlled assemblage that typically comprises robust, sharp-walled, unlined, passively filled, vertical to sub-vertical domicinia, excavated into firmground substrates (MacEachern et al. 1992b). Typically the substrate consists of dewatered, cohesive mud, due either to subaerial exposure or burial and subsequent exhumation (Frey & Seilacher 1980).

Lomnicki (1885) originally described this ichnofacies from a non-marine succession but more recent authors have considered the ichnofacies as marine (Pemberton & Frey 1985,
MacEachern et al. 1992b, Bromley 1996). Pemberton et al. (1992a) described it as environmentally wide-ranging and added that it only develops in firm, un lithified substrates such as dewatered muds. A number of authors have recognized the Glossifungites ichnofacies associated with omission surfaces where it represents a transient phase of benthic community succession as the substrate passes from softground through firmground to a hardground consistency (Goldring & Kazmierczak 1974, Fürsich 1978, Gruszczynski 1979, 1986, Savrda & Bottjer 1994). Pemberton & Frey (1985) also recognized that firmground produced by the exposure of compacted sediment during local erosion, is a major setting for this ichnofacies. A useful discussion of the stratigraphic applications of the Glossifungites ichnofacies is outlined in MacEachern et al. (1992b).

Because Glossifungites assemblages demarcate discontinuity surfaces that reflect sedimentary hiatuses (MacEachern et al. 1992b), they have been useful in the Snapper Point and Pebbley Beach Formations in aiding in the recognition of transgressive surfaces of erosion. Glossifungites assemblages are also helpful in interpreting firm mudstone deposits in a glacially-influenced lower shoreface environment (Table 4.4, Ch. 4.3.3.3), where the usual conditions were affected by perenial ice cover, and in the recognition of a possible firm substrate in a lower offshore deposit (Table 4.9, Ch. 4.4.4.3). Characteristic trace fossils (Fig. 3.7) and depositional environments of the Glossifungites ichnofacies in the study area are seen in Table 3.4.

3.2 BIOTURBATION AND ICHNOFABRICS

Bioturbation is the process by which the consistency and primary structure of sediments are displaced or modified by the activity of organisms (Richter 1936, Bromley 1990). Reworking may occur penecontemporaneously with sediment deposition or until the substrate is partly or fully cemented, resulting in borings (Taylor & Goldring 1993).

An ichnofabric is that aspect of the texture and internal structure of a bed that results from bioturbation at all scales (Ekdale & Bromley 1983). It records the primary sedimentary conditions, original endobenthic community structure and subsequent taphonomic history of either a single bioturbation event or several suites of trace fossils (Ekdale & Bromley 1983, Taylor & Goldring 1993). An ichnofabric assesses both the sedimentology and the resultant modification by bioturbation (Bockelie 1991, Ekdale & Bromley 1991, Goldring et al. 1991, Pollard et al. 1993).
Trace fossil assemblages are commonly mixed, through the superimposition and reworking of successive communities within the same sediment column (Bromley & Ekdale 1986). When ichnofabrics are composed of more than one trace suite (i.e., juxtaposition of two or more suites of burrows) a complex or composite multi-phase ichnofabric results (Bromley & Ekdale 1986). The latest traces in the burrowing sequence are usually best preserved whereas early traces are poorly preserved and commonly exist as a mottled background. Composite assemblages may be produced in two ways:

1. by a major physical change at the sea floor (substrate, salinity, rapid event deposition, etc.), resulting in a shift from one community to another; or
2. by continuous upward migration of a tiered endobenthic community during continuous deposition (Bromley & Ekdale 1986).

The latter authors stressed the importance of recognizing that the last formed, sharp-walled trace fossils represent the deepest tier which is least sensitive to the physical environment at the sea floor, because it is farthest removed from the sediment-water interface.

The use of the term ichnofabric (rather than bioturbate texture - Ritcher 1952, Schäfer 1956) has been questioned recently (e.g. by Frey & Pemberton 1990, Frey & Pemberton 1991). Ekdale et al. (1991) outlined the reasons why the two terms are related but not synonymous (for a detailed discussion see Ekdale et al. 1991, p. 100). In general, bioturbate texture is a more restricted descriptive term which does not encompass important concepts of habitat partitioning via infaunal tiering, nor does it include the important concept of degree of bioturbation that is implied by the bioturbation index (described below, Taylor & Goldring 1993).

Ichnofabric production and preservation is a function of the local biological and physical environment (Droser & Bottjer 1989). There are numerous biological controls on ichnofabric, including the life habits and behaviour of infauna, sizes of organisms and colonization rates. Physical controls include the overall rate of sedimentation and erosion, bed thickness, rates and intensity of episodic sedimentation, sediment size and sorting (Droser & Bottjer 1989).

3.2.1 Measurement of Bioturbation and Ichnofabric

Observed biologically influenced textural parameters in sedimentary rocks are commonly difficult to describe and analyze as burrows display a great range in size and complexity. Cross-
cutting of burrows and endobenthic tiering result in frequent, rapid, vertical and lateral changes in bioturbation which add to the difficulty (Bromley & Ekdale 1986).

Early workers attempted to classify bioturbation by semiquantitative measurement (Reineck 1963), and mathematical modeling (Guinasso & Schink 1975). Many workers took a descriptive approach, and consequently the literature contains numerous cases where the extent of bioturbation is described by terms such as “well-bioturbated”, “poorly-bioturbated” or “moderately-bioturbated” (Droser & Bottjer 1989). This approach produced two major difficulties. Firstly, there was no accurate basis for comparison between beds of the same facies, or between beds of different facies. Secondly, the amount of bioturbation recorded was strongly influenced by the relative abundance of bioturbation in the study area.

Droser & Bottjer (1986) devised a semiquantitative field classification scheme for ichnofabrics based on percentage of original sedimentary structures disrupted by biogenic reworking. Six ichnofabric indices were established from no bioturbation (ichnofabric index - ii=1) to complete homogenization (ii=6). These indices do not adequately reflect a number of parameters, such as ichnotaxonomic diversity, density and cross-cutting relationships that interact to produce an ichnofabric (Taylor 1991, Goldring et al. 1991, Ekdale & Bromley 1991, Taylor & Goldring 1993). In addition, Ekdale & Bromley (1991) noted that, because composite ichnofabrics typically reflect habitat partitioning by vertical tiering within the substrate, it would be inaccurate for them to be represented by a single index. The indices suggested by Droser & Bottjer (1986) are useful for coding simple ichnofabrics, such as Skolithos and Ophiomorpha fabrics (Droser & Bottjer 1987, 1989), but are not readily applied to composite ichnofabrics (Taylor & Gawthorpe 1993) such as occur in the present study area. For this reason, Droser & Bottjer’s scheme is not utilized in this study.

Taylor & Goldring (1993) used the degree of bioturbation to formulate a **bioturbation index** (BI; Fig. 3.8). The degree of bioturbation is very important as it reflects the duration of colonization, which is closely related to rates of sedimentation and erosion (Taylor & Gawthorpe 1993). This index is a descriptive scheme, which assesses the grade of bioturbation and updates the pattern-recognition methods first established in the 1950s. It clearly defines individual grades in terms of bedding distinction, burrow density and overlap, and down-plays the importance of percentage area burrowed (Taylor & Goldring 1993). The index facilitates rapid comparisons between different ichnofabrics (Taylor 1991), and aids in the formulation of ichnocoenoses (Bromley 1990, Pollard et al. 1993).
Each grade is allocated a numerical value and a descriptive term. The choice of seven categories (the number proposed by Reineck 1963) is retained here as this covers the variations in intensity and has stood the test of time (Taylor & Goldring 1993). Grades range from zero (representing an absence of bioturbation), to six (representing complete reworking): for a thorough description of each grade see Taylor & Goldring (1993). In composite ichnofabrics, where discrete second phase trace fossils are transposed over a background of BI 6 (mottled first phase trace assemblage), the scheme of Droser & Bottjer (1990) is adapted. This allocates a BI of 6:2-6:4 to those ichnofabrics that have undergone multiphase reworking (Fig. 3.8).

Ichnofabric constituent diagrams (Taylor & Goldring 1993; Fig. 3.9) are used as they provide a visual means for describing and comparing ichnofabrics by: (a) analyzing the type and extent of remaining primary fabric; (b) assessing the chronology of the tiering and order of the ichnotaxa; (c) recognizing the bioturbation as either an opportunistic or tiered equilibrium event (Goldring 1995). For a detailed description of the formulation and use of ichnofabric constituent diagrams see Taylor & Goldring (1993) and Goldring (1995).

3.2.2 Methods Of Ichnofabric Analysis

A total of 466 metres of section were examined in rock platforms and steep to vertical sea cliffs. Field sketches and photographs of the ichnofabrics were examined, and in all cases fabrics were quantified using the methods explained in Taylor & Goldring (1993). Quantitative assessments are based on areas considerably larger than those seen in the accompanying figures. Many specimens were collected, slabbed and lightly moistened to enhance the visibility of the trace fossils.

Rocks of the Pebbley Beach and Snapper Point Formations are described here as being non-bioturbated to intensely bioturbated. Composite associations make up more than half of the ichnofabrics.

3.3 TIERING OF BURROWS

Members of benthic communities occur at different levels within the substrate. This ‘ecological stratification’ (Seilacher 1978) is known as tiering (Ausich & Bottjer 1982). Tiered ichnocoenoses result from the differences in the average and maximum burrowing depths of the endobenthic taxa (Ekdale 1985). Infaunal communities are tiered in response to chemical and
physical gradients within the sediment (Bromley & Ekdale 1986), the most important factors being food supply, oxygen level and substrate firmness (Ekdale 1985). Depth and composition of trace fossil associations may also vary with sedimentation rate or grain size (Wetzel 1983), as well as early diagenetic history of the sediment and penecontemporaneous erosion (Goldring et al. 1991).

A generalized model for burrow stratigraphy based on bathyal and abyssal box cores was established by Berger et al. (1979). Ekdale et al. (1984b) added more detail based on modern pelagic deposits. Generally, a typical tiering profile consists of three layers (Fig. 3.10).

1. Directly below the sediment/water interface a mixed layer, a few centimetres thick, consists of homogenized sediment produced by total bioturbation (Thistle et al. 1985) of sediment with a high pore water content. Biogenic structures produced in this layer, including surface traces, are not usually preserved due to continual rapid biogenic mixing (Ekdale 1977).

2. Under this a transition layer contains a heterogeneous texture produced by the descent of deeper burrows (Bromley 1996) into sediment that has undergone some compaction and dewatering. Colour contrast in this layer is commonly high (Bromley 1996). Several levels may be identified (Savrda & Bottjer 1989), representing the different depths occupied by different organisms.

3. Beneath the transition layer colour contrast fades and an historical layer, that generally lies below the level of active bioturbation, exists.

The boundaries between the layers are considered to be diagenetic with bioturbation controlling the diagenesis (Bromley 1996).

In ancient strata, the burrowing depths of trace-producing organisms cannot be measured directly (unless a frozen tiered profile is developed, see next page). Trace fossil assemblages represent a composite arrangement of burrows that are produced by the vertical accretion of the sea floor during deposition and the resulting upward migration of the tiered infaunal community (Savrda & Bottjer 1989). Cross-cutting relationships of different kinds of trace fossils indicate the relative time of emplacement of particular trace types and record the tiering structure of a community.

Tiering taphonomy decreases the preservation potential of shallowly emplaced trace fossils and emphasizes deeper structures. Bromley & Ekdale (1986) and Bromley (1990) discussed the effects that tiering has on the taphonomy of trace fossils and how the deepest traces come to be the most conspicuous.
a) Deepest structures are the most complete, with only their upper parts cross-cut by shallower structures. Activity within each tier cross-cuts burrows from shallower tiers and commonly obliterates them.

b) Deeper tiers are emplaced into firmer substrates with less cognate water and thus tend to have clearly defined, sharp boundaries and are taphonomically well suited for fossilization.

c) The uppermost structures suffer from more compactional deformation.

d) Deeper structures commonly contain ‘active fill’ material contrasting in colour and texture with the surrounding sediment. This may result from rigorous particle selection by deposit-feeding organisms.

e) Inverted conveyer feeders in the deep tier introduce material from high levels which contrasts in colour and texture with the surrounding sediment.

f) The contained faecal sediment, surface material and metabolic products in the fill of the deep structures are chemically dynamic. Their emplacement within reducing, oxygen-poor sediment creates a special diagenetic microenvironment that may initiate mineralization and further enhancement of the visibility of the structure.

In the Pebbley Beach and Snapper Point Formations some post-depositional trace fossil assemblages are preserved in ‘frozen tiered profiles' (Savrda & Bottjer 1986). These profiles provide a ‘snapshot’ view of the tiering structure of the infaunal community (Droser et al. 1994), as they are produced when the community works from a stationary floor until the substrate is suddenly buried.

More commonly a steady accretion of the sea floor has occurred. Depositional rate was evidently slower than the rate of biogenic reworking and the gradual upward movement of successive tiers has allowed deeper structures to cross-cut shallower ones. The resultant ichnofabrics vary widely according to the rate of activity in different tiers (Bromley 1990).

The ichnofabric and tiering approach has been very useful in aiding the interpretation of depositional environments (e.g. zonation of the shoreface) and in recognizing potential hiatal surfaces. In the following section each ichnofabric is described and the tiered community structure interpreted. The environmental significance of each community and resultant ichnofabric is outlined. The shoreface model of Pemberton et al. (1992b) is used (see Fig. 3.11). A trace fossil key for the tiering profiles is seen in Figure 3.12.
3.4 ICHNOFABRICS AND TIERING PROFILES

Twenty-seven important ichnofabrics have been identified in the study area.

1. Phycosiphon A. Composite Ichnofabric

Figure 3.13; Plate 3.1a-c.

Lithological description: Intensely to completely bioturbated (BI = 5-6) siltstone; rare relict patches of primary lamination and sand lenses.

Ichnology: A low-diversity ichnofauna dominated by the small pervasive burrows of Phycosiphon incertum with:-

- small Rosselia socialis (Fig. 3.13);
- sparse Diplocraterion habichi associated with remnant thin layers of sand (Pl. 3.1b); and
- very rare examples of Planolites, Diplocraterion parallelum (Pl. 3.1c), Rhizocorallium? (Pl. 3.1b) and Psammichnites.

Ichnofacies: Distal Cruziana/rare Arenicolites.

Interpretation: This composite ichnofabric is the product of repeated burrowing activity by an infaunal deposit-feeding community that colonized the upper transition layer (Fig. 3.10) in a lower offshore setting (Fig. 3.11) during fairweather periods. The sand layers probably represent distal storm deposits that have been inhabited for a short period by vertical suspension-feeding burrows (Diplocraterion). The shallow tier Psammichnites and Planolites were probably preserved by sudden burial by storms. Similar ichnofabrics have been documented by Goldring et al. (1991) and Taylor & Gawthorpe (1993) from similar settings.
2. *Phycosiphon* B. Ichnofabric

Figure 3.14; Plate 3.1d

**Lithological description:** Intensely to completely bioturbated (BI = 6), silty, fine-grained sandstone; very rare, relict primary lamination visible in thin-section.

**Ichnology:** Pervasive *Phycosiphon incertum* and rare *Skolithos* (Fig. 3.14); *Skolithos* are thickly lined and are seen in thin-section to cross-cut primary lamination and *Phycosiphon* burrows.

**Ichnofacies:** Distal Cruziana/rare Arenicolites.

**Interpretation:** The *Phycosiphon* B. ichnofabric is the product of intensive opportunistic colonization by an infaunal deposit-feeding organism and a shallow tier suspension feeding tube dweller in a lower offshore environment during maximum flooding of the shelf.

3. *Diplocraterion* Ichnofabric

Figure 3.15; Plate 3.1e-f

**Lithological description:** Horizontally stratified, current rippled or HCS, fine- to medium-grained sandstone; BI = 2-4, and common laminated to scrambled (lam-scram) profiles.

**Ichnology:** A moderately diverse ichnofauna dominated by *Diplocraterion habichi* with rare *Diplocraterion parallelum, Cylindrichnus, Palaeophycus, Taenidium synyphes* and *Rhizocorallium jenense* (Fig. 4.15).

**Ichnofacies:** Arenicolites.

**Interpretation:** This ichnofabric is the product of opportunistic colonization of the upper transition layers in either event beds deposited in an offshore transition environment (Pl. 3.1f), or storm washover sands deposited in a back-barrier environment (Pl. 3.1e).
4. *Phycosiphon-Diplocraterion* Composite Ichnofabric

Figure 3.16; Plate 3.1g-i

**Lithological description:** Completely bioturbated siltstone beds (BI = 6), that either contain almost completely homogenized fine- to medium-grained sandstone or are overlain by sandstone lenses that contain relict ripple bedding and low-angle cross-bedding.

**Ichnology:** Discrete trace fossil types overprint a mottled texture which dominates the composite ichnofabric; primary ichnotaxa are difficult to discern due to the intensity of biogenic reworking and overprinting by the second phase ichnofauna (giving the ichnofabric an overall BI = 6:3). Primary fauna includes:
- *Planolites*
- small *Rosselia socialis*; and
- *Phycosiphon incertum*.

Second phase ichnofauna is dominated by *Diplocraterion habichi* (Pl. 3.1g-i) and includes:
- common *Phycosiphon incertum*; and
- rare *Palaeophycus* and escape traces (Fig. 3.16).

**Ichnofacies:** Distal or restricted Cruziana/Arenicolites or Glossifungites.

**Interpretation:** This ichnofabric has a composite history and was formed in a number of different environments. The original siltstone was deposited under slow but continuous deposition during fairweather periods when the infaunal community was able to rework the sediment completely. The sandstone beds are either the product of storm deposition (Pl. 3.1h-i) or represent a transgressive lag (Pl. 3.1g), and the ichnofauna represents an opportunistic community that was able to thrive in a substrate that was out of equilibrium with the usual silty environment. The *Diplocraterion habichi* protruding from the transgressive lag deposit (Pl. 3.1g) represent a Glossifungites ichnofacies. Where the interbeds of siltstone and sandstone are thin, long thin *Diplocraterion habichi* often pass down through several beds. The ichnofabric was formed in environments ranging from lower offshore to offshore transition and may also have been formed in backbarrier lagoon environments experiencing washover from the marine
environment. The Glossifungites example reflects a firm substrate produced during winnowing and sediment starvation associated with a marine transgression (see Chapter 5.0).

5. *Teichichnus-Rosselia/Asterosoma-Phycosiphon* Composite Ichnofabric

Figure 3.17; Plates 3.1j, 3.2a-f

**Lithological description:** Amalgamated, fine- to medium-grained HCS and low-angle cross-bedded sandstone with lam-scram profiles, rare silt-draped ripples and truncated bed tops (Pl. 3.1j); BI increases up through the bed and ranges from 0 at the base to a maximum of 6:2 at the bed top.

**Ichnology:** Ichnofauna dominated by *Teichichnus* (Pl. 3.1j, 3.2a-b) connected to a variety of integrated funnel tops ranging from simple *Rosselia socialis* (Pl. 3.2b), through complex forms of *Rosselia motivus* (Pl. 3.2c), *Rosselia rotatus* (Pl. 3.2e) and *Asterosoma* (Pl. 3.2f); *Phycosiphon incertum, Diplocraterion habichi* and *Psammichnites* (Pl. 3.2d) are common and *Rhizocorallium irregulare* (Pl. 3.2e) is rare.

**Ichnofacies:** Proximal Cruziana/Arenicolites.

**Interpretation:** This composite ichnofabric is the product of two phases of bioturbation. Shallow tier opportunistic species associated with deposition of the storm event beds have been largely overprinted by the deeper tier deposit-feeding community associated with fairweather conditions. The lack of siltstone interbeds and the intensity of reworking of the storm-deposited sandstone indicate that the beds were probably deposited in a lower shoreface environment.

6. *Teichichnus-Rosselia motivus-Diplocraterion habichi* Composite Ichnofabric

Figure 3.18; Plates 3.2g-h, 3.3a-b

**Lithological description:** Moderately to completely bioturbated (BI = 3-6:2), silty sandstone with rare, relict HCS.
Ichnology: Most beds are dominated by a background mottled texture composed of circular burrows. Discrete traces include:-

- complex *Rosselia motivus* (Pl. 3.2g) with associated *Teichichnus*;
- *Diplocraterion habichi* (Pl. 3.2h, 3.3a-b);
- *Phycosiphon incertum* (Pl. 3.3a-b, Fig. 3.18); and
- rare *Taenidium barretti* and *Taenidium synyphes*.

Ichnofacies: Proximal Cruziana/Arenicolites.

Interpretation: This ichnofabric is the result of at least two separate phases of bioturbation. The first phase represents the repeated reworking of event beds by an infaunal deposit-feeding community. The second phase is the product of opportunistic colonization of overlying storm event sandstone beds and thin storm lags. These beds were then re-inhabited by the fairweather community. *Phycosiphon* was the last to inhabit the beds and appears to have preferred the silt lining of pre-existing burrows to the surrounding host sediment. This practice of exploiting the living space of other burrows may have allowed the *Phycosiphon* producer to inhabit a deeper than normal tier position.

The intensive primary phase of bioturbation and the thick beds suggest an environment experiencing continuous sedimentation. The lack of siltstone interbeds indicates deposition in an offshore transition or lower shoreface environment.

7. Mottled Flaser-bedded Ichnofabric

Figure 3.19; Plate 3.3d

Lithological description: Intensely bioturbated (BI = 4), flaser bedded sandstone with predominantly reworked relict asymmetrical sand ripples.

Ichnology: Mottled texture with sparse *Phycosiphon incertum* (Fig. 3.19).

Ichnofacies: Difficult to determine but absence of vertical structures suggests a Cruziana ichnofacies.
Interpretation: This ichnofabric has resulted from reworking of centimetre-scale sand and silt ripples that have probably been deposited in a low-energy sediment-starved environment. The unrecognizable nature of the trace fossils may be a function of the interbedded nature of the sediment. It is possible that only a shallow tier community existed, thus limiting the preservation potential of the traces. The environment of deposition may have been lower offshore or backbarrier.

8. *Polycylindrichnus* Composite Ichnofabric

Figure 3.20; Plate 3.3c, e

Lithological description: Thick beds of intensely bioturbated (BI = 5), silty medium-grained sandstone with rare relict primary lamination which suggests that the thick beds were amalgamated units that have been subsequently homogenized.

Ichnology: Moderately diverse ichnofauna dominated by abundant, slender, vertical *Polycylindrichnus* (Pl. 3.3c) and a mottled texture characterises the ichnofabric; other traces include common:-

- very large *Rhizocorallium irregulare*;
- small *Rhizocorallium irregulare*; and
- *Phycosiphon incertum* (Fig. 3.20).

Ichnofacies: Restricted Cruziana.

Interpretation: This ichnofabric is the result of repeated bioturbation of an amalgamated sandstone unit by an infaunal deposit-feeding community in the upper transition layer. The thick, silty nature of the beds and the restricted nature of the Cruziana ichnofacies suggest that they were deposited in a lagoon environment. The homogenization of thin storm beds suggests that the unit may have been deposited at the front edge of the lagoon where sand was frequently being introduced to the backbarrier system from the marine environment during storm washover.
9. *Rhizocorallium irregulare-Asterosoma* Composite Ichnofabric

Figure 3.21; Plates 3.3f, 3.4a

**Lithological description:** Composed of a thick unit of moderately to completely bioturbated (BI = 4-6), largely homogenized silty fine-grained sandstone with rare, relict, thin storm-produced lenses.

**Ichnology:** A diverse ichnofauna dominated by long, vertically retrusive *Rhizocorallium irregulare* (Pl. 3.3f) and a mottled texture; other common traces include:

- large *Diplocraterion parallelum* displaying protrusive behavior (rarely seen in this species anywhere else in the study area - Pl. 3.3f);
- large, complex *Teichichnus* and *Asterosoma* which dominate some horizons (Pl. 3.4a);
- very large *Rhizocorallium jenense* (type B);
- *Phycosiphon incertum*;
- *Taenidium synyphes*;
- *Palaeophycus* (Fig. 3.21); and
- *Planolites* which are common in the living tubes of *Diplocraterion parallelum*.

**Ichnofacies:** Diverse Cruziana.

**Interpretation:** This ichnofabric is the product of repeated burrowing episodes by a diverse, infaunal, deposit- and suspension-feeding community that repeatedly colonized a number of event beds in an upper offshore setting. The homogenization of storm layers by the fairweather, deposit-feeding community suggests that the environment did not experience intense storm activity.
10. Escape Trace Ichnofabric

Figure 3.22; Plate 3.4b-c

Lithological description: Lobate, fine- to medium-grained HCS sandstone beds with a maximum BI of 1.

Ichnology: Escape traces, Phycosiphon incertum and rare Diplocraterion habichi (Fig. 3.22).

Ichnofacies: Escaping organisms and a rare Arenicolites ichnofacies.

Interpretation: The escape trace ichnofabric is the product of escaping organisms disturbing the bedding (Pl. 3.4b-c) in their quest to escape burial and suffocation by thick blankets of storm redeposited sand in middle shoreface down to offshore transitional settings. Phycosiphon and Diplocraterion habichi entered the substrate at a later date as opportunists.

11. Teichichnus Composite Ichnofabric

Figure 3.23; Plate 3.4d-g

Lithological description: Extensively bioturbated (BI = 5-6:4), poorly sorted, silty, fine-grained sandstone with lenses of pebbles and wood fragments almost completely biogenically reworked (Pl. 3.4d).

Ichnofacies: Cruziana, probably diverse but intensive reworking by Teichichnus has overprinted evidence of other species.

Ichnology: Mottled background texture overprinted by spectacular, long, sinuous, vertical to oblique Teichichnus sinuosus (Pl. 3.d, f, g) with associated rare Asterosoma funnels that increase in abundance (or visibility) where the Teichichnus are less intensive (Pl. 3.4e, g); Phycosiphon incertum is common (Pl. 3.4f).
Interpretation: This ichnofabric is the product of repeated intensive reworking by a deep tier infaunal deposit-feeding community that has successively colonized a number of event beds in an upper offshore setting during fairweather periods. The intensity of reworking of the beds and its position about 1 m above a transgressive surface of erosion suggests that it represents a condensed section produced during sediment starvation associated with maximum flooding.

12. *Asterosoma-Teichichnus-Diplocraterion parallelum* Composite Ichnofabric

Figure 3.24; Plate 3.5a-b

Lithological description: Intensely to completely bioturbated (BI = 5-6), poorly sorted, silty, fine- to medium-grained sandstone separated by lobate, HCS, medium- to coarse-grained sandstone lenses that are rarely bioturbated; where the coarser sandstone lobe was thin it has been biogenically homogenized producing isolated lenses (up to 15 cm), relict sandstone scour troughs in the bioturbated beds or tubular tempestites. Wanless *et al.* (1988) described tubular tempestites as forced infillings of large burrows produced during storms (see Ch. 4.4.3 for a thorough discussion of tubular tempestites).

Ichnology: Large complex *Asterosoma* with associated *Teichichnus* overprints most other traces (Pl. 3.5a-b) and the mottled background texture; other traces include:

- common *Phycosiphon incertum*;
- *Diplocraterion parallelum* that has been almost completely overprinted (Pl. 3.5a, Fig. 3.24); and
- rare *Psammichnites*.

Ichnofacies: Cruziana/Arenicolites.

Interpretation: This spectacular, composite ichnofabric is the product of at least two phases of bioturbation. The opportunistic, suspension-feeding *Diplocraterion parallelum* colonized the upper transition layer in the thin, lobate event beds following storm deposition. With the return to fairweather conditions and slow continuous deposition, the deeper tier *Asterosoma* and *Phycosiphon* community were able to rework the sediment extensively. The ichnofabric is the product of repeated bioturbation of an infaunal, largely deposit-feeding community, during
fairweather deposition, in a strongly storm-dominated transition offshore to upper offshore environment.

13. **Rosselia-Teichichnus-Diplocraterion parallelum** Composite Ichnofabric

Figure 3.25; Plate 3.5e-g

**Lithological description:** Intensely bioturbated (BI = 2-5), HCS and low-angle cross-beded, fine- to coarse-grained sandstone; relict primary lamination commonly preserved.

**Ichnology:** *Rosselia socialis* and *Rosselia rotatus* funnels with vertical to horizontal, *Teichichnus* tubes (Pl. 3.5e, g) overprint a mottled background texture (Pl. 3.5g); other common traces include:
- *Diplocraterion parallelum*;
- large *Rhizocorallium jenense* (type B, Pl. 3.5f);
- *Phycosiphon incertum*; and
- *Palaeophycus tubularis* (Fig. 3.25).

**Ichnofacies:** Distal Skolithos.

**Interpretation:** This ichnofabric has been produced by the overprinting of an infaunal suspension-feeding community by an infaunal deposit-feeding community during fairweather periods in a silt-starved, lower to middle shoreface environment. The hazy nature of the mottled background texture and the *Diplocraterion parallelum* suggest that the suspension-feeding community inhabited a soft soupy substrate.

14. **Phycosiphon-Planolites** Ichnofabric

Figure 3.26; Plate 3.5c-d.

**Lithological description:** Sparsely to moderately bioturbated (BI = 1-4 - highest where interbeds are thinnest), interbedded siltstone and sandstone; siltstone displays normally-graded
bedding and poorly developed ripple cross-laminae - sandstone has silt defined low-angle cross-bedding, and rare, poorly developed ripple cross-laminae.

**Ichnology:** Thickly bedded sections contain little bioturbation (Pl. 3.5c); a low diversity ichnofauna is composed of *Phycosiphon incertum*, small rare *Rosselia socialis* (Fig. 3.26), *Planolites* and sparse *Skolithos* which may represent a Glossifungites ichnofacies (Pl. 3.5d).

**Ichnofacies:** Distal Cruziana/Glossifungites.

**Interpretation:** This ichnofabric is the product of sparse bioturbation by an infaunal deposit-feeding community in a distal, very strongly storm-dominated, lower offshore environment, probably close to storm wavebase. Cross-stratified sandstone lenses probably represent density flows of storm-derived sand from the nearshore zone (Bann 1990). The Glossifungites ichnofacies associated with rare siltstone beds suggests that the substrate was firm and may reflect sediment starvation associated with maximum flooding of the shelf.

15. *Diplocraterion habichi-Phycosiphon* Ichnofabric

Figure 3.27; Plate 3.6a-b

**Lithological description:** Sparsely bioturbated (BI = 1-3), HCS and low angle cross-stratified, fine-grained sandstone; the dominant feature of the ichnofabric is the primary lamination.

**Ichnology:** Long thin *Diplocraterion habichi* (Pl. 3.6a) reworked by *Phycosiphon incertum* (Pl. 3.6b; Fig. 3.27); *Phycosiphon* is also common in the host sediment.

**Ichnofacies:** Arenicolites.

**Interpretation:** This ichnofabric is the product of opportunistic colonization of storm deposited sand in a very strongly storm-dominated, upper offshore environment.
16. *Diplocraterion parallelum-Macaronichnus* Ichnofabric

Figure 3.28; Plate 3.6c-f

**Lithological description:** Sparsely to intensely bioturbated (BI = 2-5), medium- to coarse-grained sandstone; ichnofabric commonly dominated by relict HCS and low-angle cross-stratification.

**Ichnology:** Moderately diverse ichnofauna dominated by large *Diplocraterion parallelum* (Pl. 3.6c-f), and smaller, often pervasive *Macaronichnus segregatus* (Pl. 3.6c) overprinting a mottled background texture (Pl. 3.6d); other traces include *Arenicolites, Skolithos* and *Phycosiphon incertum* (Fig. 3.28).

**Ichnofacies:** Skolithos.

**Interpretation:** This ichnofabric represents colonization by an infaunal suspension and deposit-feeding community in a silt-starved, middle to upper shoreface environment. *Macaronichnus* represents the dominant component of the deposit-feeding ichnofauna and is believed to indicate the activity of an organism that fed on microbes, up to several metres below the sediment-water interface (MacEachern & Pemberton 1992b).

17. *Rosselia-Rhizocorallium-Phycosiphon* Composite Ichnofabric

Figure 3.29; Plate 3.7a-b

**Lithological description:** Intensely to completely bioturbated (BI = 5-6:2), poorly sorted, silty, fine- to medium-grained sandstone with sparse relict lenses of cleaner, medium-grained sandstone (Pl. 3.7a).

**Ichnology:** A diverse trace fossil assemblage dominated by *Rosselia* (Pl. 3.7a) and *Asterosoma*, with vertical to oblique *Teichichnus* tubes (Pl. 3.7b), overprint a mottled texture; other forms identified include:-
• very large *Rhizocorallium* (Pl. 3.7a);
• small *Rhizocorallium irregulare* (Pl.3.7b);
• *Diplocraterion parallelum* and *Diplocraterion habichi* which are largely overprinted and generally only visible in plan view on the rock platform; and
• *Phycosiphon incertum* commonly preserved within the living chamber of other traces and within the host sediment (Pl. 3.7b).

**Ichnofacies:** Diverse Cruziana/Arenicolites.

**Interpretation:** This composite ichnofabric has been produced by more than one community. The infaunal suspension-feeding trace fossils appear to be related to the medium-grained sandstone storm-event beds. The sand-filled living chambers of these burrows are often the only evidence of the (homogenized) event layer and may, therefore, represent tubular tempestites. The composite ichnofabric was subsequently formed by repeated burrowing of the event beds and fairweather deposits by an infaunal deposit-feeding community, during fairweather periods in an offshore transitional environment deposited during low sedimentation rates produced by a marine transgression.

18. *Diplocraterion parallelum-Macaronichnus-Teichichnus-Rosselia*  
Composite Ichnofabric

Figure 3.30; Plate 3.7c-d

**Lithological description:** Moderately to completely bioturbated (BI = 3-6), fine- to medium-grained sandstone with rare primary low angle cross-stratification.

**Ichnoology:** The ichnofabric is dominated by a mottled texture (Pl. 3.7d); a low diversity ichnofauna consists of:-

• *Rosselia* with connected *Teichichnus* tubes;
• *Diplocraterion parallelum* commonly well-preserved in plan view (Pl. 3.7c);
• *Macaronichnus*; and
• *Phycosiphon incertum* (Fig. 3.30).
**Ichnofacies:** Distal Skolithos.

**Interpretation:** The composite ichnofabric is the result of a resilient middle tier deposit-feeding community overprinting a shallower tier suspension-feeding community in a silt-starved, middle shoreface environment.

19. *Rhizocorallium jenense* Composite Ichnofabric

Figure 3.31; Plate 3.7e

**Lithological description:** Intensely bioturbated (BI = 4-5), fine- to medium-grained sandstone with sparse primary low angle cross-bedding; beds contain abundant molluscs, including *Vacunella* in living position.

**Ichnology:** A moderately diverse ichnofauna dominated by small *Rhizocorallium jenense* (type A) and very large *Rhizocorallium jenense* (type C, Pl. 3.7d) overprint a mottled background texture; other common forms include:-

- *Teichertichnus* with very rare associated *Rosselia* funnels;
- *Diplocraterion parallelum*; and
- rare *Phycosiphon incertum* (Fig. 3.31).

**Ichnofacies:** Distal Skolithos.

**Interpretation:** This ichnofabric is the product of repeated bioturbation of storm beds, by an infaunal community, in a middle shoreface environment.

20. Mottled burrow-Glossifungites Composite Ichnofabric

Figure 3.32; Plate 3.7f

**Lithological description:** Intensely to completely bioturbated (BI = 5-6), poorly sorted, mudstone, siltstone and silty sandstone with relict, partly to completely homogenized medium-to coarse-grained sandstone and granule conglomerate beds.
Ichnology: The most obvious trace fossil is *Diplocraterion parallelum*, due to the robust sand-filled nature of the U-tube; a mottled background texture is largely overprinted by mostly vertical to irregular, sharply outlined, sand-filled burrows such as *Skolithos* and small *Arenicolites* (Pl. 3.7f). *Phycosiphon incertum* is common both in the living tubes of other traces and in the surrounding host sediment (Fig. 3.32).

Ichnofacies: Cruziana/rare Arenicolites/Glossifungites.

Interpretation: This ichnofabric has resulted from more than one phase of bioturbation. The mottled background texture represents reworking during periods of very slow deposition in an offshore environment. The sand-filled burrows have evidently been open dwelling structures during periods of sediment starvation when the substrate was firm, and they have been filled with sand and gravel introduced from the coarse-grained beds. *Diplocraterion parallelum* is also associated with thin storm-deposited layers within the silty sandstone beds and it has been largely reworked by the resident Cruziana assemblage. The ichnofabric represents the reworking of fairweather and storm deposits during fairweather periods in an offshore environment and the subsequent overprinting by an opportunistic firmground assemblage during transgressive ravinement (see Chapter 5.2.7).

21. *Macaronichnus* ichnofabric

Figure 3.33; Plate 3.7g

Lithological description: sparsely to moderately bioturbated (BI = 1-3), clean, fine- to coarse-grained sandstone with the primary cross-stratification very evident; cross-bedding types include low-angle, HCS, trough and tabular forms with large-scale wave-ripples common in the coarser fractions of the units.

Ichnology: A moderately diverse, low intensity ichnofauna dominated by pervasive *Macaronichnus segregatus* (Pl. 3.7g); other trace fossils are rare and include small *Arenicolites* often only seen as paired holes in plan view, *Phycosiphon incertum, Diplocraterion parallelum,*
Skolithos, Cylindrichnus concentricus, small Rhizocorallium jenense and Diplocraterion habichi (Fig. 3.33).

**Ichnofacies:** Skolithos.

**Interpretation:** The distinctive *Macaronichnus* ichnofabric represents the work of a deep tier, infaunal deposit-feeding community that overprinted a shallow tier, suspension-feeding community. *Macaronichnus* is generally indicative of high-energy environments (MacEachern & Pemberton 1992b). This ichnofabric represents deposition in a foreshore to shoreface setting.

22. *Polykladichnus* ichnofabric

Figure 3.34; Plate 3.8c

**Lithological description:** Clean, medium- to coarse-grained sandstone that displays low-angle cross-stratification, HCS or large-scale wave-ripples; bioturbation ranges from sparse to moderate (BI = 1-4).

**Ichnology:** A moderately diverse ichnofauna is dominated by *Polykladichnus irregularis*; other traces present include *Diplocraterion parallellum, Arenicolites, Skolithos, Macaronichnus segregatus, Palaeophycus* and *Phycosiphon incertum* (Fig. 3.34).

**Ichnofacies:** Skolithos.

**Interpretation:** The ichnofabric is the product of a suspension and deposit-feeding community in a silt-starved, middle shoreface environment. The suspension-feeding ichnofauna represents a community that was able to thrive in a high-energy environment, which was experiencing wave reworking and a constantly shifting substrate. *Polykladichnus* evidently was a deep, vertical, structure inhabited by a suspension-feeding organism. The *Macaronichnus* tracemaker is believed to feed on microorganisms up to several metres below the sediment water interface (MacEachern & Pemberton 1992b).
23. *Teichichnus-Diplocraterion parallelum* Composite Ichnofabric

Figure 3.35; Plate 3.7h

**Lithological description:** Intensely to completely bioturbated (BI = 5-6), fine- to medium-grained poorly sorted sandstone with relict coarser lenses predominantly homogenized; the sand-fill of some *Diplocraterion parallelum* tubes are the only evidence of prior existence of sandstone beds (Pl. 3.7h).

**Ichnology:** The ichnofauna may have originally been diverse but all evidence has been overprinted by *Phycosiphon* and *Teichichnus* (Fig. 3.35); very rare associated *Asterosoma* funnels are preserved.

**Ichnofacies:** Cruziana / rare Arenicolites.

**Interpretation:** The composite ichnofabric is the product of repeated bioturbation by an infaunal deposit-feeding community during fairweather periods in an upper offshore environment. This ichnofauna repeatedly overprinted the suspension-feeding community associated with emplacement of thin, storm-event beds.

24. *Monocraterion-Skolithos* Ichnofabric

Figure 3.36; Plate 3.8a

**Lithological description:** Moderately bioturbated (BI = 3), medium-grained sandstone with primary lamination that consists of either low-angle cross-stratification or tabular cross-bedding defined by chloritic laminations.

**Ichnology:** The ichnofauna contains *Monocraterion tentaculatum* and/or *Skolithos linearis* (Pl. 3.8a; Fig. 3.36).

**Ichnofacies:** Skolithos.
**Interpretation:** This ichnofabric is the result of an infaunal suspension-feeding community occupying an upper shoreface environment. The presence of *Monocraterion* or *Skolithos* seems to have been a function of the sedimentation rate. The funnelling of laminae associated with *Monocraterion* burrows is believed to be the result of the inhabitant adjusting the burrow depth during periods of rapid sedimentation.

**25. Gyrolithes Ichnofabric**

Figure 3.37; Plate 3.8d

**Lithological description:** non-bioturbated to moderately bioturbated (BI = 0-4), medium- to coarse-grained, clean, low-angle cross-stratified sandstone; bioturbation occurs in a lam-scram profile and consequently primary lamination is undisturbed in a large portion of the bed (Pl. 3.8d).

**Ichnology:** A moderately diverse ichnofauna dominated by long *Gyrolithes saxonicus*; other ichnofauna include *Diplocraterion habichi*, *Palaeophycus*, *Ophiomorpha?*, *Skolithos*, *Arenicolites* and *Polykladichnus* (Fig. 3.37).

**Ichnofacies:** Skolithos.

**Interpretation:** This ichnofabric is the product of colonization by a Skolithos ichnofacies of bed tops in a high-energy silt-free foreshore environment.

**26. Cylindrichnus eccentricus Ichnofabric**

Figure 3.38; Plate 3.8e

**Lithological description:** Sparsely to moderately bioturbated (BI = 2-3), low-angle cross-stratified, coarse-grained sandstone.
Ichnology: The low diversity ichnofauna is dominated by very large (up to 40 cm long), predominantly vertical, conical, thickly lined *Cylindrichnus eccentricus* (Pl. 3.8e); the only other trace type is rare *Diplocraterion parallelum* (Fig. 3.38).

Ichnofacies: Skolithos.

Interpretation: The ichnofabric is the result of bioturbation by a suspension-feeding community in a high-energy, silt-free, foreshore environment.

**27. Diplocraterion habichi-Thalassinoides (Glossifungites)-Phycosiphon Composite Ichnofabric**

Figure 3.39; Plate 3.8b

Lithological description: Beds of bioturbated (BI difficult to determine due to the very fine grained nature of the sediment) massive siltstone with no obvious evidence of primary lamination overlain by diamictite beds with large dropstones to 1.5 m in diameter and rare, small-scale current ripples; lenses of reworked foraminiferal tubes, logs and fragmented wood material are also associated with coarser beds.

Ichnology: *Phycosiphon incertum* is common in the siltstone and is overprinted by vertical, unlined, sand-filled *Diplocraterion habichi* and *Thalassinoides* from overlying beds of diamictite (Pl. 3.8b; Fig.3.39).

Ichnofacies: Restricted Cruziana/Glossifungites.

Interpretation: This ichnofabric resulted from at least two phases of bioturbation. The first phase consisted of an infaunal deposit feeding community that reworked the fine sediment in very quiet water conditions. The vertical, sand-filled burrows represent the traces of an opportunistic community that inhabited the substrate prior to the deposition of the coarser sediment. The structures represent the burrows of suspension-feeding organisms and reflect a Glossifungites ichnofacies. The large size of many dropstones and the fine nature of the thick interbeds of siltstone suggest that the ichnofabric was produced in a shoreface environment that
alternated between periods of wave buffering by a perennial ice cover and deposition from ice-raftled material during periods of seasonal ice cover (see Chapter 4.3.3.3 and 5.5.2).
CHAPTER 4: ENVIRONMENTS OF DEPOSITION

Twenty stratigraphic sections were measured throughout the coastal exposures of the Pebbley Beach and Snapper Point Formations. On the basis of these sections 20 sedimentary facies have been identified (Tables 4.1, 4.2, 4.4 - 4.6, 4.19). Individual sections contain multiple facies. A summary of the ichnology of the individual facies is seen in Table 4.10.

4.1 BACKBARRIER FACIES ASSOCIATION

This facies association is only present in the Pebbley Beach Formation and consists of five different facies:

1. estuarine intertidal channel facies;
2. tidal flat facies;
3. lagoon facies;
4. flood tidal delta/washover facies; and
5. tidal inlet facies.

The following sections outline the lithology, physical sedimentary structures and ichnology of each facies. A comparison is then made between overall opportunistic and background trace fossil assemblages that developed in response to rapid environmental changes between storm-wave and fairweather deposition. A summary of the characteristics of the individual facies is seen in Table 4.1.

4.1.1 Estuarine Intertidal Channel Facies

**Outcrop location:** Point Upright, Mill Point and Clear Point in the Pebbley Beach Formation.

**Description:** This facies consists of large channels filled with flaser bedded sandstone and siltstone (Pl. 4.1a-d). The channels cut down into sediments of the lagoon and tidal flat facies (see Ch. 4.1.2 and 4.1.3) with sharp erosional bases. Channel-fill consists of sand-dominated, parallel to sub-parallel inclined strata or ‘Inclined Heterolithic Stratification’ (IHS of Thomas et al. 1987), and reworked unidirectional current ripples. The top of the channel deposits are commonly marked by flat-lying sandstone beds (Pl. 4.1a-d) overlain by up to 1 m of laminated dark grey siltstone. Cutting into the flat lying sandstone beds are lensoidal units up to tens of
metres across and 1 m thick containing mud-dominated, low angle IHS (Pl. 4.1d). These represent abandonment or cut-off channel-fill deposits.

**Ichnocology:** The IHS sandstone and mudstone and the thin, flat-lying sandstone horizons are almost completely devoid of ichnofossils. Very rare *Phycosiphon incertum* and *Planolites* were recorded from siltier lenses (Fig. 4.1, Table 4.1). The dark, laminated siltstone beds at the top of the channel structures are sparsely bioturbated (Pl. 4.1d). The thin interbedding renders the interpretation of individual trace fossil types impossible. No distinct ichnofabric was evident.

**Ichnofacies:** A very restricted Cruziana ichnofacies.

**Interpretation:** Structures in the channel-fill sequence typical of combined current flow, such as ripples with reversed asymmetry, clay drapes and symmetrical ripple bed-forms with unidirectional internal cross-laminae (De Raaf *et al.* 1977), are indicative of tidal influence. The lack of bioturbation suggests that the sand-dominated IHS represent rapid deposition indicative of high fluvial discharge into the tidal regime (Ranger & Pemberton 1992) or rapid tidal sedimentation. IHS developed as lateral accretion deposits and is generally interpreted to have formed by a migrating point bar (Thomas *et al.* 1987, Howard *et al.* 1975, Rahmani 1988, Wood 1989). The tidal influence probably provided the fluctuating energy regime required to produce the heterogeneous bedding (Thomas *et al.* 1987).

The thin, flat-lying sandstone beds at the top of the channel structures were probably deposited during major storm events. The sand may have come from erosion of the cutbank during floods, or from a seaward direction during major storm surges. Rapid deposition is suggested by the lack of ichnofossils.

The mud-dominated laminated units at the top of the main channel structures are interpreted as tidal flat deposits.

### 4.1.2 Tidal Flat Deposits

**Outcrop location:** Point Upright, Mill Point, Clear Point and South Island Beach in the Pebbley Peach Formation.

**Description:** This consists of thick units (up to 5 m) of flat-lying, thinly interbedded sandstone and mudstone. Individual bed thickness in the mudstone is generally less than 3 cm, whereas in
the sandstone beds it ranges from millimetres up to 10 cm thick. The sandstone is very fine-grained and may contain horizontal laminae, current ripples with reversed asymmetry, or symmetrical ripples with unidirectional internal laminations. Flaser and lenticular bedding are the dominant physical structures (Pl. 4.1e, 4.2a) and soft sediment deformation in the form of slumps is common (Pl. 4.2b). The mudstone commonly contains shrinkage (synaeresis) cracks filled with sandstone (Pl. 4.2c-d). In plan view the cracks are spindle-shaped and they appear to have some parallel alignment (Pl. 4.2d). In vertical section the cracks are crenulate, predominantly vertical and have tapering downward terminations (Pl. 4.2c).

**Ichnology:** In vertical section the flaser and lenticular nature of the bedding makes determination of trace fossil types very difficult. Bioturbation is rare to moderate with a maximum BI of 3. Predominantly vertical burrows such as *Conostichus*, *Skolithos* and *Diplocraterion habichi* were identified. *Planolites* was also evident. Some sandstone beds contain vertical escape structures. On bedding planes a number of trace types were well preserved. These include *Phycosiphon incertum*, large horizontal *Thalassinoides*, *Rhizocorallium irregularare*, *Psammichnites*, *Gordia*, small *Rosselia socialis* and *Taenidium serpentinum* (Table 4.1).

**Ichnofacies:** A mixed restricted Cruziana / Arenicolites ichnofacies.

**Interpretation:** A tidal environment is suggested by combined flow structures such as current ripples, with reversed asymmetry or symmetrical tops, and mud drapes. Soft sediment deformation is also a common feature on tidal flats (Klein 1985). The shrinkage cracks are interpreted as the product of synaeresis rather than desiccation due to the irregularity of form and the absence of other evidence for sub-aerial exposure. Synaeresis cracks may be produced in environments where there are large fluctuations in salinity (Burst 1965). The association of the synaeresis cracks with the sand interbeds suggests that an influx of saline water accompanied the sand deposition. This was probably the result of extreme high tides such as that created by storm surges. The presence of vertical escape structures in many sand beds also indicates that the deposition of the sand was very rapid (event sedimentation).

Despite its low density, the trace fossil suite represents quite a diverse assemblage of organisms (Fig. 4.2). The reduced size of traces, containing a mixture of dwelling and feeding structures, is consistent with a brackish environment. The tidal influence, which would have
continually replenished the fauna in this environment, was probably responsible for the higher than expected assemblage diversity.

4.1.3 Lagoon Facies

**Outcrop location:** Point Upright, Mill Point, Clear Point and South Island Beach in the Pebbley Beach Formation.

**Description:** This facies consists of dark, grayish black organic-rich mudstone and dark grey sandstone that contains little or no original bedding (Pl. 4.2e-f). Beds contain common carbonaceous material and silicified logs and range from 20 cm to 1 m in thickness. Interbedded lenses of fine-grained sandstone, with significantly less bioturbation, show obvious primary lamination and are interpreted as washover facies (Pl. 4.1a-b, 4.2a).

**Ichnology:** Bioturbation is intense (BI 5-6:2) and individual ichnotaxa are difficult to determine. Identifiable traces in the mudstone include *Phycosiphon incertum*, small *Rosselia socialis*, *Planolites* and *Palaeophycus tubularis* reflecting a high density, low diversity, deposit-feeding community. Composite ichnofabrics associated with interbeds of washover sandstone are common. The secondary trace fossil assemblage associated with the washover sandstone beds is discussed in Ch. 4.1.4.

**Ichnofacies:** A size-restricted *Cruziana* ichnofacies.

**Interpretation:** The bioturbated, mud-dominated sediments (Pl. 4.2a, 4.3a) reflect low-energy conditions typical of lagoon deposits (Reinson 1992, Pemberton *et al.* 1992c). The coarser, muddy sandstone beds (Pl. 4.2e-f, 4.3b) represent slightly higher energy conditions (Pemberton *et al.* 1992c) and were probably deposited nearer to the lagoon margin where tidal currents and waves were more effective. The lagoon environment supported a low diversity, reduced-sized trace fossil assemblage (Fig. 4.3) reflecting a stressed ecosystem typical of brackish water conditions.
4.1.4 Flood-Tidal Delta / Washover Facies

Outcrop location: Point Upright, Mill Point, Clear Point and South Island Beach in the Pebbley Beach Formation.

Description: This facies is interbedded with the lagoon facies and consists of sharp-based, fine-grained sandstone to gravel beds that range in thickness from 1-60 cm. Horizontal stratification and current rippled sandstone (Pl. 4.3c) are the dominant sedimentary structures and many primary sedimentary structures have been biogenically reworked. Organic debris and logs are common. One ripple bedded silty sandstone contains large (up to 30 cm), elongate glendonites that are commonly enclosed in ovoid concretions (Pl. 4.3d-e).

Ichnology: This facies generally contains a low to high density (BI 1-6), moderately diverse trace fossil association including Diplocraterion habichi, Diplocraterion parallelum, Rhizocorallium Jenense type B, Cylindrichnus concentricus, Skolithos, Palaeophycus tubularis, Phycosiphon incertum, Rossella rotata, Teichichnus rectus, Planolites, Taenidium synyphes and escape structures.

Ichnofacies: A mixed diverse Cruziana / Arenicolites ichnofacies.

Interpretation: The presence of current ripples and escape structures indicates rapid deposition of the flood-tidal delta/washover facies. The subsequent bioturbation reflects a return to less energetic conditions typical of the lagoon environment. The sandy sedimentary surface was out of equilibrium with the usual muddy lagoon substrate and opportunistic species flourished (Fig. 4.4). The moderately diverse and prolific opportunistic assemblage contrasts markedly with the stressed biotic assemblage of the lagoon facies, suggesting that conditions remained well-oxygenated and unrestricted for some period after deposition of the washover sands.

4.1.5 Tidal Inlet Facies

Outcrop location: Clear Point in the Pebbley Beach Formation.

Description: The tidal inlet facies consists of three channel-associated lithofacies; very coarse-grained sandstone with mud rip-up clasts and coalified wood material (Pl. 4.3a); coarse-grained
sandstone with symmetrical ripples; and medium-grained sandstone with planar cross-bedding, mud-drapes, tidal bundles and silt-draped current ripples. Disarticulated and articulated bivalve shells are common on bedding planes in the medium-grained sandstone.

**Ichnology:** Bioturbation ranges from absent in the very coarse-grained lithofacies to sparse (BI 2) in the medium-grained lithofacies. Traces include *Diplocraterion parallelum, Rosselia socialis* and *Cylindrichnus concentricus* (Fig. 4.5). Silt-filled *Diplocraterion habichi* from an overlying bed form a composite ichnofabric.

**Ichnofacies:** A distal Skolithos ichnofacies.

**Interpretation:** Tidal influence in this facies is suggested from the presence of tidal bundles. The mud-drapes probably formed during slack water at high tide, when silt-sized sediment (flocs and pellets) can settle on top of sandy foresets (Einsele 1992). Shell material and mudstone rip-up clasts suggest erosion and transport by traction currents during high-energy periods. Accumulation of coarse shells and shell debris is common in shallow water tidal channels (Einsele 1992).

The low density, suspension-detritus-feeding vertical trace fossil assemblage is indicative of a well oxygenated, shifting substrate.

### 4.1.6 Pebbley Beach Formation Backbarrier Environment

This facies association comprises the above mentioned five facies types and is believed to have formed in the back barrier zone of a barrier-island complex. The formation of barrier-island complexes generally indicates a low-gradient continental shelf adjacent to a low relief coastal plain, an abundant supply of sand-size sediment and moderate to low tidal ranges (Glaeser 1978, Einsele 1992). Barrier-island systems represent a complex depositional environment characterised by three major clastic subenvironments (Fig. 4.7, Table 4.1):

1. the subtidal to subaerial barrier-beach-dune complex;
2. the back barrier zone consisting of an enclosed lagoon or estuary, wash-over deposits, flood-delta deposits and tidal flat sediments; and
3. the subtidal-intertidal tidal inlet complex that cuts through the barrier and connects the lagoon to the open sea.
In the Pebbley Beach Formation the barrier-beach-dune complex is not preserved in the exposed section. It may have been reworked by migration of the tidal inlet facies or cannibalized by the subsequent transgression.

There is a relative abundance of storm washover deposits compared with well-developed tidal inlet deposits, indicating that the environment was microtidal (Reinson 1992). The lack of large tidal inlet channels results in storm surges breaking through the barrier to form extensive washover deposits. Hayes (1975, 1979) considered microtidal barrier island systems to be wave-dominated. The lagoon deposits described here typically occur in the central basin of wave-dominated estuarine systems (Dalrymple et al. 1992).

**Ichnological Implications:** In microtidal regimes, such as this, where there are just a few narrow inlets, the lagoon waters become either brackish or hypersaline and their fauna is abnormal and of low diversity (Einsele 1992). No palaeontological evidence for hypersaline waters exists in the Pebbley Beach Formation. The Pebbley Beach Formation backbarrier ichnofossil suite is characterized by:

1. generally low diversity;
2. an impoverished marine assemblage;
3. reduced size compared to marine counterparts (especially evident in *Rosselia socialis*);
4. dominance of morphologically simple burrow structures; and
5. a mixture of characteristics common to both the Areniculites and Cruziana ichnofacies (Fig. 4.6)

These features parallel diversity trends documented from modern brackish water environments (Beynon & Pemberton 1992).

Brackish water trace fossil assemblages in estuarine and lagoon deposits reflect a steep salinity gradient in the backbarrier environment and the limited number of species capable of the physiological flexibility necessary to inhabit brackish water (Barnes 1984). Dörjes & Howard (1975) suggested that such salinity fluctuations are the result of:

1. freshwater input from terrestrial watercourses;
2. rainfall;
3. evaporation;
4. tidal-range and salinity of adjacent coastal waters;
5. coastal morphology; and
6. differences in wind direction and velocity.
Fresh water faunal diversity decreases rapidly even with slight salinity increases, whereas fully marine faunal diversity declines at a more gradual rate with decreasing salinity. The result of this is that brackish water faunal assemblages represent an impoverished marine assemblage rather than a mixture of freshwater and marine components (Ekdale et al. 1984, Wightman et al. 1987).

The reduction in size exhibited by marine organisms inhabiting brackish water, backbarrier environments represents an adaptive, morphological response by the organism to tolerate salinity-induced physical and chemical stresses (Remane & Schlieper 1971). In the Pebbley Beach Formation size reduction appears to be most pronounced among shallow tier organisms that maintain constant contact with surface brackish waters (such as Rosselia) whereas deeper tier, deposit-feeding structures such as Phycosiphon incertum display less size reduction.

High density burrowing activity reflects the fact that estuaries have very high values of benthic biomass in comparison to other aquatic habitats (Rosenberg et al. 1977). Although salinity was reduced and fluctuated regularly, lagoon environments offered shelter from wind, waves and open swells (Pemberton & Wightman 1992). They also had the advantage of being rich in food provided from a variety of sources including river input (Schelske & Odum 1961), salt marshes (Teal 1962), mangroves (Odum & Heald 1975) and the coastal marine environment (De Jonge & Postma 1974), and they had high in situ primary production (Wolff 1977). Most commonly, food came from a variety of these sources (Pemberton & Wightman 1992).

**Implications of Ichnofabrics:** Ichnofabrics within the Pebbley Beach backbarrier environment were strongly affected by the diversity of subenvironments. There is an increase in the complexity of ichnofabrics in a seaward direction due to the increased influence of marine sediments and organisms. This is most obvious in the lagoon sediments that have been frequently swamped with washover sands. Composite ichnofabrics have resulted from the introduction of foreign sandy sediment and the subsequent colonization by opportunistic burrowers such as Diplocraterion habichi (Pl. 4.3b).

Ichnofabrics are more complex along the margins of the estuaries than in the deeper channels. This is due to a significant increase in distinct biogenic structures and bioturbate textures along the channel margins where reworking of sediments by currents was less effective and conditions more suitable for habitation and burrow preservation.
In tidal flat sediments, although the faunal diversity is moderately high, the heterogeneous nature of the primary sedimentary structures and the low density of burrowing make identification of discrete trace fossils and bioturbate textures almost impossible. An ichnofabric is, therefore, unable to be recognized.

The characteristic ichnofabric of washover sandstone beds and flood-tidal delta deposits is identical to that seen in event beds from fully marine environments (Pl. 3.1e-f). This reflects the similarity of processes (i.e., a sedimentary surface that is out of equilibrium with the usual fairweather substrate and the susceptibility of the environment to opportunistic colonization) associated with the introduction of storm-deposited sandstone beds in coastal environments. The opportunistic organisms present in the washover deposits, protruded down into the organic-rich lagoon sediments producing a composite ichnofabric. As in marine environments, the opportunistic community associated with the event bed is replaced by the background faunal assemblage when conditions return to normal. In the Pebbley Beach backbarrier environment the high-diversity, opportunistic, washover community was replaced by a low-diversity, opportunistic brackish water assemblage.

4.2 FORESHORE FACIES

Outcrop location: Crampton Island, Bannisters Point and Jervis Bay in the upper Snapper Point Formation.

Description: This facies consists of well-sorted, sub-parallel to low angle and planar cross-stratified, medium- to very coarse-grained sandstone beds (Pl. 4.3f, 4.4a-c). The unit reaches over 10 m in thickness where it is exposed at the coast, and only occurs at the top of the Snapper Point Formation. Exotic megaclasts are locally common. Thin pebble conglomerate pavements are rare.

Ichnology: The diversity and abundance of trace fossils is low with the BI measuring 0-3. Biogenic mixing is difficult to determine due to a lack of silt and consequently a lack of grain size contrast. Laminated to burrowed (Howard 1971a,b, 1972) profiles are sparse but contain the most diverse trace fossil assemblages. This is now more commonly referred to as laminated to scrambled bedding (‘lam-scram’) because of the apparent interbedding of laminated and biogenically scrambled intervals (Bromley 1990; MacEachern & Pemberton 1992a). Rarely the maximum BI in the lam-scram profiles reaches 4-5. The trace fossil assemblages differ at
individual outcrops but they are generally dominated by one species. The traces present are shown in Figure 4.8. The most common forms include *Macaronichnus segregatus*, *Skolithos*, *Cylindrichnus eccentricus* (Pl. 4.4b) and *Arenicolites* (Table 4.2).

**Ichnofacies:** Skolithos ichnofacies.

**Interpretation:** The distinctive stratification and well-sorted nature of this facies is characteristic of sediments deposited in a tide-dominated foreshore environment (see Fig. 3.11). The planar laminations are produced by swash and backwash mechanisms active in this part of the shoreface (MacEachern & Pemberton 1992a).

The dominance of physical sedimentary structures over biogenic structures and the low diversity and abundance of trace fossils is due to the instability of the continually shifting substrate and to the low preservation potential for traces in this kind of environment (Howard & Frey 1984).

The trace fossil assemblage is composed entirely of burrows characteristic of the *Skolithos* ichnofacies (Fig. 4.8, also see Fig. 3.1). Most burrows represent the deeply penetrating domiciles of suspension-feeding organisms. Others such as *Palaeophycus* are less common and represent the dwellings of passively predaceous organisms that inhabited a shallow tier position and were less likely to be preserved. The preservation potential of *Macaronichnus segregatus* was high despite its apparent deposit-feeding mode of life due to the deep tier position that it occupied. Saunders & Pemberton (1986) suggested that the *Macaronichnus* organism fed on micro-organisms several metres below the sediment/water interface.

**4.3 SHOREFACE FACIES**

The shoreface zone lies between the level of low tide and maximum fairweather wave base (MacEachern & Pemberton 1992a; Fig. 3.11), and is divided into upper, middle and lower subzones.

The upper shoreface subzone is situated landward of the breaker zone and comprises a relatively distinct part of the facies succession. In contrast, the middle and lower shoreface reflect a greater degree of sedimentological and ichnological variation (MacEachern & Pemberton 1992a).
The middle shoreface is strongly influenced by storm activity and consequently storm deposits constitute much of the depositional record whereas the degree of bioturbation is highly variable (MacEachern & Pemberton 1992a).

The lower shoreface is dominated by wave energy but offshore processes continue to operate (Reinson 1984). The intensity of burrowing is still very variable and is dependent on the degree of storm dominance.

In the study area it has been possible to subdivide the shoreface facies using differences in primary sedimentary structures and ichnology.

In the following section, a description of each facies in terms of lithology, physical sedimentary structures and ichnology is given. Infaunal communities are interpreted and separated into opportunistic and resident assemblages. It has been possible to identify some ichnospecies as resilient members of the resident community.

4.3.1 Upper Shoreface Facies

**Outcrop location:** Clear Point, Snapper Point, Crampton Island, Bannisters Point, Narrawallee Beach and Jervis Bay in the Snapper Point Formation.

**Description:** This facies contains units of sandstone and fine conglomerate (Table 4.2).

Sandstone units reach over 10 m in thickness and are characterised by bi-directional planar to low-angle cross-stratification and multidirectional trough cross-stratification (Pl. 4.4f-g). Swaley cross-stratification (SCS) is rare. Very coarse-grained sandstone beds are either massive or formed into poorly developed symmetrical wave ripples. In the southern region of the study area (in the basal 3 m of the Snapper Point Formation), shell pavements of gastropods, *Eurydesma*, pectinaceans and other bivalves are common on bedding planes (Pl. 4.4e, h). Biogenic reworking is usually absent, but may locally form lam-scram profiles or partially homogenize beds (Pl. 4.4d, i). Bioturbated beds are poorly sorted and contain relict coarser lenses of gravel and pebbles.

Conglomerate beds are common and are either preserved as massive pavements up to 30 cm thick (Pl. 4.5a), or as flat-bedded units up to 50 cm thick with imbrication of clasts. Megaclasts up to 60 cm in diameter are common and silicified wood is locally sparse. Shell hash and pavements of large pectinaceans and other bivalves are very common (Pl. 4.5c).
**Ichnology:** Trace fossils are locally common but rarely abundant, and diversity, although relatively high throughout the whole study area, is low at individual outcrops. Most units have little or no bioturbation. The BI ranges from 0 to a very rare maximum of 4. The average BI is 0-2. Lam-scare profiles are sparse in sandstone beds. The trace fossil assemblage, as shown in Figure 4.9, is composed predominantly of vertical structures. Different species are locally more prevalent but overall the most common forms include *Macaronichnus segregatis*, *Skolithos*, *Arenicolites* and *Diplocraterion parallelum*. Some ichnotaxa present in this facies are not seen in other facies in the study area, e.g. *Heimdallia chatwini* and *Monocraterion tentaculatum*. Lack of silt in burrows has resulted in pervasive bioturbation that is not always obvious (Pl. 4.4i).

Ichnofabrics are usually dominated by primary sedimentary structures. Where the degree of bioturbation is high, the trace fossil assemblage is usually dominated by one ichnospecies.

**Ichnofacies:** Skolithos with very rare resilient proximal Cruziana ichnofacies.

**Interpretation:** This facies is distinctive in its dominance of multi-directional trough cross-stratification and low angle bi-directional planar cross-bedded sets. These structures reflect deposition by wave-driven currents that parallel the shoreline and interact with currents that are generated by translatory flow and plunging waves (MacEachern & Pemberton 1992a). They are typical of upper shoreface deposits (Reinson 1984). Storm deposits in the upper shoreface facies are reflected by ridge and runnel systems (Pl. 4.4g) rather than major depositional events as they are in the lower and middle shoreface, and indicate erosion of the beach face and transport of sediments to the middle and lower shoreface (MacEachern & Pemberton 1992a).

The trace fossil assemblage is typical of the Skolithos ichnofacies. Most of the structures present represent the domiciles of deeply burrowing suspension-feeding organisms that were able to withstand the continually migrating bed-forms (Fig. 4.9, also see Fig. 3.1). The *Macaronichnus* trace maker is suggested to be most common in deposits from very high-energy environments, typically from around and above the upper shoreface-foreshore contact (Saunders & Pemberton 1986). *Rosselia socialis* and *Asterosoma*, locally present in small quantities, are large and robust and represent the structures produced during the collection and later use of material by very resilient organisms typical of the Cruziana ichnofacies.
4.3.2 Middle Shoreface Facies

**Outcrop location:** Point Upright and Clear Point in the Pebbley Beach Formation, Pretty Beach, South Snapper Point, Snapper Point, Willinga Point, Nugans Point, Meroo Point, South Termeil Point, Termeil Point, Crampton Island, Bannisters Point, Narrawallee Inlet and Jervis Bay in the Snapper Point Formation.

**Description:** This facies consists of interbedded sandstone, pebble conglomerate and locally common coquinite (Table 4.2). Sandstone beds vary from 5 cm to amalgamated units over 20 m in thickness. Beds are generally well sorted and well winnowed, have sharp, erosive bases and are characterised by SCS, rare hummocky cross-stratification (HCS) or low angle cross-stratification (Pl. 4.5f). Normal grading is common. Laminations are commonly defined by fine organic detritus and may be formed into flame structures (Pl. 4.6a-b). Small- to medium-scale combined flow ripples are locally sparse. Large intraformational megaclasts are present in two localities (Pl. 4.6c). Shell pavements are common on bed tops and either contain broken shell hash or accumulations of articulated and disarticulated pectinaceans, other bivalves, gastropods and very rare brachiopods. Biogenic reworking of sandstone may be absent, form lam-scram profiles or partially homogenize beds. Bioturbated beds are poorly sorted and usually contain relict coarser lenses of gravel and pebbles.

Very coarse-grained sandstone and fine conglomerate beds are very abundant and range in thickness from 5 cm to amalgamated units over 1 m thick. Beds are preserved as large-scale, symmetrical wave ripples with wavelengths commonly reaching 1.5-2 m (Pl. 4.5b). Where beds are amalgamated, the orientation of ripple crests in alternate beds is commonly perpendicular. Ripple tops may contain black mudstone drapes or shell pavements of large, convex-up disarticulated and articulated pectinaceans or other bivalves. Megaclasts up to 30 cm in length are locally common.

Pebble conglomerate beds are common and are either preserved as large-scale symmetrical wave ripples or as thin partially reworked discontinuous layers. Shell hash and pavements of large pectinaceans and bivalves are very common. Conglomerate bed thickness ranges from < 5 cm to 30 cm.

Coquinite beds are interbedded with sandstone and pebble conglomerate, and form a 5 m thick unit in the Snapper Point Formation. Composition of the beds varies greatly and identification of individual bed boundaries is very difficult. Beds exhibit varying amounts of shell material and sorting. Some beds consist only of silt, sand and small shells less than 5 mm
in diameter (Pl. 4.5e). Some contain a mixture of small and large shells (Pl. 4.5d) and others contain substantially more clastic material than shell material.

**Ichnology:** The trace fossil assemblage present in this facies is less diverse than in the lower shoreface facies. Many beds have little or no bioturbation. The BI ranges from 0 to a very rare maximum of 5; the average BI is 1-3. Lam-scram profiles are common in sandstone beds. The trace fossil assemblage, as seen in Figure 4.10 consists predominantly of vertical structures. In sandstone beds the most common forms include *Diplocraterion parallelum*, *Macaronichnus segregatis*, *Rhizocorallium jenense* (types A, B and C), and robust funnel structures such as *Rosselia* and *Asterosoma* occurring with *Teichichnus*.

Fine conglomerate beds are commonly unbioturbated but locally contain *Polykladichnus irregularis*, *Arenicolites*, *Cylindrichnus concentricus*, *Calycraterion samsonowiczi* and *Diplocraterion habichi*.

Bioturbation in coquinite beds varies from absent to common with the most common form being very robust *Rosselia socialis*.

Ichnofabrics are generally dominated by primary sedimentary structures but composite fabrics occur in the most bioturbated units.

**Ichnofacies:** Skolithos ichnofacies with resilient proximal Cruziana ichnofacies.

**Interpretation:** This facies is characterised by sedimentary structures that reflect deposition in a high energy, wave-dominated environment typical of the middle shoreface. The thick, amalgamated sequences of SCS, HCS and low-angle cross-stratification are interpreted as storm deposits. The thickest amalgamated units obviously reflect deposition in very strongly storm-dominated settings. The presence of flame structures supports synsedimentary deformation in response to extremely rapid deposition (Raychaudhuri & Pemberton 1992).

The intensity of burrowing was dependent on the degree of storm dominance (MacEachern & Pemberton 1992a). The more intensely bioturbated units represent reworking of storm-deposited sandstone during fairweather periods. Siltstone interbeds are not preserved and their absence reflects deposition above fairweather wave base. The fairweather ichno-assemblage is dominated by the burrows of suspension-feeding organisms (representing structures typical of the Skolithos ichnofacies), and very resilient detritus- and deposit-feeding organisms interpreted as part of the Cruziana ichnofacies. The dominance of the Skolithos ichnofacies over the Cruziana ichnofacies is typical of the middle shoreface (MacEachern &
Pemberton 1992a). The general lack of burrows formed by deposit-feeding organisms probably indicates high storm intensity and/or frequency and reflects a paucity of deposited food for the Cruziana ichnofacies trace-makers to feed on (MacEachern & Pemberton 1992a). Exceptions include robust *Rosselia* and *Asterosoma*, which were able to collect and later exploit their own deposits rather than relying on encountering them in the substrate (MacEachern & Pemberton 1992a).

4.3.3 Lower Shoreface Facies

In the lower shoreface subzone, three types of deposits have been recognized:

1. very strongly to strongly storm-dominated (high energy);
2. moderately-weakly storm-affected (intermediate to low-energy); and
3. a glacially influenced marine environment of deposition where the usual conditions were affected by sheet ice cover.

4.3.3.1 Very Strongly to Strongly Storm-dominated Lower Shoreface Facies

**Outcrop location:** Point Upright, South Pebbles and Mill Point in the Pebbley Beach Formation. Pretty Beach, Termeil Point and Narrawallee Inlet in the Snapper Point Formation.

**Description:** This facies consists of interbedded sandstone, pebble conglomerate and very rare siltstone.

Sandstone beds vary from 20 cm to > 4 m in thickness. Most beds have sharp, erosional bases and contain HCS or low angle cross-stratification (Pl. 4.6d, 4.7a). Laminations may be defined by fine organic detritus or less commonly mudstone rip-up clasts. Amalgamated units are common and may reach several metres in thickness (Pl. 4.7c). Small- to medium-scale combined flow ripples are very abundant in some sections (Pl. 4.7c, Mill Point section). Ball-and-pillow structures are locally preserved (Pl. 4.6b). Silicified wood and large logs are common. One large, incomplete log, preserved parallel to bedding, was measured at over 6 m in length and 3 m across the root base (Pl. 4.7e). Biogenic reworking of sandstone may be absent, form lam-scram profiles or be relatively complete throughout beds.

Pebble conglomerate beds are abundant and range in thickness from < 5 cm to 20 cm. The bed surfaces are almost always preserved as large-scale, symmetrical wave ripples. Ripple
tops are commonly draped with up to 1 cm of black mudstone. Megaclasts up to 15 cm in length and disarticulated bivalve shells are locally common.

Siltstone interbeds are very rare in this facies and reach a maximum thickness of 20 cm.

**Ichnology:** The trace fossil assemblage in sandstone beds is very diverse, and ranges from low to high intensity (BI 0-6).

*Fugichnia* are common in clean, non-bioturbated beds and thick amalgamated units. Amalgamated units commonly contain intervals of more intensely bioturbated sediment and numerous lam-scram profiles (Pl. 4.6f).

Sparsely bioturbated units contain vertical burrows such as *Diplocraterion parallelum* and *Diplocraterion habichi*. Other forms are locally common such as *Phycosiphon incertum, Skolithos, Psammichnites gigas, Taenidium synyphes, Rhizocorallium jenense* (types A and B), *Cylindrichnus concentricus* and *Arenicolites*.

Intensely bioturbated units contain a mixed assemblage of vertical and horizontal structures dominated by robust *Rosselia socialis, Rosselia rotatus* and *Asterosoma*, together with *Teichichnus rectus, Taenidium barretti, Phycosiphon incertum* and *Planolites*. *Diplocraterion* and large *Rhizocorallium jenense* type B are also common (Fig. 4.11)

Locally, intensely bioturbated units may contain assemblages of hazy, indistinct trace fossils. In these beds the only discernible traces are *Rosselia-Asterosoma* type funnel structures, the retrusive tubes of large *Diplocraterion parallelum* and *Phycosiphon incertum*.

Pebble conglomerate beds are not usually bioturbated but locally have a BI of 2-3. The trace fossil assemblage is of low diversity and intensity and includes *Polykladichnus irregularis, Arenicolites, Cylindrichnus concentricus* and *Diplocraterion habichi*.

The trace fossil assemblage in siltstone interbeds is difficult to determine due to the BI of 6 and the common truncation of beds.

Ichnofabrics range from simple frozen tiered profiles to composite ichnofabrics. The general lack of siltstone makes it difficult to differentiate between the pre-storm and post-storm assemblages because all of the identifiable structures are in amalgamated sandstone beds and no discrete fairweather assemblages are preserved.

**Ichnofacies:** A mixed Arenicolites / proximal Cruziana ichnofacies.

**Interpretation:** Most of the structures present in this facies reflect storm deposition including HCS, low-angle cross-stratification and small to large scale waning stage combined flow
ripples. Ball-and-pillow structures in sandstone beds reflect sediment liquefaction generated by the release of elevated intergranular pore-fluid pressures. The presence of these structures suggests synsedimentary deformation in response to extremely rapid deposition (Raychaudhuri & Pemberton 1992).

The highly variable degree of burrowing was dependent on the degree of storm dominance (MacEachern & Pemberton 1992a) and the thick, clean amalgamated sandstone units represent deposition in the highest energy parts of the sequence. The abundance of *Fugichnia* in these units also supports an interpretation of high sedimentation rates producing amalgamation of beds associated with storm sedimentation (Pemberton *et al.* 1992e). In addition, the high-energy affinity of this rapid deposition is supported by the presence of mudstone rip-up clasts (Raychaudhuri & Pemberton 1992). The absence of siltstone interbeds and the presence of mudstone rip-up clasts also suggest that each successive storm was sufficiently erosive to remove any interim fairweather deposits (Raychaudhuri & Pemberton 1992).

The more intensely bioturbated units represent biogenically reworked storm-deposited sandstone. The differentiation between the background (or fairweather) trace fossils and the storm-related opportunistic species is shown in Table 4.3. The fairweather assemblage is dominated by a resilient, equilibrium community of detritus and deposit-feeding organisms (see Figs 3.2, 4.11). They are interpreted as a proximal Cruziana ichnofacies (Table 3.2, Fig. 3.2). The storm-related traces represent a community of opportunistic, mostly suspension-feeding organisms that were able to rapidly colonize sandy, storm beds prior to the recolonization by the fairweather assemblage. They represent structures typical of the Arenicolites ichnofacies.

The presence of sandstone beds containing hazy indistinct trace fossils suggests that the infaunal community existed in a soupy substrate with high pore water content, typical of rapidly deposited storm sandstone beds.

Large-scale, coarse-grained wave-rippled beds are also indicative of high-energy conditions. Thick mud-draping indicates a return to lower energy conditions during waning storm deposition (Johnson & Baldwin 1986). The sparse trace fossil assemblage in the coarse beds represents an opportunistic community typical of the Arenicolites ichnofacies. The vertical burrows of suspension-feeding organisms represent deep, silt-lined, quickly constructed domiciles able to withstand the unstable conditions at the sea floor.

The diversity of the Arenicolites ichnofacies is considerably higher than the Cruziana ichnofacies in this facies, supporting the interpretation of a strongly storm- and wave-dominated environment. The higher density of the fairweather assemblage suggests that the sequence was
deposited around or just above maximum fairweather wave base where offshore processes continue to operate and deposit feeding organisms are still able to dominate the infaunal community during fairweather periods (Fig. 3.11, Table 4.4).

4.3.3.2 Moderately-Weakly Storm-Affected Lower Shoreface Facies

Outcrop location: Snapper Point, Willinga Point and Meroo Point in the Snapper Point Formation.

Description: This facies consists of interbedded sandstone, very coarse-grained sandstone, conglomerate, diamictite and sparse siltstone (Table 4.4).

Sandstone units dominate the facies and may be completely homogenized, or range from 10 cm to a maximum of 1.5 m in thickness. Beds contain varying degrees of HCS or low angle cross-stratification, depending on the intensity of bioturbation. Units are generally composed of an amalgamation of bioturbated beds. Amalgamated beds with high proportions of primary laminations preserved are rare and reach a maximum thickness of 1 m. Small-scale combined flow ripples are locally common on top of HCS beds. Silicified wood and large logs are common. Shell material is locally abundant and either occurs as pavements of re-deposited, articulated and disarticulated valves or as assemblages with many specimens buried in life position. The life assemblages contain several species of bivalves. *Vacunella* is most commonly preserved in life position (Pl. 4.7d). Other types, including *Astartila, Megadesmus, Myonia* and large pectinaceans, are commonly preserved articulated on bedding planes or with the valves open and convex-up on bedding planes (Pl. 4.6d). Other rare forms include crinoids, spiriferid brachiopods, gastropods, stenoporid bryozoans and an unidentified bryozoan (Pl. 4.7b, f-g).

Very coarse-grained sandstone beds are abundant and are almost always preserved as large-scale, mud-draped, symmetrical wave ripples (Pl. 4.7h). Thickness ranges from < 5-30 cm. Bed bases may be erosive or loaded into the underlying sandstone unit. Pebbles and megaclasts up to 20 cm in length are locally common. Shell material is common and either occurs as broken shell hash or whole disarticulated and articulated material. The surfaces of some beds are completely covered with large, convex-up disarticulated and articulated pectinaceans.

Conglomerate and diamictite beds are sparse and the former are also most commonly preserved as large-scale symmetrical wave ripples. Some beds are massive and have lower and
upper contacts partially mixed with overlying and underlying beds. These beds are commonly the most poorly sorted and contain large, exotic, angular clasts up to 60 cm in diameter (Pl. 4.8a).

Siltstone interbeds are sparse in this facies and generally reach a maximum thickness of 25 cm. They are poorly sorted containing relict lenses of coarse sand and rare pebbles.

**Ichnology:** Sandstone beds range from being non-bioturbated to thoroughly homogenized. BIs range from 0-6 and are most commonly 4-5. Sparsely bioturbated beds are characterised by HCS and contain *Skolithos* (Pl. 2.12g-h), *Gyrochorte comosa* (Pl. 2.12h) and *Psammichnites*. Some beds contain lam-scram profiles. Trace fossil assemblages exposed on bedding planes are often spectacular but so crowded that individual ichnotaxa are impossible to identify (Pl. 4.6g). A diverse trace fossil assemblage is present in most beds. No *Fugichnia* were observed. Amalgamated units commonly contain intervals of more intensely bioturbated sediment and lenses of partially reworked coarse sand, gravel and pebbles (Pl. 4.8b). Most units contain a mixed assemblage of vertical and horizontal structures (Fig. 4.11) dominated by robust *Rosselia socialis*, *Rosselia rotatus* and *Asterosoma, Teichichnus, Phycosiphon incertum, Planolites, large Diplocraterion parallelum* and large *Rhizocorallium jenense* type C. One spectacular example of a very large *Rhizocorallium* occurs in coquinite beds in the Snapper Point Formation. The spreiten in the burrow consist of packed layers of shell hash (Pl. 2.9f). In some sections intensely bioturbated units contain hazy indistinct trace fossils. In these beds the only identified traces are *Rosselia-Asterosoma* type funnel structures, large retrusive *Diplocraterion parallelum* and *Phycosiphon incertum*.

Very coarse-grained sandstone and pebble conglomerate beds are not usually bioturbated but locally contain BIs of 1-2. The trace fossil assemblage is of low diversity and intensity and includes *Arenicolites, Cylindrichnus concentricus, Macaronichnus segregatis* and *Skolithos*.

The trace fossil assemblage of the siltstone interbeds is difficult to determine due to the intensity of bioturbation (BI of 6) and the common truncation of beds.

Ichnofabrics in this facies are mainly complex and composite.

**Ichnofacies:** A mixed proximal Cruziana / Arenicolites ichnofacies.
**Interpretation:** Many of the sedimentary structures in this facies reflect storm deposition, including the HCS, low-angle cross-stratification and the small to large-scale waning-stage combined flow ripples.

Bioturbated sandstone units represent reworked storm-deposited sandstone. Differentiation between the background (or fairweather) trace fossils and the storm-related opportunistic species is shown in Table 4.4. The assemblage is made up of a mixture of resilient, detritus- and deposit-feeding organisms (interpreted as a proximal Cruziana ichnofacies) and opportunistic, mostly suspension-feeding organisms that rapidly colonized storm beds prior to the recolonization by the resident community (Tables 3.3, 4.3). These represent structures typical of the Arenicolites ichnofacies.

The presence of amalgamated units containing hazy indistinct trace fossils suggests that the sequence had a high pore-water content.

The abundance of large-scale, coarse-grained wave-rippled beds and conglomerate, the general lack of siltstone interbeds, the lack of thick amalgamated storm sandstone beds and the intensity of the mixed Cruziana / Arenicolites ichnofacies indicates a silt-starved environment exposed to repeated periods of high energy in a fairweather-dominated environment just above maximum fairweather wave base (Fig. 3.11).

### 4.3.3.3 Interbedded Mudstone and Diamictite Facies

**Outcrop location.** South Pebbles in the Pebbley Beach Formation.

**Description:** The facies consists of diamictite beds from <5-30 cm thick interbedded with 10-100 cm thick beds of mudstone, and is only present at one locality at South Pebbles in the lower half of the Pebbley Beach Formation.

The diamictite beds form extensive planar surfaces across the rock platform. They contain erratic clasts in a very-poorly sorted silty-sandstone matrix. Exotic clasts range from angular to very rounded and reach 150 cm in diameter. There is obvious deformation of the mudstone beds under the large exotic clasts. Large silicified logs are commonly associated with the diamictite beds (Pl. 4.11a). Thin sandy diamictite layers commonly contain small-scale parallel-crested wave ripples. The contact of many of the diamictite beds with underlying mudstone beds has been substantially reworked by burrowing organisms (Pl. 4.11e), but was obviously sharp.
The interbedded mudstone is dark grey to black or reddish brown and contains no primary sedimentary structures. It exhibits a massive to fissile texture (Pl. 4.11e). Ice-rafted clasts (maximum 10 cm) are rare. Varves were not identified.

Scattered throughout the mudstone are the siliceous tubes of the large foraminifer *Bathysiphon*? (see Gooday 1983 and Hannah & Campbell 1996), which either occurs in life position or concentrated in thin layers <1 cm thick (Pl. 4.10e). Intraclasts are common in these concentrated layers.

**Ichnology:** The very fine nature of the mudstone renders the determination of a BI impossible. It has some degree of reworking by organisms but the only discernible trace is *Phycosiphon incertum*. Distinct trace fossils occur at the lower bed boundaries of the diamictite units where burrows protrude down into the underlying mudstone. Traces identified include abundant *Diplocraterion habichi* and *Thalassinoides* (Pl. 3.8b, 4.11e), and rare, large *Rhizocorallium jenense* type B (Fig. 4.15). These traces are predominantly discrete, sharp walled, unlined, and filled with gravel and sand from above. They penetrate up to 25 cm below the diamictite bed base. In plan view burrows are crowded, with up to 20 *Diplocraterion habichi* burrows present in a 10 cm square (Pl. 2.3c). No borings were identified. In the overlying sandy diamictite no traces are recognizable.

**Ichnofacies:** A restricted Cruziana ichnofacies overprinted at the top of mudstone beds by a Glossifungites ichnofacies.

**Interpretation:** The poorly sorted diamictite and the large exotic clasts occurring within fine-grained deposits provide convincing evidence for ice rafting. The lateral continuity of the facies indicates a near-horizontal sediment surface where megaclasts were not emplaced by sliding or rolling. The deformation of bedding under the megaclasts reflects penetration of the laminae by the dropstones upon impact with the sea floor plus later loading during compaction.

The absence of clastic varves (annual silt-clay couplets) in the fine-grained mudstone beds suggests that the water was relatively saline (Christie-Blick 1983) as the salinity of seawater causes rapid flocculation of fine sediment, suppressing the tendency for varves to accumulate (Boulton & Deynoux 1981; Andrews & Matsch 1983). Sediment reworking by organisms may also have removed evidence of varves.

This glacially influenced marine environment supported some of the same trace-making organisms as non-glacial marine settings elsewhere in the study area but presented several
distinct challenges to benthic organisms. These include fluctuating salinity, sedimentation rates and energy conditions (Eyles et al. 1992). The sparse occurrence of discrete *Phycosiphon incertum* indicates systematic working of the sediment, at a relatively deep tier position, by a mobile deposit-feeder, presumably in search of relatively scarce food.

The passively sand-filled sharp-walled vertical burrows along the bed boundaries of the diamictite and the mudstone units represent a suspension feeding community. They form a composite ichnofabric with the deposit-feeding community in the underlying mudstone. The presence of vertical shafts within muddy sediment is anomalous as these structures are not capable of being maintained in soft muddy substrates (MacEachern et al. 1992b). This trace fossil assemblage is therefore, interpreted as a Glossifungites ichnofacies (Table 3.4). The apparent mass colonization by vertically burrowing suspension-feeders, reflected in the abundance of burrows in plan view (up to 2000/m²), is typical of opportunistic assemblages (Levinton 1970, Pemberton & Frey 1984a) and characteristic of the Glossifungites ichnofacies (MacEachern et al. 1992b).

These burrows provide evidence that the mudstone was firm but unlithified at the time of habitation by the suspension feeding community. The firmground resulted from the removal of the soft upper portion of the substrate by wave action.

The alternation of mudstone and diamictite reflects periods of perennial ice cover and seasonal ice cover. The mudstone beds were deposited during glacial periods when the shelf was covered by perennial ice and all but the most resilient organisms were absent from the substrate. The perennial ice cover rendered wave action at the sea floor ineffectual and the resultant depositional environment underwent fine-grained, low energy, deposition from suspension.

During the initial phase of periods when seasonal fluctuations in the ice cover were prevalent, the reintroduction of wave action to the environment resulted in the removal of the upper, soft portion of the muddy sea floor and the inhabitation of the exposed firm substrate by opportunistic suspension-feeding organisms (the Glossifungites ichnofacies, Figs 3.7, 3.39, 4.15, Pls. 2.15b-c, 3.8b). The abundance of opportunistic traces rather than traces typical of the Skolithos ichnofacies suggests deposition above storm wave base but probably not much shallower than fairweather wave base.
4.4 OFFSHORE FACIES

The offshore zone lies between maximum fairweather wave base and maximum storm-weather wave base (MacEachern & Pemberton 1992a; Fig. 3.11), and is divided into offshore transition, upper offshore and lower offshore subzones.

The offshore transition and upper offshore subzones are more variable than the lower offshore subzone because of the greater degree of storm-wave action at the sediment-water interface (MacEachern & Pemberton 1992a). The offshore transition subzone occurs within the shallowest reaches of the upper offshore area as a less intensely burrowed interval, exhibiting more regular interbedding of shale and storm-generated sandstone beds (MacEachern & Pemberton 1992a).

In the study area it has been possible to subdivide both the offshore transition and the upper offshore facies using differences in lithology, primary sedimentary structures and ichnology. The different deposits recognized in the two facies are described, and interpreted to reflect the following environments of deposition:

1. very strongly storm-dominated (very high energy);
2. strongly storm-dominated (high energy);
3. moderately storm-dominated (intermediate energy); and
4. weakly storm-affected (low energy).

In the following section, a description of each facies in terms of lithology, physical sedimentary structures and ichnology is given. The background or fairweather infaunal communities are compared with the opportunistic trace fossil assemblages associated with event-bed deposition.

4.4.1 Offshore Transition Facies (Table 4.5)

4.4.1.1 Very Strongly Storm-dominated Offshore Transition Facies

Outcrop location: South Snapper Point and Termeil Point in the Snapper Point Formation.

Description: This facies consists of interbedded clean sandstone, fine conglomerate and siltstone (Pl. 4.8c-e).

The facies is dominated by sharp, erosively based, clean, fine- to medium-grained sandstone beds that are characterised by well-preserved HCS. Low-angle cross-bedding,
combined-flow ripple lamination, mudstone rip-up clasts and mud drapes are also abundant. Lam-scram bedding is common but even the most bioturbated portions, along the bed tops, only reach a maximum BI of 3. Scattered, silt-lined burrows along laminae give evidence for amalgamation of storm beds (Pl. 4.8e). Beds range in thickness from 5 cm to 120 cm with common amalgamated units ranging from 50 cm to 4 m thick. Beds are normally graded but bed-tops commonly contain layers of pebbly, shelly, coarse-grained sandstone with well-preserved large-scale, symmetrical wave ripples (Pl. 4.8e-f), that may be thickly silt draped. The sandstone beds are lobate in form and lens in and out across 50-100 m of outcrop.

Siltstone interbeds contrast spectacularly in grain size, colour and bioturbation intensity. The average bed thickness is 20 cm with a range from less than 5 cm to a rare maximum of 60 cm. Bed tops are not preserved due to truncation by overlying clean sandstone beds. Primary sedimentary structures have been obliterated by intense bioturbation but relict coarse-grained sand and pebbles are commonly scattered throughout the thicker siltstone beds. Bed bases are abrupt and minimal mixing of the siltstone and clean sandstone has taken place.

Loading beneath sandstone layers is locally common (Pl. 4.8d).

**Ichnoology:** The clean sandstone beds are rarely bioturbated with the BI ranging from 0 throughout the body of the beds to 3 along the top 5-10 cm of the beds. The low intensity, but relatively diverse, ichnofossil association is characterised by *Fugichnia* (Pl. 3.4b-c), *Diplocraterion habichi* and *Phycosiphon incertum*. Other forms are rare and include *Diplocraterion parallelum*, *Rhizocorallium jenense* type C, *Cylindrichnus concentricus*, *Skolithos*, *Palaeophycus herberti*, *Psammichnites gigas*, *Taenidium synyphes* and *Planolites*. No traces are evident in the very coarse-grained, pebbly sandstone layers.

The ichnofossil association in the siltstone interbeds is diverse and relatively intense. The BI is usually 5 and rarely 6, and represents a composite ichnofabric (Pl. 3.1i). The thin, vertical, sand-filled tubes of *Diplocraterion habichi* commonly overprint the background texture of mottled burrows. Other individual burrow types are difficult to identify. Visible forms include *Asterosoma*, *Teichichnus*, *Rosselia socialis*, *Rosselia rotatus*, *Phycosiphon incertum*, *Palaeophycus tubularis*, *Rhizocorallium irregularare* and *Planolites*.

**Ichnofacies:** A mixed diverse Cruziana / Arenicolites ichnofacies.

**Interpretation:** This facies is similar in lithology to the strongly storm-dominated upper offshore facies (see Ch. 4.4.2). The less intensely burrowed siltstone beds and the regular
interbedding of shale and sandstone suggests that the facies was deposited in slightly shallower water (MacEachern & Pemberton 1992a), probably just below fairweather wave base (Fig. 3.11).

The clean sandstone beds dominated by HCS, wave-generated and combined-flow sedimentary structures undoubtedly represent storm-deposited sandstone. Truncation of underlying bed tops and sharp erosional bases reflect the initial erosion of the sea floor by storm currents. The lack of significant bioturbation in the sandstone beds and the predominance of Fugichnia over other trace fossil types suggest that the sediment was rapidly deposited. The combined-flow and wave rippled layers along bed tops indicate progressive return to lower flow regime oscillatory conditions during waning storm deposition (Johnson & Baldwin 1986).

The bioturbated siltstone beds reflect post-storm, fairweather mud deposition reflecting either the final suspension fall-out of storm-derived sediment (post-storm mud, Pl. 4.8d), or the return to normal fairweather sedimentation (Pl. 4.8c; Johnson & Baldwin 1986).

The common amalgamation of storm beds and the repeated truncation of fairweather deposits is indicative of an environment that was experiencing intense storm activity. This facies is believed to have been deposited in a very strongly storm-dominated offshore transition environment.

4.4.1.2 Strongly Storm-Dominated Offshore Transition Facies

**Outcrop location:** Mill Point in the Pebbley Beach Formation, Snapper Point in the Snapper Point Formation.

**Description:** This facies consists of interbedded siltstone, silty sandstone, clean sandstone and fine conglomerate beds (Pl. 3.7a-b, f, 4.9b-c).

The facies is characterised by siltstone and silty sandstone beds, which range in thickness from 5 cm to a rare maximum of 100 cm. Bed tops are generally truncated. Rare parallel laminae are preserved in the finest grained beds. Otherwise primary sedimentary structures have been obliterated by bioturbation with relict, coarse-grained sandstone beds and pebble lenses predominantly homogenized. Bed junctions are commonly indistinct where mixing has taken place (Pl. 4.9a). Large coalified and silicified logs and shell material are common.

The interbedded clean units are erosively based, fine-grained sandstone to granule conglomerate beds that are dominated by HCS, and well-preserved large-scale symmetrical
wave ripples. Low-angle cross-bedding, combined-flow ripple lamination, mudstone rip-up clasts and mud drapes are also abundant. Beds display a lam-scram profile with bed-tops commonly completely biogenically mixed with the overlying siltstone bed. Bed bases have also commonly been reworked by organisms (Pl. 4.9c). Bed thickness is variable and ranges from < 5 cm to sparse 60 cm thick amalgamated units. Individual beds average 20-30 cm and reach a maximum of 60 cm. The thicker sandstone beds are lobate in form and lens in and out across 100 m of outcrop. The coarsest, wave-rippled beds often exist as disconnected ripple crests floating in a thick bed of intensely bioturbated siltstone.

**Ichnology:** The siltstone interbeds contain a diverse ichnofossil association that represents a composite ichnofabric with a BI of 4-6 (Pl. 3.7a-b, f). Individual burrow types range from being difficult to identify to discrete and spectacular. Dominant forms include *Rosselia socialis*, *Asterosoma*, *Teichichnus*, *Phycosiphon incertum*, *Palaeophycus tubularis*, *Rhizocorallium irregularare* and *Planolites*.

The coarser sandstone interbeds contain a relatively diverse ichnofossil association that is dominated by *Diplocraterion parallelum* and large *Rhizocorallium jenense* type C. Where the sandstone interbeds have been partially or completely homogenized, the sand-filled living chambers of these large burrows are commonly still evident (Pl. 2.3i, 3.7a). *Fugichnia*, *Diplocraterion habichi*, *Skolithos*, *Palaeophycus tubularis* and *Phycosiphon incertum* are common and *Macaronichnus segregatis* is common in one locality. No traces are evident in the very coarse-grained pebbly sandstone layers. The BI of the sandstone beds ranges from 0 to lam-scram.

**Ichnofacies:** A mixed diverse Cruziana / Arenicolites ichnofacies.

**Interpretation:** This facies is similar in lithology to the very strongly storm-dominated offshore transition facies (Tables 4.5, 4.6). The siltstone interbeds, representing fairweather deposition, are thicker and more poorly sorted here due to a greater degree of storm bed homogenization. Additionally, the cleaner, storm deposited sandstone beds are generally thinner in this facies and do not display the high degree of amalgamation seen in the very strongly storm-dominated facies.

The passive sandy fill in the living chambers of the large U-tubes of structures such as *Diplocraterion parallelum* and *Rhizocorallium jenense* type C may represent tubular tempestites. Tubular tempestites were defined by Wanless et al. (1988) as forced fillings of
The coarse-grained wave rippled nature of many of the storm beds is indicative of winnowing and reworking during the waning flow conditions of storm deposition. The differences between this facies and the very strongly storm-dominated units indicates that they were deposited in a similar depositional setting but that here the environment was experiencing a slightly lower degree of storm intensity and/or frequency. This suggests that this facies was deposited in a strongly storm-dominated offshore transition environment.

4.4.1.3 Moderately Storm-Dominated Offshore Transition Facies

Outcrop location: Clear Point, South Island Beach, O’Hara Island, Pretty Beach, Nugans Point and Crampton Island in the Snapper Point Formation.

Description: This facies consists of interbedded muddy sandstone, silty sandstone, fine- to medium-grained sandstone, pebbly conglomerate and diamicrite (Pl. 3.2g-h, 3.3a-b, 3.4d-g, 4.9d).

The facies is dominated by amalgamated muddy and silty sandstone beds, which range in thickness from 60 cm to 200 cm. Bed tops are commonly truncated. Relict coarse-grained lenses are preserved. Bed bases are indistinct where biogenic mixing of the silty sandstone and underlying fine- to medium-grained sandstone has occurred. Large silicified logs and well preserved plant stems are common (Pl. 4.9e-f). Dropstones are common and reach 150 cm in length (Pl. 4.10a). Body fossils are locally abundant and include Vacunella and the bryozoan Stenopora, both in life position. Notoconularia levigata is abundant in one bed where it is well preserved in phosphatic nodules. Other fossils include spiriferids, other brachiopods, fenestellids, foraminifers, rare crinoids, gastropods, pectinaceans and numerous other bivalve species. Where associated with large quantities of shell material, the beds contain either phosphate cement or early diagenetic calcite cement.

The interbedded fine- to medium-grained sandstone units are generally erosively-based and display a lam-scram profile with bed-tops commonly completely biogenically mixed with the overlying siltstone bed. Alternatively beds tops are truncated by thin coarse-grained beds (Pl. 3.2h). Relict HCS and low-angle cross-bedding is evident in beds with less bioturbation. Bed thickness ranges from 5 cm to a rare maximum of 50 cm.
Pebbly conglomerate beds range from 5-30 cm in thickness and always contain large-scale symmetrical wave ripples that may be thickly silt-draped.

Diamictite beds range in thickness from < 5 cm (where homogenization has occurred) to 30 cm. Clasts reach 60 cm in diameter.

**Ichnology**: The muddy and silty sandstone beds contain a diverse ichnofossil association. The BI ranges from 4-6. Dominant forms vary both locally and on a bed by bed basis but include *Rosselia socialis*, *Rosselia motivus*, *Rosselia rotatus*, *Asterosoma*, *Teichichnus rectus*, *Teichichnus sinuosus* and *Phycosiphon incertum*. *Palaeophycus tubularis*, *Rhizocorallium irregulare* and *Planolites* are common.

The fine- to medium-grained sandstone interbeds usually contain a mottled background texture with vertical burrows, such as *Diplocraterion habichi*, protruding from the overlying bed in a lam-scram type profile (Pl. 3.2h, 3.3b, 4.9g). This overprinting represents a composite ichnofabric. Locally, burrows may be identified in the background texture and include large complex *Asterosoma*, *Phycosiphon incertum* and *Teichichnus*. *Fugichnia* are rare in non-bioturbated beds with preserved primary HCS. Other traces that are locally abundant include *Taenidium synyphes*, *Psammichnites*, *Palaeophycus* and *Planolites*. The BI of the main body of the beds ranges from 0 to 4. Along bed-tops, where overprinting has occurred and a composite ichnofabric exists, the BI reaches 6:1.

Pebbly conglomerate beds are commonly devoid of traces but *Arenicolites*, *Skolithos*, *Rhizocorallium jenense* types A and B and *Diplocraterion parallelum* are rare locally.

Due to the very poorly sorted nature of the diamictite beds, traces were almost impossible to recognize. Pervasive *Phycosiphon incertum* was evident in muddy horizons (Pl. 3.1d).

**Ichnofacies**: A mixed diverse Cruziana / Arenicolites ichnofacies.

**Interpretation**: The thick, muddy and silty sandstone beds that dominate this facies, and the diversity and intensity of bioturbation suggest deposition in an environment that experienced lengthy periods of fairweather conditions. The scarcity of large dropstones and the abundance of plant material indicate that the source of erratics was river- or shore-ice rather than glacial ice.

The bioturbated fine- to medium-grained sandstone beds, with composite ichnofabrics containing vertical suspension-feeding burrows over a mottled background of fairweather
deposit-feeding structures, presumably represent storm-deposited sandstone beds that have been thoroughly or partially reworked during fairweather periods.

The pebbly conglomerate beds with large-scale symmetrical wave ripples are also indicative of high-energy conditions and were probably formed by winnowing during the waning flow conditions of storm deposition.

The diamictite beds suggest deposition by ice rafting and indicate that, at least periodically the environment was experiencing cold climatic conditions.

The facies is similar in lithology and ichnology to the strongly storm-dominated upper offshore facies. The significant difference is the thickness of beds that contain a very diverse and relatively intense fairweather trace fossil assemblage and the relative scarcity of non-bioturbated storm beds (Tables 4.5, 4.6). This suggests an environment experiencing less frequent storm activity. The thickness of the reworked storm beds and the common occurrence of wave rippled conglomerate beds probably indicates that storms were still relatively intense. The facies is interpreted as a moderately storm-dominated offshore transition deposit.

4.4.2 Upper Offshore Facies (Table 4.6)

4.4.2.1 Strongly Storm-Dominated Upper Offshore Facies

**Outcrop location:** South Snapper Point in the Snapper Point Formation.

**Description:** This facies consists of intensely bioturbated silty sandstone interbedded with predominantly very fine- to fine-grained sandstone beds (Pl. 4.11b-c).

The silty sandstone beds range in thickness from 20 to 140 cm and contain horizons of homogenized coarser sandier sediment. Rounded exotic clasts up to 15 cm in diameter are sparse.

The sandstone beds range from being virtually homogenized to very rare amalgamated units (Pl. 4.11b). Individual sandstone beds reach a maximum thickness of 35 cm. The beds have erosional bases and commonly contain HCS, low-angle cross-bedding and rare combined-flow ripple lamination. Bed tops contain rare coarse pebble lags that display poorly formed large-scale symmetrical wave ripples.

**Ichnology:** The silty sandstone beds are intensely bioturbated and display a composite ichnofabric characterised by fairweather traces such as large complex *Asterosoma* and
Teichichnus, Phycosiphon incertum, Rosselia socialis, Rhizocorallium irregulare and Palaeophycus tubularis. The BI ranges from 5-6:2.

The clean sandstone beds may be completely reworked, display lam-scram bedding (Pl. 4.11c) or be devoid of bioturbation. The sand-filled living tubes of large Diplocraterion parallelum may be the only remaining evidence of a previously existing sandstone layer that has subsequently been homogenized (Pl. 4.11b). The trace fossil association includes mostly vertical burrows such as Diplocraterion parallelum, Diplocraterion habichi and Skolithos; Phycosiphon incertum and Planolites are also common.

Ichnofacies: A mixed diverse Cruziana / Arenicolites ichnofacies.

Interpretation: The diversity and intensity of bioturbation and the thickness of the silty sandstone beds indicates deposition in an offshore setting.

The clean coarse erosively based sandstone beds with remnant low-angle cross-bedding, HCS and combined ripple laminae indicate deposition by storm-generated currents. Preservation of large coarse-grained ripples and amalgamation of storm beds are uncommon features of tempestites in offshore settings and reflect deposition during periods of intense storm activity. Thin predominantly homogenized storm beds reflect less intense but still frequent storm activity. Sand-filled living tubes of large burrows such as Diplocraterion parallelum represent tubular tempestites.

Collectively, the features of the fairweather and storm beds suggest that the sequence was deposited in a high energy or strongly storm-dominated upper offshore environment.

4.4.2.2 Moderately Storm-Dominated Upper Offshore Facies

Outcrop location: South Pretty Beach, Nugans Point and Crampton Island in the Snapper Point Formation.

Description: This facies contains intensely bioturbated siltstone, silty sandstone and fine-grained sandstone interbedded with cleaner sparsely to non-bioturbated, fine- to coarse-grained sandstone beds.

The intensely bioturbated beds range in thickness from 20 to 140 cm and contain horizons of homogenized coarser sandier sediment and scattered pebbles. Exotic clasts to 15 cm in diameter are rare.
The less bioturbated sandstone interbeds are predominantly homogenized but rare beds with remnant erosive bases, low-angle cross-bedding and pebble lags with large-scale symmetrical wave ripples are sparse and reach a maximum thickness of 25 cm. Rare convex-up disarticulated bivalve shells are associated with the coarsest fractions of the beds.

**Ichnology:** The intensely bioturbated beds exhibit a composite ichnofabric dominated by *Teichichnus* and *Phycosiphon incertum*. *Rosselia socialis*, *Rosselia rotatus*, *Planolites* and *Asterosoma* are also common. The BI ranges from 3-6:2.

The cleaner fine- to coarse-grained sandstone beds have usually been homogenized through the bioturbated silty sandstone, but the sand-filled living tubes of large *Diplocraterion parallelum* are commonly preserved as evidence of the previous existence of clean sandstone layers (Pl. 3.7h). Trace fossils are sparse and include vertical burrows such as *Diplocraterion parallelum*, *Diplocraterion habichi*, *Cylindrichnus concentricus* and *Skolithos*. *Phycosiphon incertum* is also common.

**Ichnofacies:** A mixed diverse Cruziana / Arenicolites ichnofacies.

**Interpretation:** The intensely bioturbated beds are similar in thickness, lithology and ichnology to the fairweather deposits from the strongly storm-dominated upper offshore facies, and also represent the reworking of fairweather and storm deposits during fairweather periods in an upper offshore setting.

The predominance of homogenization and the comparatively thinner or tubular nature of tempestites in this facies suggest that the frequency and/or intensity of storm activity influencing the depositional environment was less and that the environment may have been slightly deeper. The presence of rare remnant storm-produced sedimentary structures, such as primary lamination and large-scale coarse-grained ripples, reflects an upper offshore environment that was moderately storm-dominated.

**4.4.2.3 Weakly Storm-affected Upper Offshore Facies**

**Outcrop location:** Pretty Beach in the Snapper Point Formation.
Description: This facies consists of moderately to intensely bioturbated silty sandstone with interbedded almost-completely homogenized fine- to coarse-grained sandstone layers that are very rarely up to 5 cm thick (Pl. 3.3e and above the transgressive surface in Pl. 4.11d).

Silty sandstone beds range in thickness from 50 cm (rare) to 500 cm, and commonly contain wood fragments and large silicified logs.

Ichnology: The trace fossil association is very diverse and is dominated by large Asterosoma, Polycylindrichnus prolifer and small to very large vertically retrusive Rhizocorallium irregulare. Many other traces are locally abundant including Rosselia socialis, Rosselia rotatus, Rosselia motivus and Teichichnus. Taenidium serpentinum is rare. Commonly the tops of vertical burrows have been truncated. In plan view on large pieces of fallen float, several trace types are seen, associated with lenses of coarser-grained sandstone. These traces are generally thickly lined with silt. They include large Diplocraterion parallelum (Pl. 3.3f), large Rhizocorallium jenense type B, Diplocraterion habichi, Palaeophycus herberti, Skolithos and Taenidium synyphes. Phycosiphon incertum and Planolites are common both in the living chambers of other larger traces and within the host sediment.

The BI ranges from 4-5 and a composite ichnofabric is preserved.

Ichnofacies: A mixed diverse Cruziana / Arenicolites ichnofacies.

Interpretation: The thick silty nature of this facies, and the diversity and intensity of bioturbation, suggest deposition in an environment dominated by fairweather conditions and processes.

The homogenized coarser sandstone beds, dominated by the burrows of vertical suspension-feeding organisms, presumably represent reworked storm-deposited sandstone. Truncation of burrow tops is evidence of scour on the sea floor and is probably storm related.

The facies is similar in lithology and ichnology to the strongly and moderately storm-dominated upper offshore facies. The significant difference is the thickness of fairweather deposits and the relative scarcity of unhomogenized storm beds (Table 4.6), both suggesting an environment experiencing less intense and less frequent storm activity. The vertically retrusive spreiten present on Rhizocorallium irregulare burrows are interpreted as storm response/re-equilibrium structures. These indicate that the trace-makers were able to escape the initial adversities of the storm by retracting deep within their burrows, and then following storm
cessation and deposition of an increment of sand, re-equilibrate their burrows with the new sediment/water interface (Saunders & Pemberton 1986).

The facies is believed to have been deposited in a weakly storm-affected upper offshore environment.

4.4.3 Ichnological Interpretation of the Offshore Transition and Upper Offshore Facies

The upper offshore and offshore transition facies in the study area represent storm-influenced deposits. Sandstone and pebbly conglomerate beds were emplaced by storm-generated density currents, thus representing tempestites, and both facies were deposited below fairweather wave base. The facies exhibit a suite of trace fossils and a general succession that is characteristic of tempestites. Pemberton et al (1992c) suggested that a typical tempestite succession included:

1. a fairweather resident trace fossil suite;
2. a sharp basal contact with or without a basal lag;
3. parallel to sub-parallel laminations (reflecting HCS);
4. common escape structures;
5. burrows inhabited by opportunistic organisms that colonized the storm deposit;
6. lam-scram profiles representing increasing degrees of bioturbation from higher colonization levels; and
7. a fairweather resident trace fossil suite indicative of a return to quiescent conditions following storm abatement.

In the study area, the fairweather resident trace fossil suite is represented by a diverse assemblage, predominantly representing the burrows of deposit-feeding organisms, and is typical of the Cruziana ichnofacies (Table 3.2, Figs 4.12, 4.14). This ichnofacies is generally accepted to be characteristic of the region between fairweather and storm wave base (Frey & Seilacher 1980, Frey & Pemberton 1985). Moderately deep-tier, horizontal deposit-feeders generally dominated the fairweather community (Fig. 4.12), although the resident ichnocoenose was not everywhere the same. This difference presumably reflects subtle shifts in environmental conditions at different depositional sites. Rapid sedimentation rate, preventing the complete maturation of communities, is suggested by the complete absence of burrows such as Zoophycus and Chondrites which usually characterize the deepest (softground) tier (Bromley 1990).

Persistence of the fairweather resident assemblage was somewhat dependent on the contrasting conditions imparted by periodic storms. Storm activity obviously disrupted bottom
fauna, and probably resulted in mass stranding and the transportation of organisms to other environments (Hayes 1967, Rees et al. 1981, Dobbs & Vosarik 1983, Butman 1987). The diversity of the trace fossil assemblage generally decreased with an increase in storm intensity and/or frequency (Table 4.7).

In the very strongly storm-dominated facies, non-bioturbated mudstone lenses interbedded with storm sandstone (Pl. 4.11b) suggest either that storms were occurring frequently with depositional and erosional conditions fluctuated too rapidly for the establishment of stable populations of endobenthic organisms (Frey 1990), or that organisms only colonized to a shallow depth and the subsequent biogenic structures were removed by storm scour (Rhoads et al. 1985).

Differences in storm-bed thickness and morphology resulted in a variety of trace fossil assemblages and ichnofabrics. Although colonization of post-storm substrates evidently took place opportunistically, the final ichnofauna was related more closely to lithology, in loco environmental conditions and subsequent storm activity, than to the main storm event (Frey & Goldring 1992). Frey & Goldring (1992) suggested that burrows might be emplaced in storm beds in four principal ways:

1. by colonization of the normal graded or rippled top;
2. by colonization following partial erosion of the bed;
3. by burrows extending down from above the normal or eroded top; and
4. by extending upward from below the bed as contemporaneous or penecontemporaneous escape structures.

The surface of the storm-deposited unit obviously influenced colonization. For larval spatfall, the wave-rippled muddy substrate surface formed during storm wane is no different to the pre-storm condition and no significant difference in energy level or water depth would be expected (Frey & Goldring 1992). This resulted in similar ecological conditions to those experienced by the resident assemblage and led to recolonization by the spat of fairweather deposit feeders. This sequence of events was probably partially responsible for the complete homogenization of storm beds and for mixed Cruziana-Arenicolites assemblages. Slow rates of fine sediment deposition were also responsible for the mixed assemblages and resulted in overprinting of storm assemblages by burrows from subsequent tiers or the resident community (Frey 1990).

In contrast, a winnowed event bed top may present a substrate that is out of character with its overall sedimentary sequence. The spat of deposit-feeders are less likely to have colonized this kind of substrate, which was more attractive to the prolific spat of suspension
feeders or passive (tubicolus) carnivores (Frey & Goldring 1992). Bioturbated sandstone beds containing Diplocraterion habichi burrows filled with the same sand as the surrounding host sediment, suggest colonization of an eroded storm-bed top (Pl. 4.11c).

In some cases the ichnofauna of the storm-deposited unit was distinct from that of the overlying and underlying facies and reflects an alternating shift between the Cruziana ichnofacies and the Arenicolites ichnofacies. The storm assemblage is dominated by vertical suspension-feeders (Fig. 4.12) and represents the activities of opportunistic organisms recolonizing the substrate following storm disruption (Pemberton & Frey 1984a, Vossler & Pemberton 1988b). Opportunistic species respond rapidly to an open or unexploited niche and typically:

1. lack equilibrium population size;
2. have a density-independent mortality;
3. are able to increase their abundance rapidly;
4. have a relatively poor competitive ability;
5. display high dispersal ability; and
6. devote a high proportion of their resources to reproduction (Grassle & Grassle 1974).

Burrows that commonly display opportunistic and equilibrium characteristics in these facies are shown in Tables 4.3 and 4.7. In some instances, early and late stage opportunists could be recognized. Small Planolites, that reworked the living tube of larger structures such as Diplocraterion parallelum, and Phycosiphon incertum, which is commonly preserved within the burrows of other opportunists such as Diplocraterion habichi, are two such examples of late stage opportunistic organisms. When exploiting substratal sediment alone, these burrow types are commonly found in shallow tier positions. The practice of exploiting the waste material within other burrows allowed the producing organisms of these two traces to penetrate to deeper tier positions than they usually occupied.

The abundant occurrence and mode of life suggest that the producers of Cylindrichnus, Rosselia socialis, Rosselia motivus and Asterosoma, if not strictly opportunistic, were at least highly resilient members of the post-tempest biocoenose.

The large living tubes of Diplocraterion parallelum and Rhizocorallium jenense types B and C, that are commonly filled with cleaner and/or coarser sediment in the mixed Cruziana / Arenicolites ichnofacies assemblages (Pl. 4.11b), are good evidence for the prior existence of storm beds and thus represent tubular tempestites. Webb & Theodore (1968) have shown that intense wave action results in strong and rapid fluctuations in the hydrostatic pressure through
burrows. The difference in hydrostatic pressure causes strong and rapid pumping and sucking of fluid into and out of the burrow thus working coarser and heavier material down into the burrow (Wanless et al. 1988). Bromley (1996) stated that the capacity of the burrow systems might be high enough to swallow the entire storm lag. The Snapper Point Formation examples were probably formed during storm scour erosion and hydrostatic burrow filling.

Five different types of ichnofabric have been recognized in the Pebbley Beach and Snapper Point Formation offshore transition and upper offshore facies (Table 4.8):

1. frozen tiered Arenicolites assemblage profiles;
2. laminated-scrambled Cruziana / Arenicolites assemblage profile;
3. composite Cruziana / Arenicolites assemblage ichnofabric;
4. composite Arenicolites / Cruziana / Arenicolites assemblage ichnofabric; and
5. composite Cruziana assemblage ichnofabric.

Frozen tiered profiles (Savrda & Bottjer 1986) are rare in the study area. They form when a storm bed is deposited and subsequently colonized by an assemblage of opportunistic organisms that do not move vertically upward (Droser et al. 1994). This suggests a period of little or no deposition followed by sudden burial by another event deposit. The resultant ichnofabric represents a single community tier.

Laminated-scrambled Cruziana / Arenicolites assemblages are common in storm beds in the study area and represent bed-tops reworked by infaunal communities. The scrambled portion of the unit may represent a reworked storm-bed top, a mixture of storm-bed top and the basal portion of the overlying fairweather deposit, or of several biogenically mixed units above a laminated storm deposit.

The mixed Cruziana / Arenicolites assemblage ichnofabric is the most common in the upper offshore and transitional facies. It represents the colonization of storm beds by opportunistic organisms from the Arenicolites ichnofacies, and the subsequent replacement and overprinting of these structures by the resident Cruziana ichnofacies. The type of fabric may also result from the catastrophic infilling of large open burrows and produce fabrics typical of tubular tempestites (Tedesco & Wanless 1991).

The Arenicolites / Cruziana / Arenicolites assemblage ichnofabric is more complex and involves several successive bioturbation events. Storm deposited beds, initially colonized by a community of opportunistic organisms from the Arenicolites ichnofacies, were replaced and overprinted by the resident Cruziana assemblage during fairweather periods. The final stage of colonization, represented by long thin vertical Diplocraterion habichi burrows, occurred following the interruption of sedimentation by further storm deposition. The storm beds
associated with the third-stage of colonization are usually thin and probably represent low intensity storm deposits. This type of ichnofabric is common in the study area in facies other than offshore transition and upper offshore.

The composite Cruziana assemblage ichnofabric is common in the study area in fairweather deposits from facies representing lower energy or weakly storm-affected settings. It represents steady accretion of the sea floor. Depositional rates were slower than the rate of biogenic reworking and the gradual upward movement of successive tiers produced a composite ichnofabric (Bromley 1990).

Changes in ichnofabric type and in the BI within the same unit provide evidence for amalgamation of beds. Amalgamation of units is often difficult to recognize where homogenization of beds has occurred. It can be recognized where more intensely bioturbated sediment lies within a sedimentary unit (Frey & Goldring 1992; Pl. 4.9d).

4.4.4 Lower Offshore Facies

The lower offshore facies has been separated from the upper offshore on the basis of lithology, primary sedimentary structures, trace fossil assemblages and ichnofabrics. It has then been further subdivided on the same basis (Table 4.9). A tiering profile is seen in Fig. 4.13. Three different facies are described and interpreted:

1. bioturbated sandy-siltstone facies;
2. laminated siltstone facies; and
3. thinly interbedded mudstone, siltstone and sandstone facies.

4.4.4.1 Bioturbated Sandy-Siltstone Facies

Outcrop location: South Pebbles, Mill Point and Clear Point in the Pebbley Beach Formation.

Description: This facies consists of dark to light grey sandy-siltstone that has been thoroughly homogenized by biogenic reworking. Bed thickness averages 1 m.

Very fine- to medium-grained sandstone beds are rare to sparsely preserved and have been predominantly reworked by burrowing organisms. The sandstone lenses have sharp uneven bases and are associated with pebbles (to 5 cm in length) and convex-up disarticulated bivalve shells. Remnant undulatory parallel laminae and small-scale current ripples are common.
Contorted and deformed bedding occurs in one locality (Pl. 4.10d-e), where the vertical traces are stretched in the direction of sediment movement.

**Ichnology:** The sandy siltstone is generally intensely bioturbated and shows a BI of 5-6. The high degree of bioturbation obscures most of the individual biogenic structures and makes identification of ichnogenera difficult. Identifiable traces include pervasive *Phycosiphon incertum*, *Rosselia socialis*, *Planolites*, *Palaeophycus tubularis* and large *Rhizocorallium jenense* type B.

The sandstone lenses are commonly almost completely homogenized through the siltstone but the thicker sandstone beds are less bioturbated (BI 1-4). The trace fossil assemblage associated with the sandstone lenses is composed of abundant *Diplocraterion habichi*, sparse *Diplocraterion parallelum* and rare escape traces. Protrusion of these vertical burrows into the underlying siltstone beds has created a composite ichnofabric with a BI of 6:1.

**Ichnofacies:** A mixed distal Cruziana / Arenicolites ichnofacies.

**Interpretation:** This facies represents distal event beds in a lower offshore setting. The sandy siltstone reflects fairweather conditions. The intense bioturbate texture reflects a softground substrate, low wave energy and infrequent storm events.

The coarser sandstone beds presumably represent storm-related event deposits (distal tempestites Pl. 4.10f) with the sand transported basinward as sediment gravity flows generated by storm surge bottom return flows (MacEachern *et al.* 1992a). Wavy parallel laminae associated with these beds is interpreted as distal HCS. The thicker sandstone beds that contain evidence of escape structures record the attempts of organisms entrained within the HCS bed to reach the new sediment-water interface.

The fairweather ichnological suite is regarded as a 'distal' or 'outer' Cruziana assemblage incorporating a relatively low diversity of both deposit feeding and grazing/foraging structures. The ichnological suite of the storm beds is characteristic of tempestites in shallow marine settings (MacEachern *et al.* 1992a), and reflects opportunistic colonization and progressive replacement by fairweather resident assemblages.
4.4.4.2 Laminated Siltstone Facies

**Outcrop location:** Crampton Island, Bannisters Point and Abraham Bosom Beach (at Currarong on the northern side of Jervis Bay) in the Snapper Point Formation.

**Description:** The facies consists of an 8-10 m thick unit containing parallel beds of upward fining dark-grey to black siltstone and mudstone (Pl. 4.12a-b), with thin fine- to medium-grained sandstone lenses at the bases of beds (Pl. 4.12c-d). The unit is pervasively bioturbated but the parallel nature of the primary bedding is still evident. The thickness and abundance of sandstone at the bases of the beds decreases up through the unit.

The sandstone contains abundant megaclasts, which occur as clusters of pebbles or as individual clasts up to 60 cm in diameter. There is a definite alignment of discoidal (platy) megaclasts parallel to bedding. The megaclasts are well rounded to angular and the underlying sediment shows downwarping. There is also considerable drape of the overlying sedimentary laminae. The bioturbation is so intense that many sandstone layers and associated megaclasts have been homogenized through the siltstone, although the thicker sandstone beds contain sharp uneven bases. The facies contains an overall 5-10% of floating clasts.

Pods and layers of articulated spiriferid brachiopods (*Sulciplica*) are commonly preserved in sideritic concretions in the sandstone beds. Wood and lenses of coalified material (logs?) are common throughout the unit.

**Ichnology:** The unit is intensely bioturbated and displays a BI of 5-6. At each outcrop identifiable trace fossils differ slightly. At Jervis Bay in the northern part of the formation, the only identifiable ichnogenus is a small predominantly horizontal *Thalassinoides*. At Bannisters Point, trace fossils have a very blurred appearance and only *Phycosiphon incertum* and suspected *Teichichnus* were identified. At Crampton Island *Teichichnus rectus* occurs as discrete traces and *Phycosiphon incertum* is also evident; rare *Diplocraterion habichi* are associated with the sandier horizons but these have been almost completely overprinted by *Teichichnus rectus*.

**Ichnofacies:** A mixed distal Cruziana / Arenicolites ichnofacies.

**Interpretation:** The occurrence of megaclasts and marine fossils in the thick intensely bioturbated unit of mud- and silt-sized sediment is evidence for a glacial-marine depositional
environment. The megaclasts are interpreted as ice-rafted erratics or dropstones that were probably derived by icefloe transport. It was suggested by Ovenshine (1965) and Blick (1979) that penetration of laminae by dropstones is largely due to compaction, not impact, where there are as many laminae deflected upward adjacent to stones as downward. This was probably the case in beds in the Snapper Point Formation where parallel alignment suggests that the large elongate clasts came to rest on a firm substrate. These layers may represent fairweather deposits in a sediment-starved environment undergoing transgression (see Chapter 5.0). In other layers, vertical orientation of the elongate clasts and the blurred nature of the trace fossils suggest that the silty substrate had a reasonably high water content and was very soft. These layers reflect periods of increased sedimentation and may represent storm deposition. Periodical compaction differences suggest alternating rates of sediment input due to transgressive sediment starvation and event deposition.

This facies is believed to have been deposited around storm wavebase, during a major period of flooding of the shelf. The coarser sandstone beds represent storm-related event deposits. Storm activity may have also broken and freed shore-ice laden with erratic material. The concentrated layers of shell material in the sandstone lenses also provide evidence for winnowing and removal of finer material by current activity associated with storms or transgressive erosion. Transgressive erosion and sediment starvation may also have produced the firmer substrates associated with the aligned megaclasts.

The source of the silt may have been from seasonal meltwater sediment input. Similar muds to these are accumulating across the modern Gulf of Alaska shelf (Molnia & Carlson 1980, Powell & Molnia 1989, Carlson 1989) as a result of large volumes of silt and clay released from meltwater deltas and rivers and glacier-fed deltas along the coast (Eyles et al. 1992).

The low-diversity ichnofossil suite in the siltstone consists of deep softground burrows, characterised by both deposit feeding and grazing foraging structures. As in the other lower offshore fairweather facies, this represents a 'distal' or 'outer' Cruziana assemblage characteristic of quiet water, offshore deposits.

The destabilizing activity of the deep deposit feeders, especially *Teichichnus rectus*, may have resulted in a lack of suspension-feeding organisms. The blurred nature of the traces in some beds is indicative of poor consolidation and high water content producing a soupy silty substrate unsuitable for suspension feeders (Feder & Jewett 1988). Although grazers and foragers may have been abundant, upon compaction and dewatering these structures are unlikely to be preserved (MacEachern et al. 1992b). Inhabitants of soupgrounds and watery
softgrounds tend to cause diffusive turbulence by their passage through the substrate and produce a structureless fabric (Bromley 1990).

The ichnological suite of the storm beds, although poorly preserved, appears characteristic of tempestites in shallow marine settings, and reflects the opportunistic colonization and progressive replacement by the fairweather resident assemblage. The overprinting of the indistinct shallow tier vertical suspension-feeding traces by deep deposit feeding traces usually results in a composite ichnofabric (Eyles & Eyles 1992). In this facies the vertical suspension-feeding burrows are mostly completely overprinted and the composite ichnofabric was not obvious.

4.4.4.3 Thinly Interbedded Mudstone, Siltstone and Sandstone Facies

Outcrop location: South Snapper Point in the Snapper Point Formation.

Description: This facies consists of very fine- to fine-grained sandstone, siltstone and dark organic-rich mudstone, interbedded on a variety of scales. The sandstone beds are sharp-based <1-15 cm thick and show normal grading up to black mudstone. Primary sedimentary structures are dominated by low-angle undulatory parallel laminae, with sparse muddy rip-up clasts. The sandstone beds are commonly lobate and taper-out laterally. Beds may display lam-scram profiles (Pl. 4.12e).

Sharp-based siltstone and mudstone beds with well-developed normal grading, but lacking a basal sandstone are common and reach a maximum thickness of 10 cm. The dominant primary sedimentary structure is faint parallel laminae. These beds usually lack bioturbation.

Ichnology: Bioturbation is absent to sparse in the sandier fraction of this facies and predominantly absent from the thicker siltstone and mudstone beds. The BI ranges from 0 to a rare maximum of 5. Some of the fine-grained beds contain sand-filled *Skolithos*? burrows that are sharply outlined and interpreted as a Glossifungites ichnofacies.

Beds are rarely completely homogenized, but contain lam-scram bedding. The thin rhythmic lam-scram nature of the bedding creates a distinctive ichnofabric. Individual trace fossil types are difficult to identify due to the blurred nature of the burrows. Those identified include *Phycosiphon incertum*, *Planolites* and *Rosselia*. Some thicker sandstone lenses contain probable escape structures, but no evidence of opportunistic colonization of the bed tops has been observed.
**Ichnofacies:** A mixed distal Cruziana / possible Glossifungites ichnofacies.

**Interpretation:** The thinly bedded mudstone, siltstone and sandstone facies is interpreted as the most distal portions of storm beds deposited in the lower offshore portion of a very strongly storm-dominated environment. The low-angle undulatory parallel laminae in the thicker sandstone beds reflect distal HCS. The mudstone rip-up clasts along the laminae represent material removed from the top of the underlying fine-grained bed during the emplacement of storm sands. The dark organic-rich muds represent the waning flow portions of the sandy storm beds (as opposed to a return to fairweather deposition), and are indicative of low concentration turbidity flows incapable of suspending sand. These beds are further evidence of the distal character of the facies.

Fairweather conditions are reflected only in the biogenically scrambled portions of the sandy storm beds. No intensely-bioturbated fine-grained sediments, reflecting long periods of fairweather deposition, are preserved, suggesting that the unit was deposited in a very strongly storm-dominated environment.

The blurred nature of the traces at the top of the sandier storm-deposited beds reflects the high water content and low degree of compaction of the sediment, suggesting a soupground characteristic of rapidly deposited storm sediments. In contrast the vertical sand-filled Glossifungites ichnofacies burrows reflect a firm substrate and indicate that either soupground sediments were eroded or that at least occasionally sedimentation was slow and compaction and de-watering of fine-grained sediments occurred. This may represent a period of sediment starvation associated with maximum flooding of the shelf.

The identifiable trace fossil suite represents a distal Cruziana and rare Glossifungites ichnofacies. Several authors have noted a similar paucity of trace fossils in lithologically similar lower offshore and shelf deposits in the Viking Formation, Alberta, Canada (e.g. Leckie 1986, Hein et al. 1986, Davies 1990, Pattison 1991). They interpreted the paucity as environmentally unfavorable conditions for organisms, related to restricted marine conditions, reduced salinity and a euxinic environment. In the Snapper Point Formation this paucity is mainly due to the repeated rapid deposition of storm beds rather than to restricted infaunal habitation.

Traces associated with sandstone beds represent the burrowing activity of organisms transported during episodic storm-bed emplacement (MacEachern et al. 1992a). The apparent lack of evidence of opportunistic structures (abundant in most other event deposits in the Pebbley Beach and Snapper Point Formations) suggests that the bioturbation represents the
activity of colonizers entrained in the flow from the upper offshore and lower shoreface, rather than larval settling of opportunistic organisms. The apparent lack of fairweather deposits due to repetitive storm deposition may have inhibited the establishment of a complex resident community. Alternatively the deposition of fairweather sediment may have been minimalised by sediment starvation associated with transgressive processes and maximum flooding. Any silt that was deposited may have been removed by storm scour prior to the deposition of the subsequent storm deposit.
CHAPTER 5: CYCLICITY AND DEPOSITIONAL SYSTEMS

5.1 INTRODUCTION

This chapter integrates previously discussed high-resolution ichnofabric and ichnofacies analysis with sedimentology and environmental interpretations to identify facies cyclicity and bounding depositional surfaces. In intensely bioturbated sandstone and siltstone, ichnofabrics have provided information for detailed palaeoenvironmental and sequence stratigraphic analysis that may have been overlooked using conventional sedimentological methods. Ichnofacies analysis provides a detailed picture of environmental conditions and environmental change. In turn, this has aided in the understanding of the development of composite ichnofabrics, and led to the identification of transgressive deposits, condensed sections and the following key stratal surfaces:

Transgressive Surfaces of Erosion (TSE, or ravinement surfaces, cf. Stamp 1921): A TSE is defined as an erosional surface across which a landward shift of facies can be demonstrated (MacEachen et al. 1992a), i.e., there is stratigraphic evidence indicating an increase in water depth (Amott 1995). Wave and current action associated with erosive shoreface retreat is responsible for the formation of TSE (Swift 1975, Nummedal & Swift 1987). During transgression the shoreline moves landwards and the shelf area expands. The volume of new sediment being supplied per unit area of shelf is decreased (Posamentier et al. 1988) and the principal source of sand and gravel for deposition during a transgression is from cannibalization of previously deposited sediment (Amott 1995). With a moderate to low rate of relative sea level rise, the shoreline transgresses landward by shoreface erosion (Swift 1975). Arnott (1995) likened this mechanism to a bulldozer blade with the base approximating the depth of fairweather wave base (commonly 5-15 m). As a result, the underlying deposit is reworked and fine-grained sediments are selectively winnowed while coarse-grained material is preferentially concentrated and accumulated on the ravinement surface (Arnott 1995). The resultant deposit is called a transgressive lag (Bates & Jackson 1980).

TSE within the study area are veneered by a pebble or intraformational rip-up clast lag (transgressive lag), and some surfaces demonstrate erosional incision with the presence of a firm substrate trace fossil suite (or Glossifungites ichnofacies, see Figs 3.7, 4.15, 5.2, plate 2.1a, 3.1g, 4.2e, Table 3.4). The TSE provide optimum conditions for development of substrate controlled ichnofacies because exhumed surfaces are generated within marine or marginal...
marine environments. These particular environments favour colonization by organisms as the surface is cut, prior to significant deposition of overlying sediment (MacEachern et al. 1992b).

The Glossifungites ichnofacies is a substrate-controlled ichnocoenose which demarks discontinuity surfaces and reflects pauses in sedimentation, generally accompanied by erosion (MacEachern et al. 1992b). This ichnofacies cross-cuts the pre-existing soft-ground suite and reflects conditions that post-date the initial deposition of the underlying unit. Colonization of the firmground corresponds to an hiatus between the erosional event (which exhumed the substrate) and deposition of the overlying unit (Pemberton et al. 1992b). Opportunistic species invaded the environment during the latter stages of the erosional event, when the exhumation of a semiconsolidated, dewatered substrate (that was resistant to wave or current erosion) occurred. Sediment cohesiveness generally negated the need for reinforced burrow linings and precluded most intrastratal deposit feeders (Frey & Pemberton 1984). With the resumption of sedimentation the trace makers vacated their burrows and the open structures were filled with sediment from the overlying unit.

In the Snapper Point and Pebbley Beach Formations, the superimposition of a firmground (Glossifungites) community onto a soft ground community is indicated by the following characteristics:

- robust, sharp-walled, unlined, vertical dwelling structures within shaly intervals, which immediately appear anomalous, as such structures are not capable of being maintained in soft muddy substrates;
- passive burrow fill which demonstrates that the structure remained open after the tracemaker vacated the burrow and material from the succeeding depositional event passively filled the open structure. Collapse of the domicile following burrow vacation would have occurred if the unlined burrow had been excavated into a soft muddy substrate (MacEachern et al. 1992b);
- a ubiquitous cross-cutting relationship between robust, vertical Glossifungites burrows that overprint predominantly horizontal, diminutive trace fossils in the shaly intervals, clearly demonstrating the post-depositional origin of the Glossifungites suite;
- differences in the degree of compaction between the two assemblages and:
- a tendency to demonstrate colonization of the firm substrate in large numbers, reflecting the opportunistic nature of the Glossifungites population (Levinton 1970, Pemberton & Frey 1984).
Condensed Zones and Maximum Flooding Surfaces (MFS): A condensed zone (also termed a condensed interval or section) is a sedimentary deposit that is thin in relationship to the amount of time it represents (Taylor & Gawthorpe 1993). Condensed sections are produced during periods of little or no deposition, reflecting sediment bypass, starvation, erosion or winnowing (Taylor & Gawthorpe 1993). During transgressive phases, terrigenous clastic deposition is commonly very slow and most of the coarser sediment is confined to the alluvial floodplain and to other environments at or very close to the shoreline (Walker 1992). Condensed zones in shelf sequences are most extensive at the point of maximum regional transgression (Loutit et al. 1998) and can be used to determine the location of the MFS (Van Wagoner et al. 1990). Condensed sections have generally been documented from offshore settings (e.g. Loutit et al. 1988, Pemberton et al. 1992b, Partington et al. 1993) where the condensed zone is characterized by mudstone with little or no bioturbation, and formed under conditions of low oxygen levels (e.g. Savrda & Bottjer 1987) and low sedimentation rates. In the Snapper Point and Pebbley Beach Formations, however, condensed intervals occur in more proximal, well-oxygenated shelf to shoreface environments. Consequently, the condensed zones are characterized by intensely bioturbated intervals resulting from repeated reworking of the substrate during low sedimentation rates or sediment starvation. Condensed zones in similar, well-oxygenated environments have been documented by Taylor & Goldring (1993) and Taylor & Gawthorpe (1993).

A maximum flooding surface marks the maximum regional transgression of the shoreline (Taylor & Gawthorpe 1993), or the top of a transgressive deposit (Posamentier et al. 1988), and separates deposits reflecting transgressive conditions from the overlying deposits representing the next overall marine regression (Walker 1992). MFS are commonly associated with condensed zones and may contain other evidence of very slow sedimentation, such as phosphatic or glauconitic material (Walker 1992).

In the Snapper Point and Pebbley Beach Formations, discrete maximum flooding surfaces are uncommon. They characteristically occur at the top of a condensed section and contain wood fragments, logs and a pebbly lens which reflects the extreme sediment starvation and winnowing associated with maximum transgression. More abundant are condensed intervals which occur above almost every transgressive erosion surface. Each condensed zone is somewhat different to any other in the study area but they characteristically display a general fining upward nature accompanied by an increase in bioturbation intensity. Body fossils, wood material, pebbles and large drop stones, pyrite, phosphatic nodules and calcium carbonate
concretions are all associated with the condensed zones and are further evidence of low sedimentation rates and winnowing.

**Regressions and Regressive Surfaces of Erosion (RSE):** Marine regression refers to a basinward migration of the shoreline accompanied by a retreat of the sea (Posamentier *et al.* 1992). Regression occurs in two different ways:

1. **Normal regression** occurs on coasts where sediment supply exceeds new accommodation space (Posamentier *et al.* 1990). During periods of stillstand or of relative sea level rise, regression can still occur if the rate of sediment influx is greater than the rate of increase of accommodation space (Posamentier *et al.* 1992). This occurs as a function of eustacy and sea floor movement, the latter resulting from tectonic activity, thermal cooling, sediment loading and sediment compaction (Posamentier *et al.* 1992). If, however, the dispersive energy of the littoral environment (i.e. waves, tidal or longshore currents) is high, supplied sediment may be distributed over a widespread area, progradation of the shoreface may be precluded and regression may not occur despite high volumes of sediment input. Deposits representing normal regressive processes contain conformable basal contacts and a tendency for the adjacent coastal and alluvial plains to aggrade (Posamentier *et al.* 1992).

2. **Forced regression** (Plint 1991) occurs on shorelines experiencing a relative drop in sea level and even when there is no sediment delivered to the shoreface, a seaward shift of the shoreline must occur (Plint 1988, Posamentier & Vail 1988, Posamentier *et al.* 1990). In contrast to the conformable basal contacts produced during normal regression, the basal contacts of deposits formed during forced regressions are sharp and commonly erosional in proximal areas, grading seaward to a conformable contact (Posamentier 1992).

The erosive surface is called a regressive surface of erosion (RSE, Walker & Wiseman 1995) and forms as a result of a lowering of relative sea level and incision into underlying offshore or shelf mudstones (Pemberton *et al.* 1992b; Fig. 5.1). The reduced accommodation space produced during the lowering of sea level, eliminates the shelf-to-shoreface transitional zone, and the shoreface sands rest abruptly on the RSE. Some examples of forced regressions and RSE are described by (Reinson *et al.* 1988, Plint 1991, Plint & Norris 1991, Posamentier 1992, Pattison & Walker 1994, Walker & Wiseman 1995).

In the Snapper Point and Pebbley Beach Formations regressive facies are mainly attributable to normal regressive processes. One example of a relatively major RSE occurs at
Bannisters Point and in equivalent facies at Crampton Island in the upper Snapper Point Formation (see section 5.4.4 & Fig. 5.2). Other suspected minor RSE are exposed in the study area at Mill Point in the Pebbley Beach Formation, and at Pretty Beach and south Snapper Point in the lower Snapper Point Formation.

5.2 PEBBLEY BEACH FORMATION

5.2.1 Introduction

The type section of the Pebbley Beach Formation was originally defined by Gostin & Herbert (1973) to extend along the coast from Wasp Island in the south to the base of Clear Point in the north. The contact between the Pebbley Beach Formation and the underlying Wasp Head Formation is disconformable (Gostin 1968) and is clearly visible on Wasp Island. Only the upper part of the Pebbley Beach Formation is exposed in the coastal exposures (Gostin 1968, Gostin & Herbert 1973) between South Island Beach in the north and Point Upright in the south. Gostin (1968), and later Gostin & Herbert (1973), recognised the conformable nature of the boundary between the Pebbley Beach Formation and the overlying Snapper Point Formation below a prominent conglomerate bed at Clear Point. The boundary at this location is sharp and distinct and clearly separates the silt-dominated facies of the Pebbley Beach Formation from coarse-grained sandy facies of the Snapper Point Formation. It is herein interpreted that the contact between the Pebbley Beach Formation and the Snapper Point Formation is also exposed north of Clear Point at South Island Beach (GR:8926-603595). Here the contact is gradational and indistinct but significant changes in ichnofabric and ichnofacies occur across the boundary and the presence of a well developed Glossifungites ichnofacies along the boundary surface demonstrates the presence of a TSE (Pl. 2.1a, 4.11d, 5.1).

The present study has recognised that the Pebbley Beach Formation is composed of four cycles (parasequences) with the regressive phases displaying a progressive basinward facies shift. The following section gives a description of each cycle in terms of lithology, ichnofabric, ichnofacies and environment of deposition, and it outlines the depositional history (Fig. 5.3).

5.2.2 Cycle 1

The lowest cycle is interpreted as regressive but only the top 3 m is preserved at South Pebbles. It contains amalgamated HCS sandstone with lam-scram profiles of the *Teichichnus-*
Rosselia/Asterosoma-Phycosiphon composite ichnofabric that were produced by a mixed Cruziana/Arenicolites ichnofacies in a lower shoreface environment. It is possible that the upper portion of cycle 1 contained shallower shoreface deposits that were later removed by transgressive erosion. The regressive cycle is terminated by a TSE.

5.2.3 Cycle 2

The TSE is capped by a 30 cm thick unit of pebbly conglomerate that represents a transgressive lag produced during nearshore reworking associated with a relative sea level rise (see Chapter 5.1). Fine-grained sediments were selectively winnowed and coarse-grained sediments concentrated (as noted in Bates & Jackson 1980, Arnott 1995). Above the transgressive lag, the cycle passes abruptly into bioturbated siltstone representing lower offshore deposits containing the Phycosiphon A ichnofabric (Fig. 3.13, Pl. 3.1a-c). Above this, interbedded mudstone and diamictite beds represent a transitional offshore to lower shoreface environment, thus documenting the upward shallowing of the cycle. These beds contain the Diplocraterion habichi - Thalassinoideas (Glossifungites) - Phycosiphon composite ichnofabric (Figs 3.39, 4.15).

The alternation of mudstone and diamictite in this deposit was probably produced by fluctuating energy levels related to climatic changes produced by fifth order Milankovitch cycles (every 10,000 to 200,000 years, Fig. 5.8). The bioturbated mudstone beds reflect very slow sedimentation rates during periods of perennial ice cover. The diamictite beds represent the deposition of dropout material during warmer periods when ice cover was seasonal. A Glossifungites ichnofacies was produced prior to deposition of each diamictite bed supporting the suggestion that there were periods of erosion in shallow water (Fig. 4.15, Pls 2.15b-c, 3.8b). Erosion may have occurred when the perennial ice cover was initially breaking up and wave action was able to remove the uppermost soft sediment portion of the sea floor.

The cold period at the top of this regressive cycle indicates that the relative fall in sea level was probably climatically influenced and associated with a glacial period. The top of the parasequence represents a lower shoreface deposit which is terminated by a TSE.

5.2.4 Cycle 3

A thin (5-10 cm) wave-rippled granule conglomerate caps the ravinement surface that marks the end of cycle 2 and is interpreted as a transgressive lag (Fig. 5.3). It is overlain by bioturbated
sandy siltstone with a distal Cruziana ichnofacies (represented by the *Phycosiphon* A composite ichnofabric). The gradual disappearance of *Rosselia socialis* and an increase in bioturbation intensity upwards suggest a possible deepening of the environment due to transgression. The top 150 cm of this section consists of siltstone that is intensely bioturbated by *Phycosiphon incertum*. It contains thin sandstone and pebbly sandstone lenses associated with vertical *Diplocraterion habichi* and *Diplocraterion parallelum* burrows that represent the opportunistic colonisation of winnowed sediments produced during sediment starvation associated with the period of maximum transgression. This unit was accumulated in a lower offshore environment and represents a transgressive deposit. The change from transgressive to regressive processes is represented by a minor RSE formed during a forced regression. The RSE is capped with a thin granule lag.

Above the thin granule conglomerate layer, the sequence passes abruptly up into clean medium-grained sandstone with a mixed proximal Cruziana/Arenicolites ichnofacies deposited in an offshore transition environment. An increase in grain size and a progressive reduction in siltstone interbeds upwards suggests that the sequence shallows up to a lower shoreface succession. These sandstone beds contain the *Teichichnus - Rosselia/Asterosoma - Phycosiphon* composite ichnofabric, which reflects reworking of storm deposited sandstone beds by the resident proximal Cruziana assemblage.

The shoreface deposits are overlain by a succession of lagoonal mudstone and intertidal channel deposits typical of wave-dominated estuarine systems. A mixed restricted Cruziana/Arenicolites ichnofacies was present throughout the back-barrier deposits reflecting the fluctuating environmental conditions (Fig. 4.6).

A TSE (or ravinement surface) terminates this parasequence.

### 5.2.5 Cycle 4

This cycle represents a typical parasequence, in that it is a relatively conformable regressive succession of genetically related beds or bedsets bounded by transgressive surfaces (cf. Van Wagoner *et al.* 1988, 1990). Above the ravinement surface that terminated cycle 3, a 30 cm thick pebbly sandstone, which was probably produced in relatively shallow water during shoreface retreat, represents a transgressive lag (Fig. 5.4). The rate of relative sea level rise was moderate to low resulting in erosion and reworking of the underlying sediments. Runnegar (1979) described this layer and suggested that it resulted from winnowing in a very shallow sublittoral environment.
The top of the transgressive lag is composed of a residue of mainly large *Eurydesma hobartense* shells and coarse-grained material. Other taxa present include shallow burrowing bivalves such as *Megadesmus, Pyramus, Schizodus* and *Stutchburia*, vagrant epifaunal forms such as *Aviculopecten* and *Peruvispira*, the bellerophont *Warthia*, the spiriferid brachiopod *Ingelarella* and a biplicate species of the terebratuloid *Gilledia* (Runnegar 1979). *Eurydesma* is interpreted as an opportunistic species that flourished on hard, current-swept, sublittoral substrates but could not survive in a sandy lower shoreface environment because it would have been buried (Runnegar 1979). The sediment-starved environment present during the deposition of the transgressive lag evidently satisfied the living requirements of the *Eurydesma* animal.

A *Glossifungites* ichnofacies is present at the TSE and consists of long thin, unlined *Diplocraterion habichi* burrows which pipe down into the back-barrier sediments of cycle 3 and are filled with coarser, cleaner sandstone (Fig. 5.4, Pl. 3.1g, 4.2e-f). The resultant ichnofabric is the *Phycosiphon - Diplocraterion* composite ichnofabric (Fig. 3.16). The presence of this ichnofacies reflects the firm nature of the eroded sedimentary surface and suggests a depositional hiatus between the erosional event and the deposition of the transgressive deposit.

Above the transgressive lag, the cycle consists of silty sandstone beds that contain a distal *Cruziana/Arenicolites* ichnofacies. Again a *Phycosiphon - Diplocraterion* composite ichnofabric is present but in this case it reflects fluctuating energy levels produced by distal storm currents in a lower offshore environment. Above this the cycle coarsens to an amalgamated unit of HCS sandstone containing a *Skolithos* ichnofacies, representing progradation and the deposition of middle shoreface facies. The succession then passes upward into approximately 10 m of interbedded siltstone, thin sandstone beds and flaser and lenticular-bedded sandstone units. The ichnotaxa and BI within this facies association are variable but there is repetitive alternation between a restricted *Cruziana* ichnofacies and an *Arenicolites* ichnofacies. The resultant ichnofabrics are also widely variable and are typical of the fluctuating energy and salinity levels within a wave-dominated back-barrier environment. *Glendonites* are present within this unit and reflect a cold climate. The occurrence of glendonites within the upper, regressive part of the parasequence indicates that sea level changes were glacio-eustatically controlled. This part of the parasequence also contains a number of deformed beds with well developed ball and pillow structures, flame structures and sand volcanoes. These structures strongly suggest that the region was tectonically active, contemporaneous with deposition, and are interpreted as the result of earthquake activity.

South of Clear Point the top of the parasequence consists of a 3 m thick unit of flaser- and lenticular-bedded tidal flat deposits. To the north (at South Island Beach), the parasequence
contains an extra 3 m of silty sandstone containing the *Polycylindrichnus* composite ichnofabric produced during intense reworking of lagoon and washover deposits in a back-barrier environment.

This parasequence is terminated throughout the study area by a ravinement surface, which marks the base of the Snapper Point Formation.

### 5.3 LOWER SNAPPER POINT FORMATION

#### 5.3.1 Introduction

The depositional cycles of the lower Snapper Point Formation are accessible along the coast from Clear Point in the south to Termeil Point in the north (Fig. 5.5). The basal contact of the formation can be seen at Clear Point and at South Island Beach. The lower Snapper Point Formation contains at least 9 depositional cycles.

Cyclicity differs to that in the Pebbley Beach Formation in that lower Snapper Point Formation parasequences contain thicker transgressive deposits. The thickness of the preserved transgressive deposits increases up through the sequence until it reaches a maximum of 15-20 m at South Snapper Point (Fig. 5.5). Above this cycle, identification of bounding surfaces and transgressive deposits becomes difficult as the sequence is strongly storm dominated and contains an abundance of coarse-grained storm deposited material that has very similar properties to those typical of transgressive lags.

#### 5.3.2 Cycle 5

South of Clear Point 2-3 m of interbedded conglomerate and pebbly sandstone overlies the ravinement surface that terminates the Pebbley Beach Formation. This unit contains pavements of large *Eurydesma hobartense*, *Aviculopecten* and *Warthia*, and the spiriferid brachiopod *Ingelarella*, along with abundant preserved wood and leaf material. The lower third of the unit consists of flat-bedded conglomerate with imbricated, well-rounded clasts. The top of the unit contains a pavement of large, disarticulated *Eurydesma hobartense* shells in hydrodynamically stable orientation. The sandier fraction of the unit contains a distal Skolithos ichnofacies. This unit is interpreted as the preserved lower part of a transgressive barrier complex. Preservation of this barrier suggests that the estuarine lagoon system was over-topped by the rising relative sea level. This process is known as in-place drowning and occurs when a transgressive
barrier/lagoon system initially aggrades upward in response to rising relative sea level but is subsequently overcome (Sanders & Kumar 1975). As a result, the shoreline steps abruptly landwards, stranding the lagoon/barrier complex on the shelf. The degree of reworking determines how much of the transgressive barrier complex will be preserved (Arnott 1995).

To the north (at South Island Beach), an equivalent barrier sequence is not preserved. Instead, a 20 cm thick pebbly sandstone bed (Pl. 5.1) overlies the ravinement surface and represents the basal unit of a thin transgressive deposit. Unlike the south, where the transgressive surface erodes into a thick flaser bedded sandstone unit, the erosion surface at South Island Beach occurs at the top of a 3 m thick unit of silty sandstone interpreted as lagoon and washover deposits. This erosion surface is identified as a parasequence boundary for two main reasons:

1. there is an abrupt change in ichnofacies and ichnofabrics across the pebbly sandstone layer suggesting the replacement of back-barrier deposition by an offshore environment of deposition; and
2. it contains a Glossifungites ichnofacies.

Below the transgressive surface (the top portion of cycle 4) the facies contains the Polycylindrichnus composite ichnofabric which resulted from repeated bioturbation by a restricted Cruziana ichnofacies in a silty lagoon environment experiencing frequent storm surge washover of sand from the adjacent marine environment (Fig. 3.20, plates 3.3c, e). Above the TSE (cycle 5) the facies consists of the Teichichnus composite ichnofabric which was the product of intensive reworking of fairweather and storm deposits by a Cruziana ichnofacies in an upper offshore environment (Fig. 3.23, Plates 3.4d-g). Similar abrupt changes in ichnofabric at bounding flooding surfaces have also been recognized in prograding, siliciclastic, nearshore to offshore parasequences within Late Cretaceous sequences in Utah (Frey & Howard 1990, Pemberton et al. 1992d).

Large Arenicolites statheri (Plate 2.1a) and Skolithos burrows that extend down into the underlying silty sandstone unit represent a Glossifungites ichnofacies. The burrows are unlined, sharply walled, uncompacted and passively filled with coarse-grained sandstone (that contrasts sharply with the silty back-barrier sediments) from the overlying transgressive sand (Fig. 2.1b, Pl. 2.1a). This ichnofacies reflects the firm nature of the substrate at the time of colonization, which resulted from erosion and exhumation of dewatered back-barrier sediments during the transgression. The presence of a Glossifungites ichnofacies on the ravinement surface (Pl. 2.1a, 4.11d) is indicative of a hiatus between the eroding event and emplacement of
the transgressive sediments, with the trace-makers colonizing the semiconsolidated surface during the latter stages of ravinement when the firm substrate was resistant to further erosion.

About 1 m above the ravinement surface at South Island Beach, there is an interval of intensely bioturbated (BI 6:4), poorly sorted, silty, fine-grained sandstone with common pebbles and abundant plant material and logs (Pl. 5.1). This interval contains a *Teichichnus* composite ichnofabric dominated by spectacular long *Teichichnus sinuosus* (Pl. 2.14h-i, 3.4d-g, 4.11d) and is interpreted as a possible condensed section representing maximum flooding. The plant material and logs present within this interval are a common feature of prominent flooding surfaces associated with condensed intervals, probably resulting from transgressive inundation of forested coastal plains during rapid sea-level rise (Savrda 1995). Drifted, waterlogged wood material could be concentrated on a marine shelf during periods of sediment starvation (Savrda *et al.* 1993). The pebbles may have been transported to the marine environment by seasonal river ice and then also concentrated via winnowing and sediment starvation. This condensed interval was not recognised at Clear Point.

Above this, the sequence shows signs of progradation. The intensity of bioturbation decreases, the presence of coarse-grained storm-deposited lenses increases, and the ichnofacies gradually changes from a Cruziana ichnofacies to a mixed Cruziana/Arenicolites ichnofacies that mainly occurs in composite ichnofabrics and lam-scram profiles. The lack of RSE suggests that normal regressive processes were operating and the sea level change is attributed to a prograding shoreface facies. Above this the cycle is only preserved at South Island Beach and O’Hara Island. Dropstones and thin diamicite beds are present and become more abundant upwards. These reflect cold conditions, possibly a glacial phase of deposition, and suggest that the sea level fall was controlled by glacio-eustatic processes. It is interpreted that the parasequence shallows upward to a lower shoreface environment where it is terminated by a ravinement surface.

### 5.3.3 Cycle 6

Immediately overlying the TSE is a 20 cm diamicite bed containing dropstones up to 80 cm in diameter and phosphate cement. Ichnofossils are rare but skeletal remains, wood material and large logs are abundant. Body fossils include mostly fragmented *Notoconularia levigata*, bryozoans such as fenestellids and *Stenopora, Bathysiphon?* and other smaller foraminifers, brachiopods, gastropods, bivalves and ?algae.
Above this bed the cycle consists of about 1 m of interbedded diamictite and rare sandstone beds. Large, complete *Notoconularia levigata* (Dana) are common in the lowest sandstone bed. The unit shows an overall fining-up nature and is capped by a thin muddy diamictite that is pervasively bioturbated (BI=6) by *Phycosiphon incertum* (Pl. 3.1d).

Above this, the section is exposed at Pretty Beach in addition to South Island Beach and O’Hara Island. About 5 m of interbedded amalgamated sandstone beds and coarse-grained sandstone layers containing large dropstones (up to 1 m) and small phosphate nodules overlies the bioturbated muddy diamictite. Phosphatic oolites, disarticulated and articulated shells such as *Megadesmus*, *Aviculopecten*, *Warthia*, spiriferid brachiopods and the bryozoan *Stenopora* are all common, and are associated with an early calcite cement (cf Bann 1990) and large (up to 50 cm) irregular concretions. Cement and concretions of this nature probably formed during periods of sediment starvation and winnowing associated with the transgression. Concretions formed when calcium carbonate was able to accrete, typically nucleating around organic material or calcium carbonate shells (Brett 1995). The presence of *Eurydesma*, which flourished on a variety of hard, current-swept, sublittoral substrates and could not cope with rapid sedimentation (Runnegar 1979), also reflects the low sedimentation rate. The trace fossil assemblage here is diverse and the amount of bioturbation is high (average BI ranges from 4-6). Ichnofabrics are composite and reflect colonization of storm-deposited sandstone by opportunists (reflecting the Arenicolites ichnofacies) and the subsequent replacement by a diverse, resident Cruziana ichnofacies.

Wood material from this transgressive facies is spectacular in thin section due to its uncompacted nature and infilling of the cellular structure by collophane. Marine transgression into the adjacent coastal plain followed by concentration via sediment starvation probably resulted in this accumulation of logs on the shelf (cf. Savrda *et al.* 1993, Savrda 1995).

Phosphatic material was probably introduced to the environment by upwelling of cold waters highly concentrated in nutrient salts and phosphates (Giresse 1980). The low sedimentation rate required for oxidation and phosphatogenesis (Giresse 1980) would have been provided by sediment starvation associated with the transgressive event. Eganov (1978) described similar ancient examples of phosphorite formed during transgressive processes. Phosphatic material is common in condensed zones and reflects very slow sedimentation (Walker 1992).

This lower part of the sequence is interpreted as a condensed section deposited in a transgressive, seasonal ice-affected offshore transitional marine environment.
The transition from transgressive to regressive sedimentation is difficult to pinpoint exactly but is assumed to be within the overlying 5 m thick unit of intensely bioturbated silty sandstone. The thick silty nature and the intensity of bioturbation by a diverse proximal Cruziana ichnofacies suggest that this unit represents deposition in an upper offshore environment.

Above this the succession is abruptly overlain by a thick unit of low angle cross-bedded sandstone which grades upward to at least 15 m of clean, amalgamated SCS sandstone with rare HCS. Siltstone interbeds are absent and a Skolithos ichnofacies is preserved. These features indicate intense storm activity and deposition at or just above fairweather wave base. This part of the sequence is exposed at Pretty Beach and south Snapper Point whereas at South Termeil Point in the northern part of the study area the unit reaches over 25 m in thickness. This unit represents the culmination of the progradational event from a lower shoreface to a storm-dominated middle shoreface environment. The thickness of the middle shoreface succession at the top of this regressive sequence reflects deposition during relative sea level stillstand whereby the rate of sediment supply was balanced by the rate of creation of accommodation space. The parasequence is terminated by a TSE which marks the change to an accommodation-dominated regime and a cratonward facies shift (Fig. 5.5).

5.3.4 Cycle 7

A wave-rippled conglomerate caps the ravinement surface that terminates cycle 6. The conglomerate bed has an erosive base, clasts up to 30 cm in diameter and no obvious associated trace fossils. It reflects initial winnowing and transgressive erosion associated with the subsequent relative sea level rise which resulted in the deposition of a thick transgressive succession. The conglomerate is overlain by about 17 m of interbedded siltstone, granule conglomerate and HCS sandstone beds. Bivalve shells occur in skeletal lags at the base of the storm beds or as scattered individuals throughout the interbedded mudstone beds; this is a typical taphonomic characteristic of nearshore sediments deposited during mid to late highstand (Brett 1995). The thickness of individual storm beds decreases up through the section and the abundance of siltstone increases. The succession is spectacular in outcrop at south Snapper Point and North Termeil Point and is characteristic of a very strongly storm-dominated transitional offshore environment (Pl. 4.8c-e). The ichnofacies are typical of this kind of depositional environment, with Arenicolites ichnofacies in the storm-deposited sandstone beds and Cruziana ichnofacies replacing the Arenicolites ichnofacies at the top of the storm beds and
continuing into the interbedded siltstone beds. Logs are common throughout this part of the cycle.

The cycle fines up to about 3 m of thinly interbedded siltstone and sandstone that represent the most distal portions of storm beds in a very strongly storm-dominated, lower offshore environment (Pl. 4.12e). This part of the cycle is only exposed at south Snapper Point. Dark organic-rich muds represent waning flow deposits of the sandy storm beds (as opposed to a return to fairweather deposition), and are indicative of low concentration turbidity flows incapable of suspending sand; further evidence of the distal character of the facies. Trace fossils are rare to absent (due to the repeated rapid deposition of storm beds rather than to restricted infaunal habitation) and represent a distal Cruziana ichnofacies.

This whole thick succession of rapidly deposited storm sandstone beds is uncharacteristic of transgressive deposits described elsewhere. Van Wagoner et al. (1990) suggested that transgressive deposits are rare within parasequences and, when present, are only thinly developed (up to tens of centimetres thick). Development of a thin (condensed) transgressive deposit occurs when the shelf area expands (due to rising relative sea level) and the volume of new sediment being supplied per unit area decreases (Arnott 1995). A number of authors have suggested that parasequence architecture and stacking patterns are controlled by the ratio of sediment supply to sediment accommodation space (e.g. Curray 1964, Galloway & Hobday 1983, Posamentier et al. 1988, Swift et al. 1991, Thorne and Swift 1991). The most probable conditions responsible for the formation of a thick transgressive half-sequence (such as this one in the lower Snapper Point Formation) are a rapid creation rate of accommodation space balanced by a high rate of sediment supply.

A pebbly surface which may represent the MFS, marks the end of the lower offshore deposit. The pebbles may have been transported to the marine environment as dropstones and concentrated during winnowing and sediment starvation associated with maximum transgression. The pebble layer is overlain by about 9 m of interbedded intensely bioturbated silty sandstone with scattered pebbles, HCS sandstone and pebble conglomerate (Pl. 4.11c). The silty sandstone beds contain the Asterosoma-Teichichnus-Diplocraterion parallelum composite ichnofabric (Fig. 3.24, Plates 3.5 a-b) which represents the reworking of an Arenicollites ichnofacies by a Cruziana ichnofacies during periods of fairweather in a strongly storm-dominated upper offshore environment.

Above this a sudden shallowing of the environment is marked by a 20 cm thick conglomerate with a sharp, erosive base. This erosive surface is most likely a RSE formed during a drop in sea level produced during a minor forced regression. This erosive surface is
exposed on south Snapper Point but above this the sequence is only accessible on north Snapper Point.

The RSE is overlain by approximately 3m of thinly interbedded bioturbated sandstone, wave-rippled granule conglomerate and conglomerate. The unit contains a distal Skolithos ichnofacies composed mainly of large *Diplocraterion parallelum*, *Macaronichnus segregatis* and large *Rhizocorallium jenense* (type C) and is interpreted as a middle shoreface deposit. A TSE terminates this parasequence.

5.3.5 Cycle 8

A thin wave-rippled conglomerate lies above the ravinement surface that terminates cycle 7. The bed contains large clasts and a possible (poorly exposed) Glossifungites ichnofacies consisting of unlined, sharp-walled, sand-filled vertical burrows protruding into the underlying silty sandstone. This ichnofacies indicates erosion of soft sediment during the initial stages of transgression and subsequent habitation of the exposed firm substrate by an opportunistic community of suspension-feeding organisms.

The conglomerate is overlain by interbedded intensely bioturbated, reddish-brown siltstone, HCS and low-angle, cross-bedded, fine- to medium-grained sandstone, and wave-rippled very coarse-grained sandstone beds. An increase in the thickness of siltstone beds upward is accompanied by the gradual replacement of wave-rippled beds by HCS sandstone beds that decrease in thickness upwards. This part of the cycle is just over 3 m thick and represents an upward-deepening succession (from offshore transition to lower offshore) produced during transgression. The reddish-brown siltstone beds contain composite ichnofabrics with bioturbation indices ranging from 5-6:4, reflecting intense reworking by a diverse Cruziana ichnofacies during slow deposition in an oxidizing environment. The beds contain abundant wood material and logs (some of which have been coalified) suggesting transgressive inundation of forested coastal plains and concentration by sediment starvation (Savrda *et al*. 1993, Savrda 1995). Dropstones are also common in this part of the cycle.

Just over three metres above the TSE is an intensely bioturbated, upward fining siltstone unit. This unit contains coalified logs and a dropstone pebble layer that is believed to represent the maximum flooding surface. A high intensity-low diversity, distal Cruziana ichnofacies and the yellowish-green (pyritized) tinge of the black mudstone suggest a reducing environment probably produced during extreme sediment starvation in a lower offshore setting during the highstand of this cycle. The intense nature of the bioturbation indicates repeated reworking
during very slow sedimentation and the low diversity of the ichnofacies reflects the opportunistic nature of the community.

Above this bed the succession coarsens upwards. Siltstone interbeds are replaced by amalgamated HCS sandstone beds and wave-rippled granule and pebble conglomerates increase in abundance and thickness upwards. The intensity of bioturbation is substantially less than in the underlying condensed transgressive section, with average BI ranging from 2-4. Ichnofabrics range from simple to composite and the diversity of the trace fossil assemblage decreases upwards as the environment shallows and energy levels increase. The lower part of this coarse-grained unit is dominated by a proximal Cruziana ichnofacies. The subsequent change in the upper part of the unit to a distal Skolithos ichnofacies reflects the shallowing of the environment from lower to middle shoreface. The TSE that terminates this cycle is tentatively placed beneath a 30 cm thick wave-rippled conglomerate.

5.3.6 Cycle 9

The conglomerate bed that overlies the suspected ravinement surface consists of an amalgamation of three or more wave-rippled pebbly gravel layers. This unit was formed by winnowing during sediment starvation produced by flooding of the shelf and represents a transgressive lag. The overlying intensely bioturbated, poorly sorted silty sandstone represents the maximum flooding interval. This bed contains an Asterosoma - Teichichnus - Diplocraterion parallellum composite ichnofabric, which represents reworking by a mixed Cruziana/Arenicolites ichnofacies in a transitional offshore environment. The succession then coarsens upward and consists of interbedded HCS sandstone, wave-rippled conglomerate, bioturbated sandstone beds and shell-rich lenses. There is an increase in shell material upward with some species (such as the deep burrowing Vacunella) preserved in life position. The general decrease and then complete absence of siltstone, and the decrease in BI, upward suggests that the cycle shallows slightly and the top portion probably represents a lower shoreface environment. The parasequence is terminated by a TSE.

5.3.7 Cycle 10

This cycle is one of the most difficult to interpret, due to its thinly interbedded nature and an abundance of storm beds and thin coquinite layers. No two shelly beds are exactly alike, suggesting a complex history of deposition. A 20 cm thick sandy coquinite bed overlies the
This bed is dark purple in outcrop and contains a coarsely crystalline pyrite and phosphate cement. The bed is dominated by small (< 5 mm) articulated bivalves and larger (up to 15 cm), disarticulated or articulated *Astartilla?* and *Vacunella?* shells. Foraminifers are seen in thin section. Gravel, including quartz pebbles and very angular dropstones up to 20 cm in diameter, occurs in abundance. The trace fossil assemblage has a low diversity but the BI is high (5). The most common form is very large (up to 15 cm diameter), bulbous, concentrically lined *Rosselia socialis*; *Teichichnus* is an uncommon associate here. The top of the coquinite bed exhibits small-scale, wave-generated, parallel crested ripples.

For about 4 m above this bed, the cycle consists of interbedded HCS sandstone, bioturbated coquinitic sandstone and coquinitic granule and pebble conglomerate beds that contain large-scale wave ripples. Logs are abundant and are commonly preserved in pebble lenses that also contain abundant shell hash. Most of the HCS sandstone beds have been moderately to intensely reworked and contain abundant shells representing both life and death assemblages. An increase in trace fossil diversity and bioturbation intensity upward accompanies an increase in siltstone and in the diversity of the preserved skeletal components. This supports the suggestion of a deepening-upward succession. The coquinitic portion of cycle 10 is interpreted as a transgressive deposit. Coquinitic beds such as these commonly occur during the initial phases of transgressive flooding (cf. Brett 1996). Shell beds that overlie ravinement surfaces have been referred to as base of parasequence shell beds (or BOP beds) by Banerjee & Kidwell (1991) and typically form time averaged deposits (Brett 1996) or condensed sections. The *Vacunella* life beds (or smothered bottom deposits; Brett 1996) are most common in late transgressive to early highstand deposits (Brett & Seilacher 1991).

Above this, the parasequence coarsens upwards and siltstone interbeds disappear. The succession consists of 2-3 m of reworked storm beds and pebbly gravel beds with abundant thin lenses of disarticulated and fragmented shell material. Bioturbation intensity decreases and the background trace fossil assemblage changes from a diverse Cruziana ichnofacies to a low diversity distal Skolithos ichnofacies. The upper portions of shallowing-upward parasequences commonly contain skeletal accumulations consisting of physically reworked, typically disarticulated and fragmented skeletal material (Brett 1996). These beds have been referred to as TOP, or top of parasequence, beds (Brett 1996). In cycle 10 these beds are interpreted as the product of winnowing or sediment bypass of fine-grained material in a shallow (probably middle shoreface), high-energy environment. The TSE that terminates this cycle is one of the most prominent in the middle Snapper Point Formation and is exposed on north Snapper Point.
5.3.8 Cycle 11

A 20-30 cm thick conglomerate bed with disarticulated and fragmentary skeletal material and no bioturbation caps the ravinement surface. The top of the bed contains large-scale wave-ripples that have a wavelength exceeding 1 m.

Above this conglomerate the succession displays an overall fining-upward trend for just over 1 m. Intensely bioturbated siltstone and silty sandstone beds with scattered pebbles and relict coarse-grained layers are interbedded with granule conglomerate beds. Some of the tops of the coarse-grained beds are biogenically reworked and mixed with the overlying siltstone beds while others contain large-scale wave-ripples. The degree of bioturbation increases upward through the interbedded unit from BI 5 to BI 6. The siltstone and silty sandstone beds contain a Cruziana ichnofacies with individual trace types being very difficult to determine due to the intensity of reworking. Each bed is overprinted by a suspected Glossifungites ichnofacies which protrudes down from the overlying, coarse-grained layer. The individual Glossifungites ichnofacies consist of vertical dwelling structures such as Diplocraterion, Skolithos and small Arenicolites (Plate 3.7f). The resultant mottled burrow-Glossifungites composite ichnofabric is complex and represents at least two phases of bioturbation (see Fig. 3.32):

1. repeated reworking of the fine-grained beds during periods of very slow deposition, followed by
2. habitation of the firm sedimentary surface during periods of sediment starvation and/or soft substrate erosion.

Finally the open vertical dwelling structures were filled with coarse-grained sediment during the deposition of the overlying conglomerate beds. The presence of these firm-ground (Glossifungites ichnofacies) assemblages beneath the conglomerate veneers demonstrates the existence of several depositional hiatuses between the colonization of the firm silty substrates and emplacement of the coarse-grained material (MacEachern et al. 1992a). The Glossifungites assemblages record suspension-feeding behaviour reflecting periods of higher energy possibly associated with active ravinement (MacEachern et al 1992b). These interbedded cyclical units may represent small scale sea-level changes produced by fifth order Milankovitch cyclicity.

Overall maximum flooding is represented by a completely reworked, 30 cm thick, dark reddish-grey siltstone bed about 1 m above the main basal TSE. This bed has been repeatedly overprinted and the only discernible traces are Phycosiphon incertum and very rare small Rosselia.
Above this, the cycle exhibits upward coarsening. Bed thickness increases and the overall BI decreases to 3-5 reflecting an increase in the rate of sedimentation. Siltstone interbeds are rare and the presence of relict HCS and low-angle cross-bedding increases upward reflecting a shallowing of the environment. Thin, granule and pebbly conglomerate beds associated with an Arenicolites ichnofacies suggest alternating depositional energy levels, and represent deposition in an overall shallowing upward cycle. The parasequence is terminated by a TSE.

5.3.9 Cycle 12

A 20 cm thick pebbly granule conglomerate with abundant disarticulated and fragmentary skeletal material directly overlies the ravinement surface that terminates cycle 12. The bed has a BI of 3 and consists of a low diversity Skolithos ichnofacies containing Calycraterion, Palaeophycus tubularis, Macaronichnus segregatus and small Arenicolites. This coarse-grained bed was deposited in a relatively high energy, sediment-starved environment. It is exposed towards the top of north Snapper Point. The conglomerate was probably deposited during the early stages of sea-level rise when the accommodation area of the shelf greatly exceeded sediment input and the resultant deposit consists of material cannibalized from previously deposited shoreface sediments completely removed by erosion during transgression (Arnott 1995).

Above this, the succession changes abruptly and consists of 20 cm of moderately bioturbated reddish-black mudstone with common plant material and small articulated bivalves and fenestelid bryozoans. The trace fossil assemblage consists of small Rhizocorallium irregulare, Phycosiphon incertum, Palaeophycus herberti and Taenidium?, representing a distal Cruziana ichnofacies. The bed represents an offshore environment and marks maximum flooding of the parasequence. The basal conglomerate and the mudstone represent a thin, condensed, transgressive section deposited during progressive flooding of the shelf.

Above the condensed section, the succession coarsens considerably upward and the overall intensity of bioturbation decreases. The succession consists of interbedded clean pebbly sandstone, thin granule conglomerate beds with common large-scale wave ripples and scattered pebble lenses. A Skolithos ichnofacies is present with the assemblage diversity decreasing upward. The trace fossils are preserved as thickly lined hazy vertical structures that suggest a very loose substrate with a high pore water content reflecting rapid deposition. Some very large ball and pillow structures are preserved in this cycle and are very evident in the cliff face above.
the rock platform in the middle of north Snapper Point. These structures suggest that tectonic movement (earthquakes) may have occurred contemporaneously with deposition. The succession represents a rapidly emplaced regressive cycle deposited in a prograding lower to middle shoreface environment.

5.3.10 Cycle 13

The marine TSE that terminates cycle 12 is difficult to pinpoint but it is considered to underlie a 20 cm wave-rippled granule conglomerate that passes upwards into a 50 cm intensely bioturbated (BI=6), pebbly, fine-grained sandstone at the top of north Snapper Point. This bed contains articulated molluscs in life position and was probably deposited in a lower shoreface environment during maximum flooding. An upward coarsening of the succession accompanies a decrease in bioturbation and a shift from low-angle and HCS sandstone to wave-rippled and low angle cross-bedded sandstone, and granule conglomerate. The parasequence is interpreted as a rapidly emplaced, prograding shoreface deposit. The thin transgressive deposit that separates cycles 12 and 13, may represent an interval of subsidence, and associated rise in relative sea level, between the two prograding deposits. The top of this cycle is not exposed.

5.4 UPPER SNAPPER POINT FORMATION

5.4.1 Introduction

The upper part of the Snapper Point Formation is exposed at the coast at Bannisters Point, Narrawallee and Crampton Island, and to the north at Jervis Bay (Fig. 5.6). There is approximately 140 m of section missing from coastal outcrop between the top of the lower Snapper Point Formation (seen at Snapper and Nuggans Point) and the bottom of the upper Snapper Point Formation (exposed at Bannisters Head). This unexposed section of the formation is visible in a number of the Elcom Clyde River (ECR) drill cores including ECR 2, ECR 4, ECR 8, ECR 10 and ECR 11. (Fig. 5.7) and has been correlated to coastal sections by Tye (1995).

The contact between the Snapper Point Formation and the overlying Wandrawandian Siltstone is also absent from coastal exposures. This boundary is present in cores ECR 2, ECR 4, ECR 10 and ECR 11 (Fig. 5.7). From correlation of coastal sections with drill core data it
appears that as little as 10 - 20 m of section is missing from the top of the Snapper Point Formation in coastal exposures. The contact occurs where major foreshore facies of the upper Snapper Point Formation rapidly fine upwards and are abruptly overlain by fine-grained, intensely bioturbated, fossiliferous sandy siltstone representing the Wandrawandian Siltstone.

There is a distinct facies change between the coastal exposures of the upper Snapper Point Formation sections and those exposed in the southern, lower part of the formation. In the lower portion of the formation, sedimentation is dominated by wave-generated structures such as HCS and large-scale wave-ripples. In the upper part of the formation tidal or longshore current deposits dominate the sequence. Tye (1996) attributed this to a change from an open shelf setting to a tide-dominated constricted seaway, similar to the North Sea and English Channel (Johnson et al. 1982). It is possible that the constriction was caused by the emergence, or near emergence above sea level of the developing orogen to the east (Tye 1996). Cycles in the upper Snapper Point Formation are therefore described and interpreted as a separate set of parasequences from those in the lower part of the formation.

5.4.2 Cycle 1

The lowest exposed portion of the upper Snapper Point Formation outcrops at Bannisters Point and Narrawallee Inlet and contains over 50 m of interbedded conglomerate, clean sandstone and bioturbated medium- to very coarse-grained sandstone beds. Ichnofabrics are either simple or composite and occasionally lam-scram profiles are preserved. The BI is generally low (0-3, rarely 4 or 5) and primary sedimentary structures dominate biogenic structures. Ichnofacies are repetitive and are dominated by traces such as Macaronichnus segregatus, Skolithos, Arenicolites and Diplocraterion parallelum. These structures are typical of the Skolithos ichnofacies. In the shallower portions of the cycle traces are much less abundant and large, vertical forms such as Cylindrichnus eccentricus and Monocraterion tentaculatum are present. Ichnofacies are more diverse in the finer grained parts of the unit where traces such as Asterosoma, Rosselia socialis and Teichichnus rectus are common. These robust, vertical burrows formed by detritus- and deposit-feeding organisms reflect the lowest energy phase of the cycle and represent the resilient fairweather assemblage of a distal Skolithos ichnofacies. The nature of the ichnofabric and ichnofacies in this coarse-grained unit suggest deposition above fairweather wave base in an environment ranging in depth from middle shoreface up to foreshore in the top 5 m of the cycle. Low sediment supply has produced a sequence dominated
by event beds. The succession probably represents a prograding shoreface deposit emplaced during a period of relative sea level stillstand. The cycle is terminated by a TSE.

5.4.3 Cycle 2

The ravinement surface, which is exposed at Bannisters Point and Crampton Island, is overlain by a 5-10 cm thick, wave-rippled, pebble conglomerate which probably represents a transgressive lag. Above this the cycle consists of interbedded medium-grained sandstone and thin diamictite beds. The succession displays a coarsening upward appearance and an upward shift from a proximal Cruziana ichnofacies to a distal Skolithos ichnofacies suggesting a shallowing from a lower shoreface to a middle or upper shoreface environment. A TSE terminates the cycle.

5.4.4 Cycle 3

Overlying the TSE, 1 m of amalgamated flat-bedded conglomerate with large megaclasts represents the basal unit of a transgressive deposit. The thick, coarse-grained nature of the unit probably resulted from sediment starvation accompanied by a high input of ice-rafted material during warming of the environment and the associated relative sea level rise. This suggests a glacio-eustatically driven sea level rise.

The very coarse-grained unit is overlain by 1 m of intensely bioturbated silty sandstone that represents reworked storm and fairweather sediment deposited in a transitional offshore environment. The unit displays an increase in bioturbation and a decrease in grain size upwards reflecting progressive deepening of the environment and a possible reduction in sedimentation rates. Dropstones and diamictite layers are sparse.

Above this, the sequence is exposed at Jervis Bay in addition to Bannisters Point and Crampton Island. A 4-6 m thick unit of interbedded mudstone, siltstone and sparse sandstone beds (Pl. 4.12a-d) conformably overlies the intensely bioturbated silty sandstone. The thickness of this unit varies across the basin with a maximum thickness of 6 m at Bannisters Point. This thick, muddy unit was deposited at or just below storm wavebase during transgression. Pervasive bioturbation has not completely destroyed the parallel nature of the primary bedding. The sandstone layers contain abundant megaclasts (up to 60 cm in diameter) which decrease in abundance up through the unit. Articulated spiriferid brachiopods (Sulciplicata?) preserved in sideritic concretions, and wood material (logs) are common throughout the unit reflecting
reduced sedimentation rates and winnowing. Alignment of the dropstones parallel to bedding suggests that the large elongate clasts came to rest on a firm substrate, which also reflects possible erosion and sediment starvation. Less common layers display vertical orientation of the elongate clasts and blurred trace fossils suggesting high pore water content and more rapid sedimentation. Substrate compaction may have differed periodically due to alternating rates of sediment input related to event deposition, probably by storms.

In the southern part of the upper Snapper Point Formation (at Bannisters Point and Crampton Island), the fine-grained interbedded unit is abruptly overlain by a thick succession of well-sorted, sub-parallel to low angle and planar cross-stratified, medium- to very coarse-grained sandstone beds. These units are typical of longitudinal sand bodies, consistently reworked by longshore tidal currents. The base of this succession is erosional and contains a 10-20 cm layer of poorly sorted, very-rounded pebbles, which have a maximum diameter of 15 cm. This erosional unconformity marks an abrupt shift from a lower offshore environment to a shallow, tide-dominated foreshore environment, registering a rapid fall in relative sea level and a change from wave-dominated to tide-dominated depositional processes. The erosion surface is interpreted as an RSE formed in a proximal environment during a forced regression (Fig. 5.2).

At Jervis Bay, in the northern part of the formation, the contact between the fine-grained interbedded unit and the overlying cross-bedded sandstone bed is gradational. This reflects the more basinward position of the Jervis Bay deposits as compared to those in the southern part of the study area. The presence of RSE in proximal areas and their absence from more distal locations is characteristic of these surfaces (Posamentier et al. 1992).

Above this, the formation is unexposed at the coast. Correlation with drillcore indicates that there is an additional 10 - 20 m of very shallow marine Snapper Point Formation deposits. These are abruptly overlain by shelfal siltstone and mudstone of the Wandrawandian Siltstone which reflects middle to outer shelf deposits laid down during major flooding of the shelf.

5.5 DEPOSITIONAL HISTORY

5.5.1 Palaeogeography and Depositional Systems

The Pebbley Beach Formation and laterally equivalent inland facies (the Yarrunga Coal Measures) were deposited on a gently subsiding, sediment starved, glacially influenced coastal plain and shallow marine shelf at polar latitudes (Fig. 5.9b). These fine-grained silt-dominated
and carbonaceous facies fringed the high energy braidplain systems of the Tallong and Yadboro Conglomerates which were derived from the western cratonic margin of the basin (Tye 1995).

The Snapper Point Formation represents a major marine transgression which drowned all the previous terrestrial environments in the southern Sydney Basin (Fig. 5.9c). Sea level fluctuations are represented in the southwestern part of the basin by distinct facies changes and in the eastern part of the study area by parasequences. In the southwest, the Snapper Point Formation is characterized by alternating nearshore marine and braidplain delta deposits (Tye 1995). The surfaces that separate the braidplain delta and nearshore marine facies probably represent flooding surfaces that correlate with flooding surfaces in the eastern parasequences. Parasequences increase in thickness in the eastern part of the basin. Isopachs indicate a substantial increase in formation thickness (from 50-100 m in the west to more than 300 m near the present coast) along a linear zone which runs approximately parallel to the coastline in the south and passes inland to the west of Nowra (Tye 1995). This zone was interpreted by Tye (1995) as a major basin hinge zone that corresponded to a basement high and had a marked effect on facies distributions and fourth order Milankovitch cycle thickness. During transgression the shoreline retreated and nearshore and shoreface sediments were deposited west of the hinge zone. During regressive phases of deposition, the position of maximum progradation of the shoreline in the southwestern area was probably marked by the hinge zone. Seaward of the hinge zone high preservation potential is suggested by parasequences that have both transgressive and regressive half sequences preserved (Swift et al. 1991). The deeper marine areas to the east of the hinge, which acted as a depocentre for sediment (derived from fluvial networks located to the west), resulted in a dramatic increase in formation and component cycle thickness across the hinge zone (Tye 1995). The orientation of the palaeoshoreline was approximated by Tye (1995) as trending 025°, based on the orientation of wave ripple crests (Forbes & Boyd 1987, Leckie 1988).

It is probable that the developing orogen lay to the east of the present coast line and that its emergence or near emergence above sea level resulted in the change from an open shelf setting, present throughout the lower and middle portion of the Snapper Point Formation, to a tide-dominated constricted seaway in the upper part of the formation (Tye 1996). A tuffaceous layer within the overlying Wandrawandian Siltstone (Runnegar 1980), also suggests the emergence of the orogen at this time.

Deposition of the Pebbley Beach and Snapper Point Formation was generally aggradational which resulted from a rate of sediment supply that was approximately balanced by the rate of increase in accommodation space. In the east the formations form an aggradational
parasequence set (cf. Van Wagoner et al. 1988, Mitchum & Van Wagoner 1991). A major flooding event which resulted in a cratonward facies shift and the deposition of the fine-grained offshore facies of the Wandrawandian Siltstone consummated deposition of the Snapper Point Formation (Fig. 5.9d).

5.5.2 Cyclicity and Milankovitch Orbital Forcing

There is good evidence that much of the cyclic variation here recognized within the Pebbley Beach and Snapper Point Formations was produced by climatic rhythms induced by quasi-periodic changes in the earth's orbital parameters, i.e., Milankovitch cycles (e.g., Fischer 1986; de Boer & Smith 1994). A lack of definite age control makes determination of the periodicity of the cycles difficult (Tye 1995). Anderson (1982) estimated the periodicity of climatic variations of Permian sequences within the Delaware Basin at 100 ka years. Algeo and Wilkinson (1988) estimated that cycles of 1-20 m thickness generally have a period of 21 ka to 413 ka which falls within Milankovitch (1941) periodicity. Other Permian sequences interpreted as resulting from orbital forcing mechanisms have been identified by Frakes (1979), Anderson (1982), Borer & Harris (1991), Miller & West (1993) and Yang & Baumfalk (1994).

Three orders of cyclicity are recognised in the study area. Fourth and fifth order cyclicity are eustatic effects (commonly glacio-eustatic) which overprint the third order glacio-eustatic / tectonic cyclicity of the lower Sydney Basin sequence (see section 5.4.3). The complete lack of definite time constraints renders it virtually impossible to differentiate between fourth and fifth order cycles within the succession. Consequently, Milankovitch cycle order is recognised here on the basis of relative cycle thickness and also on the regional extent of the sequence and its bounding surfaces.

Recognition of fifth order cyclicity (200 000 - 10 000 year cycles) is hindered by the abundance of storm event beds in the study area. Consequently these high frequency cycles have only been definitely identified within the Pebbley Beach Formation where they are manifested in the form of alteration between mudstone beds with a distal Cruziana ichnofacies and diamictite beds with an associated Glossifungites ichnofacies. This cyclicity is interpreted as reflecting alterations between periods of perennial ice cover and seasonal ice cover. Tye (1995) suggested that the climate changes associated with these facies occurred contemporaneously with small scale sea-level changes. During glacial periods when the shelf was covered by perennial ice, all but the most resilient organisms were absent from the substrate and wave action at the sea floor was ineffectual. Fine-grained, low energy, deposition from...
suspension was the only active depositional mechanism. During periods when seasonal fluctuations in the ice cover were prevalent, the reintroduction of wave action to the environment resulted in the removal of the upper, soft portion of the muddy sea floor and the inhabitation of the exposed firm substrate by opportunistic suspension-feeding organisms (the Glossifungites ichnofacies) and the formation of the diamictite layers. Small scale cyclical facies changes within the Snapper Point Formation (see section 5.3.8 and Pl. 4.9c) may also be fifth order cycles.

In the Pebbley Beach and Snapper Point Formations fourth order cyclicity (500 000 - 200 000 year cycles) is manifested in the form of parasequences that are generally separated by TSE. Parasequences combine to form parasequence sets which typically comprise genetically related parasequences with distinctive stacking patterns (Mitchem & Van Wagoner 1991). The Pebbley Beach and Snapper Point Formation represent a single aggradational parasequence set. Tye (1995) identified cyclical sequences within laterally equivalent inland braidplain deposits of the Yadboro conglomerate and suggested that the cyclicity was also related to Milankovitch orbital forcing. The flooding surfaces within the conglomeratic sequence represent periods of relative sea-level rise (Tye 1995) and probably correlate with flooding surfaces in the Pebbley Beach Formation.

The fourth order Milankovitch cyclicity that appears to have been a controlling factor in the climatic and sea-level changes identified in these southern Sydney Basin deposits was probably also a controlling factor in the development of contemporaneous successions throughout Gondwana (Tye 1995). In particular, Milankovitch cylicicity may have controlled the development of coal seams within carbonaceous sequences, such as those described by Cairncross & Cadle (1988) from the Early Permian Vryheid Formation, as has been demonstrated by Arditto (1991) in the Late Permian coal bearing sequences in the southern Sydney Basin.

5.5.3 Third Order Cyclicity, Glaciation and Global implications

Third order cycles (1-10 million year cycles) span a greater time scale than is preserved within the Pebbley Beach and Snapper Point Formations. The two formations form part of the lower transgressive portion of a third order cycle that started at the base of the Shoalhaven Group. The lower part of the cycle is broadly transgressive until the change to a regressive regime at the interval of maximum flooding within the Wandrawandian Siltstone. The cycle is terminated at a ravinement surface that caps the overlying progradational Nowra Sandstone (Tye 1995). The
effects of both tectonically influenced eustacy and glacio-eustatic change appear to have been important in the formation of this third order cycle. The Tastubian transgression (outlined below), which was associated with the melting of a major ice sheet during the early Permian, coincided with the onset of transgression in the lower Shoalhaven Group. Additionally, this period of Sydney Basin deposition coincided with phases of rifting, thermal sag and incipient foreland flexure (Tye 1995). The overall transgression, from the base of the Shoalhaven Group to the maximum flooding surface within the Wandrawandian Siltstone, was probably strongly influenced by glacio-eustatic controls. The internal flooding events at the bases of the Snapper Point Formation and the Wandrawandian Siltstone were probably predominantly affected by tectonic events. The Pebbley Beach and Snapper Point Formations are characterized by an overall aggradational sedimentation pattern which indicates that sediment supply kept pace with the rate of relative sea-level rise. The latter was probably primarily influenced by glacio-eustatic processes but also strongly influenced by basin subsidence. The flooding event that occurred at the base of the Snapper Point Formation marks a sharp decrease in sediment supply to the basin which was probably related to regional subsidence. The flooding event at the base of the Wandrawandian Siltstone which marks a major cratonward facies shift (Tye 1995) was probably caused by a rapid increase in subsidence due to foreland loading. A period of tectonic quiescence followed and the sediment supply outpaced the rate of increase of accommodation space. The result was the progradation of a clastic wedge (the Nowra Sandstone) from the cratonic margin (Tye 1995). The termination of the third order cycle reflects renewed foreland accretion which caused a major flooding event and a cratonward facies shift.

Evidence for climatic change and for very cold climatic conditions exists in several places in the Pebbley Beach and Snapper Point Formations. An excellent example occurs at South Pebbles, in the Pebbley Beach Formation, where alternation between mudstone beds with a distal Cruziana ichnofacies and diamictite beds with an associated Glossifungites ichnofacies reflect fifth order Milankovitch cyclicity.

Other distinctive diamictite units are preserved at South Island Beach and Nugans Point in the lower Snapper Point Formation and at Crampton Island and Bannisters Point in the upper Snapper Point Formation. At these localities diamictite units occur as transgressive deposits and mark sea-level rises attributed to fourth order Milankovitch cyclicity. There are also a large number of localities that contain scattered large dropstones in association with large logs. One particular offshore deposit at Pretty Beach in the lower Snapper Point Formation contains several large, angular, exotic clasts, one measuring 150 cm in length, and numerous large logs. The dropstones and associated plant material indicate the existence of river and sea ice floes
which must have floated quite a distance from the shoreline before thawing and subsequently releasing their load of terrestrial clastic material into the offshore environment. The Wandrawandian Siltstone also contains numerous dropstones including very large examples at Lagoon Head and Warden Head which indicate that cold conditions were still prevalent during the period of overall third order maximum flooding.

Glendonites, on Clear Point in the Pebbley Beach Formation, are another possible indicator of cold climatic conditions. Glendonites are pseudomorphs after the mineral ikaite (CaCO3. 6H2O; Kaplan 1979) which is unstable at temperatures above 5°C, at which point it decomposes to calcium carbonate (Shearman & Smith 1985, Jansen et al. 1987). Ikaite has been recorded in several localities including Antarctica (Suess et al. 1982), Zaire deep sea fan (Jansen et al. 1987) and at Barrow, Alaska (Kennedy et al. 1987). Glendonites are present at numerous other localities within the Sydney Basin, including the Wandrawandian Siltstone at Warden Head and Jervis Bay, and reflect cold climate conditions (Carr et al. 1989).

Wanless & Shepard (1936) made the original hypothesis that sea-level fluctuations related to the late Gondwanan glaciation largely controlled the deposition of late Palaeozoic cyclothems. Based on the work of numerous authors (such as Hambrey & Harland 1981, Caputo & Crowell 1985, Johnson et al. 1985, Martinez Diez 1985, Ross & Ross 1985a, 1985b, Heckel 1986, Saunders & Ramsbottom 1986), Veevers & Powell (1987) confirmed this hypothesis and suggested that correlative cyclothem deposition, glacial events and sea-level fluctuations occurred in different parts of Europe, America, Australia and Antarctica.

Carboniferous to Early Permian deposits in South Africa (the Dwyka Formation) consist of glacial pavements and diamictite facies (Visser & Loock 1988, Visser 1990) which correspond with the Late Palaeozoic glaciation that affected much of Gondwana (episode III, Veevers & Powell 1987) and probably correlate with the southern Sydney Basin. Deposits of similar age and lithology also occur in South America and Antarctica (Eyles et al. 1993, Collison et al. 1994, López-Gamundí et al. 1994).

Veevers and Powell (1987) described three episodes of Late Palaeozoic Gondwanan glaciation;

- episode I (Famennian) was localized to Brazil and adjacent northwest Africa,
- episode II (Visean) was localized to Brazil, and
- episode III (Namurian to Sakmarian) extended throughout most of the Gondwanan supercontinent.

Episode III was extensive and occurred in three phases. The initial phase (episode IIIA) started in the Namurian in eastern Australia and South America and extended throughout Gondwana
(except northwest Africa) by the Stephanian (episode IIIB). The final glacial stage (episode IIIC) occurred during the Tastubian in southern Brazil, southern Africa, India and Australia. A major diachronous transgression (the Tastubian transgression) which affected most of the Pangean Permian Basin (Veevers et al. 1994c) is marked in Argentina, southern Africa, India and Australia by a thick shelled *Eurydesma* fauna (Veevers & Powell 1987). *Eurydesma* has been recorded in several places in eastern Australia and Gondwana (Runnegar 1979, Dickins 1984, Veevers & Powell 1987) including the Pebbley Beach and lower Snapper Point Formations. *Eurydesma* (which is a cold climate inhabitant that marks the onset of the Tastubian transgression in many Permian Gondwanan basins) occurs at numerous locations in the study area and is especially evident in a transgressive lag in the upper Pebbley Beach Formation and in the basal 20 m of the Snapper Point Formation.

The regressive episode (the Sterlitamakian regression) that occurred at the end of the final glacial stage and terminated the Tastubian transgressive phase has been attributed to possible post-glacial isostatic rebound by Veevers and Powell (1987).

Dickins et al. (1969) estimated a middle Sakmarian to early Kungurian (approximately 275 to 260 Ma) age for the deposits between the base of the Wasp Head Formation and the top of the Nowra Sandstone. The earliest date (260 Ma, late Kungurian) obtained from igneous units within the Gerringong volcanics at the top of the Shoalhaven Group (Carr 1984) places a minimum age constraint of 260 Ma on the Berry Siltstone which overlies the Nowra Sandstone.

This study interprets that the broad scale transgression present in the lower Shoalhaven Group corresponds to the Tastubian transgression that affected most of the Permian basins on the Gondwanan supercontinent (see fig. 1. Briggs 1993 after Ross & Ross 1987), and a new lithostratigraphic model is proposed (Fig. 1.3). The Pebbley Beach and Snapper Point Formations and the lower transgressive portion of the Wandrawandian Siltstone were deposited on the southeastern Gondwanan continental margin (which according to Tye 1995, had a palaeolatitude similar to that of the present day Ross Ice Shelf) during episode IIIC of Veevers et al. (1987). During this time the palaeomagnetic pole lay directly over the Sydney-Gunnedah-Bowen Basin (Powell & Li 1994).

The onset of the Sterlitamakian regressive phase in the Shoalhaven Group is interpreted to be marked by the maximum flooding surface within the Wandrawandian Siltstone. In the Permian-Triassic Pangean basins of Antarctica, South Africa and South America, tectonic events strongly influenced eustacy (cf. Baker et al. 1993, Veevers et al. 1994a, b) and in the Shoalhaven Group the change to a regressive regime has been attributed to tectonic effects by a number of authors including Veevers et al. (1994a) and Tye et al. (1996). Substantial evidence
for post-glacial isostatic rebound is not evident in the southern Sydney Basin. Progradation has been attributed to tectonic uplift in the adjacent Lachlan Foldbelt (Veevers et al. 1994a), which was caused by the rise of a forebulge at the cratonic margin associated with loading at the orogen (Tye 1995). The rise of the cratonic margin and subsequent orogenic loading resulted in a possible fall in relative sea-level. The onset of the Nowra Sandstone may, therefore, represent a forced regression. The basal contact of the Nowra Sandstone is sharp and erosional in western (proximal) areas where the Wandrawandian Siltstone is non-existent and the Nowra Sandstone unconformably overlies the Snapper Point Formation (Tye 1995). In eastern (distal) parts of the basin the contact of the Nowra Sandstone with the underlying Wandrawandian Siltstone is gradational and conformable (Tye 1995). This change from a proximally erosional to a distally conformable boundary is characteristic of RSE formed during forced regressions (Posamentier et al. 1992). The Nowra Sandstone progradational episode is correlative with the Muree Sandstone in the northern part of the Sydney Basin and probably correlates with the Porcupine Formation in the Gunnedah Basin and the upper Cattle Creek Formation or the Aldebaren Formation in the Bowen Basin (Tye et al 1996).
CHAPTER 6: CONCLUSIONS

The Early Permian (Tastubian) Pebbley Beach and Snapper Point Formations of the lower Shoalhaven Group in the southern Sydney Basin form a part of an overall transgressive succession that was deposited close to the cratonic margin of a retro-arc foreland basin.

6.1 TAXONOMIC CONCLUSIONS

a) Previous ichnotaxonomic lists from the Pebbley Beach and Snapper Point Formations are substantially inadequate and partially erroneous. Several species recognised by Carey (1978) and McCarthy (1979) have been redefined here. *Catenichnus contenticus* a species established by McCarthy (1979) is here considered to be synonymous with *Diplocraterion paralleum* Torrel.

Forty three ichnospecies from 29 genera provide a new ichnotaxonomic framework. Four new ichnospecies are described herein, *Cylindrichnus eccentricus*, *Rosselia motivus*, *Taenidium synsphes* and *Teichichnus sinuosus*. A previously unrecorded notoconulariid species (*Notoconularia levigata*) has been identified in a transgressive deposit in the lower Snapper Point Formation.

b) An intergradational link between *Asterosoma*, *Rosselia* and *Cylindrichnus*, which has been previously suggested in the literature but until now unsubstantiated, is clearly recognisable throughout the study area. *Teichichnus* is regularly associated with this ichnospecific association.

6.2 ICHNOLOGICAL CONCLUSIONS

a) The ichnofacies concept is used cautiously here in association with other aspects of sedimentology, ichnology and palaeontology to provided high resolution reconstructions of depth-related environmental gradients and degree of storm dominance. Four distinct ichnofacies are recognised in the study area. The characteristics of the Pebbley Beach and Snapper Point Formation ichnofacies are as follows:
1. The Skolithos ichnofacies:- reflects ongoing high levels of hydrodynamic energy and is represented by deep, permanent burrows of mainly suspension feeders. This ichnofacies mainly occurs in shoreface environments above minimum fairweather wave-base.

2. The Cruziana ichnofacies:- reflects lower hydrodynamic energy regimes than the Skolithos ichnofacies and is produced during fairweather processes between minimum fairweather and maximum storm wave-base. Four types of Cruziana ichnofacies are classified here:
   - proximal:- reflects the highest hydrodynamic energy portion of the Cruziana ichnofacies, generally being represented by a resilient, robust community of detritus- and deposit-feeders that reflect the reworking of storm-deposited sandstone beds during fairweather in a lower shoreface environment;
   - diverse:- more mature assemblages with complete bioturbation reflecting high ichnodiversity and slow deposition, generally represented by a community of deposit- and detritus-feeders in offshore deposits above storm wave-base;
   - distal:- contains a less diverse assemblage that is still usually completely bioturbated. The deepest tier structures tend to dominate the ichnofabric reflecting very slow deposition and habitation by deposit-feeding and grazing/foraging animals in offshore environments below fairweather and commonly below storm wave-base.
   - restricted:- typically low diversity assemblages containing diminutive traces that reflect a stressed ecosystem typical of brackish water conditions in estuarine intertidal channel and lagoon deposits. This ichnofacies is particularly useful in differentiating silty backbarrier deposits from silty lower offshore deposits in the Pebbley Beach Formation.

3. The Arenicolites ichnofacies:- generally represents post-event colonization of storm-deposited sandstone units by a relatively diverse assemblage of vertical burrows produced by opportunistic suspension-feeding organisms in offshore and occasionally lower shoreface environments.

4. The Glossifungites ichnofacies:- reflects a substrate-controlled ichnofacies composed of robust, sharp-walled, unlined, passively filled, vertical to sub-vertical suspension-feeding burrows excavated into firm substrates. Useful for the interpretation of transgressive surfaces of erosion and glacially-influenced starved shoreface environments in the Pebbley Beach Formation. This ichnofacies, in association with ichnofabric analysis,
provides evidence for a transgressive surface of erosion and formation boundary at South Island Beach that may otherwise have been undetectable.

b) Twenty seven significant ichnofabrics are identified within the Pebbley Beach and Snapper Point Formations of which 14 represent complex, composite associations whereas the remainder are simple. Simple ichnofabrics occur throughout the study area as either ‘frozen tiered profiles’ or ‘laminated to scrambled profiles’. Composite associations have been subdivided here into four categories:-

1. Composite Cruziana / Arenicolites assemblage (type A) ichnofabric: produced when an opportunistic Arenicolites ichnofacies assemblage is replaced and overprinted by a fairweather Cruziana assemblage.

2. Composite Cruziana / Arenicolites assemblage (type B) ichnofabric: produced when water and sediment are pumped down into the large U-shaped burrows of an opportunistic Arenicolites ichnofacies assemblage and then the fabric is overprinted by a fairweather Cruziana ichnofacies assemblage.

3. Composite Arenicolites / Cruziana / Arenicolites assemblage ichnofabric: produced when an Arenicolites ichnofacies assemblage is replaced and overprinted by a fairweather Cruziana ichnofacies assemblage. Truncation and storm-bed deposition then occurs and an opportunistic Arenicolites ichnofacies assemblage overprints the former Arenicolites / Cruziana assemblage.

4. Composite Cruziana assemblage ichnofabric: produced when fairweather deposition is slow and continuous and a Cruziana ichnofacies assemblage overprints itself.

c) Ichnofabrics greatly enhance the recognition and interpretation of maximum flooding intervals, condensed intervals and transgressive deposits. They are also used to recognise transgressive surfaces of erosion, maximum flooding surfaces and regressive surfaces of erosion, by registering depth and energy related facies changes across these surfaces. Variation of bioturbation index within units provides evidence for concealed bed boundaries, and this information is used, in association with ichnofacies interpretations and sedimentology, to estimate bathymetry and to provide high resolution interpretations of the degree of storm dominance within units.
d) The ichnofabric measurement schemes proposed by Droser & Bottjer (1990) and Taylor & Goldring (1993) are combined and adapted here to provide a more comprehensive system of recording ichnofabric. This system is particularly useful when classifying composite ichnofabrics in the Pebbley Beach and Snapper Point Formations.

6.3 PALAEOENVIRONMENTAL CONCLUSIONS

a) This study of behavioural and preservational characteristics of trace fossils provides a high resolution palaeoenvironmental and sequence stratigraphic interpretation of the Pebbley Beach and Snapper Point Formations. Behavioural characteristics provide information about sedimentation rates, food abundance and substrate stability while preservational characteristics amplify interpretations of substrate consistency and sedimentation rates. Palaeoenvironmental data provided by many of the trace fossils, including salinity, aeration, bathymetry, substrate stability, energy levels and deposition rates significantly increased the resolution of this study.

b) The exposed Pebbley Beach Formation is dominated by silty facies deposited in the back-barrier zone of a microtidal barrier-island complex. The system was wave-dominated and contains numerous washover deposits, which reflect the break-through of the barrier by storm surges. The trace fossil assemblage in the back-barrier environment indicates brackish water conditions.

Changes in ichnofabric complexity throughout the Pebbley Beach Formation back-barrier deposits indicate fluctuating bathymetry and energy levels.

Ichnofabrics are significantly less complex in the deeper channels than along estuary margins due to current reworking and less suitable habitat and burrow preservation conditions. Increased ichnofabric complexity in a seaward direction in the Pebbley Beach back-barrier environment reflects the increased influence of marine sediments and organisms.

In washover and flood-tidal delta deposits the characteristic ichnofabrics are identical to those of event beds in fully marine environments. Interstratification of these event beds with deposits containing a low-diversity, opportunistic brackish water assemblage differentiates them from those deposited in the marine environment.

c) Marine deposits of the Pebbley Beach and Snapper Point Formations range in depth from foreshore to lower offshore.
These foreshore deposits are tide-dominated and exclusively inhabited by the Skolithos ichnofacies.

Upper and middle shoreface deposits are wave-dominated here and mainly contain the Skolithos ichnofacies with rare resilient proximal Cruziana ichnofacies.

The combined ichnofacies and ichnofabric analysis used in this study provided an extensive complementary data-base which substantially amplified the resolution of palaeoenvironmental interpretations and allows further subdivision of the lower shoreface and offshore facies according to degree of storm dominance and glacial influence. It has been possible to accurately subdivide this interval in the Pebbley Beach and Snapper Point Formations into the lower, upper and transition offshore and the lower middle and upper shoreface facies in using differences in primary sedimentary structures and ichnology. The characteristics of Pebbley Beach and Snapper Point Formation environments are as follows:

- Lower shoreface facies are generally storm-dominated and mostly contain composite ichnofabrics produced by Arenicolites and proximal Cruziana ichnofacies. In the Pebbley Beach Formation the lower shoreface is also represented by a glacially influenced deposit containing a mixed distal Cruziana / Glossifungites ichnofacies.
- The upper offshore and offshore transition facies represent storm-influenced deposits and tempestites comprise a high proportion of the facies in both formations. Ichnofabrics are composite and comprise complex mixtures of proximal or diverse Cruziana ichnofacies and Arenicolites ichnofacies.
- Lower offshore deposits are also storm influenced with some units being strongly storm-dominated. Ichnofabrics are generally very complex and are dominated by distal Cruziana ichnofacies and associated Arenicolites ichnofacies.

6.4 CYCLOSTRATIGRAPHIC CONCLUSIONS

a) Cyclicity in the Pebbley Beach Formation was produced by Milankovitch orbital forcing. Fourth order cyclicity occurs here in the form of parasequences with regressive phases that display a progressive basinward facies shift. The Pebbley Beach Formation contains well preserved fifth order cyclicity manifested in the form of alteration between mudstone beds with a distal Cruziana ichnofacies and diamictite beds with a Glossifungites ichnofacies. This fifth order cyclicity reflects alterations between perennial and seasonal ice cover.
b) The lower Snapper Point Formation is composed of at least nine parasequences which contain substantially thicker transgressive deposits than those in the Pebbley Beach Formation. These thick transgressive half sequences are uncharacteristic of previously described transgressive deposits and reflect a rapid creation rate of accommodation space balanced by a very high rate of sediment supply. These parasequences were produced by eustatically controlled fourth order Milankovitch cyclicity.

c) The upper Snapper Point consists of three parasequences and marks a shift from wave-dominated sedimentation produced in an open shelf setting to tidal or longshore current processes produced in a tide-dominated constricted seaway. This interpretation concurs with that postulated by Tye (1996) whereby the constriction of the seaway was contemporaneous with the emergence or near emergence of the developing orogen (located to the east of the present coast line).

d) On a broad scale, the sediment supply to the Pebbley Beach and Snapper Point Formations was approximately balanced by the rate of increase in accommodation space, producing an overall aggradational deposition pattern. Regressive facies in the study area are predominantly attributed to normal regressive processes. A relatively major forced regression marked by a regressive surface of erosion occurs in the upper Snapper Point Formation reflecting a rapid fall in relative sea level.

e) The recognition of bounding depositional surfaces in the Pebbley Beach and Snapper Point Formations is greatly enhanced by the integration of ichnofacies and ichnofabric analysis. Transgressive surfaces of erosion in the study area are generally veneered by a transgressive lag and erosional incision is recognised from the presence of a Glossifungites ichnofacies. Ichnofabric changes across a Glossifungites-inhabited erosion surface in the lower Snapper Point Formation aid in the identification of the contact between the Snapper Point Formation and the underlying Pebbley Beach Formation. Maximum flooding surfaces and intervals occur above most transgressive surfaces in the study area and are also largely recognised on the basis of ichnofabric analysis. They are characterized here by a rapid fining-up of the sequence accompanied by a substantial increase in bioturbation intensity.
f) Fourth and fifth order cycles in the Pebbley Beach and Snapper Point Formation were eustatically (commonly glacio-eustatically) controlled and are superimposed on a larger and longer third order cycle that includes the overlying Wandrawandian Siltstone and Nowra Sandstone. The effects of both tectonically influenced eustacy and glacio-eustatic change were important in the formation of this third order cycle.

g) A revised lithostratigraphic model for the southern Sydney Basin is proposed here. The broad scale transgression represented by the Pebbley Beach and Snapper Point Formations is marked by the *Eurydesma* fauna and corresponds to the Tastubian Transgression that affected most of the Permian Basins on the Gondwanan supercontinent. The maximum flooding surface in the overlying Wandrawandian Siltstone marks the onset of the Sterlitamakian regressive phase which is attributed both here and throughout the Permian Gondwanan Basins to tectonically influenced eustacy. The onset of deposition of the overlying Nowra Sandstone reflects a forced regression.
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Volume II

ICHNOLOGY AND SEQUENCE STRATIGRAPHY
OF THE
EARLY PERMIAN
PEBBLEY BEACH FORMATION
AND
SNAPPER POINT FORMATION
IN THE
SOUTHERN SYDNEY BASIN.

A thesis submitted in fulfillment of
requirements for the degree of

DOCTOR OF PHILOSOPHY

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NEW SOUTH WALES
AUSTRALIA

by

KERRIE BANN

SCHOOL OF GEOSCIENCES
1998
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Measured sections from the Pebbley Beach and Snapper Point Formations
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</tbody>
</table>

Table 3.0 Scheme indicating relationships of ichnofacies with environment (modified from Bromley & Asgaard 1991). Ichnofacies present in the Pebbley Beach and Snapper Point Formations are in bold.
<table>
<thead>
<tr>
<th>VERTICAL STRUCTURES</th>
<th>SPREITEN BURROWS</th>
<th>HORIZONTAL STRUCTURES</th>
<th>STRUCTURES PRODUCED BY MOBILE ORGANISMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skolithos, Arenicolites, Cylindrichnus, Gyrolithes, Polykladichnus, Monocraterion, Calycraterion, Heimdalia, Margaretichnus, Ophiomorpha?</td>
<td>Diplocraterion habichi, Diplocraterion parallelum, Rhizocorallium jenense</td>
<td>Macaronichnus, Palaeophycus heberti,</td>
<td>Psammicnites</td>
</tr>
</tbody>
</table>

Table 3.1 Trace fossils present in the Skolithos ichnofacies in the Snapper Point and Pebbley Beach Formations.

<table>
<thead>
<tr>
<th>PROXIMAL CRUZIANA ICHNOFACIES</th>
<th>DIVERSE CRUZIANA ICHNOFACIES</th>
<th>DISTAL CRUZIANA ICHNOFACIES</th>
<th>RESTRICTED CRUZIANA ICHNOFACIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRACE FOSSILS</td>
<td>Rosselia socialis, Rosselia rotatus, Rosselia motivus, Asterosoma, Phycosiphon, Polycylindrichnus, Planolites, Palaeophycus, Rhizocorallium irregulare, Teichichnus sinuosus, Teichichnus rectus, Taenidium serpentinum, Taenidium barretti</td>
<td>Phycosiphon incertum, Rosselia socialis, Palaeophycus tubularis, Teichichnus rectus, Thalassinoides, Planolites</td>
<td>Phycosiphon incertum, Rosselia socialis, Palaeophycus tubularis, Palaeophycus tubularis, Planolites</td>
</tr>
<tr>
<td>CHARACTERISTIC ENVIRONMENTS</td>
<td>fairweather deposits in shoreface facies, especially very strongly-strongly storm-dominated lower shoreface facies</td>
<td>fairweather deposits in the moderately-weakly storm affected lowershoreface, offshore transition and upper offshore facies</td>
<td>lower offshore facies</td>
</tr>
</tbody>
</table>

Table 3.2 Characteristics of the Cruziana ichnofacies in the Pebbley Beach and Snapper Point Formations.
<table>
<thead>
<tr>
<th>VERTICAL STRUCTURES</th>
<th>SPREITEN BURROWS</th>
<th>HORIZONTAL STRUCTURES</th>
<th>STRUCTURES PRODUCED BY MOBILE OR GRAZING ORGANISMS</th>
<th>CHARACTERISTIC ENVIRONMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skolithos, Arenicolites, Cylindrichnus, Conostichus, Polykladichnus, Fugichnia,</td>
<td>Diplocraterion habichi, Diplocraterion parallelum, Rhizocorallium jenense, Phycosiphon incertum</td>
<td>Macaronichnus, Palaeophycus, Planolites, Gyrochorte</td>
<td>Psammichnites, Taenidium synyphes</td>
<td>In event beds in: tidal flats, flood tidal delta/washover deposits, middle shoreface, lower shoreface, offshore transition, upper offshore and lower offshore deposits.</td>
</tr>
</tbody>
</table>

**Table 3.3 Trace fossils present in the Arenicolites ichnofacies in the Snapper Point and Pebbley Beach Formations.**

<table>
<thead>
<tr>
<th>TRANSGRESSIVE SURFACES OF EROSION</th>
<th>GLACIALLY INFLUENCED LOWER SHOREFACE MUDSTONE AND DIAMICTITE</th>
<th>LOWER OFFSHORE INTERBEDDED MUDSTONE, SILTSTONE AND SANDSTONE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diplocraterion habichi, Arenicolites statheri, Skolithos, Arenicolites?</td>
<td>Diplocraterion habichi, Thalassinoides paradoxicus?, Rhizocorallium jenense</td>
<td>Skolithos</td>
</tr>
</tbody>
</table>

**Table 3.4 Characteristic trace fossils and depositional environments of the Glossifungites ichnofacies in the Snapper Point and Pebbley Beach Formations.**
<table>
<thead>
<tr>
<th>Facies</th>
<th>Traces</th>
<th>Ichnofacies</th>
<th>BI range</th>
<th>Characteristic sedimentary structures</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESTUARINE INTERTIDAL CHANNEL</td>
<td>Phycosiphon incertum, Planolites</td>
<td>very restricted Cruziana ichnofacies</td>
<td>rare maximum of 2</td>
<td>large channel-fills of sand-dominated inclined heterolithic stratification</td>
<td>High energy typical of high fluvial discharge or rapid tidal sedimentation in the upper reaches of a tidally influenced estuarine system.</td>
</tr>
<tr>
<td>TIDAL FLAT</td>
<td>Diplocraterion habichi, Conostichus, Skolithos, Planolites, Gordia, Phycosiphon incertum, Rhizocorallium irregularare, Rosselia socialis, Taenidium serpentinum, Psammichnites</td>
<td>a mixed Cruziana / Arenicolites ichnofacies typical of brackish water conditions</td>
<td>maximum of 3</td>
<td>Flat lying, thinly interbedded sandstone and mudstone with flaser and lenticular bedding, with common soft sediment deformation and synaeresis cracks.</td>
<td>Fluctuating, influenced by tidal currents and fluvial discharge.</td>
</tr>
<tr>
<td>LAGOON</td>
<td>Phycosiphon incertum, Rosselia socialis, Palaeophycus tubularis, Planolites</td>
<td>a size-restricted Cruziana ichnofacies reflecting a stressed ecosystem typical of brackish water conditions</td>
<td>5-6:2</td>
<td>Intensely bioturbated, organic-rich mudstone and sandstone.</td>
<td>Low energy lagoon conditions fluctuating with slightly higher energy conditions representing lagoon margin deposits where tidal and possibly wave currents were stronger.</td>
</tr>
<tr>
<td>FLOOD TIDAL DELTA/WASHOVER</td>
<td>Diplocraterion habichi, Diplocraterion parallelum, Rhizocorallium jenense B, Cylindrichnus concentricus, Palaeophycus tubularis, Phycosiphon incertum, Rosselia rotatus, Teichichnus rectus, Taenidium synyphes, Skolithos, Planolites</td>
<td>a mixed diverse Cruziana / Arenicolites ichnofacies</td>
<td>1-6</td>
<td>Sharp-based sandstone and granule conglomerate beds with horizontal stratification, current ripples and glendonites.</td>
<td>High energy typical of sands spilled over or cut through the sand barrier during storm surge.</td>
</tr>
<tr>
<td>TIDAL INLET</td>
<td>Diplocraterion parallelum, Rosselia socialis, Cylindrichnus concentricus</td>
<td>distal Skolithos ichnofacies</td>
<td>0-2</td>
<td>Coarse-grained sandstone with tidal bundles, silt-drapped current ripples and mudstone rip-up clasts.</td>
<td>High energy with occasional slack periods at high tide.</td>
</tr>
</tbody>
</table>

Table 4.1. Characteristics of the Pebbley Beach Formation backbarrier environment.
<table>
<thead>
<tr>
<th>Traces</th>
<th>Ichnofacies</th>
<th>BI range</th>
<th>Sandstone characteristics</th>
<th>Conglomerate characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FORESHORE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Macaronichnus, Skolithos, Arenicollites, Palaeophycus, Cylindrichnus eccentricus, Diplocraterion parallelum, Diplocraterion habichi, Gyrolithes, Polykladichnus, Rhizocorallium jenense A, Ophiomorpha?</em></td>
<td>Skolithos</td>
<td>0-3</td>
<td>Thick units of well-sorted, sub-parallel to low angle and planar cross-stratified, medium- to very coarse-grained sandstone beds</td>
<td>Rare thin pavements</td>
</tr>
<tr>
<td><strong>UPPER SHOREFACE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Diplocraterion parallelum, Diplocraterion habichi, Palaeophycus, Skolithos, Polykladichnus, Arenicollites, Phycosiphon, Macaronichnus, Rhizocorallium jenense, Monocraterion, Heimdalia, Calycraterion, Rosselia socialis, Asterosoma</em></td>
<td>Skolithos</td>
<td>0-2 average, very rare maximum of 3-4 in thin lam-scram units</td>
<td>Thick units (over 10 m), of sandstone with bidirectional planar to low-angle cross-stratification and multidirectional trough cross-stratification. Lam-scram profiles and homogenised beds are rare.</td>
<td>Common pavements up to 30 cm thick and rare flat-bedded units up to 50 cm thick.</td>
</tr>
<tr>
<td><strong>MIDDLE SHOREFACE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Diplocraterion parallelum, Diplocraterion habichi, Palaeophycus, Skolithos, Polykladichnus, Arenicollites, Phycosiphon, Macaronichnus, Rhizocorallium jenense C, Calycraterion, Psammichnites, Cylindrichnus, Rosselia socialis, Asterosoma, Teichichnus</em></td>
<td>Skolithos</td>
<td>0-rare maximum of 5, average of 1-3</td>
<td>Thin beds (5 cm) to thick amalgamated units (&gt; 20 m). Well sorted, well winnowed, SCS, HCS, or low-angle cross-stratified fine- to very coarse-grained sandstone. Lam-scram profiles and homogenised beds are common. Bioturbated beds are</td>
<td>Common, preserved as large-scale symmetrical wave ripples</td>
</tr>
<tr>
<td>Table 4.2. Characteristics of the foreshore, upper shoreface and middle shoreface facies in the Snapper Point Formation.</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>EARLY-STAGE OPPORTUNISTIC STRUCTURES</td>
<td>LATE-STAGE OPPORTUNISTIC STRUCTURES</td>
<td>HIGHLY RESILIENT EQUILIBRIUM STRUCTURES</td>
<td>EQUILIBRIUM STRUCTURES</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------</td>
<td>--------------------------------------</td>
<td>----------------------------------------</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>Diplocraterion habichi, Skolithos, Arenicolites, Diplocraterion parallelum, Rhizocoralium jenense, Palaeophycus</td>
<td>Phycosiphon incertum, Planolites, Psammichnites, Taenidium synyphes</td>
<td>Cylindrichnus, Rosselia socialis, Rosselia motivus, Asterosoma, Macaronichnus</td>
<td>Asterosoma, Teichichnus, Rhizocorallium irregulare, Rosselia rotatus, Polycylindrichnus, Planolites, Taenidium serpentinum, Palaeophycus</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3. Opportunistic and equilibrium structures in offshore and shoreface facies in the Pebbley Beach and Snapper Point Formations.
<table>
<thead>
<tr>
<th></th>
<th>Fairweather bed thickness</th>
<th>Fairweather traces</th>
<th>Fairweather bed BI</th>
<th>Event bed thickness</th>
<th>Event deposition traces</th>
<th>Event bed BI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Very strongly - strongly storm dominated</strong></td>
<td>predominantly &lt; 5 cm, very rarely up to 20 cm</td>
<td><em>Asterosoma, Teichichnus, Rosselia socialis, Rosselia rotata, Taenidium barretti, Phycosiphon, Planolites</em></td>
<td>6</td>
<td>homogenised through to thick amalgamated units, average individual bed thickness 50 cm</td>
<td><em>Diplocraterion paralellum, Diplocraterion habichi, Skolithos, Phycosiphon, Fugichnia, Psammichnites, Macaronichnus, Cylindrichnus, Taenidium synaphes, Rhizocorallium jenense, Arenicolites, Polykladichnus, Conostichus</em></td>
<td>0 - homogenised, lam-scram, average BI = 3, rare maximum of 5-6, very soupy sediments commonly make BI interpretation difficult</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proximal Cruziana ichnofacies</td>
<td></td>
<td></td>
<td>Arenicolites ichnofacies</td>
<td></td>
</tr>
<tr>
<td><strong>Moderately - weakly storm-affected</strong></td>
<td>5 - 20 cm</td>
<td><em>Rosselia socialis, Asterosoma, Teichichnus, Rosselia rotata, Phycosiphon, Planolites, Taenidium barretti, Palaeophycus, Rhizocorallium irregular</em></td>
<td>6</td>
<td>maximum of 80 cm, average of 20 - 40 cm, many are homogenised</td>
<td><em>Diplocraterion paralellum, Diplocraterion habichi, Skolithos, Phycosiphon, Rhizocorallium jenense A, Rhizocorallium jenense C, Arenicolites, Macaronichnus, Cylindrichnus, Psammichnites, Taenidium synaphes, Gyrochorte camosa</em></td>
<td>0 - homogenised, lam-scram, average BI = 0 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cruziana ichnofacies</td>
<td></td>
<td></td>
<td>Arenicolites ichnofacies</td>
<td></td>
</tr>
<tr>
<td><strong>Ice-covered</strong></td>
<td>10 - 100 cm</td>
<td><em>Phycosiphon incertum</em></td>
<td>impossible to determine due to the fine-grained nature of the mudstone</td>
<td>&lt; 5 - 30 cm</td>
<td><em>Diplocraterion habichi, Thalassinoides paradoxicus?, Rhizocorallium jenense</em></td>
<td>a composite fabric exists between the mudstone and the diamicite but a BI is difficult to determine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Restricted Cruziana ichnofacies</td>
<td></td>
<td></td>
<td>Glossifungites ichnofacies</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.4. Characteristics of lower shoreface facies in the Snapper Point and Pebbley Beach Formations.**
<table>
<thead>
<tr>
<th></th>
<th>Fairweather bed thickness</th>
<th>Fairweather traces</th>
<th>Fairweather bed BI</th>
<th>Storm bed thickness (cm)</th>
<th>Storm traces</th>
<th>Storm bed BI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Very strongly storm-dominated</strong></td>
<td>average 20 cm, many truncated, rarely up to 60 cm</td>
<td><em>Asterosoma, Teichichnus, Rosselia socialis, Rosselia rotatus, Phycosiphon, Palaeophycus, Rhizocorallium irregulare, Planolites</em></td>
<td>5-6</td>
<td>5 cm - amalgamated, maximum individual bed 120 cm</td>
<td><em>Fugichnia, Diplocraterion habichi, Diplocraterion parallelum, Rhizocorallium jenense A, Phycosiphon, Cylindrichnus, Skolithos, Palaeophycus, Psammichnites, Taenidium synyphes, Planolites</em></td>
<td>0-3 maximum, lam-scram</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diverse Cruziana ichnofacies</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Strongly storm dominated</strong></td>
<td>5 cm - rare to 100 cm</td>
<td><em>Asterosoma, Teichichnus, Rosselia socialis, Phycosiphon, Palaeophycus, Rhizocorallium irregulare, Planolites</em></td>
<td>4-6</td>
<td>average 20 - 30 cm, homogenised-amalgamated, maximum individual bed 60 cm</td>
<td><em>Fugichnia, Diplocraterion parallelum, Diplocraterion habichi, Skolithos, Phycosiphon, Palaeophycus, Rhizocorallium jenense C</em></td>
<td>0- homogenised, lam-scram</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diverse Cruziana ichnofacies</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Moderately storm-dominated</strong></td>
<td>60 - 200 cm</td>
<td><em>Asterosoma, Teichichnus, Rosselia socialis, Rosselia rotatus, Rosselia motivus, Palaeophycus, Phycosiphon, Rhizocorallium irregulare</em></td>
<td>2-5</td>
<td>homogenised - rare to 50 cm</td>
<td><em>Diplocraterion parallelum, Diplocraterion habichi, Skolithos, Phycosiphon, Cylindrichnus, Fugichnia, Rhizocorallium jenense B, Taenidium synyphes, Planolites, Arenicolites, Psammichnites, Palaeophycus</em></td>
<td>2- homogenised, rarely 0 in 30 cm beds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diverse Cruziana ichnofacies</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.5. Characteristics of offshore transition facies in the Pebbley Beach and Snapper Point Formations.
<table>
<thead>
<tr>
<th>Strongly storm dominated</th>
<th>Fairweather bed thickness</th>
<th>Fairweather traces</th>
<th>Fairweather bed BI</th>
<th>Storm bed thickness</th>
<th>Storm traces</th>
<th>Storm bed BI</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 - 140 cm</td>
<td><em>Asterosoma, Teichichnus, Rosselia socialis, Phycosiphon, Palaeophycus, Rhizocorallium irregular</em></td>
<td>5-6:2</td>
<td>homogenised-35 cm, rarely amalgamated</td>
<td><em>Diplocraterion parallelum, Diplocraterion habichi, Skolithos, Phycosiphon, Planolites</em></td>
<td>0- homogenised, lam-scram, tubular tempestites</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diverse Cruziana ichnofacies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moderately storm-dominated</th>
<th>Fairweather bed thickness</th>
<th>Fairweather traces</th>
<th>Fairweather bed BI</th>
<th>Storm bed thickness</th>
<th>Storm traces</th>
<th>Storm bed BI</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 - 140 cm</td>
<td><em>Asterosoma, Teichichnus, Rosselia socialis, Rosselia rotatus, Phycosiphon, Planolites</em></td>
<td>3-6:2</td>
<td>homogenised-up to 25 cm</td>
<td><em>Diplocraterion parallelum, Diplocraterion habichi, Skolithos, Phycosiphon, Cylindrichnus</em></td>
<td>0- homogenised</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diverse Cruziana ichnofacies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weakly storm-affected</th>
<th>Fairweather bed thickness</th>
<th>Fairweather traces</th>
<th>Fairweather bed BI</th>
<th>Storm bed thickness</th>
<th>Storm traces</th>
<th>Storm bed BI</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 - 500 cm</td>
<td><em>Asterosoma, Polycylindrichnus, Rhizocorallium irregular, Rosselia socialis, Rosselia rotatus, Rosselia rotatus, Teichichnus, Phycosiphon, Taenidium serpentinum</em></td>
<td>4-5</td>
<td>homogenised-(very rare 5 cm)</td>
<td><em>Diplocraterion parallelum, Diplocraterion habichi, Skolithos, Phycosiphon, Rhizocorallium jenense, Taenidium synyphes, Palaeophycus</em></td>
<td>homogenised-(very rare 0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diverse Cruziana ichnofacies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.6. Characteristics of upper offshore facies in the pebbley Beach and Snapper Point Formations.**
<table>
<thead>
<tr>
<th></th>
<th>FAIRWEATHER DEPOSITS</th>
<th>STORM DEPOSITS</th>
<th>RESULTANT ICHNOFABRIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethology</td>
<td>Predominantly deposit-feeders</td>
<td>Predominantly suspension-feeders</td>
<td>Suspension-feeders replaced by deposit-feeders</td>
</tr>
<tr>
<td>Ichnofacies</td>
<td>Diverse Cruziana assemblage</td>
<td>Arenicolites assemblage</td>
<td>Mixed Cruziana / Arenicolites assemblage</td>
</tr>
<tr>
<td>Feeding strategy</td>
<td>Equilibrium species</td>
<td>Opportunistic species</td>
<td>Mixture of equilibrium and opportunistic structures</td>
</tr>
<tr>
<td>BI</td>
<td>Predominantly &gt; 5</td>
<td>Predominantly &lt; 2</td>
<td>Predominantly 5 - 6:3</td>
</tr>
<tr>
<td>Ichnofabrics</td>
<td>Predominantly composite ichnofabrics</td>
<td>Predominantly frozen tiered profiles, lam-scram profiles and simple ichnofabrics</td>
<td>Predominantly complex, composite ichnofabrics</td>
</tr>
<tr>
<td>Diversity</td>
<td>Decreases with an increase in storm intensity and/or frequency</td>
<td>Decreases with an increase in storm intensity and/or frequency</td>
<td>Commonly very high</td>
</tr>
</tbody>
</table>

Table 4.7. Ichnological characteristics of upper offshore and offshore transition environments in the Pebbley Beach and Snapper Point Formations.
<p>| Table 4.8. Formation of ichnofabrics in the upper offshore and offshore transition facies in the Pebbley Beach and Snapper Point Formations. |</p>
<table>
<thead>
<tr>
<th>FACIES</th>
<th>Sedimentology and bed thickness</th>
<th>Fairweather traces</th>
<th>Event bed traces</th>
<th>BI</th>
<th>Ichnofabrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bioturbated Sandy Siltstone Facies</td>
<td>Biogenically homogenised sandy siltstone with an average bed thickness of 1m</td>
<td><em>Phycosiphon incertum, Rosselia socialis, Planolites, Palaeophycus tubularis</em></td>
<td><em>Diplocraterion habichi, Diplocraterion parallelum, Rhizocorallium jenense</em></td>
<td>5-6:1</td>
<td>Composite Cruziana assemblage ichnofabric and composite Cruziana / Arenicolites assemblage ichnofabric (A)</td>
</tr>
<tr>
<td>Laminated Siltstone Facies</td>
<td>Parallel-bedded siltstone and mudstone beds with sandstone bases and mega-clasts to 60 cm. Average bed thickness is &lt; 10 cm with the unit thickness reaching 10 m.</td>
<td><em>Phycosiphon incertum, Teichichnus rectus, Thalassinoides</em></td>
<td><em>Diplocraterion habichi</em></td>
<td>5-6</td>
<td>Composite Cruziana assemblage ichnofabric and rare Cruziana / Arenicolites assemblage ichnofabric</td>
</tr>
<tr>
<td>Thinly Interbedded Mudstone, Siltstone and Sandstone Facies</td>
<td>Interbedded sandstone, siltstone and mudstone with lam-scram profiles and sharp bases. Bed thickness ranges from &lt; 1-15 cm.</td>
<td><em>Phycosiphon incertum, Planolites, Rosselia</em></td>
<td><em>Skolithos</em></td>
<td>0 to a rare maximum of 5</td>
<td>Lam-scram Cruziana assemblage profile</td>
</tr>
</tbody>
</table>

Table 4.9. Characteristics of lower offshore facies in the Pebbley Beach and Snapper Point Formations.
<table>
<thead>
<tr>
<th>Facies</th>
<th>Event Bed Ichnofacies</th>
<th>Fairweather Ichnofacies</th>
<th>Ichnofabrics</th>
<th>Substrate consistency</th>
<th>Energy conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backbarrier</td>
<td>Arenicolites ichnofacies</td>
<td>Restricted Cruziana ichnofacies</td>
<td>none, simple and composite</td>
<td>soft</td>
<td>alternating</td>
</tr>
<tr>
<td>Foreshore</td>
<td>Skolithos ichnofacies</td>
<td>frozen tier profiles, simple and composite</td>
<td>loose and shifting</td>
<td>very high</td>
<td></td>
</tr>
<tr>
<td>Upper Shoreface</td>
<td>Skolithos ichnofacies</td>
<td>Skolithos / very rare proximal Cruziana ichnofacies</td>
<td>simple and composite</td>
<td>very high to high</td>
<td></td>
</tr>
<tr>
<td>Middle Shoreface</td>
<td>Arenicolites ichnofacies</td>
<td>Skolithos / proximal Cruziana ichnofacies</td>
<td>composite</td>
<td>alternating - high energy event conditions to moderate energy fairweather conditions</td>
<td></td>
</tr>
<tr>
<td>Lower Shoreface</td>
<td>Arenicolites ichnofacies</td>
<td>Proximal Cruziana ichnofacies</td>
<td>very composite</td>
<td>soft</td>
<td>alternating - high energy event conditions to moderate to low fairweather conditions</td>
</tr>
<tr>
<td>Ice covered Lower shoreface</td>
<td>Glossifungites ichnofacies</td>
<td>Distal Cruziana ichnofacies</td>
<td>composite</td>
<td>soft - firm</td>
<td>very low during perennial ice cover, high (in general) during seasonal ice cover</td>
</tr>
<tr>
<td>Transition Offshore</td>
<td>Arenicolites ichnofacies</td>
<td>Diverse Cruziana ichnofacies</td>
<td>very composite</td>
<td>soft</td>
<td>alternating low energy fairweather conditions to high energy event conditions</td>
</tr>
<tr>
<td>Upper Offshore</td>
<td>Arenicolites ichnofacies</td>
<td>Proximal to Distal Cruziana ichnofacies</td>
<td>very composite</td>
<td>soft</td>
<td>very low with some high energy event conditions</td>
</tr>
<tr>
<td>Lower Offshore</td>
<td>Arenicolites / Cruziana and rare Glossifungites ichnofacies</td>
<td>Distal Cruziana ichnofacies</td>
<td>composite to very composite</td>
<td>soft, rarely firm</td>
<td>very low with uncommon moderate to high energy event conditions</td>
</tr>
</tbody>
</table>

Table 4.10. Ichnology of the Pebbley Beach and Snapper Point Formations.
Figure 1.1 Location map of the Permian to Triassic Sydney Bowen Basin of Eastern Australia (modified from Tadros 1993).
Figure 1.2 Location map of the southern Sydney Basin (modified from Tye et al. 1996); the study area consists of all coastal exposures between Point Upright and Jervis Bay
Figure 1.3 Updated Lithostratigraphic Model for the Southern Sydney Basin (modified after Tye et al. 1996).

Note Y.C.M is the Yurrunga Coal Measures.
Figure 1.4 Conceptual model of Permian evolution of the Sydney -Bowen Basin. Phase 1 formation of grabens and half grabens (corresponds to Veevers' stage A). Phase 2 passive thermal sag across the basin (corresponds to Veevers' stage B). Phase 3 uplift and active orogen (corresponds to Veevers' stage C-F). (Modified from Baker et al. 1993).
TRACE CHARACTERISTICS DIAGRAMATIC REPRESENTATION DIAGRAMATIC REPRESENTATION OF TRANSITIONAL FORMS

**Cylindrichnus concentricus**
Mostly vertical, subcylindrical burrows that have multiple, concentrically lined walls.

**Cylindrichnus eccentricus**
Long, subcylindrical to subconical burrows, predominantly vertical with an eccentrically positioned sand-filled tube and eccentrically layered walls.

**Poly cylindrichnus**
Vertical to inclined burrows that bud off one another to form a burrow system. Individual elements consist of concentrically lined subcylindrical burrows.

**Rosselia socialis**
Conical, bulbous or funnel-shaped structure consisting of a central burrow surrounded by broad concentric laminae tapering downward to a concentrically walled stem.

**Rosselia rotatus**
Conical, bulbous or funnel-shaped structure consisting of a central burrow surrounded by intensely developed, crescentic backfill structures formed by rotary movements of the tube within the funnel. The stem is concentrically walled.

**Rosselia motivus**
Concentrically lined conical, bulbous or funnel shaped structure with extensively developed lateral spreiten. The silt-lined central shaft is vertical to inclined and also contains lateral spreiten.

**Asterosoma**
Fan-shaped burrows consisting of numerous horizontal to vertical elements radiating from a common central shaft.

**Teichichnus rectus**
Straight, unbranched wall-shaped structures consisting of a pile of retrusive, gutter-shaped laminae.

**Teichichnus sinuosus**
Long, unbranched, moderately to strongly sinuous, stacked tunnels with retrusive spreiten.

**FIGURE 2.1a:** Variation in Cylindrichnus, Rosselia, Asterosoma and Teichichnus burrows in the Pebbley Beach and Snapper Point Formations.
pebbly sandstone the base of a thin transgressive deposit

*Cylindrichnus errans*

TSE (transgressive surface of erosion)

Glossifungites ichnofacies

*Scolithos*

Pebbley Beach Formation

silty sandstone lagoon and washover deposits

Figure 2.1b Idealized representation of the Glossifungites ichnofacies at the Snapper Point/Pebbley Beach Formation boundary at South Island Beach.
Figure 2.2 Parallel alignment of *Arenicolites* isp 2 in wave-rippled granular sandstone in the Snapper Point Formation.
Formation of *Asterosoma* (modified from Chamberlain 1971), a feeding/dwelling structure formed by a vermiform organism systematically probing the sediment to enlarge the burrow and exploit the substrate vertically and laterally.

**Figure 2.3a**
Figure 2.3b Cross-section through an idealized *Asterosoma* typical of the Pebbley Beach and Snapper Point Formations.
Figure 2.4 Cross-section through a typical Snapper Point Formation Calycraterion

Figure 2.5 Cylindrichnus concentricus typical of the Pebbley Beach and Snapper Point Formations.
Figure 2.6 (a) Cylindrichnus eccentricus typical of the Snapper Point Formation.
(b) tapered funnel top thickly silt-lined sand-filled tube thickly silt-lined sand-filled tube
(c) cross-section of silt-lined funnel truncated funnel top
Figure 2.6 (d) occurrence of *C. eccentricus*

Figure 2.7 *Cylindrichnus errans*
Figure 2.8a *Diplocraterion* morphology and terminology
Figure 2.8b

Two types of *Diplocraterion* present in the Pebbley Beach and Snapper Point Formations.
Diplocraterion habichi occurrence

Figure 2.9

(a) vertical view
diverging arms very rarely preserved

protrusive spreiten

retrusive spreiten

15 - 45 mm diameter

(b) plan view
silt-lining
sand fill
connecting spreite (protrusive)

(c) plan view of lateral escape structure
Figure 2.10
Different morphology of Planolites, Macaronichnus and Palaeophycus burrows.
Figure 2.11 Phycosiphon incertum (modified from Bromley 1996).

(a) plan view, spreiten dark, marginal tube white (opposite of the usual colour-play)
(b) standard segment showing spreiten, black core and white mantle
(c) alternately meniscate and homogeneous core, two sketches correlating structural details in a 'probe and run' model: 19 probes and 19 meniscate packages. The worm has the length of a lobe.
Figure 2.12a Branching patterns of *Polykladichnus irregularis* in the Snapper Point Formation.
Figure 2.12 b Bedding plane and vertical profile of *Polykladichnus irregularis* in the Snapper Point Formation
Figure 2.13a Plan view of *Rhizocorallium irregularum*, burrow shapes and sinuosity, in the Pebbley Beach and Snapper Point Formations

Figure 2.13b Three dimensional view showing vertical sinuosity and retrusive spreiten
Figure 2.14

Three types of *Rhizocorallium jenense* in the Pebbley Beach and Snapper Point Formations

(a) Type A, horizontal to oblique with vertically retrusive spreiten.

(b) Type B, horizontal with no obvious vertical spreiten.

(c) Type C, horizontal to oblique with vertically retrusive spreiten
Figure 2.15
Idealized representation of *Rosselia motivus* in the Pebbley Beach and Snapper Point Formations.
Figure 2.16
Idealized representation of *Rosselia rotatus* in the Pebbley Beach and Snapper Point Formations.
Figure 2.17

Idealized representation of *Rosselia socialis* in the Pebbley Beach and Snapper Point Formations. (a) general morphology (b) retrusive tube (c) stacked funnel
Figure 2.18 Forms of *Skolithos linearis* in the Pebbley Beach and Snapper Point Formations.

A funnel top
B long silt-lined
C coarser-grained sediment wall
D indistinct wall
E annulated wall
Figure 2.19
Three types of *Taenidium* present in the Pebbley Beach and Snapper Point Formations.

(a) *T.barretti*

(b) *T.barretti* burrow structure, deep tier, vertical section open to the sedimentary surface

(c) *T.serpentinum*

(d) *T.synyphes*
Figure 2.20
Two species of *Teichichnus* present in the Pebbley Beach and Snapper Point Formations

(a) *Teichichnus rectus*

(b) *Teichichnus sinuosus*
Conulariid morphology modified from Babcock & Feldman (1986a).

Figure 2.21 Close-up view of the groove with rods abutting against others to form the zigzag shaped central ridge
Key to Figure 3.1

1. *Palaeophycus* 10. *Hemdalia*
2. *Skolithos* 11. *Diplocraterion parallelum*
7. *Calycraterion* 16. *Gyrolithes saxonius*
8. *Cylindrichnus*
9. *Arenicolites*

Key to Figure 3.2

2. *Taenidium barretti* 11. *Diplocraterion parallelum*
4. *Asterosoma* 13. *Diplocraterion habichi*

Key to Figure 3.3

Key to Figures 3.4 & 3.5

1. Rosselia socialis
2. Palaeophycus tubularis
3. Planolites
4. Phycosiphon

Key to Figure 3.6

1. Arenicolites
2. Cylindrichnus
3. Gyrochorte
4. Phycosiphon
5. Skolithos
6. Conostichus
7. Diplocraterion parallelum
8. Psammichnites
9. Diplocraterion habichi
10. Polykladichnus
11. Taenidium synyphes
12. Rhizocorallium jenense
13. Planolites
14. Palaeophycus
15. Macaronichnus

Key to Figure 3.7

1. Thalassiniodes
2. Arenicolites?
3. Rhizocorallium jenense
4. Diplocraterion habichi
5. Arenicolites statheri
6. Skolithos
Figure 3.1 Visual representation of trace fossils present in the Skolithos ichnofacies in the Pebbley Beach and Snapper Point Formations
Figure 3.2 Visual representation of trace fossils present in the proximal Cruziana ichnofacies in the Pebbley Beach and Snapper Point Formations
Figure 3.3 Visual representation of trace fossils present in the diverse Cruziana ichnofacies in the Pebbley Beach and Snapper Point Formations
Figure 3.4 Visual representation of trace fossils present in the distal Cruziana ichnofacies in the Pebbley Beach and Snapper Point Formations
Figure 3.5  Visual representation of trace fossils present in the restricted Cruziana ichnofacies in the Pebbley Beach and Snapper Point Formations
Figure 3.6 Visual representation of trace fossils present in the Arenicolites ichnofacies in the Pebbley Beach and Snapper Point Formations
Figure 3.7 Visual representation of trace fossils present in the Glossifungites ichnofacies in the Pebbley Beach and Snapper Point Formations
<table>
<thead>
<tr>
<th>Grade</th>
<th>Percent Bioturbated</th>
<th>Classification</th>
<th>Visual representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>No bioturbation</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1-4</td>
<td>Sparse bioturbation, bedding distinct, few discrete traces and/or escape structures</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5-30</td>
<td>Low bioturbation, bedding distinct, low trace density, escape structures often common</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>31-60</td>
<td>Moderate bioturbation, bedding boundaries sharp, traces discrete, overlap rare</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>61-90</td>
<td>High bioturbation, bedding boundaries indistinct, high trace density with overlap common</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>91-99</td>
<td>Intense bioturbation, bedding completely disturbed (just visible), limited reworking, later burrows discrete</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>Complete bioturbation, sediment reworking due to repeated overprinting</td>
<td></td>
</tr>
<tr>
<td>6:2</td>
<td>100 + up to 10% overprint</td>
<td>Mottled background with minor discrete traces overprinted</td>
<td></td>
</tr>
<tr>
<td>6:3</td>
<td>100 + 10-20% overprint</td>
<td>Mottled background with moderate overprinting by discrete traces</td>
<td></td>
</tr>
<tr>
<td>6:4</td>
<td>100 + &gt; 20% overprint</td>
<td>Mottled background with high to intense overprinting by discrete traces</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.8 Bioturbation Index (BI). Each grade is described in terms of the primary sedimentary fabric, burrow abundance and amount of burrow overlap; adapted from Taylor & Goldring (1993) and Droser & Bottjer (1990).
Order of deposition and bioturbation

Primary Fabric:
physical sedimentary structures that can be subsequently reworked (e.g. wave modified)

Secondary Fabric:
bioturbation structures

Shallow tier burrows:
low preservation potential of the indistinct (substrate low shear strength), and small feeding traces

Hiatus:
hiatal surface colonized by new community, burrow overlap pronounced (elite trace fossils, and possibly Glossifungites ichnofacies)

Deep tier burrows
high preservation potential of large feeding and dwelling structures (elite trace fossils)

Figure 3.9 An ichnofabric constituent diagram: a visual representation of an ichnofabric (modified from Taylor & Goldring 1993). Percentage area occupied by the sedimentary structures and burrow types are plotted on a log-scale along the horizontal axis. Events are recorded on the vertical axis in order of occurrence from initial sedimentation events (primary fabric) to subsequent modification by bioturbation (secondary fabric). The order of burrowing is ascertained from cross-cutting relationships which either relate to the initial community structure (infaunal tiers) or to hiatal events and the superimposition of a new infaunal community. Sedimentary unit size and burrow dimensions are shown on the vertical axis. The symbols represent vertical cross-section views of the burrows.
Mixed layer
Total bioturbation of sediments and uniform colour.

Transition layer
Distinct burrows and marked colour contrasts associated with variable oxygenation of the sediment.

Historical layer
More uniform colour, below the level to which most bioturbators reach.

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**Figure 3.10 Generalized tiering profile showing the different layers and characteristics**
<table>
<thead>
<tr>
<th>Backshore</th>
<th>Psilonichnus ichnofacies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreshore</td>
<td>High Tide</td>
</tr>
<tr>
<td></td>
<td>Low Tide</td>
</tr>
<tr>
<td>Upper Shoreface</td>
<td>Skolithos ichnofacies</td>
</tr>
<tr>
<td>Middle Shoreface</td>
<td>Feeding</td>
</tr>
<tr>
<td>Lower Shoreface</td>
<td>Suspension</td>
</tr>
<tr>
<td>Transition</td>
<td>Feeding</td>
</tr>
<tr>
<td>Upper Offshore</td>
<td>Deposit</td>
</tr>
<tr>
<td>Lower Offshore</td>
<td>Distal Cruziana ichnofacies</td>
</tr>
<tr>
<td>Shelf</td>
<td>Storm wave base</td>
</tr>
</tbody>
</table>

|              | Maximum Fairweather wave base |
|              | Proximal Cruziana ichnofacies |
|              | Distal Cruziana ichnofacies |

**Figure 3.11** Idealized shoreface model, (modified after Pemberton et al. 1992e), showing the shallow marine environments and associated ichnofacies represented in the Pebbley Beach and Snapper Point Formations.
Figure 3.12 Key for tiering diagrams

1. Diplocraterion habichi
2. Diplocraterion parallelum
3. Polykladichnus
4. Skolithos
5. Cylindrichnus
6. Fugichnia
7. Polycylindrichnus
8. Psammichnites
9. Arenicolites
10. Rosselia
11. Planolites
12. Fallospophycus
13. Ophiomorpha?
14. Rhizocorallium
15. Taenidium synyphes
16. Tiechichnus
17. Astereosma
18. Macaronichnus
19. Phycosiphon incertum
20. Taenidium synyphes
Figure 3.13 *Phycosiphon* A composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.14 *Phycosiphon* B ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.15 *Diplocraterion* ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.16 *Phycosiphon-Diplocraterion* composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile (a: traces = fair-weather assemblage; b: traces = post-storm opportunistic assemblage).
mottled burrows
HCS sandstone with Lam-Scram bedding, and common rippled tops
Psammichnites
Diplocraterion habichi
Rosselia/Asterosoma
Teichichnus
Phycosiphon
Rhizocorallium irregularare

Figure 3.17 Teichichnus-Rosselia / Asterosoma-Phycosiphon composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.18 Teichichnus-Rosselia motivus Diplocraterion habichi composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile (a traces = fair-weather assemblage; b traces = post-storm opportunistic assemblage).
Figure 3.19 Mottled flaser-bedded ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile

1. Mottled burrows

2. Phycosiphon
Figure 3.20 *Polycyllindrichnus* composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Massive sand, sparse silt & coarser sand lenses.

Mottled texture

large *Rhizocorallium jenense*

*Diplocraterion parallelum*

*Palaeophycus*

*Planolites*

*Asterosoma*

*Rhizocorallium irregulare*

*Taenidium synyphes*

*Phycosiphon*

Figure 3.21 *Rhizocorallium irregulare-Asterosoma* composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.22 Escape trace ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
1. Mottled burrows
2. *Asterosoma*
3. *Teichichnus*
4. *Phycosiphon*

Figure 3.23 *Teichichnus* composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.24 *Asterosoma-Teichichnus-Diplocraterion parallelum* composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.25 *Rosselia-Teichichnus-Diplocraterion parallelum* composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
laminated and low-angle cross-bedded mud, silt and fine sand.

Skolithos
and escape traces

Phycosiphon

Rosselia

Planolites

Figure 3.26 Phycosiphon-Planolites ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.27 *Diplocraterion habichi*-Phycosiphon ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.28 Diplocraterion parallelum-Macaronichnus ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.29 Rosselia-Rhizocorallium-Phycosiphon composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.30 Diplocraterion parallelum-Macaronichnus-Teichichnus-Rosselia composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.31 *Rhizocorallium jenense* composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile.
1. Mottled burrows
2. Skolithos
3. Arenicolites
4. Diplocraterion parallelum
5. Phycosiphon

Figure 3.32 mottled burrow-Glossifungites composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.33 *Macaronichnus* ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.34 *Polykladichnus* ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.35 *Teichichnus-Diplocraterion parallelum* composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.36 *Monocraterion-Skolithos* ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.37 *Gyrolithes* ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.38 *Cylindrichnus eccentricus* ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 3.39 *Diplocraterion habichi-Thalassinoides* (Glossifungites)-*Phycosiphon* composite ichnofabric; (a) ichnofabric constituent diagram; (b) tiering profile
Figure 4.1 Tiering profile for estuarine-intertidal channel deposits in the Pebbley Beach Formation.
Figure 4.2. Tiering profile for tidal flat deposits in the Pebbley Beach Formation.
1. Planolites
2. Palaeophycus
3. Rosselia
4. Phycosiphon

Figure 4.3. Tiering profile for lagoon deposits in the Pebbley Beach Formation.
Figure 4.4. Tiering profile for flood-tidal delta/washover deposits in the Pebbley Beach Formation.
Figure 4.5. Tiering profile for tidal-inlet deposits in the Pebbley Beach Formation.

1. Diplocraterion parallelum
2. Cylindrichnus
3. Rosselia
Figure 4.6. Tiering profile of the infaunal communities in fairweather and event deposits in the backbarrier facies association in the Pebbley Beach Formation.
Figure 4.7 Diagrammatic representation of the Pebbley Beach Formation backbarrier environment.

(a) estuarine intertidal channel facies  
(b) tidal flat facies  
(c) lagoon facies  
(d) washover facies  
(e) tidal inlet facies  
(f) barrier beach complex  
(g) shoreface facies
Figure 4.8. Tiering profile for the foreshore facies in the Snapper Point Formation.
1. Arenicolites
2. Calycraterion
3. Palaeophycus

4. Rhizocorallium jenense
5. Rosselia socialis
6. Asterosoma
7. Diplocraterion parallelum
8. Diplocraterion habichi
9. Heimdalia
10. Monocraterion
11. Polykladichnus
12. Skolithos
13. Phycosiphon
14. Macaronichnus

Figure 4.9. Tiering profile for the upper shoreface facies in the Pebbley Beach and Snapper Point Formations.
Figure 4.10. Tiering profile for the middle shoreface facies in the Pebbley Beach and Snapper Point Formations.
Figure 4.11. Tiering profile of the infaunal communities in fairweather and storm deposits in lower shoreface facies in the Pebbley Beach and Snapper Point Formations.
Figure 4.12 Tiering profile of the infaunal communities in fairweather and storm deposits in the upper offshore and transition offshore facies in the Pebbley Beach and Snapper Point Formations.
Figure 4.13 Tiering profile of the infaunal communities in fairweather and event deposition in the lower offshore facies in the Pebbley Beach and Snapper Point Formations.
Figure 4.14. Schematic diagram illustrating the distribution of common trace fossils in offshore environments in the Pebbley Beach and Snapper Point Formations.
(a) Mudstone deposited under very low energy conditions beneath a sea-ice cover.

(b) Opportunistic colonization of the firm mudstone substrate by *Diplocraterion habichi* and *Thalassinoides paradoxicus*.

(c) Deposition of diamictite and infill of the Glossifungites ichnofacies with coarse-grained material.

*Figure 4.15 Development of the Glossifungites ichnofacies at South Pebbles, Pebbley Beach Formation*
Figure 5.1 Evolution of sharp-based shoreface deposits in response to relative sea level fall. Lowering relative sea level from time 1 to time 4 results in successive lowering of fairweather wave base (FWWB) and scour of the sea floor in advance of the prograding shoreface (after Swift 1976, Plint 1988 and Posamentier et al. 1996).
Figure 5.2 Example of a forced regression in the upper Snapper Point Formation.
DEPOSITIONAL ENVIRONMENT

ICNOFACES

Snapper Point Formation

RELATIVE SEA LEVEL

HIGH

LOW

Figure 5.3 Measured section of the upper exposed Pebbley Beach Formation.
Figure 5.4 Diagrammatic representation of the Glossifungites ichnofacies at Clear Point, Pebbley Beach Formation.

- **A**: lagoonal mudstone deposits with interbedded sandy intertidal channel deposits and a mixed Restricted Cruziana/Arenicolites ichnofacies.
- **TSE (or transgressive surface of erosion)**: contains a Glossifungites ichnofacies comprising *Diplocraterion habichi* and reflects a depositional hiatus.
- **B**: a 30 cm pebbly sandstone transgressive lag capped with *Eurydesma hobatense* and other shells.
- **C**: silty sandstone beds with mixed Distal Cruziana/Arenicolites ichnofacies.
Figure 5.5a Measured section of the lower exposed Snapper Point Formation.
Figure 5.5b Measured section of the upper exposed Snapper Point Formation.

DEPOSITIONAL ENVIRONMENT

TIDE-DOMINATED FORESHORE

80 m

ICHNOFACIES

Skolithos

RELATIVE SEA LEVEL

HIGH

LOW

CYCLE 3

Forced regression

LOWER OFFSHORE

Transgressive deposit

OFFSHORE TRANSITION

Cruziana

MIDDLE-UPPER SHOREFACE

Distal Skolithos

LOWER SHOREFACE

Proximal Cruziana

FORESHORE

Skolithos

UPPER SHOREFACE

Distal Skolithos

MIDDLE SHOREFACE

For detail see Fig. 5.2.
Figure 5.6 Detailed sections of the basal contact of the Snapper Point Formation at South Island Beach and Clear point. At South Island Beach the contact is recognized on the basis of a Glossifungites ichnofacies and ichnofabric change across the flooding surface.
Figure 5.7 Measured sections of the Snapper Point Formation showing the correlation between western areas—seen in the Elcom Clyde River (ECR) drill cores (sections from Tye 1995) and the measured coastal exposure. Assuming that the formation is of similar thickness in ECR 10, ECR 11 and at the coast, it is estimated that there is approximately 100-150 m of coastal exposure missing from the centre of the formation and 5-10 m missing from the top of the formation.
Figure 5.8 Measured section of cycle 2 (at South Pebbles) in the Pebbley Beach Formation showing 5th order Milankovitch cyclicity. The diamictite beds represent periods of seasonal ice cover and the interbedded mudstone beds reflect deposition during perennial ice cover (for a detailed description see Ch 4 and 5).
Figure 5.9 Palaeogeographic development of the southern Sydney Basin (after Tye 1995)

(a) Rifting and deposition of the Clyde Coal Measures and Wasp Head Formation in grabens or half grabens.
(b) Passive thermal subsidence and deposition of the Yadboro and Tallong Conglomerates, the Yurrunga Coal Measures and the Pebbley Beach Formation.
(c) Major flooding event which initiated deposition of the Snapper Point Formation.
(d) A second major flooding event accompanied by foreland loading at the orogen, emergence of the orogen and subaerial volcanism. Deposition of the Wandrawandian Siltstone.
(e) Tectonic quiescence resulted in the progradation of a clastic wedge; the Nowra Sandstone.
(f) Renewed foreland loading accompanied a third flooding event and resulted in the deposition of the Berry Siltstone.
Figure 5.10 Reconstruction of Gondwana continents during the Late Palaeozoic showing migration path of the south magnetic pole. During the Early Permian the pole was situated in Eastern Antarctica, close to the Sydney Basin of Eastern Australia. (Modified from Crowell & Frakes 1975).
(a) *Arenicolites statheri*. Preserved as part of a Glossifungites ichnofacies beneath a transgressive surface of erosion, at South Island Beach at the base of the Snapper Point Formation.

(b) *Arenicolites* isp1. Plan view, north Termeil Point, Snapper Point Formation.

(c) *Arenicolites* isp2. Plan view, Banisters Point, Snapper Point Formation.

(d) Large floral *Asterosoma* sp., vertical section, Pretty Beach, Snapper Point Formation.

(e) *Asterosoma* sp., vertical section, South Island Beach, Snapper Point Formation.

(f) *Asterosoma* sp. with long retrusive sand-tube. Nugans Point, Snapper Point Formation.

(g) *Asterosoma* sp., vertical section, O’Hara Island, Snapper Point Formation.

(h) *Calycraterion samsonowiczi*, vertical view through two calyces. Specimen collected from the top of Snapper Point, Snapper Point Formation.

(i) *Asteriacites* sp. and associated *Skolithos*, plan view, float specimen, south Snapper Point, Snapper Point Formation.
PLATE 2.2

(a) Conostichus sp., showing apical disc (a.d). Vertical section, South Island Beach, Pebbley Beach Formation.

(b) Conostichus sp., showing apical disc (a.d). Vertical section, Mill Point, Pebbley Beach Formation.

(c) Conostichus sp., vertical section, south Snapper Point, Snapper Point Formation.

(d) Calycraterion samsonowiczi, plan view of calyxes, top of Snapper Point, Snapper Point Formation.

(e) Calycraterion samsonowiczi, plan view of calyxes with outlets visible, top of Snapper Point, Snapper Point Formation.

(f) Cylindrichnus errans, vertical cross-section showing sand-tube and lateral spreiten. South Island Beach, Snapper Point Formation.

(g-j) Cylindrichnus eccentricus, vertical view, silt-lined funnel with eccentrically positioned sand-tube. Bannisters Point, Snapper Point Formation.

(k) Cylindrichnus concentricus, vertical view, Snapper Point, Snapper Point Formation.
PLATE 2.3

(a) *Diplocraterion habichi*, cluster of burrows in plan view. Mill Point, Pebbley Beach Formation.

(b-c) *D. habichi*, plan view of unlined sand-filled burrows representing a Glossifungites ichnofacies, South Pebbles, Pebbley Beach Formation.

(d-f) *D. habichi*, vertical view. Clear Point, Pebbley Beach Formation; south of South Island Beach, Snapper Point Formation; and Mill Point, Pebbley Beach Formation.

(g-h) *D. habichi*, plan view. Mill Point, Pebbley Beach Formation; and Termeil Point, Snapper Point Formation. Note the raised rim in Pl. (h) reflecting the more resistant nature of the mucus lining on the burrow.

(i) The base of a U-Tube of *Diplocraterion parallelum* (Dp) and *Phycosiphon incertum* (P) visible as small black dots & dashes. Vertical section, Snapper Point, Snapper Point Formation.

(j) Vertical view of *D. parallelum* showing parallel arm (p.a) and retrusive spreiten. Molymook Beach sea wall (sandstone transported from Milton quarry), Snapper Point Formation.

(k) *D. parallelum*, plan view showing U-Tube openings connected by black, silty, protrusive spreite. Meroo Point, Snapper Point Formation.
PLATE 2.4

(a) *D. parallelum* showing parallel arm (p.a). Bannisters Point, Snapper Point Formation.

(b) Truncated *D. parallelum* with well-preserved retrusive spreiten. Mill Point, Pebbley Beach Formation.

(c) *D. parallelum* showing parallel arm (p.a). Nugans Point, Snapper Point Formation.

(d) Plan view of *D. parallelum* occurrence. Meroo Point, Snapper Point Formation.

(e-f) Retrusive spreiten (r.s) in *D. parallelum*. Vertical view, Molymook Beach sea wall (sandstone transported from Milton Quarry), Snapper Point Formation; Oblique view, Meroo Point, Snapper Point Formation.

(g) Large *D. parallelum* with 15 cm deep retrusive spreiten (r.s) and silt-lined, sand-filled living chamber (s.c). Vertical view, Snapper Point, Snapper Point Formation.
(a-b) Plan view of *Heimdallia chatwini*, Snapper Point, Snapper Point Formation.

(c) Plan view of the final stage burrow of *Heimdallia chatwini*, Snapper Point, Snapper Point Formation.

(d) *Gordia* sp. Plan view, South Island Beach, Pebbley Beach Formation.

(e) Plan view of *Margaritichnus* sp. Willinga Point, Snapper Point Formation.

(f-h) *Gyrolithes saxonicus* (*G*). Vertical View, Jervis Bay, Snapper Point Formation.

(i) Pectin shell with *Macaronichnus segregatis* (*M*) in the sand-fill. Vertical view, Snapper Point, Snapper Point Formation.

(j) Vertical view of *M. segregatis* (*M*). Snapper Point, Snapper Point Formation.

(k) Plan view of *M. segregatis* (*M*). Bannisters Point, Snapper Point Formation.
PLATE 2.6

(a) *Monocraterion tentaculum*, vertical view, Bannisters Point, Snapper Point Formation.

(b) Plan view of *Palaeophycus heberti* (*Ph*). Snapper Point, Snapper Point Formation.

(c) Vertical view of silt-lined *P. heberti* (*Ph*) and *Phycosiphon incertum* (*P*). Pretty Beach, Snapper Point Formation.

(d) Plan view of thickly lined *P. heberti* (*Ph*). Snapper Point, Snapper Point Formation.

(e) *Palaeophycus tubularis* (*Pt*) and small, indistinct *Phycosiphon incertum*. Vertical view, Snapper Point, Snapper Point Formation.

(f) Photomicrograph of *P. incertum*. Width of the field of view is 3 mm. Rock sample from South Island Beach, Snapper Point Formation.

(g) Binocular photomicrograph of *P. incertum* with individual segments visible (see Fig. 2.11 for a diagrammatic representation and explanation of formation. Scale increments are mm. Sample from the south side of Snapper Point, Snapper Point Formation.

(h-k) *P. incertum*. Vertical view (except (j) is plan view). (h) is from Pretty Beach, Snapper Point Formation; (i) shows reworking of *D. habichi*? burrows, from the south side of Snapper Point, Snapper Point Formation; and (j-k) are from South Pebbles, Pebbley Beach Formation.
(a-b) *Planolites montanus (Pl)*. Plan view, Clear Point, Snapper Point Formation; plan view, Clear Point, Pebbley Beach Formation.

(c) *Polykladichnus irregularis*. Vertical view, Meroo Point, Snapper Point Formation.

(d) *Polycylindrichnus prolifer*. Vertical view, South Island Beach, Pebbley Beach Formation.

(e) Vertical view of *Planolites beverleyensis*. Snapper Point, Snapper Point Formation.

(f) Plan view of *Planolites beverleyensis*. Clear Point, Snapper Point Formation.

(g) Plan view of *Diplocraterion habichi* (top left) and *Psammichnites gigas*. South Pebbles, Pebbley Beach Formation.

(h-i) *Psammichnites gigas*. Plan view, Mill Point, Pebbley Beach Formation.

(j-k) *Ophiomorpha?* Vertical view, Jervis Bay, Snapper Point Formation.
PLATE 2.8

(a-b) *Rhizocorallium irregulare*. Plan view, Pretty Beach, Snapper Point Formation.

(c-d) Plan view of large *Rhizocorallium irregulare*. Associated burrows include *Phycosiphon incertum* (black dots and dashes in the top U-tube arm of Pl. c), *Cylindrichnus concentricus* (vertical silt-lined sand tubes) and *Rosselia socialis* (left side of Pl. d). South Island Beach, Snapper Point Formation.

(e) Plan view of *Rhizocorallium jenense* (type B) with widely spaced, silt-lined spreiten. South Island Beach, Pebbley Beach Formation.

(f) Plan view of *R. jenense* (type B). Float stone at Point Upright, fallen from the Snapper Point Formation.

(g) Oblique view through *R. jenense* (type A) showing vertically retrusive spreiten (v.r.s). Bannisters Point, Snapper Point Formation.

(h) Oblique view through *R. jenense* (type A) showing a collapsed U-tube wall (c.U). Snapper Point, Snapper Point Formation.

(i) Oblique view through *R. jenense* (type A) with spreiten not preserved. Banisters Point, Snapper Point Formation.

(j) Vertical view through *R. jenense* (type A) showing two arms of the U-tube and the connecting spreite. Meroo Point, Snapper Point Formation.
PLATE 2.9

(a-b) *R. jenense* (type B). South Pebbles, Pebbley Beach Formation; Clear Point, Pebbley Beach Formation.

(c) Plan view of *R. jenense* (type C) with visible spreiten (uncommon for this type). Snapper Point, Snapper Point Formation.

(d) Plan view of long *R. jenense* (type C). Also present is *Vacunella* in life position (bottom left). Snapper Point, Snapper Point Formation.

(e) Vertical view through *R. jenense* (type C) showing the sand-filled living tube (l.t) and the spreiten (sp). Nugans Point, Snapper Point Formation.

(f) Plan view of *R. jenense* (type C) in a coquinite bed. Broken shell material defines the spreiten. Snapper Point, Snapper Point Formation.

(g) Thickly silt-lined *R. jenense* (type C) U-tube limb (U 1) curving upward toward the sedimentary surface. Snapper Point, Snapper Point Formation.

(h) Occurrence of *R. jenense* (type C) in plan view. Snapper Point, Snapper Point Formation.
PLATE 2.10

Rosselia motivus

Holotype UWF. 3807, paratypes 3808-3809.

(a) Binocular photomicrograph of a cut section through the funnel and lateral spreiten. Sample from South Island Beach, Snapper Point Formation.

(b) Binocular photomicrograph of a cut section through the lower portion of the sand tube and lateral spreiten. Small black ticks and spots are *Phycosiphon incertum*. Same sample as above.

(c) Plan view through funnels and shafts with extensive lateral spreiten. South of South Island Beach, Snapper Point Formation.

(d) Plan view through funnels with lateral spreiten. South Snapper Point, Snapper Point Formation.

(e-f) Plan view of funnels and tubes with extensive lateral spreiten. South of South Island Beach, Snapper Point Formation.
PLATE 2.11

(a) Vertical view of *Rosselia rotatus* showing the retrusive nature of the lower part of the sand tube (r.s). Mill Point, Pebbley Beach Formation.

(b) *R. rotatus* in plan view showing the funnel fill and multiple sand tubes. South Pebbles, Pebbley Beach Formation.

(c) Plan view of *R. rotatus* funnel fill showing crescentric backfill and contorted sediment. Clear Point, Pebbley Beach Formation.

(d) *R. rotatus* showing retrusive spreiten on the lower portion of the sand tube. Vertical view, Bannisters Point, Snapper Point Formation.

(e) *R. socialis* with a stacked funnel structure. Vertical view, Clear Point, Snapper Point Formation.

(f) Vertical view of *R. rotatus*. South Island Beach, Snapper Point Formation.

(g) Plan view of *R. rotatus* showing funnel fill and associated retrusive spreiten which appears very much like *Teichnichnus rectus*. South Pebbles, Pebbley Beach Formation.

(h) Plan view through several *R. rotatus* funnels and sand tubes. Some funnels exhibit multiple sand tubes. South Snapper Point, Snapper Point Formation.

(i) Plan view of *R. socialis* funnel showing mixing of the laminae in the outer portion of the funnel. Also present as small black spots is *Phycosiphon incertum*. Clear Point, Snapper Point Formation.

(j) *R. socialis* funnel underneath a bivalve shell. Plan view, Snapper Point coquinite bed, Snapper Point Formation.

(k) Plan view of double *R. socialis* funnel. Clear Point, Snapper Point Formation.

(l) *R. socialis* funnels, plan view, south of South Island Beach, Snapper Point Formation.

(m) Double *R. socialis* funnels, plan view, Snapper Point, Snapper Point Formation.

(n) Small, closely packed *R. socialis* funnels. Plan view, Clear Point, Pebbley Beach Formation.
PLATE 2.12

(a) Large *Rosselia socialis* with associated retrusive sand tubes. Vertical view, Mill Point, Pebbley Beach Formation.

(b) Stacked *R. socialis* funnel. Vertical view, Clear Point, Snapper Point Formation.

(c) Truncated robust *R. socialis* with extensive retrusive spreiten (r.s) on the sand tube. Vertical view, Meroo Point, Snapper Point Formation.

(d-e) & (g) Vertical view of truncated *Skolithos linaris*. (d) and (e) are from laterally equivalent facies at South Snapper Point and Termeil Point in the Snapper Point Formation; (e) is from Bannisters Point, Snapper Point Formation.

(f) & (h) Plan view of erosional funnel tops on *S. linaris* burrows. (h) also contains *Gyrochorte camosa* (right of the camera lens). Snapper Point, Snapper Point Formation.
(a) Binocular photomicrograph of plan view of *Taenidium synyphes* (Holotype UWF. 3810). Collected from O’Hara Island, Snapper Point Formation. Scale increments are mm.

(b) Binocular photomicrograph of *T. synyphes*. Same specimen as above.

(e) & (g) Plan view of *T. barretti* showing meniscus back-fill. Mill Point, Pebbley Beach Formation.

(f) Plan view of *T. barretti* (*Tb*) overprinting *Teichichnus rectus* (*Tr*) and *Phycosiphon incertum* (*P*). Mill Point, Pebbley Beach Formation.

(c) Plan view of *Taenidium serpentinum*. Clear Point, Pebbley Beach Formation.

(d) Plan view of *Taenidium barretti* showing sand-filled, vertical connection shafts. Mill Point, Pebbley Beach Formation.
PLATE 2.14

(a) Plan view of *Taphrhelminthopsis circularis* showing irregular circling nature. Bannisters Point, Snapper Point Formation.

(b) Plan view of *T. circularis* displaying internal, oblique striations. Bannisters point, Snapper Point Formation.

(c-d) *Teichichnus rectus*. Plan view, Snapper Point, Snapper Point Formation; Mill Point, Pebbley Beach Formation.

(e) *T. rectus* showing offset spreiten. Vertical-oblique view, South Island Beach, Snapper Point Formation.

(f) Vertical cross-section through the tunnel and spreiten of *Teichichnus sinuosus*. South Island Beach, Snapper Point Formation.

(g) Plan View of *T. sinuosus*. South Pebbles, Pebbley Beach Formation.

(h-i) Vertical-oblique view through *T. sinuosus*. South Island Beach, Snapper Point Formation.
PLATE 2.15

(a) *Thalassinoides paradoxicus*? Plan view, Jervis Bay, Snapper Point Formation.

(b-c) Plan view of unlined sand-filled *T. paradoxicus*? Representing part of a Glossifungites ichnofacies assemblage. South Pebbles, Pebbley Beach Formation.

(d) Truncated *Rosselia rotatus* burrows with an associated escape structure (connected to the top right of the right burrow). Vertical view, Snapper Point, Snapper Point Formation.

(e-f) Pouch-shaped *fugichnia* with structureless infill. Vertical view, Mill Point, Pebbley Beach Formation; South Island Beach, Pebbley Beach Formation.
(a) *Phycosiphon* A ichnofabric. *Phycosiphon incertum* seen as small dark ticks and dots. Vertical view, Mill Point, Pebbley Beach Formation.

(b) *Phycosiphon* A ichnofabric with *Diplocraterion habichi* (Dh) and *Rhizocorallium?* (Rh). Vertical view, Mill Point, Pebbley Beach Formation.

(c) *Phycosiphon* A ichnofabric with *Diplocraterion parallelum* (Dp) and its associated retrusive spreiten. The speckled appearance of the surrounding sediment is due to pervasive *P. incertum*. Vertical view, Mill Point, Pebbley Beach Formation.

(d) *Phycosiphon* B ichnofabric with pervasive *P. incertum*. Plan view, South Island Beach, Snapper Point Formation.

(e) *Diplocraterion* ichnofabric evident in the lower sandstone bed as a vertical fabric. Vertical view, Clear Point, Pebbley Beach Formation.

(f) *Diplocraterion* ichnofabric evident in sandstone. Vertical view, Mill Point, Pebbley Beach Formation.

(g) *Phycosiphon-Diplocraterion* composite ichnofabric. The vertical, unlined sand-filled burrows are *D. habichi* and represent a Glossifungites ichnofacies. Vertical view, Clear Point, Pebbley Beach Formation.

(h) *Phycosiphon-Diplocraterion* composite ichnofabric. Vertical view, Mill Point, Pebbley Beach Formation.

(i) *Phycosiphon-Diplocraterion* composite ichnofabric. Vertical view, south Snapper Point, Snapper Point Formation.

(j) *Teichichnus-Rosselia/Asterosoma-Phycosiphon* composite ichnofabric with *Rosselia* (R) and *Teichichnus* (T). Vertical view, Mill Point, Pebbley Beach Formation.
(a) *Teichichnus-Rosselia/Asterosoma-Phycosiphon* composite ichnofabric dominated by *Teichichnus*. Vertical view, Mill Point, Pebbley Beach Formation.

(b) *Teichichnus-Rosselia/Asterosoma-Phycosiphon* composite ichnofabric with *Rosselia socialis* (Rs) and *Teichichnus* (T). Vertical view, Mill Point, Pebbley Beach Formation.

(c) *Teichichnus-Rosselia/Asterosoma-Phycosiphon* composite ichnofabric with *Diplocraterion habichi* (Dh) and *Rosselia motivus* (Rm). Plan view, South Pebbles, Pebbley Beach Formation.

(d) *Teichichnus-Rosselia/Asterosoma-Phycosiphon* composite ichnofabric showing *Diplocraterion habichi* (Dh) and *Psammichnites gigas* (Ps). Plan view, South Pebbles, Pebbley Beach Formation.

(e) *Teichichnus-Rosselia/Asterosoma-Phycosiphon* composite ichnofabric with *Rosselia rotatus* (Rr) and large *Rhizocorallium* (Ri). Vertical view, South Pebbles, Pebbley Beach Formation.

(f) *Teichichnus-Rosselia/Asterosoma-Phycosiphon* composite ichnofabric with *Asterosoma* (A), note the connected *Teichichnus*-like tube at the base of the funnel structure. Vertical view, South Pebbles, Pebbley Beach Formation.

(g) *Teichichnus-Rosselia motivus-Diplocraterion habichi* composite ichnofabric with mottled *R. motivus* and possible *Teichichnus*. Vertical view, south of South Island Beach, Snapper Point Formation.

(h) *Teichichnus-Rosselia motivus-Diplocraterion habichi* composite ichnofabric with vertical, silt-lined *D. habichi* and a mottled background texture. Vertical view, South Island Beach, Snapper Point Formation.
(a) *Teichichnus-Rosselia motivus-Diplocraterion habichi* composite ichnofabric with silt-lined *D. habichi* (Dh) and *Phycosiphon incertum* (P) with a mottled background texture. Plan view, south of South Island Beach, Snapper Point Formation.

(b) *Teichichnus-Rosselia motivus-Diplocraterion habichi* composite ichnofabric with silt-lined *D. habichi* (Dh) that have been largely reworked by *Phycosiphon incertum* (P), with a mottled background texture. Vertical view, South Island Beach, Snapper Point Formation.

(c) *Polycylindrichnus* composite ichnofabric. Vertical view, South Island Beach, Pebbley Beach Formation.

(d) Mottled flazer-bedded ichnofabric. Vertical view, Mill Point, Pebbley Beach Formation.

(e) Amalgamated beds of the *Polycylindrichnus* composite ichnofabric. Vertical view, South Island Beach, Pebbley Beach Formation.

PLATE 3.4

(a) *Rhizocorallium irregular-Asterosoma* composite ichnofabric. *Asterosoma* with a mottled background texture. Vertical view, Pretty Beach, Snapper Point Formation.

(b-c) Escape trace ichnofabric. Vertical view, south side of Snapper Point, Snapper Point Formation.

(d) *Teichichnus* ichnofabric. *Teichichnus sinuosus* with scattered pebbles. Vertical-oblique view, South Island Beach, Snapper Point Formation.

(e) *Teichichnus* ichnofabric. *Asterosoma* (A) with connected *Teichichnus* (T). Vertical view, South Island Beach, Snapper Point Formation.

(f) *Teichichnus* ichnofabric. *Teichichnus sinuosus* with tube alignment. Vertical view, South Island Beach, Snapper Point Formation.

(g) *Teichichnus* ichnofabric. *Teichichnus sinuosus* with *Asterosoma* (A) and scattered pebbles. Vertical-oblique view, South Island Beach, Snapper Point Formation.
PLATE 3.5

(a) Asterosoma-Teichichnus-Diplocraterion parallelum composite ichnofabric. The base of a large truncated *D. parallelum* (Dp) associated with *Asterosoma* (A) and *Teichichnus* (T). Vertical view, south side of Snapper Point, Snapper Point Formation.

(b) Asterosoma-Teichichnus-Diplocraterion parallelum composite ichnofabric. Cross section through the living tube of a large *D. parallelum* (Dp) associated with very broad floral *Asterosoma* (A). Vertical view, south side of Snapper Point, Snapper Point Formation.

(c) Phycosiphon-Planolites ichnofabric. Laminated bedding with some lam-scram bioturbation. Vertical view, south side of Snapper Point, Snapper Point Formation.


(e) Rosselia-Teichichnus-Diplocraterion parallelum composite ichnofabric. *Rosselia rotatus* with basal *Teichichnus*-like tubes. Vertical-oblique view, Meroo Point, Snapper Point Formation.

(f) Rosselia-Teichichnus-Diplocraterion parallelum composite ichnofabric. Cross-section through the living chamber (R) and connecting spreite (black silty material between the tubes). Note also the retrusive spreiten under the living tubes defined by black silty material. *Phycosiphon incertum* (P) is also present. Vertical view, Nugans Point, Snapper Point Formation.

(g) Rosselia-Teichichnus-Diplocraterion parallelum composite ichnofabric showing a mottled texture. Vertical view, Crampton Island, Snapper Point Formation.
(a) *Diplocraterion habichi*-Phycosiphon ichnofabric. Plan view of silt-lined *Diplocraterion habichi* burrows. South side of Snapper Point, Snapper Point Formation.

(b) *Diplocraterion habichi*-Phycosiphon ichnofabric. Plan view of *Phycosiphon incertum* (P) which is seen as the small black hooks and dots. Silt-lined *Diplocraterion habichi* (Dh) burrows are also present. South side of Snapper Point, Snapper Point Formation.

(c) *Diplocraterion parallelum*-Macaronichnus ichnofabric. Oblique view through *D. parallelum* sand-filled living tubes (Dp) and retrusive spreiten (seen as black silty material under the living chamber. *Macaronichnus* burrows (M) occur as circular silt-lined tubes. Vertical-oblique view, north side of Nugans Point, Snapper Point Formation.

(d) *Diplocraterion parallelum*-Macaronichnus ichnofabric. Vertical view of a truncated *D. parallelum* burrow with some reworking by small cylindrical *M. segregatus*. Note the lam-scram nature of the clean sandstone bed. South side of Snapper Point, Snapper Point Formation.

(e-f) *Diplocraterion parallelum*-Macaronichnus ichnofabric. Vertical view of *D. parallelum* with well-developed retrusive spreiten: (e) shows a close up view of the burrows and (f) shows the truncated nature of the bed and the abundance of the burrows. Willinga Point, Snapper Point Formation.
(a) Rosselia-Rhizocorallium-Phycosiphon composite ichnofabric. Vertical view of fairweather and storm deposits that have been biogenically reworked to varying degrees. Some of the thicker storm units still remain in thin lenses (RSB). Note the thickly silt-lined Rosselia burrow (R) and large Rhizocorallium jenense type C (Rh) which also contains a thick silt lining around the sand-filled living chamber. Merry Beach, Snapper Point Formation.

(b) Rosselia-Rhizocorallium-Phycosiphon composite ichnofabric. Vertical view of a truncated Asterosoma (A) burrow with a connected retrusive Teichichnus tube. Phycosiphon incertum (P) and Rhizocorallium irregulare (Ri) are also present. Merry Beach, Snapper Point Formation.

(c) Plan view of the Diplocraterion parallelum-Macaronichnus-Teichichnus-Rosselia composite ichnofabric. Overlapping D. parallelum burrow bases (Dp) and Teichichnus rectus (T) are present. The mottled background texture mainly consists of Macaronichnus segregatus and Phycosiphon incertum. Crampton Island, Snapper Point Formation.

(d) Vertical view of the Diplocraterion parallelum-Macaronichnus-Teichichnus-Rosselia composite ichnofabric showing the mottled texture mainly composed of Macaronichnus and Rosselia.

(e) Plan view of the Rhizocorallium jenense composite ichnofabric showing a large silt-lined R. jenense Type C in the top right of the photo and a small R. jenense Type A above the camera lens. Snapper Point, Snapper Point Formation.

(f) Mottled burrow-Glossifungites composite ichnofabric with a sand-filled Diplocraterion parallelum burrow base (Dp) and sand-filled Thalassinoides burrows (Th) in the mudstone above. Vertical view, Snapper Point, Snapper Point Formation.

(g) Vertical view of the Macaronichnus ichnofabric showing the weather resistant burrow linings of the Macaronichnus segregatus (M) burrows in the clean sandstone bed. North Nugans Point, Snapper Point Formation.

(h) Teichichnus- Diplocraterion parallelum composite ichnofabric showing D. parallelum (Dp) burrow base with retrusive spreiten (left of the arrow) and silt-lined sand-filled living chamber (to the right). Teichichnus rectus (T) is also present. Vertical view Nugans Point, Snapper Point Formation.
(a) Vertical view of the Monocraterion-Skolithos ichnofabric showing the V-shaped fabric produced by Monocraterion burrows. Bannisters Point, Snapper Point Formation.

(b) Diplocraterion habichi-Thalassinoides (Glossifungites)-Phycosiphon composite ichnofabric. Vertical view showing unlined sand- and gravel-filled vertical Thalassinoides burrows. South Pebbles, Pebbley Beach Formation.

(c) Vertical view of the Polykladichnus ichnofabric showing vertical branched Polykladichnus irregularis burrows. Meroo Point, Snapper Point Formation.

(d) Gyrolithes ichnofabric showing Gyrolithes saxonicus (G) and long thin Diplocraterion habichi (Dh). Note the lam-scram nature of the bedding. Vertical view, Jervis Bay, Snapper Point Formation.

(e) Vertical view of the Cylindrichnus eccentricus ichnofabric showing numerous vertical silt-lined Cylindrichnus eccentricus. Bannisters Point, Snapper Point Formation.
(a-d) Backbarrier facies association showing estuarine intertidal channel facies (e); inclined heterolithic stratification (i); abandonment or cut off channel-fill (a); tidal flat facies (t); lagoon facies (b) with partially homogenized washover deposits (w) and flat lying sandstone bed (s & ). Vertical outcrop view, Mill Point, Pebbley Beach Formation.

(e) Flaser bedding with bi-directional ripples and clay drapes. Tidal flat facies, south Clear Point, Pebbley Beach Formation.
(a) Vertical view of the tidal flat facies (t); washover sand (w) with bioturbation produced by opportunistic organisms; and overlying lagoon facies (l). Clear Point, Pebbley Beach Formation.

(b) Slumped sediments in the tidal flat facies. Vertical view, Clear Point, Pebbley Beach Formation.

(c) Vertical view of synaeresis cracks in the tidal flat facies. Clear Point, Pebbley Beach Formation.

(d) Plan view of synaeresis cracks in the tidal flat facies. Point Upright, Pebbley Beach Formation.

(e-f) Vertical view of the transgressive surface of erosion (o) that separates Cycles 3 and 4 in the Pebbley Beach Formation. The base of the visible section consists of interbedded sandstone deposits typical of washover facies (w). The overlying bioturbated siltstone represents lagoon facies (b) and the section between (o) and (E) is a transgressive deposit that is capped with a residue that consists mainly of *Eurydesma hobartense* shells (E). Above this, amalgamated silty sandstone beds represent lower offshore facies and reflect a deepening of the environment. A Glossifungites ichnofacies containing unlined sand-filled *Diplocraterion habichi* (Dh) is present beneath the transgressive surface reflecting a firm substrate produced by the erosion of the upper soft portion of the sea floor during transgression. Clear Point, Pebbley Beach Formation.
PLATE 4.3

(a) Tidal inlet facies (t.i) with coalified wood fragments (c.w); tidal flat facies (t); and lagoon facies (l). Vertical view, Clear Point, Pebbley Beach Formation.

(b) Vertical view of the lagoon facies with *Diplocraterion habichi* (*Dh*) overprinting a mottled background texture. Clear Point, Pebbley Beach Formation.

(c) Flood-tidal delta/washover facies showing silt-draped asymmetrical current ripples. Vertical view, Clear Point, Pebbley Beach Formation.

(d-e) Washover facies with single-form glendonites. Plan view, Clear Point, Pebbley Beach Formation.

(f) Planar cross-stratified sandstone from foreshore facies at Jervis Bay, Snapper Point Formation.
(a) Vertical view of cross-bedded sandstone, foreshore facies, Bannisters Point, Snapper Point Formation.

(b) Sub-parallel to low-angle cross-bedded sandstone with *Cylindrichnus eccentricus* (arrowed). Vertical view, foreshore facies, Bannisters Point, Snapper Point Formation.

(c) Vertical view of planar cross-stratified sandstone from the foreshore facies. Crampton Island, Snapper Point Formation.

(d) Vertical view of partially homogenized sandstone beds with long thick *Skolithos linearis* (arrowed), upper shoreface facies, Jervis Bay, Snapper Point Formation.

(e) Plan view of shell molds on a sandstone bedding plane *Eurydesma hobartense* (p) and pecten (*E*). Clear Point, Snapper Point Formation.

(f) Vertical view of upper shoreface facies with trough cross-bedded sandstone (t), low-angle cross-bedding (l), large-scale wave ripples (arrowed) and sandstone beds partially homogenized by *Monocraterion* (hs). Bannisters Point, Snapper Point Formation.

(g) Vertical view of ?ridge and runnel channels or ?multidirectional trough cross-bedding. Upper shoreface facies, Bannisters Point, Snapper Point Formation.

(h) Pecten and gastropod on a bedding plane (width of view is 80 mm). Plan view, upper shoreface facies, Clear Point, Snapper Point Formation.

(i) Vertical view of upper shoreface facies with *Macaronichnus segregatus* burrows and primary lamination evident. Snapper Point, Snapper Point Formation.
(a) Massive conglomerate bed (possibly overlying a ravinement surface). Vertical section, base of the upper shoreface facies, Narrawallee Beach, Snapper Point Formation.

(b) Platform view of large-scale wave ripples, middle shoreface facies (black bag on centre ripple for scale). Nugans Point, Snapper Point Formation.

(c) Pavement of *Eurydesma hobartense* capping a conglomerate unit in the upper shoreface facies at Clear Point. This unit comprises a part of a coarse-grained transgressive deposit at the base of the Snapper Point Formation.

(d-e) Coquinite bedding plane surfaces showing the variety of shell sizes present in the middle shoreface facies on Snapper Point, Snapper Point Formation.

(f) Middle shoreface facies characterised by SCS, low-angle cross bedding wave-rippled sandstone beds and rare HCS. Nugans Point, Snapper Point Formation. Height of view is approximately 4 m.
PLATE 4.6

(a) Large-scale granule ripples in very strongly storm-dominated offshore transition facies, south side of Snapper Point, Snapper Point Formation. Hammer for scale.

(b) Vertical view of ball and pillow structures in very strongly storm-dominated lower shoreface facies on the north side of Mill Point in the Pebbley Beach Formation.

(c) Vertical view of a large intraformational clast in middle shoreface facies at Meroo Point in the Snapper Point Formation.

(d) Storm deposited HCS sandstone and interbedded fairweather mudstone beds. Very strongly storm-dominated lower shoreface facies. Termeil Point Snapper Point Formation.

(e) Convex-upwards mollusk preserved with valves open on a bedding plane in moderately-weakly effected lower shoreface facies on the north side of Snapper Point. Snapper Point Formation.

(f) Vertical view of amalgamated sandstone beds with intervals of intensely bioturbated sediment and laminated to scrambled (l.s) profiles in moderately-weakly effected lower shoreface facies. Pretty Beach, Snapper Point Formation.

(g) Bedding plane exposure of crowded trace fossil assemblage on a sandstone bed from moderately-weakly storm-effected lower shoreface facies at Willinga Point in the Snapper Point Formation.
PLATE 4.7

(a) Large-scale HCS in very strongly storm-dominated lower shoreface facies (hammer arrowed for scale). Mill Point, Pebbley Beach Formation.

(b) Unidentified bryozoan in life position? in moderately-weakly storm-effected lower shoreface facies on Snapper Point. Snapper Point Formation.

(c) Amalgamated storm-deposited sandstone beds with mud-draped small- to medium-scale combined flow ripples in very strongly storm-dominated lower shoreface facies. Mill Point, Pebbley Beach Formation.

(d) *Vacunella* in life position in moderately-weakly storm-effected lower shoreface facies. Snapper Point, Snapper Point Formation.

(e) Large log with root base intact in very strongly storm-dominated lower shoreface facies. Mill Point, Pebbley Beach Formation.

(f) Large articulated pectinacean shell in moderately-weakly storm-effected lower shoreface facies at Snapper Point in the Snapper Point Formation.

(g) Shells on the bedding plane of a storm-deposited sandstone bed in moderately-weakly storm-effected lower shoreface facies. Snapper Point, Snapper Point Formation.

(h) Large-scale coarse-grained wave ripples in moderately-weakly storm-effected lower shoreface facies. Willinga Point, Snapper Point Formation.
PLATE 4.8

(a) Large exotic angular clast in a poorly sorted bed in moderately-weakly storm-effected lower shoreface facies. Snapper Point, Snapper Point Formation.

(b) Amalgamated unit containing partially reworked beds of coarse-grained sandstone, granule conglomerate and pebble conglomerate in moderately-weakly storm-effected lower shoreface facies. Meroo Point, Snapper Point Formation.

(c) Interbedded sandstone and siltstone (post-storm mud) and large-scale wave ripples (under hammer) in very strongly storm-dominated offshore transition facies. South side of Snapper Point, Snapper Point Formation.

(d) Interbedded storm-deposited sandstone and fairweather siltstone beds. Note the loaded beds at the base of the section. Very strongly storm-dominated offshore transition facies on the south side of Snapper Point. Snapper Point Formation.

(e) Spectacular interbedded storm-deposited sandstone and fairweather siltstone beds Very strongly storm-dominated offshore transition facies on the south side of Snapper Point. Snapper Point Formation.
PLATE 4.9

(a) Lam-scram bedding in a storm-deposited sandstone. Vertical silt-lined Diplocraterion habichi along the top of the bed. Strongly storm-dominated offshore transition facies at South Island Beach in the Snapper Point Formation.

(b) Burrows of opportunistic suspension-feeders (comprising an Arenicolites ichnofacies) along the base of a storm-deposited coarse-grained sandstone bed in strongly storm-dominated offshore transition facies at Snapper in the Snapper Point Formation.

(c) Interbedded storm-deposited granule sandstone and sandy mudstone beds in strongly storm-dominated offshore transition facies at Snapper Point. Snapper Point Formation.

(d) Large argillite dropstone in a silty sandstone bed in moderately-weakly effected offshore transition facies. Pretty Beach, Snapper Point Formation.

(e) Photomicrograph of a cross-sectional view through a plant stem from moderately-weakly effected offshore transition facies. Pretty Beach, Snapper Point Formation. Long axis of the photomicrograph is 8 mm.

(f) Photomicrograph of the cellular structure of plant material? From the same unit as above. Long axis of the field of view is 0.08 mm.
PLATE 4.10

(a) Very large exotic dropstone in interbedded mudstone and diamictite unit representing glacially influenced lower shoreface facies at South Pebbles in the Pebbley Beach formation.

(b) Siliceous *Bathysiphon*? Tubes concentrated in thin layers in the same unit as above.

(c) Sandy siltstone with *Diplocraterion habichi* showing slight vertical deformation due to sediment movement. The interbedded coarse-grained sandstone beds represent distal tempestites. Lower offshore facies. Mill Point, Pebbley Beach Formation.

(d) Slightly deformed bedding with vertical *Diplocraterion habichi* burrows stretched in the direction of sediment movement. Lower offshore facies. Mill Point, Pebbley Beach Formation.

(e) Large ball and pillow structures in interbedded fine-grained sandstone beds. Lower-middle shoreface facies, Snapper Point, Snapper Point Formation.
PLATE 4.11

(a) Silicified log in a diamictite bed in a glacially influenced lower shoreface facies at South Pebbles. Pebbley Beach Formation.

(b) Strongly storm-dominated upper offshore facies with fairweather deposits (f) with completely to partially homogenized storm-deposited sandstone beds (h), amalgamated HCS sandstone beds (a), non-bioturbated post-storm mudstone deposits (m), remnant sand-filled *Diplocraterion parallelum* burrow bases (D) and scattered pebbles (p). South side of Snapper Point, Snapper Point Formation.

(c) *Diplocraterion habichi* (between the arrows) forming a lam-scram profile in a storm-deposited sandstone unit. Fairweather deposits (f) with completely to partially homogenized storm-deposited sandstone layers (h). Strongly storm-dominated upper offshore facies, south Snapper Point, Snapper Point Formation.

(d) Backbarrier fairweather deposits (f) with partially to completely homogenized storm-deposited washover sandstone beds (h). A transgressive surface of erosion (O) underlies a thin sandstone bed that represents a transgressive lag and marks the base of the Snapper Point Formation. The U-shaped burrow (*Arenicolites*) protruding from the TSE comprises a part of a Glossifungites ichnofacies. South Island Beach.

(e) Vertical, unlined, sand-filled burrows (*Diplocraterion habichi* and *Thalassinoides paradoxicus*?) that represent a Glossifungites ichnofacies, protruding from a diamictite bed into a massive mudstone unit. Glacially influenced lower shoreface facies, South Pebbles, Pebbley Beach Formation.
PLATE 4.12

(a-b) Lower offshore laminated siltstone facies abruptly overlain by upper shoreface facies and reflecting a forced regression. (a) Crampton Island, (b) Bannisters Point, upper Snapper Point Formation.

(c-d) Close-up of the lower offshore laminated siltstone facies. (h) horizontally aligned dropstones, vertically aligned dropstones (m), fairweather deposits (f) with partially to completely homogenized storm-deposited sandstone beds (s), and mottled background texture. (c) Bannisters Point, (d) Crampton Island. Upper Snapper Point Formation.

(e) Thinly interbedded mudstone, siltstone and sandstone facies representing lower offshore distal tempestites. Lam-scram profiles (ls). South side of Snapper Point, Snapper Point Formation.
PLATE 5.1

View of the transgressive surface of erosion (marked with arrows) at the boundary between The Pebbley Beach and the Snapper Point Formation at South Island Beach. The surface contains a Glossifungites ichnofacies comprised of sand-filled (U-shaped), Arenicolites statheri burrows. Note the change from a Polycylindrichnus composite ichnofabric produced by a restricted Cruziana ichnofabric in a silty lagoon environment below the TSE, to a Teichichnus composite ichnofabric produced in an upper offshore environment above the TSE.
APPENDIX  Section outlines.

**Mill Point:** Composite section, accurately correlated by walking up-dip along the headland.

**South Clear Point:** Composite section, interpretive correlation with Mill Point based on lithology, dip, ichnofabrics etc, South Clear itself is accurately correlated as for Mill Point.

**Clear Point:** Composite section, accurately correlated to South Clear Point by walking up-dip. Clear Point itself was accurately correlated in the same manner.

**South Island Beach:** Accurate interpretive correlation to Clear Point based on the recognition of the Pebbley Beach/ Snapper Point Formation boundary. South Island Beach itself is a single measured section.

**South Pretty Beach:** Interpretive correlation to South Island Beach by using Tse, lithology, ichnofabrics, dip etc. Also correlated to O’Hara Island, which is between the two coastal headlands. South Pretty Beach is a single measured section.

**Pretty Beach:** Correlated to South Island Beach, South Pretty and O’Hara Island quite easily using lithology, ichnofabrics TSE correlation, dip etc. Pretty Beach section itself is a single measured section.

**South Snapper Point:** Easily correlated to Pretty Beach by the lithology but the exact thickness of the correlative sandstone is interpretational. Correlated to South and North Termeil Points by TSE and parasequence comparisons. South Snapper Point itself is a composite section accurately correlated by moving up-dip along the headland.

**North Snapper Point:** Accurately correlated to South Snapper Point using lithology, flooding surfaces, TSE, dip and photographs of the coast line taken from a boat. Correlated to Willinga, Nuggan, Merro, North Bannisters and Narrawallee Points using TSE, parasequence similarities and drill core depth comparisons. Snapper Point itself is a composite section accurately correlated by moving up dip through the section.

**Willinga Point:** Composite section accurately correlated by moving up-dip through the section. It is correlated to Snapper and Nuggan Points by lithological comparisons, ichnofacies, ichnofabrics and parasequence similarities.

**Nuggan and Merro Points:** Composite sections accurately correlated as for other sections.

**South and North Termeil Points:** Both are single measured sections. Correlated to each other by lithology, dip and cyclic interpretations. Correlated to South Snapper Point by TSE and parasequence comparisons.
Crampton Island: Composite section, accurately correlated by walking up-dip. Accurately correlated with South Bannister Point and Jervis Bay by the thick, silty, dropstone-rich bed, also by parasequence comparisons and by the presence of the thick, trough cross-bedded unit at the top of the sections that is not seen anywhere else in the sequence.

Bannisters and Narrawallee Points: Both composite sections correlated by moving up-dip through the section. Correlated to each other by sedimentological and parasequence similarities. See above for correlations to other headlands.

Jervis Bay Sections: All single measured sections. See above for detail of correlation to other localities.
# Map Numbers and Grid references for Measured Sections

<table>
<thead>
<tr>
<th>Measured Section</th>
<th>Map Number</th>
<th>Grid References</th>
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<tbody>
<tr>
<td>Mill Point:</td>
<td>8926 1</td>
<td>GR: 582 561- 583 557</td>
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<td>South Clear Point:</td>
<td>8926 12</td>
<td>GR: 585 566- 588 565</td>
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<td>Clear Point:</td>
<td>8926 13</td>
<td>GR: 588 565 - 592 566</td>
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<td>South Island Beach:</td>
<td>8926 14</td>
<td>GR: 603 594</td>
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<td>South Pretty Beach:</td>
<td>8926 15</td>
<td>GR: 608 598</td>
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<td>Pretty Beach:</td>
<td>8926 16</td>
<td>GR: 610 602</td>
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<td>South Snapper Point:</td>
<td>8926 17</td>
<td>GR: 613 602 - 620 603</td>
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<tr>
<td>North Snapper Point:</td>
<td>8926 18</td>
<td>GR: 621 608 - 620 602</td>
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<td>Willinga Point:</td>
<td>8926 19</td>
<td>GR: 633 680- 633 678</td>
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<td>Nuggans Point:</td>
<td>8927 10</td>
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<td>Meroo Point:</td>
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<td>Termeil Point:</td>
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<td>GR: 713 877</td>
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<td>North Bannisters Point:</td>
<td>8927 14+ 15</td>
<td>GR: 712 882 - 713 880</td>
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<td>Narrawallee Inlet:</td>
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<td>GR: 703 901</td>
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<td>Jervis Bay:</td>
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<td>GR: 236 016</td>
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<td>Jervis Bay:</td>
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Key to Location Maps

For more detail of Location Maps see

Topographic Map, 1:25 000, Kioloa 8926-I-N: South Pebbles to Snapper Point.
Topographic Map, 1:25 000, Tabourie 8927-II-S: Willinga Point to Crampton Island.
Topographic Map, 1:25 000, Milton 8927-II-N: Warden Head to Narrawallee inlet.

Beach

Cliff

Measured Section

Grid Reference ——— 60
LOCATION MAP WARDEN HEAD TO NARRAWALLEE INLET

NARRAWALLEE
- Narrawallee Inlet
- Narrawallee Beach

MOLLYMOOK
- Bannisters Point
- Mollymook Beach

ULLADULLA
- Ulladulla Head
- Ulladulla Harbour
- Ulladulla Lighthouse
- Racecourse Beach

Scale 1:25 000
Stratigraphic Correlation of Coastal Outcrops
Key To Measured Sections

- Arenicolites statheri
- Arenicolites sp
- Asteriacites
- Asterosoma
- Calycraterion samsonowici
- Conostichus
- Cylindrichnus concentricus
- Cylindrichnus eccentricus
- Cylindrichnus errans
- Diplocraterion habichi
- Diplocraterion parallelum
- Gordia
- Gyrochorte camosa
- Gyrolithes saxonicus
- Heimdallia chatwini
- Macaronichnus segregatis
- Margaritichnus
- Monocraterion tentaculum
- Ophiomorpha
- Palaeophycus heberti
- Palaeophycus tubularis
- Phycosiphon incertum
- Planolites beverlyensis
- Planolites montanis
- Polycylindrichnus prolifer
- Polykladichnus irregularis
- Psammichnites gigas
- Rhizocorallium irregulare
- Rhizocorallium jenense A
- Rhizocorallium jenense B
- Rhizocorallium jenense C
- Rosselia motivus
- Rosselia rotatus
- Rosselia socialis
- Skolithos linearis
- Taenidium barretti
- Taenidium serpentinum
- Taenidium synyphes
- *Teichichnus rectus*
- *Teichnus sinuosus*
- *Thalassinoides paradoxicus*
- *Fugichnia*
- *Notoconularia levigata*
- Broken shells
- ▲ Laterally discontinuous bed
- ⬇ Shells in life position
- ▲ Composite ichnofabric
- ☐ Coal
- ☐ Juvenile shells
- ◇ Pyrite or phosphate cement

- *Taphrhelminthopsis circularis*
- HCS
  - ☐ drop stones
  - ⬇ intensive bioturbation
  - ◻ intraclasts
  - ▲ shells + orientation
  - ☐ poorly exposed section
  - ☐ log
  - ☐ deformed bedding
  - ✂ siltstone intraclasts
  - ▲ low-angle cross-bedding
  - ☐ imbricat ed clasts
  - ☐ concretions
18 items
+ 1 copy from key