Ichnology and palaeoecology of the Neogene Beaumaris Sandstone: a reconstruction of palaeoenvironments using trace fossils as interpretive tools.

A thesis submitted in fulfilment of the requirements for the degree of Master of applied biology and biotechnology

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DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

Paul Ter

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ABSTRACT

The recent discovery of trace fossils in parts of Beaumaris Sandstone presented a new aspect to the paleontology of the strata. The work that described this discovery was limited in its scope and provided information only on a small area of the outcrop. What was still unknown was the extent of the trace fossils, whether new types remained to be discovered and if they were sufficiently numerous to be used as a stratigraphic tool. To ascertain this, extensive field surveys was conducted, and representative sections were identified, with an emphasis on those areas previously thought to be unfossiliferous. The data from selected sites along the length of outcrop was analyzed, and the occurrence of different fossils (both ‘body’ and ‘ichno’) used to divide Beaumaris Sandstone into distinct units. Undescribed ichnospecies were encountered during this process, and used as a primary tool in unit construction. Ichnofossils were found to be present in large numbers and some variety, and in a state of preservation that renders them good subjects for study. Fossil crab and worm burrows, preserved in Goethite, formed the larger part of the previously undocumented types. Fossil wood casts were recorded along the whole length of outcrop. The discovery of an undescribed species of *Psilonichnus* represents the first record of this ichnogenus in Australia. A small occurrence of sea anemone trace fossils was found. These trace fossils (*Bergaueria*) have only known in Australia from Pre-Cambrian rocks prior to this, and are very rare worldwide, due to the highly specific conditions necessary for their formation. The combined use of fossil casts and burrows as stratigraphic tools is confirmed as being of equal utility as more traditional methods, presenting a valid alternate method of research.
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Beaumaris Sandstone

This work seeks to explore the ichnofauna (defined as fossil burrows and casts of living organisms) present in Beaumaris Sandstone, and use them as interpretive tools for stratigraphic and palaeoecological analysis.

A walk along the beach at low tide in the Rickett’s Point Marine Reserve will reveal, to the careful observer, specimens of what appear to be iron tubes in the rocks. Until recently (Ter & Buckeridge, 2012), they were thought to be fossils of Banksia. It is now known that they are the fossil burrows of thallasinid crustaceans, and these burrows have been described as the ichnospecies Ophiomorpha beaumarisensis (Ter & Buckeridge, 2012). They are by far the most common ichnofossil in Beaumaris Sandstone, and easily observed. Moreover, the level of preservation is quite extraordinary, to the extent that it was possible to describe it as a new species. This then leads to another question. Were there other types of burrow there, given that conditions of diagenesis were so favourable for one type? Observation of modern day ecologies reveal that where a sediment type proves favourable for one species of burrow builder, it is likely to be favourable for other species as well, thus the strong possibility of other kinds of trace fossil being present.

Ter & Buckeridge, 2012, give a type location, and a description for the ichnospecies, but make no mention of relative abundance. They also do not discuss its position in the stratigraphy of Beaumaris Sandstone, except at the type section. This is the first aim of this work, to map the occurrence and abundance of O. beaumarisensis at a number of different sites.
More careful examination of the areas that hold *O. beaumarisensis* will show that certain of these sites have other forms of fossil burrow. In some instances, these other burrows are common, and sufficiently well preserved enough to allow their description. The aim will be to map and identify the occurrence of these undescribed ichnospecies, using the multiple sites proposed for the mapping of *O. beaumarisensis*.

Ter & Buckeridge also mention the presence of casts of fossil wood, but give no more detail than this. Some specimens exhibit excellent preservation of the tree bark imprint. The second aim of this work is to map the occurrence and abundance of these casts, and if possible, to determine the type(s) of trees that made them.

A program was devised to survey and map the occurrence of these ichnofossils, with sites being chosen at regular intervals throughout the outcrop of Beaumaris Sandstone. Specifically, to explore whether these fossils occurred in sufficient numbers and at enough sites within the lithology to be used as interpretive tools. The description of any unknown ichnospecies encountered was also to be undertaken. The question posed is:

**Are trace fossils present in Beaumaris Sandstone in sufficient abundance to be used as an interpretive tool in the reconstruction of past environments?**

Research was primarily conducted by means of survey, with results being recorded on a standard field sheet and extrapolated using Sedlog software (see appendices 1 & 2). Sedlog is a freeware program developed by the University of London which allows graphical depiction of sediment structures. A group of volunteers was recruited and many hours of field research undertaken. To keep the project at a manageable level, the study was to be limited to palaeobiological analysis only, and no geochemical or thin section testing has been done.
Specific objectives were defined and applied to the interpretation of the data; these are:

- Identification of unknown ichnospecies;
- Mapping of ichnofauna occurrence;
- Division of Beaumaris Sandstone into units defined by fossil types present;
- Synthesis of fossil types to provide picture of palaeoecology;

The use of trace fossils in palaeoecology is relatively new, and it is whether they exist in sufficient abundance in Beaumaris Sandstone for that purpose that this research seeks to address.
Chapter 1

Introduction

1.1 Interpretation of traces

Living organisms leave traces of their presence in the environment on a regular basis. Whether it be the distinctive clawed footprint of a cat in a garden bed, a spider burrow, or the roots of a tree shaping the soil around itself, they all cause a discernable alteration to the surrounding environment. Many of these traces provide a clue as to the nature of the originator, even if the originating organism is no longer present. Humans have long made use of these traces in the environment. Hunting parties followed the tracks of large mammalian prey species. Tribes avoided drinking at waterholes that had obvious trace marks of crocodile activity on the banks.

In most cases, these traces are transitory. The garden bed is dug up and replanted, the spider dies and burrow collapses, the tree is blown down in a wind and a new one grows in its place. If the palaeoecologist is to make use of these changes, and base reasoned deduction on them, the information provided by the trace must be preserved in a permanent form. Most of these changes will not be preserved, as the likelihood of long term preservation of any fossil (trace or ‘body’) is very low.
Highly favourable conditions of deposition and diagenesis must occur for any trace, whether burrow, track or body imprint, to fossilize.

Where these long-term traces have been preserved in rock, they are called ichnofossils. If the traces of the originating organism have been preserved well enough that the identity and behaviour of that organism become discernable, they become a highly useful tool for biostratigraphy and paleoecology. Some species will make traces more likely to fossilize (e.g. large robust burrows, such as Ophiomorpha beaumarisensis). This may lead to a species being ‘over represented’ in the fossil record, simply due to the durability of its traces. Other organisms may have been equally abundant (an ecology is rarely monospecific) but have not had their traces preserved. This is case where most ichnofossils are found. One or two types will dominate the horizons, giving only a limited view at the ancient ecology. Where many different traces (along with ‘body fossils’ – the mineralized remains of animals) are found in a lithology, then a more complete view is possible (Pemberton et al., 1992).

1.2 Trace fossil creation

Any organism performing any activity necessarily leaves some alteration in the surrounding environment. The first cyanobacteria changed the composition of the surrounding air by respiring oxygen – leaving a discernable change to the environment. The change in the isotopic ratio of sulphur (caused by an increase in atmospheric oxygen) (Farqhuar, et al. 2000) is measurable in the rocks of two and a half billion years ago, from accumulation of oxygen as the result of cyanobacteria respiration (Farqhuar, et al. 2000). The activities of protozoa are inherently limited by the nature of their existence. Their traces are simple and inconsequential, unlikely to preserve. The rise of metazoans saw radical new forms
of morphology and more complex traces as allowed by a new, multi cellular architecture.

This change in dominance, and the creation of the first metazoan ichnofauna, took place in the Ediacaran (Seilacher, 2003). Movement was no longer limited to the strictures imposed on a single celled organism, and the larger body sizes now possible meant that larger traces were left in the environment (Dewel, et al., 2001). In the ‘Ediacaran Garden’ described by Seilacher, movement was still highly limited by morphology, so that the traces are feeding patterns on the sea bed, or resting traces, rather than defensive burrows (Seilacher, 2003). Life had evolved to the point where it left a unique record behind of its existence. Sufficient diversity of fossil (trace and ‘body’) was now being created to allow a more comprehensive view at the ancient ecology.

With the rapid diversification of organism morphology in the Cambrian, (Shu, 2008) different types of burrow became possible, and indeed necessary to survival. Organisms began constructing defensive burrows as the number and type of predatory organism increased. A great leap was made – if a creature constructs a structure with an entrance only large enough to admit itself (thus excluding predators almost invariably larger) it creates a place of safety in which to live and breed. The advantages of a burrow are obvious, and the technique is employed in the modern world by many higher order animals, including mammals.

The advent of jointed legs during the Cambrian lead to a diversification of traces made, with *Cruziana* (d’Orbigny, 1842) and *Rhusopychus* (Hall, 1852) (both trace fossils of Trilobita) entering the ichnofossil record – the more complex morphology of Arthropoda allowing different types of trace from a single organism (Minter & Lucas, 2009). The relative freedom of movement compared with
Ediacaran fauna allowed the more developed organism to make different alterations in its environment, allowing more points of reference into its behaviour. Put simply, this means that the greater the variety of traces from an organism, the more comparison that can be made between the particular source activity of a trace and the particular activity associated with sources of a different trace made by the same organism. At this point it is possible to start making inferences as to the behaviour that caused the traces. Is this the resting trace, or is this the trace caused by seeking food, given the morphology of the animal? More complex actions available to higher organisms allow a greater understanding of from the traces they create, right up to the level of *Homo sapiens*, who leave the most traces of alteration to their environment of any organism.

### 1.3 Trace fossil classification

Seilacher (1953) made the first attempt at sorting the types of trace fossil. The major groups are: Domichnia, deliberately constructed dwelling structures; Fodinichnia, burrows made by deposit feeders in the substrate; Pascichnia, grazing traces made by organisms browsing on sediment; Cubichnia, resting traces, mirroring the image of the animal as it rested on sediment and Repichnia, traces on surface of movement e.g. *Cruziana* made by trilobites (Seilacher 1953).

<table>
<thead>
<tr>
<th>Trace</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domichnia</td>
<td>Constructed dwelling structures</td>
</tr>
<tr>
<td>Fodinichnia</td>
<td>Deposit feeding burrows in sediment</td>
</tr>
<tr>
<td>Pascichnia</td>
<td>Grazing traces on sediment</td>
</tr>
<tr>
<td>Cubichnia</td>
<td>Resting traces, mirroring the image of animal</td>
</tr>
<tr>
<td>Repichnia</td>
<td>Surface movement traces</td>
</tr>
</tbody>
</table>

*Figure 1.1* Seilacher’s trace fossil classifications (1953).
As noted in (Ter & Buckeridge, 2012), an ichnogenus represents the classification of the trace making activities of an (often not concurrently preserved) animal. It is only reliably classifiable where it presents a consistent form and structure, which is attributable to a sole originator species (Ter & Buckeridge, 2012). This method of classification may present the possibility that a single originator species may be responsible for a number of ichnospecies. There is no problem with this approach, (long used in the classification of Trilobita traces) so long as the stricture that consistency of morphology of the ichnospecies is adhered to. Bromley & Asgaard, (1979), note the problems associated with assigning ichnospecies to minor variations in trace morphology. As the geological processes which combine to preserve mineralized remains of organisms (body fossils) are often different to those which preserve ichnofauna (Frey et. al, 1984), the description of an ichnospecies presents a useful approach when analyzing those strata where diagenetic forces have favoured the preservation of trace fossils. A comprehensive approach to the classification of ichnogenera can be found in Knaust and Bromley, 2012.

In his Principle of Uniformitarianism, Hutton, 1788 (p. 217), states “In examining things present, we have data from which to reason with regard to what has been; and, from what has actually been, we have data for concluding with regard to that which is to happen hereafter”. Charles Lyell 1830, would go on to present (and popularize) this theory as “the present is the key to the past”. When applied to the study of palaeoecology, it might be interpreted in this way; if a change to the ecology occurs in modern times, the species present will also change to a greater or lesser extent, dependent on the ability of the assemblage to adapt to the new conditions.
If the local environment in the present varies wildly (e.g. deforestation) then the species present will be replaced by those adapted to the new conditions. This cycle has been repeated since the beginning of life, and is reflected throughout the fossil record. The local fauna responds to the change in environmental conditions, which is then measurable by their remains, or traces of their activity that is preserved.

A change in the conditions which cause fossils to be preserved presents a challenge to the theory above, especially when the change results in a lack of any fossil remains at all. This might be useful in determining that some variation had occurred, but beyond this yields no useful information. Some remains, whether body or trace, is essential in providing constant information throughout the layers of a lithology.

A change from fossiliferous layers to horizons lacking in animal remains might then be seen as sound reason to cease interpretation of the palaeoecology. After all, what can be interpreted from a lack of data? Only if new information, using a new method (in this case, ichnology) comes to light can the interpretation continue.

Thus far, the study of palaeoecology of Beaumaris Sandstone might be interpreted as an aside to the rich palaeontological finds Beaumaris Sandstone has yielded (Etheridge, 1875, Hall & Pritchard, 1897, Singleton, 1941, Stirton, et al. 1967, Buckeridge, 1983, Fitzgerald, 2004, Piper et. al., 2006). This has been due to the narrow range, stratigraphically, of the body fossils within the strata. Their occurrence at the base of the formation yields information only about that part of the strata. The discovery of a diverse ichnofauna within the remaining parts of Beaumaris Sandstone provides the tools necessary to make informed comment about the layers lacking body fossils.
1.4 Study area

Figure 1.2 Map of Australia showing study area inset.
Figure 1.3 General location map. Area of inset shows study area.
The study area is approximately 20 kilometres south east of Melbourne, Australia, within the suburbs of Melbourne. Outcrop areas of Beaumaris Sandstone are in the form of cliffs and intertidal platforms on the shore of Port Phillip Bay. Most of the outcrop area is preserved by the Rickett’s Point Marine Reserve, though significant
sections in the southernmost parts are under threat of development. Access to many areas is regulated by the tide, with some of the better sites only accessible on a favourable low. Most areas of outcrop are on a popular public beach, which has led to the erosion of some specimens by foot traffic.

The basal part was once more easily observed (and accessed) until the greater portion was buried beneath the Beaumaris Motor Yacht Squadron (BMYS) car park in the 1960s (Beaumaris Conservation Society, 2014). The remaining part is under threat from further BMYS development and should be preserved as a matter of urgency, given the rich fossil discoveries it has yielded and importance to interpretation of the local geology.
Figure 1.5 A large part of the highly fossiliferous base of Beaumaris Sandstone was covered by a car park in early 1960s. This has severely limited access to the section. Image from Beaumaris Conservation Society website 2014.

1.5 Geological Setting

The area is part of the Port Phillip sedimentary basin (Holdgate et al., 2002). It was, along with adjoining basins shown in figure 1.5 & 1.6, formed during the break up of Gondwana, and subsequent drift north of Australia (Holdgate et al., 2002). Between the Cretaceous and the Eocene, a marine transgression took place, shown by the change in fossils from terrestrial to marine in the strata during this
time. This incursion is thought to represent an incursion of the Southern Ocean (Holdgate et al., 2002) onto the Australian mainland.

The fossils are almost exclusively marine after the late Eocene, and remain so until the Miocene, indicating a period where sediment input was derived largely from the sea. Coal deposits are present in the northern part of the basin in the early Miocene, which represent a time when a barrier system separated swamps from the sea (p. 448 of Holdgate, et al., 2002).

By the middle Miocene, the barriers had gone, as shown by the deposition of the marine Gellibrand Marl in the northern areas. Gellibrand Marl unconformably underlies Beaumaris Sandstone in the study area, but is only exposed on the lowest tides. The shoreline in the north eastern part closely followed the shoreline of the present day at this time, which did not change until after the time of the deposition of Beaumaris Sandstone. Red Bluff Sandstone, which overlies Beaumaris Sandstone, marks the change from marine to fluvial and lacustrine inputs. This represents a marine regression, which remained until the formation of the current Port Phillip Bay after the end of the Pleistocene (Holdgate et al., 2002).
Figure 1.6 (Previous page) Regional geological setting 1. Adapted from page 549 of Dickinson & Wallace, 2009.

Figure 1.7 Regional geological setting 2. From page 439 of Holdgate et al., 2002.
Figure 1.8 Geological map of study area. Adapted from Ringwood 1:63360 map no.849, Geological Survey of Victoria. Beaumaris Sandstone is referred to in the key by its pre 2012 “Black Rock Sandstone” title.
Chapter 2

Method

2.1

A team of volunteer undergraduate students was recruited and trained in making field observations. Volunteers were at all times supervised by the author and the data they generated confirmed when in the field. After careful reconnaissance, 16 geographically separated and suitable occurrences of Beaumaris Sandstone were selected to give a good representation of the entire outcrop, each horizon delineated to a standard 10m horizontal width. The horizons were specifically chosen to be geographically spread over the whole length of outcrop, as previous research has focused on a limited area. Multiple inspections of the sites at low tide were made by the research team, and occurrence of fossils noted and mapped in a field notebook. Rather than quantify precisely what is an enormous amount of individual fossils, categories of rare; (less than 1 per 10m$^2$), common (2-10 per 10m$^2$) and abundant (>10 fossils per 10m$^2$) were assigned to each type of fossil. The general condition of these fossils was also recorded, but the sheer number of fossils meant that this was an observation of the overall condition of fossils in each horizon, i.e. more than 50% of the fossils within that section of the horizon exhibited that condition. This was found to be fairly reliable, as local conditions of weathering and erosion tend to affect specimens fairly evenly. Where outstanding or unique specimens were encountered, these were noted separately. Results of these site inspections were then confirmed by a subsequent visit to each site by the author. After the first few field trips, it became apparent that the fossils present, and the rock type encountered fell broadly into three or four types, and the process was facilitated by then recording the abundance present within the range of those
types. This meant that rather than measuring each 10m$^2$ of horizon, and then recording fossil numbers, each horizon could be separated into 2-5 broad divisions, and counts simplified by calculating the abundance within that area, then standardizing to per 10m$^2$. Images were recorded by means of digital photography at each site and used to confirm fossil type and abundance. Measurement of each horizon was made using a standard 50 m. measurement reel and these results were noted in the field notebooks. Literature review of the Port Phillip Basin and Beaumaris Sandstone was undertaken to assist with identifying the strata encountered, in particular to define where the lithology began and ended. Characteristics of overlying and underlying units were noted and used in the field to identify those units encountered which were not part of Beaumaris Sandstone.

Team members were each given individual small areas at the site to investigate, with the intention of conducting a close inspection of any changes of fossil or rock type. Great care was taken to search for smaller and more cryptic fossils, as well as the larger and more obvious ones. A standard size grain chart was used to ascertain the particle size of the varying rock types by visual comparison in the field (see Appendix III). The results in the field notebooks were then tabulated and charted using Sedlog software obtained from http://www.sedlog.com/. A literature search to identify those fossils already known was conducted, in order to ascertain whether any discoveries already made could be incorporated into the system of units. In addition, many areas not included in the selected horizons were visited and the more notable fossils were recorded, though estimations of their condition and abundance were not made.

An attempt to sort the units into facies (Seilacher, 1967), which represent distinct depositional stages, was made, as this seemed to be the case based upon early data.
As the research progressed, the units found did not always represent a depositional change, though remaining distinct and discernable units within Beaumaris Sandstone. After this initial reverse, a system of classification for the rock units was devised based upon the varying fossils contained within the units. Only the more common fossils within a unit were used in this classification, to eliminate the creation of superfluous units derived from ‘one off’ or rare occurrences. This was to keep the units to a manageable number, simplify mapping of the study area and create units which might be mapped at a larger number of sites. The appearance of a unit at multiple sites assisted the derivation of an overall stratigraphy of the study area, i.e. it then became possible to detect at what height in the stratigraphy the unit occurred, and whether this varied between the sites.

When an undescribed ichnospecies was encountered, digital images and samples were taken to assist with description and identification back in the laboratory. A 10x hand lens was used for field identification and a binocular dissection microscope for more detailed work with individual fossils. A literature review of species similar to the undescribed types was undertaken and the specimens compared with similar type ichnofossils. When appropriate, description of undescribed species was made using systematic palaeontology. The discovery of an undescribed ichnospecies of *Psilonichnus* was a key in defining the strata into discernable ‘units’.

As some sites were very similar to others, the most useful 8 were chosen and the results extrapolated from Sedlog charts to the stratigraphy used in figures 5.2 & 5.3. Where the horizon results were similar, the sites were differentiated on the basis of their geographic separation, i.e. when two sites showed the same results, the one that was farthest from the next diverse one was selected. The charts for the
named sites are in Appendix 1(i). The charts for the unnamed sites are in Appendix 2(i). The raw tabulated data used to create the sedlog charts is in Appendix 3(i).

This stratigraphy was then used to make comment on discrepancies between unit occurrences at different sites, in particular the two sites which have outcrop of the two oldest units.

An analysis of fossil bathymetry was made using the more common types in Beaumaris Sandstone. This analysis was then used to estimate sea depth during the deposition times of the various units. The results of this are in figure 4.1.

Analysis of Red Bluff Sandstone was considered beyond the scope of this work and no data was collected from it, other than to note its presence overlying Beaumaris Sandstone and thickness of the layer.
Chapter 3

Results

3.1

The data tabulated from field sheets and notes can be found in Appendix vi. The data converted into Sedlog tables is in Appendix ii.

Trace fossils were found in abundance over most of the outcrop of Beaumaris Sandstone, and recorded from all sites. *Ophiomorpha beaumarisensis* is the most common ichnofossil and is highly abundant in places, forming unbroken burrow structures commonly in excess of 50 cm, and in some cases to 2m. in length. It is noticeably absent in the lowest part of the formation, and is only found in association with *Lovenia woodsii* in one small horizon at the uppermost part. Its condition is generally good, but in some areas has been affected by erosion. Fossil tree casts are found in all horizons, and were recorded from all levels of Beaumaris Sandstone, some with associated borer traces and rarely, with casts of the boring bivalves on the tree cast itself. An undescribed crab burrow, *Psilonichnus* sp., is common at the middle levels of the strata. It is found with *O. beaumarisensis* in some instances, and the two appear to represent a biocoenosis as they are form large intertwined beds in areas. Small borer traces and bivalve casts are rarely present across much of the northern two thirds of the area of outcrop. Trace fossils of sea anemones were found in a small area in the south of the lithology, and are abundant in that limited area. These *Bergaueria* are generally in poor condition as
a result of erosion, but sufficient detail remains on a few specimens to confidently diagnose them.

Mineralized remains of animals (‘body fossils’) were only present in the lowest layers in the south part of outcrop, in contrast with the ubiquitous trace fossils. *Lovenia woodsi* was by far the most common body fossil observed and is abundant and generally in good condition in one horizon, being rare in the others. A small fauna of molluscs and echinoids preserved as casts in Goethite was found in the north part of outcrop. A new phosphatic nodule bed was found, at the base of the phosphatic nodule bed nth. section, though it is much smaller and lacks the dual layer of that the the base of the phosphatic bed sth section, as described in Ter & Buckeridge, 2012.

A minor clastic deposit was found slightly north of the Beaumaris Yacht Squadron at 37°59'15.9"S 145°01'35.0"E, where two small lenses of fine gray clay are present within close proximity of each other. They contain no fossils, and are likely to have their origin as the outlet of a small creek.

Beaumaris Sandstone was found to be divisible into several distinct units, based on the occurrence of trace and body fossils. A noticeable lighter coloured ‘band’ which contains both *Psilonichnus* and *Ophiomorpha* can be seen at the base of the Rotunda section at the most northerly site, this band being present at all other sections except the type location for *O. beaumarisensis*. It remains at the same stratigraphic height in the north, then abruptly appears at around 4 m. in the cliff face at the phosphatic nodule nth. section, after its absence in the type location section. It remains at that height in the phosphatic nodule bed sth section. Beds containing almost exclusively *O. beaumarisensis* were found above and below the
band, and this was most apparent in the two nodule bed horizons, where the full sequence is exposed.

Chapter 4

SYSTEMATICS

4.1

Ichnogenus *Psilonichnus*

Furisch, 1981

*Diagnosis.* Predominantly vertical, cylindrical burrows with short horizontal or oblique side branches, upper part commonly Y-shaped (Furisch, 1981).

*Range.* Upper Jurassic to Pleistocene (Europe, USA, Japan, Australia, Caribbean).

*Remarks.*

The originating species of *Psilonichnus* is thought to have been brachyuran crustaceans (Frey *et al.*, 1984), though the original ichnospecies was described as being the burrows of callianassid shrimps (Furisch, 1981). The burrows of thallasanids are commonly placed within the ichnogenus *Ophiomorpha* (Lungdren, 1891). The difference between the two ichnogenera rests upon the presence of the
distinctive pelletal outer surface and the anastomosing habit of Ophiomorpha specimens (absent in Psilonichnus).

As stated in Nesbitt & Campbell, 2002, burrows of the smaller species of Thallasanoides often do not have the pelletal wall structure typical of Ophiomorpha, though their inclusion in Psilonichnus presents an inconsistency within the ichnogenus. A new ichnogenus for the traces of these smaller thallasanid species which lack the distinguishing characteristics of Ophiomorpha may present an answer to this. The current system of ascribing different sub orders of crustaceans as originators of the same ichnogenus presents difficulties when using them as tools for the interpretation of palaeoecology.

If ichnofauna are to be used as interpretive tools in paleoecology, then a single originator species (e.g., who may act as an indicator for temperature or depth changes) is a more useful tool than a number of different species. A single species has a narrower set of environmental parameters that it is bound by, as opposed to a group of originators that may not even be from the same genus (and thus have widely varying environmental tolerances). The difference in behavior of, for example, thallasinids and brachyurans can be quite marked, which is reflected in its burrowing. The use of a single originator provides far more utility to the palaeobiologist as an interpretive tool, as it provides a narrower set of environmental parameters with which to work. This provides a more precise interpretation of the conditions under which the burrow was made, and better data for the analysis of the overall palaeoecology.

Fossilized crab burrows have been described, though not formally classified as Psilonichnus, by a number of authorities (Utashiro, 1953; Utashiro and Horii, 1964, 1965; Utashiro et al., 1966; Oshima, 1966; Utashiro and Lebensspuren

The first ichnospecies to be described in this ichnogenus was *Psilonichnus tubiformis* (Furisch, 1981) using the diagnosis given above, with the addition of the following: “burrow diameter of 3-5 cm and maximum length over 200 cm; top Y- or U-shaped tube continues downward as a straight to slightly curved or somewhat twisted tube; short side branches at irregular intervals; filled with overlying sediment.” (Furisch, 1981, p.155).

*Psilonichnus upsilon* (Frey et al., 1984) has a diagnosis of “gently inclined, sparsely branched to unbranched, J- or Y-shaped burrows; inclined shaft straight to slightly arcuate; horizontal branches slightly to markedly curved, not horizontal. Unlined burrow; 2.5-4.5 cm in diameter, more than 1.2 m in length.” (Frey et al., 1984, p. 195). This is the first species of *Psilonichnus* to have been described as specifically being the fossilized burrows of brachyurids (Frey et al., 1984). This trace fossil fits the qualifications of a consistent morphology, attributable to a single species (*Ocypode quadrata*) (Frey et al., 1984) in a manner which the description of *P. tubiformis* is lacking.

*Psilonichnus quietus* (Myint, 2001), was described from an Eocene lithology (Shiramazu group) north of Tokyo. The diagnosis is “unlined and vertical to unlined shafts ranging in diameter from 0.4 to 2.8 cm, exhibiting four different swelling shapes, located at obtuse angles from a master shaft; swelling series point
at the same direction” (Myint, 2001: 6). This is distinguishable from the other *Psilonichnus* species by the swellings and the variability of the lining in the shaft. There are four variations given by the author, who describes them as reflecting “false branching or bifurcations”. Myint also proposes a comprehensive system of terminology to describe this ichnospecies, perhaps applicable to *P. quietus* (Myint, 2001) but not to the ichnogenus as a whole. This ichnospecies has ‘brachyuran crabs’ assigned as the originating suborder. (Myint, 2001).

*Psilonichnus lutimuratus* (Nesbitt & Campbell, 2002) is described as “vertical to very steeply inclined tubes that are lined with mud; circular in cross-section; tapering and slightly curved at base; Y-shaped, although pre-burial erosion and bioturbation preserve only J- and I-shaped burrows in most cases; 0.5-- 3 cm wide and up to 80 cm long; cemented, smooth mud lining from 2-10 mm in thickness; rare to no side branches; no bulbous areas along length of tube; smooth exterior and interior surfaces; passively filled.” (Nesbitt & Campbell, 2002, p. 899) It is distinguished from *P. upsilon* by the lateral branching and the mud lining, both of which are lacking in the holotype. (Nesbitt & Campbell, 2002) The originating species is thought to be a mud shrimp.
<table>
<thead>
<tr>
<th>Species</th>
<th>Lining</th>
<th>Swellings/bulbs</th>
<th>Branching</th>
<th>Maximum length</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>tubiformis</em></td>
<td>no</td>
<td>no</td>
<td>short, irregular</td>
<td>200 cm</td>
</tr>
<tr>
<td><em>upsilon</em></td>
<td>no</td>
<td>no</td>
<td>sparse or none</td>
<td>120 cm</td>
</tr>
<tr>
<td><em>quietus</em></td>
<td>no/rarely</td>
<td>swellings</td>
<td>common</td>
<td>250 cm</td>
</tr>
<tr>
<td><em>lutimuratus</em></td>
<td>yes</td>
<td>no</td>
<td>rare or none</td>
<td>80 cm</td>
</tr>
<tr>
<td><em>Psilonichnus</em> sp.</td>
<td>no</td>
<td>bulbs</td>
<td>common</td>
<td>80 cm</td>
</tr>
</tbody>
</table>

Figure 4.1 Comparison of *Psilonichnus* species.
Figure 4.2. *Psilonichnus* sp. seen here as an area of interconnecting burrows. The yellow arrows point to bulbate sections, though many other specimens are visible in much of the lower two thirds of the picture. Red arrows indicate sections of *O. beaumarisensis*, interwoven with the *Psilonichnus* sp. This image is a good example of the large number of well preserved ichnofossils in some parts of the Rotunda unit.

*Psilonichnus* sp.

*Description.* Circular section, unlined tunnels, consistent in width, with main branches of equal width that may rejoin the main tunnel or terminate abruptly.
Branching common. ‘J’ shaped and straight burrows are 10 to 30 mm in width and up to 80 cm long, ‘Y’ shaped burrows usually half the width of the main branch, branching at angles of 60° to 90° from the main tunnel. ‘Y’ shaped burrows are side branches, connected to the central ‘J’ shaped or straight burrow system. Semi regular oval to rectangular chambers twice the width of the main tunnel, usually as part of the main burrow, or rarely as part of the branches. The chambers appear in multiple groups connected by lengths of tunnel at the short sides of the chamber. The burrows may appear as short sections or as large interconnected systems.

No scratch marks typical of a crustacean burrow (Myint, 2001) are present. The preservation of the burrow in goethite, rather than the original sediment may have precluded their survival had they existed, the diagenetic process eliminating any fine marks the animal may have made. Alternatively, the animals may simply not have made them, due to their own morphology, or that of their burrow. No part of the originating animal has been preserved, but given the paucity of ‘body’ fossils within this unit this is not unexpected. The diagenetic forces that favoured preservation of burrows either did not allow the fossilization of their originators, or the animals had evacuated the burrows prior to infilling.

Chambers from 10-40 mm wide and 20-80 mm long. Sediment, finer than the surrounding matrix, infill burrows. Burrows are preserved in goethite (commonly) or be present in short sections as remnant infill only. Distinguish from locally common Ophiomorpha beaumarisensis by lack of pelletal walls, smaller average size, and presence of bulbate chambers in Psilonichnus sp.

Comparison. Distinguished from most other species of Psilonichnus by the presence of bulbate chambers, which are not found in other members of the
ichnogenus. *Psilonichnus quietus* (Myint, 2001) exhibits swellings in the burrow walls, but only on one side of the tunnel. It lacks the formed chambers on both sides of the main burrow of *Psilonichnus* sp. *Psilonichnus lutimuratus* (Nesbitt & Campbell, 2002), has mud lined tunnels, which *Psilonichnus* sp. does not. *Psilonichnus upsilon* (Frey et al., 1984) has sparse to no branching, where *Psilonichnus* sp. is commonly branched at short intervals.

*Type Location.* Rickett’s Point Marine Reserve.

*Age.* Latest Miocene to earliest Pliocene.

*Stratigraphy.* From the Beaumaris Sandstone.

*Remarks.* ‘J’ shaped and straight burrows are wider, and are the central burrow system, with ‘Y’ shaped burrows as side branches (see figure 4.3). Bulbs are more common on the ‘J’ shaped and straight burrows, suggesting a use for breeding or food storage.

The heavily interconnected nature of large areas of burrows suggests that the originator was a gregarious animal that lived in large colonies, and interacted with other members of its species within the burrow. The side branches may represent a single animal exploring within the sediment, with the main tunnels (at twice the width) allowing the animals to pass in opposite directions. The chambers are twice
the width of the main tunnel, and the large number of them suggest a food storage role, rather than for mating.

The complexity of the burrow system implies a relatively high order invertebrate as the originator. (Myint, 2001) The relatively sharp angles of the ‘Y’ burrow entrances would be difficult for a long bodied animal to negotiate (as seen above the yellow arrow in figure 4.3). As a short bodied, gregarious, and relatively high order invertebrate, a brachyuran crustacean is the most likely candidate as the burrow maker. Fossil crabs are found in the *Lovenia* unit of Beaumaris Sandstone, though none are preserved in the upper units. As it is present with *Ophiomorpha beaumarisensis* in the Rotunda unit, it has a similar presumed depth range to that ichnospecies, i.e. tidal to sub-tidal (Ter & Buckeridge, 2012).
Figure 4.3. A ‘Y’ shaped side tunnel is seen here in an outcrop of the Rotunda unit at 37°59'36.2"S 145°01'46.4"E, as indicated by the yellow arrow. Bulbate chambers are present along the main tunnel, shown by the red arrows. Side tunnel is half the width of the main, and chambers are twice the width of the main tunnel. 28.5 mm coin to scale.
Ichnogenus *Bergaueria*

Prantl, 1945

*Diagnosis.* Cylindrical to hemispherical, vertical burrows possessing smooth, unornamented walls, Circular to elliptical in cross section; fillings essentially structureless. Rounded base, with or without shallow depression and radial ridges. (Prantl, 1945, amended by Pemberton et. al., 1988)

*Range.* Precambrian to Pleistocene (Australia, Europe, North America).

*Remarks.* These are the domicnchian traces of sediment dwelling anemones. They maintain their position in the sediment by means of a peristaltic end, and when the animal dies, the opening it creates in the sediment is in-filled with different material. Subtle mineralization of the infill causes the trace fossil to appear different from the surrounding rock. After lithification, subsequent inversion and erosion is required to expose the *Bergaueria*.

The trace fossil appears as a series of small mounds, patterned as a group of extant sea anemones would be in the modern day (Pemberton, et al. 1988). Extant sea anemones are separated by such a distance as to minimize competition for food, the larger ones separated by a greater distance. These fossils reflect that patterning.
The distinct circular trace (where present) of the peristaltic ‘foot’ provides the basis for subdivision into ichnospecies (Arai & McGugan, 1969).

Figure 4.4 Bergaueria sp. in an intertidal exposure of Beaumaris Sandstone immediately NW of Mentone Beach, Port Phillip Bay, Victoria. 37°59'13.1"S 145°03'04.8"E. The peristaltic pattern common to Bergaueria is present, though heavily eroded, on the specimen shown by the arrow at uppermost left of the picture. It appears as a darker circle around the top of the fossil. Coin diameter 20.5mm. Image by J. Buckeridge, 2014.
**Bergaueria sp.**

*Description.* Small, rounded, irregular hemispheres of different colour (lighter or darker than the surrounding rock) material, which protrude from the parent rock. Diameter 5-40 mm, height 2-20 mm. The height is less than the width in all observed specimens. Occurs as isolated specimens (rarely) or usually as large ‘colonies’ of 10 – 50 (Prantl, 1945). Colonies often grouped by size, in groups of smaller or larger individuals. Fossils rarely conjoined, generally being separate by a distance proportionate to their size. The peristaltic traces used to distinguish other members of the ichnogenera are rarely present, and heavily eroded.

*Comparison.* These specimens show a similar colonial patterning to the description of *Bergaueria perata* (Prantl, 1945 p. 51) “Specimens occur in clusters or individually; those in large clusters are colonies are usually crowded, but do not intersect”. The size and shape are consistent with other *Bergaueria* species (see figures 4.4 & 4.5.

*Age.* Latest Miocene to earliest Pliocene.

*Stratigraphy.* From the Beaumaris Sandstone.

*Remarks.* Generally lacking the distinctive peristaltic patterning of the ichnogenus, sufficient specimens show the trace (see figure 4.4) for it be placed within the *Bergaueria*. Most of the specimens are eroded, but enough of the patterning remains to fulfill the tests for this ichnospecies. (Prantl 1945, Alpert, 1973,
Pemberton, et. al., 1988). A nearby localized fault in Beaumaris Sandstone most likely provided the inversion of the layer necessary to expose the peristaltic ends.

Only known from a small layer at the southernmost end of the lithology, but common within that limited area. This may represent a localized inversion, or the boundaries of the sea anemone range.

It is unusual in that it originates from a Neogene formation, the other occurrence in Australia being more than half a billion years older (Seilacher et al., 2005). Nearly all other incidences worldwide are from the early Paleozoic.

Figure 4.5 Bergaueria sp., showing colonial patterning similar to that of modern day sea anemone colonies.
Figure 4.6 The rings in the sand are live sea anemones dwelling in the sediment of the inter-tidal at Rickett’s Point Marine Reserve. Note spacing between animals and similarity to patterning of *Bergaueria* sp. in figure 3.5. 28.5 mm coin to scale.
Figure 4.7 Stages of Bergaueria formation 1. Anemone drawing adapted from http://usercontent2.hubimg.com/10149719_f520.jpg access date 24/6/16.
Figure 4.8 Stages of *Bergaueria* formation 2.
4.3

Casts of Serpulid/Polycheate worm burrows

Description. Circular cross section, twisting burrow structures preserved in goethite. Burrows are extensively branched and interconnected. Blocks (up to 25m$^2$) preserved as a single unit of burrows, underneath a sheet of Goethite. Burrow width varies from 5 to 15 mm and exhibit a maximum length of 100 mm between branches.

Age. Latest Miocene to earliest Pliocene

Stratigraphy. From the Beaumaris Sandstone.

Remarks. The acute angles of the branching are a key factor in determining the original occupants. This sort of burrow structure (which lacks turn arounds) could have only been inhabited by an organism with a morphology capable of navigating it, ruling out species with an exoskeleton. This leaves the most likely candidates (given the marine setting) as soft bodied Annelids or Serpulids. Both of these Phyla are found in large colonies, their burrow structures resembling the fossil ones described here to a high degree. The most easily observed specimens are located in the intertidal immediately to the north of the Beaumaris Yacht Club at the co-ordinates given in figure 3.9. Other, highly eroded specimens are also
present nearby in the intertidal rock platforms south of the Tea House. This block is contained within the Rotunda unit.

A second block of worm burrow casts exists near the Southern phosphatic nodule bed, but is only observable on the very lowest of tides. This block is positioned within the *Lovenia* unit – at the very base of Beaumaris Sandstone. That these burrows have preserved at this place is unusual, as few other burrows preserved in goethite are found in this unit. Casts of wood are preserved in goethite within the *Lovenia* unit, so this may provide an explanation for its presence.

![Figure 4.9 Burrows in a block of goethite in the intertidal at 37°98’88.8”S, 145°02’73.6”E. The top of the block has eroded in the left half of the picture, exposing the tunnels preserved beneath. A number of circular transverse sections are visible at center left of picture. Coin is 28.5 mm in diameter.](image)
Figure 4.10 From the same block as figure 4.9, this has circular burrow entrances in the goethite sheet at top of picture. 28.5 mm coin to scale.
Figure 4.11 Worm burrows in an outcrop in the intertidal at 37°59'18.7"S 145°02'54.1"E. These burrows are at the base of the *Lovenia* unit.
Figure 4.12 Closer view of burrows from same site as 4.9
Figure 4.13 Cast of tree trunk in the intertidal. The longitudinal striations are consistent with the bark of Myrtaceae. Coin is 25 mm in diameter. Boring traces can be seen below right and left of the coin.

4.4

Casts of wood

Fossil tree trunk casts, preserved in goethite. Generally as large (2-4 m) lengths and from 200 – 600 mm wide. Locally common in places, distributed widely throughout the lithology. Trunks are unbranched, except in one instance. Tree bark imprints very well preserved in some specimens.
*Age.* Latest Miocene to earliest Pliocene.

*Stratigraphy.* From the Beaumaris Sandstone.

*Remarks.* The average size of the specimens suggests that the originating trees were comparatively large. The lack of branching indicates that they most likely grew close together, with competition for light in the forest canopy the most important environmental factor. The best candidates for the originating trees are members of the Myrtaceae family, which exhibit the necessary size, bark imprint and lack of branching.

Unfortunately, no casts of fossil leaves have been found, as these would have been of more utility in the identification of the original trees than bark imprints alone.

A trace fossil fauna (boring traces and bivalve imprints) is preserved on some tree casts. The presence of *Zenatiopsis phorca* (Darragh & Gill, 1963) moulds on the casts suggests a marine origin, as these bivalves are exclusively found in marine environments (Darragh & Gill, 1963). The marine borers mean that some of the tree sections spent time at sea, before being returned to shore and their imprints preserved.

The diversity and number of borers present on some specimens (see figs. 4.14 & 4.15) mean that in some cases, the tree trunks spent some time at sea, before being brought back in shore by current or wave action and buried by sediment. Conversely, the lack of borers on many other specimens suggests that many trees did not make it to sea for long, and reinforces the idea of a near shore environment for Beaumaris Sandstone.
The shell casts and boring traces are present in some places without a tree fossil concurrently preserved, suggesting that the shoreline was widely strewn with wood debris. Much of this wood debris was not preserved, but the traces of the organisms consuming it remain preserved in the sediment nearby, once the tree had been consumed and the animals dependent upon it sought a new food source.

Figure 4.14  Fossil bivalve casts on a section of wood cast at 37° 99’17.5”S, 145° 04’26.3”E. An internal mould of *Zenatiopsis phorca* can be seen immediately left of the 25 mm. coin, indicating a marine origin.
Figure 4.15 Bivalve fossil casts on wood cast at same location as figure 4.14. The diversity and number of casts suggest that the wood spent considerable time at sea before being deposited on the shore.
Chapter 5

Rock Units

5.1 Introduction

Beaumaris Sandstone is an early Miocene to late Pliocene (Mallet, 1977), (microfossil dating), (Wallace et al., 2005) (Potassium/Argon method), ferruginous sandstone, which is highly bioturbated (Kenley, 1967). It is overlain by Red Bluff Sands and underlain by the Fyansford Formation (Ter and Buckeridge, 2012). Dickinson & Wallace, 2009 (p. 554), give a maximum age of 6.21 Ma and a minimum of 4.49 Ma, with a preferred age range between 5.98 Ma and 4.91 Ma.

Previous work on Beaumaris Sandstone has tended to describe the lithology as single rock type, generally as a red, medium grained, ferruginous sandstone (Kenley, 1967). This is correct in broad terms, as this rock type forms the larger part of the lithology. However, when studied in detail, and with regard to the most recent knowledge of the ichnology of Beaumaris Sandstone (Ter & Buckeridge, 2012), variations within the type of the generally accepted lithology become apparent. In particular, a finer grained, yellow to light ochre rock type bearing a diverse ichnofauna, is quite distinctive from the more common dark red lithology.

The presence of Ophiomorpha and other fossils, both trace and ‘body’, allows further sub division into readily recognisable units within the lithology. The use of ‘units’ rather than ‘facies’ to describe the rock types is because a facies represents a change in depositional conditions. These units are based on a combination of diagenetic conditions and depositional changes. They are nonetheless clearly distinguishable.
The cause of the change from the *Lovenia* unit to the units above is at least in part a diagenetic one. Bioturbation may also have played a part, but the proportion of responsibility of each factor is not apparent from the evidence, as the whole lithology is highly bio-turbated. What may clearly be stated is that some change occurred, and that the conditions that had favoured the preservation of the mineralized bodies of animals altered such as to favour the preservation of structures (burrows) and casts of organisms. A clue to the nature of the change is seen in Ter & Buckeridge, 2012, where the authors infer that the burrows were preserved by selective mineralization of Goethite during diagenesis. The burrows act as a matrix for the Goethite to seep through and preserve them. This must have occurred in some part in the Lovenia unit, as tree impressions are present there as well as the upper units. The bed of polychaete worm burrows present at the base of the *Lovenia* unit is also preserved in Goethite, suggesting that either a lack of burrows, or local conditions that prevented burrows from remaining intact long enough to be preserved was responsible for the lack of other burrows in this unit. The *Bergaueria* present in the lower unit are not preserved in Goethite, rather as a result of the difference in mineralization when the anemone burrows were sedimented. The change from the *Ophiomorpha* unit to the Rotunda is a result of a change in the depositional conditions. The rock type changes, but *Ophiomorpha beaumarisensis* is present throughout both units.

The Beaumaris fault runs very close along the coast near the two sites where the *Lovenia* unit is exposed (see figure 1.8), but ceases before the next site (*Ophiomorpha* type section). A localized uplift may have taken place along the fault line which raised these two sites, but did not raise other parts of Beaumaris Sandstone. This provides a solution as to why the base of the strata is exposed at these two sites, but not in any others.
<table>
<thead>
<tr>
<th>Unit</th>
<th>Colour</th>
<th>Grain size</th>
<th>Fossils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotunda</td>
<td>Yellow to ochre</td>
<td>Fine</td>
<td><em>Psilonichnus</em> sp., <em>Ophiomorpha beaumarisensis</em> and other ichnofossils. Casts of wood. Boring traces and bivalves as casts, not on wood casts.</td>
</tr>
<tr>
<td><em>Ophiomorpha</em></td>
<td>Medium to dark red</td>
<td>Medium</td>
<td><em>Ophiomorpha beaumarisensis</em>. Casts of wood. Boring traces and bivalves as casts, rarely on wood casts.</td>
</tr>
<tr>
<td>Phosphatic nodule</td>
<td>Cream to white</td>
<td>N/A</td>
<td>The nodules contain fragments of shell fossils</td>
</tr>
</tbody>
</table>

**Figure 5.1** Table of Beaumaris Sandstone unit characteristics
Figure 5.2 Stratigraphy of selected points in northern half of study area. The sections are arranged from north to south in order from left to right. A slight rise in elevation of the Rotunda unit can be seen in the Red Bluff section from the Sandringham Rotunda, then dipping gradually to the south. See figure 4 for a list of section GPS coordinates.
Figure 5.3 Stratigraphy of selected points in southern half of study area. The sections are arranged from North to South in order from left to right. The Rotunda unit, absent at the *O. beaumarisensis* type section, appears again much higher in the lithology at the two southernmost points. See figure 2.4 for a list of section GPS coordinates.
<table>
<thead>
<tr>
<th>Site</th>
<th>Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandringham Rotunda</td>
<td>37°57'08.8&quot;S 145°00'09.8&quot;E</td>
</tr>
<tr>
<td>Red Bluff</td>
<td>37°57'52.4&quot;S 145°00'38.6&quot;E</td>
</tr>
<tr>
<td>Badlands</td>
<td>37°58'16.8&quot;S 145°00'39.9&quot;E</td>
</tr>
<tr>
<td>North boundary of marine reserve</td>
<td>37°58'54.5&quot;S 145°01'05.0&quot;E</td>
</tr>
<tr>
<td>Beaumaris Yacht Club</td>
<td>37°59'18.3&quot;S 145°01'38.3&quot;E</td>
</tr>
<tr>
<td><em>O. beaumarisensis</em> type section.</td>
<td>37°59'46.89&quot;S 145°14.97&quot;E</td>
</tr>
<tr>
<td>North phosphatic nodule bed</td>
<td>37°59'35.3&quot;S 145°02'30.3&quot;E</td>
</tr>
<tr>
<td>South phosphatic nodule bed</td>
<td>37°59'21.1&quot;S 145°02'49.4&quot;E</td>
</tr>
</tbody>
</table>

*Figure 5.4* Table of section coordinates.
Figure 5.5 Age of horizon at 37°59'21.6"S 145°02'48.9"E, from p. 554 of Dickinson and Wallace, 2009, adapted to show position of rock units. This site is equivalent to the South phosphatic nodule bed site used in this work.
5.2

Rock Units:

(In chronological order from oldest to youngest)

5.2.1 Phosphatic nodule unit.

The basal contact with the underlying Gellibrand Marl is best viewed in the base of the cliffs near the South phosphatic nodule bed. A dual unit of phosphatic nodules (Ter & Buckeridge, 2012, p. 237) is present there and it is by far the best example of the two occurrences. (The other is the very minor outcrop shown in Figure 5.7, which is about 800m W. of the other)

Kenley, 1967, described this as an interval of vertebrate bones resting on the sea floor in a reducing environment. Phosphatic nodules are known to form on sea floors, especially in low energy or near shore environments (Baturin, 1981). Small fossil fragments are present within the nodules themselves. This is an equivalent of other hard ground phosphatic Miocene horizons in local basins that are associated with a marine transgression and major erosive surface (Dickinson and Wallace, 2009).
Figure 5.6 Loose phosphatic nodules that have eroded from the South bed. The hammerhead that is shown is some pictures as scale has a 147 mm head length.
Figure 5.7 North phosphatic nodule bed, showing contact with underlying Gellibrand Marl.

5.2.2 *Lovenia* unit.

This occurs exclusively in the most southerly parts of the lithology and contains nearly all the ‘body fossils’ that have been recorded from Beaumaris Sandstone (Hall & Pritchard, 1897, Kenley, 1967, Stirton *et al.*, 1967 & Buckeridge, 1983). It contains the type locality for the vertebrate *Zygomaturus gilli* (Stirton *et al.*, 1967) and invertebrates *Lovenia woodsi* (Etheridge, 1875) and *Austromegabalanus victoriensis*, Buckeridge, 1983.

The unit is a medium to light ochre, medium grained sandstone when fresh, but becomes darker and redder with induration.
It contains casts of fossil wood, and layers of shell fragments are common in the lower portion (see figure 2.9). Gastropods, bivalves and a diverse range of other invertebrates are present. Vertebrate bones are uncommonly present. *Loenia woodsi* is most abundant basally. The tests are generally arranged dorsal side up, (see figure 2.9) indication of sorting by current or wave, and that sedimentation took place after death.

Barnacle fossils are present, attached to tests of *L. woodsi* (Buckeridge, 1983), again indicating a post-death reworking for *L. woodsi*. Live spatangoids are ‘in sediment’ dwellers, their tests only being exposed after death. Planktonic cirripede larva would not have been able to attach to the test of a live specimen. This unit rarely contains ichnofossils, which become common immediately above it. A bed of polychaete worm burrows is an exception to this, and is found at the base of the unit near the South phosphatic nodule bed site. The unit is abruptly replaced above by the *Ophiomorpha* unit, with little gradation.
Figure 5.8 *L. woodsi* at base of Beaumaris Sandstone. Coin is 25 mm in diameter.
**Figure 5.9** *Lovenia* unit. The yellow arrows at top and bottom of picture indicate where *L. woodsi* tests are eroding from matrix. Note alignment of two tests at base of picture. The red arrows at center left show a fossil wood cast. There is also a layer of bivalve shell fragments running along the top of the horizon. 25 mm coin to scale.
Figure 5.10 Top of Beaumaris Sandstone near the Beaumaris Yacht Club site. This darker rock type is the the *Ophiomorpha* unit. Many specimens of *O. beumarisensis* are visible, which is typical of this unit. The lighter coloured rock in the upper part of the picture is highly weathered Red Bluff Sandstone.

### 5.2.3 Ophiomorpha unit.

Red, medium grained sandstone with abundant *Ophiomorpha beumarisensis*.

The *Lovenia* unit is replaced by a unit with the common ichnofossil *O. beumarisensis* present in place of the mineralized remains of animals. This unit
forms much of the outcrop of Beaumaris Sandstone. It appears approximately 4 meters up section at the two southernmost sites, but at sea level at all others.

There is an upper and lower bed, which ‘sandwich’ the Rotunda unit at some sites (see Figures 5.2 & 5.3). It forms the uppermost unit of Beaumaris Sandstone, having unconformable contact with the overlying Red Bluff Sand.

Both upper and lower beds are identical, and are thus considered to be the same unit. Gradation is almost non-existent – an abrupt change in the fossils takes place, and the rock become redder. Particle size remains similar.

Both adult and juvenile burrows are found. Very few other distinguishable ichnofauna are present within this rock type, either due to lack of original occurrence, or failure to preserve.

*O. beaumarisensis* is a comparatively robust burrow due to its dual lining (Ter & Buckeridge 2012), which may have weathered large waves or currents better than others. This would explain the presence of juvenile burrows, but no other ichnofossil types. Presumably the ecology was equally as diverse during the deposition of this unit as that of the Rotunda, so the sound engineering of *Ophiomorpha* may have caused it to be preserved where other burrows of similar size were not.

As shown in figures 5.2 & 5.3, this rock unit also recurs at upper levels in the lithology. Its presence in horizons common and wide spread (in contrast with the two older types), with thicknesses up to 3 m in some horizons. A small horizon which contains *Lovenia* and a limited mollusc fauna as casts are present in the uppermost part of this unit at 37° 97’10.6”S, 145° 01’08.5”E. This horizon is unusual, at it is the only known appearance of *L. woodsi* above the *Lovenia* unit.
This horizon of the *Ophiomorpha* unit contains both large and small specimens of *O. beaumarisensis*, but no other ichnofauna. A large transverse section is visible at center left, and a longitudinal section at upper mid right. Many small specimens can be seen below the 25 mm coin.

Fossil casts of wood are uncommon, but widespread in this unit. A rock platform at 37°59'43.1"S 145°02'21.1"E has fossil bivalve boring traces upon wood casts, along with casts of marine bivalves. This does not occur at any of the other sites that have fossil wood casts. This area is the best for examining wood cast specimens, as they are abundant here, and easily accessed at low tide. It may have been a place where logs that had been to sea (as evidenced by the borers & marine
mollusc casts) were washed into shallow water, stranded and then covered by sediment.

Figure 5.12 Bivalve casts on wood cast at 37°59'43.1"S 145°02'21.1"E in Ophiomorpha unit. Diameter of coin is 25 mm.
Figure 5.13 *Psilonichnus* sp. main burrows in the Rotunda unit. Coin is 25 mm in diameter.

### 5.2.4 Rotunda unit

**Etymology:** named for the public Rotunda on Beach Road, Sandringham.

Yellow to light ochre, fine grained sandstone with *Ophiomorpha beaumarisensis*, *Psilonichnus* sp. and other diverse ichnofauna. Present in the two southernmost sites as a layer high in the cliff face, but as outcrops and shore platforms at the others.

The more familiar red sandstone of the previous layer becomes a lighter, more yellow colour in this unit. The noticeable differences are the smaller particle size
(fine grained as opposed to medium) and the lighter colour (“yellow” as opposed to “red”). It contains an abundant and diverse ichnofauna, with *O. beaumarisensis* and *Psilonichnus* sp. common in this layer, and a number of less prevalent ichnospecies. Casts of wood are present, though none show the bivalve infestation detailed in the *Ophiomorpha* unit. These logs had not spent enough time at sea to attract the attentions of the borers. Bivalve casts and traces are uncommon, and are present as erratic accumulations, not associated with the fossil casts of wood.

A block of fossil polycheate worm burrows is present at the Yacht Squadron site in this unit, and appears to be similar in composition to the one at the base of the Lovenia unit, though at a markedly different level in the stratigraphy.

The presence of *Psilonichnus* sp. in association with *O. beaumarisensis* indicates a change in the conditions of deposition. A depth change to the point where the tolerance ranges of the two species overlapped, or a lessening of wave energy sufficient to allow preservation of *Psilonichnus*. A depth change may have been responsible for the decrease in wave energy, the increased depth causing waves to pass over, rather than through the burrows and allowing their preservation.

The change in particle size, along with the addition of a common ichnospecies, also suggest a change in depth, or change in the average wave size took place at the beginning of the deposition of the Rotunda unit. This then returned to the ‘normal’ conditions of the *Ophiomorpha* unit, as seen in figures 5.2 & 5.3.

The preservation of the smaller, unlined and less robust burrows of *Psilonichnus* sp., along with other small burrows during this phase of deposition indicate that quieter conditions likely prevailed during compared to the *Ophiomorpha* unit. If one factor exclusively or a combination of both is responsible is difficult to determine.
Figure 5.14 Cast of *Clypeaster gippslandicus* in Rotunda unit.
Chapter 6

Palaeoecology

6.1

Introduction

In the previous chapter on the units of Beaumaris Sandstone, division was made based on the various kinds of fossil present. This remains a convenient method of dividing the changes that occurred in the deposition of Beaumaris Sandstone, as each unit represents a variation in either the local conditions, or a change in the conditions of preservation (the latter is as important to this lithology, given the change in fossil content).

The distinct difference in fauna preserved above the Lovenia facies presents a choice as to whether a drastic alteration in the environment took place at this point. Either an almost complete change in the local ecology occurred, or the conditions of preservation were altered to provide an almost exclusively ichnofaunal assemblage. Chronologically equivalent strata from other parts of Victoria, Jemmy’s Point Formation and Grange Burn Formation, do not show this abrupt change from an environment favouring the preservation of body fossils. These lithologies contain a broadly similar fauna to the lower part of Beaumaris sandstone, but are relatively consistent in their fossil content, rather than transitioning to a mass preservation of ichnofossils. Both are relevant to this comparison as they have a phosphatic nodule bed at the base, with fossil mammal
remains (Telford, 1967) (Fitzgerald, 2004) and a shelly fauna. They contain a broadly similar fauna of barnacles, echinoids and molluscs as the *Lovenia* unit and can be considered the equivalent of this. Presumably there were burrows present during the time of deposition of these two strata, given the other broad similarities with Beaumaris Sandstone, but they have not been preserved. Neither of these equivalent strata contain the casts of trees that are found at every level of Beaumaris Sandstone.

The concurrent presence of *L. woodsi* with *O.beaumarisensis* (both preserved in goethite) at the top of Beaumaris sandstone also infers that it was the preservational conditions that changed above the *Lovenia* facies, i.e. a change in the process of diagenesis from the previous facies.
6.2

Fauna list

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<td><em>Ophiomorpha</em>, Rotunda</td>
<td>Intertidal to shallow subtidal</td>
</tr>
<tr>
<td><em>Psilonichnus</em> (trace fossil)</td>
<td>Rotunda</td>
<td>Intertidal to shallow subtidal</td>
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<td>Sub tidal</td>
</tr>
<tr>
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<td>Sub tidal</td>
</tr>
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</tr>
<tr>
<td><em>Tetraclitella</em></td>
<td><em>Lovenia</em></td>
<td>Intertidal</td>
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</tbody>
</table>

Figure 6.1 Fauna list and bathymetric ranges
Figure 6.2 *Amphistegina* sp. from the *Lovenia* unit at 37°59'40"S 145°02'23"E. Diameter of foraminifera is 4.6 mm. Image J. Buckeridge 2015.

6.3

Discussion

6.3.1

Phosphatic nodule bed

This represents a period of animal bones and teeth lying on a sea bed in a reducing environment (Kenley, 1967, Ter & Buckeridge, 2012). The success of phosphatic
accumulation over erosive forces suggests a quiet, shallow marine environment, in an area where bones were not subject to strong current or wave action, both of which would have eroded the bones.

Dickinson & Wallace, 2009 p. 547 describe the period thus; “the timing of phosphogenesis coincides with a period of transgression across the South east Australian margin following late Miocene uplift. The transgression is responsible for the erosion of the underlying Miocene sequence, creation of a period of very slow sedimentation that was favourable to phosphate formation...”. The unconformity between the Fyansford Formation and Beaumaris Sandstone occurs at the time one of the major depositions of phosphate (Dickinson & Wallace, 2009), and forms part of an erosion surface spanning much of South east Australia at the time. They also mention the presence of short burrows protruding into the Fyansford Formation from the Phosphatic nodule unit, though none of these were detected during the survey.

It was an area where animal bones were likely to be present in large numbers – the outlet of a river is a strong possibility as larger animals would be present to drink, their demise causing their bones to be washed to sea when flooding took place. Fossil marsupial remains have been found in the unit above, such as *Zygomaturus* (Stirton *et al*. 1957).

Alternately, a shallow marine area where cetaceans were common (perhaps a breeding ground) is also possible, given their appearance in the *Lovenia* facies immediately above (Fitzgerald, 2004).

A final theory is the possibility that this was simply an area on the seabed where bones accumulated from a wide catchment – a quiet backwater where the currents
petered out and deposited remains of vertebrae and fish gathered over a large area.

6.3.2

*Lovenia unit*

This contains an unusually rich assemblage; from cetacean remains (Fitzgerald, 2004, Piper et. al., 2006), *Zygomaturus* (Stirton et al., 1957), a rainforest dwelling giant marsupial, as well as penguins (Simpson, 1967 & 1970) and giant albatross (Wilkinson, 1967). There are casts of wood (Ter & Buckeridge, 2012) and a large and diverse invertebrate record (Etheridge, 1875, Darragh, 1970 & 1985, Buckeridge, 1983).

In this section at least, a large amount of data is available via the fossil record. The occurrence of casts of wood, combined with vertebrate remains of terrestrial origin provide a strong indication that the shoreline of the time was nearby – most likely covered in rainforest (see section on systematic palaeontology for more complete detail of tree casts).

The presence of large marine and shore dwelling vertebrates as well as a diverse molluscan and crustacean ecology (especially the locally common *Lovenia woodsii*, a spatangoid of medium to shallow water depth range (Etheridge, 1875) indicate a shallow to medium depth, inshore environment. The presence of a number of trophic links in the food chain indicates a diverse and thriving ecology, which was able to sustain a range of large animals.

The presence of the foraminiferan *Amphistegina* (d'Orbigny, 1826) (see figure 4.2 for image) confirms that the seas were warm, and relatively shallow (Loeblich & Tappan 1988). The cirripedes *Austromegabalanus victoriensis* and *Tetraclitella* sp.
cf. *T purpurascens* have a fairly restricted temperature and bathymetric range (Buckeridge, 1983) and provide further evidence of a sub-tropical, shallow subtidal environment.

An estuary, where dead animals were swept to sea during floods (common in a rainforest environment) provides explanation for the large numbers of shark teeth found in this facies (Hall & Pritchard, 1897).

Tree trunks may also have washed down the river to be deposited on the nearby beaches, though if the shoreline was steep and heavily wooded, this may not have been necessary to provide the required source material.
Figure 6.3 *Lovenia woodsi* test eroding from surrounding *Lovenia* unit at the South phosphatic nodule site. The surrounding matrix is highly bio-turbated. 25 mm coin to scale.
Figure 6.4 Tree cast in *Lovenia* unit near the North phosphatic nodule bed site. This layer is readily identifiable by the shelly fossils in the top section of the picture, which are not present in any other. Lateral striations on wood cast may be indicative of Myrtacae.

All of these elements combine to give a picture of a near shore environment, with forested hills and an estuary entrance. *L. woodsi* is by far the most common fossil, and becomes important to the interpretation of the overall palaeoecology when it reoccurs in a small area at the top of Beaumaris Sandstone.

6.3.3

**Ophiomorpha unit**
Immediately above the *Lovenia* facies, a change in the fauna from preserved body fossils to predominantly trace fossils occurs. The surrounding lithology does not vary noticeably, apart from this change. This consistency in the rock between the two units means that a change in the conditions of preservation is responsible, rather than a calamitous environmental event (which would be reflected in a change in the lithology).

*Ophiomorpha beaumarisensis* is by far the most abundant fossil, with few other recognisable ichnofossils present. The interpretation by Ter & Buckeridge (2012) of these ichnofossils placed them within the intertidal to sub tidal bathymetric range, and of subtropical origins. Casts of tree trunks are present along with the fauna associated with them.

This, when combined with the continued presence of the wood casts, allows the interpretation that the conditions described in the previous facies did not alter greatly; a near shore environment with a forest nearby. Whether the estuary continued to flow into the sea nearby is impossible to determine, as the vertebrate remains of the previous section are not present.

An important part of this facies is a small area near the Badlands site. A horizon contains fossils of *L. woodsi* and a limited mollusc fauna near the top of Beaumaris Sandstone. The overlying unconformable Red Bluff Sand is present very close to this occurrence, which assists in the determination of the position of the fossil band.

This is a an important place in the palaeoecology of Beaumaris Sandstone, as the preservation of *L. woodsi* ceases above the *Lovenia* unit, except for this small area. Its presence in conjunction with *O. beaumarisensis* here provides strong support for the hypothesis that conditions did not change greatly throughout the deposition
of Beaumaris Sandstone. The presence of *L. woodsi* at the upper part allows for a few possibilities. Either *L. woodsi* was extinct between the two occurrences, or was present all along, or these areas were inhabited by the animal due to its environmental preferences.

The concurrent presence with *O. beaumarisensis* allows for the elimination of the first possibility, as *O. beaumarisensis* is also found in horizons immediately above the *Lovenia* facies. The continued occurrence of *O. beaumarisensis* in all the facies above the *Lovenia* also allows the inference that the palaeo environment did not vary beyond that which a single species could tolerate. Combined with the presumed continual presence of *L. woodsi*, means that the confidence in this lack of variation is increased (i.e., it remained within the tolerance of two different species for the time of deposition).

In the case of the subtropical originator proposed by Ter & Buckeridge (2012), this means that the conditions were continuously warm throughout the deposition of Beaumaris Sandstone. The sea level is also likely to be have been reasonably constant, within the depth tolerance ranges of *O. beaumarisensis*. It is unfortunate that ichnofossils are rare at the base of lithology as a cross reference, but not unreasonable to postulate that the originator of *O. beaumarisensis* was also present at the deposition time of the *Lovenia* unit, given its concurrent presence in the area described above.

This species would not occur on a high energy beach, (the burrow structures would not survive large waves) so it can be inferred that quieter shorelines were common, rather similar to the conditions found on modern day Port Phillip Bay.
Figure 6.5. A section of *Ophiomorpha beaumarisensis* from Beaumaris Sandstone in the intertidal at Rickett’s Point Marine Reserve. The pelletal re-inforcement of the burrow is easily seen. This may have caused the preservation of *O. beaumarisensis* in such a large scale – its burrows were stronger and more able to withstand diagenesis than others. Coin is 25 mm.
Figure 6.6 *Lovenia woodsi* is found in the *Ophiomorpha* unit near the top of Beaumaris sandstone in a small area near the Badlands site. 25 mm coin to scale.

### 6.3.4 Rotunda unit

Conditions were different during this stage, evidenced by the change in rock type, and the addition of *Psilonichnus* sp. to *O. beaumarisensis*. Rarer examples of other ichnofossils are also present, though highly localised. *L. woodsi* is not preserved in this facies, and casts of tree trunks are still present, if uncommon. This facies has
two ichnospecies in conjunction, meaning that the environment had altered to the extent that it now fell within the tolerances of *Psilonichnus* sp., though remaining within the tolerance of *O. beaumarisensis*. The presumed originator (a crab) does not give any real information as the likely palaeo depth, though the *O. beaumarisensis* means the depth remained inter to sub tidal. The possibility that *Psilonichnus* sp. was present, but simply not preserved in the *Ophiomorpha* unit must be taken into account as well. Conditions for preservation seem to have been particularly favourable in this facies, and the presence of a varied ichno fauna (compared to the *Ophiomorpha* facies) does not necessarily mean that a larger species assemblage was present.

The continuing nearby presence of land is confirmed by the wood casts present. The overall environmental change then, was slight. Temperatures remained within the tolerance of *O. beaumarisensis*, and rain was still plentiful enough to sustain forests.

*Psilonichnus* is ascribed to an “inshore/bay” environment by Nesbitt & Campbell (p 5, 2006), which is consistent with a gradual change in the surrounding paleoecology.

As has been discussed in the unit chapter, the change in lithology is interpreted to have been from an increase in depth of the sea. The builders of *O. beaumarisensis* would be tolerant to a rise in temperature, given the subtropical to tropical range of its originator. An increase in global temperatures (causing a rise in sea levels as polar ice caps melt) may have been responsible. A seismological event, causing localised sinking, followed by later uplift, presents as a less likely alternative scenario (Wallace, *et al.* 2005).
Figure 6.7 Rotunda unit, with *Psilonichnus* sp. at centre right of picture.
6.4

Conclusion

This study advances knowledge of Beaumaris Sandstone by introducing ichnology to its analysis, and confirming the presence of trace fossils across most of its outcrop. This adds another element to its already rich fossil record, and one that is ubiquitous across the whole length of outcrop, rather than being confined to a small area in the south. The discovery of consistent and persistent layers of trace fossils has allowed a new division of Beaumaris Sandstone into readily recognizable units, separated by fossil content. These units incorporate previous fossil discoveries and the results of field surveys undertaken in this study.

Two ichnogenera new to Beaumaris Sandstone were recorded, with the discovery of *Psilonichnus* sp. being the first record of this genus in Australia. Body fossils and ichnofossils (with the exception of fossil wood casts, which are present at all levels) were found not to be present in the same stratigraphic layers, supporting a hypothesis that diagenetic changes were responsible for the difference, rather than a change in environment. This is further supported by the concurrent presence of *O. beaumarisensis* and casts of *L. woodsi* in one small area, indicating that *L. woodsi* may have present during the whole of deposition of Beaumaris Sandstone, but the conditions necessary to preserve it did not exist, while being favourable to the mass preservation of trace fossils.

Fossil evidence supports a hypothesis that a subtropical environment was present during the time of deposition. The persistent presence of tree casts indicates Beaumaris Sandstone was deposited near land for the whole of its formation. A river may have been present, at least for the first stage of deposition. Conditions
did not vary enough to render *L. woodsi* or the originator of *O. beaumarisensis* locally extinct during this time, so any change in conditions was gradual, and within the temperature range tolerance of two species. While local conditions would have varied (as with shorelines of modern day Rickett’s Point itself), the persistent presence and good state of preservation of *O. beaumarisensis* meant that the beaches were low impact. This supports the hypothesis of a quiet bay environment, in which the originator species was able to construct large burrows, which would not be possible on a high impact beach. The data supports a hypothesis of an inter-tidal to sub-tidal depositional environment for Beaumaris Sandstone. The nearby shoreline was forested, and the presence of a wide variety of fossils indicates that a diverse local ecology was present between 6 and 4.5 million years ago. The climate was stable enough to allow a continuity of species during the approximately 1.5 million years of deposition.
Chapter 7

References


Beaumaris Conservation Society webpage: [http://www.bcs.asn.au/m8_bmys_.htm](http://www.bcs.asn.au/m8_bmys_.htm) access date 15/2/15.


Lyell, Charles. Principles of geology: being an inquiry how far the former changes of the earth's surface are referable to causes now in operation. Vol. 1. J. Kay jnr. & brother, 1830.


APPENDIX

1

Sedlog data from named sites

GPS co-ordinates for sites are listed in figure 2.4.

Note that Sedlog only provides a facility to map ‘facies’ rather than ‘units’

Phosphatic nodule bed unit = Facies 1

\textit{Lovenia} unit = Facies 2

\textit{Ophiomorpha} unit = Facies 3

Rotunda unit = Facies 4
## Key to charts

### Lithologies
- Matrix-supported conglomerate
- Sandstone

### Symbols
- Nodules and concretions
- Bivalves
- Echinoids
- Logs
- Vertebrates
- Intense bioturbation
- Vertical burrows
- Horizontal burrows
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**Red Bluff Sand**

**Ophiomorpha unit**
APPENDIX

2

Sedlog data from unnamed sites

GPS co-ordinates are given on the sheet

Sites in order from North to South
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<td>6.5 MA</td>
<td>Red Bluff Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Red Bluff Sand
- Ophiomorpha unit
Red Bluff Sand

Ophiomorpha unit
<table>
<thead>
<tr>
<th>AGE</th>
<th>FORMATION</th>
<th>SCALE (m)</th>
<th>LITHOLOGY</th>
<th>LIMESTONES</th>
<th>STRUCTURES / FOSSILS</th>
<th>NOTES</th>
<th>BIOTURBATION</th>
<th>FACIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4 MA</td>
<td>Braunsuris</td>
<td>1</td>
<td>1</td>
<td>Sandstone</td>
<td></td>
<td>Ophiomorpha unit</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>5.4 MA</td>
<td>Braunsuris</td>
<td>1</td>
<td>2</td>
<td>Sandstone</td>
<td></td>
<td>Rotunda unit</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>37°59'35.9&quot;S 145°0'14.7&quot;E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- MUD, SAND, GRAVEL
- CLAY, Silt, Fine, Medium, Coarse
- RUT & BOUND
- GRAN, PEBB, COBB, BOWL

Diagram:
- 1, 2, 3, 4
<table>
<thead>
<tr>
<th>AGE</th>
<th>FORMATION</th>
<th>SCALE (m)</th>
<th>LITHOLOGY</th>
<th>LIMESTONES</th>
<th>STRUCTURES / FOSSILS</th>
<th>NOTES</th>
<th>BIOTURBATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;5.4 MA</td>
<td>Red Bluff Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.4 MA</td>
<td>Beaumaria Sandstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Red Bluff Sand

Ophiomorpha unit
<table>
<thead>
<tr>
<th>AGE FORMATION</th>
<th>SCALE (m)</th>
<th>LITHOLOGY</th>
<th>LIMESTONES</th>
<th>STRUCTURES / FOSSILS</th>
<th>NOTES</th>
<th>BIOTURBATION</th>
<th>FACIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4 MA</td>
<td>10</td>
<td>Daily</td>
<td>Mud, Sand</td>
<td>Red Bluff Sand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5-3.0 MA</td>
<td>5</td>
<td>Gravel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5-2.0 MA</td>
<td>4</td>
<td>Pebble</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5-1.0 MA</td>
<td>3</td>
<td>Cobble</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5-0.0 MA</td>
<td>2</td>
<td>Boulders</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Red Bluff Sand
- Ophiomorpha unit
<table>
<thead>
<tr>
<th>AGE</th>
<th>FORMATION</th>
<th>SCALE (m)</th>
<th>LITHOLOGY</th>
<th>STRUCTURES / FOSSILS</th>
<th>NOTES</th>
<th>Bioturbation</th>
<th>FACIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;5.4 MA</td>
<td>Red Bluff Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.4 MA</td>
<td>Beaufort Sandstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.4 MA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.4 MA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beaufort Sandstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Red Bluff Sand
- Ophiomorpha unit
- Rectula unit
- Ophiomorpha unit
- Lovenia unit
APPENDIX

Image from Pilbara Geology website:
access date 15/8/14
APPENDIX

4

Occurrence and relative abundance by site.

Relative abundance is determined by the number of specimens observed within each vertical meter of section outcrop, with sections defined as 10 m. across (effectively 10m²). The condition of the fossils is noted in the remarks. Condition being defined as the majority of fossils observed exhibiting this state of preservation. For convenience, the heights at which a noticeable change in fossils and rock appearance has been used to differentiate each outcrop.

Key to relative abundance (per 10 m²)

<table>
<thead>
<tr>
<th>Abundance</th>
<th>1 (rare)</th>
<th>2-10 (common)</th>
<th>&gt;10 (abundant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>*</td>
<td>**</td>
<td>***</td>
</tr>
</tbody>
</table>
1. Rotunda Section

<table>
<thead>
<tr>
<th>Height</th>
<th><em>O. beaumarisensis</em></th>
<th><em>Psilonichnus</em> sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8-6.1 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>1.6-3.8 m.</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td>Good condition</td>
</tr>
<tr>
<td>0-1.6 m.</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td></td>
<td>Rare borer traces</td>
<td>Fine grained, yellow</td>
</tr>
</tbody>
</table>
2. Red Bluff section.

<table>
<thead>
<tr>
<th>Height</th>
<th>$O.\ beaumarisensis$</th>
<th>$Psilonichnus\ sp.$</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-10 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>1.8-4 m.</td>
<td>***</td>
<td></td>
<td></td>
<td>*</td>
<td>Medium grained, red</td>
<td>Good condition</td>
</tr>
<tr>
<td>0.2-1.8 m.</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td>Fine grained, yellow</td>
<td>Good condition</td>
</tr>
<tr>
<td>0-0.2 m.</td>
<td>**</td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td>Poor condition</td>
</tr>
</tbody>
</table>

Casts of *L. woodsii* are present approximately 100m north of this site, as detailed in the text.

<table>
<thead>
<tr>
<th>Height</th>
<th><em>O. beaumarisensis</em></th>
<th><em>Psilonichnus sp.</em></th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2-7.8 m.</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>1-2.2 m.</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td>Good condition</td>
</tr>
<tr>
<td>0-1 m.</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td>Rare casts of gastropods and <em>Clypeaster gippslandicus</em> Borer traces</td>
<td>Fine grained, yellow.</td>
<td>Good condition</td>
</tr>
</tbody>
</table>
4. Northern boundary of the marine reserve

<table>
<thead>
<tr>
<th>Height</th>
<th><em>O. beaumarisensis</em></th>
<th><em>Psilonichnus sp.</em></th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7 – 6.8 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>0.4-3.7 m.</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td>Fair condition generally, but some of the longest intact lengths of <em>O. beaumarisensis</em> are found in this section.</td>
</tr>
<tr>
<td>0-0.4 m.</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td>Fine grained, yellow</td>
<td>Good condition.</td>
</tr>
</tbody>
</table>
## 5. Beaumaris yacht club

<table>
<thead>
<tr>
<th>Height</th>
<th>O. beaumarisensis</th>
<th>Psilonichnus sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2-5.7 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>0.3-2.2 m.</td>
<td>***</td>
<td></td>
<td>*</td>
<td></td>
<td>Medium grained, red</td>
<td>Fair condition</td>
</tr>
<tr>
<td>0-0.3 m.</td>
<td>**</td>
<td>***</td>
<td></td>
<td>Polyvcheate worm burrows present in large continuous blocks (up to 2m²). Rare borer traces and bivalve casts.</td>
<td>Fine grained, yellow</td>
<td>Fair condition</td>
</tr>
</tbody>
</table>
## Section 6. *O. beaumarisensis* type section

<table>
<thead>
<tr>
<th>Height</th>
<th><em>O. beaumarisensis</em></th>
<th><em>Psilonichnus</em> sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.8-6.6 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>0-3.8 m.</td>
<td>***</td>
<td>*</td>
<td>Rare borer traces and bivalve casts.</td>
<td>Medium grained, red</td>
<td>Good condition and some very good intact lengths are found in this section. Highly abundant juvenile burrows in places.</td>
<td></td>
</tr>
</tbody>
</table>
### Section 7. North phosphatic nodule bed

<table>
<thead>
<tr>
<th>Height</th>
<th>O. beaumarisensis</th>
<th>Psilonichnus sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9-8.6 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>4.4-5.9 m.</td>
<td>***</td>
<td></td>
<td></td>
<td>*</td>
<td>Medium grained, red</td>
<td>Fair condition</td>
</tr>
<tr>
<td>3.8-4.4 m.</td>
<td>**</td>
<td>**</td>
<td></td>
<td>*</td>
<td>Fine grained, yellow</td>
<td>Fair condition</td>
</tr>
<tr>
<td>2.3-3.8 m.</td>
<td>***</td>
<td></td>
<td></td>
<td>*</td>
<td>Medium grained, red</td>
<td>Fair condition</td>
</tr>
<tr>
<td>0.2-2.3 m.</td>
<td>**</td>
<td></td>
<td>**</td>
<td>L. woodsi abundant. Layers of broken bivalve shells. Cirripedes rarely present on L. woodsi tests.</td>
<td>Medium grained, red</td>
<td>L. woodsi generally in good condition, intact bivalve shells rare</td>
</tr>
<tr>
<td>0.0-0.2 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Phosphatic nodule bed, contact with Gellibrand Marl</td>
<td></td>
</tr>
</tbody>
</table>
Section 8. Southern phosphatic nodule bed

<table>
<thead>
<tr>
<th>Height</th>
<th><em>O. beaumarisensis</em></th>
<th><em>Psilonichnus</em> sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8-9 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>4.9-5.8 m.</td>
<td>**</td>
<td>*</td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td>Fair condition</td>
</tr>
<tr>
<td>4.2-4.9 m.</td>
<td>**</td>
<td>***</td>
<td>*</td>
<td></td>
<td>Fine grained, yellow</td>
<td>Good condition</td>
</tr>
<tr>
<td>2.1-4.2 m.</td>
<td>**</td>
<td>*</td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td>Fair condition</td>
</tr>
<tr>
<td>1-2.1 m.</td>
<td>*</td>
<td></td>
<td></td>
<td><em>L. woods</em> common</td>
<td>Medium grained, red</td>
<td>Fair condition</td>
</tr>
<tr>
<td>0.7-1 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Phosphatic nodule bed.</td>
</tr>
<tr>
<td>0.3-0.7 m.</td>
<td>*</td>
<td></td>
<td></td>
<td><em>L. woods</em> common</td>
<td>Medium grained, red</td>
<td>L. woods* fair condition. Layers of broken bivalves.</td>
</tr>
<tr>
<td>0-0.3 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Phosphatic nodule bed. Contact with</td>
</tr>
</tbody>
</table>
Site at 37°56'43.7" S 144°59'43.3" E (unnamed site)

<table>
<thead>
<tr>
<th>Height</th>
<th>O. beaumarisensis</th>
<th>Psilonichnus sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4-5.3 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>0-1.4 m.</td>
<td>**</td>
<td></td>
<td>*</td>
<td></td>
<td>Medium grained, red</td>
<td>Good condition</td>
</tr>
</tbody>
</table>

Gellibrand Marl.
Site at 37°58'38.2"S 145°00'57.6"E (unnamed site)

<table>
<thead>
<tr>
<th>Height</th>
<th>O. beaumarisensis</th>
<th>Psilonichnus sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 -6.9 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>0-2.1 m.</td>
<td>***</td>
<td>*</td>
<td></td>
<td>Borer traces rare</td>
<td>Medium grained, red</td>
<td>Fair condition</td>
</tr>
</tbody>
</table>
Site at 37°59'08.4"S 145°01'25.8"E (unnamed site)

<table>
<thead>
<tr>
<th>Height</th>
<th><em>O. beaumarisensis</em></th>
<th><em>Psilonichnus sp.</em></th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6-5.8 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>0-1.6 m.</td>
<td>**</td>
<td>*</td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td>Bad condition</td>
</tr>
</tbody>
</table>
Site at 37°59'35.9"S 145°01'47.2"E (unnamed site)

<table>
<thead>
<tr>
<th>Height</th>
<th>O. <em>beaumarisensis</em></th>
<th><em>Psilonichnus</em> sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6-2 m.</td>
<td>**</td>
<td>*</td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td>Fair condition</td>
</tr>
<tr>
<td>0-0.6 m.</td>
<td>***</td>
<td>**</td>
<td>Rare bivalve casts and borer traces</td>
<td>Fine grained, yellow</td>
<td>Poor condition</td>
<td></td>
</tr>
</tbody>
</table>
Site at 37°59'41.6"S 145°02'06.3"E (unnamed site)

<table>
<thead>
<tr>
<th>Height</th>
<th><em>O. beaumarisensis</em></th>
<th><em>Psilonichnus</em> sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1-5.6 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>0-2.1 m.</td>
<td>**</td>
<td></td>
<td>*</td>
<td></td>
<td>Medium grained, red</td>
<td>Poor condition</td>
</tr>
</tbody>
</table>
Site at 37°59'45.8"S 145°02'18.8"E (unnamed site)

<table>
<thead>
<tr>
<th>Height</th>
<th>O. beaumarisensis</th>
<th>Psilonichnus sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3-6.8 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>0-3.3 m.</td>
<td>***</td>
<td>*</td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td></td>
</tr>
</tbody>
</table>
Site at 37°59'38.4"S 145°02'26.6"E (Unnamed site)

<table>
<thead>
<tr>
<th>Height</th>
<th>$O.\ beaumarisensis$</th>
<th>$Psilonichnus$ sp.</th>
<th>Fossil wood casts</th>
<th>Other fossils</th>
<th>Lithology</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4-8.8 m.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Medium grained, yellow to gray</td>
<td>No fossils</td>
</tr>
<tr>
<td>5.1-6.4 m.</td>
<td>***</td>
<td></td>
<td></td>
<td>*</td>
<td>Medium grained, red</td>
<td>Fair</td>
</tr>
<tr>
<td>4.2-5.1 m.</td>
<td>**</td>
<td>**</td>
<td></td>
<td></td>
<td>Fine grained, yellow</td>
<td>Fair</td>
</tr>
<tr>
<td>2.8-4.2 m.</td>
<td>**</td>
<td></td>
<td>*</td>
<td>Rare borer traces</td>
<td>Medium grained, red</td>
<td>Fair</td>
</tr>
<tr>
<td>0-2.8 m.</td>
<td>*</td>
<td>L. woodsi common, molluscs rare, Two shark’s teeth present</td>
<td></td>
<td></td>
<td>Medium grained, red</td>
<td>Poor, Fragmented shell layers common.</td>
</tr>
</tbody>
</table>