

# SECTION

## CHAPTER 8

### VERTICAL CYLINDRICAL BURROWS

## 8.1. INTRODUCTION

Vertical cylindrical burrows are mainly produced for dwelling and are one of the most widespread, well known, and commonly reported types of burrows from the geological record. Many of these burrows are assigned to the ichnogenus 'Skolithos' or related ichnogenera. These ichnogenera are poorly treated in the literature and some of them have never even been illustrated. Additionally, earlier nomenclatural practice involved the creation of names that extended synonymy lists and added more confusion. Hence these vertical cylindrical burrows have been given different scientific names in situations involving morphologically identical forms that occur in different geological formations or in different geographic areas (James, 1891). Another difficulty that has added to the nomenclature problem is resolution of the producer organisms responsible for these burrows. Because of their simple cylindrical-shape and bedding-normal disposition, there are potentially many organisms that may have been responsible for these burrows: e.g., plants, sponges, annelids, corals, brachiopods, pelecypods; and there is the possibility that some of them are even of inorganic origin (James, 1891; Richter, 1920; Howell, 1943; and Osgood, 1970); some are similar to root-penetration structures (cf. Chapter 16). The general classification of these vertical cylindrical burrows is proposed in Text-Fig. 8.1 in an attempt to solve some of the ichnotaxonomic problems concerning these burrows.

## 8.2. SUMMARY TAXONOMIC HISTORY OF VERTICAL CYLINDRICAL SKOLITHOS-TYPE BURROWS

The first vertical cylindrical dwelling-burrow described was assigned to the Ichnotaxon Skolithos Haldemann (1840) but without illustration. Two major events occurred in the naming of Skolithos: (1) the taxonomic relegation of Haldemann's ichnotaxon to generic rank called Scolithus by Hall 1847; and, (2) reinstatement of the correct original spelling (i.e. Skolithos) by Howell (1943). Skolithos, or closely related vertical cylindrical burrows, are in general presently interpreted as the dwelling-burrows of annelids or phoronids, and rocks containing an abundance of such burrows are referred to as "pipe rock" (e.g., Hallam & Swett, 1966). The abundance of such vertical dwelling-burrows indicates a shallow-marine environment. The Skolithos ichnofacies (by which is meant the assemblage of trace fossils indicative of that facies, cf. Text-Fig. 3.1 and Table 3.1) was established by Seilacher (1967) as shallowest marine assemblage in his bathymetric zonation of trace fossil suites. Additionally, sporadic occurrences of Skolithos burrows are known from offshore deeper-marine areas and as well as from non-marine areas (Text-Fig. 5.1).

### 8.2.1. General definition of Skolithos Haldemann (1840), and relationship with other burrows

The ichnogenus Skolithos is defined as a single, vertical- or very steeply-inclined, unbranched, cylindrical to subcylindrical burrow, perfectly straight or curved with lined/unlined wall. The diameter of the tube varies from 1 mm to 15 mm, and its

length from a few centimetres up to 1m. The burrow wall may be distinct or indistinct, smooth or rough, and it may be annulated. The presence of a prominent funnel-shaped aperture was not mentioned in the earliest definitions (Haldemann, 1870; Hall, 1847; Howell, 1943). The funnel-shaped morphology of the aperture was subsequently included in the definition (Alpert, 1974) primarily because the vertical burrows of Monocraterion (Torell, 1870), which are morphologically very similar to those of Skolithos, differ only in having a prominent funnel-shaped aperture. The absence of this funnel-shaped aperture can result from erosion, and consequently the inclusion of a funnel-shaped aperture in the definition of ichnogenera is not acceptable for this reason. The burrows may occur as isolated entities at one extreme or as densely crowded colonies at the other extreme. The degree of relative crowding or spacing of the burrows has occasionally and mistakenly been used as an important criterion for discrimination at the ichnogenic level (e.g., Tigillites Rouault, 1850). Nevertheless, the population density of the burrows actually is very important, but its potential importance is palaeoecological rather than ichnotaxonomic. Where it can be used as an ichnotaxonomic tool, the relative population density is a criterion that is more appropriately used at the specific and/or varietal level of the classification (cf. Text-Fig. 8.1 and Table 8.1) because in most cases the relative density of the burrows varies laterally. It is not acceptable to name crowded burrows as one ichnogenus and sparse populations of the same burrow as another different ichnogenus. The full length of these burrows varies from several centimetres to a metre or more. However, the

length parameter of the burrows is, in most cases, uncertain, because many burrows actually penetrate several beds but limited exposure of such relationships commonly precludes resolution of the full vertical extent of individual burrows.

Large vertical burrows (i.e., burrows with diameters in excess of 15 mm) must be excluded from the classification of Skolithos because no species of Skolithos are known to exceed that burrow diameter (Alpert, 1974). Large vertical cylindrical burrows with diameters in excess of 15 mm are currently referred to Pilichnia (Chamberlain, 1971) which was specifically erected to accommodate such burrows. These larger burrows were probably produced by a different type of organism to that/those that produced the smaller ones (i.e., Skolithos). Large root-penetration structures, particularly root-concretions (cf. chapter 16) can have diameters in excess of 15 mm, but such structures are normally unambiguously of non-animal origin on the basis of their downward-branching and downward-tapering morphology. A branching morphology has recently been described in a new ichnotaxon attributed to Skolithos (i.e. Skolithos ramosus Elphinstone & Walter (in Walter et al., 1989)), which is not accepted in the present classification (discussed later in this chapter; see also Text-Fig. 8.1 and Table 8.1).

### 8.3. THE PROPOSED CLASSIFICATION OF VERTICAL CYLINDRICAL TRACES

The proposed classification covers all small- to medium-scale vertical cylindrical to subcylindrical burrows and root-penetration structures, the latter regarded in this context as trace fossils (see Chapter 16). In the classification the

TEXT-FIG. 8.1. Proposed classification for vertical cylindrical burrows and root-penetration structures (considering the latter as trace fossils as discussed in Chapter 16). The vertical cylindrical burrows are divided into two major categories as follows: (1) non-branching vertical cylindrical burrows which include Skolithos proper and other related non-branching burrows (this classification is partly based on Alpert, 1974); and (2) branching vertical cylindrical burrows which normally exhibit both upward-branching and downward-branching. The morphological criteria, genetic relationships and ethological inferences on which the classification is based are detailed in Table 8.1. The prior and revised ichnotaxonomic names of the burrows accommodated in the present classification (which are detailed in the diagram) are given in Table 8.2. Asterisks indicate traces that occur in the present study area.

# VERTICAL CYLINDRICAL TRACES

## PRODUCED BY ANIMALS

Burrows made for feeding / dwelling



## PRODUCED BY PLANTS

Root-penetration structures, exhibiting branching / bifurcation & downward-tapering

Rhizoliths roots & rootlets

Type E

Trace fossils

Type A

\* Root-cast

Type B

\* Root-mould

Type C

\* Root-tubule

Type D

\* Root-concretion

\* Root-petrification structures (body fossils)

[DISCUSSED IN CHAPTER 16]

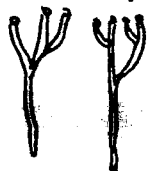
Branching / bifurcation present (upwards / downwards)

Branching / bifurcation absent

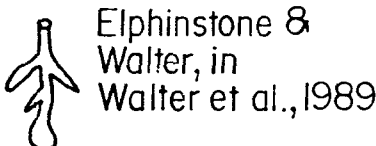
Barrenjoeichnus mitchelli  
ichno. gen. sp. nov.



Polykladichnus irregularis  
Fürsich, 1981



Skolithos ramosus  
(non Skolithos)



Rosselia socialis  
Dahmer, 1937  
in Frey & Howard, 1984.



-----OTHERS

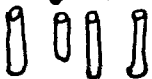
\* Skolithos  
Haldeman, 1840



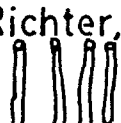
Cylindrichnus  
(Toots in Howard 1966)



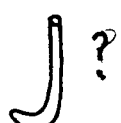
Neoskolithos  
Kegel, 1966



Sabellarifex  
(= Sabellarites)  
Richter, 1920



Siphonichnus  
Mason, 1985



Cylindricum  
Linck, 1949



Pilichnia  
Chamberlain, 1971



(Classification based in part on Alpert, 1974).

\* S. linearis  
Haldeman, 1840



cylindrical, long straight & very steeply inclined

\* S. verticalis  
Hall, 1843



cylindrical / prismatic, shorter, straight / curved almost vertical

\* S. ingens  
Howell, 1945



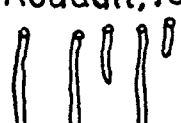
bulges at irregular intervals

\* S. annulatus  
(Howell, 1957)



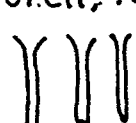
with ring-like annulation

\* S. tigillites  
(Rouault, 1850)



less crowded (? S. magnus Howell 1944)

\* S. monocraterion  
(Torrell, 1870)



with funnel-shaped apertures

TEXT-FIG. 8.1

TABLE 8.1. Significant features and other criteria of major and minor genetic value (i.e., based mainly on ethological criteria) in the proposed classification of vertical cylindrical linear trace fossils (cf. Text-Fig. 8.1)

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**Significant features**

(Diagnostic characteristics at and above the ichnogenic level: type of producer, manifesting feeding or dwelling activity)

(1) (c) Random Distribution and Dispersal.

- (1) Produced by animal (mainly by suspension-feeders for dwelling).
- (2) Produced by plants (due to penetration of roots and rootlets gathering nutrient from the soil).

**Major accessory features**

(Features used for classification of burrows at the generic level and for root-penetration structures at the type level).

- (1) Presence/absence of branching.
- (2) Branching upwards and downwards in animal burrows.
- (3) Branching downwards only in root-penetration structures.
- (4) Tapering upwards/downwards or bulbous termination.
- (5) Nature of infillings (e.g., passive/active in animal burrows or void-filling or replacement in root petrification).

**Major accessory features**

(Features used for classification at the specific level: morphological variations of the burrows or root-penetration structures)

- (1) Size (length/diameter), shape (e.g., cylindrical, subcylindrical, prismatic, straight/curved).
- (2) Funnel-shaped apertures.
- (3) Annulation/ring-structures.
- (4) Presence/absence of reduction halos in root-penetration structures.

**Minor accessory features**

(Features used for classification at the specific and also at the varietal level)

- (1) Orientation of the burrow/root-penetration structures (e.g., vertical/bedding-normal or inclined).
- (2) Population density and nature of distribution of the burrows/root-penetration structures. Comparisons can be made by using the distance-to-nearest-neighbour method of Pemberton & Frey (1984) or the number of counts per specific area method of Pickett (1972).



Table 8.1. (continued)

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- (3) Nature of population (e.g., dense/crowded or sparse).
- (4) Nature of distribution/dispersion.
  - (a) Uniform/even/irregular distribution and dispersion (cf. Text-Fig. 7.9).
  - (b) Clustered/gregarious distribution and dispersion.
  - (c) Random distribution and dispersion.

TABLE 8.2. Revised nomenclature of the non-branching proper Skolithos Alpert (1974) and other branching Skolithos-like vertical cylindrical structures.

PREVIOUS NAME	PROPOSED NAME
(NON-BRANCHING)	
(1) <u>Skolithos linearis</u> Haldeman, 1840.	(1) <u>Skolithos linearis</u> Haldeman, 1840.
(2) <u>Skolithos verticalis</u> (Hall, 1843).	(2) <u>Skolithos verticalis</u> (Hall, 1843).
(3) <u>Skolithos ingens</u> Howell, 1945.	(3) <u>Skolithos ingens</u> Howell, 1945.
(4) <u>Skolithos annulatus</u> (Howell, 1957).	(4) <u>Skolithos annulatus</u> (Howell, 1957).
(5) <u>Tigillites</u> (Rouault, 1850).	(5) <u>Skolithos tigillites</u> (Rouault, 1850).
(6) <sup>1</sup> <u>Skolithos magnus</u> Howell, 1944.	(6) <u>Skolithos tigillites?</u> (Rouault, 1850).
(7) <u>Monocraterion</u> (Torell, 1870).	(7) <u>Skolithos monocraterion</u> (Torell, 1870).
(BRANCHING)	
(8) <u>Skolithos ramosus</u> Walter et al., 1989	(8) Non- <u>Skolithos</u> new scientific name required.
(9) <u>Polykladichnus</u> Fürsich, 1981.	(9) <u>Polykladichnus</u> Fürsich, 1981.
(10) New ichnogen. sp nov.	(10) <u>Barrenjoeichnus mitchelli</u> new ichno. gen. sp. nov.

<sup>1</sup> Skolithos magnus Howell (1944) is described as a distinct species by Alpert (1974), but its definition probably agrees with either Tigillites (Rouault, 1850), or Skolithos verticalis Haldeman (1840), or with Skolithos linearis (Hall, 1840).

major group of animal traces is regarded as feeding- and/or dwelling-burrows (Text-Fig. 8.1). These animal burrows can be subdivided into two major subgroups, based on the presence/absence of branching. This subdivision is important and necessary for several ichnotaxonomic reasons: firstly, the forms characterized by a branching morphology are very different from the non-branching form of Skolithos proper; secondly, this variation in morphology is crucially important for the differentiation of the different ichnotaxa and their separation from Skolithos and can be explained as manifesting important behavioral differences; and thirdly, because these branches could represent (a) auxiliary openings or tunnels for water circulation (e.g., to facilitate oxygen and food supply for suspension-feeders), or (b) storage passages for waste (e.g., faecal pellets), or (c) escape-tunnels for use against predators or natural hazards.

The branching type of vertical cylindrical burrows can be subdivided into four main ichnogenera (Text-Fig. 8.1):

- (1) Barrenjoeichnus mitchelli new ichnogenus; locally bifurcate upward or downward; non-branching burrows of this ichnogenus are almost comparable with Cylindrichnus Howard (1966) and Siphonichnus Mason (1985). These burrows have also been studied in terms of their population density and the statistically preferred inclination of the burrows has also been interpretation in palaeocurrent terms (discussed later in this chapter);
- (2) Polykladichnus irregularis Fursich (1981), characterized by multiple upward-branching traces; and
- (3) Skolithos ramosus Elphinstone & Walter (in Walter et al.

1989); branched with bulbous terminus; not regarded herein as a valid Skolithos.

- (4) Rosselia socialis Dahmer (1937); upward-branching burrow characterized by numerous concentric internal rings in transverse cross-section.

The subdivision of non-branching vertical cylindrical burrows in Text-Fig. 8.1 includes Skolithos proper and other related or similar ichnogenera which are defined by their relative size (diameter and length) and other morphological characteristics. The present classification of Skolithos Haldemann (1840) (which classification is partly based on the concepts of Skolithos as described by Alpert, 1974) recognizes six distinct ichnospecies (cf. Text-Fig. 8.1):

- (1) S. linearis Haldemann (1840); straight, almost cylindrical, very steeply inclined and very long;
- (2) S. verticalis (Hall, 1843); burrows cross-section can be subcylindrical or prismatic where in mutual contact; straight to slightly curved and almost normal to the bedding; shorter than S. linearis;
- (3) S. ingens Howell (1945); burrow bulges or is enlarged at irregular intervals;
- (4) S. annulatus Howell (1957); defined by its ring-like annulations on cylindrical burrows;
- (5) S. tigillites Rouault (1850); the most morphologically similar burrow to S. linearis and S. verticalis, but characteristically less crowded than the latter two; and
- (6) S. monocraterion Torell (1870); characterized by well defined funnel-shaped apertures.

Skolithos magnus Howell (1944), was described as a distinct species by Alpert (1974), but its definition is very similar to those of Tigillites (Rouault, 1850), Skolithos verticalis Haldeman (1840), and Skolithos linearis (Hall, 1840).

The branching pattern (bifurcation or trifurcation) in the vertical cylindrical burrows can be either upwards or downwards and constitutes the only major distinction between these forms and unbranched Skolithos proper. Alpert (1974) has reviewed the literature on Skolithos and suggested in his revision of this ichnotaxon that the branching morphology is not acceptable in the definition of Skolithos.

Most of the other forms referred to Skolithos by Alpert (1974, p.605) are either poorly described, are nomen nudum, or are of inorganic origin, and some are possibly even body fossils.

#### 8.4. SYDNEY BASIN EXAMPLES OF UNBRANCHED SKOLITHOS-LIKE BURROWS

The first published record of the ichnogenus Skolithos (worm tubes) in the Sydney Basin was by Pickett (1972) from the Upper Permian Erins Vale Formation of the southern part of the basin, a study that also included a population-density analysis of these traces. The Erins Vale Formation is remarkable for its abundance of worm tubes which are ubiquitous features throughout its geographic extent. The marine palaeoenvironmental affinity of the Erins Vale Formation is demonstrated by these trace fossils.

A second record of Skolithos (Tigillites) in the Sydney Basin was published by Carey (1978) in respect of the Lower Permian Snapper Point Formation at its type locality at Snapper

Point in the southern part of the basin. Carey interpreted the Snapper Point Formation as a regressive marine facies complex of a linear clastic shoreline.

The third record of Skolithos and Skolithos-like burrows (Cylindrichnus Howard, 1966 and Rossilia Dahmer, 1937) in the Sydney Basin was published by McCarthy (1979) in regard to the marine Lower Permian Wasp Head Formation of the southern part of the basin. These vertical cylindrical shafts of Skolithos and Skolithos-like burrows are the most common trace fossils in the shoreface-foreshore environments of this formation.

The present record of Skolithos and Skolithos-like vertical cylindrical burrows in the study area is the fourth discovery of such traces in the Sydney Basin and their first discovery in the very much younger Middle Triassic rocks of the Newport Formation of the upper Narrabeen Group. Several new species of Skolithos are described from these Triassic rocks.

## 8.5. SYSTEMATIC ICHNOTAXONOMY

### 8.5.1. Non-branching Skolithos-type burrows

Skolithos linearis Haldeman, 1840

Plate 58, Fig. f

(see synonymy list in Alpert, 1974)

**Diagnosis (taxonomic assignment):** Subcylindrical, slightly curved or straight, almost vertical or steeply-inclined burrows, with shaft diameter of about 0.5 cm to 1 cm, and length about 30 cm to 50 cm. The burrow wall is distinct and smooth (without ornamentation).

**Remarks (diagnostic features):** Actually, various forms and shapes

are recorded from the studied specimens. The burrows are normally closely crowded, but some occur as semi-isolated entities separated from neighbors by 10 to 20 cm. Some manifest a funnel-shaped aperture and can be classified as S. monocraterion (Torell, 1870) in the present classification.

**Description and ethology:** Most of the burrows are of subcylindrical shape, slightly curved to sinuous or are straight, and are vertical or steeply inclined to the bedding-plane surface. The burrows occupy whole beds as colonies with sporadic concentration or overcrowding in certain patches. In one of the exposures containing such patches of burrows their relative density in between the clusters is sparse to semi-isolated. The opening of the burrows is circular if not also funnel-shaped. Burrow diameter is about 0.5 cm to 1 cm and in maximum length is about 50 cm.

**Comparison:** The nature of the burrow orientation and burrow size are comparable with the neotype material designated by Howell (1943, pl.1, fig.2). The burrows lack striations and instead have a smooth distinct dark-coloured wall, in both of which respects they differ from S. linearis described by Fenton & Fenton (1934). Some burrows have funnel-shaped openings and hence can be referred to Monocraterion (Torell, 1870) (= S. monocraterion (Torell, 1870) in the present classification).

**Distribution:** The rock sample containing the studied examples was collected from trace fossil subinterval ID1 of the Lower Newport Member at Long Reef Point (area 3). Similar Skolithos burrows which lack funnel-shaped openings are associated with vertical

cylindrical burrows with funnel-shaped apertures (i.e., S. monocraterion) in the same trace fossil interval (ID1) at Bungan Head (area 12) (Plate 71 Fig. d).

**Studied material:** The studied burrows in sample 301/MU.44391 (Plate 58 Fig. f) come from trace fossil subinterval ID1 of the Lower Newport Member, at Long Reef Point. None of the material studied at the Bungan Head locality (cf. Plate 71 Fig. d) was retrieved from the field.

**Preservation and association:** The vertical cylindrical burrows are preserved as full-relief forms in fine sandstone units, and are believed to be dwelling-burrows (domichnia). They are not associated with any other trace fossils or body fossils.

**Ichnofacies and palaeoenvironmental affinities:** Skolithos is the type trace fossil of the shallow-marine Skolithos ichnofacies of Seilacher (1967). However these burrows can be found in non-marine (Boyer, 1979) and deep-marine (Crimes, 1977) environments as well. The Skolithos ichnofacies ordinarily grades landward into supratidal or terrestrial zones and seaward into the Cruzi-ana ichnofacies (see Text-Fig. 3.1 and Frey & Pemberton, 1984). Actually, vertically orientated burrows, including Skolithos, commonly occur in the foreshore and shoreface of beaches, bars, and spits. The Skolithos ichnofacies is indicative of relatively high-energy levels of waves and currents (even in tempestite or storm deposits, cf. Branchley, 1985 and Dott & Bourgeois, 1982) and are characteristic of clean, well-sorted, loose or shifting substrates. Most trace fossil makers of Skolithos are suspension-feeders and the substrate serves mainly as an anchoring/dwelling medium (more or less permanent). The organisms



typically construct more or less deep vertical burrows or burrow-systems as domiciles in such substrates (because of their agitated and shifting character), normally with a distinct reinforced wall-lining.

The palaeobathymetric interpretation of the ichnogenus Skolithos cannot be based solely on their presence or absence (as discussed above), but must be judged on the basis of the associated physical sedimentary structures, body fossils and any other relevant evidence.

**Skolithos verticalis** (Hall, 1843)

Plate 58, Figs. a, c & d

(see synonymy list in Alpert, 1974)

**Diagnosis (taxonomic assignment):** Subcylindrical to prismatic in transverse section (in cases where the burrows are in mutual contact), normally curved, sinuous or straight, vertical or steeply-inclined with smooth (unornamented) wall. Burrow diameter is about 0.5 cm and length varies from 10 cm to 20 cm.

**Remarks (diagnostic features):** The burrows are crowded and packed and show prismatic outline in cross-section where they are laterally in contact. In one bed the burrows show a somewhat preferred inclination towards a certain direction (Plate 58, Figs. c & d). The burrow walls are smooth but irregular, especially where they are in lateral contact. Funnel-shaped openings are not present.

**Description and ethology:** The burrows comprise simple subcylindrical-shaped vertical shafts in situations where they are not in lateral contact with each other and are of more prismatic, curved or steeply-inclined character where they are in lateral contact.

The burrows occupy every part of the rock which is accordingly extensively bioturbated. The burrows in these crowded pipe-rocks exhibit a somewhat preferred orientation (apparently mainly towards the northwest). The openings of the burrows are circular/subcircular or prismatic in shape and are connected via a small neck (of smaller diameter) to the cylindrical-shaped shaft. The burrows are locally so crowded and packed that a population-density study (using the distance-to-nearest-neighbour method is not appropriate. The diameter of the burrows is about 0.5 cm and their length varies from 10 to 20 cm.

**Comparison:** The Skolithos verticalis burrows are generally shorter and smaller and are more commonly inclined and curved than are the burrows S. linearis Haldeman (1840). The present studied examples of S. verticalis differ from S. verticalis (Hall, 1843; described in Alpert, 1974) in respect of their more crowded nature compared to the latter.

**Distribution:** The studied examples occur in trace fossil subinterval ID1 of the Lower Newport Member at St. Michaels Cave (area 5). S. verticalis also occurs in trace fossil subintervals ID2 and ID4 at this same locality.

**Studied material:** None of the studied materials illustrated in Plate 58 Figs. a, c and d have been retrieved from the field.

**Preservation and association:** The burrows are preserved as full-relief forms (domichnia) in fine sandstone units, and are not associated with any other trace fossils.

**Ichnofacies and palaeoenvironmental affinities:** As for Skolithos linearis.

Skolithos annulatus (Howell, 1957)

Plate 59, Figs. a, b & f

(see synonymy list in Alpert, 1974)

**Diagnosis (taxonomic assignment):** Burrows are cylindrical to subcylindrical, slightly curved, vertical or steeply-inclined; they are packed or crowded in Plate 59, Figs. a and b and less crowded in Plate 59, Fig. f. Burrow diameter is about 0.5 cm to 0.8 cm maximum and burrow length is commonly about 10 cm. The rings or annulations are irregularly arranged from 1 mm to 5 mm apart and are 1 mm to 2 mm wide (= "length" of Alpert, 1974, p.665).

**Remarks (diagnostic features):** The relative density of the burrows is variable where they occur as crowded groups (Plate 59, Figs. a and f). The annulation of the burrows is evident only on longitudinal and oblique sections (Plate 59, Fig. b; in which illustration the burrows are widely spaced).

**Description and ethology:** Subcylindrical, slightly curved, vertical to steeply-inclined shafts that can be either tightly packed (Plate 59, Figs. a & f) or unpacked to semi-isolated (Plate 59 Fig. e); the burrows in all of these photographs in Plate 59 are probably of same species. The unpacked burrows are steeply-inclined rather than vertical, are curved and also have well defined annulations compared to the packed burrows. The burrows occur in very fine sandstone and siltstone and were passively infilled by overlying sediment (which is lighter-coloured, coarser and cleaner sand). There is no indication of meniscus structure of faecal origin in the infilled burrows. The

burrows are normally short and curved, and are defined by their annulation or rings. The wall is distinct but not straight. The annulation rings are 1 mm to 2 mm wide and are arranged irregularly, the distance separating them varying from 0.5 cm to 1 cm.

**Comparison:** The S. annulatus burrows are shorter, more curvilinear than those of S. linearis and S. verticalis and differ from the latter in respect of the presence of annulations. The S. annulatus burrows of the study area differ from type specimen of S. annulatus Howell (1957; described in Alpert, 1974) by virtue of their greater density compared to the latter.

**Distribution:** S. annulatus occurs in trace fossil interval D at St. Michaels Cave (area 5), Hole in the Wall (area 11), Mona Vale Head (area 14), and Warriewood Beach (area 6).

**Studied material:** The only sample collected from the field (sample 501/MU.44401) is illustrated in Plate 59, Fig. f. This comes from trace fossil subinterval ID1 of the Lower Newport Member at St. Michaels Cave; the other burrows illustrated in Plate 59 were not retrieved from the field.

**Preservation and association:** The burrows are preserved as full-relief forms in very fine sandstone units, and are believed to have been produced as dwelling-burrows (domichnia); the burrows are not associated with other trace fossils.

**Ichnofacies and palaeoenvironmental affinities:** As for S. linearis.

#### Skolithos tigillites (Rouault, 1850)

Plate 60, Fig. a

Tigillites (Rouault, 1850); see also Alpert, 1974.

**Diagnosis (taxonomic assignment):** Cylindrical-shaped, straight, vertical or steeply-inclined burrows, typically about 10 cm long and 0.5 cm wide. The burrows have a very distinct unornamented straight wall; they do not occur crowded together but are typically about 3 cm to 5 cm or more apart.

**Remarks (diagnostic features):** The burrows are normally evenly-spaced and separated one from the other by about 3 to 5 cm. However, in some places their distribution is less evenly-spaced and they are crowded together in clusters.

**Description and ethology:** Cylindrical, straight, vertical to steeply-inclined burrows with diameter of 0.5 cm and length up to 10 cm. In Plate 50, Fig. a, the burrows are viewed from the underside of a red-coloured fine sandstone bed overlain by coarse sandstone. The individual burrows descend from the contact between these two different units. The burrows are normally not crowded and their lateral spacing or distance-from-nearest-neighbor is about 3 cm to 5 cm. The burrow wall in general is well defined or distinct and is either smooth or corrugated.

**Comparison:** The degree of burrow crowding (density) has been used as an ichnotaxonomic characteristic (e.g., in Tigillites Rouault, 1850; and in Sabellarites or Sabellarifex Richter, 1920). The burrow density is an important ecological variable that is probably influenced or controlled by the rate of deposition etc. The density of burrows is retained as an ichnotaxonomic characteristic in the present classification at the specific level but not at the ichnogeneric level. The relative crowding of burrows can be defined by measurement of the burrow spacing between neighbours (cf. Pemberton & Frey, 1984). The limiting

*Skollia monobrochus*

distance between two nearest neighbors that characterizes this ichnospecies (as defined in the present classification) is 2 to 5 cm or more. *Tigillites*, 1979.

**Distribution:** The studied examples illustrated in Plate 60, Fig. a, come from the trace fossil subinterval ID1 of the Garie Formation (= Lower Newport Member) at Warriewood Beach (area 6). These same burrows also occur at Bungan Head (area 13) in trace fossil subinterval ID2.

**Studied material:** The burrows illustrated in Plate 60, Fig. a (sample 601/MU.44406) were collected from the Garie Formation at Warriewood Beach. No other specimens were retrieved from the field.

**Preservation and association:** These vertically orientated burrows are preserved as full-relief forms in fine sandstone units and are not associated with any other trace fossils. The pelecypod illustrated in Plate 74, Fig. d, and similar pelecypods collected by Grant-McKee et al. (1985) are believed to be from the same trace fossil subinterval at Warriewood Beach (area 6).

**Ichnofacies and palaeoenvironmental affinities:** The interpreted palaeoenvironment is somewhat similar to that of *S. linearis* and *S. verticalis*, but because of the less-crowded relative density of *S. Tigillites*, the environment might have been subject to a more rapid rate of deposition than in the case of the other two ichnospecies and hence have been palaeoecologically less favourable as a dwelling site for the inhabitants which would accordingly have experienced less competition from neighbours for space and sustenance.

Skolithos monocraterion

Plate 58, Fig. f  
Plate 71, Fig. d

Monocraterion Torell, 1870.

**Diagnosis (taxonomic assignment):** Vertical cylindrical burrows with funnel-shaped openings.

**Remarks (diagnostic features):** Subcylindrical to cylindrical, slightly curved to straight almost vertical or steeply-inclined burrows. The actual length of the burrows is difficult to ascertain because they penetrate more than one bed; the burrow diameter is about 0.5 cm to 1 cm with funnel-shaped apertures. The burrow wall is very distinct and the burrows are passively filled with structureless fine white-coloured sand that is coarser than the host sediment (which is siltstone and very fine sandstone).

**Description and ethology:** Subcylindrical to cylindrical burrows, most commonly perfectly straight and either vertical or very steeply inclined to the bedding. The diameter of the burrows varies from 0.5 cm to 1 cm and the diameter of the V-shaped funnel aperture is typically 2 mm to 4 mm greater than this diameter. The length of the burrows shown in Plate 58, Fig. f, is more than 10 cm; but the length of the burrows illustrated in Plate 71 Fig. d, can not be ascertained because no vertical sectional view is available. The burrows are crowded with less than 1 cm separating neighbours. These burrows are believed to have been produced for dwelling by suspension-feeders. The wider funnel-shaped apertures support this view that the burrows were made by suspension-feeders which used them for permanent dwell-

ing. The burrows are believed to be passively filled by structureless sand that is noticeably coarser than the host sediment.

**Comparison:** Some burrows described here as S. linearis Haldeman (1840) (Plate 58 Fig. f), can be assigned to this species on the basis of the presence of funnel-shaped apertures. Some broken segments of burrows or erosionally truncated burrows of this species may lack funnel-shaped apertures. Consequently the absence a funnel-shaped of aperture can be the result of erosional loss, necessitating caution in the taxonomic assignment of such traces beyond generic level.

**Distribution:** The studied specimen illustrated in Plate 58, Fig. f, is from trace fossil subinterval ID1 of the Lower Newport Member at Long Reef Point (area 3) and the specimen illustrated in Plate 71, Fig. d, is also from the same trace fossil subinterval at Bungan head (area 13). S. monocraterion does not occur in any other trace fossil subintervals or at any other localities apart from those mentioned above.

**Studied material:** The studied specimen illustrated in Plate 50 Fig. f (301/MU.44391) is from Long Reef Point (area 3). The studied examples illustrated in Plate 71 Fig. d, have not been retrieved from the field.

**Preservation and association:** The burrows are preserved as full-relief forms in very fine sandstone units and are believed to have been developed for dwelling by suspension-feeders. These burrows are not associated with other trace fossils.

**Ichnofacies and palaeoenvironmental affinities:** As for S. linearis and S. verticalis.



Skolithos sp?

Plate 60, Figs. b & c

**Diagnosis (taxonomic assignment):** Vertically orientated, subcylindrical burrows.

**Remarks (diagnostic features):** The burrows illustrated in the figures of Plate 60 are almost evenly-spaced. Application of population-density studies using the distance-to-nearest-neighbour method is necessary in order to allow these burrows to be classified as Skolithos tigillites, or Skolithos linearis or Skolithos verticalis. The typical limiting distance between two neighbors of S. tigillites applied in the present classification (cf. above discussion) is 2 to 5 cm or more. Measurements of the diameter of individual burrows are documented in Table 8.4 and Text-Fig. 8.3; the shape of the burrows is variable but their wall is invariably corrugated.

**Description:** Mainly subcylindrical, but individually variable in shape; straight to slightly curved, vertical or steeply-inclined burrows with an average diameter of 0.44 cm (Table 8.4); the length of the burrows is small compared to S. linearis and S. verticalis although in most cases the length of the burrow<sup>is</sup> not resolvable due to lack of the necessary exposure. The burrows are infilled with sediment similar to that of the host rock (buff-grey fine sandstone).

**Comparison and application of DNN method for spatial distribution and dispersion:** One of the study specimens (201/MU.44386) was used for population density analysis by the distance-to-nearest-neighbour method (cf. Clark & Evans, 1954; and Pemberton & Frey, 1984). The application of this method is necessary because the

TEXT-FIG. 8.2. Map of bedding-plane in sample 210/MU. 44386, (illustrated in Plate 60, Fig. c) showing openings of vertical cylindrical burrows (Skolithos sp?). Burrows are represented by large and small dots relative to their individual sizes (but not to scale). Direction of nearest neighbour is indicated by the arrows. Numbers beside burrows (burrow number) and between burrows (nearest-neighbour distance in cm) correspond to those in Table 8.4. Locations of and distances between the burrows are approximate (cf. Table 8.4).



TABLE 8.3. Distance-to-nearest-neighbour (DNN) measurements of Skolithos sp? burrows in sample 201/MU.44386 (illustrated in Plate 60, Fig. c, and Text-Fig. 8.2).

Br. No.	Nearest Neighbour	Distance to Nearest Neighbour (cm) (r)	Br. No.	Nearest Neighbour	Distance to Nearest Neighbour (cm) (r)
1.	2	2.37	48.	47	0.70
2.	3	1.51	49.	48	1.10
3.	2	"	50.	51	0.17
4.	5	0.69	51.	50	"
5.	6	0.38	52.	51	1.17
6.	5	"	53.	54	0.30
7.	8	0.42	54.	53	"
8.	7	"	55.	56	0.63
9.	8	0.64	56.	55	"
10.	9	1.43	57.	58	0.62
11.	12	0.65	58.	59	0.31
12.	11	"	59.	60	0.19
13.	12	1.28	60.	59	"
14.	13	1.30	61.	62	0.24
15.	16	0.72	62.	76	0.12
16.	15	"	63.	65	0.58
17.	18	0.60	64.	65	1.05
18.	19	0.36	65.	66	0.19
19.	18	"	66.	67	0.05
20.	17	0.92	67.	66	"
21.	22	0.51	68.	67	0.36
22.	21	"	69.	68	0.65
23.	22	1.73	70.	71	2.19 *
24.	25	0.75	71.	72	0.84
25.	24	"	72.	71	"
26.	27	0.09	73.	74	0.61
27.	26	"	74.	73	"
28.	29	0.48	75.	74	0.95
29.	28	"	76.	62	0.12
30.	29	0.88	77.	78	0.42
31.	32	0.81	78.	77	"
32.	31	"	79.	80	0.28
33.	31	1.10	80.	81	0.12
34.	33	1.49	81.	80	"
35.	36	1.34	82.	81	0.44
36.	37	0.40	83.	85	0.21
37.	38	0.30	84.	85	0.41
38.	37	"	85.	83	0.21
39.	38	0.30	86.	85	0.38
40.	41	0.40	87.	88	0.46
41.	42	0.35	88.	87	"
42.	43	0.20	89.	90	0.15
43.	42	"	90.	89	"
44.	43	0.60	91.	92	0.24
45.	46	0.70	92.	91	"
46.	47	0.70	93.	94	0.64
47.	48	0.70	94.	93	"

TABLE 8.3. (continued)

Br. No.	Nearest Neighbour	Distance to Nearest Neighbour (cm) (r)	Br. No.	Nearest Neighbour	Distance to Nearest Neighbour (cm) (r)
95.	97	0.28	106.	107	0.96
96.	97	0.04 *	107.	108	0.58
97.	96	"	108.	107	"
98.	97	0.41	109.	110	0.24
99.	100	0.78	110.	109	"
100.	99	"	111.	112	0.45
101.	100	1.62	112.	111	"
102.	103	0.91	113.	112	1.54
103.	104	0.24	114.	115	0.04
104.	105	0.19	115.	116	0.04
105.	104	"	116.	115	0.06

n = 116  
 $\bar{x}$  = 0.576  
 $\Sigma x$  = 66.84  
 $\Sigma x^2$  = 62.07  
 $\sigma(n-1)$  = 0.453  
 $\sigma n$  = 0.45  
 $\Sigma r$  = 66.84 (Ex)  
 $(\Sigma r)/N$  = 0.576 (ra or  $\bar{x}$ )

Observed range (\*) = 0.04 - 2.19  
Coefficient of variation  $V = \frac{100S}{\bar{x}} = \frac{100 \times 0.45}{0.576} = 78.13$

(1)  $\bar{x} \pm S = 0.576 \pm 0.45 = (1.046) (0.126) = 68.27\%$   
(2)  $\bar{x} \pm 2S = 0.576 \pm 0.90 = (1.476) (-0.324) = 95\%$   
(3)  $\bar{x} \pm 3S = 0.576 \pm 1.35 = (1.926) (-0.774) = 99.73\%$

Total area coverage of the sample = 483 cm<sup>2</sup>

P = n/area = 116/483 = 0.24 density/unit area  
re = 1/2 p = 1/0.98 = 1.02  
R = ra/re = 0.576/1.02 = 0.565  
 $\sigma_{re} = 0.26136/ N \times p = 0.0495$   
C = ra - re/ re = 8.97

Interpretation

(1) Low density population; (2) No significant departure from random (R = 0.565); (3) Population is randomly dispersed.

Table 8.3. (continued)

---

Explanation

List of symbols and definitions of concepts employed in nearest neighbour (after Clark & Evans, 1954; and Pemberton & Frey, 1984).

$N$	Number of measurements.
$r$ or $(x)$	Distance to nearest neighbour.
$p$	Density per unit area.
$\Sigma r$ or $(\Sigma x)$	Summation of the measurements of distance to nearest neighbour.
$r_a = \Sigma r / N$ ( $\bar{x}$ )	Means of the series of distance-to-nearest-neighbour.
$r_e = 1/2 \sqrt{p}$	Mean distance-to-nearest-neighbour expected in an infinitely large random distribution of density $p$ .
$R = r_a / r_e$	Measure of the degree to which the observed distribution departs from random expectation with respect to the distance to nearest neighbour.
$\sigma_{re} = 0.26136 / \sqrt{(N \cdot p)}$	Standard error of the mean distance-to-nearest neighbour in a random distribution population of density $p$ .
$C = \frac{r_a - r_e}{r_e}$	Standard variate of the normal curve.

TABLE 8.4. Measurements of the diameters of the numbered vertical cylindrical burrows Skolithos sp? in sample 201/MU.44386 (illustrated in Plate 60 Fig. c, and Text-Fig. 8.2).

Br. No.	Diameter (cm)	Br. No.	Diameter (cm)
1.	0.32	50.	0.72
2.	0.25	51.	0.24
3.	0.26	52.	0.69
4.	0.50	53.	0.45
5.	0.70	54.	0.40
6.	0.45	55.	0.32
7.	0.39	56.	0.35
8.	0.66	57.	0.48
9.	0.60	58.	0.79
10.	0.46	59.	0.50
11.	0.64	60.	0.27
12.	0.41	61.	0.51
13.	0.43	62.	0.38
14.	0.56	63.	0.67
15.	0.56	64.	0.61
16.	0.47	65.	0.32
17.	0.54	66.	0.52
18.	0.49	67.	0.35
19.	0.28	68.	0.31
20.	0.67	69.	0.52
21.	0.52	70.	0.28
22.	0.58	71.	0.36
23.	0.87 *	72.	0.43
24.	0.28	73.	0.49
25.	0.56	74.	0.25
26.	0.66	75.	0.51
27.	0.42	76.	0.62
28.	0.63	77.	0.41
29.	0.48	78.	0.46
30.	0.74	79.	0.20
31.	0.46	80.	0.25
32.	0.62	81.	0.21
33.	0.26	82.	0.39
34.	0.59	83.	0.27
35.	0.51	84.	0.28
36.	0.23	85.	0.46
37.	0.40	86.	0.55
38.	0.61	87.	0.30
39.	0.70	88.	0.29
40.	0.54	89.	0.64
41.	0.37	90.	0.37
42.	0.28	91.	0.26
43.	0.23	92.	0.20
44.	0.23	93.	0.28
45.	0.35	94.	0.36
46.	0.18 *	95.	0.18
47.	0.32	96.	0.25
48.	0.39	97.	0.23
49.	0.77	98.	0.53

TABLE 8.4. (continued)

Br. No.	Diameter (cm)	Br. No.	Diameter (cm)
99.	0.28	108.	0.28
100.	0.23	109.	0.64
101.	0.40	110.	0.29
102.	0.26	111.	0.78
103.	0.34	112.	0.52
104.	0.33	113.	0.66
105.	0.24	114.	0.66
106.	0.53	115.	0.41
107.	0.27	116.	0.55

$n = 116$   
 $\bar{x} = 0.439$   
 $\sigma_n = 0.163$   
 $\sigma(n-1) = 0.164$   
 $\sum x = 50.89$   
 $\sum x^2 = 25.42$

Observed range (\*) = 0.18 - 0.87

Coefficient of variation  $V = \frac{100S}{\bar{x}} = \frac{100 \times 0.163}{0.439} = 37.13$

$$(1) \bar{x} \pm S = (0.439 \pm 0.276) = (0.602) (0.276) = 68.27\%$$

$$(2) \bar{x} \pm 2S = (0.439 \pm 0.326) = (0.765) (0.113) = 95\%$$

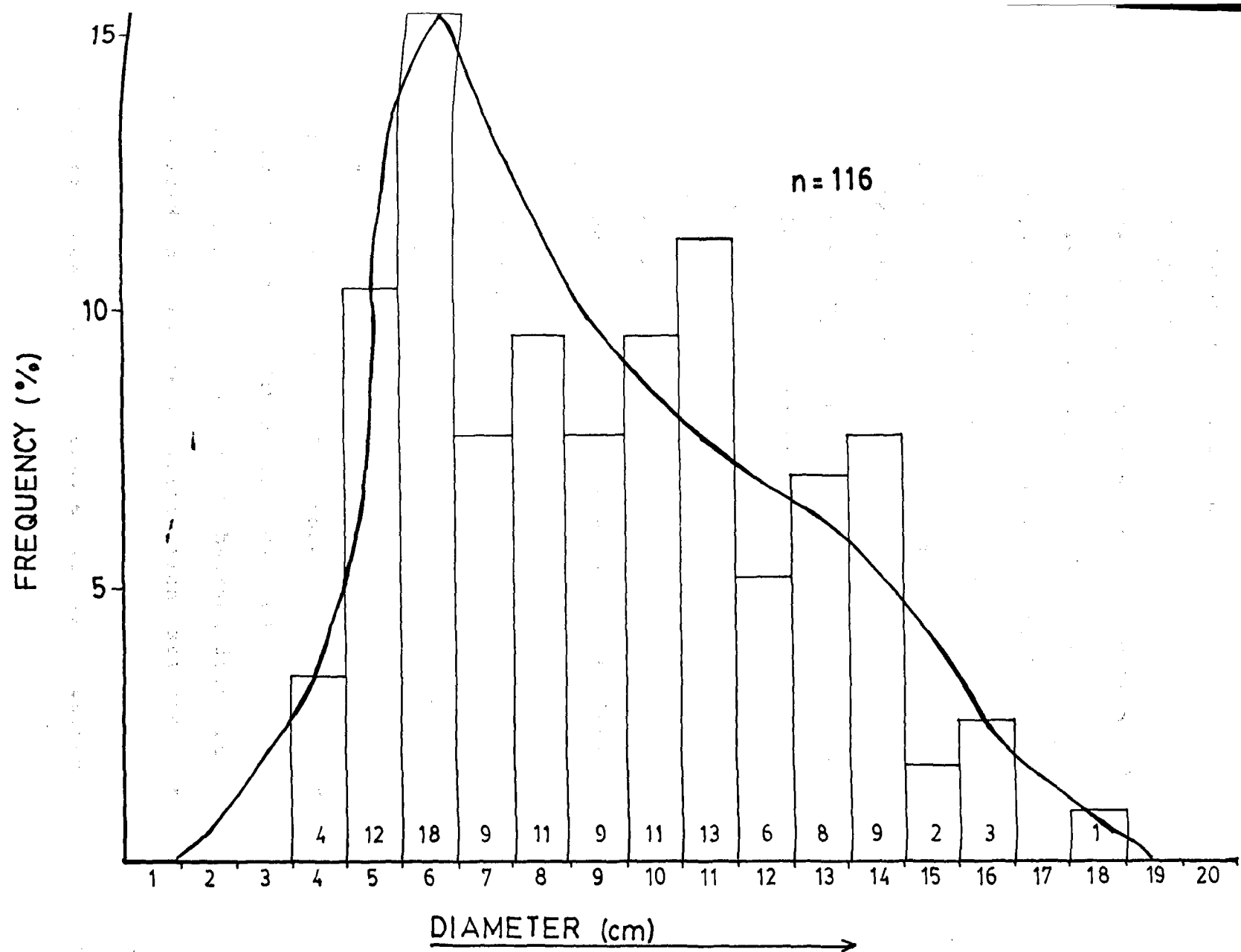
$$(3) \bar{x} \pm 3S = (0.439 \pm 0.489) = (0.928) (-0.05) = 99.73\%$$



TEXT-FIG. 8.3. Histogram of measured diameters of vertical cylindrical burrows (Skolithos sp?) in sample 201/MU.44389 (data from Table 8.4). The distribution shows a bell-shaped right-skewed curve.

Class limits  
(0.05 cm intervals)

1.	0	-	5
2.	6	-	10
3.	11	-	15
4.	16	-	20
5.	21	-	25
6.	26	-	30
7.	31	-	35
8.	36	-	40
9.	41	-	45
10.	46	-	50
11.	51	-	55
12.	56	-	60
13.	61	-	65
14.	66	-	70
15.	71	-	75
16.	76	-	80
17.	81	-	85
18.	86	-	90
19.	91	-	95
20.	96	-	100



TEXT - FIG. 8.3

burrows are separated and probably belong to S. tigillites. The technique of utilizing the distance from an individual to its nearest neighbor was first introduced by Hertz (1909) and was refined and updated by Clark & Evans (1954, & 1955). This analysis provides a measurement of the degree to which the distribution of individuals in a population departs from that of a random distribution. The mean of the whole population ( $r_a$  or  $\bar{x}$  in the explanation of Table 8.3) can be worked out to determine the ichnospecific affinity of the Skolithos burrows in the present classification. This technique of distance-to-nearest-neighbour is best applied to populations that can be mapped on bedding planes. Because the exposures containing Skolithos burrows in the study area are mainly vertical walls, the measurement technique had to be adapted to the nature of the outcrops. One large block (sample 201/MU.44386) was extracted from the vertical outcrop face at the horizon selected for analysis and the area of the bedding-plane surface of the sample was determined by graphic methods. All burrows in the sample were charted and plotted, and the distance-to-nearest-neighbour data were recorded (Text-Fig. 8.2 and Table 8.3). The equations used in Table 8.3 and the procedure outlined here (below) are from Clark & Evans (1954) and Pemberton & Frey (1984). In a population with N individuals and a density (p), the distance (r) from each individual to its nearest neighbor is measured. The mean observed distribution is given by  $r_a = \sum r/N$ , and the mean distribution expected if the population is random is given by  $r_e = 1/2.p$ . The ratio  $r_a/r_e$  (R) is then used as a measure of departure from the expected random disper-

sion. In a random distribution, R equals unity; under conditions of aggregation, R approaches zero; and under conditions of maximum spacing, R is greater than unity. If the value of R indicates that the given population is not randomly distributed, the significance of the departure of  $r_a$  from  $r_e$  can be tested by the normal curve. The test of significance of the measure is given by  $c = (r_a - r_e) / r_e$ , where  $c$  is the standard variate of the normal curve, and  $r_e$  is the standard error of the mean distance to the nearest neighbor in a randomly distributed population of the same density as the observed population.

These DNN population-density analyses embody study of both simple vertical (single-entrance) burrows in the present chapter (Text-Fig. 8.2) and U-shaped (multi-entrance) vertical burrows in Chapter 7 (Text-Fig. 7.6). The DNN technique is limited in its application to these types of burrows. The burrow dispersion as measured by the DNN parameter is important because, in a geographic sense, the dwelling-burrows constitute a proximal fixed position of the inhabitant organism. The other important application of the DNN parameter is in differentiating the various ichnospecies of Skolithos in terms of the present classification (e.g., S. tigillites was initially defined by Rouault (1850) as a variety or form of Skolithos characterized by relatively low burrow density, a definition or concept that has been followed by other workers and preserved in the present classification). In the present study DNN data allow this type of differentiation to be placed on a numerical basis. The significant differences in population density between S. tigillites and other Skolithos ichnospecies are tested using the 't' test,

TABLE 8.5. Details of statistical tests involved in the discrimination of various species of Skolithos from the study area and elsewhere on the basis of relative distance of inter-burrow spacing (i.e., population density) and burrow diameter.

NO.	AREA OF STATISTICAL COMPARISON of <u>Skolithos</u>	No. OF TEST	TEST RESULT D.N.N	TEST RESULT WIDTH	DEGREE OF FREEDOM	DIFFERENCE IS NOT SIGNIFICANCE					DIFFERENCE IS PROBABLY SIGNIFICANCE				DIFFERENCE IS SIGNIFICANCE		
						>.50 100- 50%	0.50 50%	0.40 40%	0.20 20%	0.10 10%	0.05 5%	.025 2.5%	.02 2%	.01 1%	.005 .5%	.002 .2%	.001 .1%
1.A.	Turimetta (Bald Hill Claystone, Mid Triassic) vs. Labrada (Bradore Formation, Lower Cambrian)	t1	'T' test 3.82		N 213												1
		t2	3.279		218												2
		t3	2.732		256												
		t4	2.492		276									3			
		t5	3.382		315								4				5
		t6	3.529		326												6
		t7	3.11		356									7			
1.B.	" "	t1	Student 'T' test 9.789		116												1
		t2	8.09		"												2
		t3	7.04		"												3
		t4	5.96		"												4
		t5	11.87		"												5
		t6	13.36		"												6
		t7	11.82		"												7
2.A.	Turimetta (Bald Hill Claystone, Mid Triassic) vs. South Ontario (Thorold Formation Mid Silurian)	t1	'T' test 6.92		N 137												1
		t2	3.945		137												2
		t3	3.23		150												3
		t4	3.185		132												4
		t5	1.475		148				5								
		t6	1.649		152					6							
		t7	5.169		178												7
		t8	1.313		183				8								
		t9	1.556		202				9								
2.B.	" "	t1	Student 'T' test 22.83		116												1
		t2	13.5		"												2
		t3	10.6		"												3
		t4	12.8		"												4
		t5	4.52		"												5
		t6	5.05		"												6
		t7	14.34		"												7
		t8	3.45		"												8
		t9	4.35		"												9

Table 8.5 (continued)

NO.	AREA OF STATISTI- CAL COMPARISON of <u>Skolithos</u>	No. OF TEST	TEST RESULT D.N.N	TEST RESULT WIDTH	DEGREE OF FREEDOM	DIFFERENCE IS NOT SIGNIFICANCE					DIFFERENCE IS PRO- BABLY SIGNIFICANCE				DIFFERENCE IS SIGNIFICANCE		
						>.50 100- 50%	0.50 50%	0.40 40%	0.20 20%	0.10 10%	0.05 5%	.025 2.5%	.02 2%	.01 1%	.005 .5%	.002 .2%	.001 .1%
3.	Turimetta Head (Bald Hill Clay- stone, Mid Trias- sic) vs. (1) <u>S. linearis</u> (Haldemann, 1840) (2) <u>S. verticalis</u> Hall, 1843 (3) <u>S. Magnus</u> Howell, 1944 (4) <u>S. Ingens</u> Howell, 1945 (5) <u>S. annulatus</u> Howell, 1957	Z1 Z2 Z3 Z4 Z5		'Z' test 0.53 1.64 3.99 3.13 4.67	N 2 2 2 1			1								3 4 5	
4.	Turimetta Head (Bald Hill Clay- stone, Mid Trias- sic) vs. <u>Tigillites</u> Snapper Point For- mation, Permian (Carey, 1978)	Z		'Z' test 9.205	N 2												
5.	Turimetta Head (Bald Hill Clay- stone, Mid Trias- sic) vs. <u>S. linear</u> <u>is</u> Wasp Head form- ation, Permian (McCarthy, 1979)	Z		'Z' test 0.239	N 1												

'student t' test and 'zm' test in Table 8.5, and the calculations for these tests are given in Appendix 1.4.

The DNN statistics of spatial distribution and dispersion of the Skolithos sp? burrows (cf. Table 8.3, sample 201/MU.44386) indicate that: (1) The Skolithos sp? burrows in sample MU.44386 are aggregated as a whole; (2) the population interaction has produced a low density distribution (0.24 density/unit-area); (3) this low density population seems to be randomly dispersed; (4) there is no significant departure from random ( $R = 0.568$ ).

The spatial distribution of the population is influenced by many physical and biological parameters (e.g., trophic levels). The aggregation of the population as exhibited by many organisms normally can result from heterogeneity of environmental phenomena (e.g., Connell, 1956 & 1963). Contrastingly, a random distribution pattern can be ascribed to geographically variable factors: (1) random larval settlement (Connell, 1956); (2) random abundance and distribution of food resources (Hairston, 1959); (3) random movements of individual organisms (Levinton, 1972).

In sample MU.44386 the mean distance between nearest neighbours is less than 1 cm ( $\bar{x} = 0.576$  cm) and hence these burrows cannot be referred to S. tigillites in terms of the present classification.

**Distribution:** The studied specimen illustrated in Plate 60 Fig. b is from trace fossil subinterval IE9 of the topmost part of the Middle Newport Member at South Palm Beach (area 4b). The other

specimen illustrated in Plate 60 Fig. c is from trace fossil subinterval ID1 of the lower part of the Lower Newport Member at Turimetta Head (area 2). Other similar uncrowded Skolithos burrows occur in the same stratigraphic subinterval (ID1) at Warriewood Beach (area 6) and Hole in the Wall (area 11).

**Studied material:** The burrows illustrated Plate 60 Fig. b occur in collected sample 402/MU.44395; those in Plate 60 Fig. c occur in sample 201/MU.44386.

**Preservation and association:** The burrows are preserved as full-relief forms in grey to buff-grey fine sandstone units. The burrows are believed to have been developed for dwelling by suspension-feeders. The burrows are not associated with any other trace fossils in either subinterval at any of the three localities.

**Ichnofacies and palaeoenvironmental affinities:** As for Skolithos linearis and S. verticalis.

#### 8.5.2 Branching (Barrenjoeichnus-type) burrows

Barrenjoeichnus mitchelli ichno. gen. sp. nov.

(Branched vertical cylindrical burrows)

Plate 55, Figs. a & b  
Plate 56, Figs. a - e  
Plate 57, Figs. a - e  
Plate 74, Fig. d (holotype).

**Type species:** B. mitchelli ichno. sp. nov.

**Name derivation:** 'Barrenjoe' (type locality, Barrenjoe Head), 'ichnus' (for trace) and 'mitchelli' for Dr. P.B. Mitchell of the School of Earth Sciences, Macquarie University.

**Diagnosis (taxonomic assignment):** Vertical to steeply-inclined subcylindrical burrows with variable diameter (tapering downward



or upward). Some burrows exhibit either upward or downward branching, but not both within the one individual.

**Remarks (diagnostic features):** Most of the studied burrows exhibit a steep inclination towards a common, preferred, direction, most evident in sectional views (Plate 55, Figs. a & b). Sporadic burrows exhibit a solitary branch that may be either upward or downward. The diameter of individual burrows commonly varies and can be manifested by either downwards or upwards tapering.

**Description, ethology, and population-density and burrow-orientation studies:** Vertical to steeply-inclined with preferred orientation of the direction of lean, cylindrical to subcylindrical, commonly tapering and sporadically branching burrows developed in fine to very fine sandstone and siltstone units. The fine sandstone host sediment is quartzose and the very fine sandstone and siltstone are micaceous and contain sporadic plant remains. No animal remains have been observed in association with these burrows. The burrows are normally filled with fine sand (normally coarser than the host sediment) in very fine sandstone or siltstone. In transverse cross-section the burrows exhibit a concentric ring-like internal structure. Some burrows are also bounded by (or lined with) thin dark-coloured (probably carbonaceous) concentric layers. The burrow diameter is uniform in cases where the burrow shape is cylindrical, and measures about 0.5 cm to 1.5 cm (Appendix 1.5). However, the burrow diameter obviously varies in burrows which tend to taper either upward (Plate 56 Fig. d) or downward (Plate 56 Figs. a & b). Sporadic burrows branch either

upward (Plate 55 Fig. a; Plate 56 Figs. b & c; and Plate 57 Fig. c) or downward (Plate 57 Fig. c). The angle of branching from the primary (i.e., main) burrow is normally an acute angle (Appendix 1.5). The geographic direction of branching is also important for ethological study and was measured (Appendix 1.5). Details of population-density and burrow-orientation studies are documented in Enclosures III.5 and III.7.

In the present study of the vertical cylindrical burrows the branching phenomenon is considered to be a very important characteristic because it manifests a major change in the animal's behaviour. Moreover, the upward and downward branching would seem to record different modes of behaviour. Upward-directed branches probably constituted auxiliary tunnels or openings (where it can be demonstrated that these reached the contemporary sediment surface) for use in water circulation, escaping, or the storing of unwanted materials (e.g., especially faecal stuff). Downward-directed branches probably constituted ordinary extra dwelling space, or space used for breeding or farming, storing of faecal stuff etc. Unlike other kinds of branching burrows (e.g., Thalassinoides and Ophiomorpha) which are characterized by turn-arounds, these branching burrows of Barrenjoeichnus do not have a turn-around. Similarly, the non-branching burrows of Barrenjoeichnus do not have a turn-around. Similarly, the non-branching burrows of Barrenjoeichnus lack a turn-around. A short upward-directed branch which did not reach the contemporary surface may have served as a temporary dwelling chamber for the animal or a refuge during high-tide conditions (in this case the organism would have occupied the pocket of

trapped air above the water inside the branch-tunnel, cf. Schäfer, 1972, p.466-469). Study of the population density of these burrows on bedding-plane exposures can not be made using the distance-to-nearest-neighbour method because of the assumed presence of branches on some burrows, which branches cannot be reliably differentiated from their parent burrows in such exposures. However, an alternative approach can be taken using a different method on bedding-normal exposures of the burrows; this method is illustrated in Plate 74, Fig. d and also in Enclosure III.5. This method is especially designed for vertical outcrop sections with vertically or near-vertically orientated burrows (but can also be applied to other kinds of burrows).

This method of population-density study employs a 4-m-wide grid on which each burrow's location is separately recorded, and hence the spatial distribution of all burrows within the grid, are mapped level-by-level in that trace fossil subinterval. Additionally, the burrow length and burrow orientation relative to the bedding plane were recorded for many individual burrows in vertically-exposed large-scale galleries of Barrenjoeichnus mitchelli at outcrop 1 (see logged sections in Enclosures III.4 & III.5) and outcrops 2 (see Enclosure III. 4) at Barrenjoey Head. This kind of grid-mapping was centred on a vertical reference line on the exposure (see Plate 74 Fig. d and Enclosure III.5) located within parts of the gallery where the burrows were well exposed and readily accessible. The horizontal grid was laid off in 2x1-m-wide intervals on each side of the vertical reference line. The four 1-m-wide cells in the grid were coded from left to

right: W, X, Y, and Z. Each of the horizontal lines in Enclosure III-5 (i.e., T1, T2, T3, T4 etc.) is defined by a stratigraphic level of conspicuous upward termination of numerous burrows notwithstanding the downward penetration or overlap of such levels by some burrows which begin in the sediment immediately above (Plate 74 Fig. d and Enclosure III.5). The horizontal zones B1, B2, B3 etc. refer to specific bioturbation zones or intervals defined at bottom and top by surfaces (= time lines) T1, T2 etc. In the photograph in Plate 74 Fig. d, some of the individual holotype burrows which were retrieved from the field are relocated within the grid in their original field position relative to each other (but obviously not to true original scale). Note that most of the burrows terminate upwards at T-lines. Some burrows depicted in Enclosure III.5 whose upper termination lies below a T-line are actually broken burrows whose upper part is missing in the face of the exposure.

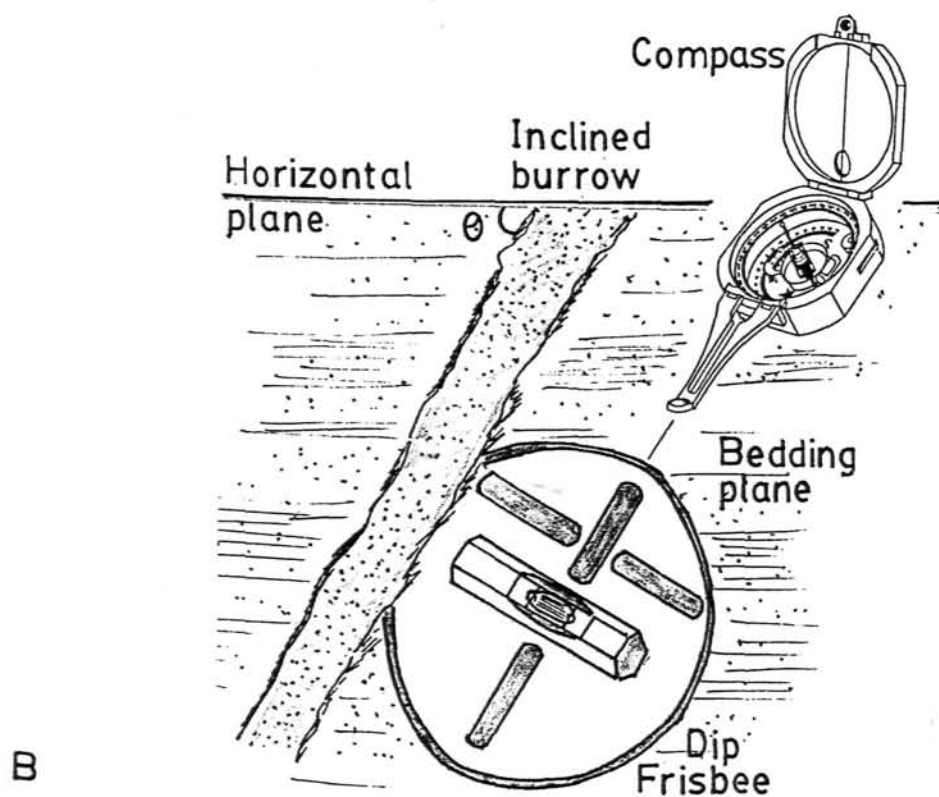
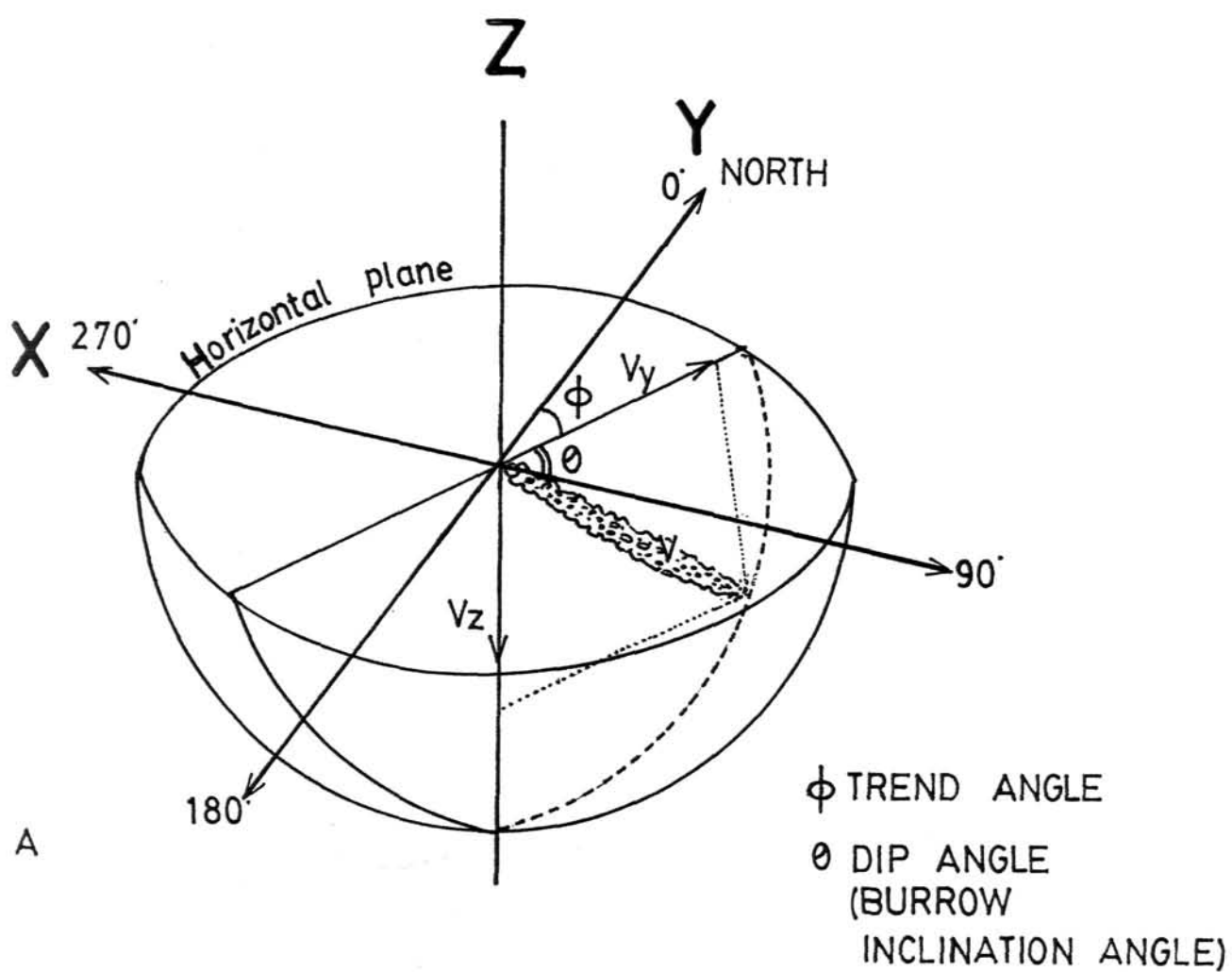
Another important burrow parameter that was measured in the logged sections is their orientation or inclination relative to the bedding plane (which is almost horizontal at Barrenjoey Head where those logs were measured; average structural tilt =  $2^{\circ}$  to  $3^{\circ}/170^{\circ}$ ).

This orientation measurement is very important because many of the burrows show a preferred direction of lean, a phenomenon that may manifest animal behaviour linked to various environmental parameters such as: (1) bottom-current or tidal current movements (i.e., burrows aligned to enhance intake of oxygen or food); (2) orientation of shoreline or off-shore direction; (3) direction of palaeoslope. In the present study the preferred orientation of the burrows is believed to manifest the

direction of bottom currents, possibly of tidal origin. The inclination of individual burrows within each specific level is recorded in Appendix 1.5 and these data are summarized geographically in Enclosure III.7. The palaeoenvironmental interpretation and population studies of these burrows are illustrated in Enclosure III.7.

The method used in measuring the inclination angle and azimuth or trend angle of the inclined burrows is illustrated in Text-Fig. 8.4 (see also Hohenegger & Pervesler, 1985). The orientation can be represented as a unit-vector resolved into two components:  $V_y$ , the horizontal and  $V_z$ , the vertical component.  $V_y$  represents the azimuth or trend direction ( $\phi$ ) and  $V_z$  represents the dip angle ( $\theta$ ). The inclination or dip angle of the burrow is measured downward from a horizontal plane centred at the vector origin, and the trend angle of the burrow is measured clockwise from north (azimuth). The inclination angle ( $\theta$ ) and trend angle ( $\phi$ ) data are tabulated in Appendix I.5 (for outcrop 1) and in Appendix I.6 (for outcrop 2) at Barrenjoey Head (area 1), and the frequency distribution of these data are summarized in Tables 8.6 and Table 8.7. Stereographic projections of the burrow inclination angles and rose diagrams of their trend angles are given in Enclosures III.6A - III.6E. The location of T-lines on the measured trace fossil logged sections is defined in Enclosures III.5 and III.7A, B and C. The azimuths of branching of burrows was also measured in logs TF1 and TF2 at outcrop 1; these measurements are documented in Appendix 1.7 and are summarized graphically in Enclosure III.6E.

TEXT-FIG. 8.4. Method of measuring the inclination angle ( $\theta$ ) and azimuth or trend angle ( $\phi$ ) of steeply-inclined cylindrical burrows of Barrenjoeichnus mitchelli ichnogen. sp. nov. The orientation of a burrow is shown represented as a unit vector (V) in a lower hemispheric projection;  $V_y$  is the azimuth or trend of the inclined burrow and  $V_z$  is the vertical axis. A vector is characterized by the dip or inclination angle ( $\theta$ ) and the trend angle ( $\phi$ ) (Hohenegger & Pervesler, 1985). Dip angles are measured downward from a horizontal plane centred at the vector origin, and trend angles are measured clockwise from north.

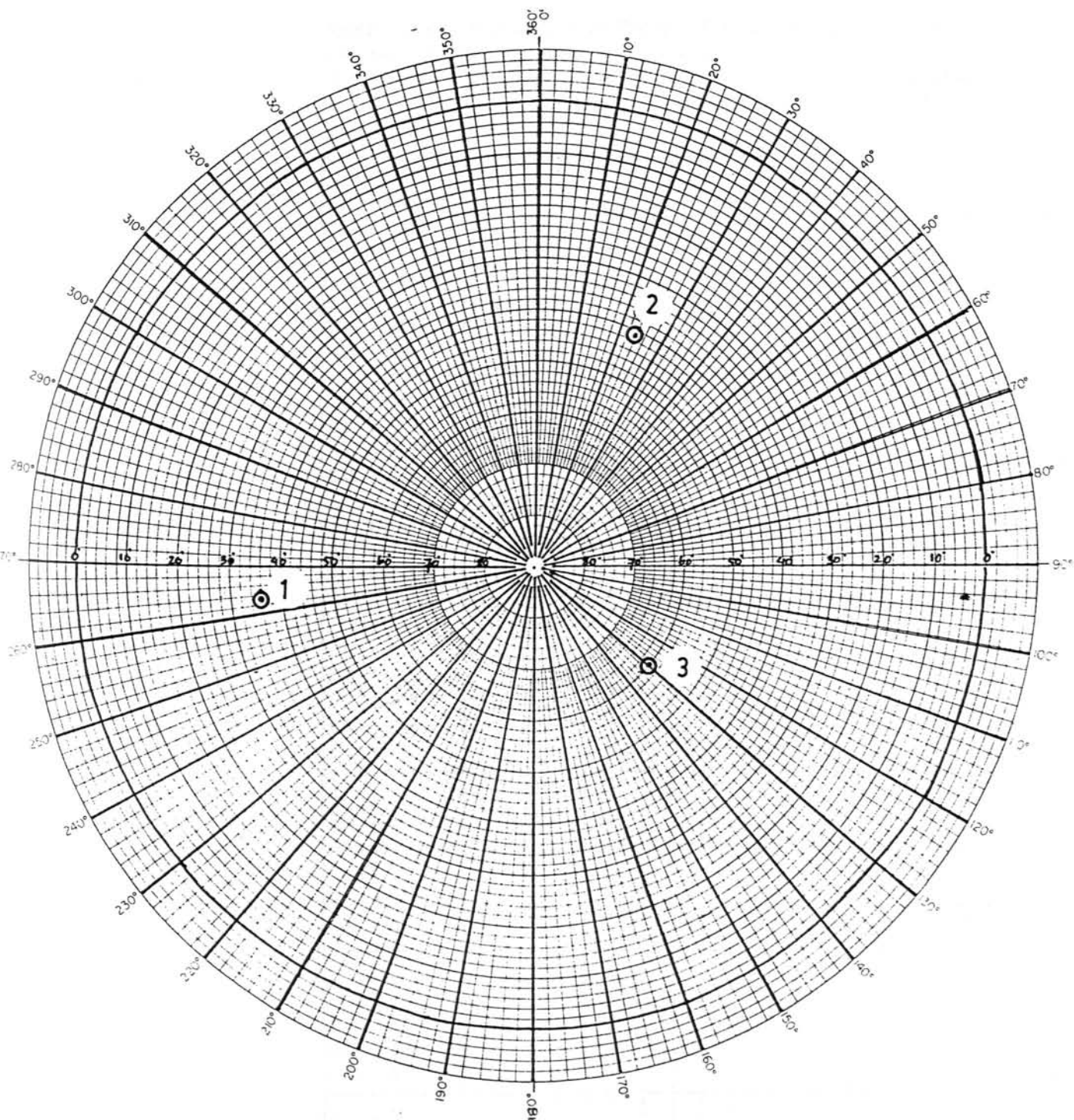


TEXT-FIG. 8.4

**TEXT-FIG. 8.5.** Stereographic projection displayed on 'Schmidt-net' of three hypothetical examples of inclined burrows whose attitude is defined by dip angle ( $\theta$ ) and trend angle ( $\phi$ ). The vector origin can be defined as the upper opening end of the burrow (centre of the stereo-net). The vector of the burrow points downwards. The measurement is analogous to measurements used in structural geology, in that the burrow vectors can be described by the two angles mentioned above (cf. Text-Fig. 8.5). These angles are plotted onto a hemisphere whose centre is the common origin of all burrow vectors. The vector intersects the hemisphere and the direction of each vector (trend angle  $\phi$  - measured clockwise from north) can be represented by a point on the surface of the sphere.



DIAGRAM FOR HYPOTHETICAL INCLINED BURROWS



TREND ANGLE - 0° - 360°  
DIP (BURROW INCLINATION) ANGLE - 1° - 89°

- EXAMPLES (1) 36°/ 263°  
(2) 41°/ 024°  
(3) 60°/ 130°

TEXT-FIG. 8.5.

**TABLE 8.6.** Frequency distribution of burrow trend angles ( $\phi$ ) of steeply-inclined burrows of the new ichnotaxon Barrenjoeichnus mitchelli. The data are grouped into 36 10° class intervals. The bioturbation units defined in Plate 74 Fig. d and Enclosure I11.5 are shown in the left-hand column. A: Frequency distribution of trend angles of burrows at outcrop 1 GR.4520,8277, Barrenjoey Head (area 1), Broken Bay (9130-I-N). B: Frequency distribution of trend angles of burrows at outcrop 2 GR. 4502,8275, Barrenjoey Head (area 1), Broken Bay (9130-I-N). C: Frequency distribution of burrow trend angle data pooled from outcrops 1 and 2.

Bioturbation cells/units	Trend angle ( $\phi$ ) classes																																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	N
(Outcrop 1)																																					
TF1																																					
B1X - B1Y		1			1	7	3	6	2	2	5					1							1								1			1			32
B2X - B2Y					3	6	5	6	5	4												1		1	1	4											35
TF2																																					
B1X - B1Y						1	3	1	1														2	6	1						2					17	
B2X - B2Y				1		1	3	6	3	1	1										1		1	4	3						1				1	30	
B3X - B3Y					3	2														1	1				1											8	
TF3																																					
B1X-B1Y-B1Z							1		1	6	2															9	11	34	16	4							84
B2X-B2Y-B2Z									1																1	10	11			1							24
TF4																																					
B1X - B1Y								1	2	1	4															1										9	
B2X - B2Y								8	18	20	3	2													1	2	6		1		1					63	
B3X - B3Y								1	2	2																	1									7	
B4X - B4Y								1	3	4																										8	
B5X - B5Y						2	1	2	3	2	1														2											13	
Total Outcrop (1)	0	1	1	1	7	19	16	32	41	42	16	2				1				1	2	1	4	11	13	26	28	35	18	4	5	0	1	1	1	330	
(B)																																					
Bioturbation cells/units																																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
Outcrop (2)																																					
TF																																					
B1X - B1Y										1	5	3	3														1	1	1							15	
B2X - B2Y										1	6	2			1											1	1	2	1	1						16	
B3X - B3Y										1		3	4	4	1																					13	
Total Outcrop (2)										3	11	8	7	4	2												1	2	3	2	1					44	
(C)																																					
Total Outcrop (1) & (2)	0	1	1	1	7	19	16	32	41	45	27	10	7	4	2	1	0	0	0	1	2	1	4	11	13	27	30	38	20	5	5	0	1	1	1	0	374

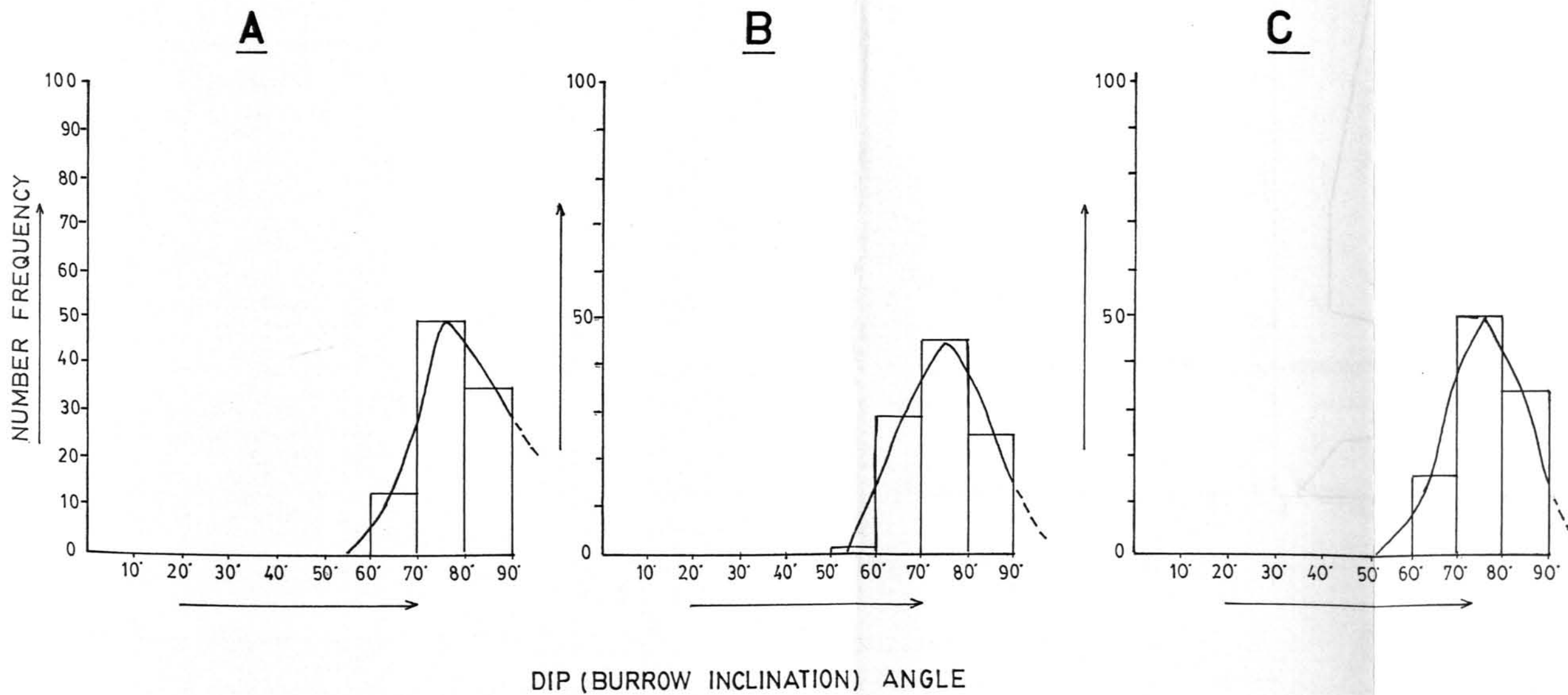
Class	Degrees
1	1 - 10
2	11 - 20
3	21 - 30
4	31 - 40
5	41 - 50
6	51 - 60
7	61 - 70
8	71 - 80
9	81 - 90
10	91 - 100
11	101 - 110
12	111 - 120
13	121 - 130
14	131 - 140
15	141 - 150
16	151 - 160
17	161 - 170
18	171 - 180
19	181 - 190
20	191 - 200
21	201 - 210
22	211 - 220
23	221 - 230
24	231 - 240
25	241 - 250
26	251 - 260
27	261 - 270
28	271 - 280
29	281 - 290
30	291 - 300
31	301 - 310
32	311 - 320
33	321 - 330
34	331 - 340
35	341 - 350
36	351 - 360

TABLE 8.7. Frequency distribution of dip (burrow inclination) angles ( $\theta$ ) of *Barrenjoeichnus mitchelli*. The frequency data are grouped into 9  $10^\circ$  classes as indicated. The bioturbation units defined in Plate 74 Fig. d and Enclosure III.5 are shown in the left-hand column. A: Frequency distribution of dip angles ( $\theta$ ) of burrows at outcrop 1 GR.4520,8277, Barrenjoey Head (area 1), Broken Bay (9130-I-N). B: Frequency distribution of dip angles ( $\theta$ ) of burrows in outcrop 2 GR.4520,8275, Barrenjoey Head (area 1), Broken Bay (9130-I-N). C: Frequency distribution of burrow dip angle data pooled from outcrops 1 and 2.

A Bioturbation cells/units	Dip angle ( $\theta$ ) classes										Classes Degrees
	1	2	3	4	5	6	7	8	9	N	
(Outcrop 1)											1      1 - 10
TF1											2      11 - 20
B1X - B1Y	0	0	0	0	1	2	3	18	8	32	3      21 - 30
B2X - B2Y	0	0	0	0	0	1	2	17	15	35	4      31 - 40
TF2											5      41 - 50
B1X - B1Y	0	0	0	0	0	0	4	9	4	17	6      51 - 60
B2X - B2Y	0	0	0	0	0	0	8	12	10	30	7      61 - 70
B3X - B3Y	0	0	0	0	1	0	0	4	3	8	8      71 - 80
TF3											9      81 - 89
B1X-B1Y-B1Z	0	0	0	0	0	2	12	49	21	84	
B2X-B2Y-B2Z	0	0	0	0	0	0	6	8	10	24	
TF4											
B1X - B1Y	0	0	0	0	0	0	1	5	3	9	
B2X - B2Y	0	0	0	0	0	0	5	31	27	63	
B3X - B3Y	0	0	0	0	0	0	0	1	6	7	
B4X - B4Y	0	0	0	0	0	0	1	4	3	8	
B5X - B5Y	0	0	0	0	0	0	1	6	6	13	
Total Outcrop 1	0	0	0	0	2	5	43	164	116	330	
B Bioturbation cells/units	Dip angle ( $\theta$ ) classes										
	1	2	3	4	5	6	7	8	9	N	
Outcrop 2											
TF1											
B1X - B1Y	0	0	0	0	0	0	7	6	2	15	
B2X - B2Y	0	0	0	0	0	0	3	9	4	16	
B3X - B3Y	0	0	0	0	0	1	3	5	4	13	
Total Outcrop 2	0	0	0	0	0	1	13	20	10	44	
C Total: Outcrops 1 & 2	Dip angle ( $\theta$ ) classes										
	1	2	3	4	5	6	7	8	9	N	
	0	0	0	0	2	6	56	184	126	374	

TEXT-FIG. 8.6. Frequency histograms of dip angle ( $\theta$ ) of Barren-joeichnus mitchelli in  $10^\circ$  intervals. Truncated normal distribution is fitted to the histogram.

- A. Frequency distribution of the burrows from outcrop 1 GR. 4520,8277 Broken Bay (9130-I-N).
- B. Frequency distribution of the burrows from outcrop 2 GR. 4502,8275 Broken Bay (9130-I-N).
- C. Frequency distribution of the burrows from outcrops 1 and 2 combined.



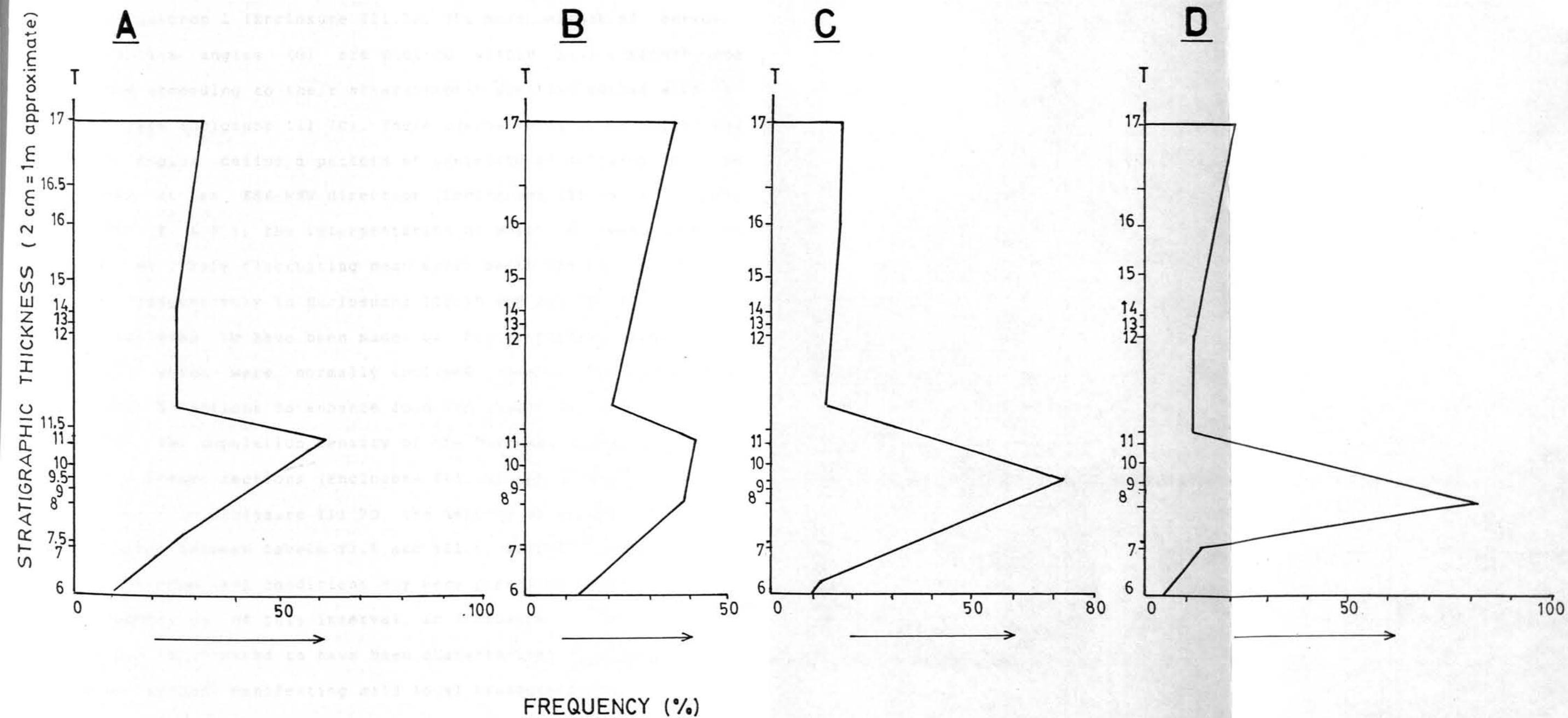
TEXT-FIG. 8.6

TEXT-FIG. 8.7 Population density distributions of burrows of Barrenjoeichnus mitchelli in four logged sections at outcrop 1 (GR. 4520,8277 Broken Bay 9130-I-N). The population study commenced at level T6.0 and proceeded upwards to level T17.0 in each of these logged sections. The horizontal axis shows the burrow population along each line as a percent of the total number of burrows counted in all T-lines at each section. The detailed location of each section is shown in Enclosure III.7G.

- A. Population density distribution of burrows in logged section TF1.
- B. Population density distribution of burrows in logged section TF2.
- C. Population density distribution of burrows in logged section TF3.
- D. Population density distribution of burrows in logged section TF4.

(The overall interpretation of the population density distribution of these four logged sections is shown in Enclosure III.7).





TEXT-FIG. 8.7

The orientation measurements of the burrows are plotted for specific levels in the measured sections TF1, TF2, TF3, and TF4 at outcrop 1 (Enclosure III.7). The measurements of burrows' inclination angles ( $\theta$ ) are plotted within half-circles) are located according to their stratigraphic position marked with 'T' lines (see Enclosure III.7C). These burrow inclination angles and trend angles define a pattern of preferred orientation of the burrows in an ESE-WNW direction (Enclosures III.6A - C, and III.7C, E & F.), the interpretation of which is summarized in terms of likely fluctuating mean water depth and current directions respectively in Enclosures III.7D and III.7H. The burrows are believed to have been made by filter-feeding suspension-feeders which were normally inclined towards the prevailing current directions to enhance food and oxygen intake (Enclosure III.7H). The population density of the burrows varies upsequence in the logged sections (Enclosure III.7C) and is summarized for outcrop 1 in Enclosure III.7D. The density of burrow population is greater between levels T7.5 and T11.5, suggesting more favourable environmental conditions may have prevailed during the time of deposition of this interval. In Enclosure III.7D this time interval is inferred to have been characterized by greater water depths, perhaps manifesting mild local transgressions.

The following interpretations regarding the type of producer of the burrows and the environmental setting can be deduced from the burrow measurements taken in the logged sections: (1) the burrows are about 1 cm in average diameter (maximum can exceed 2 cm) and about 10 cm in length (maximum length can exceed 0.5 m; (2) the burrows are invariably steeply-



inclined and some are branched either upward or downward; (3) the lean of the burrows tends to define a preferred ESE-WNW orientation (interpreted here to manifest alignment in the prevailing current, with the dominant current direction having been either generally from the east or the west; (4) the independent palaeocurrent measurements from other sedimentary structures (ripple cross-laminations) measured by Cowan (1987) and during the present study (Enclosure III.3) confirm the present interpretation; (5) The organisms that made the burrows are interpreted to have been filter-feeders that established their burrows as permanent dwellings; (6) the organisms that produced these burrows were preferably aligned in (i.e., inclined into) the prevailing current to increase their intake of food and probably also of oxygen; (7) the interpreted palaeoenvironmental setting is believed to have been a shoreline or shallow sand-flat of a fluvially-dominated estuary or coastal lagoon. The burrows are normally associated with small transported plant fragments.

**Comparison:** Unbranched burrows of the new ichnogenus Barrenjoeichnus are comparable with Cylindrichnus concentricus Howard (1966). The burrows described by Howard are 1 to 2 cm in diameter, with a concentric wall-layer, and are preserved as full-relief forms in orientations that range from horizontal to vertical relative to bedding. In Howard's illustrations of these burrows they seem to taper downwards and are not branched. In the burrows studied here, the branching characteristic is more obvious and is considered to be both ethologically and ecologi-

cally important. These burrows differ from the other major variety of vertical cylindrical burrow, Skolithos Haldeman (1840), by their larger diameter, concentric wall-layer and branching character.

**Distribution:** The burrows are geographically widely distributed throughout the entire study area, especially in the Upper Member of the Newport Formation in trace fossil subinterval IF1 and IF2 (see map, Enclosure III.1); good developments occur at Barrenjoey Head (area 1) in the north and, in the south at Blue Fish Point (area 20), and Cabbage Tree Bay (area 19). Other trace fossil subintervals within the Middle Member of the Newport Formation (IE5 and IE7) also yield these burrows at Little Head (area 7) and Careel Head (area 9) but the burrow developments are less extensive there than at Barrenjoey Head.

**Studied material:** Most of the studied materials are from outcrop 1 (GR.4520,8277) and outcrop 2 (GR.4502,8275) at Barrenjoey Head, Broken Bay (9130-I-N). The holotype burrows (in sample 105/MU.44372) are illustrated in Plate 74 Fig. d, collected from trace fossil subinterval IF1 of the Upper Newport Member at outcrop 1.

**Preservation and association:** The burrows are preserved as full-relief forms (domichnia) produced by filter-feeding organisms. The burrows are not associated with any other types of burrows but are commonly associated with small transported plant fragments (the latter being confined to siltstone units).

**Ichnofacies and palaeoenvironmental interpretation:**

Barrenjoeichnus is believed to belong to the Skolithos ichnofacies developed in the proximal parts of a fluvially-dominated coastal lagoon or shallow estuary.