The palynology of the Middle Jurassic (Bajocian-Bathonian) *Wanaea verrucosa* dinoflagellate cyst Zone of the North West Shelf of Australia

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ABSTRACT

The marine and terrestrial palynology of the Middle Jurassic *Wanaea verrucosa* Zone from the Perseus-3A, Sunrise-2 and Sunset West-1 wells of the North West Shelf of Australia was studied in detail. These three wells represent brackish and shallow marine successions from the Northern Carnarvon and Bonaparte basins respectively. The palynological data derived from these three wells constitute the basis for the formal definition of this important dinoflagellate cyst biozone and its three constituent subzones. The base of the Lower *Wanaea verrucosa* Subzone is defined by the inception of the index species and is a relatively sparse, low diversity microphytoplankton assemblage; species richness increases up-section. The base of the succeeding Middle *Wanaea verrucosa* Subzone is defined by the range base of *Valvaeodinium spinosum,* and the Upper *Wanaea verrucosa* Subzone is defined by the incoming of the large and distinctive species *Endoscrinium kempiae*. Other stratigraphically-important datums include the inceptions of ?*Bradleyella adela* in the lower subzone, *Leptodinium* spp. and *Wanaea lacuna* in the middle subzone, and *Endoscrinium* spp. and *Ternia balmei* within the upper subzone. Important range tops include *Mancodinium semitabulatum* and *Phallocysta granosa* in the middle subzone, and *Nannoceratopsis deflandrei* in the upper subzone. These and other datums are compared with European ranges to assign a Late Bajocian to Early Bathonian age to the *Wanaea verrucosa* Zone.

The dinoflagellate cyst associations are dominated by cosmopolitan taxa, particularly at the generic level. Endemic Australasian forms such as *Phallocysata granosa* and *Ternia balmei* are relatively minor in significance. However, two new species, *Meiourogonyaulax straussii* sp. nov. and *Valvaeodinium cookii* sp. nov. are established and are unknown from other localities. The species *Jansonia scarffei* is reattributed as *Fostericysta scarffei* (Tykoezinski et al. 2001) comb. nov. Taxa with epicystal and multiplate precingular archaeopyles are prominent; this represents the coeval evolutionary explosion of the gonyaulacacean dinoflagellate cysts observed in the latest Early to Late Bajocian of Europe. By contrast, the succeeding Callovian to Oxfordian interval in Australasia and Europe is dominated by endemic taxa. This may be an indication of the development of forms with specific environmental preferences during the Callovian and Oxfordian and/or the establishment of barriers to the passive dispersal of dinoflagellates within Tethys. However, this phenomenon may be partially an artefact of further diversification.

The associated spore-pollen assemblages are transitional from the upper *Dictyotosporites complex* to the lower *Contignisporites cooksoniae* zones. The latter zone is defined by the first appearance of the index species, but considerable care is required to separate this species from the many intermediate forms of *Striatella-Contignisporites* that occur through this interval. The palynofloras are dominated by araucariacean monosaccates (particularly *Callialasporites* spp.),corystospermbisaccates (mostly *Alisporites* spp.) and moderately diverse bryophyte-lycophyte-pteridophyte spore assemblages.

Keywords: biostratigraphy; dinoflagellate cysts; *Wanaea verrucosa* Zone; Middle Jurassic (Bajocian-Bathonian); North West Shelf; Australia.

1. Introduction

The North West Shelf of Australia is a passive continental margin comprising the Northern Carnarvon, Roebuck, Offshore Canning, Browse and Bonaparte basins (Fig. 1). These five depocentres collectively make up the extensive Westralian Superbasin and represent the most important hydrocarbon province in Australia. Longley et al. (2002) reviewed the petroleum geology of this region that includes multiple source, reservoir and seal units of Early Carboniferous to Late Cretaceous age. These include the fluvio-deltaic and marginal marine sandstones of the Legendre and Plover formations that form important Middle Jurassic reservoir units in the Northern Carnarvon and Bonaparte basins respectively. This interval is represented by the *Nannoceratopsis deflandrei*, *Wanaea verrucosa* and *Wanaea indotata* dinoflagellate cyst zones.

Microfossil-based biostratigraphy has been extensively used during both the hydrocarbon exploration and production phases across the North West Shelf. The standard Mesozoic palynomorph zonation for the North West Shelf is Helby et al. (1987). This is an integrated dinoflagellate cyst and spore-pollen biozonation scheme for the Late Permian (Changshingian) to the Palaeocene (Danian) interval. The dinoflagellate cyst zonal component generally provides substage level resolution from the Middle Triassic (Anisian) to Palaeocene. Further taxonomic work chiefly on the Jurassic (Toarcan-Tithonian) by Helby and Partridge (2001) and Riding and Helby (2001a-h) established many key marine microphytoplankton taxa that significantly increased the biostratigraphical resolution across this interval. These index species have allowed the definition of many dinoflagellate cyst subzones, some of which were illustrated, but not defined, by Helby et al. (1987, fig. 47) and Foster (2001, fig. 2). Further revisions were figured by Helby et al. (2004) and Partridge (2006) on chart/poster-style publications along with the bioevents that define each zone and subzone. Subsequently, the ranges of many of the important dinoflagellate cyst index taxa for the Mid Triassic to earliest Cretaceous (Ladinian-Berriasian) zones were provided by Riding et al. (2010a), who reviewed and revised the chronostratigraphical ages for the zones in this interval. However, the new zones and subzones listed by Helby et al. (2004) and Partridge (2006) remained unformalized. These zones can nevertheless be used in applied petroleum geology studies because their parameters in terms of the defining bioevents were clearly illustrated.

This contribution is focussed on the Late Bajocian to Early Bathonian *Wanaea verrucosa* dinoflagellate cyst Zone and its three constituent subzones. In this paper we formally define the zone, and the three subzones, and provide detailed palynological documentation of this interval in three important reference sections. The successions studied are from the Perseus-3A well in the Northern Carnarvon Basin, and the Sunrise-2 and Sunset-West-1 wells in the Bonaparte Basin (Fig. 1; Appendix 1).

2. The *Wanaea verrucosa* Zone - background

The *Wanaea verrucosa* Zone was first illustrated by Foster (2001, fig. 2) for the Bathonian (Middle Jurassic) of the North West Shelf of Australia. This dinoflagellate cyst zone replaced the upper part of the *Caddasphaera halosa* Zone of Helby et al. (1987). The *Wanaea verrucosa* Zone was subsequently illustrated, with defining bioevents, by Helby et al. (2004, figs. 1, 4) and Partridge (2006). Its base and top are delimited by the range bases of *Wanaea verrucosa* and *Wanaea indotata* respectively. The base of the zone was also defined by the apparent extinction of *Nannoceratopsis deflandrei,* but the current study considerably extends this range. The zone was subdivided into three subzones defined on the range bases of *Wanaea verrucosa, Valvaeodinium spinosum* and *Endoscrinium kempiae* (Helby et al., 2004; Partridge, 2006). The only other biostratigraphical data depicted was the range base of *Ternia balmei* within the youngest of these subzones (Helby et al., 2004, fig. 4). Riding et al. (2010a, p. 562) revised the Bathonian age of the zone to Late Bajocian to Early Bathonian based on key dinoflagellate cyst datums established in Europe (Fig. 2).

According to Riding et al. (2010a), the *Wanaea verrucosa* Zone is characterised by high diversity assemblages of largely undescribed species with species richness increasing up-section. The described taxa within this zone were noted to include *Endoscrinium kempiae, Nannoceratopsis* spp., *Pareodinia ceratophora, Pareodinia halosa, Phallocysta granosa, Ternia balmei, Valvaeodinium spinosum, Wanaea enoda, Wanaea lacuna* and *Wanaea verrucosa* (see Riding et al., 2010a, p. 562).

3. The palynology of the *Wanaea verrucosa* Zone in the Perseus-3A, Sunrise-2 and Sunset West-1 wells

In this study, 64 conventional core samples from the Perseus-3A, Sunrise-2 and Sunset West-1 wells (Fig. 3) were investigated for palynology. In the Northern Carnarvon Basin, 14 samples were selected from the fluvio-deltaic Legendre Formation in the Perseus-3A well; this succession consists of a series of coarseningupward cycles deposited in low energy, non-marine and brackish environments through to marginal and shallow marine settings. The remaining 50 samples from the Sunrise-2 and Sunset West-1 wells, in the Bonaparte Basin, are from shallow marine deposits in the uppermost Plover Formation. The samples largely produced abundant, terrestrial palynofloras with a lower proportion of marine microphytoplankton. The latter includes a moderately diverse dinoflagellate cyst assemblage that forms the principal focus of this contribution due to their stratigraphical utility across the North West Shelf.

In the majority of the samples investigated, low diversity associations of gymnospermous pollen dominate, including abundant *Araucariacites* spp., *Callialasporites* spp. and undifferentiated bisaccate pollen (mostly the corystosperm genus *Alisporites*). Common *Classopollis* spp. represent cheirolepidacean conifers, whilst the frequently co-occuring taxodiacean species *Exesipollenites tumulus* and *Perinopollenites elatoides* were also sporadically recorded. Further pollen species recorded in low numbers included *Cycadopites* spp., *Vitreisporites pallidus* and rare trisaccate types.

There is also a moderate diversity and abundance of pteridophyte, bryophyte and lycodpod spores throughout the intervals studied; these assemblages are commonly dominated by *Cyathidites* spp., *Dictyophyllidites* spp., *Gleicheniidites* spp., *Ischyosporites/Klukisporites* spp., *Neoraistrickia* spp., *Osmundacidites* spp. and *Retitriletes* spp. Common accessory species included *Antulsporites saevus*, *Annulispora* spp., *Coronatispora* spp., *Dictyotosporites complex, Foveosporites canalis, Sestrosporites pseudoalveolatus* and *Staplinisporites caminus.* There is also a stratigraphically significant transition from *Striatella* to *Contignisporites* through the zone, with common intermediate forms.

Reworked pollen and spores were noted throughout the successions in all three wells. These allochthonous forms are largely of Permian age and include highly distinctive types such as *Diatomozonotriletes townrowii*, *Didecitriletes ericianus*, *Dulhuntyispora dulhuntyi*, *Granulatisporites trisinus*, *Indotriradites* spp., *Microbaculispora villosa*, *Plicatipollenites* spp., *Praecolpatites sinuosus*, *Protohaploxypinus* spp., *Pseudoreticulatispora pseudoreticulata*, *Striatoabieites multistriatus* and *Striatopodocarpidites* spp.

However, the main focus of the study was on the moderately diverse marine microphytoplankton assemblages that are present in the three selected wells. The relative proportions of dinoflagellate cysts are highly variable across the *Wanaea verrucosa* Zone, but they generally represent 15-40% of the palynofloras in the two Bonaparte Basin wells and 1-20% of the palynofloras in the Perseus-3A well in the Northern Carnarvon Basin. The significantly sparser dinoflagellate cyst assemblages in the Perseus-3A well reflect the more marginal marine and brackish or even nonmarine environments across the Bajocian-Bathonian interval in the Northern Carnarvon Basin compared to the dominantly shallow marine successions across much of the northern Bonaparte Basin. These dinoflagellate cyst associations are dominated by *Ctenidodinium* spp., the *Dissiliodinium-Durotrigia* group, *Escharisphaeridia* spp., *Meiourogonyaulax* spp., *Pareodinia* spp. and *Wanaea verrucosa*. Other common or stratigraphically significant forms include ?*Bradleyella adela*, *Kallosphaeridium hypornatum*, *Leptodinium* spp., *Mancodinium semitabulatum*, *Nannoceratopsis deflandrei*, *Phallocysta granosa*, *Ternia balmei*, *Valvaeodinium cookii* sp. nov., *Valvaeodinium spinosum* and *Wanaea enoda*. Miscellaneous palynomorphs such as acritarchs (largely *Micrhystridium* spp.), *Botryococcus*, foraminiferal test linings and prasinophytes (e.g. *Pterospermella australiense*) are present in relatively minor poroportions, and appear to be of limited stratigraphical significance.

The dinoflagellate cyst systematics, including the establishment of *Meiourogonyaulax straussii* sp. nov. and *Valvaeodinium cookii* sp. nov., are presented as Appendix 2. The non-dinoflagellate cyst palynomorphs are simply listed in Appendix 3 whilst the quantitative counts of both terrestrial and marine palynomorphs are given in Appendix 4 (Tables 1-6). Selected dinoflagellate cyst specimens are illustrated in Plates I-X, and all the figured material is housed in the Commonwealth Palaeontological Collection (CPC) of Geoscience Australia, Canberra, ACT, Australia. A register of figured specimens is included as Appendix 5.

3.1. The Perseus-3A well

The Perseus-3A well was drilled in the Northern Carnarvon Basin (Fig. 1; Appendix 1) to a total depth of 3915 m to the Upper Triassic Mungaroo Formation. Fourteen conventional core samples were examined from the Middle Jurassic *Wanaea verrucosa* Zone; the quantitative distribution of palynomorphs in these samples is depicted in Tables 1 and 4 of Appendix 4. The samples generally produced relatively abundant, fair- to well-preserved palynomorph associations. The organic residues are consistently dominated by terrestrially-derived palynomorphs, with subordinate marine microphytoplankton (Tables 1, 4). In seven of the 14 samples, dinoflagellate cysts represent less than 10% of the palynofloras. This relative sparsity of marine microplankton is consistent with a brackish water depositional setting. This contention is supported by the consistent, albeit rare, occurrences of the freshwater/brackish alga *Botryococcus* (Table 4). A further 15 samples from this interval were not studied in detail; these samples contained extremely sparse dinoflagellate cyst assemblages (<1% of total palynomorphs) and are probably representative of brackish to non-marine environments.

3.2. The Sunrise-2 well

The Sunrise-2 well is located immediately northeast of the Sunset West-1 well in the Bonaparte Basin (Fig. 1; Appendix 1). It penetrated 2350 m into the fluvial-deltaic Lower-Middle Jurassic Plover Formation. Twenty-nine samples from the upper, more marine, sections of the Plover Formation were examined herein. The quantitative distribution of palynomorphs in these samples is illustrated in Tables 2 and 5 of Appendix 4. The samples yielded moderately diverse terrestrial and marine palynomorphs with dinoflagellate cysts commonly making up 20-50% of the total assemblages. The preservation ranged from poor- to well-preserved. However, the thermal alteration index is moderately higher in this well than the other two wells examined; most spores and pollen are dark orange to brown and are at peak maturity for oil generation.

3.3. The Sunset West-1 well

The Sunset West-1 well was drilled to a total depth of 2505 m in the Lower Jurassic, fluvially dominated sections of the Plover Formation in the northern Bonaparte Basin (Fig. 1; Appendix 1). Twenty-one samples from the *Wanaea verrucosa* Zone in the shallow marine, upper Plover Formation were studied herein; the quantitative distribution of palynomorphs in these samples is depicted in Tables 3 and 6 of Appendix 4. They generally produced abundant and poor- to well-preserved palynomorph associations. However, the uppermost three samples yielded relatively sparse, poorly-preserved palynofloras. The organic residues in the lower and middle subzones are mostly dominated by terrestrially derived pollen and spores, with subordinate marine microphytoplankton (9-29% dinoflagellate cysts of the total palynofloras). However, the upper subzone is substantially more marine, with dinoflagellate cysts accounting for 21% to 76% of the total palynomorphs.

3.4. Palaeoecological palynology

The palynomorph assemblages are largely dominated by pollen and spores with a low to moderate diversity marine microphytoplankton component. Gymnosperm pollen, particularly araucariacean types, are abundant throughout all three wells together with moderately diverse and abundant bryophyte-lycophyte-pteridophyte spore communities. The predominance of the araucariacean pollen, and to a lesser extent corystosperm bisaccates, is suggestive of warm, largely non-seasonal and temperate to moderately humid environments (Reyre, 1980; Mohr, 1989; Abbink 1998). This increase in abundance of araucariacean pollen and the marked decrease in cheirolepidacean pollen, such as *Corollina* and *Exesipollenites*, reflects the change from the drier and possibly warmer conditions that prevailed in the Early Jurassic (Filatoff, 1975; McKellar, 1996; Sajjadi and Playford, 2002) and marks a prolonged period of relative climate stability. These moister conditions in the Middle Jurassic are also reflected in the moderate diversity of filicalean fern, and bryophytic moss and liverwort spores.

The predominance of gymnosperm pollen over spores in the *Wanaea verrucosa* Zone in both the Sunrise-2 and Sunset West-1 wells probably reflects the transport time to shallow marine environments in the Bonaparte Basin, as opposed to proximity to suitable habitats; araucariacean trees are more likely to occur away from deltaic and most coastal environments, but their pollen is readily transported to such settings. Similarly, the comparable abundances of pollen to spores and the much reduced marine microphytoplankton abundance in Perseus-3A reflects the shorter transport distances into the marginal marine to brackish and intermittently non-marine environments in parts of the Northern Carnarvon Basin. These coastal plain to very nearshore environments, possibly in a somewhat restricted basin, are considered analogous with the Bathonian Great Estuarine Group of northwest Scotland. This unit represents shallow water, paralic conditions where the salinity was largely brackish and is characterised by dinoflagellate cyst assemblages with low species richness (Riding et al., 1991, figs. A4-A10); the composition of these assemblages is broadly comparable to those of the North West Shelf.

In the two Bonaparte Basin wells studied herein, the greater diversity and abundance of marine microphytoplankton allows some inferences to be made regarding the fluctuating marine depositional environments. There is a moderate increase in abundance and diversity of dinoflagellate cysts through the Middle and Upper *Wanaea verrucosa* subzones, which suggests a shift from a very nearshore setting in the Lower subzone to shallow marine (though still nearshore) palaeoenvironments in the overlying subzones. This is reflected in the overall progression from a fluvially-dominated/tide-influenced succession for the Lower *Wanaea verrucosa* Subzone and underlying sections to a wave-dominated/tide-influenced interval that covers the Middle-Upper *Wanaea verrucosa* Subzones as indicated by integrated studies of the sedimentology, ichnology and wireline log profiles for these wells (Ainsworth et al., 2008; fig. 4.6).

A nearshore depositional environment is not only suggested by the dominance of pollen and spores to marine microphytoplankton, but also by the relative abundance of certain dinoflagellate cyst groups. *Meiourogonyaulax* are thick-walled, robust, dinoflagellate cysts considered typical of nearshore environments (Harris and Tocher, 2003) and are likely to preserve well with minimal damage in differing environments and after variable laboratory preparations (Mantle 2009b); their abundance through the *Wanaea verucosa* Zone should thus be relatively free from preservational or processing artefacts. The prominence of *Meiourogonyaulax* in the Middle and Upper subzones probably reflects normal salinity, shallow marine conditions, as is also reflected by the increase in foraminiferal test linings and spiny acritarchs. *Ternia balmei* is another species that is thought have been largely nearshore in occurrence; it first occurs in the Upper *Wanaea verrucosa* Subzone.

4. The definition of the *Wanaea verrucosa* Zone

In this section, the *Wanaea verrucosa* Zone of Foster (2001), Helby et al. (2004) and Partridge (2006) is formally defined.

Wanaea verrucosa Zone

Definition: The interval between the range base of *Wanaea verrucosa* and the range base of *Wanaea indotata.*

Age: Late Bajocian to Early Bathonian (Riding et al., 2010a).

Type sections: The shallow marine successions in the Sunrise-2 (2155.74-2107.42m) and Sunset West-1 (2247.05-2200.17m) wells in the northern Bonaparte Basin are proposed as reference sections for the *Wanaea verrucosa* Zone and its constituent subzones.

Accessory forms: The *Wanaea verrucosa* Zone is characterised by low to moderate diversity dinoflagellate cyst assemblages dominated by the genera *Ctenidodinium, Dissiliodonium-Durotrigia, Escharisphaeridia, Pareodinia* and *Wanaea*. *Batiacasphaera* and *Nannoceratopsis* are also consistently present in relatively low proportions.

Associated spore-pollen zones: upper *Dictyotosporites complex* to lower *Contignisporites cooksoniae* zones (insert reference here)

Remarks: The base of the *Wanaea verrucosa* Zone is marked by the range base of the important Middle-Late Jurassic genus, *Wanaea* (see Riding and Helby, 2001b, figs. 11, 12). In Australia, *Wanaea enoda* and *Wanaea verrucosa* have their inceptions at this point, as observed in the three wells studied herein (Fig. 4). The range base of this distinctive and large genus is an ideal biostratigraphical marker. Although the *Wanaea verrucosa* Zone assemblages are typically dominated by pollen and spores, the index species is consistently present, often in significant proportions.

Subzones: The Sunrise-2 and Sunset West-1 wells in the Bonaparte Basin are subdivided into Lower, Middle and Upper subzones along similar lines to those illustrated by Helby et al. (2004). However, alternative marker species are also noted, and general assemblage trends may be as useful in identifying these subzones. The Perseus-3A well has yielded considerably sparser and lower diversity dinoflagellate cyst assemblages; it cannot be confidently subdivided as in the Bonaparte Basin wells. Hence the comments on the subzones below may only apply to the Bonaparte Basin rather than the whole of the North West Shelf.

Lower *Wanaea verrucosa* Subzone

Definition: The interval between the range base of *Wanaea verrucosa* and the range base of *Valvaeodinium spinosum.*

Remarks: The base of this subzone is formally defined as the first occurrence of *Wanaea verrucosa*. The lower half of the subzone is characterised by an abundance of *Dissiliodinium*/*Durotrigia*-type cysts (20-66% of dinoflagellate cysts) in an otherwise low diversity assemblage (Fig. 4; Tables 1-6). Important accessory forms include *Nannoceratopsis deflandrei* subsp. *deflandrei*, ?*Egmontodinium* sp. A. and *Phallocysta granosa*. The rare occurrence of *Mancodinium semitabulatum* subsp. *semitabulatum* is an important stratigraphical tie to Bajocian assemblages in Europe; there are no previously published records of this genus for the southern hemisphere. It is restricted to the Lower Subzone, with only one specimen recorded from the base of the Middle Subzone in the Sunset West-1 well (Table 3). Another potential marker species is *Meiourogonyaulax* sp. B; it occurs consistently towards the top of the Lower Subzone with only record in the Middle Subzone.

Middle *Wanaea verrucosa* Subzone

Definition: The interval between the range base of *Valvaeodinium spinosum* and the range base of *Endoscrinium kempiae.*

Remarks: The base of this subzone is formally defined as the first occurrence of *Valvaeodinium spinosum*. However, this species is uncommon towards the base of its range and is best used in conjunction with the first appearance of *Valvaeodinium cookii* sp. nov (Fig. 4). The latter species first appears at the same level, but is marginally commoner in both the Sunrise-2 and Sunset West-1 wells. It does not appear to range above the Middle Subzone. Another key species is ?*Bradleyella adela* which first occurs in the uppermost Lower Subzone but is present as a notable acme in the Middle Subzone (Fig. 4) where it accounts for 12-37% of the total palynomorphs before abruptly disappearing at or immediately above the base of the Upper Subzone. There is also a restricted acme of *Phallocysta granosa* in two samples (2121.63 and 2117.06 m, where it represents 15% and 5% of the dinoflagellate cysts, respectively) in the Sunrise-2 well (Table 2) and high abundances of *Meiourogonyaulax* throughout most of the subzone. The latter genus first occurs in the Lower Subzone, but the abundance and diversity increases substantially in the Middle Subzone. However, subdividing many of the forms is impractical as there is clearly a high degree of intraspecific variability.

Overall, the microphytoplankton diversity is considerably higher than in the underlying subzone, including such short ranging species as *Wanaea lacuna* that appears to be restricted to a narrow interval within the Middle Subzone. Other marker events include the inception of several dinoflagellate cyst genera with single-plate precingular archaeopyles, such *Aldorfia*, *Endoscrinium* and *Leptodinium*, towards the top of the subzone. Important final appearance datums include *Mancodinium semitabulatum* subsp *semitabulatum* at the base of the zone and *Nannoceratopsis deflandrei* subsp. *senex* and *Valvaeodinium cookii* sp. nov. towards the top of the subzone. Notable accessory species include *Evansia* sp. A, *Kallosphaeridium hypornatum*, *Pareodinia* sp. A and *Wanaea verrucosa*.

Upper *Wanaea verrucosa* Subzone

Definition: The interval between the range base of *Endoscrinium kempiae* and the range base of *Wanaea indotata*.

Remarks: The base of this subzone is formally defined as the first occurrence of *Endoscrinium kempiae* (Fig. 4). This large and distinctive species is a good biostratigraphical marker, but it can be rare in the lower parts of its range. The subzone is characterised by a marked increase in the abundance and diversity of *Ctenidodinium*, particularly spinose forms, and the consistent presence, albeit in low numbers, of dinoflagellate cysts with single-plate precingular archaeopyles. The

Upper Subzone can also be distinguished from the underlying subzones by the general absence of *Nannoceratopsis deflandrei* and ?*Bradleyella adela*; both these morphotypes occur as extremely rare components at the base of the subzone. *Valvaeodinium spinosum* is also notably commoner throughout this subzone with a minor acme towards the base. The range base of *Ternia balmei* is a further important bioevent that occurs within the Upper Subzone.

5. The age of the *Wanaea verrucosa* Zone

The dinoflagellate cyst assemblages recovered from the *Wanaea verrucosa* Zone largely comprise cosmopolitan genera such as *Ctenidodinium, Dissiliodinium, Durotrigia, Meiourogonyaulax, Pareodinia* and *Wanaea* (Tables 1-3). This association is characteristic of the Late Bajocian to Bathonian using comparisons elsewhere in the world, principally Europe (see section 6).

The *Wanaea verrucosa* Zone, or its equivalents, was assigned a Middle-Late Bathonian age by Helby et al. (1987, fig. 12) that was later revised to an Early-Middle Bathonian age by Helby et al. (2004, fig. 4) and Partridge (2006); this assignation was not based on any independent stratigraphical evidence. Riding et al. (2010a, fig. 8) reassessed the age as Late Bajocian to Early Bathonian following a review of previously reported dinoflagellate cyst occurrences. This revised age is based upon dinoflagellate cyst evidence from Europe, for example the range base of *Valvaeodinium spinosum*, which is placed close to the Early-Late Bajocian transition. The present study, however, represents the most comprehensive published account on the palynofloras of the *Wanaea verrucosa* Zone and these data are used here to further investigate the age of this interval. This section is subdivided into discussion of the maximum and minimum ages of the zone, followed by a brief overview.

5.1. The maximum age of the Wanaea verrucosa Zone

There are several forms present in the material studied which have intra-Bajocian range bases in Europe. These comprise *Acanthaulax crispa*, *Aldorfia* spp., *Atopodinium* spp., *Ctenidodinium* spp., *Endoscrinium* spp., *Meiourogonyaulax* spp., *Nannoceratopsis* sp. cf. *N. spiculata*, *Rhynchodiniopsis* spp., *Valensiella ovulum, Valvaeodinium spinosum, Valvaeodinium vermicylindratum* and simple (i.e. nonflanged) species of *Wanaea*. These genera and species all have inceptions during the 'mid' Bajocian in Europe. Their range bases are all within the Stephanoceras humphriesianum and Strenoceras subfurcatum zones which straddle the Early/Late Bajocian transition (Prauss, 1989; Gowland and Riding, 1991; Riding et al., 1991; Feist-Burkhardt and Wille, 1992; Feist-Burkhardt, 1994; Feist-Burkhardt and Monteil, 1997). Hence this is consistent with the Late Bajocian age suggested by Riding et al. (2010a) as the maxium age for the *Wanaea verrucosa* Zone.

5.2. The minimum age of the Wanaea verrucosa Zone

Nannoceratopsis deflandrei occurs as a common accessory species in the Lower-Middle *Wanaea verrucosa* subzones (Tables 2-3); these occurrences help provide a minimum age for the zone as the consistent range top of this species (as *Nannoceratopsis gracilis*) is close to the Early-Late Bajocian transition (i.e. the Stephanoceras humphriesianum and Strenoceras subfurcatum zones) in Europe (Gowland and Riding, 1991; Riding et al., 1991; Feist-Burkhardt and Wille, 1992; Feist-Burkhardt and Monteil, 1997). Isolated occurrences have, however, been reported from the Bathonian and Callovian (Riding et al., 1985; Prauss, 1989). These records are sporadic and extremely sparse, and hence may represent reworking. Therefore, the consistent presence of *Nannoceratopsis deflandrei* in the two Bonaparte Basin wells is strongly suggestive of the Bajocian of Europe. This contention is strengthened by the absence of *Nannoceratopsis pellucida sensu stricto* Deflandre 1938, which normally has an intra-Bathonian range base in Europe (Riding et al., 1985; 1991; Feist-Burkhardt and Wille, 1992). Importantly *Mancodinium semitabulatum* subsp. *semitabulatum* also has a similar last appearance datum (the Stephanoceras humphriesianum zone) in Europe (Riding 1984), thus providing further strong evidence of a pre-Bathonian age. The occurence of *Acanthaulax crispa* is also suggestive of the 'mid' to Late Bajocian interval by comparison with Europe (Prauss, 1989; Feist-Burkhardt and Wille, 1992; Feist-Burkhardt and Monteil, 1997). However, individual dinoflagellate cyst ranges should be noted with caution whilst fully considering the overall composition of the assemblage. For example, the apparent extinction of *Valvaeodinium spinosum* is Late Bathonian in Europe (Riding et al., 1985; Prauss, 1989; Feist-Burkhardt and Wille, 1992; Riding and Thomas, 1992), but it is commonly recorded up to at least the Early Oxfordian *Ctenidodinium ancorum* Zone in Australia (Mantle, 2009b).

5.3. Overview

The *Dissiliodinium caddaense* and *Nannoceratopsis deflandrei* zones are the two immediately subjacent zones to the *Wanaea verrucosa* Zone. The *Dissiliodinium caddaense* Zone is considered to be of Early Bajocian age (Witchellia laeviuscula Zone) on the basis of ammonite and strontium isotope evidence (Riding et al., 2010b). The *Nannoceratopsis deflandrei* Zone was assigned to the Early-Late Bajocian by Riding et al. (2010a) based on calcareous nannofossil evidence.

The unit succeeding the *Wanaea verrucosa* Zone is the *Wanaea indotata* Zone. Based on calcareous nannofossil and dinoflagellate cyst evidence, the *Wanaea indotata* Zone was assigned to the Early-Late Bathonian by Riding et al. (2010a). Hence, the maximum Late Bajocian and the minimum Early Bathonian ages assigned to the *Wanaea verrucosa* Zone by Riding et al. (2010a) are entirely credible given the independent evidence used to assign the ages of the adjacent zones.

However, the biostratigraphical evidence derived from ranges established in Europe implies that the *Wanaea verrucosa* Zone may be latest Early to Late Bajocian in age (i.e. the Stephanoceras humphriesianum to Strenoceras Parkinsonia parkinsoni zones). Riding et al (2010a, p. 562) acknowledged this situation and stated that “assemblages from the *Wanaea verrucosa* Zone are far more characteristic of the Late Bajocian than the Bathonian based on comparisons with Europe”. The presence of *Nannoceratopis deflandrei* and *Mancodinium semitabulatum* subsp. *semitabulatum* present the strongest support of this older age.

However, contra this evidence for a predominantly pre-Bathonian age is the prominence and relative diversity of *Ctenidodinium*, particularly in the Upper *Wanaea verrucosa* Zone. This genus is not especially abundant or diverse in the Bajocian of Europe (Riding et al., 1991; Feist-Burkhardt and Monteil, 1997), but is prominent in the Bathonian (Riding et al., 1985; Feist-Burkhardt and Monteil, 1997; Riding et al., 1999). An example is the Bathonian Great Estuarine Group of northwest Scotland, where *Ctenidodinium* spp. are relatively abundant; this contrasts with the underlying Bajocian strata where this genus is relatively sparse (Riding et al., 1991). Moreover, the taxonomic spectrum and the diversity levels of dinoflagellate cysts in the

Bathonian Great Estuarine Group of Scotland are broadly similar to the floras from the *Wanaea verrucosa* Zone (Riding et al., 1991, fig. A6). Significantly, both the Australian and Scottish material are from successions deposited in marginal to shallow marine settings.

In summary, the *Wanaea verrucosa* Zone is still considered most likely to be Late Bajocian to Early Bathonian in age, following Riding et al. (2010a), but may range as old as latest Early Bajocian.

6. The palaeobiology of the *Wanaea verrucosa* Zone assemblages of the North West Shelf and comparison with coeval palynofloras

The palynofloras from the *Wanaea verrucosa* Zone from the three successions studied here are markedly similar to associations from the Bajocian-Bathonian transition reported elsewhere in the world. In this section the palynofloras from the North West Shelf, with emphasis on dinoflagellate cysts, are discussed in terms of various aspects of palaeobiology and compared to key reports from other continents. This section is subdivided into marine and terrestrial palynofloras.

6.1. Marine palynomorphs

The dinoflagellate cyst associations recovered from the three wells studied are largely composed of the following genera: *Batiacasphaera*, *Ctenidodinium, Dissiliodinim, Durotrigia, Endoscrinium, Escharisphaeridia, Leptodinium, Meiourogonyaulax, Nannoceratopsis, Phallocysta, Pareodinia, Valvaeodinium* and *Wanaea* (Tables 1-3). These genera are all typical of the Late Bajocian to Bathonian interval globally, specifically in Africa, the Americas, the Arctic, Asia and Europe. Key publications for comparison include: Aboul Ela and Aly (1988a), Aboul Ela and Mahrous (1990), Aboul Ela and El-Shamma (1997), Geleta (1998), El-Shamma et al. (2001) and El Beialy et al. (2002) for Africa; Johnson and Hills (1973) and Bujak and Williams (1977) for the Americas; Smelror (1987) for the Arctic; Thusu and Vigran (1985), Kumar (1987), Thusu et al. (1988), Ilyina (1991), Riding and Ilyina (1996; 1998), Riding et al. (1999), Mau Shaozhi and Bian Lizeng (2000) for Asia; and (for example) Gocht (1970), Fenton and Fisher (1978), Davey (1980), Fenton et al. (1980), Fenton (1981), Riding et al. (1985; 1991), Prauss (1989), Dodekova (1990), Feist-Burkardt and Monteil (1997; 2001) and Gedl (2008) from Europe.

The Aalenian and earliest Bajocian interval is characterised by relatively low diversity dinoflagellate cyst floras. Forms such as *Mancodinium semitabulatum* Morgenroth 1970*, Moesiodinium raileanui* Antonesçu 1974, *Nannoceratopsis deflandrei, Nannoceratopsis dictyambonis* Riding 1984, *Nannoceratopsis gracilis* Alberti 1961, *Phallocysta elongata* (Beju 1971) Riding 1994, *Scriniocassis priscus* (Gocht 1979) Below 1990 and *Scriniocassis weberi* Gocht 1964 are typical (Feist-Burkhardt, 1990; Feist-Burkardt and Monteil, 1997; Feist-Burkhardt and Pross, 2010). However in the latest Early Bajocian (Stephanoceras humphriesianum Zone) and the early-mid Late Bajocian (Strenoceras subfurcatum and Strenoceras garantiana zones), gonyaulacacean dinoflagellate cysts underwent a major phase of explosive evolution (Fensome et al., 1996, fig. 1). During this interval, gonyaulacacean taxa with epicystal and multiplate precingular archaeopyles such as *Ctenidodinium, Dissiliodinium, Durotrigia* and *Wanaea* were extremely prominent (Feist-Burkardt and Monteil, 1997; 2001). Multiplate precingular archaeopyles (as in *Dissiliodinium*) appeared in the Aalenian, prior to the inception of epicystal archaeopyles (as in *Wanaea*) in the Bajocian (Gowland and Riding, 1991). This transition probably involved the fusing of plate sutures throughout the epicyst (Stover and Helby, 1987, figs. 4A-4D). Furthermore, the single-plate (3’’) precingular archaeopyle, for example in *Acanthaulax crispa* in the latest Early Bajocian (Stephanoceras humphriesianum Zone), was probably derived from the early mutiplate excystment apertures in *Dissiliodinium* and/or *Durotrigia* (see Feist-Burkardt and Monteil, 1997, fig. 4). It appears that these early gonyaulacacean genera were experimenting with archaeopyle styles in order to discover the most effective modes of excystment. This experimentation phase persisted into the Bathonian. However, by the Callovian, most gonyaulacaceans have either apical or single-plate (3’’) precingular archaeopyles. These two excystment types then became stabilised, and they remain the predominant gonyaulacacean archaeopyle styles throughout the remainder of the Mesozoic and throughout the Cenozoic up to the present day.

As mentioned earlier, the Late Bajocian to Early Bathonian interval worldwide is characterised by relatively low diversity dinoflagellate cyst associations dominated by species of *Ctenidodinium, Escharisphaeridia, Meiourogonyaulax, Pareodinia, Valvaeodinium* and *Wanaea*. The species *Ctenidodinium sellwoodii* (Sarjeant 1975)

Stover and Evitt 1978 (and its synonyms *Ctenidodinium*? *stauromatos* (Sarjeant 1976) Stover and Evitt 1978 and *Ctenidodinium tenellum* Deflandre 1938) is especially abundant and geographically widespread. This taxon was interpreted as being euryhaline and/or eurythermal (Riding et al., 1985; 1991). There is significant evidence of dinoflagellate cyst provincialism in the Bathonian (e.g. Riding and Ilyina (1996; 1998; Riding et al., 1999), however widespread forms such as *Ctenidodinium sellwoodii* and *Meiourogonyaulax* spp. are recorded throughout the northern hemisphere and beyond.

The principal region in the northern hemisphere which exhibits significant provincialism of Bathonian dinoflagellate cysts is the Arctic region. Here, presumed cold-tolerant forms such as *Ambonosphaera calloviana* Fensome 1979, *Evansia janeae* Piasecki 2001, *Evansia wigginsii* (Smelror 1988) Below 1990, *Lacrymodinium warreni* Albert et al. 1986, *Paraevansia brachythelis* (Fensome 1979) Below 1990, *Paragonyaulacysta calloviensis* Johnson and Hills 1973 and *Paragonyaulacysta retiphragmata* Dörhöfer and Davies 1980 are present (Smelror, 1988a,b; Piasecki et al., 2004).

The dinoflagellate cyst floras documented here from the *Wanaea verrucosa* Zone are hence entirely typical of the Late Bajocian-Early Bathonian interval. Relatively few taxa are present which are confined to Australasia. These include *Endoscrinium kempiae, Meiourogonyaulax straussii* sp. nov., *Phallocysta granosa, Ternia balmei, Valvaeodinium cookii* sp. nov., *Wanaea enoda* and *Wanaea verrucosa*. Notably, the only exclusively Austral genus is *Ternia*. This situation is highly unusual for eastern Gondwanan Jurassic dinoflagellate cyst floras. The overlying Callovian to Tithonian interval in Australasia is dominated by indigenous southern hemisphere taxa (Helby et al., 1987; Riding and Helby, 2001b-g; Mantle, 2009a, b; Riding et al., 2010).

One explanation for this phenomenon may be that the East African Seaway (Mozambique Corridor) had not opened, and the Central American Seaway (Hispanic Corridor) and the Viking (or North Sea) Corridor, were either narrow or highly restricted respectively, during the Bajocian and Bathonian (Ager, 1975; Smith et al., 1994; Moyne et al., 2004, fig. 1). This was due to both relatively low sea levels and tectonic factors. The consequent enclosed aspect and smaller extent of Tethys at this time may have significantly enhanced the strength of the principal oceanic gyres and possibly the westerly-flowing Tethys circumglobal current (TCC), thereby enabling the effective passive dispersal of dinoflagellate cysts across Tethys due to higher oceanic energy levels. Dinoflagellate cysts can potentially traverse otherwise inhospitable palaeoclimatic/palaeolatitudinal belts because they are resting cysts and hence dormant. This means that they are potentially more mobile than, for example, molluscs which were palaeoclimatically partitioned during the Middle Jurassic (Callomon, 2003). When the three aforementioned major seaways opened during the Callovian or Oxfordian (Irurralde-Vinent, 2006; Riding et al., 2011), it is possible that this new oceanic configuration meant that the northern and southern Tethyan gyres became weaker and more partitioned, hence diminishing the potential for the passive dispersal of dinoflagellate cysts. This contention is supported by the findings of Riding et al. (2011), who reported that the dinoflagellate cyst assemblages from the Callovian of south central Argentina are of European aspect and lack any characteristically Austral taxa. This succession from the Neuquén Basin almost exclusively comprises northern hemisphere (Euro-Atlantic) and cosmopolitan taxa. Another factor may be that the low-diversity Bajocian-Bathonian forms may be more euryhaline and/or eurythermal than their significantly more diverse Callovian-Tithonian conterparts. However, Enay (1980) and Hallam (1983) have contended that Jurassic biotic endemism was principally controlled by eustasy and tectonic factors, and that palaeotemperature played a relatively minor role. Despite this, fluctuating palaeotemperatures caused several ammonite migrations between the Boreal and Tethyan realms during the Jurassic. For example, in the Bathonian, Tethyan ammonites migrated northwards towards the Boreal Ocean, helped by the opening of marine connections in the North Sea area (Poulsen and Riding, 2003, fig. 6). This factor may indicate that at least some of the typical Bajocian-Bathonian dinoflagellate cysts had a Tethyan origin, and migrated into northern Europe from the south.

6.2. Terrestrial palynomorphs

The pollen and spores recovered from the Perseus-3A, Sunrise-2 and Sunset West-1 wells are mostly dominated by low-diversity assemblages of gymnospermous pollen that often constitute over 50% of the entire palynofloras. *Araucariacites* spp., bisaccate pollen and *Callialasporites* spp. are consistently prominent, with lower proportions of *Classopollis* spp., *Cycadopites* spp., *Perinopollenites elatoides*, trisaccate pollen and *Vitreisporites pallidus* (Tables 4-6). Bryophyte-lycophyte-pteridophyte spores were generally recovered in smaller proportions than pollen, and they normally comprise 20-30% of the entire palynoflora. The spore floras are dominated by *Baculatisporites/Osmundacidites* spp., *Cyathidites* spp., *Dictyophyllidites* spp., *Gleicheniidites senonicus*, *Ischyosporites/Klukisporites* spp., *Neoraistrickia* spp. and *Retitriletes* spp. Lesser numbers of *Antulsporites saevus*, *Cibotiumspora* spp., *Concavissimisporites* spp., *Contignisporites* spp., *Coronatispora* spp., *Leptolepidites* spp., *Sestrosporites pseudoalveolatus*, *Staplinisporites caminus* and *Stereisporites* spp. were also observed (Tables 4-6). This pollen-spore palynoflora indicates a hinterland vegetated by conifer forests (dominated by Araucariaceae and Coniferales) with an understorey of relatively diverse stands of club mosses and various types of ferns (largely Filicopsida, Lycopodiaceae, Osmundaceae and Schizaeaceae).

The abundant levels of *Araucariacites* and *Callialasporites*, together with relatively diverse spores such as *Baculatisporites/Osmundacidites* spp., *Cyathidites* spp., *Dictyophyllidites* spp., *Ischyosporites/Klukisporites* spp. and *Neoraistrickia* spp. are typical of the Late Bajocian to Bathonian interval worldwide. The major elements of the floras compare extremely well with coeval reports from Africa (Helal, 1965; Thusu and Vigran, 1985; Aboul Ela and Aly, 1988b; Thusu et al., 1988), Arabia (Sajjadi et al., 2007), Australasia (Balme, 1964; Filatoff, 1975; Helby et al., 1987; Thorn, 2001), Canada (Pocock, 1970a,b; Bujak and Williams, 1977), Europe (Traulau, 1968; Guy-Ohlson, 1986; 1989; Srivastava, 1987; Boulter and Windle, 1993; Koppelhus and Nielsen, 1994; Nielsen et al., 2010), India (Vijaya, 2000; 2009), Russia (Ilyina, 1985; 1986) and South America (Menendez, 1968; Volkheimer et al., 2008).

The worldwide distribution of the Middle Jurassic araucariaceae-fern dominated palynofloras confirm the extensive connections within Laurasia and Gondwana , which were clustered around the Tethys Ocean (Smith et al., 1994, map 10). This would have allowed floras to potentially disperse/migrate long distances. It is also evident that the principal floral elements, such as the parent plants of *Callialasporites,* were relatively tolerant of variations in, for example, palaeolatitude. Furthermore, the cosmopolitan nature of these floras indicates that the global palaeoclimate was relatively uniform. Despite the overall similarities of the Middle Jurassic terrestrial palynoflora, some forms largely endemic to the southern hemisphere were recorded from the wells studied. These include *Anapiculatisporites* *dawsonensis*, *Antulsporites saevus, Contignisporites cooksoniae, Dictyotosporites complex, Foveosporites canalis, Sculptisporis moretonensis* and *Trachysporites infirmus*.

7. Conclusions

The dinoflagellate cyst associations recorded from the *Wanaea verrucosa* Zone in the three wells examined herein are dominated by cosmopolitan forms, especially at the generic level. The assemblages are most reminiscent of the Late Bajocian by comparisons with apparently coeval floras from Europe. The Bajocian was an interval in which the cyst-forming dinoflagellates diversified rapidly, with an explosion in gonyaulacacean forms. Bajocian and Bathonian dinoflagellate cyst associations worldwide are dominated by taxa with epicystal and multiplate precingular archaeopyles such as *Ctenidodinium, Dissiliodinium, Durotrigia,* and *Wanaea*. Gonyaulacacean dinoflagellate cysts underwent further significant diversification in the succeeding Callovian and Oxfordian stages. The Callovian to Oxfordian interval in Europe and Australasia is characterised by endemic taxa. It is possible that these further evolved Callovian/Oxfordian floras had more specific environmental preferences than the Bajocian/Bathonian assemblages, however it may be that there were new barriers to the dispersal of dinoflagellate cysts across the Tethys in the Callovian/Oxfordian.

Quantitative palynological assessements of the shallow marine successions of the upper Plover Formation in the northern Bonaparte Basin confirm a tripartite subdivision of the *Wanaea verrucosa* Zone into Lower, Middle and Upper subzones. However this subdivision cannot be confidently replicated for the lower diversity assemblages and more marginal marine environments of the Northern Carnarvon Basin; the marker species are rare or absent in this depocentre. The abundance of *Dissiliodinium*/*Durotrigia*-type cysts in the Lower Subzone, followed by an increasing diversity of *Meiourogonyaulax* and *Ctenidodinium* in the Middle and Upper subzones respectively, is largely representative of the Bajocian to Bathonian transition through this interval. The common occurrence of *Nannoceratopsis deflandrei* and rare examples of *Mancodinium semitabulatum* subsp. *semitabulatum* in the Lower and Middle subzones suggest the *Wanaea verrucosa* Zone may extend down to the latest Early Bajocian.

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APPENDIX 1: LOCATION AND OPERATORS OF THE WELLS STUDIED

Well name and number	**Latitude**	**Longitude**	**Operator**
Perseus-3A	19˚ 31’ 27.580”S	116˚ 06’ 20.635”E	Woodside
Sunrise-2	09˚ 29’ 57.931”S	128˚ 06’ 12.397”E	Woodside
Sunset West-1	09˚ 38’ 06.806”S	127˚ 53’ 57.840”E	Woodside

APPENDIX 2.SYSTEMATIC PALAEONTOLOGY OF DINOFLAGELLATE CYSTS

In this section, taxonomic notes pertaining to the key dinoflagellate cyst taxa are presented. The genera are listed alphabetically. Where measurements are quoted, these are given in micrometres (μm) as minimum, (mean) and maximum respectively.

Acanthaulax Sarjeant 1968 emend. Sarjeant 1982

Acanthaulax crispa (Wetzel 1967) Woollam & Riding 1983 (Plate VII, fig. 12)

Remarks: *Acanthaulax crispa* was recorded in one sample at xxx m (put this in) in the Upper *Wanaea verrucosa* Subzone in Sunrise-2 (Table 2). In Europe this species ranges from the Early-Late Bajocian (Prauss, 1989; Feist-Burkhardt and Wille, 1992; Riding and Thomas, 1992; Feist-Burkhardt and Monteil, 1997) with questionable Bathonian occurrences from Scotland (Riding et al., 1991).

Aldorfia Stover & Evitt 1978

Aldorfia sp. A (Plate VII, fig. 11)

Remarks: A distinctive morphotype of *Aldorfia* was encountered sporadically and rarely in all three wells studied (Tables 1-3). This form lacks an apical horn or protuberance, hence has an ovoidal dorsoventral outline. It has a thin ectophragm, and the tabulation is normally exhibited only by the cingulum and the archaeopyle. The sparsity of *Aldorfia* sp. A means that it is not formally described herein.

Aldorfia spp.

Remarks: *Aldorfia* spp., often small morphotypes , were recorded in low numbers from samples SW4-SW8 (2217.98-2211.11 m) in the Sunset West-1 well (Table 3).

Atopodinium Drugg 1978 emend. Masure 1991

Atopodinium sp.

Remarks: A single specimen of *Atopodinium* was recorded from 3244.18 m in the Perseus-3A well (Table 1). It is an elongate, subpentagonal form with a flat, thickened, antapical plate. This form most closely resembles *Atopodinium haromense* Thomas & Cox 1988. It is too rare to erect as a new species.

Batiacasphaera Drugg 1970 emend. Morgan 1975

Batiacasphaera spp.

Remarks: *Batiacasphaera* spp. were encountered throughout in the Sunrise-2 and Sunset West-1 wells (Tables 2, 3). *Batiacasphaera* spp. are herein distinguished from representatives of *Escharisphaeridia* in being subcircular to ovoidal in outline, slightly longitudinally elongate, and lacking prominent accessory archaeopyle sutures and a discernible cingulum (Erkmen and Sarjeant, 1980, p. 62). By contrast, forms of *Escharisphaeridia* spp. are typically wider than they are long. This genus is morphologically simple and extremely long-ranging. Hence, representatives of *Batiacasphaera* were not speciated herein.

Bradleyella Woollam 1983

?*Bradleyella adela* (Fenton et al. 1980) Woollam 1983 (Plate IV, figs. 1-12)

Dimensions (30 specimens measured):
Length of cyst including operculum: 29 (40) 50 μm
Equatorial width of cyst: 28 (34) 40 μm
Thickness of autophragm: ca. 1 μm

Remarks: The cysts recorded herein as ?*Bradleyella adela* are small, subspherical to ovoidal, dorsoventrally flattened species that are easily overlooked because most specimens exhibit only the faintest degree of tabulation, an irregularly scabrate, coarsely granulate or irregularly microreticulate autophragm and no readily discernible archaeopyle. Better preserved specimens do exhibit some tabulation in the form of low, rounded ridges, particularly along the cingular and postcingular sutures. The tabulation on the epicyst is consistently more obscure; this is in contrast to the generic description in Woollam (1983, p. 194) that stated the 'parasutures are preferentially developed on the epicyst'. Furthermore, none of the specimens studied show the degree of tabulation as expressed on the holotype (Fenton et al., 1980, pl. 14, fig. 3), although this specimen is also larger and more clearly marked than the figured paratypes (Fenton et al., 1980, pl. 14, figs. 1-2, 4). Rare specimens show apparent long thin spines (2-17 μm long), largely concentrated around the apex and/or antapex (Plate IV, figs. 7, 11).

The archaeopyle of these specimens is also rather enigmatic. Many specimens show a split/splits along the anterior margin of the cingulum (Plate IV, figs. 3, 9, 12), and could be considered to be epicystal. However a similar proportion of specimens exhibit splits around a single precingular plate (Plate IV, figs. 1, 10), whilst others show an almost complete disintegration of the epicyst. This was also noted by Fenton et al. (1980) who considered the epicyst to be 'prone to break up along the parasutures'. It is this uncertainty of the epicystal nature of the archaeopyle, together with the better defined hypocystal sutures and more comprehensively granulate or locally microreticulate ornament, that preclude a definitive specific assignment. A thorough restudy of the type material is needed to fully resolve this issue.

?*Bradleyella adela* is an excellent and abundant marker species for the Middle *Wanaea verrucosa* Subzone, although it does occur, in much reduced numbers, immediately above and below this subzone (Fig. 4).

Chlamydophorella Cookson & Eisenack 1958 emend. Duxbury 1983

Chlamydophorella spp.

Remarks: *Chlamydophorella* spp. was recorded in one sample at xxx m (put this in) in the Upper *Wanaea verrucosa* Subzone in the Sunrise-2 well (Table 2). Similar forms occur in the overlying *Wanaea indotata* Zone, and are common from the *Ternia balmei* Zone up to the Early Cretaceous.

Ctenidodinium Deflandre 1938 emend. Benson 1985

Ctenidodinium sp. A (Plate IV, figs. 13-15)

Remarks: *Ctenidodinium* sp. A was recorded in all three successions studied but is moderately prominent in only the Upper *Wanaea verrucosa* Subzone in the Sunrise-2 well (Table 2). It is a morphotype of *Ctenidodinium* which exhibits extremely sparse, frequently suppressed tabulation. The sutures are partially indicated by low, discontinuous sutural ridges or sporadic lineations of low-relief ornamentation (PlateIV, , fig. 14). Some specimens may have occasional short, slender, distally sharp sutural spines. The autophragm is moderately thick and robust, scabrate to locally microreticulate and highly prone to folding. *Ctenidodinium* sp. A can be elongate ovoidal to squat in shape and it normally lacks an apical horn or protuberance. The simple morphology and low sutural ridges make *Ctenidodinium* sp. A similar to the Callovian species *Ctenidodinium planocristatum* Riding & Helby 2001. However, *Ctenidodinium planocristatum* has a thinner, smooth autophragm, is fully tabulate and has a more uniform, subspherical outline (Riding and Helby 2001d, fig. 5). Although *Ctenidodinium* sp. A exhibits an epicystal archaeopyle, it may be difficult to distinguish badly-preserved specimens from representatives of *Dissiliodinium* or *Durotrigia*, especially if the epicyst is damaged.

Ctenidodinium sp. B (Plate V, figs. 1-3, 5-6)

Remarks: *Ctenidodinium* sp. B is extremely prominent in the Upper *Wanaea verrucosa* Subzone of the Sunrise-2 and Sunset West-1 wells (Tables 2, 3). It is a relatively squat morphotype, often being significantly wider than it is long. This form is characterised by low sutural crests or ridges surmounted by short processes, most of which are expanded distally but may be blunt, capitate, or bifurcate and are commonly longest at the antapex. The bifid distal terminations are composed of short, often simple furcae but others form a distinct anchor-shaped tip. Some of the distal furcae are extremely short and are only identifiable at relatively high magnifications. The insertion density of the processes also varies significantly on a single specimen and across the population. *Ctenidodinium* sp. B is similar to other squat species of

Ctenidodinium which have relatively short sutural spines. These include *Ctenidodinium sellwoodii* (Sarjeant 1975) Stover & Evitt 1978, *Ctenidodinium*? *stauromatos* (Sarjeant 1976) Stover & Evitt 1978 and *Ctenidodinium tenellum* Deflandre 1938. However, this form is clearly most similar to *Ctenidodinium ancorum* Riding & Helby 2001 from the Callovian of Australia due to the preponderance of distally-expanded spines. However, the majority of *Ctenidodinium ancorum* have bifurcate sutural processes which exhibit distinctly recurved furcae with narrow neck-like constrictions immediately below the bifurcation (Riding and Helby, 2001d, figs. 3G, J). These anchor or grapnel-shaped distal terminations so typical of *Ctenidodinium ancorum* are only occasionally present in *Ctenidodinium* sp. B which is used herein as a broader form-based concept. The scabrate to locally microreticulate autophragm of *Ctenidodinium* sp. B is also thicker and more robust than that of *Ctenidodinium ancorum sensu stricto*.

Ctenidodinium sp. C (Plate V, figs. 7-9)

Remarks: *Ctenidodinium* sp. C is relatively prominent in the lower half of the *Wanaea verrucosa* Zone in the Perseus-3A well and irregularly common in the Upper *Wanaea verrucosa* Subzone of the Sunrise-2 and Sunset West-1 wells (Tables 2, 3). This morphotype is variable in shape, with both elongate and squat specimens observed (Plate V, figs 7, 9). It is characterised by a relatively thick, robust autophragm which is variably scabrate to spinose, locally microreticulate or comprehensively microreticulate. The tabulation is exhibited by low sutural ridges or crests which are surmounted by short, solid, distally-sharp spines which are longer at gonal points. These relatively inconspicuous crests are often finely fenestrate and along with the fine spines surmounting them, form the characteristic feature of this morphotype.

Ctenidodinium spp. (Plate V, fig. 4)

Remarks: This grouping includes all other forms of the genus not attributable to *Ctenidodinium* sp. A, B or C.

Dissiliodinium Drugg 1978 emend. Feist-Burkhardt & Monteil 2001

Dissiliodinium sp. A (Plate VI, figs. 1, 2, 4-6)

Remarks: *Dissiliodinium* sp. A was recorded throughout the three wells studied here; it is especially prominent in the Lower *Wanaea verrucosa* Subzone in the Sunrise-2 well (Table 2). This morphotype is relatively large, with a scabrate to granulate autophragm. The only indications of tabulation are the archaeopyle, and the sparse, discontinuous sutural ridges present on some specimens. These partially tabulate specimens are invariably characterised by a cingulum (Plate VI , figs. 1, 5). Feist-Burkhardt and Monteil (2001; p.58) emended *Dissiliodinium* to include only weakly to non-tabulate specimens where any tabulation is 'expressed by negative structures' whilst retaining those specimens with obvious tabulation delimited by 'elevated parasutural features such as septa, crests or ridges' within *Durotrigia*. As the current specimens vary from non-tabulate to very faintly tabulate, the end-member morphotypes could be placed in different genera; in this study they are grouped together as *Dissiliodinium* sp. A. Some specimens of *Dissiliodinium* sp. A are comparable to *Dissiliodinium* sp. (no antapical node) of Helby et al. (1987, fig. 16E).

Dissiliodinium spp. (Plate VI, fig. 3)

Remarks: This material includes all the other forms of *Dissiliodinium* which are not attributable to *Dissiliodinium* sp. A. These specimens are typically smaller than *Dissiliodinium* sp. A, and may be thick-walled and granulate or have a thin, psilate autophragm.

Durotrigia Bailey 1987

Durotrigia spp. (Plate VI, figs. 7-10)

Remarks: Only morphotypes with a type 1P-5P archaeopyle, and with paratabulation consistently expressed by elevated sutural crests or ridges are included within *Durotrigia*. Morphotypes attributable to this genus occur throughout all three wells, and are intermittently common.

Egmontodinium Gitmez & Sarjeant 1972

?*Egmontodinium* sp. A (Plate IX, figs. 1-3)

Remarks: ?*Egmontodinium* sp. A was recorded rarely throughout the *Wanaea verrucosa* Zone of the Sunrise-2 and Sunset West-1 wells; it was consistently present in only the lower subzone of Sunset West-1 (Table 3). ?*Egmontodinium* sp. A is a distinctive morphotype that is tentatively assigned to *Egmontodinium* as it is covered by numerous short (3-10 μm), nontabular, relatively broad processes and appears to have an apical archaeopyle. These processes are parallel-sided, expanded distally with oblate, bi- or trifurcate distal extremities and are apparently hollow. The latter feature is not typical of *Egmontodinium*. No indications of tabulation are present. Furthermore most specimens do not show an archaeopyle, and the few specimens that may have apical archaeopyles are inconclusive. Hence, the generic assignment is tentative.

?*Egmontodinium* sp. A is superficially similar to *Egmontodinium toryna* (Cookson & Eisenack 1960) Davey 1979 which has far fewer solid processes with simpler distal terminations and a definite apical archaeopyle. The present form was not recorded in sufficient numbers to be formally described.

Endoscrinium (Klement 1960) Vozzhennikova 1967 emend. Riding & Fensome 2002

Remarks: Representatives of *Endoscrinium* first appear at the base of the Upper *Wanaea verrucosa* Zone. This range base appears to have regional stratigraphical significance.

Endoscrinium kempiae (Stover & Helby 1987) Lentin & Williams 1989 (Plate VII, fig. 10)

Remarks. The large and distinctive species *Endoscrinium kempiae* first appears at the base of the Upper *Wanaea verrucosa* Subzone in the Sunrise-2 and Sunset West-1 wells (Tables 2, 3), and in all but the lowest three samples of the unsubdivided *Wanaea verrucosa* Zone in Perseus 3A (Table 1). The range base of this taxon defines the base of the 7ciai Subzone as depicted by Helby et al. (2004, fig. 4) and the Upper *Wanaea verrucosa* Subzone herein (Fig. 2). *Endoscrinium kempiae* is normally present in low proportions in this upper subzone, however a minor acme is present in sample sample SR3, at the top of the subzone in the Sunrise-2 well (2107.52/.47 m). *Endoscrinium kempiae* ranges into and throughout the overlying *Wanaea indotata* and *Ternia balmei* zones and irregularly up to the *Ctenidodinium ancorum* Zone (Helby et al., 1987, fig. 15; Mantle, 2009b, fig. 6).

Endoscrinium luridum (Deflandre 1938) Gocht 1970 (Plate VII, figs. 7, 9)

Remarks: This species was recorded sparsely in the uppermost Upper *Wanaea verrucosa* Subzone in the Sunrise-2 well (Table 2). The specimens recorded herein are slightly more angular than the holotype (Deflandre, 1938, pl. 5, figs. 4, 5) and may exhibit a significantly narrower pericoel and/or short apical horn. However, these minor differences are deemed to be within the scope of intraspecific variability. *Endoscrinium luridum* is a reliable marker for the Mid Oxfordian to Kimmeridgian interval of the northern hemisphere (Riding and Fensome, 2002, fig. 2), hence its range base in Australia appears to be significantly older. However, the genus *Endoscrinium* is well represented in the Bajocian-Bathonian interval in Europe (Riding et al., 1985; Feist-Burkhardt and Monteil, 1997; Riding et al., 2010a, pl. I, fig. 6).

Endoscrinium sp. cf. *E. luridum* (Deflandre 1938) Gocht 1970 (Plate VII, fig. 8)

Remarks: *Endoscrinium* sp. cf. *E. luridum* is present in low proportions in the Upper *Wanaea verrucosa* Subzone of the Sunrise-2 and Sunset West-1 wells (Tables 2, 3). Although it is closely comparable with the type of *Endoscrinium luridum* illustrated by Deflandre (1938, pl. 5, figs. 4, 5) from the Early Oxfordian of northern France, it differs in having a rounded subpentagonal outline without the distinctly angular hypocyst and protruding antapex of the type material. The hypocyst is broadly longitudinally symmetrical, hence it differs profoundly from *Endoscrinium asymmetricum* Riding 1987. This morphotype was not sufficiently abundant to be formally described.

Escharispharidia Erkmen & Sarjeant 1980

Remarks: Representatives of *Escharispharidia* were recorded throughout all three wells studied (Tables 1-3). This genus is distinguished from *Batiacasphaera* in normally being wider than long, and having prominent accessory archaeopyle sutures which are typically widely separated; furthermore a cingulum is frequently present (Erkmen and Sarjeant, 1980, p. 62). The deep accessory archaeopyle sutures which ‘gape’ emphasise the squat shape of isolated loisthocysts of this genus. Representatives of the similar genus *Batiacasphaera* are subcircular to ovoidal in outline and typically lack deep accessory archaeopyle sutures. In this study, forms of *Escharispharidia* spp. are not identified to species level because individual taxa are profoundly problematical to consistently recognise. Moreover, forms of this genus are not stratigraphically significant throughout the *Wanaea verrucosa* Zone.

Escharispharidia sp. A (Plate II, fig. 3)

Remarks: *Escharispharidia* sp. A is characterised by a granulate autophragm, long 'gaping' accessory archaeopyle sutures and frequent indications of a cingulum. This morphotype was illustrated as *Chytroeisphaeridia* (now *Escharispharidia*) *pocockii* Sarjeant 1968 by Filatoff (1975, pl. 29, figs. 5, 6) from the Middle Jurassic of the onshore Perth Basin. However the type material of *Escharispharidia pocockii* (Sarjeant 1968) Erkmen & Sarjeant 1980 (i.e. Sarjeant, 1968, pl. 3, fig. 9) lacks accessory archaeopyle sutures and has a much thicker autophragm than the specimens figured by Filatoff (1975), thus this name is not applied herein.

Escharispharidia sp. B. (Plate II, fig. 3)

Remarks: This form, like *Escharispharidia* sp. A, has well-developed accessory archaeopyle sutures and it also sometimes exhibits vague indications of a cingulum. However, the autophragm is smooth to scabrate rather than comprehensively granulate. The specimen figured as *Chytroeisphaeridia chytroeides* (Sarjeant 1962) Downie & Sarjeant 1965 by Filatoff (1975, pl. 29, fig. 2) from the Middle Jurassic of Western Australia is apparently referable to *Escharispharidia* sp. B. This specimen cannot, however, be *Chytroeisphaeridia chytroeides* because the latter has a precingular and not an apical archaeopyle. It can be difficult to consistently distinguish *Escharispharidia* sp. B from specimens of *Escharispharidia* sp. A with extremely low-relief ornamentation.

Evansia Pocock 1972 emend. Below 1990

Evansia sp. A (Plate IX, figs. 10-12)

Dimensions (10 specimens measured):
Length of cyst including operculum: 52 (56) 62 μm
Equatorial width of cyst: 36 (38) 43 μm
Thickness of autophragm: 1-2 μm

Remarks: *Evansia* sp. A is a typically small member of this genus, with a thick, robust autophragm, a prominent cingulum marked by thick folds and a small to moderate apical horn surmounted by a short, solid apicular structure 1-2 μm long. The surface ornament is predominantly granulate to verrucate with some elements fusing to form short rugulae; the ornament becomes notably coarser towards the antapex. This morphotype is not formally described here or attributed to any existing species because insufficient material is available. However, it is broadly comparable with

Evansia zabros (Davies 1983) Jansonius 1986 from the Bathonian to Oxfordian of North America. The latter species is characterised by uneven antapical bulges and adcingularly-aligned coarse grana. It is also larger, often more elongate and lacks the prominent folds delimiting the cingulum of *Evansia* sp. A. The latter feature, and the rugulate ornament are particularly reminiscent of *Pareodinia* sp. 1 of Feist-Burkhardt and Monteil (1997, pl. 5, figs. 6, 7) that was recorded from the Late Bajocian to Early Bathonian of northern France. *Evansia* sp. A is sparsely present in all three wells, and ranges from the upper Lower *Wanaea verrucosa* Subzone to the lower part of the Upper *Wanaea verrucosa* Subzone (Fig. 4; Tables 1-3).

Fostericysta Riding 2005

Fostericysta scarffei (Tykoezinski et al. 2001) comb. nov. (Plate VIII, fig. 1)

Jansonia scarffei Tykoezinski et al. 2000, p. 84-86, pl. 1, figs. 1-5, pl. 4, figs. 10-13.

Dimensions (5 specimens measured):
Length of cyst including operculum: 21 (23) 25 µm
Equatorial width of cyst: 22 (23) 26 µm
Thickness of autophragm: ca. 1-2 µm

Remarks: *Fostericysta* Riding 2005 was established for small, gonyaulacalean, proximate to proximochorate, acavate cysts with a 'prominent, incised paracingular region' and an apical archaeopyle (Riding and Helby, 2001e, p. 114). The type species, *Fostericysta eclipsiana* (Riding & Helby 2001) Riding 2005, has 'low parasutural ridges or low crests, which are surmounted by denticles and/or spines'. *Fostericysta scarffei* clearly shares the diagnostic, deeply incised, broad cingulum, as well as having a noticeably thick, dark-walled appearance and a similar tabulation pattern. Thus, the species is transferred to *Fostericysta*.

Fostericysta scarffei is a rare component of the Upper *Wanaea verrucosa* Subzone in the Sunrise-2 and Sunset West-1 wells (Tables 2, 3), and was recorded at 3195.10 m in the Perseus-3A well. The Australian specimens possess a slightly narrower cingulum and shorter denticles surmounting the sutural ridges, but are otherwise closely comparable to the type material. *Fostericysta scarffei* is slightly smaller than the Callovian-Oxfordian species, *Fostericysta eclipsiana*, lacks the very distinctive dark accumulation body and has a larger, more equant 1''' plate. *Fostericysta scarffei* was originally recorded from the Middle-Late Bathonian of central England (Tykoezinski et al., 2000).

Jansonia Pocock 1972 emend. Riding & Walton in Riding et al. 1991

Jansonia spp. (Plate VIII, figs. 2-5)

Remarks: *Jansonia* spp. were recorded sporadically in all three wells with a first appearance datum within the Lower *Wanaea verrucosa* Zone in Sunset West-1 (Table 3). Most specimens are broadly similar to *Jansonia psilata* Martínez et al. 1999, but some exhibit a granulate autophragm and an adnate operculum; they are thus also comparable with *Jansonia manifesta* Riding & Walton in Riding et al. 1991. Although there is a minor acme at 2111.1 m in Sunrise-2 (5% of total palynomorphs; Table 2), this genus is otherwise rare, and individual specimens are not given specific status due to their variable surface ornament, wall thickness and outline.

Kallosphaeridium de Coninck 1969 emend. Jan du Chêne et al. 1985

Kallosphaeridium hypornatum Prauss 1989 (Plate II, figs. 13-16)

Remarks: *Kallosphaeridium hypornatum* is present in low numbers throughout the *Wanaea verrucosa* Zone in all three wells studied, but is most prominent and consistent in the Middle Subzone (Tables 1-3). This is the first report of this species from the southern hemisphere. This taxon was first described from the Bajocian of northwest Germany by Prauss (1989).

Kalyptea Cookson & Eisenack 1960 emend. Wiggins 1975

Kalyptea stegasta (Sarjeant 1961) Wiggins 1975

Remarks: *Kalyptea stegasta* was encountered extremely rarely at 3244.18 m (sample P29) in the Perseus-3A well (Table 1). This kalyptrate species has subequal apical and antapical horns (Sarjeant, 1961, pl. 15, fig. 15). In this study, weakly bicornate forms are referred to *Pareodinia* spp.

Leptodinium Klement 1960 emend. Stover & Evitt 1978

Leptodinium? *ancoralium* Mantle 2005 (Plate VII, fig. 3)

Remarks: *Leptodinium*? *ancoralium* is a distinctive form with bifurcate, anchor-tipped spines surmounting prominent sutural crests. It is recorded from only one sample (SR3; 2107.52/.47 m) in Sunrise-2. This extends the range base below the first appearance datum in the *Ternia balmei* Zone (Mantle, 2009a, p. 57).

Leptodinium spp. (Plate VII, fig. 6)

Remarks: Although first appearing in the uppermost part of the Middle *Wanaea verrucosa* Zone, representatives of *Leptodinium* first consistently occur in the Upper Subzone, and are potentially useful markers for this interval. *Leptodinium* is most typical of the Late Jurassic in Europe (Klement, 1960), but representatives have been reported from the Middle Jurassic (Bajocian-Bathonian) of the northern hemisphere (e.g. Riding et al., 1985; 1991).

Most specimens referable to *Leptodinium* in this study were not speciated. This is because of the sparsity of material and the significant morphological variability observed. Many of the specimens encountered are large, and have a rounded subquadrangular to ovoidal dorsoventral outline (Plate 7, fig. 6). These forms are most similar to the Late Jurassic species *Leptodinium arcuatum* Klement 1960, *Leptodinium eumorphum* (Cookson & Eisenack 1960) Sarjeant in Davey et al. 1969 and *Leptodinium mirabile* Klement 1960. However, the specimens recorded herein have a more rounded outline than the distinctly angular, pentagonal species

Leptodinium arcuatum and *Leptodinium eumorphum*; furthermore, they all lack the characteristically subdivided sulcal region of *Leptodinium mirabile* (see Cookson and Eisenack, 1960, pl. 37, figs. 1-3; Klement, 1960, pl. 6, figs. 5-7). The sulcal area in the material studied herein is relatively narrow. Moreover, the sutural crests on the *Wanaea verrucosa* Zone material are significantly variable in height.

Mancodinium Morgenroth 1970 emend. Below 1987b

Mancodinium semitabulatum subsp. *semitabulatum* (Morgenroth 1970) Fensome et al. 1993 (Plate X, figs. 11-15)

Remarks: *Mancodinium semitabulatum* subsp. *semitabulatum* was recorded rarely in the Lower and lowermost Middle *Wanaea verrucosa* subzones in the Sunrise-2 and Sunset West-1 wells (Tables 2, 3). These forms possess short, relatively thick, capitate spines or gemmae that are noticeably reduced in and around the sulcal area. These specimens are similar to those figured by Below (1987b; pl. 4, figs. 1-15). The precingular, anterior intercalary and apical plates may all be lost in archaeopyle formation, or any number of these plates may remain attached. In the latter case, the plates are normally partially separated. This is the first published record of this genus in the southern hemisphere; in Europe it ranges from the Late Pliensbachian to Early Bajocian (Morgenroth, 1970; Below, 1987b; Riding and Thomas, 1992).

Meiourogonyaulax Sarjeant 1966

Remarks: Representatives of *Meiourogonyaulax* were recorded throughout the *Wanaea verrucosa* Zone (Tables 1-3). These forms are not referable to any existing species. Most of the observed morphotypes are thick-walled with strong ornamentation, have poorly-defined tabulation, and frequently have accumulation bodies and attached opercula .

Meiourogonyaulax straussii sp. nov. (Plate I, figs. 1-16)

Description: A species of *Meiourogonyaulax* which is ellipsoidal in dorsoventral outline; an apical horn or protuberance is entirely lacking. The autophragm is robust, thick, comprehensively rugulate to irregularly reticulate and locally may bear elements of low-relief ornamentation such as baculae, denticles/echinae, tubercles, and verrucae. The density and type of this ornament is highly variable, ranging from largely spinose forms to comprehensively rugulate morphotypes. Locally, the coalescence of verrucae and rugulae gives rise to a pseudoreticulate texture. The spinose-baculate elements are typically irregularly distributed and are highly variable in form, for example they may be either distally blunt, sharp or oblate. These elements are consistently most well-developed on the hypocyst, and especially around the antapical (1'''') plate, although some specimens are comprehensively spinose. The sexiform gonyaulacacean tabulation is indicated by the apical archaeopyle, the prominent crests which consistently mark the apparently undivided laevorotatory cingulum, and by low, frequently discontinuous sutural ridges or crests which delineate the remaining plate series. The tabulation is largely suppressed in the apical and antapical areas. Frequently, the crests/ridges in the precingular and postcingular plate series become lower and more discontinuous in a polar direction either side of the cingulum, becoming entirely suppressed towards the middle point of these series. The sutural crests/ridges, where developed, dominantly have irregular distal margins formed by denticles, but they can occasionally be distally smooth or fenestrate. Relatively large, dark accumulation bodies which are subspherical to ovoidal in outline are centrally attached to the cyst body on most specimens. The sulcus is apparently undivided, relatively narrow and longitudinal. The archaeopyle is apical; the simple operculum is nearly always attached. Minor accessory archaeopyle sutures may be developed in the precingular plate series.

Dimensions (30 specimens measured):
Length of cyst including operculum: 45 (60) 75 μm
Equatorial width of cyst: 58 (69) 82 μm
Height of ornamentation: 0.5-4.0 μm
Thickness of autophragm: 1-1.5 μm

Comments: *Meiourogonyaulax straussii* sp. nov. is easily recognised by its thick and robust, rugulate to irregularly reticulate autophragm, the prominent cingulum, its partially-developed sutural crests/ridges, the variable low-relief ornamentation which is best developed around the antapex, the frequently attached simple apical operculum and the prominent accumulation bodies. The morphology of the sutural crests/ridges is highly variable, they typically have irregularly denticulate distal margins, but these can also be distally smooth or fenestrate. This species is prominent, even when working at relatively low magnifications due to its thick autophragm, which imparts a strong body colour.

Comparison: *Meiourogonyaulax straussii* sp. nov. differs from all other species of *Meiourogonyaulax* in bearing significantly incomplete tabulation. Stover and Evitt (1978, p. 62) stated that the tabulation is 'generally complete'. The species which is most similar is *Meiourogonyaulax reticulata* Dodekova 1975, which has a thick, reticulate autophragm and a frequently attached operculum. However, the tabulation of *Meiourogonyaulax reticulata* is fully indicated by low, distally-smooth sutural ridges (Riding, 1983, pl. 1).

Holotype and type locality: Plate I, Figs. 5-6. Sunset West-1 well (2216.84 m), Bonaparte Basin, Timor Sea. Slide no. 2, EF T39/2, CPC no. 41142.

Stratigraphical distribution: *Meiourogonyaulax straussii* sp. nov. was observed commonly in the *Wanaea verrucosa* Zone in both the Sunrise-2 and Sunset West-1 wells. Itt first appears in the middle part of the Lower Subzone, is common to abundant in the upper half of the Middle Subzone to the lower part of the Upper Subzone and ranges sporadically into the overlying *Wanaea indotata* Zone (Tables 2, 3). *Meiourogonyaulax straussii* was also recorded in low to moderate numbers in the *Wanaea verrucosa* Zone of the Perseus-3A well (Table 1).

Meiourogonyaulax sp. A (Plate II, figs. 1-2)

Dimensions (10 specimens measured):
Length of cyst excluding operculum: 48 (53) 60 μm

Equatorial width of cyst: 44 (55) 61 μm
Thickness of autophragm: > 1 μm

Remarks: *Meiourogonyaulax* sp. A is a simple form with a granulate to microreticulate autophragm, long accessory archaeopyle sutures and tabulation which is faintly delimited by aligned grana or low crests/ridges that may be finely fenestrate. It differs from most forms of *Meiourogonyaulax* in the *Wanaea verrucosa* Zone in lacking an adnate operculum and only rarely displaying an obvious accumulation body. *Meiourogonyaulax* sp. A is notably smaller than *Meiourogonyaulax viriosa* Riding & Helby 2001, and lacks the fully developed tabulation marked by continuous, slender crests. However, similar forms are present through the Callovian and early Oxfordian of Australia. In the present study, *Meiourogonyaulax* sp. A is uncommon in all three wells from the uppermost part of the Lower *Wanaea verrucosa* Subzone to the lowermost part of the Upper Subzone. This interval coincides with the peak density and diversity of *Meiourogonyaulax* in the *Wanaea verrucosa* Zone.

Meiourogonyaulax sp. B (Plate II, figs. 5-8)

Dimensions (12 specimens measured):
Length of cyst excluding operculum: 48 (53) 57 μm
Equatorial width of cyst: 50 (54) 59 μm
Thickness of autophragm: ca. 1 μm
Length of processes: 1-4 μm

Remarks: This small to medium sized form of *Meiourogonyaulax* is relatively thick-walled, with a comprehensive cover of grana and short baculae or spines. The spines may be capitate, bifurcate or blunt-tipped; rarely the furcae coalesce to form finely fenestrate sutural crests or a localised reticulum. The tabulation is only weakly expressed by low, discontinuous ridges of coalescent grana; typically only the cingulum is discernible, but the pre- and postcingular plates may also be faintly evident. The archaeopyle margin is formed of deep accessory sutures and the operculum is free. *Meiourogonyaulax* sp. B is a rare but important marker with a restricted range in the upper part of the Lower *Wanaea verrucosa* Subzone in the

Sunrise-2 and Sunset West-1 wells (Fig. 4; Tables 2, 3); one specimen was also recorded in the lowermost Middle *Wanaea verrucosa* Subzone in the Sunset West-1 well. This form is not present in sufficient numbers to be formally described.

Meiourogonyaulax sp. C (Plate II, figs. 9-12)

Dimensions (14 specimens measured):
Length of cyst including operculum: 52 (57) 63 μm
Equatorial width of cyst: 43 (52) 56 μm
Thickness of autophragm: ca. 1 μm

Remarks: *Meiourogonyaulax* sp. C is a distinctive form with a thick, granulate to microreticulate autophragm, low sutural ridges, an adnate operculum and a thick, dark accumulation body. The low ridges often have denticulate margins and the cingulum is typically well-developed. *Meiourogonyaulax* sp. C is marginally darker and thicker-walled than *Meiourogonyaulax* sp. A but is readily differentiated by the usually attached operculum, obvious accumulation body and more prominent sutural ridges. It shares these first two features with *Meiourogonyaulax straussii* sp. nov., but should not be confused with this larger, more coarsely ornamented species. It is a notable feature of the *Wanaea verrucosa* Zone assemblages that the majority of forms with apical archaeopyles have an adnate operculum and a dark accumulation body. These accumulation bodies are mostly subcircular and are attached close to the cingulum.

Meiourogonyaulax spp.

Remarks: This material includes all the other forms of *Meiourogonyaulax* which are not attributable to *Meiourogonyaulax straussii* sp. nov. or *Meiourogonyaulax* sp. A, B or C. There is large diversity of forms through the Middle and Upper *Wanaea verrucosa* subzones that cannot easily be grouped into consistent taxa. .

Mendicodinium Morgenroth 1970 emend. Bucefalo Palliani et al. 1997

Mendicodinium spp.

Remarks: Squat ovoidal forms of *Mendicodinium* with a relatively thick, smooth autophragm and an attached epicystal archaeopyle were recorded throughout the *Wanaea verrucosa* Zone in low numbers (Tables 1-3). The preservation of these rare forms precludes a confident assignement to any existing species, so they are simply termed *Mendicodinium* spp.

Nannoceratopsis Deflandre 1938 emend. Piel & Evitt 1980

Nannoceratopsis deflandrei Evitt 1961 subsp. *deflandrei* (autonym) (Plate X, figs. 16-18)

Remarks: *Nannoceratopsis deflandrei* subsp. *deflandrei* was recorded in low numbers throughout the *Wanaea verrucosa* Zone in the Sunrise-2 and Sunset West-1 wells (Tables 2, 3). The range top of the species is within the Upper *Wanaea verrucosa* Subzone. This subspecies has a relatively smooth to scabrate autophragm, a strongly developed dorsal antapical horn and a relatively weakly developed ventral antapical horn. The ventral horn is commonly reduced to little more than a prominent 'shoulder' (Plate X, fig. 18).

Nannoceratopsis deflandrei Evitt 1961 subsp. *senex* (van Helden 1977) Ilyina in Ilyina et al. 1994 (Plate X, figs. 21-23)

Remarks: This distinctive subspecies was recorded consistently in the Middle *Wanaea verrucosa* Subzone in the Sunrise-2 and Sunset West-1 wells, but only rarely in the Lower Subzone (Tables 2, 3). The autophragm of *Nannoceratopsis deflandrei* subsp. *senex* is smooth to scabrate, and only the dorsal antapical horn is developed. The entire lack of a ventral antapical horn imparts a rounded subquadrangular shape to this subspecies.

Nannoceratopsis spiculata Stover 1966 (Plate X, fig. 20)

Remarks: *Nannoceratopsis spiculata* was observed in one sample (SW8, 2217.98 m) in the Sunset West-1 well. This distinctive species has two subequal antapical horns. The right and left lateral surfaces are slightly different in size, giving the impression of cavation at the distal extremities of the antapical horns (Stover, 1966, fig. 1, pl. 8, figs. 1-5). *Nannoceratopsis spiculata* is typical of the latest Early Bajocian to Mid Callovian interval in Europe (Stover, 1966; Fenton et al., 1980; Riding et al. 1985; 1991; Prauss, 1989; Feist-Burkhardt and Monteil, 1997).

Nannoceratopsis spp. (Plate X, fig. 19)

Remarks: This material includes all other forms of *Nannoceratopsis* that are not attributable to *Nannoceratopsis deflandrei* or *Nannoceratopsis spiculata*.

Pareodinia Deflandre 1947 emend. Below 1990

Remarks: Representatives of *Pareodinia* occur throughout the *Wanaea verrucosa* Zone in varying proportions in all three wells (Tables 1-3). A wide variety of forms were observed, many of which are difficult to consistently place into existing species and the vast majority of the specimens exhibit accumulation bodies (Plate IX, figs. 5, 9). All the forms below include kalyptrate and non-kalyptrate forms.

Pareodinia halosa (Filatoff 1975) Prauss 1989 emend. Prauss 1989 (Plate IX, fig. 8)

Remarks: This distinctive kalyptrate species was recorded in significant proportions throughout in the Sunrise-2 and Sunset West-1 wells (Tables 2, 3) and as a rare component of the Perseus-3A assemblages (Table 1). Consistently common occurrences of *Pareodinia halosa* are mostly confined to the *Nannoceratopsis deflandrei* and *Wanaea verrucosa* zones (Mid Bajocian to Early Bathonian) in

Australia, although this taxon is present in low to moderate proportions from the Early Bajocian to Early Cretaceous of Australia (Riding et al., 2010, fig. 12). Normally the kalyptra of *Pareodinia halosa* is broadly subcircular in outline, reflecting the outline of the cyst body. However, relatively small numbers of this species are characterised by extremely irregular kalyptras. In these forms, the periphery of the kalyptra has numerous irregular extensions which impart a spinose appearance (e.g. Plate IX, fig. 8). These ‘spinose’ morphotypes are present throughout the *Wanaea verrucosa* Zone.

Pareodinia sp. A (Plate IX, figs. 14-16)

Dimensions (10 specimens measured):
Length of cyst including apical horn: 48 (58) 72 µm
Equatorial width of cyst: 44 (51) 60 µm
Thickness of autophragm: ca. 1 µm

Remarks: *Pareodinia* sp. A is a distinctive form with a thick, finely granulate autophragm; the cyst body is subspherical in shape and has a very short (4-9 µm) apical horn (Plate IX, fig. 16). There is insufficient material in the wells studied to erect a new species. This form is present in low numbers in all three wells from the upper part of the Lower *Wanaea verrucosa* Subzone to the lower part of the Upper *Wanaea verrucosa* Subzone (Fig. 4; Tables 1-3).

Pareodinia spp. (Plate IX, figs. 5-7, 9, 13)

Remarks: The majority of representatives of *Pareodinia* were not subdivided, and are simply placed in *Pareodinia* spp. Included in this grouping are forms similar to *Pareodinia ceratophora* Deflandre 1947 emend. Gocht 1970, elongate forms, squat morphotypes with short apical horns, antapically granulate types, and kalyptrate and non-kalyptrate forms. This plexus is extremely difficult to subdivide consistently; the individual forms appear to represent members of a morphological continuum. *Pareodinia* spp. were recorded in moderate numbers throughout the *Wanaea verrucosa* Zone in all three wells (Tables 1-3).

Phallocysta Dörhöfer & Davies 1980 emend. Riding 1980

Phallocysta granosa Riding and Helby 2001 (Plate X, figs. 1-4, 6-10)

Remarks: *Phallocysta granosa* was recorded in relatively low proportions throughout the Lower and Middle *Wanaea verrucosa* subzones in the Sunrise-2 and Sunset West-1 wells (Figure 4; Tables 2, 3). A significant acme is recorded in the Middle Subzone in Sunrise-2, where *Phallocysta granosa* consistutes 7.3%, 0.7%, and 2.4% of the total palynomorphs in three consecutive samples from 2121.63 m to 2117.06m.

The present work confirms that *Phallocysta granosa* has a densely granulate to spinulate periphragm as stated by Riding and Helby (2001c, p. 61). This phenomenon is clearly exhibited by the holotype (Riding and Helby, 2001c, figs. 1G-H). However, the latter authors figured six specimens of *Phallocysta granosa* from the Sunset-1 well (not included in the present study) which clearly have a micrograndulate to granulate periphragm (Riding and Helby, 2001c, figs. 1A-F). These micrograndulate forms are considerably rarer end members of a morphological continuum in the Sunrise-2 and Sunset West-1 wells; most specimens recorded herein are comprehensively spinulate or coarsely granulate with at least some short, simple spines.

Phallocysta spp. (Plate X, fig. 5)

Remarks: Rare, non-spinose forms of *Phallocysta* were recorded in all three wells. Included within this grouping are small, subspherical, scabrate to micrograndulate forms (Plate X, fig. 5), and types that are broadly similar to *Phallocysta erregulensis* (Filatoff 1975) Stover & Helby 1987. The latter forms are marginally smaller, less prone to folding of the endo- and periphragm and with shorter apical horns than those figured by Stover and Helby 1987 (fig. 11).

Prolixosphaeridium Davey et al. 1966 emend. Davey 1969

Prolixosphaeridium spp.

Remarks: *Prolixosphaeridium* spp. were only recorded in the uppermost part of the Upper *Wanaea verrucosa* Subzone in the Sunset West-1 well (Table 3). Forms similar to *Prolixosphaeridium capitatum* (Cookson & Eisenack 1960) Singh 1971 are included in this group; this species occurs as a common accessory species from the *Wanaea indotata* to *Dingodinium swanense* zones (Helby et al., 1987; Mantle, 2009b).

Rhynchodiniopsis Deflandre 1935 emend. Jan du Chêne et al. 1985

Rhynchodiniopsis sp. cf. *R*? *regalis* (Gocht 1970) Jan du Chêne et al. 1985

Remarks: Low numbers of a distinctive acavate gonyalacacean form were recorded from the Perseus-3A and Sunrise-2 wells (Tables 1, 2). It has an apical horn, thick autophragm, an ovoidal amb and proximally fenestrate/distally denticulate sutural crests. The cyst organisation and the distinctive morphology of the sutural crests are reminiscent of *Rhynchodiniopsis*? *regalis.* However, the type material has a distinctly angular (subpentagonal) outline, and higher, more ornate sutural crests (Gocht, 1970, fig. 10, pl. 33, figs. 5-7). The range of *Rhynchodiniopsis*? *regalis* in Europe is latest Early Bajocian to Late Bathonian (Gocht, 1970; Fenton et al., 1980; Riding, 1984; Riding et al. 1985; 1991; Riding and Thomas, 1992; Feist-Burkhardt and Monteil, 1997).

Rhynchodiniopsis spp. (Plate VII, figs. 1-2, 4-5)

Remarks: Forms attributable to *Rhynchodiniopsis* were observed in low proportions from all three wells (Tables 1-3). These morphotypes are acavate, ovoidal to subpentagonal in outline and with a variety of spinose ornamentation on the sutural crests. The spines may possess complex splayed or furcate tips (Plate VII, figs. 1, 4-5) and project directly from gonal points or surmount low simple or fenestrate crests.

The fenestrae may be reduced (Plate VII, fig. 2) or well-developed (Plate VII, fig. 1). Some specimens are densely folded.

Sentusidinium Sarjeant & Stover 1978

Sentusidinium spp.

Remarks: *Sentusidinium* spp. were encountered sporadically throughout the *Wanaea verrucosa* Zone in the Sunrise-2 and Sunset West-1 wells (Tables 2, 3).

Ternia Helby & Stover 1987

Ternia balmei Helby & Stover 1987 (Plate IX, fig. 4)

Remarks: *Ternia balmei* is an extremely distinctive species that first appears in the Upper *Wanaea verrucosa* Subzone in the Sunrise-2 and Sunset West-1 wells (Fig. 4; Tables 2, 3). This agrees with the range base of *Ternia balmei* as depicted by Helby et al. (2004, fig. 4) and Partridge (2006) in their 7ciai subzone. However, it is only consistently present in the Upper *Wanaea verrucosa* Subzone in Sunrise-2 and is thus too rare to be a reliable marker species in all wells. *Ternia balmei* ranges into and throughout the overlying *Wanaea indotata* and *Ternia balmei* zones (Helby et al., 1987; 2004; Partridge, 2006)

Valensiella Eisenack 1963 emend. Courtinat 1989

Valensiella ovulum (Deflandre 1947) Eisenack 1963

Remarks: *Valensiella ovulum* is present in low numbers in the Upper *Wanaea verrucosa* Subzone in the Sunrise-2 and Sunset West-1 wells (Fig. 4, Tables 2, 3), and throughout much of the undivided *Wanaea verrucosa* Zone in Perseus-3A (Table 1).

This small species is prominent in the Late Bajocian and Bathonian of Europe (Gocht, 1970; Riding et al., 1985; Feist-Burkhardt and Monteil, 1997).

Valvaeodinium Morgenroth 1970 emend. Below 1987

Valvaeodinium cookii sp. nov. (Plate VIII, figs. 16-25)

Description: A small species of *Valvaeodinium* with a squat, subspherical outline and normally a flattened antapical margin. The autophragm is moderately thick (ca. 1-1.5 μm) and dark brown; the surface is scabrate to granulate with a variable density and distribution of short processes. These elements may be baculate, short capitate spines or rarely spines with blunt, bifurcate tips. The latter features are only resolvable using high power objectives. Some specimens have a relatively dense covering of these fine processes (Plate VIII, fig. 16), but they are largely confined to gonal or intergonal positions on most individuals with only a few scattered intratabular elements (Plate VIII, figs. 17). Tabulation is indicated by the archaeopyle and low crests and ridges of variable thickness (0.5-2 μm) and distribution. These sutural features may be surmounted by short processes particularly at the gonal points and are most prominent on the hypocyst, particularly around the precingular plates. The archaeopyle is interpreted to be type AI, formed through the loss of a single apical and intercalary plate (assumed to be the 3' and 1a plates as is typical for the genus). This combination archaeopyle that leaves three apical plates in place leads to a rather pointed apex when the cyst is viewed laterally (Plate VIII, fig. 19); again, a common feature of the genus. The operculum may be free or one or both of the opercular plates may remain attached, albeit loosely. The full tabulation formula is frequently not fully resolvable , but is clearly consistent for *Valvaeodinium* i.e.: 4', 1a, 5", ?6c, 5"', 1"".

Dimensions (20 specimens measured):
Length of cyst including operculum: 28 (33) 38 μm
Equatorial width of cyst excluding spines: 29 (35) 40 μm
Length of spines: 1-3 μm
Thickness of autophragm: ca. 1-1.5 μm

Comments: *Valvaeodinium cookii* sp. nov. is characterised by short sutural spines, variable crests and ridges delimiting an incomplete tabuation, and a typically squat, subspherical outline. The sutural ridges vary from thin, short crests with an irregular notched to finely spinose margin (Plate VIII, figs. 17-18), to low, thick, granular ridges (Plate VIII, figs. 20, 23, 25). The tabulation is commonly best developed on the hypocyst where the precingular plates are typically prominent; the sutural ridges may appear as thick folds of the cyst wall.

Comparison: *Valvaeodinium cookii* sp. nov. is markedly less cyclindrical and rather squatter and flatter-based than most other species of *Valvaeodinium*. The prominent tabulation is also a rare feature of the genus. *Valvaeodinium euareatum* Prauss 1989 is a closely comparable species from the Early to Middle Bajocian of northwest Germany. It is similarly squat with well-developed tabulation and a covering of fine, acuminate to capitate spines. However, *Valvaeodinium euareatum* has a much denser covering of these spines with a more even, intratabular distribution. The spines may also coalesce to form a fine reticulum; this is not a feature of *Valvaeodinium cookii* sp. nov. Furthermore, the well-defined sutural ridges of *Valvaeodinium euareatum* display a more complete tabulation.

Holotype and type locality: Plate VIII, fig. 25. Sunrise-2 well (2122.33 m), Bonaparte Basin, Timor Sea. Slide no. 2, EF P29/2, CPC no. 41198.

Stratigraphical distribution: *Valvaeodinium cookii* sp. nov. is an important marker species for the Middle *Wanaea verrucosa* Subzone. It first appears at the base of this subzone, together with *Valvaeodinium spinosum*, in both the Sunrise-2 and Sunset West-1 wells (Fig. 4; Tables 2, 3); it is a commoner, more consistent marker than the latter species in both wells, but its broader regional distribution is unknown. *Valvaeodinium cookii* sp. nov. is particularly prominent in the Sunrise-2 well, where it peaks at 3% of the total palynomorphs in sample SR10 (2117.06 m). The range top of *Valvaeodinium cookii* sp. nov. is close to the top of the Middle *Wanaea verrucosa* Subzone. It was not recorded in the Perseus-3A well.

Valvaeodinium spinosum (Fenton et al. 1980) Below 1987 (Plate VIII, figs. 6-12)

Remarks: The range base of this distinctive, relatively small, species marks   the base of the Middle *Wanaea verrucosa* Subzone (following the 7ciaii subzone of Helby et al., 2004). However, it is relatively rare through this subzone in the Sunrise-2 and Sunset West-1 wells before a minor acme at the base of the Upper Subzone. This acme ranges from 2% of total palynomorphs in the Sunset West-1 well, up to 5% of total palynomorphs in the Sunrise-2 well (Fig. 4, Tables 2-3). The majority of individuals in the Middle Subzone are squat or subspherical (PlateVIII, figs. 7-10), and become more cylindrical up-section ; most specimens in the Upper Subzone are notably more elongate (Plate VIII, figs. 6, 11-12). This morphological succession was noted for *Valvaeodinium spinosum* and other species s of *Valvaeodinium* by Feist-Burkhardt and Monteil (1997, p. 48).

Valvaeodinium vermicylindratum Below 1987 (Plate VIII, figs. 13-15)

Remarks: This species was encountered in the Perseus-3A and Sunset West-1 wells, and questionably in the Sunrise-2 well (Tables 1-3). This is the first southern hemisphere report of this Late Bajocian-Early Bathonian marker (Feist-Burkhardt and Monteil, 1997).

Valvaeodinium sp. cf. *V. vermipellitum* Below 1987

Remarks: A form similar to *Valvaeodinium vermipellitum* was recorded in one sample (SW8, 2217.98m) in the Upper *Wanaea verrucosa* Subzone in the Sunset West-1 well (Table 3). The ornament is less dense, and fewer spines coalesce to form a finer, less complete reticulum than in the type material.

Wanaea Cookson & Eisenack 1958 emend. Riding and Helby 2001

Wanaea enoda Riding & Helby 2001 (Plate III, fig. 3)

Remarks: Most specimens of *Wanaea enoda* observed in this study were irregularly scabrate, rather than possessing a completely psilate autophragm, and were often squatter than the distinctly subconical hypocysts of the type material from the Magobu-1 well in Papua New Guinea (Riding and Helby 2001b). *Wanaea enoda* was observed in extremely low proportions throughout the *Wanaea verrucosa* Zone in all three wells studied (Tables 1-3).

Wanaea indotata Drugg 1978

Remarks: The inception of *Wanaea indotata* marks the base of the late Early to Late Bathonian *Wanaea indotata* Interval Zone.

Wanaea lacuna Riding & Helby 2001 (Plate III, figs. 6, 9)

Remarks: This cavate species of *Wanaea* was recorded in small numbers from a restricted interval within the Middle *Wanaea verrucosa* Subzone in the Sunrise-2 and Sunset West-1 wells (Fig. 4; Tables 2, 3). This confirms the findings of Riding and Helby (2001b), who described this taxon from the equivalent 7ciaii subzone in the Sunrise-2 well between 2122.33 m and 2122.05 m.

Wanaea verrucosa Riding & Helby 2001 (Plate III, figs. 1-2, 4-5, 7-8)

Remarks: *Wanaea verrucosa*, the index species of this zone, occurs throughout the three wells studied and is normally present in significant proportions (Tables 1-3). The thickness of the autophragm, ornamentation and size of the antapical horn are somewhat variable. Forms with a thin, granulate autophragm and a relatively small antapical horn (Plate III, figs. 2, 5, 7-8) are present throughout, but are most prominent in Lower and Middle *Wanaea verrucosa* subzones. By contrast, morphotypes with a significantly thicker and more robust autophragm and with relatively high relief ornamentation, comprising dense baculae, grana and/or pilae (Plate III, figs. 1, 4) are confined to the uppermost Middle and Upper *Wanaea* *verrucosa* subzones. The latter forms normally exhibit prominent antapical horns. The type material of Riding and Helby (2001b, fig. 9) appears to entirely comprise these younger morphotypes.

The low-relief ornamentation of the older, purely granulate, forms can make the distinction between *Wanaea enoda* and *Wanaea verrucosa* difficult to make using low or medium power objectives. *Wanaea enoda* should be confined to forms which have a smooth to irregularly scabrate autophragm and no coarser ornament. The range bases of these two species are coeval (Riding and Helby, 2001b, figs. 11, 12).

APPENDIX 3. LIST OF THE NON-DINOFLAGELLATE CYST PALYNOMORPHS

Appendix 3 lists all pollen, spores and miscellaneous palynomorphs recorded in this study with author citations for the species.

Pollen:

Araucariacites australis Cookson 1947
Araucariacites spp.
Callialasporites spp.
Classopollis spp.
Cycadopites spp.
Exesipollenites tumulus Balme 1957
Perinopollenites elatoides Couper 1958
Plicatipollenites spp. (reworked)
Praecolpatites sinuosus (Balme & Hennelly 1956) Bharadwaj & Srivastava 1969 (reworked)
Protohaploxypinus spp. (reworked)
Striatoabieites multistriatus (Balme & Hennelly 1955) Hart 1964 (reworked)
Striatopodocarpidites spp. (reworked)
Vitreisporites pallidus (Reissinger 1939) Nilsson, 1958

Spores:

Anapiculatisporites dawsonensis Reiser & Williams 1969

Annulispora spp.

Antulsporites saevus (Balme 1957) Archangelsky & Gamerro 1966

Baculatisporites-Osmundacidites spp.

Cibotiumspora juncta (Kara-Murza 1956) Zhang 1978

Cibotiumspora spp.

Concavissimisporites verrucosus Delcourt & Sprumont 1955

Concavissimisporites spp.

Contignisporites cooksoniae (Balme 1957) Dettmann 1963

Contignisporites spp.

Coronatispora telata (Balme 1957) Dettmann 1963

Coronatispora spp.

Cyathidites spp.

Diatomozonotriletes townrowii Segroves 1970 (reworked)

Dictyophyllidites spp.

Dictyotosporites complex Cookson & Dettmann 1958

Didecitriletes ericianus (Balme & Hennelly 1956) Venkatachala &Kar 1965 (reworked)

Dulhuntyispora dulhuntyi Potonié 1956 emend. Price 1983 (reworked)

Foveosporites canalis Balme 1957

Gleicheniidites senonicus Ross 1949

Gleicheniidites spp.

Granulatisporites trisinus Balme &Hennelly 1956

Granulatisporites spp. (reworked)

Indotriradites spp. (reworked)

Ischyosporites-Klukisporites spp.

Leptolepidites spp.

Matonisporites spp.

Microbaculispora villosa (Balme &Hennelly 1955) Bharadwaj 1962 (reworked)

Neoraistrickia spp.

Pseudoreticulatispora pseudoreticulata (Balme &Hennelly 1956) Bharadwaj &Srivastava1969 (reworked)

Retitriletes spp.

Sculptisporis moretonensis (de Jersey 1964) McKellar in press

Sestrosporites pseudoalveolatus (Couper 1958) Dettmann 1963

Staplinisporites caminus (Balme 1957) Pocock 1962
Stereisporites spp.
Striatella spp.
Trachysporites infirmus (Balme 1957) McKellar in press

Miscellaneous palynomorphs:
Botryococcus spp.
Circulisporites spp.
foraminiferal test linings
Leiofusa sp.
Leiosphaeridia spp.
Micrhystridium spp.
Nummus apiculatus Riding & Helby 2001
Pterospermella australiense (Deflandre & Cookson 1955) Eisenack 1972
Veryhachium spp.

APPENDIX 4: QUANTITATIVE RANGE CHARTS

The quantitative palynomorph distribution data for this project is given in Appendix 4. Tables 1-3 are the dinoflagellate cyst range charts and Tables 4-6 include the data for the other palynomorph groups.

Table 1. Quantitative dinoflagellate cyst data for the 14 samples studied from the Perseus-3A well. The numbers refer to counted specimens. Material observed outside the counts is indicated by an ‘X’. Three dots (…) indicate that the form is absent.

Table 2. Quantitative dinoflagellate cyst data for the 29 samples studied from the Sunrise-2 well. The numbers refer to counted specimens. Material observed outside the counts is indicated by an ‘X’. Three dots (…) indicate that the form is absent.

Table 3. Quantitative dinoflagellate cyst data for the 21 samples studied from the Sunset West-1 well. The numbers refer to counted specimens. Material observed

outside the counts is indicated by an 'X'. Three dots (…) indicate that the form is absent.

Table 4. Quantitative data on pollen, spores and miscellaneous palynomorphs for the 14 samples studied from the Perseus-3A well. The numbers refer to counted specimens. Material observed outside the counts is indicated by an 'X'. Three dots (…) indicate that the form is absent. The seven right hand columns depict the total numbers of dinoflagellate cysts, pollen and spores and percentages.

Table 5. Quantitative data on pollen, spores and miscellaneous palynomorphs for the 29 samples studied from the Sunrise-2 well. The numbers refer to counted specimens. Material observed outside the counts is indicated by an 'X'. Three dots (…) indicate that the form is absent. The seven right hand columns depict the total numbers of dinoflagellate cysts, pollen and spores and percentages.

Table 6. Quantitative data on pollen, spores and miscellaneous palynomorphs for the 21 samples studied from the Sunset West-1 well. The numbers refer to counted specimens. Material observed outside the counts is indicated by an 'X'. Three dots (…) indicate that the form is absent. The seven right hand columns depict the total numbers of dinoflagellate cysts, pollen and spores and percentages.

APPENDIX 5: REGISTER OF FIGURED SPECIMENS

All dinoflagellate cyst specimens figured herein are listed with essential details. These specimens are curated in the Commonwealth Palaeontological Collection (CPC) of Geoscience Australia, Canberra, ACT, Australia. The dinoflagellate cyst genera and species are listed alphabetically. The locations of the specimens on the slides are provided as 'England-Finder' (EF) co-ordinates.

[Appendix 5 is attached as an excel spreadsheet]

FIGURE CAPTIONS

Fig. 1. The North West Shelf of Australia illustrating the locations and extents of the Northern Carnarvon, Roebuck, Offshore Canning, Browse and Bonaparte basins (collectively the Westralian Superbasin), and the locations of the Perseus-3A, Sunrise-2 and Sunset West-1 wells.

Fig. 2. A comparison of the chronostratigraphical position of the *Wanaea verrucosa* dinoflagellate cyst zone and equivalent zones in successive zonation schemes. The shaded areas represent the *Wanaea verrucosa* Zone and subzones, or the equivalent portion of the *Caddasphaera halosa* Zone. The diagonal hatched area indicates a gap in the dinoflagellate cyst zonation.

Fig. 3. Lithological and gamma ray logs of the successions studied herein from the Perseus-3A, Sunset West-1 and Sunrise-2 wells (from west to east). The dinoflagellate cyst zones follow Helby et al. (2004) and Partridge (2006), and the subzones are as described herein.

Fig. 4. The stratigraphical distribution of selected dinoflagellate cysts throughout the *Wanaea verrucosa* Zone from the two Bonaparte Basin wells (Sunrise-2 and Sunset West-1) studied herein, depicted from the data compiled from Tables 2-3 of Appendix 4. The dashed, thin and thick lines indicate that the taxa are rare (i.e. only present outside the count), consistently present or abundant respectively. *Valvaeodinium spinosum, Endoscrinium kempiae* and *Wanaea verrucosa* are in bold font because they are the principal index taxa for the *Wanaea verrucosa* Zone and its constituent subzones.

Plate I. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 μm.

1-16. *Meiourogonyaulax straussii* sp. nov. 1-2, paratype, dorsoventral view, high and median foci, respectively. 3-4, oblique view, median and high foci, respectively. 5-6, holotype, dorsoventral view, low and high foci, respectively. 7-8, dorsoventral view, low and high foci, respectively. 9-10, paratype, dorsoventral view, high and low foci, respectively. 11-12, ventral view, high and median foci, respectively. 13-14, paratype, ventral view, high and low foci, respectively. 15-16, dorsoventral view, high and low foci, respectively.

Plate II. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 µm.

1-2. *Meiourogonyaulax* sp. A. 1, dorsoventral view, high focus. 2, dorsoventral view, high focus.
3. *Escharisphaeridia* sp. A, dorsoventral view, high focus.
4. *Escharisphaeridia* sp. B, dorsoventral view, high focus.
5-8. *Meiourogonyaulax* sp. B. 5, dorsoventral view, high focus. 6. dorsoventral view, median focus. 7. dorsoventral view, high focus. 8. dorsoventral view, high and median foci combined.
9-12. *Meiourogonyaulax* sp. C. 9, dorsoventral view, high focus. 10, dorsoventral view, high focus. 11, dorsoventral view, high focus. 12, dorsoventral view, high focus.
13-16. *Kallosphaeridium hypornatum* Prauss 1989. 13, ventral view, high focus. 14. dorsoventral view, low and median foci combined. 15, dorsoventral view, high focus. 16, dorsoventral view, high and median foci combined.

Plate III. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 µm.

1-2, 4-5, 7-8. *Wanaea verrucosa* Riding & Helby 2001. 1, high/median focus. 2, high focus. 4, high and median foci combined. 5, median focus. 7, high focus. 8, high focus.
3. *Wanaea enoda* Riding & Helby 2001, high focus.
6, 9. *Wanaea lacuna* Riding & Helby 2001. 6, median focus. 9, median focus.

Plate IV. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 µm.

1-12. ?*Bradleyella adela* (Fenton et al. 1980) Woollam 1983. 1, dorsoventral view, median focus. 2, dorsal view, high focus. 3, dorsal view, high focus. 4, ventral view, high focus. 5, lateral view, high focus. 6, dorsal view, high focus. 7, dorsoventral view, median focus. 8, dorsoventral view, median focus. 9, dorsal view, high focus. 10, dorsal view, median focus. 11, lateral view, median focus. 12, dorsoventral view, median focus.

13-15. *Ctenidodinium* sp. A. 1, dorsoventral view, low focus. 2, dorsoventral view, high focus. 3, oblique view, high focus.

Plate V. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 μm.

1-3, 5-6. *Ctenidodinium* sp. B. 1-2, hypocyst, lateral view, median and low foci, respectively. 3, lateral view, high and median foci combined. 5, dorsal view, high focus. 6 lateral view, median focus.

4. *Ctenidodinium* sp., hypocyst, dorsal view, high focus.

7-9. *Ctenidodinium* sp. C. 7, ventral view, median focus. 8, lateral view, median focus. 9, lateral view, median focus.

Plate VI. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 μm.

1-2, 4-6. *Dissiliodinium* sp. A. 1, dorsal view, median focus. 2, ventral view, high focus. 4, lateral view, high focus. 5, dorsal view, high focus. 6, ventral view, high and median foci combined.

3. *Dissiliodinium* sp., dorsal view, median focus.

7-10. *Durotrigia* spp. 7, dorsal view, median focus. 8-9, ventral view, high and low foci respectively. 10, dorsal view, high focus.

11-12. ?*Durotrigia* sp., ventral view, low and high foci, respectively.

Plate VII. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 µm.

1-2. ?*Rhynchodiniopsis* spp. 1, polar view, median focus. 2. polar view, high and median foci combined.

3. *Leptodinium*? *ancoralium* Mantle 2005, lateral view, high and median foci combined.

4-5. *Rhynchodiniopsis* spp. 4, lateral view, median focus. 5, dorsoventral view, high and median foci combined.

6. *Leptodinium* sp., ventral view, high focus.

7, 9. *Endoscrinium luridum* (Deflandre 1938) Gocht 1970. 7, ventral view, high focus. 9, dorsal view, high focus.

8. *Endoscrinium* sp. cf. *E. luridum* (Deflandre 1938) Gocht 1970, lateral view, high focus.

10. *Endoscrinium kempiae* (Stover & Helby 1987) Lentin & Williams 1989, ventral view, high, median, and low foci combined.

11. *Aldorfia* sp., ventral view, high focus.

12. *Acanthaulax crispa* (Wetzel 1967) Woollam & Riding 1983, ventral view, high and median foci combined.

Plate VIII. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 µm.

1. *Fostericysta scarffei* (Tykoezinski et al. 2001) comb. nov., ventral view, high focus.

2-5. *Jansonia* spp. 2, dorsal view, high focus. 3, ventral view, high focus. 4, dorsal view, high focus. 5, ventral view, high focus.

6-12. *Valvaeodinium spinosum* (Fenton et al. 1980) Below 1987. 6, dorsal view, high focus. 7, dorsal view, median focus. 8, lateral view, high and median foci combined. 9, dorsal/lateral, median focus. 10, lateral view, median focus. 11-12, lateral view, median and high foci respectively.

13-15. *Valvaeodinium vermicylindratum* Below 1987. 13-14, ventral view, high and median foci, respectively. 15, dorsal view, high and median foci combined.

16-25. *Valvaeodinium cookii* sp. nov. 16, lateral view, high and median foci combined. 17. dorsal-lateral view, high focus. 18, paratype, dorsal view, high focus. 19, lateral view, high and median foci combined. 20, dorsal view, high focus. 21, ventral view, low focus. 22, dorsal view, high and median foci combined. 23, paratype, dorsal view, median focus. 24, dorsal view, high and median foci combined. 25. holotype, ventral view, median focus.

Plate IX. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 μm.

1-3. ?*Egmontodinium* sp. A. 1, median focus. 2, median focus. 3, median focus.
4. *Ternia balmei* Helby & Stover 1987, anteroventral view, median focus.
5-7, 9, 13. *Pareodinia* spp. 5, dorsal view, high focus. 6, dorsal view, median focus. 7, dorsolateral view, median focus. 9, lateral view, median focus. 13, ventral view, high focus.
8. *Pareodinia halosa* (Filatoff 1975) Prauss 1989 emend. Prauss 1989, median focus.
10-12. *Evansia* sp. A. 10, dorsoventral view, high and low foci combined. 11, dorsal view, high focus. 12, lateral view, median focus.
14-16. *Pareodinia* sp. A. 14, dorsoventral view, median focus. 15, lateral view, median focus. 16, dorsoventral view, high and low foci combined.

Plate X. Selected dinoflagellate cyst taxa from the *Wanaea verrucosa* Zone of the Perseus-3A, Sunrise-2 and Sunset West-1 wells. The scale bars represent 10 μm.

1-4, 6-10. *Phallocysta granosa* Riding & Helby 2001. 1-2, low and high foci, respectively. 3, median focus. 4, median focus. 6, high focus. 7, dorsal view, median focus. 8, median focus. 9, median focus. 10, ventral view, low focus.
5. *Phallocysta* sp., high focus.
11-15. *Mancodinium semitabulatum* subsp. *semitabulatum* (Morgenroth 1970) Fensome et al. 1993. 11-12, ventral view, high and low foci, respectively. 13, ventral view, high focus. 14-15, ventral view, low and high foci, respectively.

16-18. *Nannoceratopsis deflandrei* Evitt 1961 subsp. *deflandrei* (autonym). 16, right lateral view, high focus. 17, right lateral view, median focus. 18, right lateral view, median view.

19. *Nannoceratopsis* spp., right lateral view, median focus.

20. *Nannoceratopsis spiculata* Stover 1966, right lateral view, median focus.

21-23. *Nannoceratopsis deflandrei* Evitt 1961 subsp. *senex* (van Helden 1977) Ilyina in Ilyina et al. 1994. 21, left lateral view, high focus. 22, right lateral view, high focus. 23, right lateral view, high focus.