A review of the Middle Triassic to Late Jurassic dinoflagellate cyst biozones of the North West Shelf of Australia

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ABSTRACT

The chronostratigraphical ages of the 20 dinoflagellate cyst zones and one dinoflagellate cyst assemblage for the Middle Triassic (Ladinian) to the Jurassic-Cretaceous transition of the North West Shelf of Australia have been comprehensively and objectively reviewed. Evidence from macropalaeontology, calcareous, phosphatic and silicious micropalaeontology, cosmopolitan dinoflagellate cysts, miospores and strontium isotopes made available after the establishment of these zones in the 1980s has been used to reinterpret this important zonal scheme. The *Shublikodinium* Superzone is renamed herein as the *Rhaetogonyaulax* Superzone. The *Rhaetogonyaulax* Superzone is reinterpreted as being Ladinian to Early Sinemurian, mainly using conodont data. It is thus significantly shorter in duration than was originally envisaged (Late Anisian to Late Pliensbachian). The *Luehndea* Assemblage is a low diversity dinoflagellate cyst association which marks a eustatic rise; it is subdivided into two subzones. It is of latest Pliensbachian to Early Toarcian age, based largely on palynological evidence. The Bajocian to earliest Oxfordian *Pareodinia ceratophora* Superzone represents the inception of the continuous Mesozoic-Cenozoic dinoflagellate cyst record in Australia. It comprises seven zones, which appear to be slightly older than originally interpreted based on evidence from ammonites, calcareous nannofossils, strontium isotope stratigraphy and dinoflagellate cysts. The overlying *Pyxidiella* Superzone is characterised by diverse dinoflagellate cyst associations. It is Early Oxfordian to Kimmeridgian in age, and comprises three zones. The bases of the *Wanaea spectabilis* and *Wanaea clathrata* zones are reinterpreted as being slightly older than originally envisaged. The superjacent *Fromea cylindrica* Superzone is Tithonian to earliest Valanginian and modified ages are indicated for four of the nine zones. This unit is dominated by endemic dinoflagellate cysts, reflecting a global trend towards provincialism at this time due to a regressive eustatic regime.

Keywords: biostratigraphy; dinoflagellate cysts; Mesozoic; Australia

1. Introduction

An integrated dinoflagellate cyst and spore-pollen biozonation for the Late Permian (Gzhelian) to Palaeocene (Danian) was published by Helby et al. (1987a). This landmark study was begun in the 1970s; it was presented at symposia and circulated informally prior to publication in 1987. The necessary extensive taxonomic documentation was published in 13 papers within the same volume (Jell, 1987). This important biostratigraphical scheme rapidly became the standard Mesozoic palynozonation used in exploration geology on the North West Shelf of Australia (Fig. 1). Helby et al. (1987a) includes a Middle Triassic (Anisian) to Palaeocene (Danian) dinoflagellate cyst zonal scheme comprising 45 zones, 44 of which are subdivided into seven superzones. The resolution of this zonal scheme is somewhat variable, but generally it provides substage level subdivision. It is clear that a significantly greater level of precision is possible because a series of alphanumeric subzones were illustrated, but not defined (Helby et al., 1987a, fig. 47).

Recently the biozonation of Helby et al. (1987a) has been significantly refined in terms of its resolution. In a series of taxonomic papers largely on the Jurassic, Helby and Partridge (2001) and Riding and Helby (2001a-h) described 55 new dinoflagellate cyst and acritarch species. Many of these taxa allow the definition of subzones within the biozonation of Helby et al. (1987a). These intervals, numbered with alphanumeric codes, were illustrated by Foster (2001, fig. 2). The subzones remain informal, however the datums which allow this relatively refined biozonation to be recognised have been illustrated by Helby et al. (2004) and Partridge (2006).

Compared with similar biozonations, this zonal scheme has relatively few ties to the Mesozoic Global Boundary Stratotype Section and Points (GSSPs) (Helby et al, 1987a, figs. 4, 12, 19, 32). By contrast, the European Jurassic dinoflagellate cyst biozonations of Woollam and Riding (1983), Riding and Thomas (1992) and Poulsen and Riding (2003) are closely calibrated throughout to the Sub-Boreal ammonite zonation. Furthermore, there are many more published data on Jurassic dinoflagellate cysts from Europe in comparison to Australia.

Based on the ranges of certain key taxa in Helby et al. (1987a), there are apparently some incoherencies in the stratigraphical ranges of important cosmopolitan taxa between Australasia and Europe. For example, Davey (1988), Riding and Fensome (2002) and Riding (2003; 2005a) commented that the range tops of species such as *Nannoceratopsis pellucida, Rigaudella aemula* and *Scriniodinium crystallinum* are significantly younger in Australasia than in Europe. Reworking and/or palaeogeographical and/or palaeolatitudinal factors may explain this apparent heterochroneity. Furthermore, Riding and Helby (2001b) and Riding and Fensome (2002) illustrated and commented on disparities in the ranges of species of *Wanaea* and *Endoscrinium/Scriniodinium* respectively between the Northern and Southern hemispheres. For example, Riding and Helby (2001b, fig. 12) commented that, generally, Australian species of *Wanaea* are somewhat younger than their European counterparts. Subsequently, Riding (2003) suggested that the ages of most of the early Bajocian to early Berriasian Australasian dinoflagellate cyst zones of Helby et al. (1987a) appear to be anomalously young when compared with European ranges of cosmopolitan taxa.

In this paper, we attempt to comprehensively and objectively review the ages of the Australasian dinoflagellate cyst zones of Helby et al. (1987; 2004) and Partridge (2006) from the Middle Triassic (Ladinian) to the Late Jurassic (Tithonian). This study is based on biostratigraphical evidence developed since the publication of Helby et al. (1987a), and new Australian Jurassic dinoflagellate cyst and other palaeontological data.

2. The Late Triassic and Jurassic geology of the North West Shelf of Australia

The North West Shelf represents the passive continental margin of northwestern Australia and comprises the Northern Carnarvon, Roebuck, Offshore Canning, Browse and Bonaparte basins (Fig. 1). This large area, also known as the Westralian Superbasin, is an extensive depocentre approximately 2400 km long and 400 km wide. The region represents the premier hydrocarbon province in Australia as summarised in Longley et al. (2002). Late Triassic and Jurassic strata occur across Australia with predominantly non-marine deposits in the onshore eastern basins, and mixed terrestrial-marine sediments in the major northwestern and western basins. Most onshore Triassic-Jurassic strata are non-marine, largely fluvial-dominated successions that are devoid of dinoflagellate cysts; they will not be discussed further. Thick Jurassic marine successions are largely confined to the North West Shelf, with a thin transgressive package in the Perth Basin.

The North West Shelf formed as an intracratonic rift with the earliest known tectonic activity occurring in the Cambrian, and the first continental slivers rifted off during Devonian to Permian fragmentation (Metcalfe, 1990). The final significant period of terrane dispersal, which led to the break-up of Gondwana, occurred in the Late Triassic to Late Jurassic. Rifting commenced in the Carnian and Norian and a concurrent uplift and erosion event, the 'Fitzroy Movement' (Forman and Wales, 1981), along the northwest margin of Australia provided large volumes of sediment to the newly formed depocentres. Thick Carnian-Norian fluvio-deltaic successions were deposited as the Mungaroo Formation in the Northern Carnarvon Basin and the upper Keraudren Formation in the Offshore Canning Basin. These were subsequently overlain by the transgressive, paralic to shallow-marine successions of the Brigadier and Bedout formations, respectively. Marine sediments in the Bonaparte and Browse basins are represented by the paralic to shallow marine Pollard, Challis and Nome formations (Fig. 2). The oldest consistently recorded dinoflagellate cyst assemblages in Australia, the *Rhaetogonyaulax* Superzone, are known from the Upper Carnian to Rhaetian marine beds of the North West Shelf.

The Lower Jurassic succession of the North West Shelf comprises much marginal marine and some non-marine sedimentation. Marine environments persisted in the Northern Carnarvon Basin, where shallow marine to paralic conditions are represented by the North Rankin Formation and the Murat Siltstone. The sometimes sparse dinoflagellate cyst assemblages of the *Dapcodinium priscus* Zone are recorded from the North Rankin Formation and the underlying Brigadier Formation in the Northern Carnarvon Basin, and the lower Plover Formation in the Bonaparte Basin (Fig. 2). The thick Early Jurassic lower Plover Formation successions in the Bonaparte and Browse basins contain marine, paralic and fluvial sediments. Stratigraphically important but sparse dinoflagellate cyst assemblages of the *Luehndea* Assemblage have been recovered from the lower Plover Formation of the Jabiru and Skua oilfields (Riding and Helby, 2001a; Fig. 2). Dinoflagellate cyst abundance and diversity are extremely low in the Early Jurassic to early Middle Jurassic of Australia. Dinoflagellate cysts are absent or rare in the Late Sinemurian to Early Bajocian; this is similar to the coeval record in the Northern Hemisphere (Riding and Thomas, 1992).

Progressive deepening throughout the Middle Jurassic is evident from the increased coastal plain and tidal channel deposits within the upper Plover Formation of the Bonaparte and Browse basins, occasional marine influence in the fluvio-deltaic Depuch Formation of the Offshore Canning Basin, the marine Cadda Formation in the North Perth Basin and the persistent marine environments in the Northern Carnarvon Basin (Fig. 2). In the latter basin, the restricted marine Athol Formation and overlying deltaic Legendre Formation contain moderately abundant dinoflagellate cyst assemblages. These associations represent the major radiation of gonyaulacacean dinoflagellate cysts in Australia. In the Bonaparte and Browse basins, the major increase in dinoflagellate cyst diversity occurs in the Callovian deltaic to nearshore deposits of the Elang, Laminaria and Montara formations (Fig. 2).

Thick successions of marine claystones, siltstones and fine sandstones represent the major fill of the Late Jurassic depocentres of the North West Shelf. The Dingo Claystone is particularly thick (~3500 m), and is one of the key source rocks in the Northern Carnarvon Basin. It is overlain by the shallow to deep marine Angel Formation and the submarine fan sands of the Dupuy Formation (Fig. 2). In the Browse and Bonaparte basins, a similarly rapid transgressive phase occurred across underlying shallow marine and deltaic successions. This is represented by the Vulcan Formation and the Frigate Shale; these Late Jurassic marine deposits contain extremely abundant and diverse dinoflagellate cyst assemblages.

3. Overview of Triassic and Jurassic marine palynology

Triassic and Jurassic dinoflagellate cysts have been intensively studied since the 1960s, and Riding and Sarjeant (1985), Riding and Thomas, (1992) and Riding and Ioannides (1996) outlined their history of study. For the Northern Hemisphere, the majority of publications on this topic are from northwest Europe, where the standard Triassic and Jurassic stage stratotypes and GSSPs are located, and many of these data are correlated with the standard ammonite zonation. Some of the major papers on this topic are Wiggins (1973), Bujak and Fisher (1976), Raynaud (1978), Woollam and Riding (1983), Riding and Sarjeant (1985), Riding and Thomas (1988;

1992; 1997), Feist-Burkhardt and Wille (1992), Poulsen (1996), Feist-Burkhardt and Monteil (1997), Riding et al. (1999), Riding (2005b) and Bucefalo Palliana and Burati (2006). Riding and Ioannides (1996) gave a review of Jurassic dinoflagellate cysts with a comprehensive bibliography. These authors also described major trends in the global provincialism of these marine palynomorphs.

Backhouse (1988), Riding and Ioannides (1996) and Mantle (2009a) assessed the literature on Jurassic dinoflagellate cysts from Australasia. The earliest publications on Austral Mesozoic dinoflagellate cysts were the results of the extensive collaborative work between Isabel C. Cookson of Melbourne and prominent European palynologists, firstly Georges Deflandre and subsequently, Alfred Eisenack (e.g. Deflandre and Cookson 1955; Cookson and Eisenack, 1958; 1960). This early research was principally taxonomic, and the first comprehensive dinoflagellate cyst biozonation covering the Jurassic was Helby et al. (1987a). This scheme was the result of much work done on behalf of the petroleum exploration industry in offshore Australia by the authors and workers such as Ott (1970). Davey (1988) produced a Middle Jurassic (Bathonian) to Early Cretaceous (Aptian) palynozonation for Papua New Guinea. The correlation of this zonal scheme with that of Helby et al. (1987a) was discussed by Francis and Westermann (1993) and Davey (1999). Other papers on Australasian and Antarctic marine Jurassic palynology include Filatoff (1975), Wiseman (1980), Wilson (1984), Wilson and Helby (1986; 1987), Stover and Helby (1987a,b), Backhouse (1988), Helby and Wilson (1988), Helby et al. (1988), Welsh (1990), Riding et al. (1992), Sarjeant et al. (1992), Snape (1992), Bint and Marshall (1994), Burger (1994; 1996), Nicoll and Foster (1994); Parker (1986), Riding and Helby (2001a-g), Backhouse et al. (2002), Riding and Fensome (2002), Mantle (2005; 2009a,b), Riding (2005a) and Riding et al. (2010).

Tying Australian Jurassic palynozonation schemes to the geological timescale or making valid correlations to the more tightly constrained European dinoflagellate cyst zonations has always been problematic. There are very few Jurassic ammonite localities in Australia and those that are documented or specimens fortuitously recovered from boreholes are often highly endemic. However, there are fossiliferous Jurassic sections with well-preserved ammonite-belemnite-bivalve faunas in India (Krishna et al. 1982, Garg et al. 2003), Indonesia (Sato et al., 1978; Challinor and Skwarko, 1982; Westermann and Callomon, 1988; Challinor, 1991), New Zealand (Stevens, 1965, 1997; Challinor, 1999, 2001, 2003), and Papua New Guinea (Norvick, 1973; Challinor, 1990; Sukamto and Westermann, 1992). The key papers detailing dinoflagellate cyst assemblages associated with these molluscan faunas are Helby et al. (1987a), Helby and Hasibuan (1988), Helby et al. (1988), Francis and Westermann (1993) and Garg et al. (2003). These papers document the few macrofaunal ties to the geological timescale for Australasian Jurassic dinoflagellate cysts. However, the endemic nature of many of these faunas means that correlation to the standard European ammonite zonation is a convoluted process that for some assemblages involves multiple steps using macrofaunal tie points across several continents.

Calcareous nannofossils may also have great potential as a correlative microfossil group on the North West Shelf. The most widely utilised Jurassic nannofossil zonation (NJ zonation scheme of Bown and Cooper, 1998) resulted from many studies of European successions and is directly correlated with the standard European ammonite successions. Howe (2000) stated that the NJ nannofossil zones appear to be readily applicable to Australian successions and he detailed calcareous nannofossil assemblages from 17 petroleum exploration wells in the Northern Carnarvon Basin and Timor Sea. The spore-pollen and dinoflagellate cyst zones for these samples were also listed, thus providing an important set of independent Jurassic microfossil ties to the geological timescale. However, this study remains a pilot project and until more Australian successions (particularly continuous sections) are studied there will remain some uncertainties. There must be a distinct possibility that some similar or even identical calcareous nannofossils have different ranges in Australasia compared to the Northern Hemisphere as is widely observed amongst the dinoflagellate cyst faunas.

Conodont elements are another critical but much under-studied correlative tool for marine successions of the Australian Triassic. Important papers on successions in the North West Shelf (Nicoll & Foster, 1994, 1998; Nicoll, 2002) provide valuable conodont ties points for the more widely available palynological assemblages. As for the calcareous nannofossils, the conodont zonations developed in the Northern Hemisphere appear to be consistently applicable across the North West Shelf. However, whilst some moderately abundant and diverse conodont faunas have been recovered, there are also some tie points that are based on very few or fragmented specimens. Another major consideration is that facies changes can have a major influence on conodont distribution and there are currently too few suitable lithologies to fully model these changes in Australian successions.

4. Stratigraphical palynology

In this section the 20 Middle Triassic (Anisian-Ladinian) to earliest Cretaceous (earliest Berriasian) dinoflagellate cyst zones of Helby et al (1987a; 2004) and Partridge (2006), and the one dinoflagellate cyst assemblage of Riding and Helby (2001a) are reviewed with emphasis on their respective ages. The 20 dinoflagellate cyst zones are within four of the seven Mesozoic dinoflagellate cyst superzones of Helby et al (1987a). The original tie points, subsequent relevant stratigraphical information and the ages of the relevant cosmopolitan dinoflagellate cyst taxa are discussed as appropriate.

A schematic comparison of the zonations of Helby et al (1987a), Helby et al. (2004)/Partridge (2006) and the present interpretation is given as Figs. 3, 4. The various supporting stratigraphical data used herein for the age assessments of the Middle Jurassic to earliest Cretaceous dinoflagellate cyst zones are summarised in Fig. 5. Comparative range charts for selected Middle Triassic (Anisian) to earliest Cretaceous (earliest Berriasian) dinoflagellate cysts from Alaska, Australia, the Arctic, Europe, New Zealand and Russia as appropriate are presented as Figs. 6-10. These diagrams are designed to enable the comparison of the ranges of key marker dinoflagellate cysts from appropriate regions. The majority of the data were taken from the literature and unpublished public domain literature such as released well completion reports. Fig. 11 is a compilation of the most important Middle Jurassic (Bajocian) to earliest Cretaceous (earliest Berriasian) dinoflagellate cyst marker species of the North West Shelf of Australia.

Full author citations and the related bibliography for all the dinoflagellate cyst taxa quoted may be found in Fensome and Williams (2004).

4.1 The Rhaetogonyaulax *Superzone of Helby et al. (1987a), revised herein*

Helby et al. (1987a) established the Middle Triassic to Early Jurassic *Shublikodinium* Superzone. The name is changed herein to the *Rhaetogonyaulax* Superzone because *Shublikodinium* is a junior synonym of *Rhaetogonyaulax* according to Stover and Evitt (1978) and Lentin and Williams (1989). The *Rhaetogonyaulax* Superzone was defined on a composite succession from the Bonaparte Basin, and was interpreted as being Middle Triassic (Late Anisian) to Early Jurassic (Late Pliensbachian) by Helby et al. (1987a, fig. 46). It is based on the presence of the *Rhaetogonyaulax* (*Shublikodinium*) Flora, a low-diversity suite of mainly rhaetogonyaulacoid and suessioid dinoflagellate cysts. This assemblage is confined to marginal basins in Western Australia and Indonesia. Helby et al. (1987a) established six zones within the *Rhaetogonyaulax* Superzone. The ages of the youngest four Triassic subdivisions were revised by Nicoll and Foster (1994) as a result of conodont biostratigraphy – conodonts provide the best independent age control for the Middle to Late Triassic palynozones of the North West Shelf.

Helby et al. (1987a, fig. 8) illustrated 12 dinoflagellate cysts from the *Rhaetogonyaulax* Superzone. *Susadinium* sp. A is now *Susadinium*? *australis* and is interpreted as Early Toarcian (Riding and Helby, 2001a). Of the remaining 11 taxa, six are known from Europe; these are *Beaumontella langii, Dapcodinium priscus, Heibergella*? *kendelbachia, Rhaetogonyaulax rhaetica, Suessia swabiana* and *Sverdrupiella* spp. The remaining five (*Sahulidinium ottii, Hebecysta balmei, Rhaetogonyaulax wigginsii, Suessia* sp. A and *Wanneria listeri*) are so far known only from Australia. The ranges of the principal Ladinian to Sinemurian cosmopolitan dinoflagellate cysts are illustrated in Fig. 6. Australasian-European provincialism is more marked than it appears because the latest Carnian-Sinemurian part of the *Rhaetogonyaulax* Superzone also contains low diversity suites of undescribed dinoflagellate cysts (Helby et al., 1987a). Wilson and Helby (1986) was the first published report of Triassic dinoflagellate cysts from Australasia. Subsequent contributions include Helby et al. (1987a,b), Stover and Helby (1987a), Helby and

Wilson (1988), Brenner (1992), Burger (1994; 1996), Nicoll and Foster (1994),Backhouse and Balme (2002), and Backhouse et al. (2002).

Despite similarities at the generic level (Fig. 6), Middle Triassic to earliest Jurassic dinoflagellate cysts exhibit marked provincialism. The most diverse Mid-Late Triassic associations are from the Carnian and Norian of arctic Canada, where diversity may reach 19 species (Bujak and Fisher, 1976), and Alaska where Wiggins (1976) listed 42 species on his summary range chart. These Arctic palynofloras are dominated by *Sverdrupiella* and its close relatives *Hebecysta, Heibergella* and *Noricysta*. The *Sverdrupiella* suite had a circum-Pacific distribution during the Norian (Helby et al, 1987b). Species of this plexus in arctic Canada and Australasia are different, and diversity is much reduced in the Southern Hemisphere (Helby and Wilson, 1988). Moreover, representatives of the *Sverdrupiella* suite are extremely rare in the Rhaetian of Europe (Morbey and Dunay, 1978; Riding and Thomas, 1992). The dinoflagellate cyst record in Europe is confined to the latest Triassic (Rhaetian), where eight species are known (Riding and Thomas, 1992, fig. 2.8). This flora is dominated by the cosmopolitan species *Rhaetogonyaulax rhaetica* (see Orbell, 1973; Fig. 6).

Despite some provincial differences, the Rhaetian to Hettangian dinoflagellate cyst records of Europe and Australia also exhibit significant similarities. For example the oldest occurrences of *Rhaetogonyaulax rhaetica* in the earliest Rhaetian, and the presence of *Dapcodinium priscus* in the absence of *Rhaetogonyaulax rhaetica* in the Hettangian-Early Sinemurian appear to have widespread correlative significance (Fig. 6). It is also clear that facies control strongly influenced the stratigraphical distribution of marine palynomorphs during the Triassic and Early Jurassic. Major eustatic shifts and marine transgressions appeared to have controlled certain bioevents. For example, the influx of dinoflagellate cysts including *Rhaetogonyaulax rhaetica* during the Early Rhaetian of Europe was probably related to the transgressive surface close to the base of the UAB-1 2nd-Order Supercycle of Haq et al. (1987).

4.1.1 The *Sahulidinium ottii* Zone of Helby et al. (1987a)

This stratigraphically isolated, monospecific association represents the oldest record of unequivocal dinoflagellate cysts in the world. It is known only from samples containing a *Staurosaccites quadrifidus* Spore-pollen Zone assemblage. The age control for the *Sahulidinium ottii* and *Staurosaccites quadrifidus* zones was based on the occurrences of Early-Middle Anisian ammonoids and bivalves in older strata and Carnian dinoflagellate cysts in younger strata (Wiggins, 1973; Skwarko and Kummel, 1974; Helby et al., 1987a, fig. 4). Based on this indirect evidence, Helby et al. (1987a, fig. 8) assigned their *Sahulidinium ottii* Zone to the Late Anisian-Early Ladinian. However, the range of this species is herein considered to lie within the Ladinian to earliest Carnian based on equivocal conodont data (fragments of *Paragondolella* spp.) from the Cape Londonderry Formation in the Kelp Deep-1 well (unpublished data). This conodont data suggests the *Staurosaccites quadrifidus* Spore-pollen Zone may range up to the earliest Carnian. Furthermore, the *Sahulidinium ottii* Zone reference section consists of a thin (~3m) interval in the Sahul Shoals-1 well and is suggestive of a relatively short zonal duration; there is currently no definite evidence for an Anisian age (Fig. 6).

4.1.2 The *Rhaetogonyaulax wigginsii* Zone of Helby et al. (1987a), revised by Nicoll and Foster (1994)

The *Rhaetogonyaulax wigginsii* Zone of Helby et al. (1987a), revised by Nicoll and Foster (1994) was defined by the range bases of *Rhaetogonyaulax wigginsii* and *Wanneria listeri* (Helby et al., 1987a, fig. 8). The original name was the *Shublikodinium wigginsii* Zone of Helby et al. (1987a). The inception of *Rhaetogonyaulax wigginsii* in the latest Carnian represents the base of the continuous Late Triassic-earliest Jurassic dinoflagellate cyst record in Australia. Only *Rhaetogonyaulax wigginsii* and *Suessia swabiana* occur in this zone (Helby et al., 1987a, fig. 8). The dating of this zone as latest Carnian to mid Norian is based on correlation with the *Samaropollenites speciosus* Spore-pollen Zone of Helby (1987a), and the *Epigondolella triangularis, Metapolygnathus primitius*, and *Metapolygnathus communisti* conodont zones from the reference section, the Sahul Shoals-1 well from the North West Shelf of Australia (Nicoll and Foster, 1994). This is broadly consistent with the oldest occurrence of *Rhaetogonyaulax* spp. in the latest and Late Carnian of Alaska and arctic Canada, respectively (Wiggins, 1973; Bujak and Fisher, 1976; Helby et al., 1987a, fig. 4; Fig. 6).

4.1.3 The *Wanneria listeri* Zone of Helby et al. (1987a), revised by Nicoll and Foster (1994) and Backhouse et al. (2002)

The original *Suessia listeri* Zone (Helby et al., 1987a, fig. 8) was defined by the range bases of the index species and *Hebecysta balmei*. Nicoll and Foster (1994) and Backhouse et al. (2002) renamed this unit the *Wanneria listeri* Zone. *Rhaetogonyaulax wigginsii, Suessia swabiana, Wanneria listeri* and various undescribed taxa are present in this interval (Helby et al., 1987a, fig. 8).

Nicoll and Foster (1994, p.105) reported a single conodont tie point (*Epigondolella bidentata*) from the uppermost part of the zone in the reference section, the Ashmore Reef-1 well. Helby et al. (1987a, fig.4) used the range bases of *Heibergella* and *Sverdrupiella* in the overlying *Hebecysta balmei* Zone to assign a Norian or older age to the *Wanneria listeri* Zone. However, Bujak and Fisher (1976, table 1) indicated that the inceptions of *Heibergella* and *Sverdrupiella* in the Sverdrup Basin of arctic Canada are of Carnian age (Fig. 6). The boundary between the *Wanneria listeri* and *Hebecysta balmei* zones appears to be somewhat facies-controlled, and conodont evidence indicates considerable overlap in the zonal ranges (Nicoll and Foster, 1994, figs. 2, 4). The range base of inconsistent *Classopollis/Corollina* spp. at the base of the *Wanneria listeri* Zone in Australia coincides with the increase in abundance of this pollen in Europe (Morbey, 1978; Visscher et al., 1980; Fig. 6).

Largely based on the supporting conodont evidence, the *Wanneria listeri* Zone is considered herein to be of Middle-Late Norian age.

4.1.4 The *Hebecysta balmei* Zone of Helby et al. (1987a), revised by Nicoll and Foster (1994) and Backhouse et al. (2002)

The *Hebecysta balmei* Zone is defined as the interval between the inceptions of *Hebecysta balmei* and *Rhaetogonyaulax rhaetica* (Helby et al., 1987a, fig. 8). *Hebecysta balmei* and *Sverdrupiella* spp. are both confined to this biozone, although *Sverdrupiella* spp. are more typical towards the middle of the zone (R. Helby personal communication) rather than at the base of the zone as depicted by Helby et al. (1987a). *Wanneria listeri* is the main accessory dinoflagellate cyst with rare *Noricysta* sp., *Dapcodinium* sp., *Rhaetogonyaulax wigginsii* and *Suessia swabiana* found in only a few wells.

The age of this zone was assigned to the Middle-Late Norian by Helby et al. (1987a) based on the inceptions of *Heibergella* and *Sverdrupiella* in the Canadian arctic. Similar range bases for these genera were also recorded by Wiggins (1976) for Alaska and for *Sverdrupiella* in New Zealand (Helby and Wilson, 1988). These datums, however, may occur in the Carnian of northern Canada (Bujak and Fisher, 1976; Fig. 6). The Middle-Late Norian age was revised to Late Norian to earliest Rhaetian by Nicoll and Foster (1994; 1998) and Backhouse et al. (2002). This was based on conodont and pollen data from the reference sections, the Mt. Ashmore-1B and Ashmore Reef-1 wells, respectively. The *Hebecysta balmei* Interval Zone is associated with the *Epigondolella postera,* and *Epigondolella bidentata* conodont zones (Nicoll and Foster, 1994; 1998), and the *Minutosaccus crenulatus* Spore-pollen Zone of Helby et al. (1987a). Nicoll and Foster (1994) also recorded the co-occurrence of conodonts of the *Misikella hernsteini* Conodont Zone within the *Hebecysta balmei* and *Rhaetogonyaulax rhaetica* zones thus indicating that the zonal boundaries are either diachronous or overlap within the range of the *Misikella hernsteini* Conodont Zone (as depicted by Nicoll and Foster, 1994, p. 103). The *Hebecysta balmei* Zone is attributed herein to the Middle - Late Norian or possibly to earliest Rhaetian (Fig. 6).

4.1.5 The *Rhaetogonyaulax rhaetica* Zone of Helby et al. (1987a) revised by Nicoll and Foster (1994), Backhouse and Balme (2002) and Backhouse et al. (2002)

This zone is defined by the range of prominent *Rhaetogonyaulax rhaetica,* although this is probably somewhat facies controlled with *Rhaetogonyaulax rhaetica* prominent in open marine settings and scarce in some shallower marine environments where *Wanneria listeri* is typically the most abundant dinoflagellate cyst. The inception of *Dapcodinium priscus* also marks the base of this unit, and the top is further delineated by an increase in abundance of *Dapcodinium priscus* and the range bases of *Beaumontella langii, Heibergella kendelbachia* and *Suessia* sp. A (Helby et al., 1987a, fig. 8). Accessory forms comprise *Rhaetogonyaulax wigginsii, Suessia swabiana, Noricysta* sp. and a low-diversity suite of undescribed forms.

The *Rhaetogonyaulax rhaetica* Zone was interpreted as being of Early-Middle Rhaetian age based on the inception and decline of the index species (Helby et al., 1987a, fig. 4). This age was revised to Early to Late Rhaetian by Nicoll and Foster (1994; 1998) on conodont evidence. Bralower et al. (1992) and Brenner et al. (1992) reported Rhaetian calcareous nannofossils and ostracods from the lower and upper parts of the *Rhaetogonyaulax rhaetica* Zone from the Wombat Plateau, offshore Western Australia. The *Rhaetogonyaulax rhaetica* Zone and the *Ashmoripollis reducta* Spore-pollen Zone were both correlated with the *Misikella hernsteini* and *Misikella posthernsteini* conodont zones, based on data from the Ashmore Reef-1 well (Nicoll and Foster, 1994; 1998). This age is consistent with the presence of *Rhaetogonyaulax rhaetica* in the Rhaetian of Europe (e.g. Morbey, 1975; 1978; Morbey and Dunay, 1978; Powell, 1992; Fig. 6). In the U.K. *Rhaetogonyaulax rhaetica* is common to abundant at the Westbury Formation-Lilstock Formation transition, and is frequently prominent in the unequivocal Late Rhaetian Cotham Member (e.g. Morbey, 1978; Warrington et al., 1980; Warrington and Whittaker, 1984; Lott and Warrington, 1988). The entire range of *Rhaetogonyaulax rhaetica* hence confirms the conodont dating of the *Rhaetogonyaulax rhaetica* Zone in Australia as early to late Rhaetian (Fig. 6). The major reappearance of dinoflagellate cysts at the base of the Rhaetian Stage in the Northern Carnarvon Basin also closely mirrors the progression from non-marine to marine conditions in Europe at that time. The *Rhaetogonyaulax rhaetica* Zone of Australia is therefore coeval with the *Rhaetogonyaulax rhaetica* Interval Biozone of Powell (1992) in Europe.

In summary, there is significant palynological evidence for the Rhaetian age of the *Rhaetogonyaulax rhaetica* Zone of Australia. For example, the range bases of the dinoflagellate cysts *Beaumontella langii, Dapcodinium priscus, Heibergella kendelbachia* and *Rhaetogonyaulax rhaetica* are within the Rhaetian in both Australia and Europe (Fig. 6). Herein, the Australian range top of *Rhaetogonyaulax rhaetica* is placed slightly below the Rhaetian-Hettangian boundary.The range top of common *Rhaetogonyaulax rhaetica* is in the late Rhaetian and the top of the zone is placed at this point.

4.1.6 The *Dapcodinium priscus* Zone of Helby et al. (1987a)

This zone is defined as the entire range of prominent *Dapcodinium priscus*. The base is also marked by the range tops of *Rhaetogonyaulax wigginsii* and prominent *Wanneria listeri* and *Rhaetogonyaulax rhaetica*, and the range bases of *Beaumontella langii, Heibergella kendelbachia* and *Suessia* sp. A (Helby et al., 19087a, fig. 8). Accessory forms comprise *Beaumontella langii, Heibergella kendelbachia*, sparse *Rhaetogonyaulax rhaetica, Suessia swabiana, Suessia* sp. A and a low-diversity association of undescribed forms. Helby et al. (1987a) commented that it is possible to subdivide this zone into two informal subzones. This was formalised by Backhouse and Balme (2002) who placed the Jurassic/Triassic boundary at the top of the lower subzone, coeval with the top of the *Ashmoripollis reducta* Spore-pollen Zone. Dinoflagellate cyst diversity is highest in the lower subzone, where other Triassic species are present. By contrast, the upper subzone is characterised only by the index species; this is associated with the *Corollina torosa* Spore-pollen Zone of Helby et al. (1987a) (Backhouse et al., 2002, fig. 9). As discussed above, *Susadinium* sp. A. is now *Susadinium*? *australis* and occurs within the overlying Early Toarcian *Luehndea* Assemblage of Riding and Helby (2001a).

The *Dapcodinium priscus* Zone was considered to be of Middle Rhaetian to Late Pliensbachian (possibly earliest Toarcian) age by Helby et al. (1987a, p. 15). This is based on the decline of *Rhaetogonyaulax rhaetica* at the base of the zone, and the incoming of abundant *Dapcodinium priscus* and *Corollina* within this interval (i.e. at the top of the *Ashmoripollis reducta* Spore-pollen Zone). However, *Corollina* is also typically abundant in the Rhaetian of Europe (Morbey, 1978; Fig. 6). In both Australia and Europe, *Dapcodinium priscus* ranges from the latest Triassic into the earliest Jurassic. In Europe it is most consistent in the Rhaetian and Hettangian, and is present only sporadically in the Early Sinemurian (Morbey, 1978; Feist-Burkhardt and Wille, 1992; Riding and Thomas, 1992). Therefore, based on a correlation with Europe, the *Dapcodinium priscus* Zone of Helby et al. (1987a) is reinterpreted as being of latest Rhaetian to Early Sinemurian age (Fig. 6). This accords with the situation in many well intervals in Australia, where in the Jurassic *Dapcodinium priscus* is most common in the lowest part of the upper *Dapcodinium priscus* subzone and is scarce in the highest part of its range. It is not recorded above the mid part of the *Corollina torosa* Spore-pollen Zone. The latest Rhaetian of Europe is characterised by a marked decline in *Rhaetogonyaulax rhaetica,* and an increase in

Dapcodinium priscus (see Courtinat and Piriou, 2002). In summary, the base of the *Dapcodinium priscus* Zone of Australia is considered to be within the latest Rhaetian because of a correlation with the decline in *Rhaetogonyaulax rhaetica* in the Northern Hemisphere, and the virtually synchronous ‘switchover’ with *Dapcodinium priscus* (Fig. 6). Other typical Triassic dinoflagellate cysts, notably *Suessia swabiana* and *Heibergella*? *kendelbachia*, also occur in the lower *Dapcodinium priscus* subzone.

The top of the *Dapcodinium priscus* Zone is interpreted herein to be of Early Sinemurian age based on correlation with the range of this species in Europe. Placing the top of the *Dapcodinium priscus* Zone at this point means that the Late Sinemurian and most of the Pliensbachian interval are devoid of dinoflagellate cysts in Australia (Figs. 6, 7). This situation is similar in the Northern Hemisphere, where the only records of dinoflagellate cysts are monospecific assemblages of *Liasidium variabile* in the Late Sinemurian (Weiss, 1986; Brittain et al., 2010).

4.2 The Luehndea *Assemblage of Riding and Helby (2001a)*

The *Luehndea* Assemblage of Riding and Helby (2001a) represents a significant addition to the zonation of Helby et al. (1987a) (Fig. 7). It is not placed into the scheme of dinoflagellate cyst superzones of Helby et al. (1987a) because it represents a relatively short interval, and it is isolated from the subjacent and superjacent dinoflagellate cyst successions by non-marine intervals (Foster, 2001, fig. 2; Helby et al., 2004).

The *Luehndea* Assemblage is a distinctive, low-diversity dinoflagellate cyst assemblage, which is present in the late Early Jurassic of the Timor Sea area and offshore Western Australia. It is considered to be a marginal marine association.

Riding and Helby (2001a) described an endemic flora of nine dinoflagellate cyst species from the lower Plover Formation in the Jabiru and Skua oilfields of the Timor Sea. Two dinoflagellate cyst suites were recognised. These are the *Susadinium*? Suite, which is succeeded by the more diverse *Skuadinium* Suite (Riding and Helby, 2001a, fig. 12). The two subdivisions represent dinoflagellate cyst subzones 9Bii and 9Bi respectively of Foster (2001, fig. 2). These subzones were not used in the zonations of Helby et al. (2004) and Partridge (2006) because it is not known if they, or the *Kekryphalospora distincta* Spore-pollen Zone of Foster (2001) and Riding and Helby (2001a), can be recognised regionally. This brief influx of marine microplankton overlies paralic strata, hence it is interpreted as representing a base level rise. This was probably the Early Toarcian global eustatic rise of Haq et al. (1987). Rare specimens of *Luehndea* have also been recovered from the Northern Carnarvon and Perth basins and illustrates this Early Toarcian eustatic sea-level rise is probably more widely recognisable across the northern and western Australian basins than previously thought.

The interval which includes the *Luehndea* Assemblage was considered to be earliest Toarcian by Helby et al. (1987a) based on the occurrence of *Susadinium* sp. A (= *Susadinium*? *australis*). Riding and Helby (2001a) defined the assemblage and correlated it to the Early Toarcian based on comparisons with European dinoflagellate cyst genera. Specifically, the overlapping ranges of *Luehndea* and *Susadinium*?, together with *Mendicodinium* and *Nannoceratopsis*, indicate that the assemblage is of Early Toarcian age (Morgenroth, 1970; Riding, 1987; Riding and Thomas, 1992; Bucefalo Palliani et al., 1997a,b; Bucefalo Palliani and Mattioli, 1998; Fig. 7). The recognition of *Luehndea septata* in samples up to 20-30 m below the entire *Luehndea* Assemblage suite suggests the assemblage may, in part, range down into the latest

Pliensbachian (Fig. 7). The associated spore-pollen floras are entirely consistent with the Toarcian. In particular, the occurrence of the spore *Kekryphalospora distincta* supports this correlation (Fenton and Riding, 1987; Fig. 7). Riding and Helby (2001a) also stated that two samples from the Coojong-1 well in the Northern Carnarvon Basin, earlier noted by Howe (2000) to be from the NJ5b and NJ6 calcareous nannofossil zones, contained *Luehndea* Assemblage palynofloras. This provides strong independent evidence for the latest Pliensbachian to Early Toarcian age assigned herein to the *Luehndea* Assemblage.

4.3 The Pareodinia ceratophora *Superzone of Helby et al. (1987a)*

The *Pareodinia ceratophora* Superzone was considered to be of Early Bajocian to earliest Oxfordian age, and is recognised in Western Australia, South Australia, northern Queensland and Papua New Guinea (Helby et al., 1987a). This extensive distribution is due to the dominantly nearshore/shallow marine nature of the Bajocian to lowermost Oxfordian strata of Australasia. The superzone is characterised by the consistent occurrence of *Pareodinia ceratophora* and a diversification of dinoflagellate cysts throughout. This radiation includes the inceptions of important gonyaulacacean lineages, for example the range base of *Wanaea* in the Late Bajocian. The oldest subdivision, the *Dissiliodinium caddaense* Zone, represents a widespread marine transgression; this appears to be related to the Early Bajocian part of the LZA-1 Supercycle of Haq et al. (1987). This was followed by a regression during the Late Bajocian-Early Bathonian (Helby et al., 1987a, fig. 46). Following this eustatic fall, an apparently continuous record of marine palynomorphs throughout the Middle and Late Jurassic and most of the Cretaceous was established (Helby et al., 1987a, figs. 45, 46).

The trend of a transition from low-diversity dinoflagellate cyst floras dominated by genera such as *Dissiliodinium, Nannoceratopsis* and *Pareodinia* in the Bajocian, followed by a radiation of gonyaulacacean forms including the inceptions of genera with epicystal archaeopyles (e.g. *Ctenidodinium* and *Wanaea*) in the Bathonian, and further diversification during the Callovian and earliest Oxfordian is global (Figs. 8, 9). This floral succession is observed throughout the Americas, Australasia, Europe and the Middle East (e.g. Johnson and Hills, 1974; Bujak and Williams, 1977; Davies, 1983; Woollam and Riding, 1983; Prauss, 1989; Conway, 1990; Poulsen, 1996; Quattrocchio et al., 1996). This evolutionary pattern is therefore of high chronostratigraphical significance, albeit at a broad level of resolution. The stratigraphical ranges of selected cosmopolitan dinoflagellate cyst taxa within this Superzone are illustrated as Figs. 8 and 9.

4.3.1 The *Dissiliodinium caddaense* Zone of Helby et al. (1987a), revised by Helby et al. (2004)

The *Dissiliodinium caddaense* Zone was defined using the total range of *Meiourogonyaulax* sp. A of Helby et al. (1987a). However, the definition of this Early Bajocian biozone was redefined by Helby et al. (2004) as the range of consistent *Dissiliodinium caddaense*. This was because the tripartite subdivision of the zone, based on an acme of *Dissiliodinium caddaense* in the middle part of the unit, noted by Helby et al (1987a, fig. 15) cannot be recognised outside of the Perth Basin. Diversity was relatively low throughout the *Dissiliodinium caddaense* Zone; Helby et al. (1987a, fig. 15) and Riding et al. (2010) reported twelve taxa. These include the long-ranging *Batiacasphaera* spp., *Nannoceratopsis* spp., *Pareodinia ceratophora*, *Pareodinia halosa* and *Pareodinia* spp. The more restricted *Dissiliodinium* *caddaense*, *Dissiliodinium* sp. (no antapical node) of Helby et al. (1987a), *Meiourogonyaulax* sp. A, *Nannoceratopsis deflandrei*, *Nannoceratopsis spiculata*, and *Phallocysta erregulensis* are also present. Acmes of *Dissiliodinium caddaense* and *Phallocysta erregulensis* may be present in the middle part, and *Dissiliodinium* sp. (no antapical node) characterises the upper part of the zone (Helby et al., 1987a, fig. 15).

The *Dissiliodinium caddaense* Zone is dated as Early Bajocian on the basis of the molluscan faunas of the Newmarracarra Limestone of the Champion Bay Group and correlatives such as the Cadda Formation in the Perth Basin (Filatoff, 1975, p. 7, fig. 2). Arkell and Playford (1954), Arkell (1956) and Playford et al. (1975) stated that the Newmarracarra Limestone faunas are referable to the early Bajocian Discites and Laeviuscula chronozones, possibly extending into the Sauzei and Humphriesianum chronozones. This was refined to the early Laeviuscula Chronozone (Westermann and Wang, 1988; Riding et al., 2010) on the basis of ammonite and strontium isotope evidence from the Northern Carnarvon Basin (Tusk-1 and 2 wells). This tie point to the early Laeviuscula Chronozone is accurate and reliable; it is the best link to the European standard succession in the entire Jurassic of Australia. Foraminiferal data are also consistent with the Early Bajocian (Apthorpe, 1994; 2003). Calcareous nannofossils indicate a correlation with the uppermost NJ8 and NJ9 nannofossil zones, which gives a Middle Aalenian to Early Bajocian age (Howe, 2000). Thus the *Dissiliodinium caddaense* Zone is interpreted herein to range from the base of the Bajocian to the top of the NJ9 Nannofossil Zone. Hence it encompasses the entire Laeviuscula Chronozone.

In terms of dinoflagellate cyst biostratigraphy, *Dissiliodinium* spp., *Nannoceratopsis* spp., *Pareodinia ceratophora*, *Pareodinia halosa* and *Wanaea* sp.

are known from the Early Bajocian of Europe (e.g. Fenton and Fisher, 1978; Fenton, 1981; Feist-Burkhardt, 1990; Riding et al., 1991; Feist-Burkhardt and Monteil, 1997; Fig. 8). *Dissiliodinium, Pareodinia* and *Wanaea* are especially significant because the range bases of these genera are typically Bajocian (Fig. 8). The range top of *Nannoceratopsis deflandrei* and the range base of *Nannoceratopsis spiculata* are both Early Bajocian (Stover, 1966; Gowland and Riding, 1991; Feist-Burkhardt and Monteil, 1997), whilst the range base of *Dissiliodinium* is relatively concurrent in the Aalenian and Bajocian of Europe and Australasia, respectively (Fig. 8). Furthermore, the lack of diverse gonyaulacacean dinoflagellate cysts strongly suggests that this zone is largely of Early Bajocian age (Feist-Burkhardt and Wille, 1992, fig. 2; Feist-Burkhardt and Monteil, 1997, figs 4, 5).

Phallocysta erregulensis is confined to the *Dissiliodinium caddaense* Zone and closely resembles *Phallocysta elongata*. The latter differing only in having a consistently smooth endocyst, a geniculate, type 3I, periarchaeopyle and being somewhat less variable in outline. *Phallocysta elongata* ranges from the latest Toarcian to the Early Bajocian in Europe (Riding, 1994) and hence in a morphostratigraphical sense, *Phallocysta erregulensis* is consistent with the Early Bajocian (Fig. 8).

A potential Middle Jurassic evolutionary lineage can be invoked in that *Dissiliodinium caddaense* appears be an evolutionary precursor of *Wanaea*. The specimens of *Dissiliodinium caddaense* illustrated by Stover and Helby (1987a, figs 4A-D) closely resemble the early, simple (energlynoid/non-flanged) representatives of *Wanaea*, especially *Wanaea verrucosa* (see Riding and Helby, 2001b). *Dissiliodinium* has a multiplate (1-5P) polyplacoid precingular archaeopyle and *Wanaea* has an epicystal archaeopyle. However, if the precingular plates in *Dissiliodinium caddaense* did not separate laterally and apically (i.e. from the apical plate series), the archaeopyle type would change from being polyplacoid precingular to epicystal. The morphologies are otherwise similar, so it seems possible that *Wanaea* originated in this way. This scenario is typical of the experimentation in archaeopyle styles in the Bajocian (Feist-Burkhardt and Monteil, 2001).

4.3.2 The *Nannoceratopsis deflandrei* Zone of Foster (2001) and Helby et al. (2004)

The *Caddasphaera halosa* Zone of Helby et al. (1987a) proved to be somewhat poorly defined and understood. Consequently, this unit was replaced by the *Nannoceratopsis deflandrei* and *Wanaea verrucosa* zones by Helby et al. (2004). These zones were defined on more distinctive taxa than the *Caddasphaera halosa* Zone. This strategy also allowed the closing of the stratigraphical gap in the zonation between the *Dissiliodinium caddaense* and *Caddasphaera halosa* zones of Helby et al. (1987a, fig. 15).

The *Nannoceratopsis deflandrei* Zone of Helby et al. (2004) was defined as the interval between the range top of consistent *Dissiliodinium caddaense* and the range top of *Nannoceratopsis deflandrei*, together with the range base of *Wanaea verrucosa*. Two divisions can be recognised based on the range base of ‘spiny varieties’ of *Ctenidodinium* (Helby et al., 2004, figs. 1, 4). This zone is characterised by low diversity assemblages. These comprise *Acanthaulax* cf. *crispa*, *Batiacasphaera* spp., *Ctenidodinium* spp. (spiny varieties), *Dissiliodinium* sp. (no antapical node), *Nannoceratopsis deflandrei, Nannoceratopsis* cf. *spiculata, Nannoceratopsis* spp., *Pareodinia ceratophora*, *Pareodinia halosa, Pareodinia* spp., *Phallocysta granosa* and *Scriniocassis* sp. (Helby et al., 1987a, fig. 15; unpublished data).

The *Nannoceratopsis deflandrei* Zone was assigned to the Late Bajocian by Helby et al. (2004, figs. 1, 4) and Partridge (2006). The only independent evidence of the age of this unit is from the calcareous nannofossil assemblages in the partially coeval *Dictyotosporites complex* Spore-pollen Zone. These suggest a correlation with the NJ9 or younger nannofossil zones (Howe, 2000) which are considered indicative of an Early Bajocian or younger age.

The presence of *Acanthaulax* cf. *crispa, Ctenidodinium* spp., *Dissiliodinium* spp., *Nannoceratopsis deflandrei, Nannoceratopsis* cf. *spiculata, Nannoceratopsis* spp. and *Pareodinia* spp. is consistent with a mid Bajocian age when compared to the Northern Hemisphere dinoflagellate cyst record (Fig. 8). For example, according to Feist-Burkhardt and Monteil (1997, figs. 4,5), the range bases of *Acanthaulax crispa, Ctenidodinium* spp. and *Nannoceratopsis spiculata,* and the range top of *Nannoceratopsis deflandrei* (as *Nannoceratopsis gracilis*) lie close to the Early-Late Bajocian transition (Fig. 8). The presence of *Scriniocassis* sp. is also consistent with the Early-Late Bajocian transition (Riding and Thomas, 1992). The low-diversity nature of the assemblages in the *Nannoceratopsis deflandrei* Zone is most similar to Early Bajocian of the Northern Hemisphere (Riding, 1987; Feist-Burkhardt, 1990; Riding et al., 1991; Feist-Burkhardt and Monteil, 1997).

Given that the underlying *Dissiliodinium caddaense* Zone is of unequivocal Early Bajocian age, the *Nannoceratopsis deflandrei* Zone is interpreted here as being of late Early to Late Bajocian age due to evidence from calcareous nannofossils and dinoflagellate cysts. On the basis of European dinoflagellate cyst ranges, this interval includes the Early-Late Bajocian transition. Hence the base of the *Nannoceratopsis* *deflandrei* Zone has been extended into the Early Bajocian (Figs. 4, 8). This zone is only recognized in a small number of wells through what is normally a non-marine or marginal marine succession.

4.3.3 The *Wanaea verrucosa* Zone of Foster (2001) and Helby et al. (2004)

The *Wanaea verrucosa* Zone replaced the upper part (7ci) of the *Caddasphaera halosa* Zone of Helby et al. (1987a). This zone is defined by the stratigraphical range of *Wanaea verrucosa*. The base and top are also defined by the apparent extinction of *Nannoceratopsis deflandrei* and the inception of *Wanaea indotata* respectively.

This zone yields dinoflagellate cyst associations with a high diversity of largely undescribed species (R. Helby, personal communication). The described taxa comprise *Batiacasphaera* spp., *Ctenidodinium ancorum*, *Endoscrinium kempiae, Nannoceratopsis* spp., *Pareodinia ceratophora*, *Pareodinia halosa, Pareodinia* spp., *Phallocysta granosa, Ternia balmei*, *Valvaeodinium spinosum, Wanaea enoda, Wanaea lacuna* and *Wanaea verrucosa* (see Helby et al., 1987a, fig. 15; Riding and Helby, 2001b, figs. 11, 12; Helby et al., 2004; unpublished data). The diversity increases up-section, and the range bases of *Valvaeodinium spinosum* and *Endoscrinium kempiae* define three subzones (Foster, 2001, fig. 2; Helby et al., 2004, fig. 4; Partridge, 2006).

The *Wanaea verrucosa* Zone or equivalents were assigned to the Early to Middle Bathonian, with no independent evidence (Helby et al., 1987a, fig. 12; Helby et al., 2004, fig. 4; Partridge, 2006). In Europe, the occurrences of simple (non-flanged) species of *Wanaea,* in the absence of prominent *Ctenidodinium* spp. are indicative of the Late Bajocian (Feist-Burkhardt and Monteil, 1997, figs. 4, 5; Fig. 8). *Ctenidodinium* spp. are present in the Late Bajocian, however this genus became prominent in the Early Bathonian in the Northern Hemisphere (Riding et al., 1985; Feist-Burkhardt and Monteil, 1997, figs. 4, 5; Riding et al., 1999, fig. 15; Fig. 8). The range base of *Valvaeodinium spinosum* is typically close to the Early-Late Bajocian transition (Feist-Burkhardt and Monteil, 1997). Furthermore, specimens recorded in this zone as *Endoscrinium luridum* are similar in morphology to the European taxon *Endoscrinium asymmetricum*. The range base of *Endoscrinium asymmetricum* is early Late Bajocian (Feist-Burkhardt and Wille, 1992, fig. 2), hence a correlation is eminently possible based on this morphostratigraphical evidence.

In summary, the highly diverse yet largely undescribed assemblages from the *Wanaea verrucosa* Zone are far more characteristic of the Late Bajocian than the Bathonian based on comparisons with Europe. Hence, the *Wanaea verrucosa* Zone is here assigned to the Late Bajocian to Early Bathonian (Fig. 8).

4.3.4 The *Wanaea indotata* Zone of of Helby et al. (1987a)

The *Wanaea indotata* Zone of Helby et al. (1987a) is the interval between the range bases of *Wanaea indotata* and *Wanaea digitata*. There is an acme occurrence of *Fusiformacysta challisiana* in the middle of the zone. This zone typically yields moderately diverse dinoflagellate cyst assemblages, including undescribed morphotypes. *Aldorfia aldorfensis, Chytroeisphaeridia chytroeides, Ctenidodinium ancorum, Durotrigia* spp., *Ellipsoidictyum/Valensiella* spp., *Endoscrinium kempiae, Endoscrinium luridum, Fusiformacysta terniana, Glossodinium dimorphum, Lithodinia protothymosa*, *Nannoceratopsis pellucida*, *Nummus apiculus* (acritarch), rare *Pareodinia ceratophora, Pareodinia halosa, Ternia balmei, Valvaeodinium spinosum* and rare *Wanaea enoda* are also present (Helby et al., 1987a, fig. 15; Riding and Helby, 2001b,d; Riding and Fensome, 2002, fig. 2; unpublished data).

The *Wanaea indotata* Zone was given a latest Bathonian to earliest Callovian age by Helby et al. (1987a). The base was revised to early Late Bathonian by Helby et al. (2004) and Partridge (2006). The first occurrence of *Wanaea digitata* at the top of the zone was used as independent evidence by Helby et al. (1987a) to apply an earliest Callovian age to this boundary. In Europe, this datum is intra-mid Callovian (Riley and Fenton, 1982). Calcareous nannofossils from immediately below a horizon referable to the *Wanaea indotata* Zone in the Capella-1 well are ascribed by Howe (2000) to the NJ11 calcareous nannofossil Zone. The NJ11 Zone, as utilised in the Northern Hemisphere, is latest Bajocian to early Late Bathonian and this represents the only independent age control for the *Wanaea indotata* Zone.

By comparison with European dinoflagellate cyst floras, the *Wanaea indotata* Zone is highly unlikely be younger than Middle Callovian due to the absence of complex flanged forms of *Wanaea, Rigaudella aemula, Stephanelytron* spp. and consistent *Gonyaulacysta jurassica* (see Feist-Burkhardt and Wille, 1992; Riding and Thomas, 1997, fig. 2; Riding, 2005b; Fig. 8). The presence of forms such as *Aldorfia aldorfensis, Ctenidodinium sellwoodii/tenellum, Ellipsoidictyum/Valensiella* spp. and *Korystocysta* spp. are highly characteristic of the Bathonian (Gocht, 1970; Riding et al., 1985; Fig. 8). The *Ctenidodinium sellwoodii/tenellum* group is especially significant. In Europe, *Ctenidodinium sellwoodii* first occurs in the Bajocian and is consistently common to abundant throughout the Bathonian (Riding et al., 1985; 1991; Feist-Burkhardt and Monteil, 1997; Fig. 8). Similarly, in Australia, the range base of *Ctenidodinium ancorum* (similar morphotype to the *Ctenidodinium* *sellwoodii/tenellum* complex) extends down to the upper *Wanaea verrucosa* Zone and is consistently common through the *Wanaea indotata* to *Ctenidodinium ancorum* zones (Riding and Helby, 2001d). These bioevents are considered to be broadly synchronous in the latest Bajocian to Bathonian of Europe and Australasia. Thus supporting a latest Bajocian age for the *Wanaea verrucosa* Zone and a Bathonian age for the *Wanaea indotata* Zone. The presence of *Glossodinium dimorphum* in this zone is interesting. The range base of this species in the Northern Hemisphere is Middle Oxfordian (e.g. Riding and Thomas, 1992). Hence its range base is sigificantly older in the Southern Hemisphere.

In summary, the *Wanaea indotata* Zone is assigned herein to the late Early to Late Bathonian on the basis of evidence from calcareous nannofossils and dinoflagellate cysts.

4.3.5 The *Ternia balmei* Zone of Helby et al. (2004)

The *Wanaea digitata* and *Rigaudella aemula* zones of Helby et al. (1987a) proved difficult to use due to widespread inconsistency in the recognition of the oldest occurrence of *Riguadella aemula* between Australian basins due to facies differences (Helby et al., 2004). The range base of *Rigaudella aemula* was used to delineate the *Wanaea digitata* and *Rigaudella aemula* zones by Helby et al. (1987a). Hence Helby et al. (2004) replaced these two zones with three new subdivisions, the largely Callovian *Ternia balmei, Voodooia tabulata* and *Ctenidodinium ancorum* zones. This was deemed a better strategy than revising the existing zones.

The *Ternia balmei* Zone replaced the *Wanaea digitata* Zone and the lower part (subzones 7aiibii and 7aiibi) of the *Rigaudella aemula* Zone of Helby et al. (1987a).

The *Ternia balmei* Zone was defined as the interval between the range base of *Wanaea digitata* and the range top of *Ternia balmei*. The zone can be subdivided using the range bases of *Riguadella aemula* and *Voodooia tabulata,* the range top of *Lithodinia protothymosa* and the *Durotrigia magna* acme (Helby et al. (2004, figs 1, 3).

The dinoflagellate cyst assemblages of the *Ternia balmei* Zone are significantly more diverse than the underlying subdivisions. These associations include the dinoflagellate cysts *Chytroeisphaeridia chytroeides, Ctenidodinium ancorum, Ctenidodinium fuscibasilarum, Ctenidodinium planocristatum, Durotrigia magna, Ellipsoidictyum/Valensiella* spp.*, Fostericysta eclipsiana, Fusiformacysta challisiana, Glossodinium dimorphum, Gonyaulacysta jurassica, Lithodinia protothymosa, Meiourogonyaulax penitabulata, Meiourogonyaulax viriosa, Nannoceratopsis pellucida, Nannoceratopsis reticulata, Paragonyaulacysta* spp., *Pareodinia ceratophora,* rare *Pareodinia halosa, Rigaudella aemula, Tabulodiniun senarium, Ternia balmei, Tubotuberella dangeardii, Voodooia tabulata,* prominent *Wanaea digitata, Wanaea indotata, Woodinia pedis* and *Yalkalpodium elangiana* (see Helby et al., 1987a; Riding and Helby, 2001d; Riding and Fensome, 2002, fig. 2; Mantle 2009a,b; unpublished data). The acritarchs *Nummus apiculus* and *Wuroia capnosa* are also present.

The *Ternia balmei* Zone was assigned to the Early to Late Callovian by Helby et al. (2004). Helby et al. (1988) described macrofaunas and palynofloras referable to the *Ternia balmei* Zone from the Oraka Sandstone of Kawhia, North Island, New Zealand. These authors assigned an undifferentiated Callovian age to this biota, significantly emending the Late Callovian to Kimmeridgian age of Hudson et al. (1987). The age of the Oraka Sandstone was also discussed by Stevens (1997, p. 97).

Calcareous nannofossils provide only a rather imprecise Bathonian or younger age for the *Ternia balmei* Zone (Howe, 2000).

Helby et al. (1987a, fig. 12) used the European range base of *Wanaea digitata* at the base of the Zone to derive a Middle Callovian age. The range base of complex flanged forms of *Wanaea* (including *Wanaea digitata*) is Middle-Late Callovian in Europe (Riley and Fenton, 1982; Riding and Thomas, 1992; Fig. 9). The inception of diverse dinoflagellate cysts including *Atopodinium prostatum, Clathroctenocystis asaphes*, *Gonyaulacysta eisenackii,* consistent *Gonyaulacysta jurassica, Limbodinium absidatum, Paragonyaulacysta* spp., *Rhynchodiniopsis cladophora, Rigaudella aemula, Sirmiodinium grossii*, *Stephanelytron* spp. and *Tubotuberella dangeardii* are indicative of the Callovian Stage in Europe (e.g. Riding, 1987; 2005b; Feist-Burkardt and Wille, 1992; Martill et al., 1994; Riding and Thomas, 1992; 1997). A comparison of these ranges with those for Australia is given in Fig. 9. For example the range base of consistent *Gonyaulacysta jurassica* occurs close to the base of this zone in Australia (unpublished data). In Europe the range base of consistent records of this species is in the Early-Middle Callovian (Riding et al., 1999; Fig. 9). The presence of the *Ctenidodinium*, *Durotrigia* and *Meiourogonyaulax/Lithodinia* groups in the *Ternia balmei* Zone (Riding and Helby, 2001d) is further support for a Callovian age. These genera are prominent in the Callovian, and far less typical of the Oxfordian in Europe (Fig. 9). *Fostericysta eclipsiana* is similar in morphology to *Jansonia scarffei,* however the latter species is confined to the Middle-Late Bathonian (Tykoezinski et al., 2000).

To conclude, the *Ternia balmei* Zone is herein considered to be of Early to Middle Callovian age (Figs. 4, 9).

4.3.6 The *Voodooia tabulata* Zone of Helby et al. (2004)

The *Voodooia tabulata* Zone replaced subzones 7aiiaii and 7aiiai from the upper part of the *Rigaudella aemula* Zone of Helby et al. (1987a). It was defined as the interval between the range tops of *Ternia balmei* and *Voodooia tabulata* (Helby et al., 2004, fig. 1). The dinoflagellate cyst assemblages are extremely similar in both diversity and taxonomic spectrum to those from the underlying *Ternia balmei* Zone. Inceptions of Australasian species in this zone include *Cygnusicysta talterniana, Systematophora geminus, Tringadinium bjaerkei, Tringadinium comptum, Tubotuberella apatela* and *Woodinia bensonii* (see Riding and Helby, 2001e).

This unit was assigned to the Late Callovian by Helby et al. (2004). There are no reliable macrofaunal ties for the Australian Callovian biozones, thus the dinoflagellate cyst correlations for this and adjacent zones and the Early Oxfordian macrofaunal tie points for the immediately younger *Wanaea spectabilis* Zone provide the strongest evidence for a Late Callovian age for the *Voodooia tabulata* Zone.

The dinoflagellate cyst correlations supporting this latest Callovian age are represented by the diverse dinoflagellate cyst associations which include stratigraphically significant and geographically widespread forms such as *Atopodinium prostatum,* consistent *Gonyaulacysta eisenackii, Gonyaulacysta jurassica, Limbodinium absidatum, Mendicodinium* spp., *Rhynchodiniopsis cladophora, Rigaudella aemula, Scriniodinium dictyotum, Tabulodinium senarium, Tubotuberella apatela, Tubotuberella dangeardii* and *Wanaea digitata* (see Davey, 1988; Helby et al., 1987a; unpublished data; Fig. 9). In Europe, there was a similar significant increase in dinoflagellate cyst diversity in the Late Callovian, with many important and characteristic taxa having inceptions (e.g. Riding and Thomas, 1992, fig. 2.11). The presence of common *Ctenidodinium, Lithodinia* and

Meiourogonyaulax in the *Voodooia tabulata* Zone is additional support for restricting this zone to the Late Callovian (see section 4.3.5).

4.3.7 The *Ctenidodinium ancorum* Zone of Helby et al. (2004)

The *Ctenidodinium ancorum* Zone was defined as the interval between the range top of *Voodooia tabulata* and the range base of S*criniodinium crystallinum* (Helby et al., 2004, figs. 1, 3; Partridge, 2006). The range top of *Ctenidodinium ancorum* marks the middle part of the zone (Helby et al., 2004, figs. 1, 3). However, in a detailed study of nine wells from the Bayu-Undan Field, Timor Sea, Mantle (2009b) found that the last occurrences of *Voodooia tabulata* and *Ctenidodinium ancorum* were largely synchronous. In Undan-2, *Voodooia tabulata* was recorded with a younger last appearance datum than *Ctenidodinium ancorum*. Thus, the last appearance datum of *Voodooia tabulata* may not always be a consistent boundary marker for the *Ctenidodinium ancorum* and *Voodooia tabulata* zones in the Timor Sea region. It may also be that the Callovian unconformity removed parts of the *Ctenidodinium ancorum* Zone.

The *Ctenidodinium ancorum* Zone *sensu* Helby et al. 2004 replaced subzones 7aib and 7aia from the uppermost part of the *Rigaudella aemula* Zone of Helby et al. (1987a). The 7aib assemblages are substantially similar to those in the underlying *Voodooia tabulata* Zone although diversity is somewhat decreased (section 4.3.6; Fig. 9). However, the 7aia assemblages are essentially *Wanaea spectabilis* Zone assemblages without *Scriniodinium crystallinum*. Mantle (2009b) considered that this subzone should represent the lowermost *Wanaea spectabilis* Zone. As the *Ctenidodinium ancorum* Zone appears somewhat ambiguously constrained, and is typically a thin interval, further investigations may deem it necessary to place the lower and upper portions of this zone into the *Voodooia tabulata* and *Wanaea spectabilis* zones respectively. One endemic Australasian species with an inception in the currently accepted framework for this zone is that of rare *Pyxidiella pandora*.

This unit was assigned to the Early Oxfordian by Helby et al. (2004). An earliest Oxfordian age is consistent with the marked decrease in abundance of *Ctenidodinium*, *Lithodinia* and *Meiourogonyaulax,* as is also recorded in Europe (Fig. 9). Furthermore, the respective Late Callovian and Early Oxfordian ages of the subjacent *Voodooia tabulata* and the superjacent *Wanaea spectabilis* zones support the earliest Oxfordian age herein assigned to the *Ctenidodinium ancorum* Zone.

4.4 The Pyxidiella *Superzone of Helby et al. (1987a)*

The *Pyxidiella* Superzone of Helby et al. (1987a) was named after the Late Jurassic dinoflagellate cyst *Pyxidiella pandora*, and is based on the *Dingodinium jurassicum* Zone of Evans (1966). It comprises three dinoflagellate cyst zones, and ranges in age from the early Oxfordian to Kimmeridgian according to Helby et al. (1987a; 2004) and Partridge (2006). The Superzone is characterised by abundant and diverse dinoflagellate cyst assemblages, with several important inceptions (Helby et al., 1987a, fig. 15). *Pyxidiella* Superzone palynofloras are present across the North West Shelf and the Papuan Basin. The formation of grabens in the North West Shelf led to the deposition of thick, organic-rich Oxfordian-Kimmeridgian sediments. By contrast, in areas unaffected by these tectonic controls, the coeval strata are thin and intermittent. Organic-rich source rocks of this age were developed worldwide at this time (Miller, 1990).

4.4.1 The *Wanaea spectabilis* Zone of Helby et al. (1987a)

The *Wanaea spectabilis* Zone was defined as the interval between the range base of *Scriniodinium crystallinum,* and the range base of consistent *Wanaea clathrata* (Helby et al., 1987a; 2004). Stratigraphically important datums within this zone include the range tops of *Fostericysta eclipsiana*, *Systematophora geminus, Wanaea digitata* and consistent *Microdinium jurassicum,* the range bases of *Dingodinium jurassicum*, *Gonyaulacysta ceratophora*, *Oligosphaeridium* spp., *Wanaea spectabilis* and *Wanaea talea,* and acmes of *Cygnusicysta talterniana, Oligosphaeridium* spp., and *Woodinia bensonii* (Helby et al. 1987a; Riding and Helby, 2001e; Helby et al., 2004, figs. 1, 3; Partridge, 2006). Helby (1987a, fig. 15) illustrated *Wanaea spectabilis* as ranging throughout this biozone. This species is now interpreted as being confined to the upper part of this zone, with rare specimens present in the lowermost part of the *Wanaea clathrata* Zone (Riding and Helby, 2001b, figs. 11, 12; Helby et al., 2004, figs. 1, 3; Partridge, 2006).

There is a marked increase in dinoflagellate cyst diversity at the base of this zone with many specific inceptions (Helby et al., 1987a, fig. 15). Cosmopolitan taxa present in this zone include *Chytroeisphaeridia cerastes, Clathroctenocystis asaphes, Ellipsoidictyum cinctum, Endoscrinium galeritum, Endoscrinium luridum, Fromea tornatilis*, *Gonyaulacysta centriconnata*, *Gonyaulacysta eisenackii*, *Gonyaulacysta jurassica, Leptodinium ambiguum, Leptodinium mirabile, Limbodinium absidatum, Mendicodinium groenlandicum, Nannoceratopsis pellucida*, *Pareodinia* spp., *Rhynchodiniopsis cladophora*, *Rigaudella aemula, Scriniodinium crystallinum, Scrinodinium dictyotum, Sentusidinium* spp., *Stephanelytron-Lagenadinium* spp., *Tubotuberella apatela, Tubotuberella dangeardii* and *Wanaea digitata/fimbriata* (see

Davey, 1988; 1999; Helby et al., 1987a, fig. 15; Riding and Fensome, 2002, fig. 2; unpublished data). Indigenous Australasian forms include *Cassiculosphaeridia solida, Chlamydophorella wallala, Cygnusicysta talterniana* (acme), *Dingodinium jurassicum, Dingodinium swanense, Fostericysta eclipsiana, Fusiformacysta challisiana, Gonyaulacysta ceratophora, Microdinium jurassicum, Nummus tithonicus* (acritarch), *Oligosphaeridium swanense, Productodinium chenii, Prolixosphaeridium capitatum, Pyxidiella pandora, Systematophora geminus, Tringadinium bjaerkei, Tringadinium comptum, Wanaea spectabilis, Wanaea talea, Woodinia bensonii* and *Yalkalpodium elangiana* (see Davey, 1988; Helby et al., 1987a; Riding and Helby, 2001b,d,e,f,g; Riding and Fensome, 2002). Hence the trend of relatively high dinoflagellate cyst diversity initiated during the Late Callovian is continued throughout the Oxfordian in both Australia and Europe. Wilson and Helby (1987) described an Oxfordian dinoflagellate cyst association from North Canterbury, New Zealand which closely resembles both Australian and European Early-Middle Oxfordian palynofloras.

The *Wanaea spectabilis* Zone was deemed to be Early to Middle Oxfordian by Helby et al. (1987a, p. 29). Foster (2001, fig. 2), Helby et al. (2004) and Partridge (2006) revised this to Early to Late Oxfordian. The Oxfordian correlation was based on unpublished ammonite evidence provided by W.J. Arkell (Helby et al., 1987a, fig. 12). This material, from the Cape Range-1 well between 1620 and 1585 m, lies in the middle part of the *Wanaea spectabilis* Zone (Helby and Powis, 1981). J. Backhouse (unpublished data) noted that Helby et al. (1987a, p. 17) mistakenly attributed these ammonites to the *Wanaea clathrata* Zone. Francis and Westermann (1993, p. 86, figs. 7,8) stated that the ammonites in the Cape Range-1 well are large *Perisphinctes* sp., and are possibly referable to the Middle Oxfordian *Mayaites-Perisphinctes*

Assemblage of the Sula Islands, Indonesia (Arkell, 1956; McWhae et al., 1958). This is broadly consistent with the Late Oxfordian ammonites from Kawhia, New Zealand found in two samples probably referable to the *Wanaea spectabilis* Zone (Helby et al., 1988). These two samples are from the base of the Ohineruru Formation which Stevens (1997) attributed to the Early Kimmeridgian but is now considered Middle Oxfordian (Campbell et al., 2004). Howe (2000) could only assign samples from this zone to the NJ9 Nannofossil Zone or younger, which means an age no older than Bathonian. However, some samples from the Alaria-1 well yielded calcareous nannofossil assemblages that are probably referable to the NJ15b and NJ16 nannofossil zones. This suggests, at least in part, a latest Oxfordian to Kimmeridgian age. The interpretations of Francis and Westermann (1993, fig. 7) were adapted by Davey (1999, p. 30), who concluded that the top of his LJ11 Zone is no younger than Middle Oxfordian. The majority of the non-dinoflagellate cyst biostratigraphical evidence indicates a Middle-Late Oxfordian age for the *Wanaea spectabilis* Zone.

Many of the cosmopolitan taxa recorded in the *Wanaea spectabilis* Zone of Australia are characteristic of the Oxfordian in the Northern Hemisphere (see above). Examples include *Atopodinium prostatum, Clathroctenocystis asaphes, Endoscrinium galeritum, Fromea tornatilis, Gonyaulacysta centriconnata, Limbodinium absidatum, Rigaudella aemula, Scriniodinium crystallinum, Stephanelytron* spp. and *Wanaea digitata/fimbriata* (e.g. Feist-Burkhardt and Wille, 1992; Riding and Thomas, 1992; Fig. 9). Specifically, *Fromea tornatilis, Gonyaulacysta centriconnata, Limbodinium absidatum, Rigaudella aemula,* and *Wanaea digitata/fimbriata* are characteristic of the Early-Middle Oxfordian in Europe (Riding and Thomas, 1997; Riding et al., 1999; Riding, 2005b). Davey (1988; 1999) recorded *Wanaea digitata/fimbriata* from the *Wanaea spectabilis* Zone of Papua New Guinea; this species is a reliable Early

Oxfordian marker throughout the Northern Hemisphere (e.g. Riding and Thomas, 1992). The prominent presence of *Gonyaulacysta ceratophora* in this interval is also significant because this Australian species is similar in morphology to *Gonyaulacysta jurassica* subsp. *adecta* var. *longicornis* (Riding, 2005a). The latter is characteristic of the Early-Middle Oxfordian of Europe (Riding and Thomas, 1997; Riding, 2005b; Fig. 9). Additionally, the range bases of consistent *Dingodinium*, *Leptodinium* and unequivocal *Systematophora* are markers for the Oxfordian; these genera are rare or unknown from the Callovian in the Northern Hemisphere (Riding and Thomas, 1992). Hence the dinoflagellate cyst evidence for the *Wanaea spectabilis* Zone points to the Early-Middle Oxfordian. This is broadly consistent with Francis and Westermann (1993, fig. 7), and compares with a Middle-Late Oxfordian age on the non-dinoflagellate cyst biotas (see above).

In summary, on the balance of all the biotal evidence and the ages of the adjacent zone, the *Wanaea spectabilis* Zone is interpreted as being of Early to early Late Oxfordian age (Figs. 4, 9).

4.4.2 The *Wanaea clathrata* Zone of Helby et al. (1987a)

The *Wanaea clathrata* Zone was defined as the interval between the range base of consistent *Wanaea clathrata* and the range top of *Wanaea clathrata* (Helby et al. (1987a; 2004). The diverse accessory forms are substantially similar to those from the underlying *Wanaea spectabilis* Zone. However the range bases of *Indodinium khariense, Striatodinium lineatum* and *Striatodinium ottii* occur in this zone (Riding and Helby, 2001f).

The *Wanaea clathrata* Zone was interpreted as latest Oxfordian to earliest Kimmeridgian by Helby et al. (1987a; 2004), Foster (2001) and Partridge (2006). Helby et al. (1987a, fig. 19) indicated that the Kimmeridgian ammonites (*Kossmatia* sp.) and belemnites (*Retroceramus galoi*) are present in the upper part of the zone (Arkell, 1956; Balme, 1957; Wiseman, 1980). This material from the Cape Range-1 (1316-1189 m) and Cape Range-2 (1380-1212 m) wells in the Carnarvon Basin was considered to be “possibly Middle or Early Kimmeridgian” by Wiseman (1980). However, Francis and Westermann (1993, p. 86) asserted that the identification of *Kossmatia* sp. is possibly a misidentification of the Late Oxfordian “*Perisphinctes*” *sularus-moluccanus* group (“*P. indicus*”). Francis and Westermann (1993, p. 81) also described Middle or Late Oxfordian molluscan faunas from the Misool Islands, Indonesia associated with the *Wanaea clathrata* Zone. Consequently, Francis and Westermann (1993, fig. 7) assigned the *Wanaea clathrata* Zone to the Late Oxfordian. Davey (1988, fig. 3) also interpreted the *Wanaea clathrata* Zone as being Early-Middle Oxfordian on dinoflagellate cyst evidence; this was subsequently revised to Middle-Late Oxfordian (Davey, 1999, figs 8, 9). However, Helby and Hasibuan (1988, fig.1, sample 64/65) recorded bivalve (*Malayomaorica malayomaorica*) and belemnite (*Retroceramus haasti*) species whose range overlap strongly supports an Early Kimmeridgian age for the upper *Wanaea clathrata* Zone. Further evidence that the *Wanaea clathrata* Zone is probably not wholly Oxfordian is provided by latest Oxfordian to earliest Kimmeridgian calcareous nannofossils associated with the underlying *Wanaea spectabilis* Zone (Howe, 2000). The overlying *Dingodinium swanense* Zone is rarely more than a few hundred metres thick and it would also appear exaggerated for it to span the entire Kimmeridgian. Although, the non-dinoflagellate cyst biotal evidence for the age of the *Wanaea clathrata* Zone is somewhat problematical (see above) a Late Oxfordian to Early Kimmeridgian age is assigned herein (Figs. 4, 9).

The dinoflagellate cyst associations in the *Wanaea clathrata* Zone are substantially similar to those in the underlying *Wanaea spectabilis* Zone, and only marginally lower in diversity (Davey, 1988, p. 30). This unit is distinguished by the prominent occurrence of *Wanaea clathrata,* to the virtual exclusion of all other species of *Wanaea* (Riding and Helby, 2001b, figs 11, 12). The lowered diversity partly reflects the absence of typically Early and Middle Oxfordian taxa such as *Fromea tornatilis, Limbodinium absidatum* and *Wanaea talea*. Many of the species in the *Wanaea clathrata* Zone are typical of the Middle and Late Oxfordian of the Northern Hemisphere. These comprise *Ellipsoidictyum cinctum, Endoscrinium galeritum, Endoscrinium luridum, Gonyaulacysta jurassica,* the *Leptodinium ambiguum-mirabile-subtile* complex, *Leptodinium* spp., *Mendicodinium groenlandicum, Nannoceratopsis pellucida, Rigaudella aemula, Scriniodinium crystallinum, Scriniodinium dictyotum, Stephanelytron-Lagenadinium* spp., *Systematophora* spp., *Tubotuberella apatela* and *Tubotuberella dangeardii* (see Helby et al., 1987a; Davey, 1988; Riding and Fensome, 2002; unpublished data; Fig. 9). An important occurrence is that of *Endoscrinium luridum* in Papua New Guinea (Davey, 1988, fig. 14); the range base of this species marks the Middle Oxfordian in Europe (Riding and Thomas, 1992; 1997). The range top of *Endoscrinium galeritum* also occurs within the zone (Riding and Fensome, 2002). In the Northern Hemisphere, this bioevent is normally in the Late Oxfordian (Partington et al., 1993; Riding et al., 1999, fig. 25). The presence of consistent *Dingodinium* and *Leptodinium* is also highly characteristic of the Oxfordian. *Wanaea fimbriata* is present in the *Wanaea clathrata* Zone in Papua New Guinea (Davey, 1988; unpublished data). However the range top of *Wanaea fimbriata* lies in the Early Oxfordian of Europe (e.g. Riding, 1984; 1987). A similar apparent incoherency is that, in Europe, the range top of *Wanaea* spp. lies at the Early-Middle Oxfordian transition (e.g. Riding and Thomas, 1992). Hence this important genus has a significantly younger range top in Australasia (Helby et al., 1987a; Riding and Helby, 2001b, fig. 12; Fig. 9). Despite these anomalies, the *Wanaea clathrata* Zone is here attributed to the Late Oxfordian to Early Kimmeridgian. This slightly extends the base of the zone as depicted by Helby et al. (2004) and Partridge (2006) but is in close agreement with the initial publication (Helby et al., 1987a). The key lines of evidence are the dinoflagellate cyst associations (in particular the range top of *Endoscrinium galeritum* and the range base of rare *Cribroperidinium* spp.), coupled with the probable Late Oxfordian ammonites from Western Australia, the Middle Oxfordian to Early Kimmeridgian molluscan faunas from Indonesia and the ages of the adjacent zones.

4.4.3 The *Dingodinium swanense* Zone of Helby et al. (1987a)

The *Dingodinium swanense* Zone was defined as the interval between the range tops of *Wanaea clathrata* and *Dingodinium swanense* by Helby et al. (1987a; 2004) and Partridge (2006). *Dingodinium swanense* is frequently abundant in the upper part, and *Tubotuberella missilis* is confined to the middle part of this zone (Helby et al., 1987a, fig. 15; Helby et al., 2004, fig. 1). *Craspedodinium swanense* and *Cribroperidinium corrugatum* are also confined to this unit (Riding and Helby, 2001f). The range bases of *Endoscrinium irregulare, Gonyaulacysta fenestrata, Gonyaulacysta* cf. *fenestrata, Hadriana cincta* and *Mombasadinium parvelatum,* together with the range tops of *Oligosphaeridium swanense, Rhynchodiniopsis* *cladophora*, *Striatodinium lineatum* and *Striatodinium ottii* occur in this zone (Riding and Helby, 2001f).

The marine microplankton associations are significantly similar in content and relative proportions to those from the underlying *Wanaea clathrata* Zone. The accessory forms are diverse, and include *Cassiculosphaeridia solida, Cygnusicysta talterniana, Dingodinium jurassicum, Egmontodinium* cf. *torynum, Gonyaulacysta ceratophora, Indodinium khariense, Leptodinium ambiguum, Leptodinium mirabile, Nannoceratopsis pellucida, Nummus tithonicus* (acritarch), *Oligosphaeridium* cf. *diluculum, Pareodinia ceratophora, Peridictyocysta mirabilis, Productodinium chenii*, *Prolixosphaeridium capitatum, Pyxidiella pandora, Rigaudella aemula, Scriniodinium crystallinum, Tringadinium bjaerkei* and *Tubotuberella missilis* (see Davey, 1988; 1999; Helby et al., 1987a, fig. 15; Riding and Helby, 2001f,g; unpublished data).

The *Dingodinium swanense* Zone was considered to be Kimmeridgian by Helby et al. (1987a, p. 29; 2004) without independent evidence. However, Davey (1988, fig. 3; 1999, figs. 8, 9) stated that the equivalent of this zone, the lower part of his *Cribroperidinium perforans* Zone, is Late Oxfordian based on the occurrence of common *Scriniodinium crystallinum*. This evidence is deemed to be questionable because the range top of this species in the Southern Hemisphere is apparently Tithonian, i.e. significantly younger than Late Oxfordian (Riding and Fensome, 2002, fig. 2). Francis and Westermann (1993, fig. 7) correlated this zone to the latest Oxfordian-Early Kimmeridgian based on molluscan evidence. Helby et al. (1988) identified the *Dingodinium swanense* Zone in the Waikutakuta Siltstone and the Kowhai Point Siltstone of Kawhia, New Zealand. These lithostratigraphical units were dated as ?late Early Kimmeridgian and Late Kimmeridgian using radiolaria

(Aita and Grant-Mackie, 1992) and ammonites (Stevens, 1997). Samples from the *Dingodinium swanense* Zone in the Alaria-1 well yielded calcareous nannofossils characteristic of the Early Tithonian (Howe, 2000). Clearly, the biostratigraphical evidence for the age of the *Dingodinium swanense* Zone is somewhat incoherent.

Endemism between the Northern and Southern hemispheres was relatively marked during this interval. However, cosmopolitan dinoflagellate cysts present in the *Dingodinium swanense* Zone include *Endoscrinium luridum, Leptodinium ambiguum-mirabile-subtile, Nannoceratopsis pellucida*, *Rhynchodiniopsis cladophora, Rigaudella aemula, Scriniodinium crystallinum* and *Tubotuberella dangeardii*. This association is characteristic of the Oxfordian-Kimmeridgian interval (e.g. Riding and Thomas, 1988; 1992; 1997; Riding, 2005b; Fig. 10). Based on this association, particularly the occurrences of species such as *Leptodinium ambiguum, Leptodinium mirabile, Rhynchodiniopsis cladophora* and *Tubotuberella dangeardii,* the dinoflagellate cyst data for the *Dingodinium swanense* Zone is considered to support a Kimmeridgian rather than a Tithonian age.

To summarise, the *Dingodinium swanense* Zone is deemed to be of Early to Late Kimmeridgian age based on dinoflagellate cysts, molluscs and radiolaria, and the ages of the adjacent zones.

4.5 The Fromea cylindrica *Superzone of Helby et al. (1987a) (pars)*

The *Fromea cylindrica* Superzone is based on the *Cannosphaeropsis mirabilis-Cannosphaeropsis mirabilis/Scriniodinium attadalense* zones of Evans (1966), and comprises nine zones ranging in age from Early Tithonian to Early Valanginian (Helby et al., 2004; Partridge, 2006). Helby et al. (1987a, fig. 11) compared the zones to the six surfaces and units II to V of Wiseman (1979; 1980, respectively). The four oldest zones are considered herein. Helby et al. (2004) commented that the high level of biostratigraphical resolution in this Early Tithonian to earliest Berriasian interval gives an average duration for a single subzone of approximately 250,000 years. The superzone is developed throughout the offshore basins of north and west Australia and Papua New Guinea in a wide variety of depositional settings where Helby et al. (1987a) considered it to be characterised by the 'often prominent occurrence of *Belodinium dysculum, Egmontodinium torynum, Fromea cylindrica* and *Peridictyocysta mirabilis*'. However the abundance of these species varies across the region and they are rather uncommon marker species in some basins.

The *Fromea cylindrica* Superzone is dominated by endemic Australasian dinoflagellate cysts. The intense provincialism around the Jurassic-Cretaceous transition reflects a regressive regime (Haq et al., 1987); the endemism affected most fossil groups (Casey, 1973; Abbink et al., 2001 and references therein). Cosmopolitan dinoflagellate cysts are distinctly subordinate, and some geographically-widespread species appear to have disparate stratigraphical ranges between the hemispheres. Hence this interval appears to represent the maximum incoherence in terms of species content and biostratigraphy between the Northern and Southern hemispheres. Within the Northern Hemisphere, there was also some provincialism between the dinoflagellate cysts in the Boreal and Tethyan provinces at this time (Fisher and Riley, 1980; Dodekova, 1994).

4.5.1 The *Cribroperidinium perforans* Zone of Helby et al. (1987a)

The *Cribroperidinium perforans* Zone was defined as the interval between the range top of *Dingodinium swanense* and the range base of *Omatia montgomeryi* (Helby et al., 1987a). Supplemental datums within this zone include the range bases of *Belodinium dysculum*, *Belodinium nereidis*, *Belowicysta balteus*, *Belowicysta* sp. A and *Peridictyocysta mirabilis* (Helby et al. 1987a; Riding and Helby, 2001g), and the range tops of *Gonyaulacysta fenestrata, Hadriana cincta, Indodinium khariense* and *Mombasadinium parvelatum* (Helby et al., 1987a; 2004, fig. 2; Riding & Helby, 2001f). The range tops of the acme occurrences of *Cribroperidinium perforans* and *Impletosphaeridium pachydermum* in the lower and upper parts of the zone respectively allow the delineation of three subdivisions (Helby et al, 1987a, fig. 21; Helby et al., 2004, fig. 2).

Helby et al. (1987a) reported that the diversity in this zone is moderate. Further accessory forms include *Cassiculosphaeridia solida, Dingodinium jurassicum, Endoscrinium irregulare, Fromea cylindrica, Gonyaulacysta ceratophora, Impletosphaeridium pachydermum, Leptodinium eumorphum, Meiourogonyaulax bulloidea, Nannoceratopsis pellucida, Nummus tithonicus* (acritarch), *Pareodinia ceratophora, Pyxidiella pandora*, prominent *Rigaudella aemula* and *Scriniodinium crystallinum* (see Helby et al., 1987a, fig. 21; Riding and Helby, 2001f,g).

The *Cribroperidinium perforans* Zone was assigned to the earliest Tithonian by Helby et al. (1987a; fig 19). This is supported by belemnite and bivalve evidence from three wells in Papua New Guinea which indicates a Late Oxfordian to Early Tithonian age for this zone (Stevens, 1965; Helby et al., 1987a, appendix 3). Helby et al. (1987a) also commented that the reports of *Cribroperidinium*? *perforans* from the Northern Hemisphere by Williams (1977) and Sarjeant (1979) are of Early Tithonian age. *Cribroperidinium* is abundant and diverse throughout the Kimmeridgian and Tithonian of the Northern Hemisphere, however, the European range of *Cribroperidinium*? *perforans* is not deemed to be especially biostratigraphically significant (Cookson and Eisenack, 1958; Below, 1981).

This interval has been interpreted as being significantly older than earliest Tithonian; Davey (1988; 1999) and Burger (1996) assigned it to the Late Oxfordian. Francis and Westermann (1993) placed the *Cribroperidinium perforans* Zone in the Early Kimmeridgian. However, Helby and Hasibuan (1988) and Francis and Westermann (1993, p. 81, 87) reported that palynofloras from the ?uppermost *Cribroperidinium perforans* Zone and the *Omatia montgomeryi* Zone in Misool, Indonesia are associated with ammonites, belemnites and calcareous nannofossils of Kimmeridgian-earliest Tithonian aspect. Francis and Westermann (1993, p. 86) also mentioned a considerable body of ammonite evidence from Kawhia, New Zealand which indicates an Early Tithonian age for the *Cribroperidinium perforans* Zone (Helby et al., 1988). However, Francis and Westermann (1993, p. 86) stated that there is some doubt as to the identification of these ammonites. Subsequently, the ammonite data from New Zealand associated with the *Cribroperidinium perforans* Zone was reviewed by Stevens (1997). The key material is from the lower Kinohaku Siltstone to the lower Puti Siltstone near Kawhia from which an Early Tithonian age was established (Stevens, 1997; Campbell et al., 2004). Because this New Zealand material is from only part of the *Cribroperidinium perforans* Zone, this unit is considered to be at least partly Early Tithonian. This is entirely consistent with the bivalve-belemnite data evidence from Papua New Guinea (Stevens, 1965) and macrofaunal data from Misool (Helby and Hasibuan, 1988; Francis and Westermann, 1993).

There are few stratigraphically useful cosmopolitan dinoflagellate cyst datums within the *Cribroperidinium perforans* Zone of Australasia. The range top of *Leptodinium* spp. is within this unit in Papua New Guinea (Davey, 1988), and this datum is broadly consistent with Europe. Intriguingly, the *Cribroperidinium perforans* Zone lies stratigraphically below the range tops of *Endoscrinium luridum*, *Nannoceratopsis pellucida* and *Scriniodinium crystallinum* (Fig. 11). These datums are characteristically Kimmeridgian in Europe (Woollam and Riding, 1983; Riding and Thomas, 1988). In Papua New Guinea, the above taxa coexist with forms which typically have range bases in the Tithonian-Berriasian such as *Cyclonephelium* spp., *Histiophora* sp., *Oligosphaeridium diluculum* and *Stiphrosphaeridium dictyophorum* (see Davey, 1988; 1999; Fig. 10). These forms do not overlap with *Endoscrinium luridum* and the other Kimmeridgian forms in Europe (Riding and Thomas, 1988). The apparently younger ranges may be due to genuine heterochroneity or reworking. Significant reworking events of Middle to Late Jurassic sediments are well known across the North West Shelf (Bint and Marshall, 1994; unpublished data).

Taking consideration of the biostratigraphical evidence from calcareous nannofossils, dinoflagellate cysts and molluscs, together with the the ages of the adjacent zones, the *Cribroperidinium perforans* Zone is interpreted herein as being of earliest Tithonian age, while acknowledging that the zone may also be partly Kimmeridgian in age.

4.5.2 The *Omatia montgomeryi* Zone of Helby et al. (1987a)

The *Omatia montgomeryi* Zone represents the interval between the range base of *Omatia montgomeryi* (equivalent to the range tops of *Gonyaulacysta fenestrata* and

Hadriana cincta), and the range tops of *Omatia montgomeryi*, *Belowicysta balteus* and *Belowicysta* sp. A of Riding and Helby (2001g) (Helby et al., 1987a; 2004, fig. 2). The entire range of the acme occurrence of *Omatia montgomeryi* is present in the middle part of the zone, and this allows the delineation of three subdivisions (Helby et al, 1987a, fig. 21; Helby et al., 2004, fig. 2).

The dinoflagellate cyst diversity in this zone is moderate to high. Forms typically present include *Batiacasphaera* spp., *Belodinium dysculum, Belodinium nereidis*, *Cassiculosphaeridia solida*, *Cribroperidinium* spp., prominent *Dingodinium jurassicum, Endoscrinium irregulare, Fistulacysta simplex, Fromea cylindrica, Gonyaulacysta jurassica*, prominent *Herendeenia pisciformis*, *Impletosphaeridium pachydermum*, *Komewuia glabra*, *Leptodinium eumorphum, Meiourogonyaulax bulloidea, Nannoceratopsis pellucida, Nummus similis* (acritarch), *Nummus tithonicus* (acritarch), *Oligosphaeridium* cf. *diluculum, Omatia montgomeryi*, *Pareodinia ceratophora*, *Peridictyocysta mirabilis*, *Pyxidiella pandora*, prominent *Rigaudella aemula, Scriniodinium crystallinum, Sentusidinium* spp. and *Systematophora palmula* (Helby et al., 1987a, fig. 21; Davey, 1988; 1999; Riding and Helby, 2001g).

The *Omatia montgomeryi* Zone was assigned to the Early Tithonian by Helby et al. (1987a, fig. 19) based on the ages of adjacent zones with no independent evidence. Other workers, however, have interpreted it as being significantly older. It was assigned to the Late Oxfordian-Early Kimmeridgian by Davey (1988) and Burger (1996), and to the Early Kimmeridgian by Davey (1999). Francis and Westermann (1993, p.87) placed this unit largely in the Late Kimmeridgian; however, these authors admitted that this age assessment was somewhat tentative, being interpolated between Late Oxfordian and Early Tithonian correlation points. Helby and Hasibuan (1988) and Francis and Westermann (1993, p. 81, 87) also reported that dinoflagellate cysts of the *Omatia montgomeryi* Zone in Misool, Indonesia have been found together with Kimmeridgian-earliest Tithonian calcareous nannofossils and molluscs. The calcareous nannofossils are indicative of the *Watznauria communis* Nannofossil Zone (Francis and Westermann, 1993). Ammonite data from New Zealand associated with the *Omatia montgomeryi* Zone (Helby et al., 1988) are considered by Stevens (1997) to be indicative of the Early Tithonian. Samples f8628 and f8625 of Helby et al. (1988), both from the Puti Siltstone, are referable to the *Omatia montgomeryi* Zone. The Early Tithonian ammonite data of Stevens (1997) is based on widespread material from the Himalayas, Madagascar and Mexico. Further support for a late Early Tithonian age comes from Indian ammonite assemblages. Garg et al. (2003) recovered dinoflagellate cysts typical of the *Omatia montgomeryi* Zone from a *Hildoglochiceras-Virgatosphinctes* ammonite assemblage in northern Indian Tethyan successions.

The range top of common/consistent *Scriniodinium crystallinum* occurs in Australia and Papua New Guinea within the *Omatia montgomeryi* Zone, and *Endoscrinium luridum, Nannoceratopsis pellucida, Rigaudella aemula, Stephanelytron scarburghense* and *Tubotuberella dangeardii* are also present (Helby et al., 1987a, fig. 21; Davey, 1988; 1999; Figs. 10, 11). These species all have Kimmeridgian range tops in Europe (Riding and Thomas, 1988), hence appear to range stratigraphically higher in the Southern Hemisphere. Some of these occurrences may be due to extensive reworking. The macrofaunal evidence for the Early Tithonian appears to be robust, due to the presence of dinoflagellate cysts from Papua New Guinea which are typical of the Tithonian-Berriasian interval such as *Circulodinium compta, Cyclonephelium* spp., *Histiophora* sp., *Oligosphaeridium diluculum* and *Stiphrosphaeridium dictyophorum* (see Davey, 1988; 1999).

Following review of the available biostratigraphical evidence and the ages of the adjacent zones, the *Omatia montgomeryi* Zone is interpreted herein as being wholly within the Early Tithonian (Figs. 4, 10).

4.5.3 The *Dingodinium jurassicum* Zone of Helby et al. (1987a)

The *Dingodinium jurassicum* Zone is the interval between the range tops of *Omatia montgomeryi*, *Belowicysta balteus* and *Belowicysta* sp. A of Riding and Helby (2001g), and the range top of the acme occurrence of *Nummus similis* (Helby et al., 2004, fig. 2). This zone can potentially be resolved into ten subdivisions based on the range tops of *Batiacasphaera crassicingulata* (acme), *Cassiculosphaeridia solida* (acme), *Carnarvonodinium striatigranulatum*, *Atopodinium* sp., *Carnarvonodinium morganii* (acme), *Bonbonadinium granulatum* and *Belodinium nereidis* (acme), and the range bases of *Bonbonadinium granulatum, Belodinium nereidis* (acme), *Balcattia cheleusis, Dissimulidinium purattense* and *Rhynchodiniopsis serrata* (acme) (Helby et al., 2004, fig. 2).

Dinoflagellate cyst diversity in the *Dingodinium jurassicum* Zone is high according to Helby et al. (1987a). Other forms typically present include *Aidelocysta clavata, Ampulladinium variabile, Balcattia cheleusis, Belodinium dysculum, Biorbifera ferox,* rare *Bourkidinium granulatum, Broomea simplex, Circulodinium densebarbatum,* prominent *Dingodinium jurassicum, Egmontodinium torynum, Endoscrinium irregulare, Fromea cylindrica, Impletosphaeridium pachydermum,* prominent *Komewuia glabra, Leptodinium eumorphum, Meiourogonyaulax bulloidea, Meiourogonyaulax diaphana, Nannoceratopsis pellucida,* prominent *Nummus similis* (acritarch), *Nummus tithonicus* (acritarch), *Omatidinium amphiacanthum,* *Papuadinium apiculatum, Pareodinia ceratophora*, *Peridictyocysta mirabilis*, *Perisseiasphaeridium inusitatum*, *Pyxidiella pandora*, *Rigaudella aemula,* prominent *Rhynchodiniopsis serrata*, abundant *Sentusidinium* spp., *Sirmiodinium grossii* (triangular variety), *Stanfordella granulosa*, *Systematophora areolata*, *Systematophora palmula* and *Valensiella delicata* (Helby et al., 1987a, fig. 21; Bint and Marshall, 1994, fig. 4; Riding and Helby, 2001g).

The *Dingodinium jurassicum* Zone is of late Early- early Late Tithonian age according to Helby et al. (1987a, p. 31, 39); this is supported by macrofaunal evidence (Teichert, 1940; Brunnschweiler, 1954; 1960; Stevens, 1965; Playford et al., 1975). However, molluscan assemblages recovered from the *Dingodinium jurassicum* Zone of the Canning Basin, Western Australia and Papua New Guinea are solely Early Tithonian (Helby et al., 1987a, appendix 3). Whilst, the buchid bivalve and belemnite assemblages associated with the *Dingodinium jurassicum* Zone from 3801.5 m in the Omati-1 well, Papua New Guinea, and from 360.9 m in the Broome-3 well, Western Australia were reinterpreted as latest Kimmeridgian to late Early Tithonian by Francis and Westermann (1993, p. 85, 86).

Other reports have assigned an older age to this interval, however these age differences are not as significant as in the subjacent zones. Davey (1988) placed the equivalent interval, which was subdivided into five dinoflagellate cyst zones, into the Early Kimmeridgian to late Early Tithonian. Davey (1999, fig. 8) subsequently revised this to Early Kimmeridgian-Earliest Tithonian and changed the parameters of the zone. Welsh (1990, p. 378, 379) assigned the *Dingodinium jurassicum* Zone to the Kimmeridgian to Middle Tithonian. This author stated that the four lowermost zones of Davey (1988) are difficult to recognise in Papua New Guinea, and reclassified them as subzones of the *Dingodinium jurassicum* Zone. The correlations of Davey

(1988; 1999) and Welsh (1990) were all based on a succession of range tops of key European dinoflagellate cyst markers. Burger (1996) deemed this zone to be Middle Kimmeridgian to Early Tithonian.

Snape (1992) reported *Dingodinium jurassicum* Zone dinoflagellate cyst associations from the Antarctic Peninsula that occur with Tithonian ammonites (Whitham and Doyle, 1989). A correlation to the Late Kimmeridgian-Early Tithonian was preferred by Francis and Westermann (1993), who stated that dinoflagellate cyst Assemblage B described by Jain et al. (1984) from the Spiti Shale of Malla Johar, northern India is referable to the uppermost *Dingodinium jurassicum* Zone. This equates to the earliest Tithonian *Torquatisphinctes-Aulacosphinctoides* ammonite assemblage. However, Garg et al. (2003) carried out further investigations on dinoflagellate cyst assemblages recovered directly from the fine-grained matrix of/from ammonites collected in the same region. Their work suggests a late Early Tithonian age for the *Omatia montgomeryi* Zone; this requires a younger age for the overlying *Dingodinium jurassicum* Zone. The range base of the spore genus *Cicatricosisporites*/*Ruffordiaspora* within the Spiti Shale succession further supports the Tithonian age (Jain et al., 1984; Vijaya and Kumar, 2002). Francis and Westermann (1993) mentioned occurrences of the mid Tithonian ammonite *Uhligites* associated with the lower part of the *Dingodinium jurassicum* Zone from New Zealand (Bradshaw and Challinor, 1992). Stevens (1997) also noted a late Early Tithonian age for the *Dingodinium jurassicum* Zone for ammonites from the Puti Siltstone, New Zealand.

There are few potentially significant cosmopolitan dinoflagellate cyst species in the *Dingodinium jurassicum* Zone in Australia (Helby et al., 1987a, fig. 21). However, *Rigaudella aemula* is present and the range top of consistent

Nannoceratopsis pellucida occurs in Australia and Papua New Guinea within this zone. Additionally, *Endoscrinium luridum,* rare *Scriniodinium crystallinum, Stephanelytron spp.* and *Tubotuberella dangeardii* are also present (Helby et al., 1987a, fig. 21; Davey, 1988; 1999; Fig. 10). These all have range tops in the Kimmeridgian of Europe (Riding and Thomas, 1988), hence appear to range significantly younger in the Southern Hemisphere. It is possible that some of these occurrences represent reworking. The occurrences of typically Tithonian-Berriasian dinoflagellate cysts in this zone, in Australia and Papua New Guinea, is consistent with the evidence from macrofossils for a mid Tithonian age. These include *Batioladinium* sp., *Circulodinium compta, Circulodinium densebarbatum,* common *Cribroperidinium* spp., *Cyclonephelium* spp., *Endoscrinium attadalense, Kleithriasphaeridium* sp., *Oligosphaeridium diluculum,* rare *Scriniodinium campanula, Stiphrosphaeridium dictyophorum, Systematophora palmula, Tanyosphaeridium* spp., and *Valensiella delicata* (see Davey, 1988; 1999).

In conclusion, the *Dingodinium jurassicum* Zone is considered herein to be of late Early to early Late Tithonian age due to macrofossil evidence from Antarctica, New Zealand, Papua New Guinea and Western Australia, data from key European dinoflagellate cyst markers, together with the Early Tithonian and Late Tithonian-earliest Berriasian ages of the immediately adjacent zones.

4.5.4 The *Pseudoceratium iehiense* Zone of Helby et al. (1987a)

The *Pseudoceratium iehiense* Zone represents the interval between the range top of the acme occurrence of *Nummus similis,* and the range top of *Pseudoceratium iehiense* (Helby et al., 1987a; 2004, fig. 2). This interval can potentially be subdivided into eight subzones. These are based on the range tops of frequent *Circulodinium densebarbatum*, frequent *Rhynchodiniopsis serrata, Balcattia cheleusis,* frequent *Perisseiasphaeridium inusitatum, Nummus tithonicus* (acme), *Circulodinium densebarbatum, Biorbifera ferox, Dissimulidinium purattense* and *Gardodinium angustum*. The key range bases are *Nummus tithonicus* (acme), consistent *Imbatodinium kondratjevii*, consistent *Pseudoceratium iehiense* and *Clathroctenocystis calabaza* (Helby et al., 2004, fig. 2).

Helby (1987a, p. 39, fig. 21) defined this zone as the total range of *Pseudoceratium iehiense*. However, Helby et al. (2004) commented that the range base of *Pseudoceratium iehiense* is extremely rare or completely absent in the older part of its range, i.e. in the lower part of this zone. This datum would be close to the Jurasssic-Cretaceous transition. Bint and Marshall (1994) adjusted their *Dingodinium jurassicum-Pseudoceratium iehiense* zonal boundary to reflect this. Helby et al. (2004) retained the original extents of these zones and used the range top of the *Nummus similis* acme to define the base of the *Pseudoceratium iehiense* Zone.

The trend of relatively high marine microplankton diversity is maintained in the *Pseudoceratium iehiense* Zone (Helby et al., 1987a). Accessory forms not listed above include *Aidelocysta clavata*, *Ampulladinium variabile, Batioladinium paeminosum, Batioladinium radiculatum, Belodinium dysculum, Belodinium nereidis, Bourkidinium granulatum, Broomea simplex,* rare *Carnarvonodinium morganii, Dingodinium jurassicum, Egmontodinium torynum, Endoscrinium irregulare, Flamingoia cometa, Fromea cylindrica, Impletosphaeridium pachydermum, Kalyptea wisemaniae, Leptodinium eumorphum, Meiourogonyaulax bulloidea, Meiourogonyaulax diaphana, Nummus similis* (acritarch)*, Omatidinium amphiacanthum, Papuadinium apiculatum, Peridictyocysta mirabilis,* *Pseudoceratium robustum, Pseudoceratium weymouthense, Pyxidiella pandora, Rigaudella aemula,* prominent *Sentusidinium* spp., *Sirmiodinium grossii* (triangular variety), *Stanfordella granulosa, Systematophora areolata, Systematophora palmula, Tubotuberella vlamingii* and *Valensiella delicata* (see Helby et al., 1987a, fig. 21; Davey, 1988; Bint and Marshall, 1994, fig. 4; Riding and Helby, 2001g).

Helby et al. (1987a, p. 39) assigned the *Pseudoceratium iehiense* Zone to the Late Tithonian to Early Berriasian. The Late Tithonian range base of the spore genus *Cicatricosisporites/Ruffordiaspora* in Europe was used as independent evidence for the age of the middle part of this zone. This conclusion was endorsed by Davey (1988, p. 27) and Backhouse (1988). *Cicatricosisporites* is prominent in the latest Jurassic and Early Cretaceous of Europe (Batten, 1996; Davey, 1999; Tiwari, 1999a,b). However, it is possible that this datum is diachronous due to migrations from low to high palaeolatitudes in both hemispheres (Dettmann and Playford, 1969; Burger, 1990). This means that the genus appeared earlier, probably during the Kimmeridgian in the Great Artesian Basin and during the Tithonian in the Canning and Carnarvon basins (Burger, 1989). Sajjadi and Playford (2002a,b) placed this datum in the mid Tithonian of the Eromanga Basin. There is limited macrofossil data in the latest Tithonian to Hauterivian of Australia. However, Helby et al. (1987a, appendix 3) recorded Valanginian to Hauterivian macrofaunas from Papua New Guinea associated with the *Pseudoceratium iehiense* Zone; these appear to be anomalously young. Bint and Marshall (1994) reported that zircon crystals from a series of altered volcanic ash beds at the top of the *Pseudoceratium iehiense* Zone from the Wanaea-2 well in the offshore Northern Carnarvon Basin, Western Australia yielded earliest Cretaceous radiometric ages.

Some authors have attributed a slightly older, entirely Tithonian, age to this interval. Davey (1988; 1999) assigned the equivalent interval to the *Pseudoceratium iehiense* Zone to the late Early-Late Tithonian. The lowermost part of the *Pseudoceratium iehiense* Zone has also been identified in the Sula Islands, Indonesia in ammonite and bivalve-rich beds (Francis and Westermann, 1993). These strata are part of the latest Tithonian-earliest Berriasian *Blandfordiceras-Haplophylloceras-*Himalayatidae ammonite assemblage. Welsh (1990, figs 1, 2) assigned the *Pseudoceratium iehiense* Zone to the latest Tithonian, and Burger (1996) deemed this unit to be Early-Late Tithonian in age.

The only 'anomalously young' Late Jurassic dinoflagellate cyst species present in this unit is *Rigaudella aemula* (Helby et al., 1987a, fig. 21; Davey, 1988 figs. 6, 14). The range top of this species is Middle Oxfordian in Europe (e.g. Riding, 2005b). Some of the Tithonian occurrences in the Southern Hemisphere probably represent reworking (Davey, 1988, fig. 6). There are certain potentially significant cosmopolitan dinoflagellate cyst datums in the *Pseudoceratium iehiense* Zone in Australia. The presence of *Ctenidodinium culmulum* is consistent with the Late Tithonian-earliest Berriasian of Europe (Woollam and Riding, 1983). The occurrence of *Imbatodinium kondratjevii* also supports the Tithonian age of this zone (Bint and Marshall, 1994, fig. 4; Fig. 10). Riding et al. (1999, fig. 26) reported *Imbatodinium* spp., including *Imbatodinium kondratjevii*, from the Tithonian of the Moscow Basin, Russia. Another bioevent which may be useful is the oldest occurrence of 'pseudoceratioid' dinoflagellate cysts. These are genera such as *Muderongia, Phoberocysta* and *Pseudoceratium* which closely resemble the modern genus *Ceratium* (see Wall and Evitt, 1975). In the Northern Hemisphere, *Muderongia simplex* (= *Muderongia* sp. A of Davey, 1979) occurs in the Late Tithonian (Riding et al., 2000; Fig. 10). In the Southern Hemisphere, *Pseudoceratium iehiense, Pseudoceratium robustum* and *Pseudoceratium weymouthense* occur in the same interval (Bint and Marshall, 1994). It seems likely that these synchronous ranges are biostratigraphically significant (Fig. 10). Stevens (1987, p. 195) commented on the morphological similarities between *Scriniodinium prolatum* from offshore Western Australia and *Scriniodinium pharo* from Europe. These two species are large, and have well-developed apical horns; they are both present around the Jurassic-Cretaceous transition (Riding and Fensome, 2002, fig. 2; Fig. 10). Other typically Tithonian-Berriasian dinoflagellate cysts in the *Pseudoceratium iehiense* Zone include *Cassiculosphaeridia* spp., *Circulodinium densebarbatum, Cribroperidinium* spp., *Cyclonephelium* spp., *Endoscrinium attadalense, Oligosphaeridium diluculum*, rare *Scriniodinium campanula, Stiphrosphaeridium dictyophorum*, *Systematophora palmula, Tanyosphaeridium* spp. and *Valensiella delicata* (see Davey, 1982; 1988; 1999; Heilmann-Clausen, 1987; Fig. 10).

In conclusion, the *Pseudoceratium iehiense* Zone is considered herein to be of Late Tithonian-Early Berriasian age based on the macrofossil evidence of Francis and Westermann (1993), various palynological data, the radiometric dating of Bint and Marshall (1994) and the mid Tithonian and Early Berriasian ages of the adjacent zones (Helby et al., 1987a; 2004; Partridge, 2006).

5 Brief overview of Triassic-Jurassic dinoflagellate cyst provincialism

Because the majority of dinoflagellates are marine, motile, planktonic and unicellular, dinoflagellate cysts have potentially extremely wide geographical distributions. Several Triassic-Jurassic species such as *Dapcodinium priscus,* *Glossodinium dimorphum, Gonyaulacysta jurassica, Nannoceratopsis pellucida, Rhaetogonyaulax rhaetica, Rigaudella aemula, Scriniodinium crystallinum, Suessia swabiana* and *Systematophora areolata* are cosmopolitan. There are also large floral similarities at higher taxonomic levels, in addition to notable morphological similarities and trends. The cosmopolitan forms quoted above are also stratigraphically significant. They can therefore help in interregional correlation, assuming that any heterochroneity associated with, for example, slow migrations over their global distribution and major reworking events are not significant.

The Triassic-Jurassic dinoflagellate cyst succession is substantially similar over much of the Northern Hemisphere, i.e. the Americas, Europe, the Middle East, Russia and western Asia (Riding and Ioannides, 1996). For example, Jurassic marine palynofloras from the Neuquén Basin, Argentina are closely comparable with coeval assemblages from Europe (Quattrocchio and Volkheimer, 1990; Quattrocchio et al., 2007). No endemic Australasian taxa have been recorded from South America. By contrast, there are significant proportions of endemic taxa in Australasia. These include *Belowicysta balteus, Dissiliodinium caddaense, Hadriana cincta, Sahulidinium ottii, Skuadinium* spp., *Ternia balmei, Tringadinium bjaerkei, Tubotuberella missilis* and *Woodinia pedis*. These forms may have had specific tolerances in terms of palaeolatitude, palaeotemperature etc., which confined them to southeast Tethys. This endemism, and some apparent stratigraphical incoherency, means that the correlation of the Australian zones to their European counterparts is not straightforward. Despite the endemism, the partial global continuity gives microfossil groups such as dinoflagellate cysts a marked advantage over macrofossil groups including the ammonites, which we~~a~~re by comparison intensely provincial.

There appears to have been major floral differences between western and eastern Tethys during the Triassic and Jurassic. In the west (i.e. eastern North America, Europe, North Africa and the Middle East) the dinoflagellate cyst associations are markedly different to coeval assemblages from eastern Tethys (i.e. Australasia, eastern Asia and northeastern India). This scenario is mirrored by other fossil groups, in which this pan-Tethyan endemism is significantly more profound. The strongest eastern Tethyan ties exist between Australia, Indonesian, New Zealand and Papua New Guinea where many of the dinoflagellate cyst zones are workable across the whole region. However, there are also marked similarities between Late Jurassic Australasian/Indonesian palynofloras and those recorded in east Africa (Jiang et al. 1992, Schrank 2005, Msaky, 2007), India (Jain et al. 1984, Garg et al. 2003), and Madagascar (Chen, 1978, 1982). These include many species which are rarely or never recorded in European assemblages, including: *Broomea ramosa, Broomea simplex, Carnarvonodinium morganii, Cribroperidinium perforans, Dingodinium jurassicum, Indodinium khariense, Komewuia glabra, Mombasadinium parvelatum, Nummus similis* (acritarch), *Omatia montgomeryi, Productodinium chenii, Wanaea clathrata*, and *Wanaea spectabilis*. Most of these palynofloras also share considerable similarities with European palynofloras, thus they are potentially important tie points between European and Australian dinoflagellate cyst assemblages. However, better independent age control of these assemblages is required before they can be reliably correlated. The northern Indian assemblages have further issues regarding reworking, marginal preservation and the complex, structural terrain with associated stratigraphic uncertainties.

Despite the limited marine circulation between the western Tethys and the Pacific through the Central American Seaway during the Triassic and Jurassic, the Tethys circumglobal current (TCC) flowed westwards in tropical palaeolatitudes

(Bush, 1997). Because of the gentle temperature gradient between the tropics and the poles during Mesozoic greenhouse conditions, north-south currents were much weaker than today. This also means that oceanic upwelling would have been suppressed in comparison to that during icehouse conditions. The westward flow of the TCC would have tended to aid migrations of planktonic organisms from eastern to western Tethys during this interval. However, endemic Australasian dinoflagellate cyst taxa have not been recorded west of east Africa and India (Jiang et al., 1992; Garg, et al., 2003). It is possible that the continuity of shelfal palaeoenvironments, partially stagnant oceans and/or unknown latitudinal, temperature or other constraints prevented the westward migration of endemic Austral dinoflagellate cysts.

There are far more published data on Triassic-Jurassic dinoflagellate cysts from Europe and adjacent regions than in Australasia and eastern Asia. Southern Hemisphere studies on measured sections with detailed sample-by-sample information such as the report on the Middle Jurassic to Lower Cretaceous successions of Papua New Guinea by Davey (1988) are few. It is clear that the relative lack of detailed (quantitative) published records across Australia and New Zealand is a major impediment to in-depth comparisons with coeval floras elsewhere in the world. Meaningful comparisons require similar datsets. Efforts need to be made to disseminate detailed palynological records through key released well sections in the North West Shelf to allow biotal similarities and differences to be objectively and comprehensively assessed.

6 Conclusions

This study has comprehensively and objectively reviewed the chronstratigraphical extents of the Middle Triassic (Ladinian) to earliest Cretaceous (earliest Berriasian) dinoflagellate cyst zones established by Helby et al. (1987a; 2004), Riding and Helby (2001a) and Partridge (2006) for the North West Shelf of Australia. When available, non-palynomorph fossil groups are used to independently tie these zones to the geological timescale. The stratigraphical ranges of key Australasian dinoflagellate cysts are also compared to the more tightly constrained European zones to help confirm these tie points. A summary of the confirmed and reinterpreted ages of the 20 dinoflagellate cyst zones and one dinoflagellate cyst assemblage is given in Figs. 3, 4.

The main reinterpretations pertaining to the *Rhaetogonyaulax* Superzone of Helby et al. (1987a) is that its stratigraphical extent is now considered to be Ladinian to Early Sinemurian. By contrast, Helby et al. (1987a) illustrated this unit as being Late Anisian to Late Pliensbachian (Fig. 3). The oldest occurrences of *Rhaetogonyaulax rhaetica* in the Late Triassic, and the presence of *Dapcodinium priscus* in the absence of *Rhaetogonyaulax rhaetica* in the earliest Jurassic appear to have widespread correlative significance (Fig. 6). In Europe and Australasia, they indicate the earliest Rhaetian and Hettangian-Early Sinemurian respectively. As a consequence of this, the age of the *Dapcodinium priscus* Zone is considered herein to be latest Rhaetian to Early Sinemurian in age (Fig. 3). It is clear that facies variations strongly influenced the stratigraphical distribution of marine palynomorphs during the Triassic and Early Jurassic. Major eustatic shifts and marine transgressions appeared to have controlled certain bioevents. More taxonomic work is required before global provincialism can be comprehensively assessed for the Middle-Late Triassic and across the Triassic-Jurassic boundary.

The *Luehndea* Assemblage of Riding and Helby (2001a) is a low-diversity dinoflagellate cyst assemblage which was developed in marginal marine conditions in the Timor Sea and offshore Western Australia. It can be subdivided into two subzones and is interpreted as being of latest Pliensbachian to Early Toarcian age, The Assemblage probably reflects the Early Toarcian eustatic rise.

The *Pareodinia ceratophora* Superzone represents the inception of the continuous, gonyaulacacean-dominated, dinoflagellate cyst record in Australia. The superzone is well represented, despite the paralic nature of much of the strata of this age in Australia. The superzone includes seven zones, all of which appear to be slightly older than were interpreted by Helby et al. (1987a). The Middle Jurassic was a critical phase in the general trends of dinoflagellate cyst evolution. The record of the major lineages in Australia is similar to that in the Northern Hemisphere. Gonyaulacacean forms became established in the low-diversity Bajocian floras and rapidly diversified through the succeeding Bathonian and Callovian stages. The oldest subdivision of the *Pareodinia ceratophora* Superzone, the *Dissiliodinium caddaense* Zone, is interpreted to be Early Bajocian in age rather than Early-Late Bajocian (Helby et al., 1987a) based on reliable evidence from dinoflagellate cysts, nannofossils and strontium isotopes. The lack of ammonites and paucity of nannofossil data require the use of cosmopolitan dinoflagellate cyst species as the major tie points throughout the remainder of the *Pareodinia ceratophora* Superzone. The occurrence of simple (non-flanged) *Wanaea* spp. in the absence of prominent *Ctenidodinium* spp. supports a Late Bajocian age for the base of the *Wanaea verrucosa* Zone. The *Wanaea indotata* Zone is interpreted as earliest to Late Bathonian in age on dinoflagellate cyst and nannofossil evidence. The remaining three zones in the *Pareodinia ceratophora* Superzone lack good independent control points, although the most reliable dinoflagellate cyst bioevents for correlation to Europe are the large decreases in *Ctenidodinium* spp. and *Meiourogonyaulax-Lithodonia* spp. in the earliest Oxfordian, thus supporting this age for the *Ctenidodinium ancorum* Zone.

The three zones of the *Pyxidiella* Superzone are Early Oxfordian to Kimmeridgian in age, as proposed by Helby et al. (1987a). The only changes to the ages of these zones are the slightly older bases for the *Wanaea spectabilis* and *Wanaea clathrata* zones. The Superzone is characterised by diverse dinoflagellate cyst associations and is well-developed in Western Australia, the Timor Sea region and the Papuan Basin. The oldest subdivision is the *Wanaea spectabilis* Zone, marked by an increase in dinoflagellate cyst diversity, and dated as Early Oxfordian to probably intra Late Oxfordian. This is consistent with ammonite faunas from Indonesia, New Zealand, and the Northern Carnarvon Basin. A latest Oxfordian to earliest Kimmeridgian age is suggested for the *Wanaea clathrata* Zone on the basis of somewhat slender dinoflagellate cyst and molluscan evidence. The *Dingodinium swanense* Zone is interpreted as being intra Early to Late Kimmeridgian based on molluscan, nannofossil and radiolarian ages.

The *Fromea cylindrica* Superzone is developed throughout Australasia and includes nine subdivisions, of which the four Jurassic zones are considered herein. The Superzone is dominated by endemic dinoflagellate cysts and this interval represents the maximum global stratigraphical incoherence. This reflects a global trend towards endemism at this time, caused by a generally regressive eustatic regime. The *Cribroperidinium perforans* Zone is interpreted as being earliest Tithonian. The late Early Tithonian age for the *Omatia montgomer*yi Zone is supported by ammonite data. The most convincing independent ages for the *Dingodinium jurassicum* Zone are from ammonite assemblages in New Zealand and Antarctica. The zone is considered to be late Early to Late Tithonian in age. The base of the *Pseudoceratium iehiense* Zone is placed within the Late Tithonian based on macrofaunal, palynological and radiometric evidence. The upper part of the zone lies in the Early Berriasian.

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Fig. 1. Map illustrating the location and extents of the major Mesozoic sedimentary basins (shaded grey) of Australia. The basins shaded in dark grey represent the North West Shelf of Australia.

Fig. 2. The Upper Triassic (Carnian) to Upper Jurassic (Tithonian) lithostratigraphical framework for the North Perth, Northern Carnarvon, Offshore Canning, Browse and Bonaparte basins of Australia. The lithostratigraphical ornaments are generalised. Sandstone = stipple; siltstone = double dots; mudstone – horizontal lines; heterolithic intervals (interbedded mudstones, sandstones and siltstones) = alternating dots and dashes; coals = thick black lines; v = volcanic rocks. HMP = Helby, Morgan and Partridge (1987a; 2004).

Fig. 3. A comparison of three chronostratigraphical interpretations of Middle Triassic (Anisian) to Early Jurassic (Toarcian) dinoflagellate cyst zones of the Australian Helby, Morgan, and Partridge (HMP) zonation. These are the present study, HMP 2004; 2006 (=Helby et al., 2004; Partridge et al., 2006) and HMP 1987 (=Helby et al., 1987a). The grey intervals are devoid of dinoflagellate cysts.

Fig. 4. A comparison of three chronostratigraphical interpretations of Middle Jurassic (Aalenian) to Early Cretaceous (earliest Berriasian) dinoflagellate cyst zones of the Australian Helby, Morgan, and Partridge (HMP) zonation. These are the present study, HMP 2004; 2006 (=Helby et al., 2004; Partridge et al., 2006) and HMP 1987 (=Helby et al., 1987a). The grey intervals are devoid of dinoflagellate cysts.

Fig. 5. The supporting stratigraphical information which was used in this study for the chronostratigraphical interpretations of the 14 Middle Jurassic (Bajocian) to earliest Cretaceous (earliest Berriasian) dinoflagellate cyst zones of Australia. The NJ zones are based on calcareous nannofossils.. HMP = Helby, Morgan, and Partridge dinoflagellate cyst zonations; NZ = New Zealand.

Fig. 6. A comparative range chart of selected palynomorphs (dinoflagellate cysts and pollen) for the Middle Triassic (Ladinian) to the Early Jurassic (Sinemurian) of Alaska, the Arctic, Europe, Australia and New Zealand. The Australian spore-pollen zones are of Helby et al. (1987a). The Australian conodont zones are of Nicoll and Foster (1994; 1998). The dinoflagellate cyst zones are all within the *Rhaetogonyaulax* Superzone and represent the age interpretations herein.

Fig. 7. A comparative range chart of selected palynomorphs (dinoflagellate cysts, pollen and spores) for the Early Jurassic (Pliensbachian-Toarcian) of Europe/Russia and Australia. The only Australian biozone in this interval is the *Luehndea* Assemblage of Riding and Helby (2001a). The Northern Hemisphere dinoflagellate cyst zones are those of Poulsen and Riding (2003). The interrupted thin lines, the thin solid lines and the thick solid lines indicate rare/inconsistent occurrences, consistent occurrences and prominent occurrences respectively.

Fig. 8. A comparative range chart of selected palynomorphs (dinoflagellate cysts and spores) for the Middle Jurassic (Bajocian and Bathonian) of Europe and Australia. The dinoflagellate cyst zones depicted all represent the age interpretations herein. The

Northern Hemisphere dinoflagellate cyst zones are those of Poulsen and Riding (2003). The interrupted thin lines, the thin solid lines and the thick solid lines indicate rare/inconsistent occurrences, consistent occurrences and prominent occurrences respectively.

Fig. 9. A comparative range chart of selected dinoflagellate cysts for the Middle and Late Jurassic (latest Bathonian to earliest Kimmeridgian) of Europe and Australia. The dinoflagellate cyst zones depicted all represent the age interpretations herein. The Northern Hemisphere dinoflagellate cyst zones are those of Poulsen and Riding (2003). The interrupted thin lines, the thin solid lines and the thick solid lines indicate rare/inconsistent occurrences, consistent occurrences and prominent occurrences respectively.

Fig. 10. A comparative range chart of selected dinoflagellate cysts for the Late Jurassic (earliest Kimmeridgian to earliest Cretaceous (earliest Berriasian) of Europe and Australia. The dinoflagellate cyst zones depicted all represent the age interpretations herein. The Northern Hemisphere dinoflagellate cyst zones are those of Poulsen and Riding (2003). The interrupted thin lines, the thin solid lines and the thick solid lines indicate rare/inconsistent occurrences, consistent occurrences and prominent occurrences respectively.

Fig. 11. A compilation of selected important marker dinoflagellate cysts for the Middle Jurassic (Bajocian) to earliest Cretaceous (earliest Berriasian) of Australia. The dinoflagellate cyst zones depicted all represent the age interpretations herein. The

interrupted thin lines, the thin solid lines and the thick solid lines indicate rare/inconsistent occurrences, consistent occurrences and prominent occurrences respectively. These range data have been compiled, where possible, from published accounts and released well reports, thus representing the taxonomic concepts of many palynologists over a significant period of time. Some ranges may have been inadvertently extended due to variable species concepts and occurrences of caved or reworked specimens.

Plate I. Transmitted light photomicrographs of 10 dinoflagellate cyst taxa from the Middle Jurassic to earliest Cretaceous of Australia, England and Scotland. The scale bars represent 10 µm. This Plate is intended to emphasise the morphological similarities between pairs of virtual coeval key marker taxa from the Northern and Southern hemispheres. Note the marked morphological closeness between the five pairs of forms, which are also mentioned in the running text. The five pairs are: *Scriniodiniuum pharo* and *Scriniodinium prolatum*; *Gonyaulacysta jurassica* subsp. *adecta* var. *longicornis* (large morphotype) and *Gonyaulacysta ceratophora*; *Endoscrinium asymmetricum* and *Endoscrinium luridum*; *Ctenidodinium sellwoodii* and *Ctenidodinium ancorum;* and *Phallocysta elongata* and *Phallocysta erregulensis*.

1. *Scriniodiniuum pharo* (Duxbury 1977) Davey 1982. A well-preserved specimen in dorsal view; note the prominent apical horn. BGS specimen MPK 13888, Main gas feeder trench number 2, Manor Farm, North Runcton, Kings Lynn, Norfolk, England (NGR TF 6515 1555), outcrop sample; Bed 6 (= Basal Cretaceous Nodule Bed),

Sandringham Sands, Lower Cretaceous, Lower Berriasian (Runctoni Chronozone). Stacked image - high and medium focus.

2. *Gonyaulacysta ceratophora* (Cookson & Eisenack 1960) Riding 2005. A well-preserved specimen in dorsal view; note the elongate outline, the partially-developed tabulation, the low-relief sutural ornamentation in the antapical area and the relatively short hypocyst. GA specimen CPC 38835, Arunta-1 well (11° 58’ 26.58’’S; 124° 57’ 11.06’’E), sidewall core at 1805.00 m; Lower Vulcan Formation, Upper Jurassic, Middle Oxfordian. Low focus.

3. *Gonyaulacysta jurassica* (Deflandre 1939) Norris & Sarjeant 1965 subsp. *adecta* Sarjeant 1982 var. *longicornis* (Deflandre 1939) Downie & Sarjeant 1965 (large morphotype). A well-preserved specimen in dorsal view; note the prominent, elongate apical horn and the apical protuberance on the endocyst. BGS specimen MPK 6711, foreshore at Digg, west shore of Staffin Bay, Trotternish Peninsula, Isle of Syke, Scotland (NGR 473 690), outcrop sample; Digg Siltstone Member, Staffin Shale Formation, Upper Jurassic, Middle Oxfordian (Tenuiserratum Chronozone). Stacked image - high and medium focus.

4. *Scriniodinium prolatum* Stevens 1987. Dorsal view of the holotype. DOIR specimen (Geological Survey of Western Australia) F1187, Eendracht-1 well (19° 54' 28.9" S; 112° 14' 35.2" E), sidewall core 240 at 2318.5 m; Barrow Group equivalent, Lower Cretaceous, Lower Berriasian. Stacked image – low and high focus.

5. *Endoscrinium asymmetricum* Riding 1987. A well-preserved specimen in dorsal view. BGS specimen MPK 13887, southern England, specific locality unknown, Middle Jurassic, Bathonian (undifferentiated). Stacked image – high, medium and low focus.

6. *Endoscrinium luridum* (Deflandre 1939) Gocht 1970. A well-preserved specimen in dorsal view; note the antapical protuberance on the endocyst (slightly folded). GA specimen CPC 39219, Challis-11 ST1 well, (12° 05' 51.9" S; 125° 03' 20.81" E), sidewall core 55 at 1552.5 m; Lower Vulcan Formation, Upper Jurassic, Lower Oxfordian. Stacked image – medium and low focus.

7. *Ctenidodinium sellwoodii* (Sarjeant 1975) Stover & Evitt 1978 group. A form with relatively low, sparse sutural denticulate ornament in dorsal view. BGS specimen MPK 3351, BGS Seabarn Farm Borehole, Dorset, England (NGR SY 6263 8054), core sample at 350.63-349.63 m; Lower Fuller’s Earth, Middle Jurassic, Lower Bathonian.

8. *Ctenidodinium ancorum* Riding & Helby 2001. A form with moderately stout, anchor-tipped, sutural processes in tilted antapical view. GA specimen CPC 39413, Undan-1 (11° 02' 29.71" S; 126° 36' 20.93" E), sidewall core 32 at 2998.8 m, Elang Formation, Upper Jurassic, Lower Oxfordian. Stacked image – medium and low focus.

9. *Phallocysta elongata* (Beju 1971) Riding 1994. A relatively elongate morphotype in right lateral view. BGS specimen MPK 4342, BGS Cockle Pits Borehole, Yorkshire, England (NGR SE 9323 2865), core sample at 11.12 m; Lincolnshire Limestone Formation, Middle Jurassic, Lower Bajocian (Discites Chronozone). Medium focus.

10. *Phallocysta erregulensis* (Filatoff 1975) Stover & Helby 1987. A well-rounded specimen with reduced granular ornamentation. GA specimen CPC 40195, Sunset West-1 (09 38' 8.06" S; 127 53' 57.840" E) sidewall core 84 at 2337.5 m, Middle Jurassic, Lower Bajocian. Stacked image – high, medium, and low focus.