

Carboniferous miospore biostratigraphy of the North Sea

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Chronostratigraphy	Onshore palynostratigraphy	Offshore Biozones	Macroplanktonology	Phytology	
Late C. (Carboniferous part 1)	Wangshania D	<i>T. schueta</i> - <i>T. schueta</i> - <i>T. schueta</i>	K	W1	W1
		<i>T. schueta</i> - <i>T. schueta</i> - <i>T. schueta</i>	K	W1	W1
	Mudanian	<i>T. schueta</i> - <i>T. schueta</i> - <i>T. schueta</i>	J	W2	W2
		<i>T. schueta</i> - <i>T. schueta</i> - <i>T. schueta</i>	J	W2	W2
	Duchastan	<i>M. munda</i> - <i>M. munda</i> - <i>M. munda</i>	I	W3	W3
		<i>M. munda</i> - <i>M. munda</i> - <i>M. munda</i>	I	W3	W3
	Langsettian	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	H	W4	W4
		<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	H	W4	W4
	Yardian	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	G	W5	W5
		<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	G	W5	W5
Maudslayi	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	F	W6	W6	
	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	F	W6	W6	
Kilbrickenian	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	E	W7	W7	
	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	E	W7	W7	
Alportian	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	D	W8	W8	
	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	D	W8	W8	
Chadlean	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	C	W9	W9	
	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	C	W9	W9	
Avalonian	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	B	W10	W10	
	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	B	W10	W10	
Chadlean	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	A	W11	W11	
	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	A	W11	W11	
Conoverian	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	0	W12	W12	
	<i>E. schueta</i> - <i>E. schueta</i> - <i>E. schueta</i>	0	W12	W12	

Figure 1 North Sea Carboniferous miospore biozones and their relationship to onshore biozones and chronostratigraphy. No vertical scale implied.

Stages	Palynostratigraphy			
	Biozones	Sub-biozones	Defining criteria	Associated range tops
Wangshania D	W1	W1a	<i>C. schueta</i>	<i>E. schueta</i> spp.
	W2	W2a	<i>M. munda</i>	<i>E. schueta</i> spp.
Mudanian	W3	W3a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W4	W4a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Duchastan	W5	W5a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W6	W6a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Langsettian	W7	W7a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W8	W8a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Yardian	W9	W9a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W10	W10a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Maudslayi	W11	W11a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W12	W12a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Kilbrickenian	W13	W13a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W14	W14a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Alportian	W15	W15a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W16	W16a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Chadlean	W17	W17a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W18	W18a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Avalonian	W19	W19a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W20	W20a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Chadlean	W21	W21a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W22	W22a	<i>E. schueta</i>	<i>E. schueta</i> spp.
Conoverian	W23	W23a	<i>E. schueta</i>	<i>E. schueta</i> spp.
	W24	W24a	<i>E. schueta</i>	<i>E. schueta</i> spp.

Figure 2 North Sea Dinantian miospore biozones. No vertical scale implied.

Stages	Palyostratigraphy					
	Biozones	Sub-Biozones	Defining criteria	Associated range tops	Associated range bases	
Liasium (part.)	W1	W1a	1) <i>A. madoi</i>	1) <i>T. madoi</i> , <i>M. pascuensis</i>	1) <i>C. ghermesensis</i> , <i>R. cf. madoi</i> , <i>R. dabo</i> , <i>D. dabo</i>	
		W1b	W1b1	1) <i>D. brechtalpinus</i> , <i>paucicostatus</i>		
			W1b2	1) <i>R. carpense</i> v. s.		
Murchisonia	W2	W2a	1) <i>F. pascuensis</i>	1) <i>F. pascuensis</i>	1) <i>F. pascuensis</i> , <i>F. madoi</i>	
		W2b	W2b1	1) <i>E. archidani</i>	1) <i>C. erpiti</i>	1) <i>A. dolensensis</i> , <i>D. madoi</i> , <i>R. madoi</i> , <i>C. madoi</i> , <i>D. madoi</i>
			W2b2	1) <i>M. madoi</i>	1) <i>D. pascuensis</i>	1) <i>M. madoi</i>
Undersanton	W3	W3a	1) <i>R. carpense</i> v. s.		1) <i>R. dabo</i> , <i>D. madoi</i>	
		W3b	W3b1	1) <i>R. madoi</i> , <i>C. madoi</i>	1) <i>R. madoi</i> , <i>C. madoi</i>	1) <i>C. madoi</i> , <i>R. madoi</i>
			W3b2	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>
Alportia	W4	W4a	1) <i>G. madoi</i>	1) <i>C. madoi</i> , <i>R. madoi</i>	1) <i>A. madoi</i>	
		W4b	W4b1	1) <i>F. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>
			W4b2	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>
Cheloniceras	W5	W5a	1) <i>C. madoi</i>	1) <i>C. madoi</i>	1) <i>C. madoi</i>	
		W5b	W5b1	1) <i>F. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>
			W5b2	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>
Ambergian	W6	W6a	1) <i>F. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>	
		W6b	W6b1	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>
			W6b2	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>
Pentoniceras	W7	W7a	1) <i>C. madoi</i>	1) <i>C. madoi</i>	1) <i>C. madoi</i>	
		W7b	W7b1	1) <i>F. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>
			W7b2	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>
Bregantia (part.)	W8	W8a	1) <i>C. madoi</i>	1) <i>C. madoi</i>	1) <i>C. madoi</i>	
		W8b	W8b1	1) <i>F. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>
			W8b2	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>

Figure 3 North Sea Namurian miospore biozones. No vertical scale implied.

Stages	Palyostratigraphy					
	Biozones	Sub-Biozones	Defining criteria	Associated range tops	Associated range bases	
Westphalian II (part.)	W1	W1a	1) <i>A. madoi</i>	1) <i>T. madoi</i> , <i>M. pascuensis</i>	1) <i>C. ghermesensis</i> , <i>R. cf. madoi</i> , <i>R. dabo</i> , <i>D. dabo</i>	
		W1b	W1b1	1) <i>D. brechtalpinus</i> , <i>paucicostatus</i>		
			W1b2	1) <i>R. carpense</i> v. s.		
Babington	W2	W2a	1) <i>F. pascuensis</i>	1) <i>F. pascuensis</i>	1) <i>F. pascuensis</i> , <i>F. madoi</i>	
		W2b	W2b1	1) <i>E. archidani</i>	1) <i>C. erpiti</i>	1) <i>A. dolensensis</i> , <i>D. madoi</i> , <i>R. madoi</i> , <i>C. madoi</i> , <i>D. madoi</i>
			W2b2	1) <i>M. madoi</i>	1) <i>D. pascuensis</i>	1) <i>M. madoi</i>
Duchastan	W3	W3a	1) <i>R. carpense</i> v. s.		1) <i>R. dabo</i> , <i>D. madoi</i>	
		W3b	W3b1	1) <i>R. madoi</i> , <i>C. madoi</i>	1) <i>R. madoi</i> , <i>C. madoi</i>	1) <i>C. madoi</i> , <i>R. madoi</i>
			W3b2	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>
Langshian	W4	W4a	1) <i>G. madoi</i>	1) <i>C. madoi</i> , <i>R. madoi</i>	1) <i>A. madoi</i>	
		W4b	W4b1	1) <i>F. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>
			W4b2	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>
Strobilium (part.)	W5	W5a	1) <i>C. madoi</i>	1) <i>C. madoi</i>	1) <i>C. madoi</i>	
		W5b	W5b1	1) <i>F. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>	1) <i>F. madoi</i> , <i>R. madoi</i>
			W5b2	1) <i>R. madoi</i>	1) <i>R. madoi</i>	1) <i>R. madoi</i>

Figure 4 North Sea Westphalian biozones. No vertical scale implied.

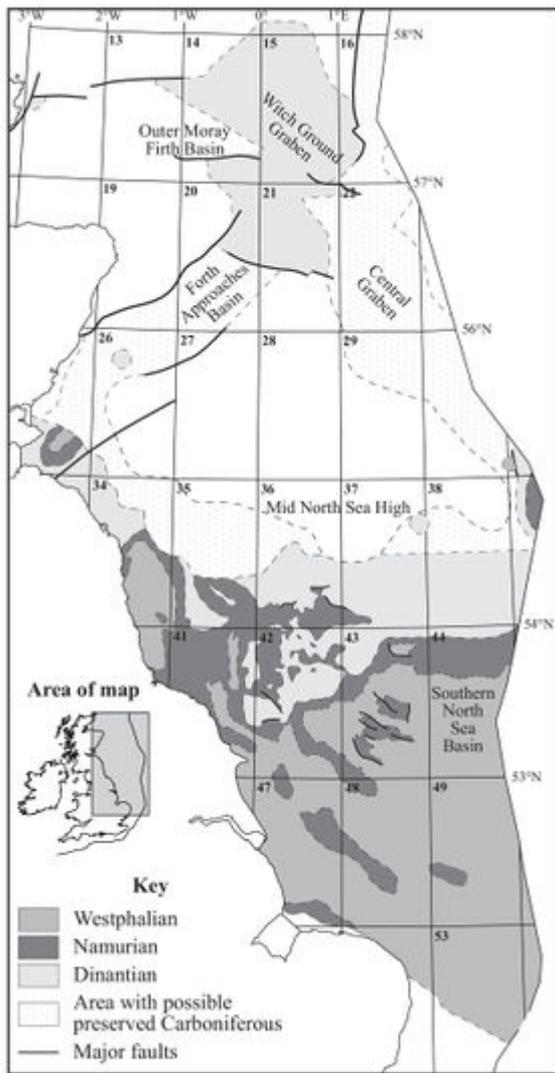


Figure 5 Distribution of Carboniferous rocks, beneath Permian and younger cover, in the UK sector of the North Sea (after Cameron 1993a, 1993b, Maynard & Dunay 1999, Bruce & Stemmerik 2003).

Stages	Palynostratigraphy		Lithostratigraphy			
	Biozones	Sub-Biozones	Cameron (1993b)		Besly (2002)	
			Formations	Informal units	Informal formations	Informal members
Westphalian D (pars.)	W7	W7c	Schooner Formation	Upper Ketch unit	Bodlon formation	
		W7b		Lower Ketch unit	Ketch formation	Upper Ketch member
W7a	Lower Ketch member					
Bolsovian	W6	W6b		Lower Schooner unit	Claver formation	Upper Claver member
		W6a	Lower Claver member			
		W5b				
Duckmantian	W4	W5a	Wintoe Coal Formation	Wintoe formation	Lower Claver member	
		W4c				
		W4b				
		W4a				
Langsettian	W3	W3a	Caster Coal Formation	Caster formation		
		W2b				
	W2a					
	W1b					
	W1a					
Yeadonian (pars.)	NS (pars.)	NSc	Milstone Grit Formation		Not defined	

Figure 6 Correlation of the North Sea Westphalian miospore biozones with the UK sector lithostratigraphy. No vertical scale implied.

By **D. McLean, B. Owens, R. Neves**

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Summary

Extensive palynological data from more than 300 Carboniferous well sections in the United Kingdom sector of the North Sea are synthesized into a miospore biozonation for the area. To facilitate their use in subsurface geology, the biozones are defined, where possible, by the stratigraphical range tops of significant and distinctive miospore taxa. The biozones are correlated with onshore British and European biozones and standard European chronostratigraphy by palynological correlations and a limited number of macrofaunal control points. Eighteen biozones are recognized, ranging in age from the late Tournaisian to the Westphalian D, and these mainly correlate to the onshore miospore biozones. A series of 40 sub-biozones are defined, which are recognizable at least within the North Sea area and some are also recognizable in Britain and continental Europe. Practical use of the biozones allows for several biostratigraphical applications at a range of geographical and stratigraphical scales.

Introduction

Biostratigraphic correlation of the European Carboniferous at outcrop and in cored boreholes conventionally relies upon ammonoids, brachiopods, corals, non-marine bivalves and macrofloras. Foraminifera, conodonts and palynomorphs are also important in correlating Early Carboniferous strata (George et al. 1976, Riley 1993), although the foraminifera and conodonts are of less value in correlating Late Carboniferous strata. Here, much of the marine macrofauna (bivalves, brachiopods, crinoids, fish, gastropods, ichnofaunas) may possess no intrinsic stratigraphical value, but, in the absence of ammonoids, can be used as proxy indicators of stratigraphically significant marine bands (Calver 1968, Goosens et al. 1974). In drilling for hydrocarbons, the scarcity of coherent rock material (cores and side-wall cores) generally limits the use of biostratigraphy based upon conventional macrofossils. Fragmentary ditch cuttings provide the standard type of subsurface sample material off shore, and so biostratigraphy is reliant upon the smaller microfossil groups. Foraminifera and ostracods may be extracted from ditch cuttings, but conodonts are too large to be preserved whole within such samples. Further, these fossil types occur in such limited concentrations, or in stratigraphically limited intervals (e.g. Late Carboniferous marine bands), as to make their study impracticable. In the Carboniferous of the North Sea the onus falls upon microscopic plant remains (miospores) to provide biostratigraphic subdivision and correlation (McLean & Murray 1996, Maynard et al. 1997). Miospores are generally well preserved and abundant in non-marine and non-carbonate marine facies. They may be present in carbonate and redbed sequences, but are usually less diverse and less well preserved.

In the literature on North Sea Carboniferous exploration there are only two studies in which macrofaunal biostratigraphy is described. The identification of ammonoids recovered from targeted rotary sidewall cores by Riley (in O'Mara et al. 1999) allowed the recognition of several Marsdenian to early Langsettian marine bands in the Trent field. Interwell correlation of these horizons provided the framework for a sedimentary sequence stratigraphy of the reservoir interval of the field.

Secondly, Turner et al. (1991) identified macrofaunas characteristic of the Vanderbeckei Marine Band in cores from the Murdoch field. These and associated non-marine bivalve faunas (illustrated in McLean 1993) have been used in association with palynostratigraphy to correlate the late Langsettian to early Duckmantian sequences in the Murdoch field through exploration and development phases (McLean & Murray 1996, McLean & Davies 1999).

1. Development of offshore palynostratigraphy

With the exception of some Stephanian stages, chronostratigraphic units of the European Carboniferous are determined by the presence of marine macro- and microfaunas, whether distributed throughout a rock sequence or restricted to particular marine horizons. Biostratigraphic zonations for Carboniferous fossil groups studied at outcrop have been developed in relation to these units. The discovery of economic accumulations of gas in the offshore subsurface Carboniferous led to demand for detailed correlations. Because of the difficulties in using most fossil groups described above, this was provided by the direct transference of the western European onshore miospore zonation (Clayton et al. 1977) to sections in the North Sea (see for example Leeder et al. 1990a,b). This process is justifiable given the similarities of Carboniferous sequences across northwestern Europe, and the similarities of the distributions of miospores in those sequences. Further, such an approach allows the distribution of miospores off shore to be related, via the distribution of miospores on shore, to the chronostratigraphic stages. However, difficulties in this correlation route became apparent, as exemplified by conflicting interpretations and applications of the palynostratigraphy of the Namurian sequence in well 48/3-3 (Leeder et al. 1990b, Collinson et al. 1993). To some extent these difficulties arose from the recognition of standard onshore biozones

using non-diagnostic miospore taxa (i.e. taxa not used in the definition of the onshore biozones). The solution lies in understanding the stratigraphical distributions of miospore taxa *in relation to one another* in the North Sea Carboniferous. This method is the basis for intra-North Sea correlations and has led to the erection of North Sea miospore biozones. A later step is to correlate these biozones to the onshore biostratigraphic schemes and thence to the standard chronostratigraphic stages. Even for short stratigraphical intervals this process requires the synthesis of a large volume of data, particularly for Carboniferous miospores, which commonly occur in assemblages containing 70+ taxa, and often 120+ taxa.

To date there are only two miospore biozonation schemes in the public domain specific to the North Sea Carboniferous. The scheme for the Westphalian by McLean (1995a) is an early draft of that presented here for the same interval. The biozones described for the whole Carboniferous by Maynard et al. (1997) are vaguely defined and of limited stratigraphical resolution ([Figure 1](#)).

Accumulation of palynostratigraphical data over the past 30 years and more has allowed the development of a miospore biozonation scheme specific to the North Sea. This is based upon the synthesis of data from more than 13000 productive palynological samples from more than 300 Carboniferous well sections. The biozonation includes data from both coal seams and mudstone/siltstone lithologies. The fact that different lithologies and facies yield different palynological assemblages (both of miospore taxa and total organic debris) is well known (Neves 1958) and provides the basis for high-resolution palynofacies studies (e.g. for the Westphalian of the Caister field by Ritchie & Pratsides 1993, and for the late Westphalian onshore Netherlands by Van de Laar & Van der Zwan 1996). It is also recognized that the stratigraphical ranges of most, if not all, miospore taxa seen in coal seams are shorter than their ranges in clastic strata. Consequently, the best palynological dataset includes assemblages from all lithological types. The biozonation is homotaxial (*sensu* Scott 1965) in approach (i.e. it is based upon the relative order of appearances and disappearances of taxa), but remains comparable to the framework provided by the onshore zonations. The onshore biozones were consciously defined to reflect the evolution of the Carboniferous microflora. As such, their bases are principally defined by the first appearances of certain morphologically distinctive and stratigraphically restricted taxa. However, because of the scarcity of cored sections in the North Sea, the offshore biozones are defined, where possible, on the last stratigraphical occurrences (range tops or first downhole appearances) of zonal taxa. This method makes the biozones applicable to ditch cuttings material. Selection of zonal taxa is based upon the consistent occurrence of the range top or base of each taxon in several well sections. Consequently, several relatively common taxa, which, given their representation in onshore biozones would be expected to be stratigraphically significant, have proved not to be (at least within the limitations of the database). For example, the intra-Namurian range top of the highly distinctive form *Ibrahimisporites magnificus* occurs at inconsistent levels with respect to certain other taxa taken as standards, and so is excluded as a significant biostratigraphical event. The range base of *Cadiospora magna* (traditionally considered to be a Westphalian D marker taxon, e.g. Smith & Butterworth 1967, Maynard et al. 1997) occurs irregularly in the mid- and early Bolsovian of the North Sea UK sector. Other taxa (e.g. *Fragilipollenites radiatus* and *Pteroretis primum*), although morphologically distinctive, occur so rarely as to preclude the recognition of consistent range limits. On the other hand, some taxa, particularly in the late Namurian (e.g. *Ahrensisporites beeleyensis*, *Alatisporites nudus* and *Triquitrites nodosus*) are rare but have consistent stratigraphical limits, and so are considered significant.

Definitions of the Dinantian, Namurian and Westphalian biozones are shown on [Figure 2](#), [Figure 3](#), [Figure 4](#) respectively. Full citations for all taxa are given in the Appendix. Individual biozones are defined by the range top or base of a particular miospore taxon and represent interval or partial-range biozones. As such, they differ from the standard approach to Carboniferous

palynostratigraphy, where assemblage biozones (Smith & Butterworth 1967) or concurrent range biozones (Neves et al. 1972, 1973, Clayton et al. 1977, Owens et al. 1977) have traditionally been used. It is recognized that any one defining taxon will not always be represented in a section. So, some associated taxa whose range tops or bases are known to occur *in proximity to* that of the defining taxon are also indicated.

Nomenclature of the biozones is made for ease of use and it avoids the binomial system usual for onshore Carboniferous miospore biozones. The bases of most of the North Sea biozones are defined by stratigraphical range tops, with the defining taxa occurring in the biozone below that which they define. As this may lead to some confusion, the biozones here are not named after miospore taxa, as is conventional, but are numbered sequentially. Standard practice determines that type sections need not be defined for biozones (Hedberg 1976) and these are not designated here. However, the North Sea biozones will be incorporated into a major review of European Carboniferous palynostratigraphy. Standard sections for pan-northwest European biozones will be provided in this new scheme (Clayton et al. 2003).

Work by one author (DM) has allowed the recognition of limited and scattered independent (macropalaeontological) control points in cored sections, which provide some calibration of the palynological zonation. Miospore biozones have been determined for the whole of the Carboniferous that occurs in the northern and southern parts of the North Sea ([Figure 1](#)), but the level of stratigraphical resolution of these is variable. To a large extent, stratigraphical resolution is determined by the number of well sections available for study reflecting the stratigraphical distribution of hydrocarbon targets and economic reservoirs. Most of the data are clustered in Westphalian strata (in the northern part of the Southern North Sea Basin ([Figure 5](#)), with lesser amounts in mid- to late Dinantian strata (in the Outer Moray Firth Basin). Data from the Namurian are sufficient to allow a refined and robust biozonation, although data from the pre-Holkerian are provided by only a few well sections, mostly around the margins of the offshore Carboniferous basins. Palynostratigraphy of these older strata is further limited by the existence of Tournaisian sandstone-rich redbed facies (Buchan Formation of Cameron 1993a) which are commonly barren.

2. North Sea Carboniferous biozones

2.1 Dinantian biozones

The North Sea Dinantian miospore biozones ([Figure 2](#)) essentially reflect the biostratigraphic zonation established in northern Britain and the Midland Valley of Scotland (Neves et al. 1972, 1973, Clayton et al. 1977, 1978), and appear to be consistent in occurrence and applicability from the northern margins of the Cleveland Basin to the northern part of Quadrants 14 and 15. However, several key wells, such as 43/2-1 (Maynard & Dunay 1999) on the southern flank of the mid-North Sea High, have not been studied. Sub-biozones are locally recognizable. Higher-resolution events have been identified in and correlated with the Asbian to Holkerian sections in densely sampled, closely spaced wells in the Forth Approaches Basin and the Outer Moray Firth Basin. As no independent offshore macrofaunal data are available, correlation of the Dinantian biozones with the chronostratigraphic scale is made by reference to the Midland Valley of Scotland, which has limited independent biostratigraphic control. Some limited correlation is provided by the recognition of palynostratigraphical “events” ([Figure 1](#)) that are known to be synchronous over large areas (Clayton 1985, 1996, Clayton et al. 1990, Turner *in* Cameron 1993a). Although Turner (*ibid.*) recognized the first downhole occurrences of *Indotriradites explanatus*, *Tumulispota malevkensis* and *Raistrickia condylosa* as significant mid-Tournaisian marker levels, no early to mid-Tournaisian assemblages were recorded in this study. Maynard et al. (1997) considered *Raistrickia clavata*, *Spelaotrilletes pretiosus* and *Vallatisporites vallatus* to represent the “mid” Courceyan of the North

Sea (their biozone B). However, these taxa are known from younger strata on shore. The Tournaisian miospore biozones of Higgs et al. (1988) are included in [Figure 1](#) for completeness.

2.2 Namurian biozones

The Namurian palynozonation ([Figure 3](#)) is based upon several thick well sections in the Southern North Sea Basin. These are mostly without any macrofaunal control other than a few late Kinderscoutian and Marsdenian goniatite occurrences. The miospore biozonation remains work in progress pending detailed palynostratigraphic study of the key goniatite-dated sections in the Trent area. The North Sea biozones are comparable to those developed for sections in onshore northern England (Owens et al. 1977) but, as with the offshore Dinantian biozones above, definition is made using range tops of zonal taxa, where possible. Comparison with the onshore biozones and the recognition of widely recognized palynological “events” (Turner in Cameron 1993a, 1993b, Clayton 1996, Owens 1996) provides correlation with the Namurian stages ([Figure 3](#)). The zonation has been applied across the northern part of the Southern North Sea Basin and is applicable to younger parts of the Firth Coal Formation (Cameron 1993a) to the north of the Mid North Sea High.

2.3 Westphalian biozones

The Westphalian biozonation ([Figure 4](#)) is based upon a large data-set from the Southern North Sea Basin. Many wells provide extensive sections that have been cored or have yielded sidewall cores. An early version of the Westphalian miospore zonation was presented by McLean (1995a). The Westphalian biozones and sub-biozones are recognizable across the basin with little variation. Relatively good macrofossil control is available in the form of marine faunas that identify the Vanderbeckei, Maltby and Aegiranum marine bands in certain cored well sections (e.g. McLean 1993, McLean & Murray 1995). Non-marine bivalve and macrofloral assemblages have also been identified from cores. Some of these sections provide additional independent control points (McLean & Davies 1999), but generally these have not been studied systematically and the potential of these fossil groups from the North Sea Carboniferous remains unrealized.

The miospore zonation has been applied throughout the Southern North Sea Basin and into the Dutch and German sectors of the North Sea. It also proves relevant to Westphalian sections in the subsurface of onshore northern Germany, The Netherlands and northern France. Perhaps more importantly, significant features of the biozonation are being used to reassess the biostratigraphy of important onshore sections, including the Westphalian Stage boundary stratotypes in the British coalfields (Owens et al. 1985, McLean et al. in press).

No palynological assemblages of definitive Stephanian age have yet been recognized in the UK sector of the North Sea. It has been suggested that Stephanian strata may be preserved in the northern part of the Dutch sector, although biostratigraphical evidence to support this is lacking (Van Adrichem Boogaert & Kouwe 1993).

3. Applications of Carboniferous palynostratigraphy

The palynostratigraphic scheme has been applied to the offshore Carboniferous at a range of geographical and stratigraphical scales to allow several types of interpretation.

3.1 Recognition of Carboniferous strata

In exploration drilling, the recognition of Carboniferous strata and their differentiation from lithologically similar rocks may be readily performed by palynological analysis (e.g. Martin et al. 2002). This may be particularly significant in the differentiation of otherwise undated dark mudstone

units in short rat-holes.

3.2 Subcrop mapping

Palynostratigraphy provides a basis for mapping of the Permian subcrop (in the Southern North Sea Basin) or younger subcrop (in areas north of the Mid North Sea High) at various levels of stratigraphical resolution. The recognition and stratigraphical placement of thin unconformity-bounded Carboniferous remnants around the basin margins extend knowledge of the known original distribution of Carboniferous strata.

3.3 High-resolution interwell correlation

The correlation of lithostratigraphical units between well sections is the fundamental palynostratigraphic methodology in hydrocarbon exploration. Claims that palynology provides only low-resolution biostratigraphy in the offshore Carboniferous (e.g. to stage level; Leeder et al. 1990b) are now seen as untenable (see [Figure 1](#)). Correlation of miospore biozones now equals or exceeds the level of resolution achieved by most other Carboniferous fossil groups, with the notable exception of the ammonoids. Further, the framework provided by the biozones allows more detailed intra-biozonal correlations to be made. These may be based upon relatively short-lived palaeoclimatic or facies signals within the palynological data, or upon data from other disciplines such as geochemistry or wireline log analysis (Leeder et al. 1990b, Besly et al. 1993, Davies & McLean 1996, Pearce et al. 2005). Detailed analysis of closely sampled sections may allow the recognition of palynologically distinctive mud-stone or coal units. Correlation of these has provided the basis for detailed subdivision and correlation of Westphalian reservoir units (e.g. coal seam correlations in the Langsettian and Duckmantian of the Murdoch, Caister and Chiswick fields; and correlation of intra-reservoir units within the Murdoch-Caister reservoir sandstone unit). Case studies have been presented for the Murdoch field in McLean & Murray (1996) and McLean and Davies (1999), and for the Caister field in Ritchie & Pratsides (1993).

The development of a higher-resolution miospore biozonation has also allowed more detailed lithostratigraphical interpretations. In particular, the recognition of biozone boundaries associated with some of the principal Westphalian marine bands provides a basis for refined correlations. Note that the Aegiranum, Maltby, Amaliae and Listeri marine bands are not associated with biozone boundaries in the scheme of Clayton et al. (1977), and the same is true for the Cambriense, Aegiranum, Maltby and Amaliae marine bands in the scheme of Maynard et al (1997; [Figure 1](#)). In the current study, emphasis has been placed upon the relationship of palynostratigraphy to the distribution of marine bands, and biozone boundaries identified accordingly. This means that the present scheme has a relatively high-resolution correlation potential. Further, the stratal subdivisions that it provides are likely to be genetically related in a sequence stratigraphical or palaeoclimatological sense.

Application of the scheme in the area on the northern margin of the Southern North Sea Basin has allowed the recognition of a major intra-Westphalian unconformity. Here, sequences towards the centre of the basin preserve a more-or-less complete record of Langsettian, Duckmantian and early to mid-Bolsoviaian coal-bearing strata overlain by redbeds of late Bolsoviaian age. To the northeast, the strata immediately beneath the redbeds become older, although palynological evidence from the redbeds indicate that these remain of mid-Bolsoviaian age. Such age interpretations are difficult to reconcile with the lithostratigraphy of Cameron (1993b), but, in the lithostratigraphy of Besly (2002), the base of the Lower Ketch Formation unconformably overlies the Cleaver and Westoe formations ([Figure 5](#)). In well 44/21-3 (Pearce et al. 2005), the Lower Ketch Formation rests on early Bolsoviaian coal-bearing rocks of the Upper Cleaver Member (*sensu* Besly 2002). Use of the new biozonation in wells slightly farther north indicates that strata above the horizon of the Aegiranum

Marine Band are not preserved, and that the redbeds lie upon late Duckmantian strata. In wells still farther northeast the Ketch Formation shows progressive onlap of the early Duckmantian, Langsettian and Namurian. In such cases the base of the Ketch Formation is evident in the absence of several biozones across the unconformity (Pearce et al. 2005).

The relationships of the Westphalian biozonation to the lithostratigraphic systems of Cameron (1993b) and Besly (2002) is shown in [Figure 6](#). Recognition of the biozones allows a level of calibration of the lithostratigraphic units. Importantly, the diachronous nature of the boundaries of the units defined by Cameron (1993b) become readily apparent where they cross biozone boundaries related to major marine bands, for example, where the biozones allow the discrimination of strata below the Aegiranum Marine Band (latest Duckmantian) from those of earliest Bolsovian age above that horizon.

Some of the boundaries of the lithostratigraphical units of Besly (2002) are defined by major marine bands that can be correlated with the palynostratigraphy ([Figure 1](#)). Recognition of these marine bands, using palynological or other criteria, is key to accurate lithostratigraphic understanding of the Late Carboniferous of the North Sea.

3.4 Low- to medium-resolution interwell correlation

Primary redbed facies such as the Bolsovian to Westphalian D Ketch Formation are typically barren or contain only poor palynological assemblages. Persistent sampling and careful preparation of material from these units does provide some palynological recovery, which allows limited stratigraphical interpretation. It is unlikely that such biostratigraphy will ever rival the resolution provided by geochemical techniques or facies modelling (Stone & Moscariello 1999, Moscariello 2000), but palynology can provide a level of stratigraphical constraint (see the case study from the Ketch field in Pearce et al. 2005).

3.5 Regional correlation

The miospore biozones are recognized over a large area of Carboniferous rocks from which few data have previously been available. The Carboniferous strata of the North Sea Basin link those of the UK and northwestern European Carboniferous basins. A better understanding of these basins will allow better correlation farther afield into eastern Europe (cf. Owens et al. 1978) and western North America. Central to this process is the recognition of significant laterally extensive marine horizons. Integration of palynofacies studies (e.g. Van de Laar & Fermont 1990) with spectral gamma-ray or geochemical data provides a means for the recognition and correlation of these marine bands in the subsurface (Davies & McLean 1996, McLean et al. 2002, Pearce et al. 2002).

3.6 Provenance studies

Westphalian strata in the Southern North Sea Basin commonly contain reworked Devonian miospores and pre-Devonian acritarchs. The identification of re-working may provide constraints on the sedimentary provenance of the Westphalian rock material. Similar results are known from onshore Late Carboniferous strata (Streel & Bless 1980, McLean 1995b, Chisholm et al. 1996, McLean & Chisholm 1996). The palynological data provide information on the relatively recent sources of sediment compared to the ancient (often pre-Palaeozoic) sources identified by heavy-mineral studies (Morton et al. 2005). The recognition of re-worked older Carboniferous palynomorphs in Westphalian strata may provide information on the phases of intra-Carboniferous incision and erosion.

3.7 Offshore to onshore comparisons

This study is based upon a wealth of palynostratigraphical data from offshore Carboniferous sections. Synthesis of these indicates similarities and differences between the palynology of the offshore and the onshore basins and shows areas in which the biostratigraphic subdivisions of the onshore Carboniferous strata may be improved. A few examples are given here. Stratigraphically restricted late Viséan palynomorph assemblages from the Forth Approaches Basin contain miospore taxa described from the Carboniferous of the present-day Arctic (Ravn 1991). These have been only rarely described from coeval strata on shore in the Midland Valley of Scotland (Turner & McLean 1999), but have correlation potential and may provide information on vegetation migration pathways and palaeoclimate. Secondly, many distinctive but undescribed miospore taxa are known from the offshore Carboniferous. Similarly, forms described from the Carboniferous of the United States that are rare in the onshore UK, may be relatively common off shore. The stratigraphical potential of these for European palynostratigraphic correlation is gradually becoming appreciated.

4. Conclusions

A series of palynostratigraphic biozones for the Carboniferous of the North Sea are presented. These are related to onshore Carboniferous stratigraphy by palynological and macrofaunal correlations. They provide the basis for a variety of stratigraphical interpretations at various stratigraphical and geographical scales.

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Template:Anchor Appendix: Alphabetical list of cited palynomorph names

Acanthotriletes acritarchus Neville in Neves et al. 1973

Acanthotriletes castanaea Butterworth & Williams 1958

Acanthotriletes echinatoides Artüz 1957

Acanthotriletes falcatus (Knox) Potonié & Kremp 1955

Acanthotriletes? pilus Neves 1961

Acanthotriletes triquetrus Smith & Butterworth 1967

Adelisorites multiplicatus Ravn 1979

Ahrensiporites beeleiyensis Neves 1961

Ahrensiporites duplicatus Neville in Neves et al. 1973

Ahrensiporites guerickei (Horst) Potonié & Kremp ex Horst 1955

Alatisporites hoffmeisterii Morgan 1955

Alatisporites nudus Neves 1958

Alatisporites pustulatus (Ibrahim) Ibrahim 1933

Apiculatasporites spinososaetosus (Loose) Ravn 1986

Apiculatasporites variocorneus (Sullivan) Ravn 1986

Bascaudaspora canipa Owens 1983

Bellisporites nitidus (Horst) Sullivan emend. Smith & Butterworth 1967

Biharisporites haaksbergensis Bless et al. 1977

Camptotriletes bucculentus (Loose) Potonié & Kremp 1955

Camptotriletes corrugatus (Ibrahim) Potonié & Kremp 1955

Camptotriletes cristatus Sullivan & Marshall 1966

Camptotriletes superbus Neves 1961

Chaetosphaerites pollenisimilis (Horst) Butterworth & Williams 1958

Cingulizonates bialatus (Waltz) Smith & Butterworth 1967

Cingulizonates loricatus (Loose) Butterworth & Smith in Butterworth et al. 1964

Cingulizonates cf. *capistratus* (Hoffmeister et al.) Staplin & Jansonius *sensu* Smith & Butterworth 1967

Cirratriradites annulatus Kosanke & Brokaw in Kosanke 1950

Convolutispora ampla Hoffmeister et al. 1955

Convolutispora circumvallata Clayton 1971

Convolutispora laminosa Neves 1961

Convolutispora varicosa Butterworth & Williams 1958

Corbulispora cancellata (Waltz) Bharadwaj & Venkatachala 1962

Crassispora aculeata Neville 1968

Crassispora kosankei (Potonié & Kremp) Bhardwaj emend. Smith & Butterworth 1967

Crassispora maculosa (Knox) Sullivan 1964

Cribrosporites cribellatus Sullivan 1964

Cristatisporites connexus Potonié & Kremp 1955

Cristatisporites solaris (Balme) Butterworth & Smith in Butterworth et al. 1964

Cristatisporites splendidus Artüz 1957

Cuneisporites rigidus Ravn 1979

Deltoidospora smithii Ravn 1986

Densosporites Berry emend. Butterworth et al. 1964

Densosporites duriti Potonié & Kremp 1956

Densosporites gracilis Smith & Butterworth 1967

Densosporites intermedius Butterworth & Williams 1958

Densosporites pseudoannulatus Butterworth & Williams 1958

Densosporites sphaerotriangularis Kosanke 1950

Densosporites spinosus Dybová & Jachowicz 1957

Densosporites vulgaris Neves 1961

Diatomozonotriletes Naumova emend. Playford 1963

Diatomozonotriletes magnus Beju 1970

Diatomozonotriletes fragilis Clayton in Neves et al. 1973

Dictyomonolites swadei Ravn 1986

Dictyotriletes bireticulatus (Ibrahim) emend. Smith & Butterworth 1967

Dictyotriletes karadenizensis Artüz 1957

Dictyotriletes muricatus (Kosanke) Smith & Butterworth 1967

Dictyotriletes probireticulatus Butterworth & Mahdi 1982

Dictyotriletes vitilis Sullivan & Marshall 1966

Endosporites globiformis (Ibrahim) Schopf et al. 1944

Endosporites zonalis (Loose) Knox 1950

Fabasporites pallidus Sullivan 1964

Florinites Schopf in Schopf et al. 1944

Florinites junior Potonié & Kremp 1956

Florinites similis Kosanke 1950

Fragilipollenites radiatus Konyali in Agrali et al. emend. McLean 1997

Granasporites medius (Dybová & Jachowicz) Ravn et al. 1986

Grandispora spinosa Hoffmeister et al. 1955

Grumosisporites inaequalis (Butterworth & Williams) Smith & Butterworth 1967

Grumosisporites papillosus (Ibrahim) emend. Smith & Butterworth 1967

Grumosisporites rufus (Butterworth & Williams) Smith & Butterworth 1967

Grumosisporites varioreticulatus (Neves) emend. Smith & Butterworth 1967

Grumosisporites verrucosus (Neves) emend. Smith & Butterworth 1967

Hymenospora murdochensis McLean et al. *in press*

Indotriradites explanatus (Luber) Playford 1990

Jayantisporites Lele & Makada 1972

Knoxisporites glomus Inosova et al. 1976

Knoxisporites stephanephorus Love 1960

Knoxisporites triradiatus Hoffmeister et al. 1955

Kraeuselisporites echinatus Owens et al. 1966

Kraeuselisporites ornatus (Neves) Owens et al. 1966

Kraeuselisporites sp. A. Neville *in* Neves et al. 1973

Latensina trileta Alpern 1958

Lundbladispora gigantea (Alpern) Doubinger 1968

Laevigatosporites densus Alpern 1958

Lycospora nitida Artüz 1957

Lycospora noctuina noctuina Grebe 1972

Lycospora pusilla (Ibrahim) Schopf et al. 1944

Lycospora rotunda Bhardwaj 1957

Lycospora subtriquetra (Luber) Potonié & Kremp 1954

Microreticulatisporites harrisonii Peppers 1970

Microreticulatisporites nobilis (Wicher) Knox 1950

Microreticulatisporites punctatus Knox 1950

Monilospora mutabilis Staplin 1960

Mooreisporites bellus Neves 1961

Mooreisporites fustis Neves 1958

Mooreisporites trigallerus Neves 1961

Murospora intorta (Waltz) Playford 1962

Murospora margodentata Beju 1970

Murospora parthenopia Neves & Ioannides 1974

Neoraistrickia inconstans Neves 1961

Paleospora fragila Habib 1966

Perotrilites perinatus Hughes & Playford 1961

Perotrilites tessellatus (Staplin) Neville in Neves et al. 1973

Plicatispora scolecophora (Neves & Ioannides) Higgs et al. 1988

Potoniespores delicatus Playford 1963

Proprisporites laevigatus Neves 1961

Proprisporites rugosus Neves 1958

Punctatisporites irrasus Hacquebard 1957

Punctatisporites minutus Kosanke 1950

Punctatisporites obliquus Kosanke 1950

Punctatosporites Ibrahim emend. Alpern & Doubinger 1973

Punctatosporites granifer Potonié & Kremp 1956

Punctatosporites rotundus Bharadwaj 1957

Radiizonates aligerens (Knox) emend. Staplin & Jansonius 1964

Radiizonates cf. *difformis* (Kosanke) Staplin & Jansonius *sensu* Smith & Butterworth 1967

Radiizonates faunus (Ibrahim) Smith & Butterworth 1967

Radiizonates striatus (Knox) Staplin & Jansonius 1964

Radiizonates cf. *striatus* (Knox) Staplin & Jansonius 1964 *sensu*
Smith & Butterworth 1967

Radiizonates tenuis (Loose) Butterworth & Smith in Butterworth et al. 1964

Raistrickia? abdita (Loose) Schopf et al. 1944

Raistrickia aculeata Kosanke 1950

Raistrickia clavata Hacquebard emend. Playford 1964

Raistrickia condylosa Higgs 1975

Raistrickia corynoges Sullivan 1968

Raistrickia fulva Artüz 1957

Raistrickia microhorrida (Horst) Potonié & Kremp 1955

Raistrickia nigra Love 1960

Reinschospora speciosa (Loose) Schopf et al. 1944

Reinschospora triangularis Kosanke emend. Ravn 1979

Remysporites magnificus (Horst) Butterworth & Williams 1958

Reticulatisporites polygonalis (Ibrahim) Loose emend. Smith & Butterworth 1967

Reticulatisporites reticulatus (Ibrahim) Ibrahim 1933

Reticulitriletes falsus (Potonié & Kremp) Ravn 1986

Reticulitriletes mediareticulatus (Ibrahim) Ravn 1986

Reticulitriletes reticulocingulum (Loose) Ravn 1986

Rotaspora Schemel emend. Smith & Butterworth 1967

Rotaspora ergonuli (Agrali) Sullivan & Marshall 1966

Rotaspora fracta Schemel emend. Smith & Butterworth 1967

Rotaspora knoxiae Butterworth & Williams 1958

Rugospora corporata Neves & Owens 1966

Savitrisporites concavus Marshall & Smith 1965

Savitrisporites camptotus (Alpern) Doubinger 1968

Savitrisporites nux (Butterworth & Williams) Sullivan emend. Smith & Butterworth 1967

Schopfites claviger Sullivan 1968

Schulzospora Kosanke 1950

Schulzospora campyloptera (Waltz) Hoffmeister et al. 1955

Schulzospora ocellata (Horst) Potonié & Kremp 1955

Schulzospora rara Kosanke 1950

Schopfites dimorphus Kosanke 1950

Sinuspores sinuatus Artüz emend. Ravn 1986

Spelaeotriletes arenaceus Neves & Owens 1966

Spelaeotriletes pretiosus (Playford) Neves & Belt 1970

Spelaeotriletes pretiosus windsorensis Utting 1987

Spelaeotriletes triangulus Neves & Owens 1966

Spencerisporites radiatus (Ibrahim) Felix & Parks 1959

Spinospirites Alpern 1958

Spinozonotriletes uncatatus Hacquebard 1957

Stenozonotriletes coronatus Sullivan & Marshall 1966

Stenozonotriletes triangularis Neves 1961

Tantillus triquetrus Felix & Burbridge 1967

Tholisporites biannulatus Neves 1961

Tholisporites scoticus Butterworth & Williams 1958

Thymospora Wilson & Venkatachala 1963

Thymospora pseudothiessenii (Kosanke) Wilson & Venkatachala 1963

Thymospora obscura (Kosanke) Wilson & Venkatachala 1963

Thymospora verrucosa Alpern 1959

Torisporea securis Balme emend. Alpern et al. 1965

Tricidarisporites balteolus Sullivan & Marshall 1966

Trinidulus diamphidios Felix & Paden 1964

Tripartites distinctus Williams in Neves et al. 1973

Tripartites nonguerickei Potonié & Kremp ex Smith & Butterworth 1967

Tripartites vetustus Schemel 1950

Triquitrites Wilson & Coe emend. Potonié & Kremp 1954

Triquitrites comptus Williams in Neves et al. 1973

Triquitrites marginatus Hoffmeister et al. 1955

Triquitrites nodosus Neves 1961

Triquitrites cf. *protensus* Kosanke 1950 *sensu* Smith & Butterworth 1967

Triquitrites sculptilis Balme emend. Smith & Butterworth 1967

Triquitrites tribullatus (Ibrahim) Schopf et al. 1944

Triquitrites trivalvis (Waltz) Potonié & Kremp 1954

Tumulispora malevkensis (Naumova) Turnau 1978

Vallatisporites vallatus Hacquebard 1957

Verrucosisporites baccatus Staplin 1960

Verrucosisporites congestus Playford 1964

Verrucosisporites donarii Potonié & Kremp 1955

Verrucosisporites eximius Playford 1962

Verrucosisporites microverrucosus Ibrahim 1933

Verrucosisporites morulatus (Knox) emend. Smith & Butterworth 1967

Verrucosisporites nodosus Sullivan & Marshall 1966

Vestispora cancellata (Dybová & Jachowicz) Wilson & Venkatachala 1963

Vestispora fenestrata (Kosanke & Brokaw) Wilson & Venkatachala emend. Spode, *in* Smith & Butterworth, 1967

Vestispora laevigata Wilson & Venkatachala 1963

Vestispora lucida (Butterworth & Williams) Potonié 1960

Vestispora magna (Butterworth & Williams) Wilson & Venkatachala
emend. Spode, *in* Smith & Butterworth, 1967

Vestispora pseudoreticulata Neves 1964

Vestispora tortuosa (Balme) Spode, *in* Smith & Butterworth, 1967

Waltzispora polita Staplin 1960

Westphalensisporites irregularis Alpern 1958

Zonalosporites Ibrahim 1933

Zonalosporites magnus (Venkatachala) Ravn 1986

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