IS05/18 Investigation of the palynology, stratigraphy and palaeogeography of Carboniferous rocks in Western Irish offshore basins; Annual project progress report (Year 2); A.Haddow, TCD, 5 April 2008

1. Introduction

Nineteen hydrocarbon exploration wells have encountered Carboniferous strata in the Porcupine, Slyne, Erris, Donegal and Rockall sedimentary basins offshore Western Ireland (Figure 1). The rocks have been almost exclusively dated using plant spores (palynostratigraphy), e.g. Robeson *et al.* (1988). Coal-rich upper Carboniferous strata is widely perceived to be the source rock of gas encountered in the 1996 Slyne Basin Corrib field discovery (Spencer and MacTiernan, 2001) and the 2003 Rockall Trough Dooish gas condensate discovery.

Geological uncertainties concerning the Carboniferous succession include the exact age of well sections, the palaeogeographic evolution of offshore Western Ireland during that period and the regional distribution of source, sealing and reservoir lithologies.

Previous palynostratigraphic interpretations of the 19 wells have been largely based on the original Carboniferous Western European miospore zonal scheme of Clayton *et al*. (1977). Recent advances in Western European palynostratigraphy, e.g. Owens *et al.* (2004) and McLean *et al.* (2005), have resulted in a modified zonal scheme (Clayton *et al.*, 2003), increasing the number of biozones and sub-biozones that can be recognised (Figure 2). This provides an opportunity for high resolution palynostratigraphic reinterpretations of the offshore Irish strata.

The integration of accurately dated well sections with seismic based sequence stratigraphy provides an opportunity to reconstruct the palaeogeographic evolution of offshore Western Ireland during the Carboniferous. Regional variations in depositional environment and lithofacies can be identified through the seismic mapping of time related strata, together with the analysis of seismic event geometries, palynofacies and borehole lithologies. Palaeogeographic reconstructions also help define the regional distribution of potential source, reservoir and sealing lithologies.

The thermal maturity of Carboniferous rocks in the Porcupine, Erris and Donegal basins has been previously studied by Robeson (1988) and Corcoran & Clayton (2001) through vitrinite reflectance analysis. Recent advances in spectrophotometric microscopy offer an alternative method of thermal maturity assessment through the quantitative measurement of spore colour and spore fluorescence colour. Access to spectrophotometric microscope equipment located at Memorial University of Newfoundland provides an opportunity to develop novel techniques of quantitative spore colour measurement. Calibrating the measurements with existing vitrinite reflectance data enables the development of comparative thermal maturity scales that can be used for future thermal maturity analysis.

Carboniferous sequences encountered in hydrocarbon wells from the Newfoundland/Scotian shelf area, Grand Banks and Sydney Basin, offshore Eastern Canada, show similarities to the Carboniferous succession offshore Western Ireland, reflecting the proximity of the Porcupine basin and the Eastern Canadian shelf prior to North Atlantic rifting (Robeson, 1988). The revised Western European miospore zonal scheme provides an opportunity to correlate the Carboniferous palynostratigraphy of key wells from offshore Eastern Canada with that of offshore Western Ireland.

2. Research Objectives

- Reinterpret the palynostratigraphy of the 19 offshore Western Ireland Carboniferous well sections using the revised Western European miospore zonal scheme of Clayton *et al.* (2003).

- Create a series of palaeogeographic reconstructions of offshore Western Ireland during the Carboniferous.

- Develop methods of quantitatively measuring the thermal maturity of fossil spores from key well sections using spectrophotometric microscopy.

- Correlate the Carboniferous palynostratigraphy of key wells from offshore Eastern Canada with that of offshore Western Ireland.

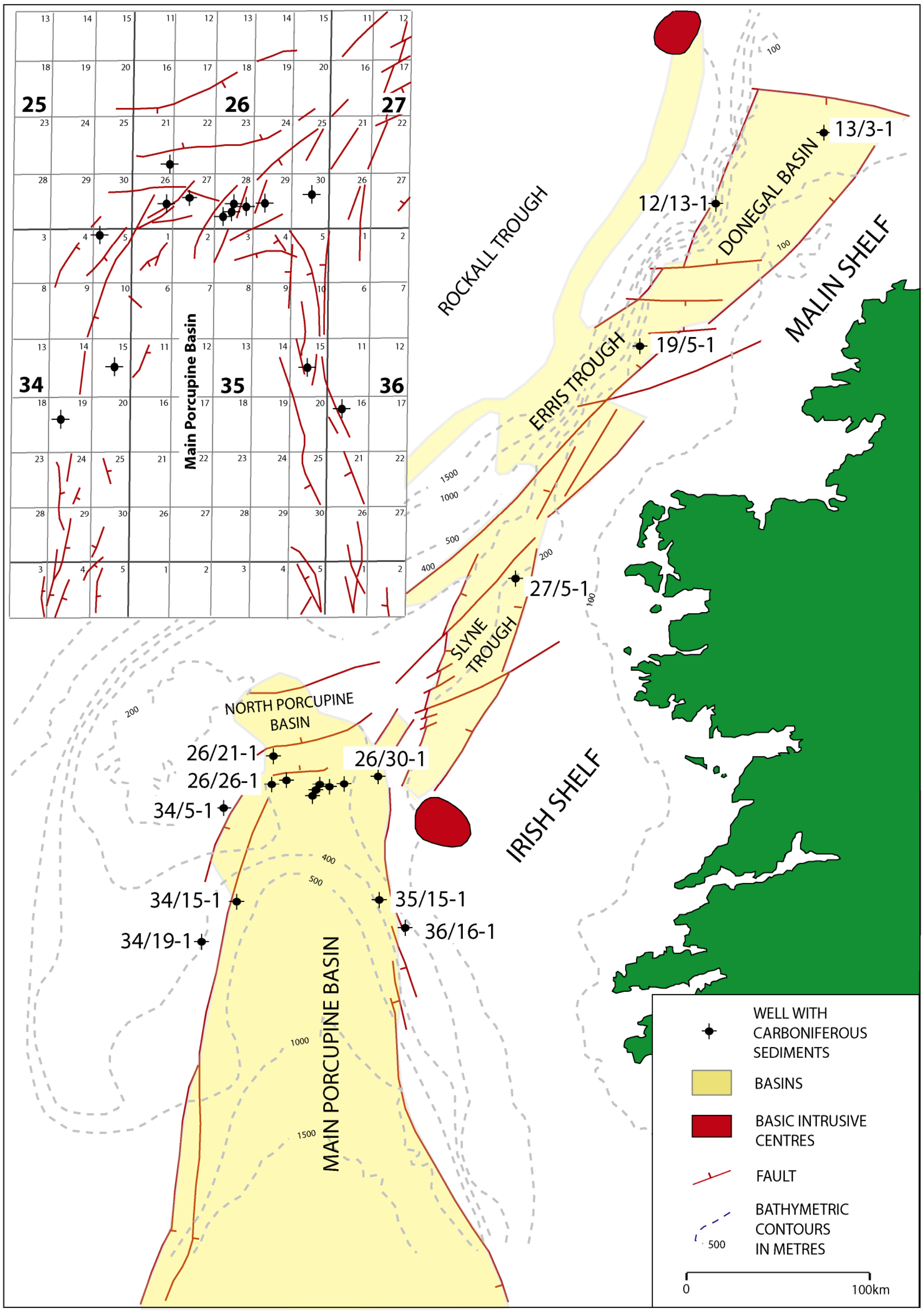

Figure 1; Location map of sedimentary basins offshore Western Ireland and wells that penetrate Carboniferous strata (modified from Robeson *et al.*, 1988). The location of one study well remains confidential.

SYSTEM	SUB SYSTEM	GLOBAL SERIES	GLOBAL STAGE	REGIONAL W. EUROPEAN STAGE	REGIONAL SUBSTAGE	OLD BIOZONES	REVISED BIOZONES & SUB-BIOZONES (CLAYTON *et al.* 2003)	
CARBONIFEROUS	PENNSYLVANIAN	UPPER	GZHELIAN	AUTUNIAN		VC	STEPHANIAN REVISION IN PROGRESS	
			KASIMOVIAN	STEPHANIAN	C	N.B M		
					B			
					A	ST		
					CANTABRIAN			
		MIDDLE	MOSCOVIAN	WESTPHALIAN	WESTPHALIAN D	OT	*Thymospora pseudothiessenii*	*Angulisporites splendidus*
								Thymospora verrucata
								Westphalensisporites irregularis
					BOLSOVIAN (Westphalian C)	SL	*Vestispora fenestrata*	*Raistrickia aculeata*
								Torispora securis
						NJ	*Triquitrites sculptilis*	
		LOWER	BASHKIRIAN		DUCKMANTIAN (Westphalian B)		*Microreticulatisporites nobilis*	*Vestispora magna*
								Lycospora noctuina noctuina
							Sinuspores sinuatus	
					LANGSETTIAN (Westphalian A)	RA	*Schulzospora rara*	
							Radiizonates aligerens	
							Vestispora cancellata	
						SS	*Spelaeotriletes arenaceus*	
							Dictotriletes probireticulatus	
				NAMURIAN (Upper)	YEADONIAN	FR	*Reticulatisporites reticulatus*	
					MARSDENIAN	KV	*Crassispora kosankei*	
					KINDERSCOUTIAN			
					ALPORTIAN	SO	*Lycospora subtriquetra*	*Cirratriradites rarus*
					CHOKIERIAN			*Apiculatisporis variocorneus*
	MISSISSIPIAN	UPPER	SERPUKHOVIAN	NAMURIAN (Lower)	ARNSBERGIAN	TK	*Mooreisporites trigallerus*	
					PENDLEIAN	NC	*Cingulizonates cf. capistratus*	*Verrucosisporites morulatus*
								Bellispores nitidus
		MIDDLE	VISEAN	VISEAN	BRIGANTIAN	VF	*Tripartites vetustus*	
					ASBIAN	NM	*Triquitrites marginatus*	*Murospora margodentata*
								Murospora parthenopia
						TC	*Schulzospora campyloptera*	
					HOLKERIAN	TS	*Knoxisporites stephanephorus*	
					ARUNDIAN	PU	*Lycospora pusilla*	
					CHADIAN			
		LOWER	TOURNESIAN	TOURNESIAN	COURCEYAN	CM	*Schopfites claviger*	
						PC	*Spelaeotriletes pretiosus*	
						BP	*Spelaeotriletes balteatus*	
						HD	*Cristatisporites hibernicus*	
						VI	*Cyrtospora cristifera*	
DEVONIAN				U. DEVONIAN	FAMENNIAN	LN	*Verrucosisporites nitidus*	
						LE	*Indotriradites explanatus*	
						LL	*Retispora lepidophyta*	

Figure 2; Biozones and sub-biozones of the recently revised Carboniferous miospore zonation of Western Europe (Clayton et al., 2003) compared with the previous zonation developed by Clayton *et al.* (1977), Clayton *et al.* (1978), Clayton (1985) and Higgs (1988). Also shown are the latest Subcommission on Carboniferous Stratigraphy (SCCS) ratified Carboniferous global subsystems, series and stages (see Heckel and Clayton, 2006).

3. Palynostratigraphic Reinterpretations

3.1 Methodology

Existing palynological datasets are derived from Robeson (1988) and various oil company biostratigraphy reports. The majority of data is derived from the analysis of borehole cuttings and the occasional sidewall core sample. Depth of spore occurrence is inputted into a Microsoft Filemaker database for ease of data manipulation.

New cuttings samples are processed for palynological analysis by initially placing the sample in hydrochloric acid to dissolve any calcium carbonate present and then in hydrofluoric acid to remove silicate minerals. After approximately one to two weeks, the non-organic rock matter is dissolved, leaving an organic residue which is mounted onto slides for analysis.

Biozones of the revised Western European miospore zonal scheme are identified by the first downhole occurrence (range top) or last downhole occurrence (range base) of specific miospore taxa (Enclosure 1). To date, 13 of the 19 well palynostratigraphic data sets have been reinterpreted in terms of the revised miospore zonal scheme. Results for a selection of wells are shown below.

3.2 Results

3.2.1 Well 27/5-1

The 27/5-1 well provided an opportunity to reinterpret an existing palynostratigraphic dataset (Millennia, 1996) in terms of the revised Western European miospore zonal scheme, undertake palynostratigraphic interpretations on a suite of new samples and subsequently combine both sets of results.

3.2.1.1 Millennia 1996 Palynostratigraphic Interpretations

Millennia identified a succession of Westphalian rocks unconformably overlain by Permian strata (Enclosure 2). A total of 30 Carboniferous samples were analysed (including 12 sidewall core samples) between 1643m and 1910m. Palynostratigraphic interpretations were based on Millennia's in-house Carboniferous miospore zonal scheme.

Millennia identified the Westphalian C substage from 1643m on the first downhole occurrence of frequent *Crassispora kosankei* and *Lycospora* spp. The top Westphalian B was picked at 1660m on the first downhole occurrence of *Raistrickia saetosa*, *Cirratriradites saturni*, *Cingulizonates loricatus* and *Endosporites globiformis*. Millennia tentatively dated the rocks from 1699 - 1784m as Westphalian B/A, cautiously positioning the top Westphalian A Vanderbecki marine band at 1699m on the occurrence of acanthomorph acritarchs. The presence of Westphalian A rocks at 1792m were confirmed by the only occurrence of *Radiizonates aligerens*.

3.2.1.2 Millennia Data Reinterpreted Using the Revised Western European Miospore Zonal Scheme

Millennia's palynostratigraphic data has been subsequently reinterpreted using the revised Western European Carboniferous miospore zonal scheme of Clayton *et al.* (2003) (Enclosure 3).

- *Westphalian C*

The mid-Westphalian C / ***Raistrickia aculeata Sub-biozone*** is tentatively positioned from 1643 - 1696m on the occurrence of *Raistrickia aculeata* at 1660m and within the 1696m sidewall core sample (SWC). Presence of the miospore within a SWC sample should indicate a non-caved occurrence. However, the remaining spore assemblage present between 1643 and 1696m includes *Leiotriletes sphaerotriangulus, Calamospora breviradiata, Punctatosporites punctatus, Granulatisporites* *granulatus* and *Densosporites anulatus*, indicating a lower Westphalian C age. The occurrence of *Savitrisporites nux* at 1660m in particular indicates the presence of a biozone no younger than the *Torispora securis Sub-biozone*.

The ***Torispora securis Sub-biozone*** top is tentatively picked at 1696m on the last downhole occurrence of *Raistrickia aculeata*. Confidence in the pick position is low due to an absence of *Torispora securis* and *Vestispora fenestrata* whose occurrence should define the sub-biozone. In addition, the ***Triquitrites sculptilis Biozone*** top cannot be picked due to a lack of miospores species whose range limits define the biozone top i.e *Torispora securis, Vestispora fenestrata* or *Grumosisporites varioreticulatus*.

- *Westphalian B*

The top Westphalian B / ***Vestispora magna Sub-biozone*** top cannot be picked due to a lack of miospore species whose range limits define the sub-biozone top. The ***Lycospora noctuina noctuina Sub-biozone*** top is positioned at 1750m on the last downhole occurrence of *Punctatosporites granifer*. The last downhole occurrence of *Leiotriletes parvus* at 1760m confirms an age no older than the Westphalian B whilst the occurrence of *Cristatisporites solaris* within the 1784m SWC indicates the continued presence of the *Lycospora noctuina noctuina Sub-biozone*.

The occurrence of *Cristatisporites solaris* within the 1784m SWC sample constrains the top ***Sinuspores sinuatus Biozone*** to below 1784m. However, positioning of the exact top biozone depth is prevented by an absence of miospore species whose range limits define the biozone top.

Reworked spores occurring within the Westphalian B strata include *Lycospora subtriquetra* (range top in Westphalian A), *Kraeuselisporites ornatus (*range top in Westphalian A), *Leiotriletes tumidus* (range top in Namurian) and *Convolutispora cerebra* (range top in Namurian).

- *Westphalian A*

The top Westphalian A / ***Schulzospora rara Biozone*** top cannot be picked due to a lack of species whose range limits define the top of the biozone. The ***Radiizonates aligerens Biozone*** top is tentatively positioned at 1792m based on the single occurrence of *Radiizonates aligerens*. The presence of *Florinites mediapudens, Florinites visendus* and *Cyclogranisporites multigranus* at 1796m confirm an age no older than the upper Westphalian A. Occurrences of *F. mediapudens, Florinites junior*, and *Calamospora laevigata* within the deepest sample depth of 1910m indicate an age no older than the Westphalian A.

Evidence of reworked spores within the Westphalian A strata include occurrences of the Namurian miospores *Knoxisporites cinctus* at 1792m and *Grumosisporites verrucosus* at 1811m with *Convolutispora tesselata* (range top in Namurian) occurring at 1783m.

3.2.1.3 Palynostratigraphic Interpretations of New Cuttings Samples

The palynological content of 27 new cuttings samples between 1642 and 1900m were analysed. Palynostratigraphic interpretations were based on the revised Western European Carboniferous miospore zonal scheme of Clayton *et al.* (2003) (Enclosure 4).

- *Palynostratigraphy Undefined*

A poor recovery of miospores occurs in samples from 1642 to 1663m. An assemblage dominated by *Disaccites striatiti* suggests an age no older than the *Vestispora fenestrata Biozone*, although key defining species such as *Torispora securis* and *Vestispora fenestrata* are absent. At present, the age of the samples remain undefined.

- *Westphalian C*

The ***Triquitrites sculptilis Biozone*** is identified from 1663m based on a mid-lower Westphalian C spore assemblage comprising *Savritisporites nux, Apiculatisporites spinososaetosus, Reticulatisporites* *polygonalis, Dictyotriletes bireticulatus, Verrucosisporites microverrucosus* and *Cirratriradites megaspinosus*. An absence of *Torispora securis*, *Vestispora fenestrata* and *Raistrickia aculeata* suggests that the younger *Vestispora fenestrata Biozone* has not been penetrated.

- *Westphalian B*

The top Westphalian B / ***Vestispora magna Sub-biozone*** top is defined by the first downhole occurrence of *Ahrensisporites guereckei* at 1672m. The first downhole occurrence of *Densosporites duriti* at 1726m confirms an age no younger than Westphalian B.

The ***Lycospora noctuina noctuina Sub-biozone*** top is positioned at 1738m on the last downhole occurrence of *Vestispora magna*, whilst the last downhole occurrences of *Acanthotriletes triquetrus* and *Cristatisporites solaris* at 1738m confirm an age no older than mid-Westphalian B. The sub-biozone is also characterised by the first downhole occurrence of *Punctatisporites minutus* at 1771m.

The first downhole occurrence of *Sinuspores sinuatus* defines the top of the ***Sinuspores sinuatus Biozone*** at 1789m. A single occurrence of the Westphalian A species *Radiizonates aligerens* at 1804m is considered reworked.

- *Westphalian A*

The first downhole occurrence of *Apiculatisporites variocorneus* defines the top of the ***Schulzospora rara Biozone*** and top Westphalian A at 1825m. Occurrences of *Camptotriletes superbus* at 1849m and *Waltzispora polita* at 1861m confirm an age no younger than Westphalian A. It is inferred that the biozone extends to the well TD.

3.2.1.4 New Sample Palynostratigraphic Interpretations and Millennia Interpretations Combined

The new sample palynostratigraphic interpretations were subsequently combined with the reinterpreted Millennia palynostratigraphic data (Enclosure 5).

- *Palynostratigraphy Undefined*

The occurrence of *Crassispora kosankei, Lycospora* spp and *Disaccites striatiti* from 1642-1660m should indicate presence of a biozone no older than the *Vestispora fenestrata Biozone*. However, in the absence of key biozone defining species, the biostratigraphy remains undefined.

- *Westphalian C*

Presence of the ***Triquitrites sculptilis Biozone*** from 1660m is represented by a mid-lower Westphalian C miospore assemblage including *Savritisporites nux, Apiculatisporites spinososaetosus, Vestispora tortuosa, Verrucosisporites microverrucosus, Granulatisporites granulatus, Punctatosporites punctatus, Densosporites anulatus, Cingulizonates loricatus, Cirratriradites megaspinosus, and Reticulatisporites polygonalis*. Absence of *Torispora securis* and *Vestispora fenestrata* suggest that the younger *Vestispora fenestrata Biozone* has not been penetrated. There remains uncertainty about Millennia's identification of *Raistrickia aculeata* at 1660m and within the 1696m SWC as the range of the miospore is restricted to biozones younger than the *Triquitrites sculptilis Biozone*. The Millennia slides have been requested to enable confirmation of the spore identification.

- *Westphalian B*

The top Westphalian B / ***Vestispora magna Sub-biozone*** top is picked on the first downhole occurrence of *Ahrensisporites guereckei* at 1672m. A miospore assemblage including *Densosporites duriti, Vestispora magna, Cristatisporites solaris* and *Acanthotriletes triquetrus* confirms a Westphalian B age.

The deepest occurrence of *Punctatosporites granifer* defines the ***Lycospora noctuina noctuina Biozone*** top at 1750m. The last downhole occurrences of *Leiotriletes parvus* at 1760m and *Cristatisporites solaris* within the 1784m SWC confirm an age no older than Westphalian B.

The ***Sinuspores sinuatus* Biozone** top is defined by first downhole occurrence of *Sinuspores sinuatus* at 1789m. It is inferred that the occurrences of *Radiizonates aligerens* at 1792m and 1804m are due to reworking.

- *Westphalian A*

The first downhole occurrence of *Apiculatisporites variocorneus* defines the ***Schulzospora rara* Biozone** top and top Westphalian A at 1825m. Occurrences of *Camptotriletes superbus* at 1849m and *Waltzispora polita* at 1861m confirm an age no younger than the Westphalian A. The occurrences of *Florinites mediapudens*, *Florinites junior*, and *Calamospora laevigata* within the deepest sample depth of 1910m indicate an age no older than Westphalian A. It is inferred that the *Schulzospora rara Biozone* extends to the well TD.

3.2.2 Well 36/16-1

Robeson (1988) originally divided the 36/16-1 stratigraphy into Cretaceous rocks (from 4200') unconformably overlying a succession of Stephanian to Westphalian A age strata (from 4330'), with the top Westphalian A proving difficult to pick (Enclosure 6). A second unconformity was positioned at 8390' marking a transition into Namurian age rocks (from 8390'-TD).

3.2.2.1 Reinterpretations using the revised Western European miospore zonal scheme

- *Cretaceous (Albian)*

Revised interpretations confirm the presence of Cretaceous age strata from 4200' based on the occurrence of *Cicatricosisporites australiensis, Cebropollenites mesozoicus* and *Cyclonephelium distinctum* (Enclosure 6).

- *Westphalian D*

From 4330', a lack of species restricted to the Stephanian, a consistent occurrence of the Westphalian D spore *Thymospora obscura* and an assemblage of spores whose range tops are restricted to the Westphalian D, i.e. *Thymospora pseudothiessenii, Mooreisporites cf. inusitatus, Westphalensisporites irregularis, Vestispora laevigata, Raistrickia saetosa, Cadiospora magna* and *Laevigatosporites minimus* indicate the presence of Westphalian D age strata / ***Thymospora verrucata* Sub-biozone**. The occurrence of *Triquitrites tribullatus* at 4330' in particular indicates penetration of the lower part of the *Thymospora verrucata Sub-biozone*. Westphalian D rocks are also characterised by the occurrence of the Westphalian D miospore *Cirratriradites annuliformis* at 4370 and 4400'.

- *Westphalian C*

The top Westphalian C / ***Westphalensisporites irregularis* Sub-biozone** top is repositioned to 4400' based on the last downhole occurrence of *Thymospora obscura*. The top Westphalian C is also defined by the first downhole occurrence of *Raistrickia cf. superba* at 4450'.

The ***Raistrickia aculeata* Sub-biozone** top is defined by the last downhole occurrence of *Thymospora pseudothiessenii* at 4520'. The biozone is also characterised by the occurrence of *Raistrickia aculeata*. The first downhole occurrences of *Savitrisporites nux and Vestispora tortuosa* define the ***Torispora securis* Sub-biozone** top at 4850'. A lower Westphalian C age is confirmed by a spore assemblage comprising *Grumosisporites granulatus, Calamospora breviradiata, Torispora securis* and *Disaccites striatiti.*

The deepest non-caved occurrence of *Vestispora fenestrata* defines the top of the ***Triquitrites sculptilis* Biozone** at 6100'. A Westphalian C age is confirmed by the occurrence of *Microreticulatisporites sulcatus* at 6100'.

- *Westphalian B*

The top Westphalian B / ***Vestispora magna Sub-biozone*** top remains at 6200' based on the first downhole occurrences of *Cristatisporites indignabundus* and *Lophotriletes cf. gibbosus.* The last downhole occurrence of *Triquitrites sculptilis* defines the top of the ***Lycospora noctuina noctuina Sub-biozone*** at 7300'. The Westphalian B rocks are also characterised by occurrences of *Savitrisporites concavus*, *Cristatisporites solaris* and *Lophotriletes cf. microsaetosus.* Unfortunately, the ***Sinuspores sinuatus Biozone*** cannot be picked due to an absence of the biozone defining miospores i.e. *Sinuspores sinuatus*. A number of new samples have been taken below 7300' to enable the biozone top to be defined.

- *Westphalian A*

The last downhole occurrence of *Radiizonates tenuis* defines the top Westphalian A / ***Schulzospora rara Biozone*** top at 7890'. A spore assemblage characterised by the occurrence of *Raistrickia cf superba, Waltzispora polita, Vestispora pseudoreticulata Florinites pumicosus* and *Endosporites globiformis* at 8000' confirms a Westphalian A age.

Due to the absence of key defining species, the top depth of the ***Radiizonates aligerens Biozone*** cannot be defined. A number of new samples between 7890 and 8100' are currently being analysed to define the top of the biozone. However, the top of the ***Vestispora cancellata Biozone*** can be defined by the last downhole occurrence of *Vestispora pseudoreticulata* at 8100'.

- *Arnsbergian*

The first occurrence of Arnsbergian age strata / ***Mooreisporites trigallerus Biozone*** is tentatively repositioned to 8300' based on an only occurrence of *Schulzospora ocellata* at 8300' and the last downhole occurrence of *Florinites* spp. Occurrences of *Radiizonates cuesta* at 8390 and 8360' confirm an Arnsbergain age. However, as there is evidence of reworked spores within the shallower Westphalian A strata, it is possible that the Namurian spores could also be reworked. A number of new samples have been taken below 8300' to investigate this interpretation.

3.2.3 Well 26/28-2

Robeson (1988) originally divided the 26/28-2 stratigraphy into Jurassic strata (from 2140-2270m) unconformably overlying a succession of Stephanian (from 2270m), Westphalian D (from 2300m) and Westphalian C age strata (from 2575m) (Enclosure 7).

3.2.3.1 Reinterpretations using the Revised Western European miospore zonal scheme

- *Stephanian*

Revised interpretations confirm the presence of Stephanian age strata from 2270m (Enclosure 7). The occurrence of *Angulisporites splendidus* at 2270 and 2275m verifies the presence of the Stephanian / ***Angulisporites splendidus Biozone***.

- *Westphalian D*

The top Westphalian D / ***Thymospora verrucata Sub-biozone*** top is confirmed at 2300m by the first downhole occurrences of *Westphalensisporites irregularis, Florinites junior, Thymospora obscura, Laevigatosporites minimus*, *Endosporites zonalis* and *Alatisporites hoffmeisterii*, in addition to an absence of *Angulisporites splendidus.*

- *Westphalian C*

The top Westphalian C / ***Westphalensisporites irregularis Sub-biozone*** top is repositioned at 2425m on the last downhole occurrence of *Thymospora obscura*. A Westphalian C age is confirmed by the first downhole occurrences of *Granulatisporites microgranifer* at 2425m and *Lophotriletes microsaetosus* at 2475m.

The ***Raistrickia aculeata* Sub-biozone** top is picked on the non-reworked top downhole occurrence of *Cingulizonates loricatus* at 2525m. A Westphalian C spore assemblage is characterised by the occurrence of *Raistrickia cf. superba* and *Vestispora costata.*

The ***Torispora securis* Sub-biozone** top is defined by the first downhole occurrence of *Vestispora tortuosa* at 2620m. The sub-biozone is characterised by the non-reworked occurrence of *Savitrisporites nux* and by the occurrence of *Vestispora fenestrata* and *Torispora securis*. Both *V. fenestrata* and *T. securis* occur in the deepest sample (2690m) indicating presence of the sub-biozone at this depth.

3.2.4 Well 26/30-1

The original 26/30-1 palynostratigraphic interpretation was undertaken by Paleoservices (King *et al.*, 1982) (Enclosure 8). King *et al.* tentatively dated strata from 4762' as Jurassic, unconformably overlying a succession of Westphalian C age strata from 5,093'.

3.2.4.1 Reinterpretations using the revised Western European miospore zonal scheme

- *Jurassic - Carboniferous unconformity at 5093'*

Rocks above the 5093' unconformity are confirmed as Jurassic in age.

- *Westphalian C*

The occurrence of frequent *Lycospora* spp. from 5093' confirms the first occurrence of Carboniferous strata. Presence of *Dictyotriletes bireticulatus* from 5093 – 5595' indicates an age no younger than the Westphalian C / ***Vestispora fenestrata* Biozone** (Enclosure 8). The occurrence of *Vestispora fenestrata* and *Vestispora costata* at 5093' indicates the presence of a biozone no older than the *Vestispora fenestrata Biozone*. An absence of spores that define Westphalian B age rocks within deeper samples indicates presence of the biozone at the deepest sample depth of 5595'.

4. Palaeogeographic reconstructions

Samples from three wells are being investigated for evidence of marine incursions during the mid-upper Westphalian and Stephanian. Twenty-seven samples from the 26/21-1 and 34/5-1 wells have been processed for palynofacies analysis. In addition, a series of slides from the 36/16-1 well created by Robeson (1988) are currently undergoing palynofacies analysis. The results will be incorporated into the Carboniferous palaeogeographic reconstructions.

5. Correlation of Offshore Western Ireland Palynostratigraphy with Eastern Canada

Access has been gained to palynological data for the Blue H-28 well, which penetrated 170m of Carboniferous rocks in the Grand Banks of offshore Eastern Canada. The palynostratigraphy of the Carboniferous strata will be reinterpreted using the revised Western European zonal scheme and the results correlated with the offshore Western Irish palynostratigraphic interpretations.

6. An Assessment of the Maturity of Carboniferous Rocks Offshore Western Ireland using Microspectroscopy

6.1 Overview

In autumn 2007, a 3-month visit was undertaken to the Department of Earth Sciences, Memorial University of Newfoundland. The purpose of the visit was to use microspectroscopy equipment to develop novel techniques of quantitatively measuring spore colour and spore fluorescence colour in order to measure the thermal maturity of Carboniferous rocks from offshore Western Ireland.

When buried and exposed to elevated temperatures, rocks with a high organic content reach thermal maturity, i.e. organic compounds alter to generate hydrocarbons (Figure 3). The standard industry technique for assessing thermal maturity is the change in reflectivity of vitrinite (fossilised woody material), which increases with temperature and maturity (Figure 3). However, vitrinite is not always present in rock strata. Alternative methods of measuring thermal maturity are based on changes in the chemical and physical properties of fossil plant spores extracted from the rock. Measurements are commonly qualitative, including the visual measurement of change in spore colour under transmitted light (e.g. Staplin, 1969) or change in fluorescence colour when exposed to ultra-violet light. However, as these techniques are visual estimates, results can vary depending on the interpreter. Advances have been made in computer based image analysis to numerically model the colour change of fossil acritarchs with increasing maturity (Duggan, 2007), although these fossils are restricted to sediments of a marine origin.

The quantitative measurement of spore fluorescence as a maturity indicator was successfully achieved in the 1970's and early 1980's (e.g. van Gijzel, 1982). Unfortunately, the technique failed to become an oil industry standard due to the amount of time required to collect, process and analyse the fluorescence data compared to vitrinite reflectance and qualitative spore colour analysis. As a result, very little research has been undertaken on this technique in recent years.

Dr. Elliott Burden, at the Department of Earth Sciences, Memorial University, recently acquired a spectrophotometric microscope that enables the quantitative measurement of light emitted from microscopic samples including plant spores. With the addition of high-end computer software, rapid data collection and analysis is possible. The aim of the visit was to use the equipment to develop methods of quantitatively measuring the thermal maturity of fossil spores from the 34/5-1 and 36/16-1 wells located in the Porcupine Basin, offshore Western Ireland (Figure 1). Measurements were taken of the:

1. Spore fluorescence when exposed to ultra-violet light; and
2. Wavelength of visible light transmitted through the spores.

Measurements were calibrated with existing vitrinite reflectance data (Robeson *et al*., 1988; Robeson, 1989) with the aim of developing comparative maturity scales that can be used for future thermal maturity analyses.

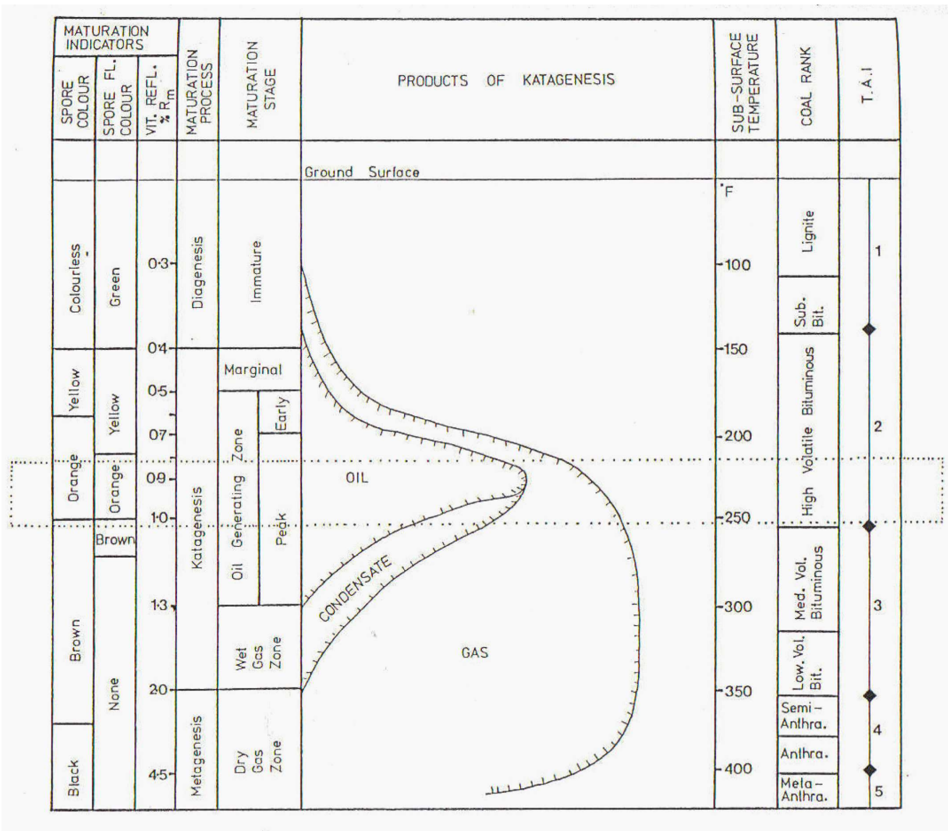

Figure 3; Changes in vitrinite reflectance, spore colour and spore fluorescence colour reflect increasing sub-surface temperature and thermal maturation (from Robeson 1988)

6.2 Methods

6.2.1 Existing vitrinite reflectance data

Existing vitrinite measurements for the two study wells were previously compiled by Robeson (1988). Both show an increase in vitrinite reflectance (Rr%) with thermal maturity and depth (Figures 6, 7). Samples analysed in this study are shown in purple. Values of Rr% for 34/5-1 are more tightly distributed than 36/16-1 with Rr% values at 6100 and 6300ft appearing anomalously low.

6.2.2 Material examined

Fossilised plant spores were extracted from nine rock samples, selected from depths in the 34/5-1 well that coincide with existing vitrinite reflectance data. Placing the rock samples in hydrochloric acid then hydrofluoric acid dissolved the carbonate and silicate minerals, leaving a spore-rich organic residue which was subsequently mounted onto microscope slides for analysis. Nine slides created by Robeson (1988) from a previous study were used for the 36/16-1 well. Spores of the smooth walled *Laevigatosporites* genus were selected for thermal maturity analysis due to their simple, smooth wall structure, long geological range and relatively common occurrence.

6.2.3 Fluorescence microspectometry

Using the spectrophotometric microscope, spores of the genus *Laevigatosporites* were individually exposed to high intensity ultraviolet light. The UV light excites electrons within the spore resulting in the emission of fluorescent light within the visible spectrum (between 400 and 700nm). A microspectrophotometer attached to the microscope measured the intensity and wavelength of the emission spectra at set time intervals (0sec, 30sec, 1min and 2min). Photodiodes and computer software analysed the data, plotting a spectral trace on an XY chart of fluorescent wavelength against intensity (Figure 4). This procedure was repeated on up to 20 spores per sample (depending on spore occurrence).

6.2.4 Transmitted light microspectometry

Individual *Laevigatosporites* spores were exposed to visible light. The intensity and wavelength of the light transmitted through the spore was measured and plotted as a spectral trace (Figure 4). This procedure was repeated on up to 20 spores per sample depth. In order to numerically compare spectral traces, computer software was used to construct a line at 750nm to intersect each trace. The distance to the trace measured perpendicularly from half way up the 750nm line was defined as a "Full Width at Half Height" value which was subsequently plotted.

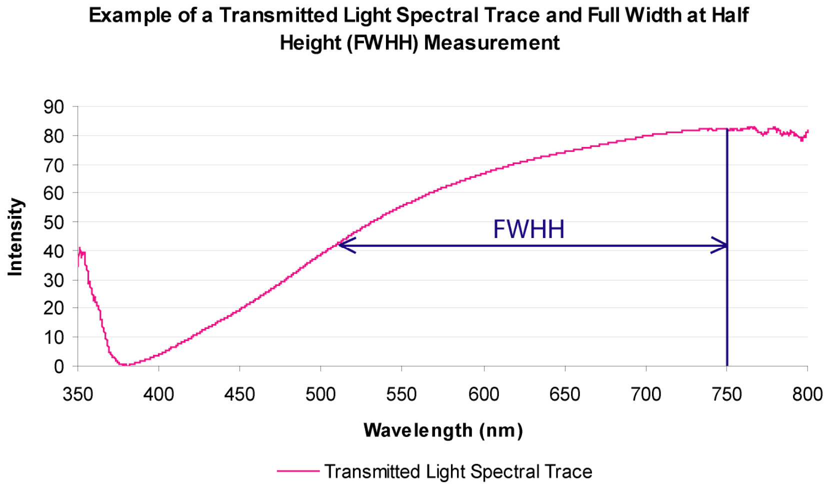

Figure 4; Typical transmitted light spectral trace with Full Width at Half Height (FWHH) measurement

6.3 Results and discussion

6.3.1 Spore fluorescence measurements

Fluorescence spectral traces from well 34/5-1 show prominent peaks that represent the highest intensity light wavelengths emitted. When the peaks are normalised, it is apparent that there is an increase in their wavelength value with increasing depth and maturity (Figures 5 and 8, Table 1). When average peak wavelength values per sample depth are plotted against vitrinite reflectance (Figure 9, Table 1) the correlation coefficient (R-squared value) implies that 82% of the spread of the fluorescence data can be explained by the vitrinite reflectance values.

Depth (m)	Average Peak Wavelength (nm) with Std Dev	Vitrinite Reflectance (Rr%) with Std Dev
825	574.9 (+/- 4.1)	0.69 (+/- 0.04)
865	574.8 (+/- 2.9)	0.72 (+/- 0.04)
940	574.0 (+/- 3.3)	0.79 (+/- 0.08)
1000	575.1 (+/- 2.3)	0.84 (+/- 0.06)
1095	577.4 (+/- 3.9)	0.84 (+/- 0.05)
1185	577.7 (+/- 3.7)	0.86 (+/- 0.07)
1270	580.0 (+/- 4.3)	0.87 (+/- 0.05)
1330	583.0 (+/- 3.8)	0.93 (+/- 0.08)
1460	585.8 (+/- 0.5)	1.06 (+/- 0.08)

Table 1; 34/5-1 average fluorescence spectral peak wavelength values and corresponding vitrinite reflectance values (Rr%).

Unfortunately, during the study it was realised that the 36/16-1 slides were unsuitable for fluorescence analysis due to their exposure to ultra-violet light in previous experiments. Exposure to ultra-violet light results in a permanent change to the fluorescence spectra emitted by the spore.

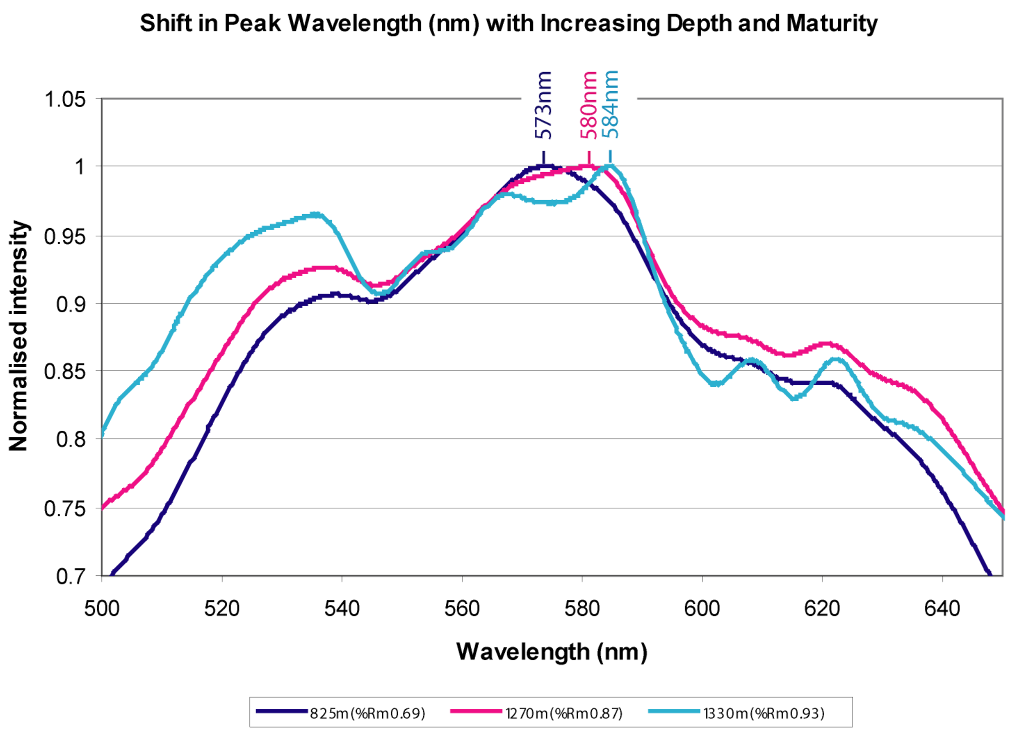

Figure 5; 34/5-1 normalised spectral traces show an increase in peak wavelength values with an increase in depth and thermal maturity

- *675nm fluorescence measurement*

It was also noted that the average value of the normalised spectral curves taken at 675nm show a general trend of increasing with depth and maturity (Figure 10, Table 2). When compared to vitrinite reflectance data the R-squared value implies that 72% of the spread of the data can be explained by the vitrinite reflectance values (Figure 11).

Depth (m)	Average 675nm value with Std Dev	Vitrinite Reflectance (Rr%) with Std Dev
825	0.52 (+/- 0.08)	0.69 (+/- 0.04)
865	0.49 (+/- 0.05)	0.72 (+/- 0.04)
940	0.47 (+/- 0.08)	0.79 (+/- 0.08)
1000	0.56 (+/-0.03)	0.84 (+/- 0.06)
1095	0.59 (+/- 0.06)	0.84 (+/- 0.05)
1185	0.59 (+/- 0.06)	0.86 (+/- 0.07)
1270	0.64 (+/- 0.08)	0.87 (+/- 0.05)
1330	0.66 (+/- 0.06)	0.93 (+/- 0.08)
1460	0.67 (+/- 0.07)	1.06 (+/- 0.08)

Table 2; 34/5-1 average 675nm values and corresponding vitrinite reflectance values

6.3.2 Transmitted light measurements

- *34/5-1*

When plotted, the average Full Width at Half Height values for the 34/5-1 well show a decreasing trend with increasing depth and maturity (Figure 12, Table 3). When compared to vitrinite reflectance data (Figure 13) the R-squared value implies that 74% of the spread of the data can be explained by the vitrinite reflectance values.

Depth (m)	Average FWHH with Std Dev	Vitrinite Reflectance (Rr%) with Std Dev
825	236.1 (+/- 25.1)	0.69 (+/- 0.04)
865	250.3 (+/- 15.4)	0.72 (+/- 0.04)
940	248.2 (+/- 17.3)	0.79 (+/-0.08)
1000	227.6 (+/- 23.1)	0.84 (+/-0.06)
1095	223.0 (+/- 30.4)	0.84 (+/-0.05)
1185	234.4 (+/-18.1)	0.86 (+/-0.07)
1270	225.4 (+/-20.9)	0.87 (+/-0.05)
1330	212.3 (+/-18.0)	0.93 (+/-0.08)
1460	198.1 (+/- 18.9)	1.06 (+/- 0.08)

Table 3; 34/5-1 average Full Width at Half Height (FWHH) values and corresponding vitrinite reflectance values

- *36/16-1*

The average values of Full Width at Half Height for the 36/16-1 well show a decreasing trend with increasing depth and maturity (Figure 14, Table 4). When compared to vitrinite reflectance data (Figure 15) the R-squared value implies only 27% of the spread of the data can be explained by the vitrinite reflectance values. However, if the two low vitrinite reflectance values at 6100 and 6300ft are omitted, the R-squared value increases to 68% (Figure 16).

Depth (ft)	Average FWHH with StdDev	Vitrinite Reflectance (Rr%) with StDev
4330	255.6 (+/- 18.8)	0.58 (+/- 0.07)
4520	244.3 (+/- 15.3)	0.76 (+/- 0.06)
4770	234.1 (+/- 23.7)	0.78 (+/- 0.08)
4850	222.6 (+/- 18.0)	0.92 (+/- 0.08)
5100	218.4 (+/- 30.6)	0.89 (+/- 0.08)
5280	214.5 (+/- 46.9)	0.96 (+/- 0.05)
5740	224.1 (+/- 16.1)	1.13 (+/- 0.06)
6100	192.4 (+/- 20.6)	0.89 (+/- 0.11)
6300	152.5 (+/- 18.3)	0.95 (+/-0.17)

Table 4; 36/16-1 average Full Width at Half Height (FWHH) spectral trace values and corresponding vitrinite reflectance values

Combining the two transmitted light datasets results in an R-squared value of 39% (Figure 17). However, if the 6100 and 6300ft values from 36/16-1 are omitted, the correlation coefficient improves to 66% (Figure 18).

6.4 Conclusions

The results for all methods investigated show trends that reflect the increase in vitrinite reflectance and thermal maturity seen in both wells. Unfortunately, the results include substantial standard deviations due to the presence of anomalously immature and mature spores in most samples.

Of all of the thermal maturity indicators investigated, the method that shows the closest relationship (highest correlation coefficient) with vitrinite reflectance is the measurement of fluorescence spectral peak values, showing an increase in wavelength with increasing vitrinite reflectance and maturity. Standard deviations are small enough for the values listed to be used as an indication of vitrinite reflectance and thermal maturity.

The transmitted light results show a trend of Full Width at Half Height decreasing with increasing thermal maturity. The Full Width at Half Height values for the 34/5-1 well show the best correlation with vitrinite reflectance whilst the relationship between the 36/16-1 FWHH data and vitrinite reflectance data is poor unless anomalous vitrinite reflectance data points are omitted. Overall, the quantitative measurement of transmitted light results show potential as a proxy for vitrinite reflectance.

Dr. Burden is looking to build on the quantitative spore fluorescence and transmitted light research undertaken during my 3-month visit to include the analysis of spores with a lower maturity than those studied. It is hoped that the combined results will provide quantitative scales that can be used commercially to predict the thermal maturity of rock samples.

6.5 Acknowledgements

I would like to thank the Ireland-Newfoundland Partnership for their generous postgraduate scholarship to fund my visit to Newfoundland and Dr. Elliott Burden for his hospitality and assistance during my visit.

7. Meetings Attended

The Canadian Palaeontology Conference 2007 was attended from September 23-25 in St Johns, Newfoundland. An oral presentation on the palynostratigraphic reinterpretation of two offshore Western Irish Carboniferous well sections was made and well received.

A presentation describing the thermal maturity research undertaken at Memorial University was made at the Ireland Newfoundland Partnership (INP) board meeting on 11 December 2007.

8. Plans for the next 12 months

- Complete palynostratigraphic reinterpretations for remaining Irish wells.

- Reinterpret the Canadian Blue H-28 well palynostratigraphy. Correlate with offshore Western Irish palynostratigraphic interpretations.

- Complete palynofacies work on the 26/21-1, 34/5-1 and 36/16-1 wells. Undertake sequence stratigraphic investigations. Construct palaeogeographic maps for time slices throughout the Carboniferous.

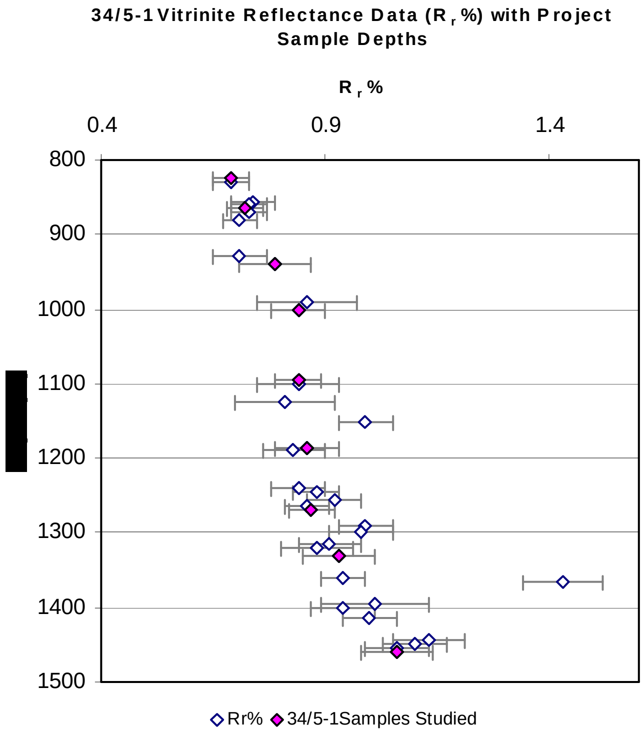

Figure 6; 34/5-1Vitrinite reflectance values (Rr%) with standard deviations against depth (m) (after Robeson 1988). Sample depths used in this study are shown in purple.

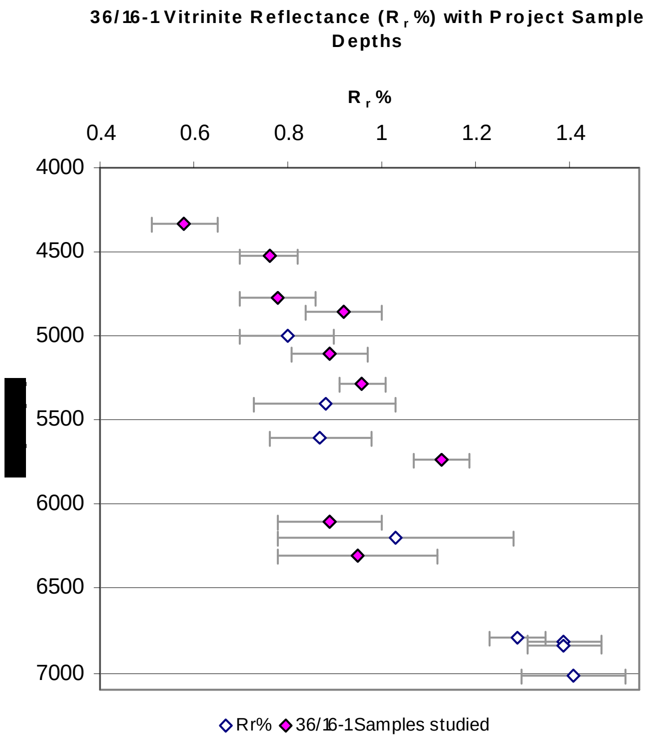

Figure 7; 36/16-1 Vitrinite reflectance values (Rr%) with standard deviations from 4330 – 7020ft (after Robeson 1988). Sample depths used in this study are shown in purple

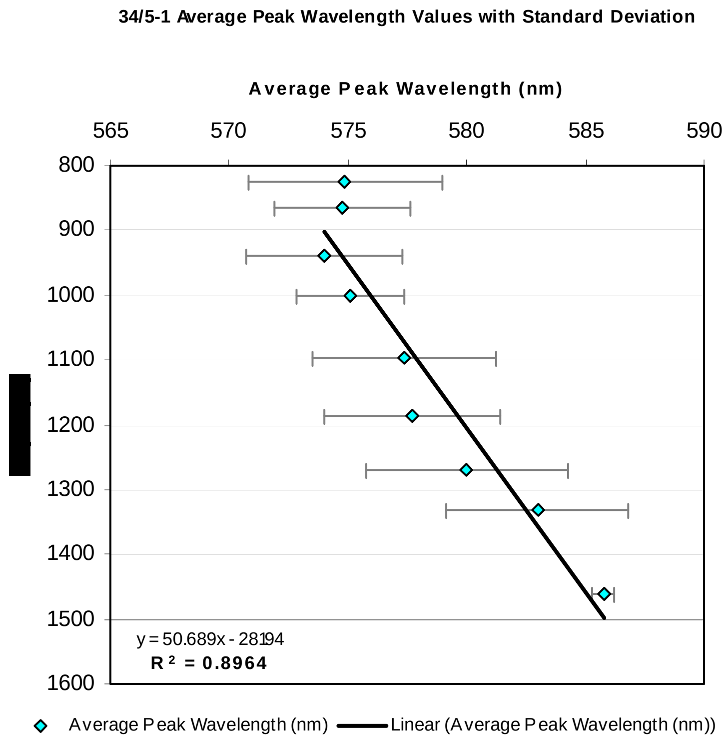

Figure 8; 34/5-1 Average fluorescence spectral trace peak wavelength values (nm) with standard deviations against depth (m)

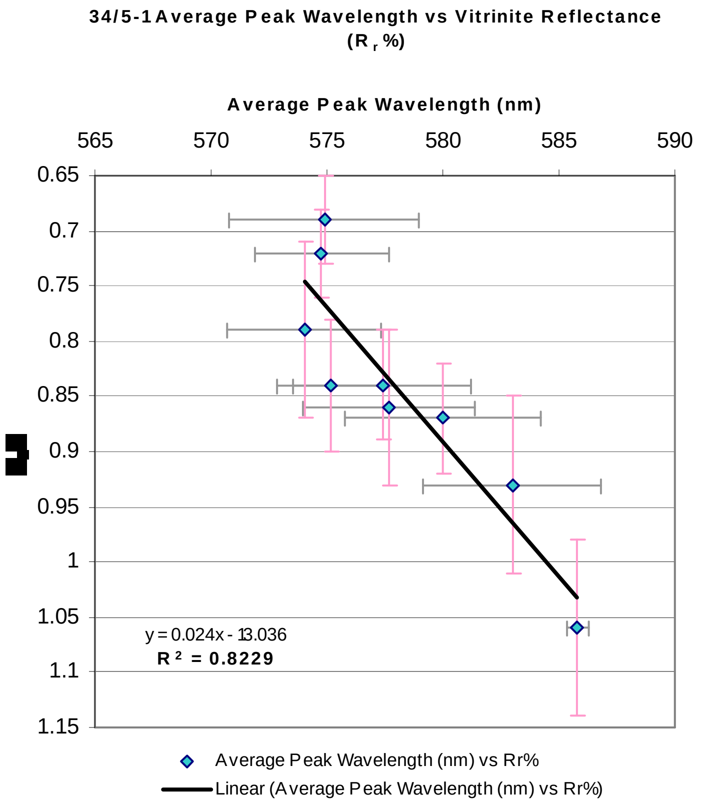

Figure 9; 34/5-1 Average fluorescence spectral trace peak wavelength values (nm) against vitrinite reflectance values (Rr%). Standard deviations of both datasets area also plotted.

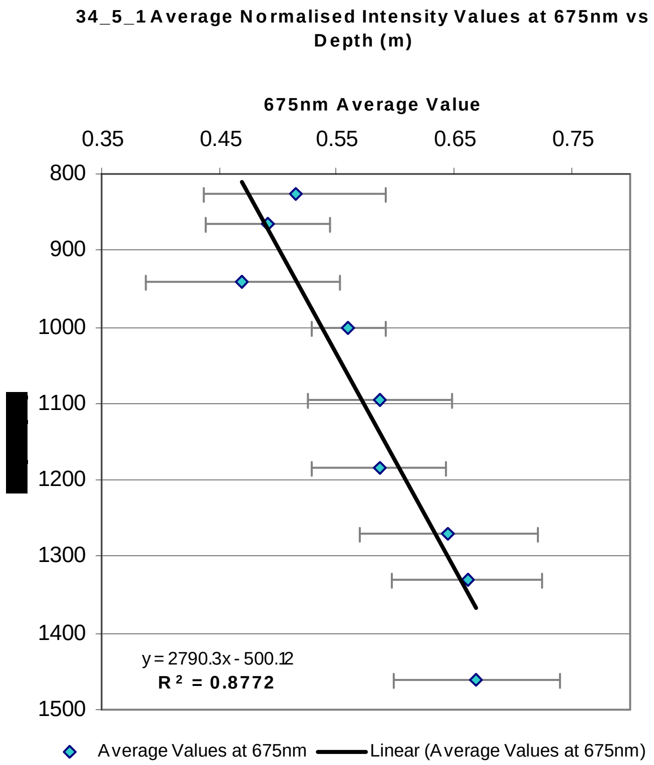

Figure 10; 34/5-1 Average normalised fluorescence intensity values at 675nm with standard deviations against depth (m).

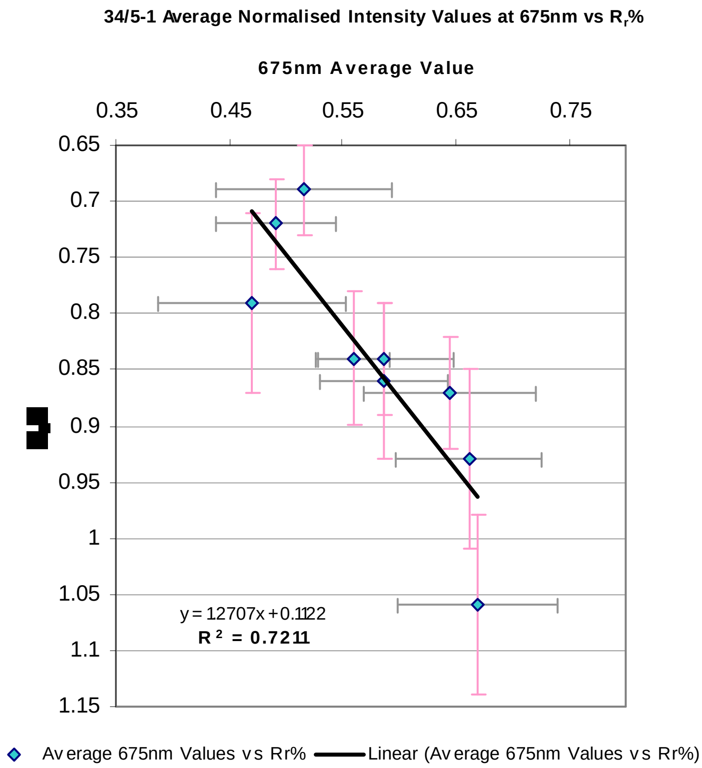

Figure 11; 34/5-1 Average normalised fluorescence intensity values at 675nm against vitrinite reflectance (Rr%). Standard deviations of both datasets area also plotted.

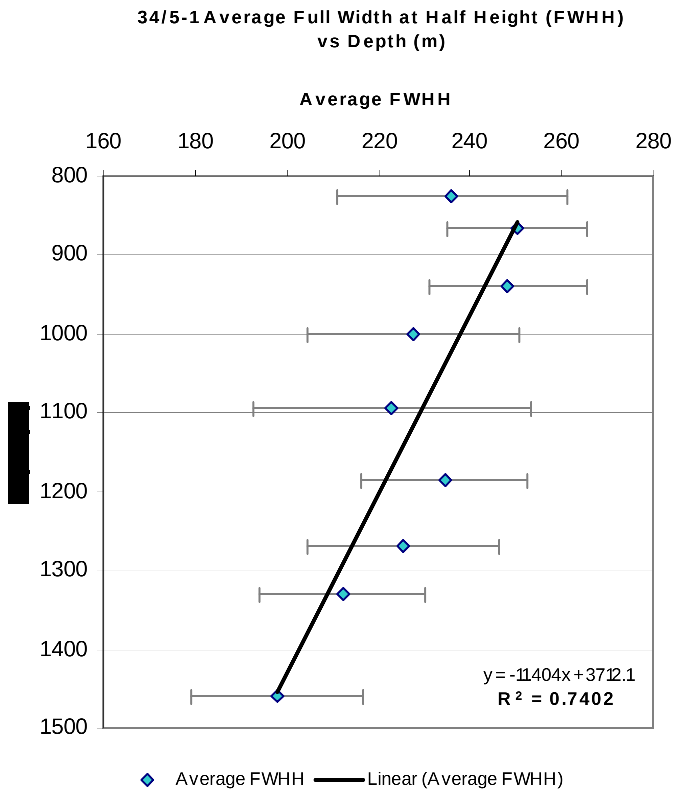

Figure 12; 34/5-1 Average Full Width at Half Height values with standard deviations against depth (m).

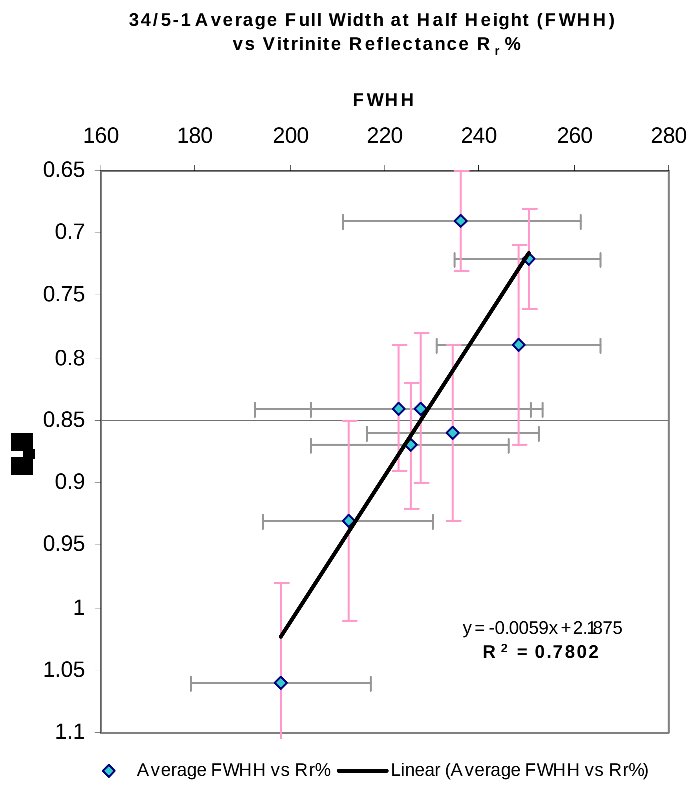

Figure 13; 34/5-1 Average Full Width at Half Height values against vitrinite reflectance (Rr%) with standard deviations for both datasets.

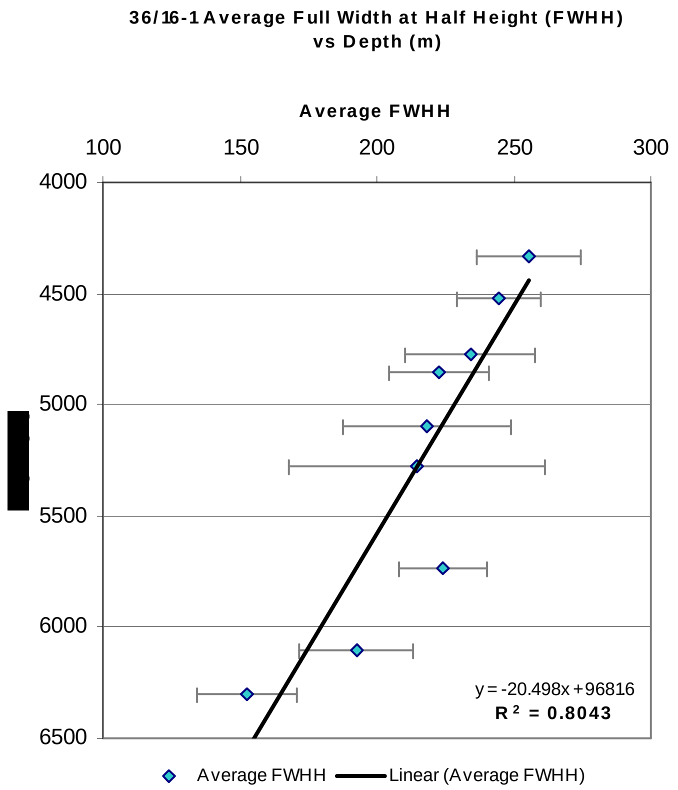

Figure 14; 36/16-1 Average Full Width at Half Height values with standard deviations against depth (m).

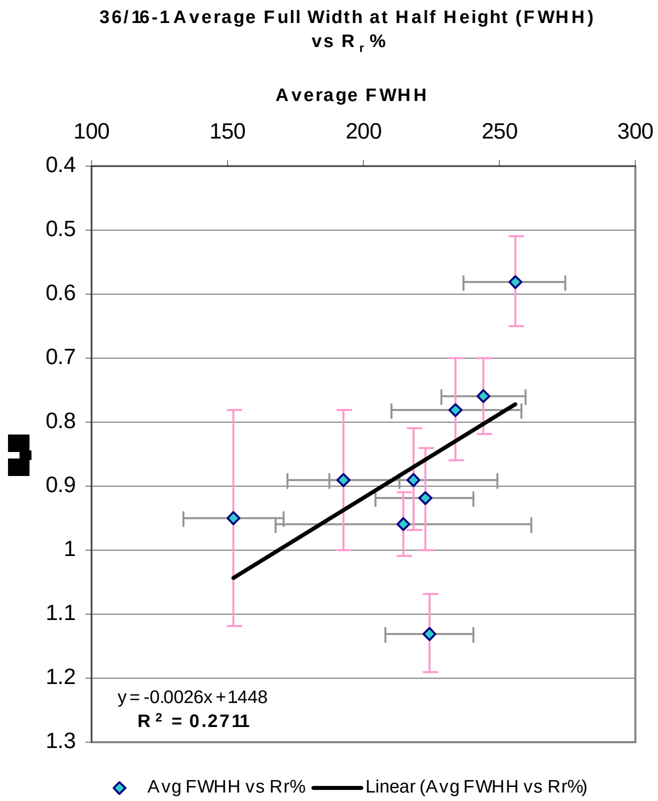

Figure 15; 36/16-1 Average Full Width at Half Height values against vitrinite reflectance (Rr%) with standard deviations for both datasets.

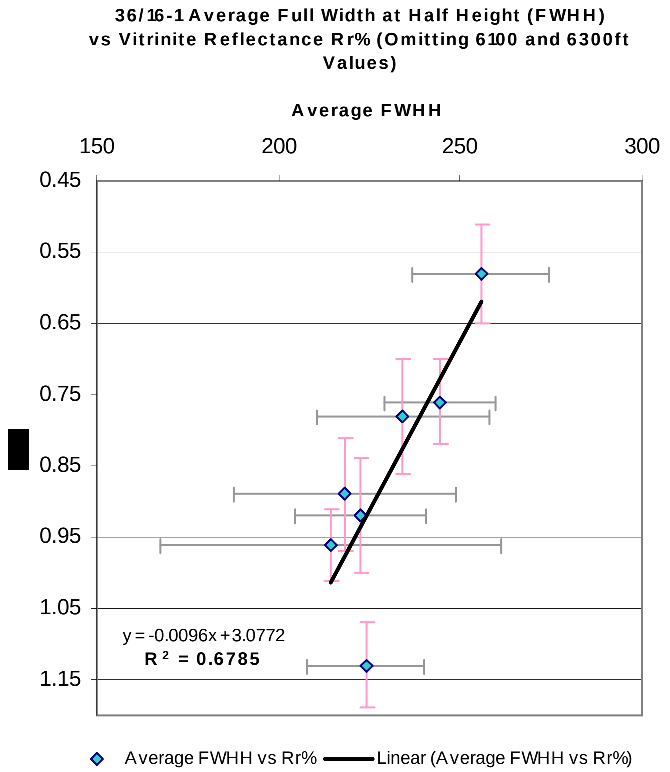

Figure 16; 36/16-1 Average Full Width at Half Height values against vitrinite reflectance Rr% with standard deviations (omitting vitrinite reflectance values at 6100 and 6300ft).

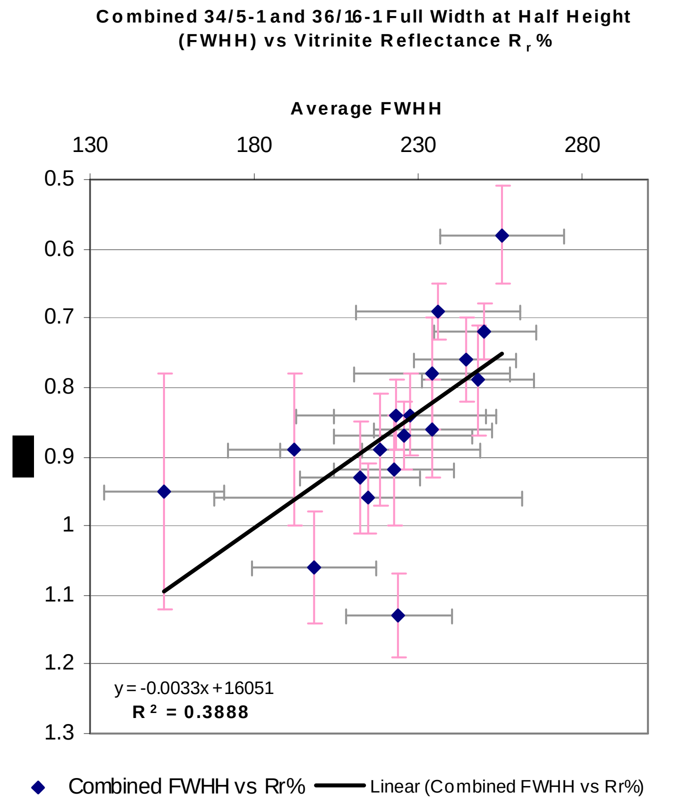

Figure 17; Combined 34/5-1 and 36/16-1 Average Full Width at Half Height values against vitrinite reflectance (Rr%) with standard deviations for both datasets.

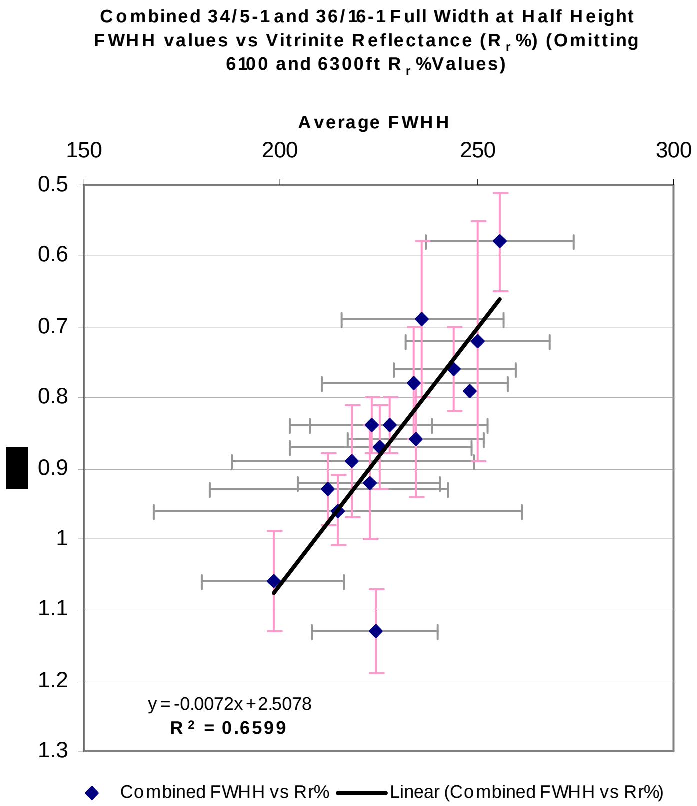

Figure 18; Combined 34/5-1 and 36/16-1 Average Full Width at Half Height values against vitrinite reflectance (Rr%) with standard deviations (omitting vitrinite reflectance values at 6100 and 6300ft).

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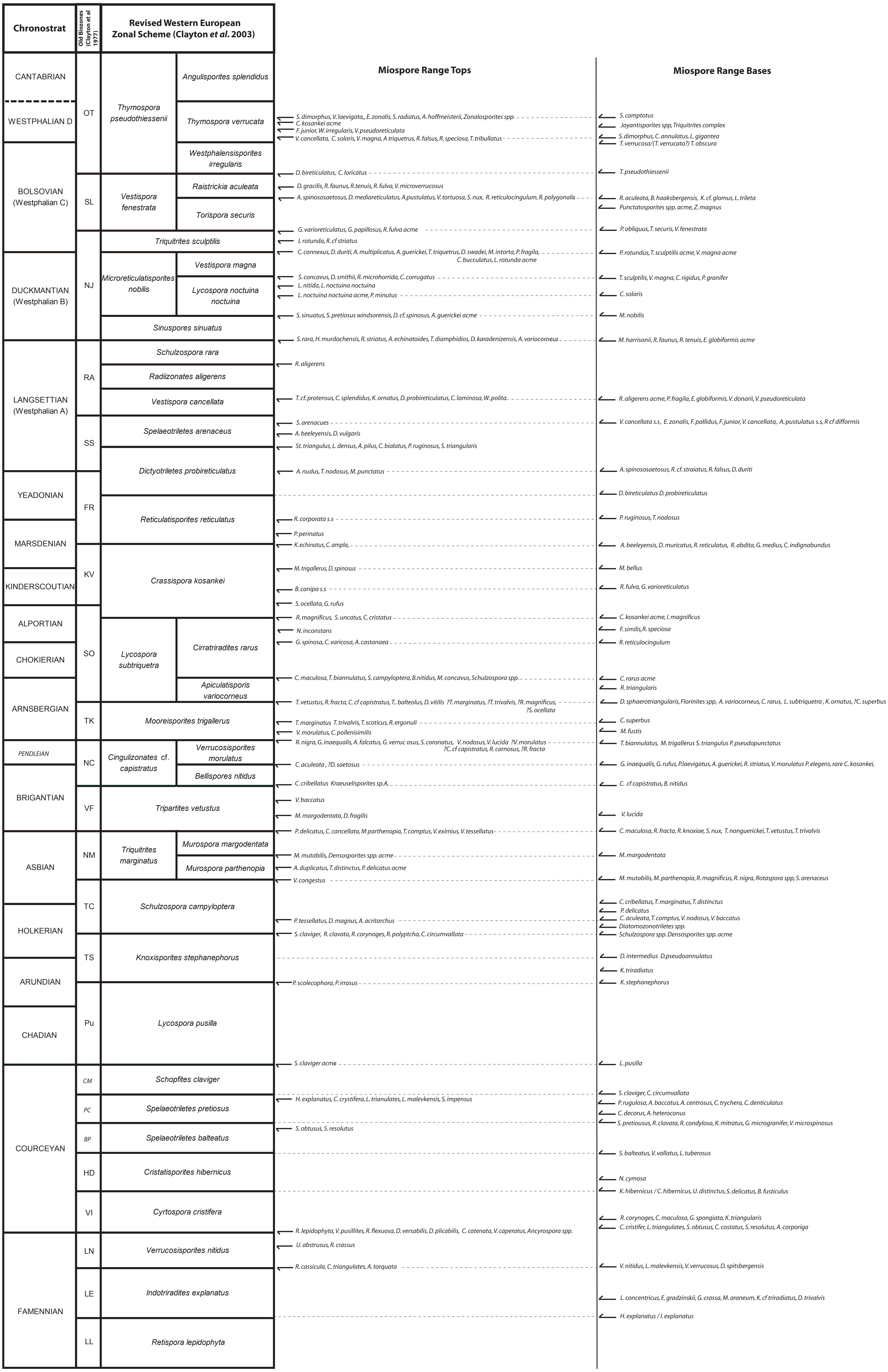
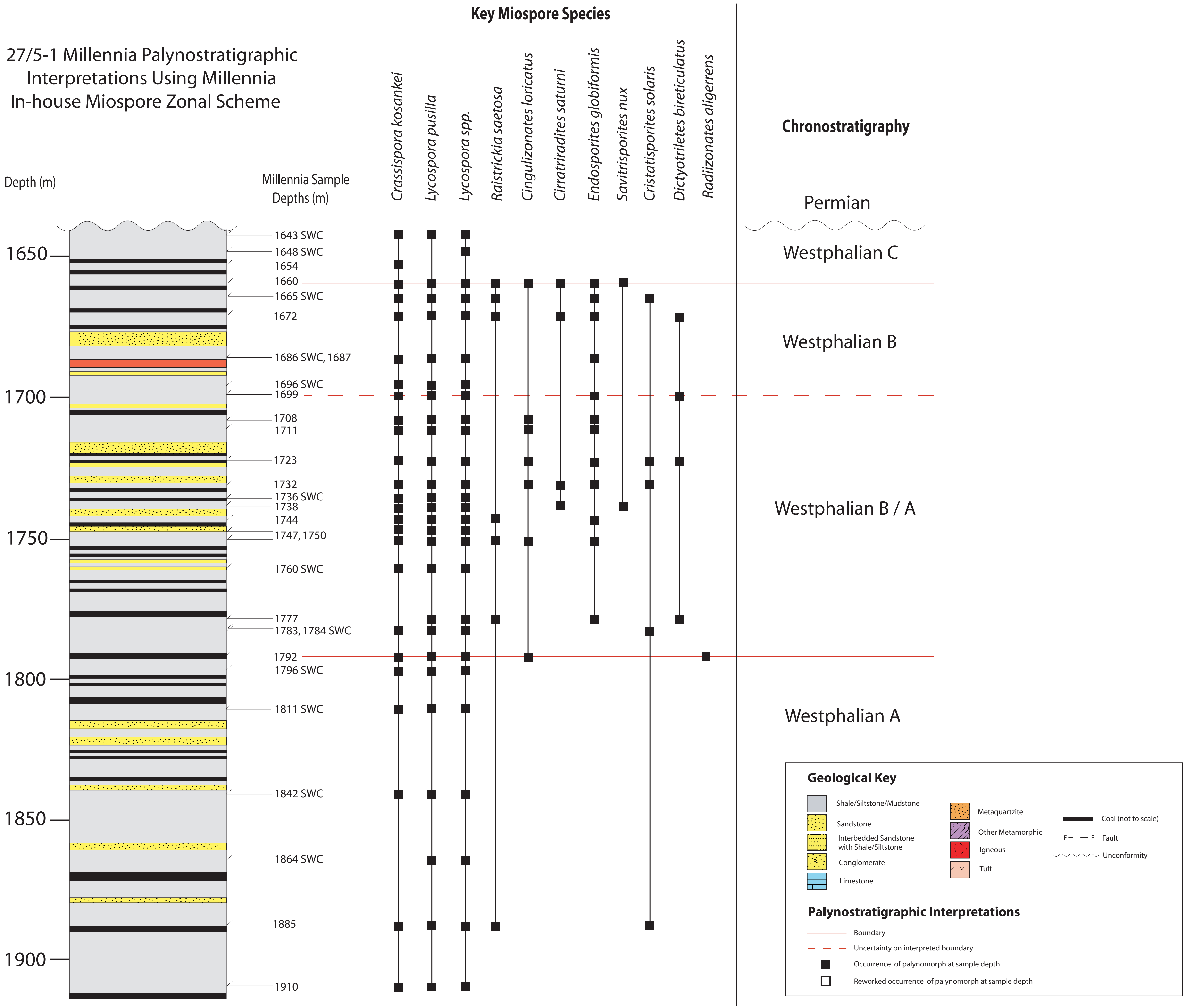
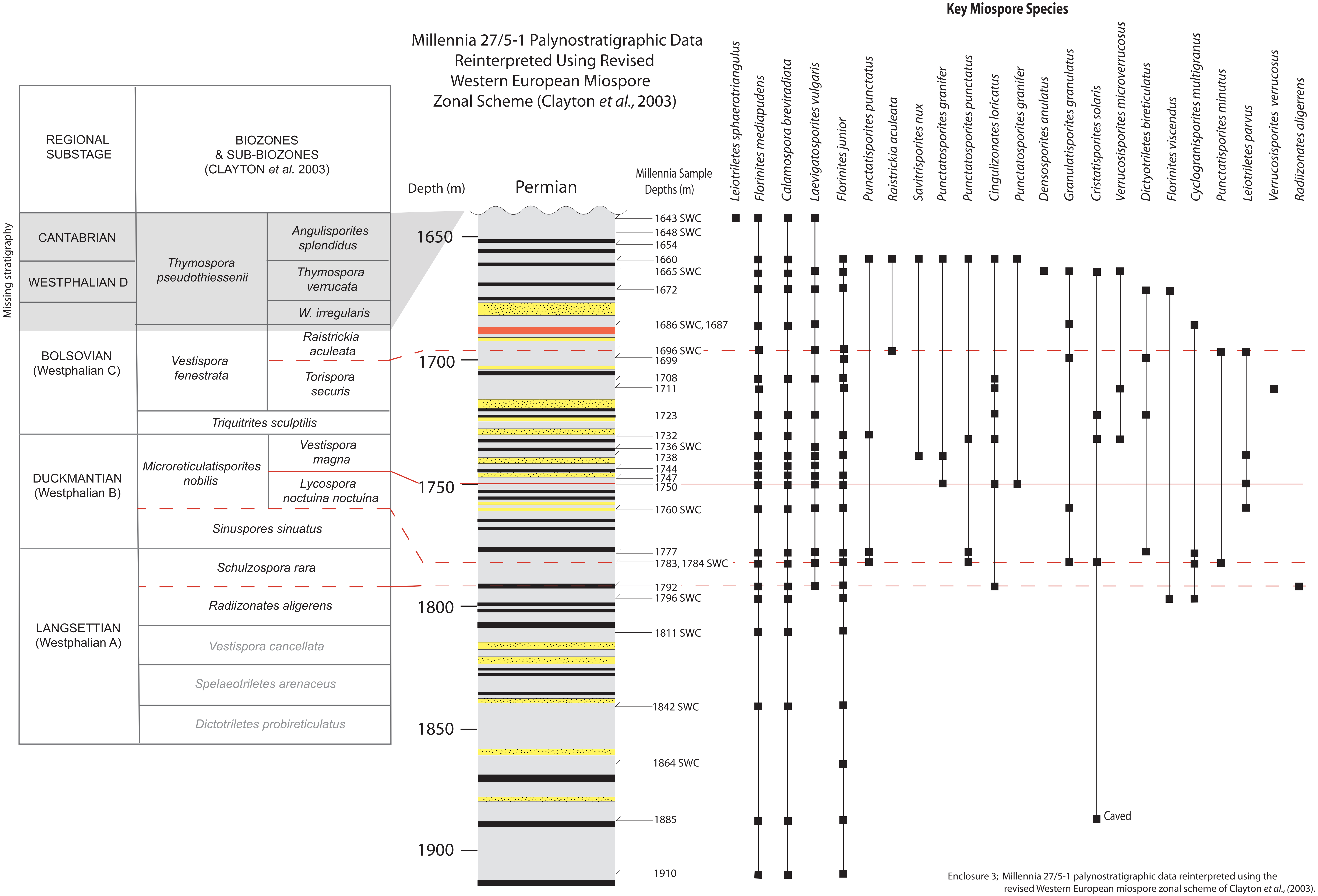


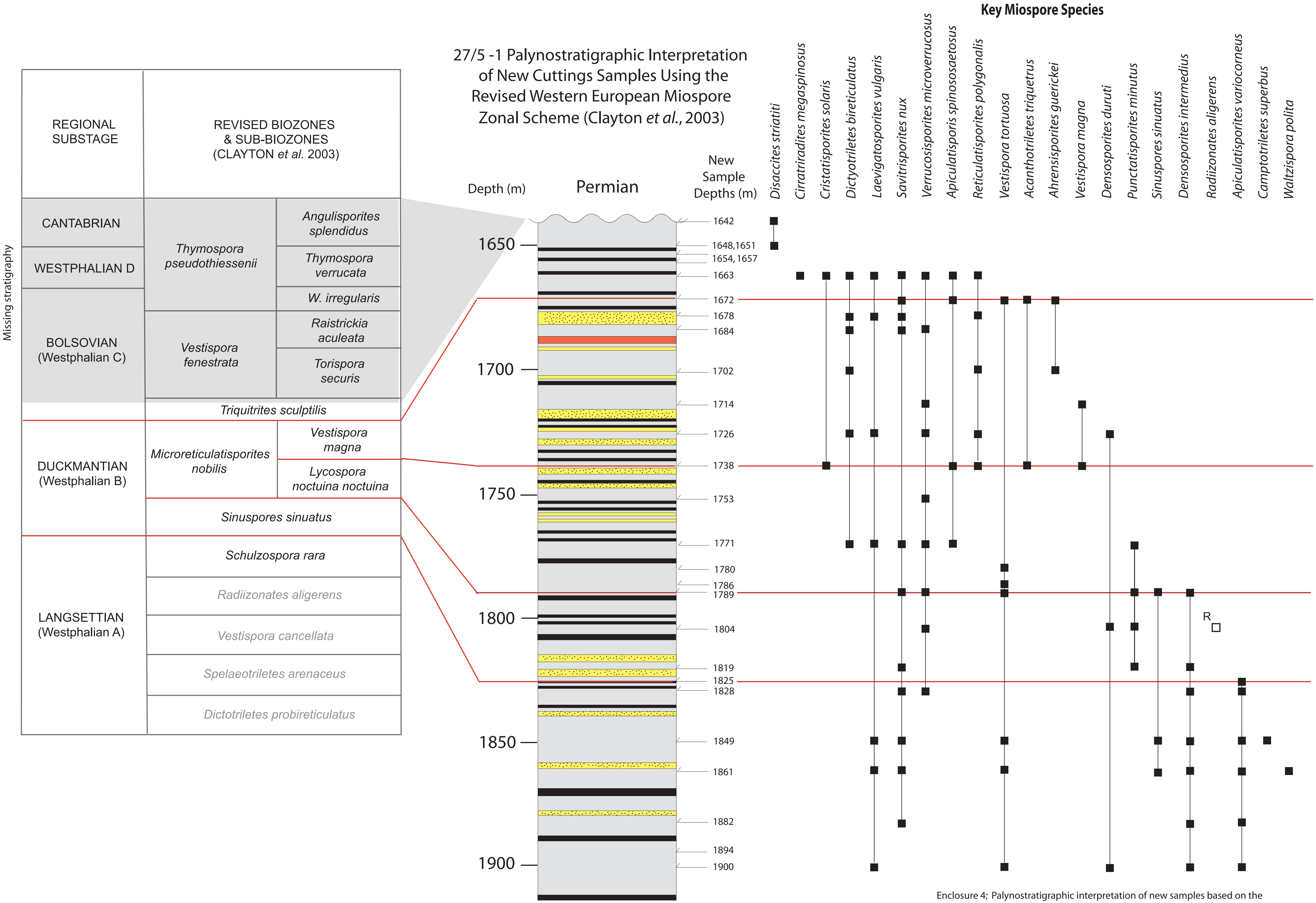
Enclosure 1; Revised Western European miospore zonal scheme of Clayton et al. (2003) with ranges of key taxa



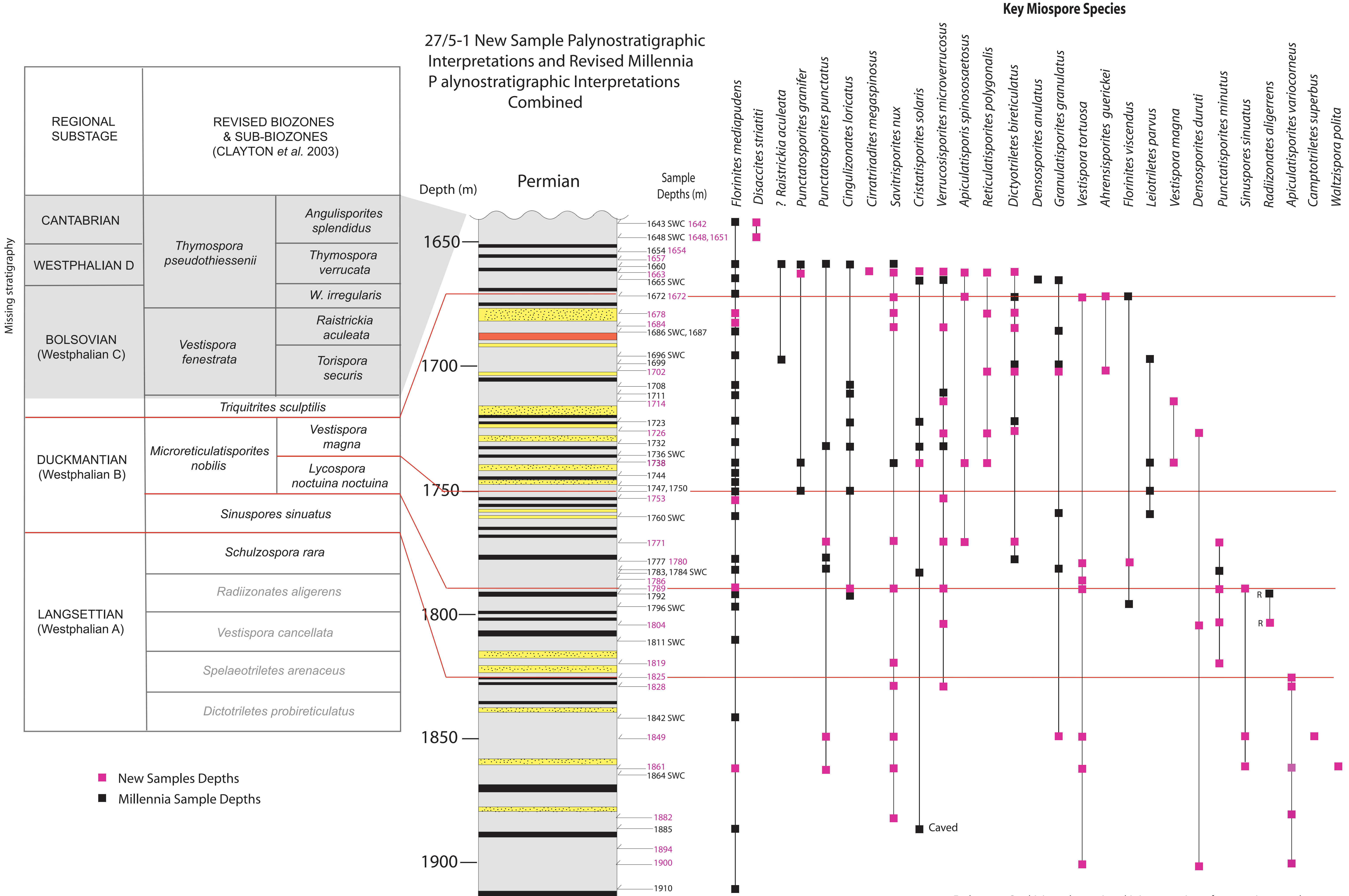
Enclosure 2; Millennia 27/5-1 palynostratigraphic interpretations based on Millennia in-house Carboniferous miospore zonal scheme



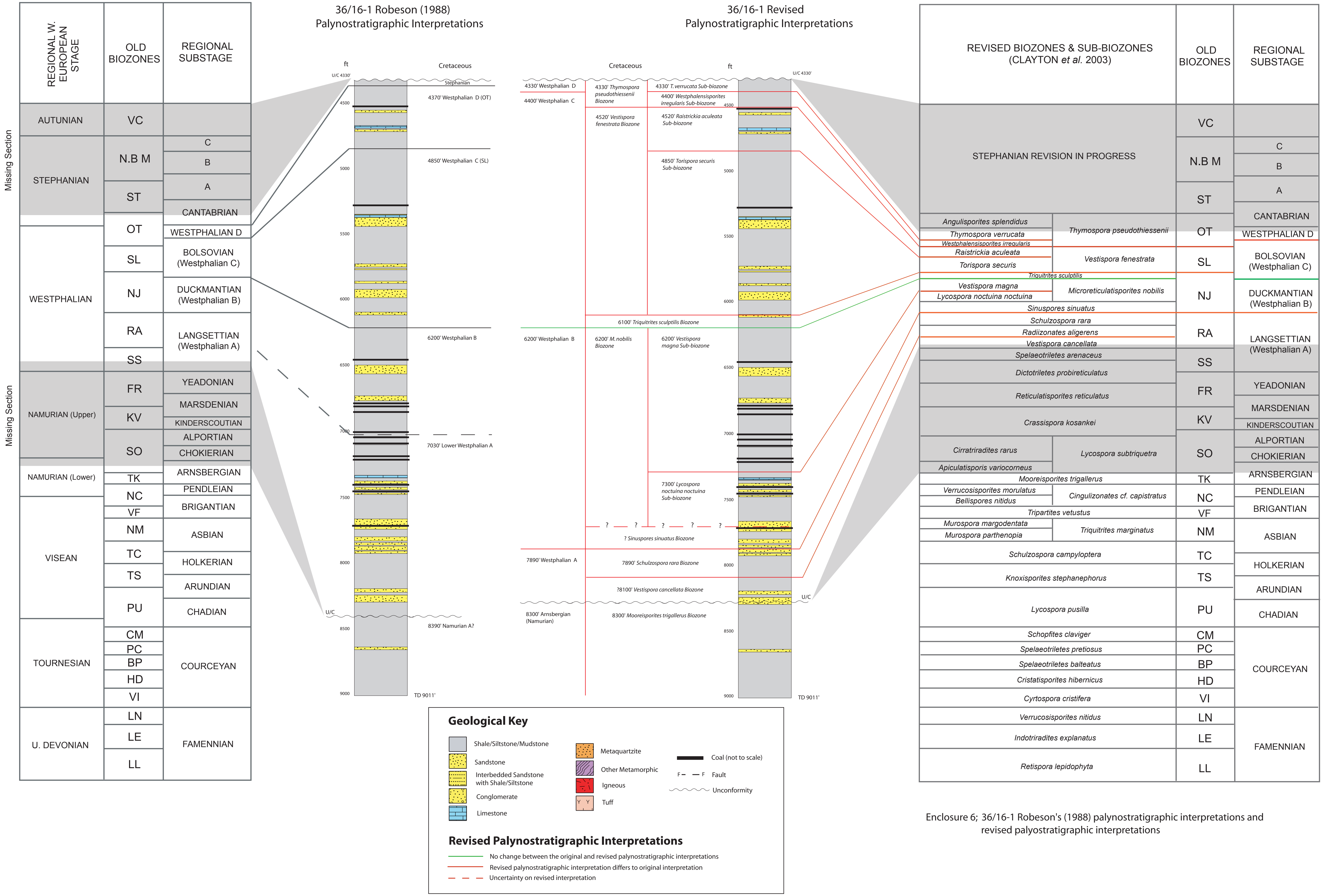
Enclosure 3; Millennia 27/5-1 palynostratigraphic data reinterpreted using the revised Western European miospore zonal scheme of Clayton *et al.*, (2003). For Geological Key see Enclosure 2.



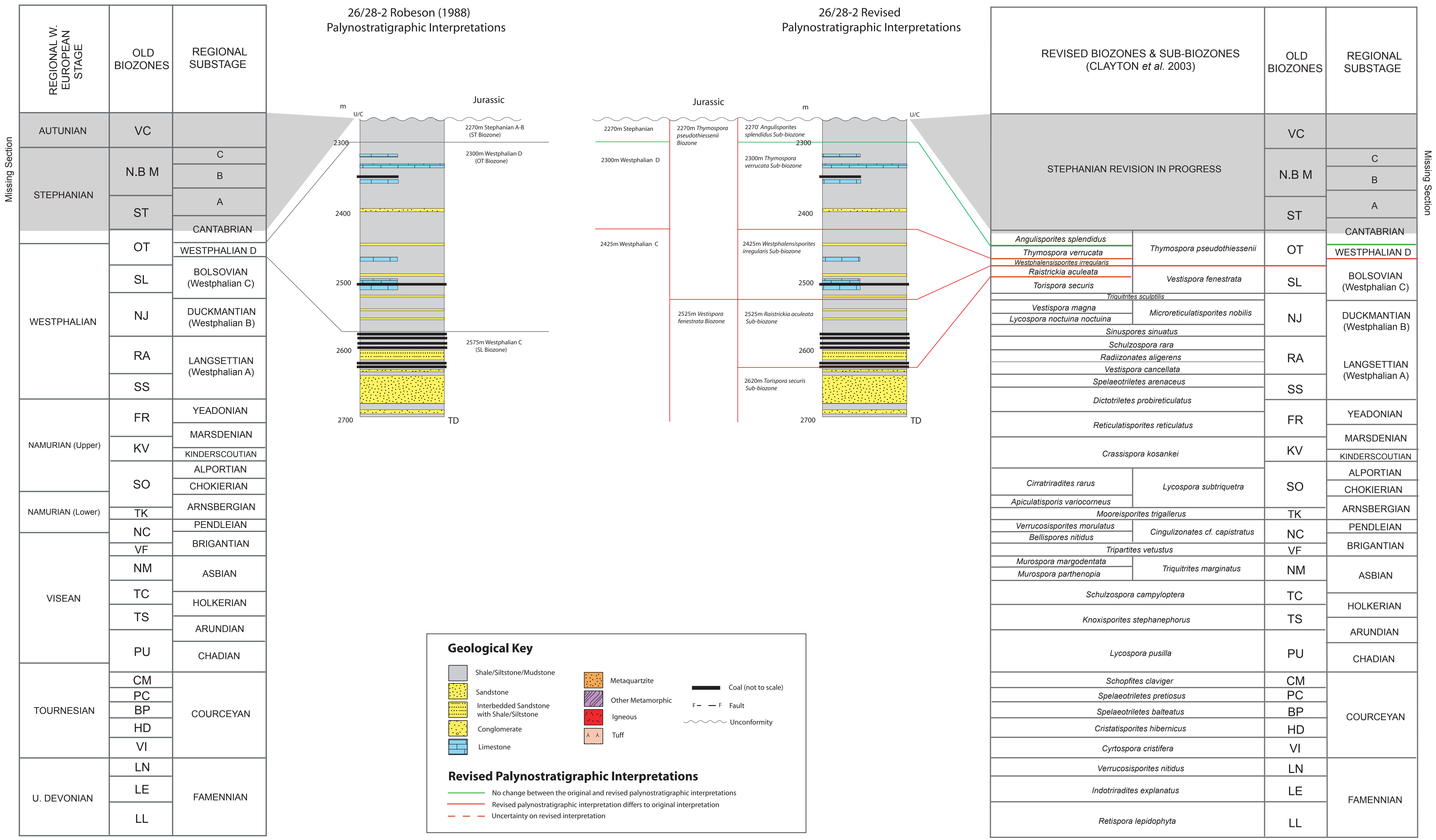
Enclosure 4; Palynostratigraphic interpretation of new samples based on the revised Western European miospore zonal scheme of Clayton *et al.,* 2003
For Geological Key see Enclosure 2.



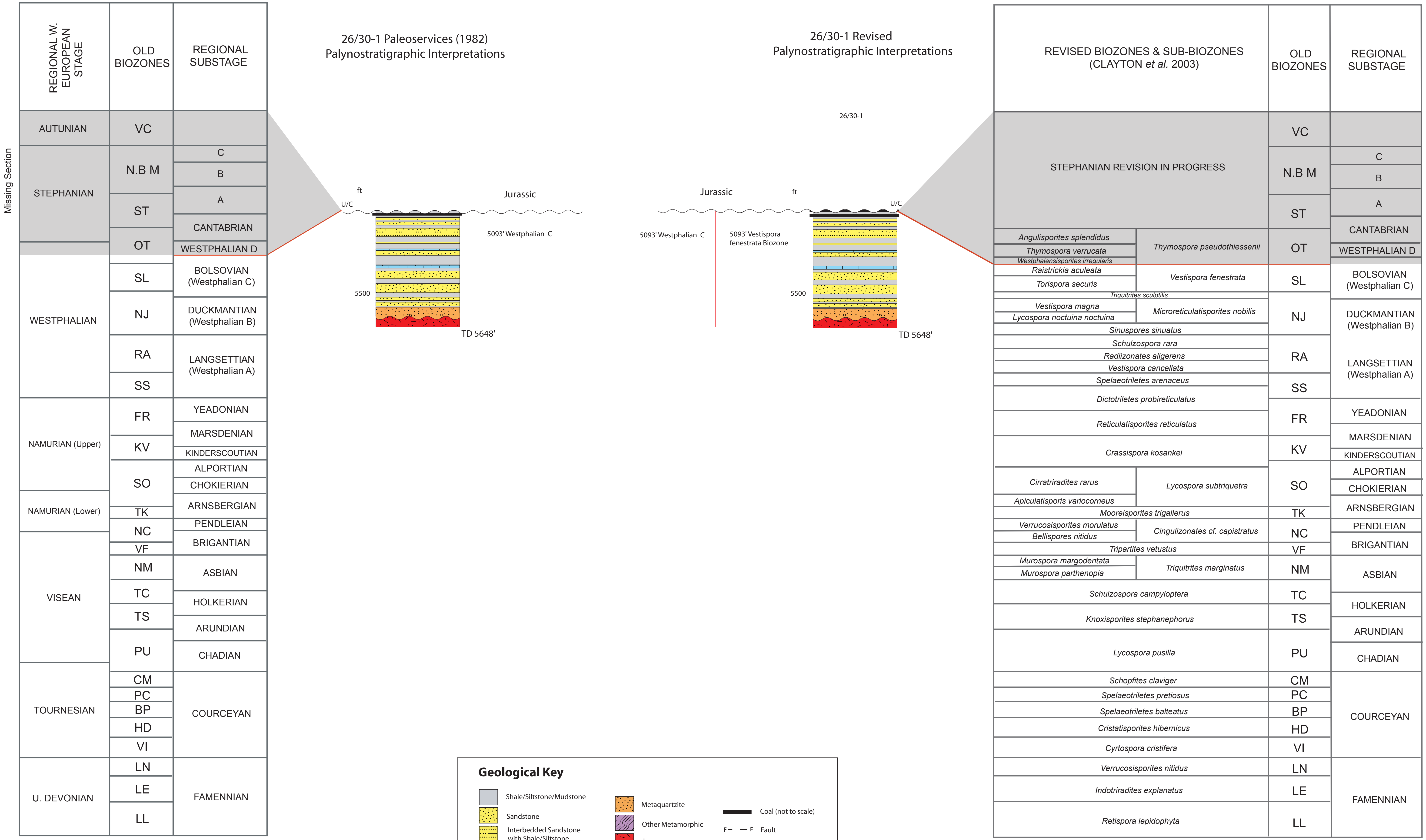
Enclosure 5; Combining palnostratigraphic interpretations of new cuttings samples with reinterpeted Millennia data for 27/5-1. For Geological Key see Enclosure 2.

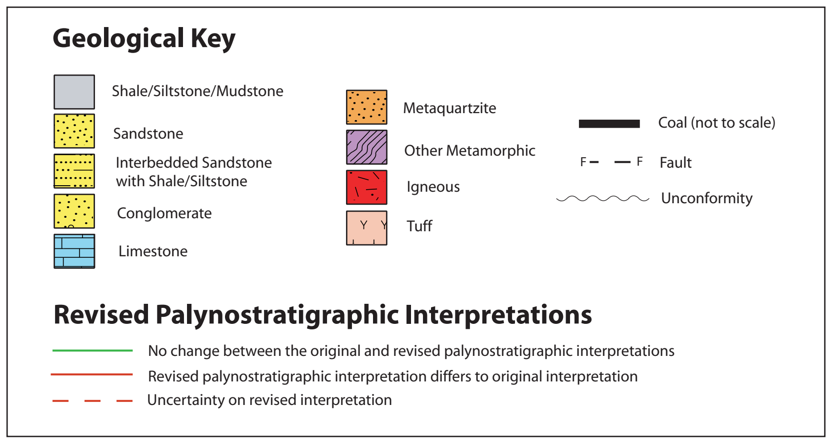


Enclosure 6; 36/16-1 Robeson's (1988) palynostratigraphic interpretations and revised palyostratigraphic interpretations



Enclosure 7; 26/28-2 Robeson's (1988) palynostratigraphic interpretations and revised palyostratigraphic interpretations





Enclosure 8; 26/30-1 Revised palyostratigraphic interpretations and Paleoservices (1982) palynostratigraphic interpretations