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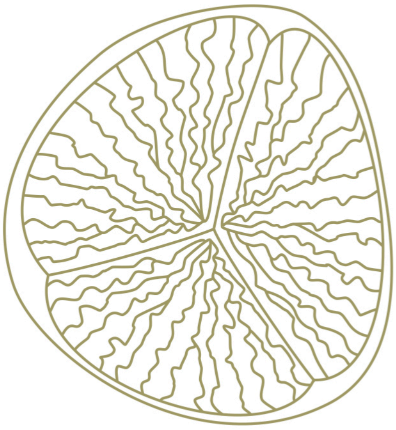

Devonian Miospore Palynology in Western Gondwana:

An application to oil exploration

Pierre Breuer
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Volume I: Explanatory Notes

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An application to oil exploration

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Abstract

Devonian miospore assemblages from 16 sections in Saudi Arabia and North Africa are studied in order to characterize the palynostratigraphy of the northern margin of western Gondwana which remains poorly known in Saudi Arabia. The preliminary taxonomic work identifies more than 200 miospore species, including a lot of new species endemic to western Gondwana. Numerous species have still to be more precisely circumscribed because of their large morphological variability. Others show continuous intergrading morphological variation. The morphological variability of each taxon is one of the main problems in any palynological study. It is due to phylogenetic evolution, ontogeny (maturation of sporangia) and taphonomic factors.

Although the standard Devonian miospore zonations established in Euramerica (Richardson & McGregor, 1986; Streel et al., 1987) are commonly used in most of the palynological studies, they are not always easily recognizable in western Gondwanan localities because of the endemic nature of the assemblages. Therefore, a new local/regional biozonation based on the characteristics of the miospore assemblages described here was needed for a more accurate correlation. The new established biozonation consists of 9 assemblage zones, 8 interval zones and 2 acme zones, extending from the late Pragian to the late Givetian and possibly the early Frasnian. The new defined biozones are compared to other coeval biozones defined in the literature. Thanks to this new local/regional biozonation, reliable correlations are established between sections.

Numerous oilfields occur in the Devonian from western Gondwana. A biozonation based on the first down-hole occurrence of species is developed for oil exploration. Thanks to this type of biozonation, only the top of a biozone has to be reached in order to be identified. The use of this biozonation is facilitated by the choice of easily recognizable and common index species. This provisional downward biozonation consists of 8 interval zones. Although it seems relatively reliable by comparison with the previously defined upward biozonation, it needs to be further tested on other drilled sections.

The review of the Emsian-Givetian miospore assemblages from the literature allows to evaluate the provincialism of assemblages on a worldwide scale during this interval. Coefficient of similarity is calculated between palynofloras from northern Euramerica, southern Euramerica, eastern Gondwana, southwestern Gondwana and northwestern Gondwana. The resulting low values correspond to low to moderate similarity of miospore assemblages between the considered regions in the Emsian-Givetian interval. The provincialism may be explained by a latitudinal climatic gradient as no palaeogeographic barrier is known during this time interval. Indeed, both Euramerican and Gondwanan land masses were very close as soon as the earliest Devonian. Despite a certain degree of provincialism, floristic interchanges existed. Northwestern Gondwana constituted an intermediate warm temperate region with shared taxa mainly from more arid Euramerican localities in the North, and cooler southwestern Gondwanan localities in higher latitudes. However, it seems that a progressive homogenization of the vegetation took place in Middle Devonian as the standard Euramerican biozones are more easily recognized in Givetian than in Eifelian and Emsian. This transition from provincialism to cosmopolitanism during the Devonian is not only shown by palynofloras but also by the palaeogeographic distribution of many other fossil groups. It is likely due to a decrease of the latitudinal climatic gradient in Middle Devonian.

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Chapter 1 – Introduction

Significant progress has been made in seismic prospecting during the past twenty last years, but the demand for increasingly finer stratigraphic resolution remains a priority in hydrocarbon exploration and production programmes. Despite the contribution of chemostratigraphy and sedimentology to the resolution of many problems of oil exploration, biostratigraphy remains unsurpassed in providing ages and palaeoenvironmental interpretations (Mahmoud Abdul-Baqi, Vice-President of the Exploration Organization at Saudi Aramco, in Al-Hajri & Owens, 2000).

Oil exploration is practically always carried out by drilling. Therefore, the probability of finding macrofossils in a core sample a few centimetres in diameter is extremely unlikely, especially in siliciclastic sediments. In addition, cores are relatively uncommon and cuttings of few millimetres in diameter represent the bulk of the study material. Thus, the majority of macrofossils are destroyed during drilling. Sampling of fine-grained sediments (shale) provides a considerable number of intact palynomorphs for study. A few grams of sediment can contain huge amounts of these microfossils. These reasons explain why palynology occupies an important place among the various biostratigraphic disciplines used in oil exploration, especially in terrestrial environments.

The majority of the Devonian oilfields are situated in western Gondwanan areas (Middle East, North Africa and South America). Saudi Aramco, which prospects on the Arabian Plate, has provided samples from 14 boreholes/wells necessary for this study. The Devonian stratigraphy of the Arabian Plate still remains incompletely known despite recent studies published (e.g. Al-Hajri et al., 1999; Al-Hajri & Owens, 2000; Loboziak & Streel, 1995b; Steemans, 1995; Loboziak, 2000; Al-Ghazi, 2007; Breuer et al., 2007). The palynostratigraphic studies of Gondwanan miospores rely mainly on biostratigraphic zonations established on the Euramerican continent (Richardson & McGregor, 1986; Streel et al., 1987). They did not utilize the endemic species, which cannot be used for intercontinental correlations. These endemic species, however, can be of a great utility for a refined local stratigraphy. Consequently, it is essential to develop a biostratigraphic zonation based on endemic miospores for the local correlations and more cosmopolitan species for interregional biostratigraphy. Thus it is necessary to exploit to the maximum the stratigraphic potential, offered by the northern Gondwanan typical palynomorphs and the endemic forms to the Arabian Peninsula. Two additional boreholes from North Africa (Libya and Tunisia) have been studied in order to compare them with the results from Saudi Arabia. These sections were already the subject of two papers (Loboziak & Streel, 1989; Loboziak et al., 1992a) but their current study, in the light of results from Saudi Arabia, allows a more detailed view on Devonian palynology mainly on the northern margin of western Gondwana (northwestern Gondwana).

In biostratigraphy, the zonations are usually based on the first occurrence of species and, therefore, are established from base to top, i.e. upwards. In oil exploration, the use of such a type of biozonation is disadvantageous since caving in ditch cutting samples makes the first occurrences less reliable. That constitutes one of the reasons why zonation based on last occurrences (i.e. downward biozonation) is commonly used in oil exploration and is tentatively developed here for Devonian Saudi oilfields.

1.1. Location of the studied areas

The first set of wells is located in northwestern Saudi Arabia (Fig. 1.1). The six investigated boreholes (BAQA-1, BAQA-2, JNDL-1, JNDL-3, JNDL-4 and S-462) were drilled through the Jauf and Jubah Formations. The preliminary results from the first five boreholes were partly published in Breuer et al. (2005, 2007). Borehole S-462 was already studied by Hemer & Nygreen (1987) and then subsequently by Loboziak (2000).

The second study area is located in eastern Saudi Arabia (Fig. 1.1) and comprises eight wells (ABSF-29, HWYH-956, FWRH-1, KHRM-2, NFLA-1, UTMN-1830 and YBRN-1). The intervals studied have not been published and are also from the Jauf and Jubah Formations.

Two boreholes from the Ghadames Basin in North Africa have been examined (Fig. 1.1). Borehole A1-69 was drilled in Libyan portion of the basin while borehole MG-1 is from Tunisia. They were drilled through, from base to top, the Ouan-Kasa, Awaynat Wanin I, Awaynat Wanin II and Awaynat Wanin III Formations. Devonian palynological studies of these boreholes were published in Loboziak & Streel (1989) and Loboziak et al. (1992a).

1.2. Regional geological background

Through much of the Palaeozoic, North Africa and the Arabian Plate belong to the geographically extensive northern passive margin of Gondwana (northwestern Gondwana) bordering the Rheic Ocean (Fig. 1.2). This margin also includes Turkey, central and northwest Iran, Afghan, Indian and other minor plates.

Much of this region was covered intermittently by shallow epeiric seas that bordered lowlands, which represent the low-relief erosion surface formed on the Precambrian basement. Consequently shallow-marine, littoral, and fluvial sandstone, siltstone, and shale were deposited from the end of the Neoproterozoic. This depositional cycle was firstly interrupted during the Late Ordovician-Early Silurian by south polar glaciations. Sea-level rise and fall caused regressions and transgressions of the ocean flanking Gondwana and a corresponding migration of sedimentary facies on the stable shelf. In the Late Silurian, the influence of a major global sea level drop combined with regional Silurian progradation resulted in a major Late Silurian hiatus in most parts of the northwestern Gondwana. Some geologists (e.g. Berberian & King, 1981) cite the Late Silurian hiatus as evidence for epeirogenic uplift associated with the Caledonian Orogeny. The late Silurian hiatus was followed by a Devonian transgression caused by a global sea level rise. The extent of the shelf seas changed in response to succeeding transgressions and regressions as the Devonian advanced. Their palaeogeographical setting was at this time mainly tropical to subtropical (Beydoun, 1991). Then epeirogenic activity, reflecting the initial collision between Gondwana and Laurussia (Hercynian Orogeny), increased in Middle to Late Devonian resulting in an increase of stratigraphic complexity. These resulting hiatus, unlike the Late Silurian hiatus, were not accompanied by a major drop in global sea level and, therefore, may be entirely attributed to regional uplift (Husseini, 1991). The Hercynian orogenic activity made active the margin of northwestern Gondwana during the Carboniferous and eroded locally Devonian sedimentary rocks.

1.3. Methodology

Saudi Aramco provided 380 samples from the studied boreholes/wells. Among them, 236 were productive and were used for palynological analysis. The 144 others were either barren or contained very few biostratigraphically significant palynomorphs. The residues and slides from the North African studied sections are from the collections of the Laboratory of Palaeontology of the University of Lille (France). Of the 96 available samples, 84 were productive and usable for palynological study. In total, 301 core samples and 29 cutting samples were productive and used in this work. All samples were collected from dark-coloured, fine-grained, shaly sandstones, siltstones and shales because they are usually the most suitable for palynological study. Saudi Aramco supplied the lithostratigraphy, lithology, drilling data and eventual sedimentological analysis of the different boreholes/wells. The few available lithological and sedimentological data for North Africa are compiled in Massa (1988), Streel et al. (1990) and Ben Rahuma et al. (2007).

All samples were processed according to standard palynological laboratory methods (Streel, 1965). Each sample was crushed and 10-25 grams were demineralised in 10% HCl and 40% HF. The residue of the most poorly-preserved samples was oxidized in 65% HNO_3 and $KClO_3$ and sieved through a 10 µm mesh. Subsequently, a hot bath in 25% HCl eliminated the remaining fine mineral particles. The residue of all samples was rinsed through a 10 µm mesh. The final residue was mounted on palynological slides using Euparal or Eukit resin. One to four slides were made for each productive sample. The slides from some levels of well HWYH-956 are stored in the collections of Saudi Aramco in Dhahran (Saudi Arabia), and those from borehole A1-69 in the collections of the Laboratory of Palaeontology of the University of Lille (France). The samples and the palynological slides from boreholes BAQA-1, BAQA-2, JNDL-1, JNDL-3 and JNDL-4 are housed in the Centre for Palynology of the University of Sheffield (UK) and the remainder of studied material is in the collections of the Laboratory of 'Paléobotanique, Paléopalynologie et Micropaléontologie' of the University of Liège (Belgium).

A palynological slide can contain up to 5000 individual specimens, which may belong to several dozens of different taxa. As several hundred of palynological slides have been studied in this work; the photographic documentation was extensive. An efficient tool was needed to manage this collection and to classify the numerous palynomorph photomicrographs. A Palynological Data Base was created using FileMaker Pro 7.0© software. This data base allows the encoding of photographs with their documentation: name of borehole/well, sample, slide, England Finder Co-ordinates (EFC), genus and species names, etc. In addition, key words about the morphological characteristics were included for each photograph in the file. A search engine was created because the data base contains huge amounts of information. Thus specimens can be searched according to their localities or their morphological criteria. Finally, the results of the search can be printed on rough draft photographic plates.

The first approach to the palynological study consists in the identification of the different miospore forms present in the samples. Palynological slides were investigated using a transmitted light microscope (Zeiss AxioLab). Numerous palynomorph images (more than 4200) were taken and encoded in the Palynological Data Base in order to gain an understanding of the studied material and to compare with the complex miospore literature. In addition, this intensive photography allows illustration of the variability for each miospore species (see Volume III). Most of these photomicrographs were taken by using PixeLink Capture SE© software coupled with Adobe Photoshop 7.0© and PixeLink© digital camera (model PL-A662) which gives a maximum magnification of 1000x. Biometric data for description of the different species were measured using Zeiss AxioVision LE 4.1© software.

Each slide was scanned using 40x, 63x and 100x objectives in order to record all present miospore taxa. Some specimens were photographed to proceed to their identification. All miospore taxa recognized or defined in this work are described, compared and illustrated in the Volume III. In addition, their stratigraphic and palaeogeographic occurrence is recorded according to the Devonian palynological literature. After the first observation and the identification of species, which compose the palynological assemblages, quantitative species counts were carried out for each stratigraphic level of several sections (BAQA-1, BAQA-2, JNDL-1, JNDL-3, JNDL-4, ABSF-29, HWYH-956, KHRM-2, SDGM-462 and UTMN-1830). At least 250 miospore specimens per slide were counted when specimens were numerous enough. Miospores, acritarchs (leiospheres and sculptured acritarchs) and other group of palynomorphs (chitinozoans, scolecodonts, etc.) were counted in order to determine their relative percentages.

Finally, all palynological data were entered in StrataBugs 1.8© software, which allows the management of biostratigraphic data. By using StrataBugs, biostratigraphic and geologic data for each section can be recorded, stored, manipulated and displayed. Different groups of miospores were created to attempt to characterize better the studied palynological assemblages. They are listed in Appendix 1.1 (see Volume II). The miospores are subdivided into 4 main groups: cryptospores, megaspores, monolete and trilete spores. They are classified into morphological groups: simple laevigate, sculptured with concentric, discrete or anchor elements, reticulate/foveolate, radial-patterned spores, papillate and convolute/rugulate spores. They are also grouped according to their exine structure: spores of uniform thickness, cingulate, patinate, zonate and cavate spores. Note that a unique species can be represented in several groups. In addition, the palaeogeographic affinity of each miospore is taken into account. The typical endemic Gondwanan species can be distinguished from the cosmopolitan species which occur in many different locations all over the world. Consequently for each section, stratigraphic range of encountered miospore taxa and the evolution of the relative abundance of the different palynological groups are plotted in different charts in Volume II. In addition, a curve of diversity is plotted and represents the number of miospore taxa encountered per sample. This diversity does not represent the real diversity of the ancient vegetation since the Palaeozoic miospore taxonomy is in fact parataxonomy (see Volume III). As counting has been carried out for several sections (BAQA-1, BAQA-2, JNDL-1, JNDL-3, JNDL-4, ABSF-29, HWYH-956, KHRM-2, SDGM-462 and UTMN-1830), their relative graphs are based on the relative abundance of specimens. The percentages of each individual taxon are calculated in comparison with the whole palynological assemblage (all palynological groups are included) whereas these from the different miospore groups are calculated in comparison only with the miospore assemblage (palynological groups other than miospores are excluded). As no specimen counting has been carried for other sections (A1-69, FWRH-1, MG-1, NFLA-1, S-462, YBRN-1), their relative charts are based on the relative abundance of each miospore group as a percentage of all groups found in the same sample. For example, if a miospore group represented by two species co-occurs with eight other species belonging to other groups, the relative percentage of this group for this sample equals to 20%. Thus, these results have to be interpreted with caution because the number of specimens per category remains unknown. We have to keep in mind that a category with a high percentage may be characterized by a small number of specimens. That can be due to a unique species belonging to another group that dominates the spore assemblage or the paucity in organic matter of the sample. One must be aware of the interpretation limits of such graphs; some general trends among miospore genera and morphological groups can only be defined.

1.4. Devonian miospore and land plant evolution

Some of the most crucial steps in land plant evolution occurred during the Devonian. Terrestrial flora evolved from a sparse cover of small simple plants to large trees growing in structured plant communities with sophisticated reproductive systems. This evolution was reflected also by major innovations and increasing complexity in spore morphology, which occurs throughout Devonian and can be related to the palaeobotanical evidence to understand the Devonian vegetational history (Marshall, 1996).

The most characteristic features of miospore evolution are summarized and illustrated in Fig. 1.3. The first miospores recovered from the Ordovician and Early Silurian are cryptospores, i.e., spores in obligate tetrad or dyad following dispersal. The oldest are known with certainty in the Llanvirnian (Strother, 1996; Le Hérissé et al., 2007). The first undoubted trilete spores originated in Ordovician (Steemans, 1999). These first spores are small (about 20-30μm), simple and smooth; however Steemans (pers. comm., 2007) has recently recorded the first sculptured spores in Late Ordovician from Saudi Arabia. Distal thickening of the exine (patina) was differentiated in the meantime. Diversification of trilete spores began from middle Silurian while cryptospore populations became impoverished. Indeed more complex forms of trilete spores appeared and could exceed the 50 μm size limit. They were accompanied by the first upright land plants without vascular tissue. Proximal radial muri and interradial papillae as well as diverse sculptural patterns (verrucate, foveolate, reticulate, apiculate and rarely biform) appeared during Late Silurian. At the end of Silurian, miospores increased significantly in size, abundance and morphological complexity reflecting the diversification of plant life on land. The Devonian Period was a time of explosive phase of miospore diversification. Spiny (echinate) sculpture originated in the Lochkovian, along with biform spines. Zonate miospores, i.e., miospores bearing an equatorial extension of the external layer of the exine first appeared also from Lochkovian. Camerate or cavate miospores, i.e., miospores having a cavity between the two layers of exine, evolved from the two-layered zonate miospores and display almost all kinds of exinal sculpture, including typical biform elements and bifurcated spines. Monolete spores appeared in the Emsian according to the literature (e.g. Traverse, 2007), but they were never as numerically significant as trilete spores. By the end of the Early Devonian, miospores already developed most of their Devonian characteristics (Alpern & Streel, 1972; Richardson & McGregor, 1986). During most of the Early Devonian, miospores were diverse but rather small in size. The average spore diameter increased from less than 25 μm (the size of extant bryophyte spores) to 50–150 μm (the size of extant fern spores). Their parent plants were homosporous, and it is only in the latest Early Devonian that the heterospory seems to appear with miospores reaching occasionally megaspore size (200 μm). A renewal of the palynofloras occurred in the late Emsian, mainly due to a marked increase in miospore size. This event is characterised notably by the appearance of large, prominently spinose zonate and pseudosaccate spores belonging to the *Grandispora/Samarisporites* complex and the disappearance of several smaller forms, such as reticulate species common in Early Devonian. These large spinose zonate-pseudosaccate miospores proliferated and were abundant throughout the Eifelian. Grapnel-tipped spines, which had appeared in apparently unrelated generic groups during the Emsian, became common in the Middle Devonian. These sculptural elements might help to hook on arthropods for dispersal (Kevan et al., 1975). Thus larger and more complex spores dominated the Eifelian and the populations show a general continuum in spore size from 20 to more than 200 µm. The size distribution of spore populations suggests at that time the development of functional heterospory. That broad size distribution continued in the Givetian with further differentiation of microspore and megaspore populations in both size and morphology. Meanwhile the plant size increased with the development of the arborescent habit. Indeed, the first trees and consequently forests appeared in Middle Devonian. The large spinose zonate-pseudosaccate miospores, which had reached their acme in the Givetian, became gradually rarer in the Frasnian. A return to palynofloras dominated by smaller-sized miospores is commonly documented from below the Frasnian/Famennian boundary up to the end of Devonian. Most of the miospores returned to the 50–150 µm size range, possibly in response to new strategies in land plant reproduction such as the differentiation of the seed and prepollen (Loboziak et al., 2005). The first occurrence of endoreticulate miospores near that stage boundary could reflect such a change. In the Late Devonian, heterospory was well-established, with clearly defined microspores and megaspores in addition to early seeds. An important element of the floras was the progymnosperm *Archaeopteris*, with its secondary wood enabling it to become truly arborescent. These changes in land plants during the Devonian, from homospory to heterospory and seeds, together with the greatly increased size and morphological sophistication, reflect the diversification of reproductive strategy (Chaloner & Sheerin, 1981; Chaloner & Hemsley, 1991).

1.5. Palynostratigraphy

By their abundance, diversity, preservation potential and facies, dispersed spores provide a record of the evolution of terrestrial plant life. They are transported from their parent plants by running water and wind and dispersed in huge numbers into a range of terrestrial and nearshore marine sedimentary environments that allows direct chronostratigraphic correlation between marine and nonmarine sedimentary successions. In addition, miospores are easily retrieved and concentrated from sediments.

Correlation remains the primary application of palynology. Reliable biostratigraphy is dependent on the ability to define, differentiate and recognize correlative units. The International Stratigraphic Guide promotes agreement on principles of stratigraphic classification and development of a common acceptable stratigraphic terminology and rules of stratigraphic procedure (see Salvador, 1994).

1.5.1. Biozone definition

Biostratigraphic units or biozones represent bodies of strata that are defined on the basis of the ranges of contained fossils. They exist only where the particular diagnostic feature or attribute on which they are based has been identified. Biozones, therefore, are objective units based on the identification of fossil taxa. Since they depend on taxonomic practice, changes in their taxonomic base may enlarge or reduce the body of strata included in a particular biostratigraphic unit. A biostratigraphic unit may be based on a single taxon, on combinations of taxa, on relative abundances, on specified morphological features, or on variations in any of the many other features related to the content and distribution of fossils in strata (see 1.5.2). The same interval of strata may be zoned differently depending on the diagnostic criteria or fossil group chosen. Thus, there may be several types of biozones in the same interval of strata that may have gaps between them or overlaps of their vertical and horizontal ranges. Biostratigraphic units are distinct from other kinds of stratigraphic units (lithostratigraphic, magnetostratigraphic, chronostratigraphic, etc.) because their fossils show evolutionary changes through geologic time that are not repeated in the stratigraphic record. This makes the fossil assemblages of any age distinctive from any other. The boundaries of biostratigraphic units may coincide locally with those of lithostratigraphic units, however in this case caution is needed because the boundaries of biozones may be controlled by sedimentological factors. Commonly the boundaries of biostratigraphic units lie at different stratigraphic horizons or cross lithostratigraphic units (Salvador, 1994).

1.5.2. Types of biozones

Four major types of biozones are used in the palynological literature and are recognized by the International Stratigraphic Guide (Hedberg, 1976; Salvador, 1994):

- **The range zones**: they are subdivided into two subtypes. Firstly, the interval zones represent strata between the successive stratigraphically highest and/or lowest occurrences of index taxa. The boundaries of an interval zone are defined by the occurrence of the biohorizons selected for its definition. Interval zones defined as the stratigraphic section comprised between the lowest occurrence of two specified taxa ('lowest-occurrence zone') are useful, preferably in surface work or cored wells (Fig. 1.4a). Interval zones defined as the stratigraphic section comprised between the highest known occurrence (first down-hole occurrence) of two specified taxa ('highest-occurrence zone') are particularly useful in the oil industry where subsurface stratigraphic work is generally made from drill cuttings (Fig. 1.4b). Secondly, the Oppel Zones (Fig. 1.4c) characterize the overlapping parts of the range zones of two specified taxa. According to Hedberg (1976), these zones may be defined as an association or aggregation of selected taxa of restricted and largely concurrent ranges, chosen as indicative of approximate contemporaneity. This type of zone may include taxa additional to those specified as characterizing elements of the zone, but only the two specified taxa are used to define the boundaries of the zone. The boundaries of a concurrent-range zone are defined in any particular stratigraphic section by the lowest stratigraphic occurrence of the higher-ranging of the two defining taxa and the highest stratigraphic occurrence of the lower-ranging of the two defining taxa.

- **The assemblage zones** (Fig. 1.4d): they include strata characterized by an association of three or more distinctive taxa that, taken together, distinguish it in biostratigraphic character from adjacent strata. The boundaries of an assemblage zone are drawn at biohorizons marking the limits of occurrence of the specified assemblage that is characteristic of the unit. Not all members of the assemblage need to occur in order for a section to be assigned to an assemblage zone. The total range of any of its constituents may extend beyond the boundaries of the zone.

- **The acme or abundance zones** (Fig. 1.4e): they are composed of strata characterized by maxima in the relative abundance of one or more taxa. The unusual abundance of a taxon or specified group of taxa in the stratigraphic record may result from a number of processes that are of local extent, but may be repeated in different places at different times. For this reason, the only sure way to identify an abundance zone is to trace it laterally. The boundaries of an abundance zone are defined by the biohorizons across which there is notable change in the abundance of the specified taxon or taxa that characterize the zone.

- **The lineage zones**: they relates to the body of strata containing specimens representing a specific segment of an evolutionary lineage. It may represent the entire range of a taxon within a lineage (Fig. 1.4f) or only that part of the range of the taxon below the appearance of a descendant taxon (Fig. 1.4g). The boundaries of lineage zones approach the boundaries of chronostratigraphic units. A lineage zone differs from a chronostratigraphic unit in being restricted, as all biostratigraphic units, to the actual spatial distribution of the fossils. Consequently, lineage zones are theoretically the most reliable means of correlation of relative time by use of the biostratigraphic method. The boundaries of a lineage zone are determined by the biohorizons representing the lowest occurrence of successive elements of the considered evolutionary lineage. In practice, it may be difficult to establish limits in a lineage when the morphological variation is continuous (see Volume III).

Some palynologists in some situations use ‘phases’ (Fig. 1.4h) instead of zones. ‘Phases’ emphasize the gradual development over time of successive assemblages rather than the complete distinctiveness of each assemblage. Therefore, the boundaries of phases are fuzzy.

1.5.3. Uncertainty factors

The different types of biozones presented above seem in theory easy to implement but the reality is more complicated. Indeed, the fossil record encountered in the stratigraphic sections we want to correlate is influenced by a number of factors, making biostratigraphic analysis and zonation complex. These are the principal uncertainty factors which have influence on the accuracy of a stratigraphic correlation or any type of biostratigraphic analysis. They are mainly both the result of personal bias in observation and identification, and inherent properties of the fossil record (Gradstein et al., 1985). These uncertainty factors influencing the fossil record (Fig. 1.5) are mainly:

- **Confidence of taxonomic identification**: it is the first source of misinterpretation in palynology. In general, confidence of taxonomic identification is directly proportional to the number of specimens found. The taxonomic concept adopted by the palynologists can be the cause of confusion at the time of comparisons between results from different authors (see Volume III). That is why working with the same taxonomic concept is essential. In addition, the poor preservation of the organic matter makes the miospore identification difficult or impossible.

- **Sampling details and the frequency of fossil taxa**: population and sampling densities directly influence the chance that the total stratigraphic range of a given species has been observed (Gradstein et al. 1985).

- **Facies control**: miospores in water act as sedimentary particles. They are silt- and finest sand-sized clasts and therefore are mostly transported with fine silt, as they sort out along with slightly smaller mineral particles. Well-sorted claystones and well-sorted coarse sandstones do not ordinarily contain trace of palynomorphs. Most of carbonate sediments are poor in miospores (Traverse, 2007).

- **Environmental changes**: the presence or absence of taxon is controlled also by the ecological factors that prevailed at the time of deposit of miospores. Fossils are sensitive indicators of past environments, sedimentation patterns and their distributions.

- **Sedimentation rate**: extremely low rates of sedimentation may result in fossils of different ages and different environments being mingled or very intimately associated in a very thin stratigraphic interval, even in a single bed (condensed section). On the contrary, high sedimentation rates may prevent to observe rare taxa, specimens being diluted in large amounts of sediments. The sedimentary record distorts the simple time-space information.

- **Reworking**: this problem can obviously lead to great difficulties with the determination of last occurrences in particular, because reworking of palynomorphs from older sediments can appear to extend the range of taxa upwards.

- **Caving**: this phenomenon is well-known in oil industry. It results from drilling which induce contamination by fall of rock fragments from the borehole annulus. Palynological cutting samples contain *in situ* material from the maximum depth reached by the drilling mixed with palynomorphs from the open hole. Observed bases of fossil ranges are difficult to use and are generally extended (too old). Tops, however, are unaffected.

Finally, the rate and effects of these uncertainty factors on the presence or absence of a given species remain generally obscure and cannot be detected prior the extensive sampling and biostratigraphic analysis. On the other hand, the repeated observations in numerous different sections allow understanding of these factors. The increase of studied samples and sections increase, therefore, the relative precision of biozonation.

1.5.4. Devonian miospore zonations

Publications about the stratigraphic distribution of Devonian miospores started effectively with the study of Naumova (1953) on the Russian Platform in the northeast Euramerican Continent. Then, various authors undertook subsequent works in various parts of the Devonian System in different areas all over the world but especially in Euramerica.

Two zonal concepts are adopted in the study of Devonian miospore successions. The first concept is the assemblage zone, notably used by Richardson & McGregor (1986) in their miospore zonation of the Old Red Sandstone Continent and adjacent regions, videlicet Euramerica (Fig. 1.6). Richardson & McGregor (1986) described assemblage zones which are defined on the basis of a combination of different criteria, such as the co-occurrence of characteristic species, the first inception of selected species, and the appearance of selected morphological features. This concept was proposed as the only one which would allow correlation on a global scale. Indeed, the Euramerican Continent and adjacent regions obviously belong to different phytogeographic provinces, and therefore it was necessary to apply such a comprehensive zonal scheme in order to accommodate a maximum of available data.

The second concept is the interval zone, defined on the basis of first and/or last occurrences of selected taxa and used by Streel et al. (1987) in their biozonation of the type marine Devonian strata of the Ardenne-Rhenish regions in Western Europe (Fig. 1.6). This miospore zonal scheme comprises a series of interval zones entirely erected within the limits of a single phytogeographic province, contrary to the assemblage zones of Richardson & McGregor (1986). The advantage of the interval zones is that they allow unequivocal correlation with interval zones based on varied fossil groups.

Avkhimovitch et al. (1993) established a Middle and Late Devonian miospore zonation in Eastern Europe (Fig. 1.6) by using a concept of assemblage zone based on the acme of characteristic taxa, whereas their first inception is seldom taken into account.

As regards the Devonian from western Gondwana, the most significant miospore zonations were established in the Algerian Illizi Basin (Jardiné & Yapaudjian, 1968), the Libyan Ghadames Basin (Massa & Moreau-Benoit, 1976; Moreau-Benoit, 1989), the Amazon, Parnaíba and Paraná Basins in Brazil (e.g. Daemon et al., 1967) and the Cordillera Oriental in Bolivia (McGregor, 1984). Local/regional biozonations were developed in these initial works. However, subsequent miospore investigations in western Gondwana (e.g. Burjack et al., 1987; Loboziak et al., 1988; Streel et al., 1988; Loboziak & Streel, 1989; Loboziak et al., 1992a, b) demonstrated, from the Emsian at least, comparable successions of first occurrences of several common index species of the Euramerican zonal schemes of Richardson & McGregor (1986) and Streel et al. (1987). That is why these two main Devonian miospore zonations were usually applied for western Gondwana sections in many recent publications (e.g. Loboziak & Streel, 1995b, Loboziak et al., 1996, 1997, 2000; Loboziak, 2000; Melo & Loboziak, 2003). Indeed, Loboziak et al. (1989) and Streel et al. (1990b) demonstrated that southern Euramerica and western Gondwana constituted a unique major phytogeographic province during the Middle and Late Devonian. Although several endemic miospore species are restricted to western Gondwanan areas (Loboziak et al., 1988; Loboziak & Streel, 1989, 1995a), many of them represent useful zonal markers for the regional biozonation, because their ranges can be dated and calibrated by associated miospore species also present in southern Euramerica (Loboziak & Melo, 2002).

McGregor & Playford (1992) compared Canadian miospore assemblages with those from eastern Gondwana (Australia). They concluded that the degree of palynological parallelism implies cosmopolitanism in the Devonian land vegetation between Canada and Australia, and supports suggestions of geographic proximity between Euramerica and eastern Gondwana during Middle through Late Devonian time to allow considerable floristic interchange. However, they also focused on the incidence of certain endemic spore taxa, confined to either Canada or Australia, that signify some floristic provincialism or phytogeographic segregation.

Chapter 2 – Saudi Arabia

2.1. Introduction

Recently, Saudi Aramco drilled a number of fully cored shallow boreholes (BAQA-1, BAQA-2, JNDL-1, JNDL-3 and JNDL-4) in northwestern Saudi Arabia with the intention of studying the nature of the Devonian deposits of this area. These boreholes have been studied from a palynological point of view in order to establish a detailed biostratigraphy (Breuer et al., 2005b, 2007) and correlations with sections from eastern Saudi Arabia. Another cutting-sampled borehole (S-462) also has been investigated to complete palynological data of this region. In addition, 8 cored wells (ABSF-29, FWRH-1, HWYH-956, KHRM-2, NFLA-1, SDGM-462, UTMN-1830 and YBRN-1) from eastern Saudi Arabia have been examined to evaluate the lateral variation of the miospore assemblages. Palynology (particularly dispersed plant spores) is the primary tool used in biostratigraphical dating and correlation of the Devonian deposits of Arabia supplementing marine faunas that are confined to the Jauf Formation (e.g. Boucot, 1984; Boucot et al., 1989). To date, however, there are only relatively few publications which document the taxonomy and distribution of dispersed spores in the Devonian of Arabia (Hemer & Nygreen, 1967; Loboziak & Streel, 1995b; Steemans, 1995; Al-Hajri et al., 1999; Loboziak, 2000; Al-Ghazi, 2007; Breuer et al., 2007). Therefore, detailed miospore taxonomy was absolutely needed during this study (see Volume III).

2.2. Regional geological background

During the Devonian, the Arabian Plate formed part of the northern passive margin of Gondwana, and lay just in southern tropical latitudes (Beydoun, 1991). Much of Arabia was subaerially exposed, with shallow seas extending over the remaining area. Substantial Devonian deposits accumulated, essentially as broad transgressive-regressive cycles: a retrogradational cycle (fining-upward) encompassing the Tawil and Jauf Formations, and a progradational cycle (coarsening-upward) through much of the Jubah Formation (Sharland et al., 2001). In Saudi Arabia, Devonian sedimentary rocks are only known to be exposed in the type outcrop area of northwestern Saudi Arabia (Nafud Basin, previously Tabuk and Widyan Basins) and in the southwest (e.g. Wajid outcrop), adjacent to the exposed Precambrian Arabian Shield (Fig. 2.1). Most of Devonian deposits occur in subsurface, not only in the northwest but also in eastern Saudi Arabia.

2.3. Description of the studied sections

The Devonian strata of Saudi Arabia occur within a more or less conformable package of Late Silurian-earliest Carboniferous deposits, which are subdivided into the Tawil, Jauf and Jubah Formations (Steineke et al., 1958; Powers et al., 1966; Powers, 1968; Meissner et al., 1988) (Fig. 2.2). A regional disconformity separates this package from older (middle Silurian: Wenlock) deposits of the underlying Qalibah Formation. Regional unconformities also separate this package from younger strata above: either the pre-Unayzah Unconformity (from the Permo-Carboniferous Unayzah Formation) or the pre-Khuff Unconformity (from the Middle Permian Khuff Formation), particularly on structural highs such as the central Arabian

Arch and the Ghawar structure (Fig. 2.3). Current understanding of the ages of these deposits suggests that the oldest deposits of the Tawil Formation, occurring directly above the disconformity, are of Late Silurian (Ludlow-Pridoli) age, and the youngest parts of the formation are of Early Devonian (Pragian) age (Stump et al., 1995; Al-Hajri & Paris, 1998). The Jauf and Jubah Formations are usually Emsian to Frasnian in age, although it has recently been discovered that in places the Jubah Formation deposits extend up into the latest Famennian to earliest Tournaisian (Al-Hajri et al., 1999; Clayton et al., 2000).

These formations reflect, in order of succession, shifts in sedimentation from siliciclastics (Tawil Formation) to mixed siliciclastics and carbonates (Jauf Formation) and a return to siliclastics (Jubah Formation). The deposits of the Late Silurian-earliest Carboniferous package are generally continental to nearshore shallow marine. There are regional-scale facies changes. For example, the Jauf Formation changes from marine in northwestern Saudi Arabia to marginal marine/continental in central and southern regions (Al-Hajri et al., 1999; Al-Hajri & Owens, 2000) (Fig. 2.3).

Dispersed spores are the chief biostratigraphical tool utilized to date and correlate the deposits of the Tawil, Jauf and Jubah Formations (Al-Hajri et al., 1999). It should be noted, however, that the occurrence of rich spore assemblages is sporadic. In many of the extensive sandstone and limestone sequences, rich spore assemblages are only recovered from thin siltstone/shale intercalations. Furthermore, as one moves east, burial depths of the Devonian deposits increase, and high thermal maturation levels negatively affect preservation of palynomorphs. Additional biostratigraphical evidence is provided by other fossil groups collected at the surface exposures (e.g., Boucot et al., 1989; Forey et al., 1992). For example, trilobites and conodonts indicate that the uppermost Sha'iba and Qasr members (lower Jauf Formation) are Pragian-early Emsian in age and brachiopods suggest that the Hammamiyat Member (upper Jauf Formation) is late Emsian in age in northwestern Saudi Arabia.

The first part of this study concerns cored boreholes drilled as part of the Saudi Aramco shallow core investigation of the Devonian deposits of northwestern Saudi Arabia. The studied boreholes are mainly located in two distinct areas separated by about 350 km. Two boreholes (BAQA-1 and BAQA-2) are near Baq'a in the Nafud Basin, while the others (JNDL-1, JNDL-3 and JNDL-4) are located in the vicinity of Domat Al-Jandal also in the Nafud Basin (Fig. 2.4). Another cutting borehole (S-462) situated more in the north has been re-studied. The second part of this study is based on 8 cored wells (ABSF-29, HWYH-956, FWRH-1, KHRM-2, NFLA-1, SDGM-462, UTMN-1830 and YBRN-1) which are situated close to each other in eastern Saudi Arabia (Fig. 2.4).

All studied boreholes/wells were drilled across, from base to top, the Jauf and Jubah Formations. These lithological units have been described from outcrops as following.

2.3.1. Jauf Formation

Lithology

This lithostratigraphic unit crops out in northwestern Saudi Arabia (Powers et al., 1966; Powers, 1968). The formation is notably described in the explanatory notes of several geological maps where it is recognized (Vaslet et al., 1987; Wallace et al., 1996, 1997; Janjou et al., 1997a, 1997b; Lebret et al., 1999). The Jauf Formation in outcrop also was studied by Helal (1965), Bahafzallah et al. (1981), Al-Laboun (1982, 1986) and Al-Husseini & Matthews (2006). From a palaeontological point of view, the Jauf Formation was notably investigated for brachiopods (Boucot et al., 1989), fishes (Forey et al., 1992) and miospore assemblages in subsurface (Steemans, 1995; Al-Hajri et al., 1999). Over many structures and palaeo-highlands the formation is absent because of Late Palaeozoic uplift and erosion (Wender et al., 1998; Konert et al., 2001) (Fig. 2.3.). In eastern Saudi Arabia, the Jauf Formation is recognized only in the subsurface (e.g. Wender et al., 1998, Al-Hajri et al., 1999).

The formation ranges in thickness from 200-335 m in eastern Saudi Arabia to about 300-330 m in northwest Saudi Arabia. It overlies disconformably or unconformably the continental to shallow-marine Tawil Formation, and is unconformably overlaid with the continental Jubah Formation (Fig. 2.2). Although the shift from continental (Tawil) to marine (Jauf) sedimentation would presumably involve a hiatus, some authors state that the contact between the Jauf Formation and underlying Tawil Formation is conformable (e.g. Powers, 1968; Vaslet et al., 1987; Al-Hajri et al., 1999). Others declare that the Jauf Formation overlies the Tawil Formation in disconformity (Janjou et al., 1997a; Wallace et al., 1997) or unconformity (Wallace et al., 1996). Although the contacts between the Jauf and Jubah Formations appear to be conformable according to (Al-Hajri et al., 1999), the upper part of the Jauf Formation (Murayr Member) is unconformably overlaid with Jubah sandstone beds (Janjou et al., 1997a, Wallace et al., 1996, 1997). This major erosional boundary between the Murayr tidal sandstone and the Jubah fluviatile sandstone reflects an abrupt change in the sedimentary environment.

The alternating siliciclastics and carbonates of the Jauf Formation only in northwestern Saudi Arabia (Fig. 2.3) have been used to subdivide this formation into five members: the Sha'iba (oldest), Qasr, Subbat, Hammamiyat and Murayr (youngest) Members (Fig. 2.2). The five members constitute a conformable succession according to Wallace et al. (1996, 1997). Although the lithological character of the whole Jauf Formation changes little throughout the area of outcrop (northwestern Saudi Arabia), the different members are described according to the region where the studied boreholes cut through them.

- **Sha'iba Member**: This unit is only drilled by borehole BAQA-2. In the Baq'a quadrangle (Vaslet et al., 1987), the Sha'iba Member in outcrop is composed in the lower part of beige fine-grained sandstone sometimes with cross-bedding and reworked clay galls and plant remains. This sandstone interval is capped by a ferruginous surface. The interval above comprises green to red, micaceous silty claystone including rare pinkish, laminated, silty dolomite at the base. The two uppermost meters are composed of yellow to pinkish, lenticular dolomite intercalated with ochre, laminated, fine-grained sandstone and green, micaceous, silty claystone. Estimate of the thickness inside the Baq'a quadrangle in the Al Muyyah section is 26 m (Vaslet et al., 1987). In the Baq'a quadrangle, the contact between the Jauf and the underlying Tawil Formations is sharp and marked by a reworking of the palaeosol capping the Tawil sandstone and is conformable according to Vaslet et al. (1987).

- **Qasr Member**: This unit is drilled by boreholes BAQA-1 and BAQA-2. In the Baq'a quadrangle (Vaslet et al., 1987), the Qasr Member in outcrop is composed, in the lower part, of beige to grey, oolitic and stromatolitic dolomite with reworked clay galls at the base. The stromatolites show a columnar pattern. The overlying interval is brown, micaceous, clayey siltstone of 4 m in thickness. The uppermost 6 m comprises grey to yellowish, sparitized dolomite. Massive benches of very bioclastic facies with oolites at the top and more laminated facies near the base occur. Estimate of the thickness inside the Baq'a quadrangle in the Al Muyyah section is 14 m (Vaslet et al., 1987).

- **Subbat Member**: This unit is drilled by borehole BAQA-1 in Baq'a quadrangle and in borehole JNDL-4 in the Al-Jawf quadrangle. In the Baq'a quadrangle (Vaslet et al., 1987), the Subbat Member in outcrop is mainly composed of grey or white, fine-grained, commonly cross-bedded or laminated sandstone, intercalated with greenish silty claystone. In the lower part, a decimetre-sized layer of subbituminous coal occurs with abundant plant remains. In the Al-Jawf quadrangle (Wallace et al., 1997), the Subbat Member in outcrop is greyish-red, greyish-pink, maroon, greenish-grey, and greyish-green shale that contains detrital mica on bedding surfaces. Shale is silty and secondary gypsum veins are common. Interbedded greyish-red, grey, and reddish-grey sandstone beds range from several centimetres to 2 m in thickness. Near the top of the member, a prominent reddish-tan-weathering ripple-marked sandstone is about 2 m thick. Estimates of the thickness are 100 m (Helal, 1965; Vaslet et al., 1987), 113.4 m (Powers, 1968), or about 113 m (Boucot et al., 1989).

- **Hammamiyat Member**: This unit is drilled by boreholes JNDL-1 and JNDL-3. In the Al-Jawf quadrangle (Wallace et al., 1997), the Hammamiyat Member in outcrop is a zone of moderate grey-, tan-, or light-greyish-yellow-weathering, stromatolitic, finely crystalline limestone interbedded with shale. Helal (1965) and Boucot et al. (1989) described six limestone zones that range from 4-11 m in thickness, which are separated by light-grey, greyish-brown, and yellowish-brown shale and rare beds of grey, fine-grained sandstone. Stromatolites are as much as one meter in diameter and occur as laterally linked hemispheroids and as isolated heads that are 10-20 cm in diameter. The limestone beds from cliffs and laterally extensive dip slopes. Shale beds contain primary gypsum in thin layers and secondary gypsum fills fractures and joints. Estimates of the thickness in the Al-Jawf quadrangle are 118 m (Helal, 1965; Wallace et al., 1997), 106.3 m (Powers, 1968) or 105 m (Boucot et al., 1989).

- **Murayr Member**: This unit is drilled by borehole JNDL-3. The Murayr Member was previously named the 'transition zone member' (Powers, 1968) or the Fiy'adh Member (Al-Hajri et al., 1999). In the Al-Jawf quadrangle (Wallace et al., 1997), the Murayr Member in outcrop is light grey and light-greyish-brown and weathers to reddish-brown and greyish-brown sandstone. Sandstone, siltstone and shale beds are poorly indurated and weather to moderate-angle rubble-covered slopes. Sandstone is thinly bedded (2-8 cm), and contains ripple cross-lamination, planar lamination, rib-and-furrow structure, and small- and medium-scale crossbeds. Sandstone beds generally coarsen upward and are mostly medium-grained at the base and fine-grained in the upper part of the member; most grains are subangular and subrounded. The sandstone is micaceous and some beds contain fragments of fish bones. The shale and siltstone are light green to light tan, and these fine-grained rocks contain abundant secondary gypsum and one thin bed of chert. A gastropod coquina bed near the top of this unit was first described by Lozej (1983), and although only 2-3 cm thick, it is an easily recognizable marker bed near the top of the Murayr Member (Janjou et al., 1997a, b). Along the southern border of the quadrangle this coquina marker bed is absent and a yellowish-grey, sandy limestone (20 cm thick) occurs at about the same stratigraphic level below 2 m thick beds of greyish-green shale. Secondary gypsum occurs as veins in sandstone and shale. The Murayr Member is 33 m thick to the north of Domat Al-Jandal but thins near this locality.

Palaeontological data

The Sha'iba Member yielded brachiopods known from the Pragian and possibly also the Emsian. Abundant fish debris was also found and appears to confirm the early Pragian age of these beds (Janjou et al., 1997a). The Qasr Member contains abundant fish remains the range of which is from late Lochkovian to early Pragian (Janjou et al., 1997a). Boucot et al. (1989) also found in this unit conodonts indicative of middle Pragian to middle Emsian age and trilobites suggesting a 'Siegenian' to Emsian age span. The Subbat Member does not contain invertebrate fossils but one coarse-grained layer yielded rare undated vertebrate remains (Janjou et al., 1997a). The Hammamiyat Member is rich in vertebrate and invertebrate fossils, and contains notably several highly fossiliferous strata that yielded Emsian brachiopods (Bahafzallah et al., 1981; Boucot et al., 1989) accompanying bryozoans, gastropods, bivalves, cephalopods, crinoids, and fish debris of minor stratigraphic interest. Some fish spines of the Hammamiyat Member are known only from the Emsian to Givetian from Gondwana (Lelièvre et al., 1995). The Murayr Member comprises several layers rich in vertebrate remains, two taxa of which are known in the Middle to Late Devonian. Fragments of *Prototaxites*, which is a tree-like fungus that is restricted to Devonian age, were collected in place from the base through to the top of the Murayr Member. Remains of vascular plants (Psylophitales?) were also found in the clayey layers at the base of the member (Wallace et al., 1997). Finally, some faunas were thus collected from the many fossiliferous layers in the whole Jauf Formation. Boucot et al. (1989) who studied samples from the Qasr and Hammamiyat Members assigned a Pragian to early Emsian age to the Jauf Formation on the basis of brachiopods, trilobites, conodonts and fish remains. Forey et al. (1992) drew the same conclusion from fish remains found in the whole Jauf Formation. Janjou et al. (1997a) concluded that the collected faunas indicate an age ranging from Pragian (in the Sha'iba Member) to early to late Emsian (in the Hammamiyat Member); the Qasr Member being assigned to the Pragian. They stated that none of the vertebrate taxa found in the Jauf Formation is typically characteristic of the Eifelian.

As regards the palynology, Al-Hajri et al. (1999) identified recently D4A Subzone in samples from the lower part of the Jauf Formation and upper part of the underlying Tawil Formation in northwestern Saudi Arabia. This zone has an age range of early Pragian to late Emsian. These authors associated D3/D4 Palynozone with the lower part of the Jauf Formation in northwestern and eastern Saudi Arabia, and favour an Emsian age. They attributed the D3B Subzone, which is widespread in Arabia, to the Hammamiyat and possibly the Subbat Members, and suggested a likely late Emsian age. D3A Subzone is defined in the upper Jauf and lower Jubah Formations, and is suggested as late Emsian-early Eifelian. The Jauf Formation is correlated in subsurface to the Misfar Group in Oman (Hughes-Clarke, 1988) containing palynomorphs of late Emsian-early Eifelian age (Hughes & Clark, 1988; Al-Siyabi et al., 2001).

Depositional environment

The basal part of the Sha'iba Member was deposited in a transgressive, shallow-marine and nearshore setting of low local relief (Boucot et al., 1989). Siliciclastic lagoonal systems are confined marine environment which are characterized by claystones and thin sandstone bodies deposited at the mouth of distributary channels under a tidal influence. This environment succeeded fairly abruptly to the sand deltaic system of tidal influence of the upper part of the Tawil Formation. The basal discontinuity is marked by clayey oolitic ironstone that is interpreted as a transgression surface (Janjou et al., 1997a). At the top of the member, the association of ball-and-pillow structures and cross-stratitified sandstone beds containing fish remains, indicates a bay-type environment in which thin sandstone bodies accumulated either at the mouths of tidal distributary channels, or in sandy flats under mixed tidal and wave influences (Janjou et al., 1997a).

Then the clastic beds in the Qasr Member were deposited in deeper water than those of the Sha'iba Member (Boucot et al., 1989). Stromatolitic and oncolitic limestone beds represent deposition in a shallow-marine, subtidal environment in the photic zone. Beds containing fish remains may record brackish-water estuarine conditions (Boucot et al., 1989). Janjou et al. (1997a) interpreted the sediments of the Qasr Member to represent a carbonate lagoon environment in which clayey sedimentation was succeeded by stromatolitic carbonates characteristic of an environment relatively distant from terrigenous sediment sources. The progressive reduction in the influx of terrigenous material toward the top of the member may reflect a relative rise in sea level and led to the deposition of the stromatolitic carbonates.

Sedimentological analysis show that the deposits of the Subbat Member are mainly composed of three main facies (Al-Husseini & Matthews, 2006): At the base, an onlap facies (in crevasses) deposited in a period of sea-level fall, in the middle part, a channel-fill facies that may correspond to the period of maximum regression; An upper facies of meander-bar sandstone deposited under tidal influence; it may reflect the resumption of a transgressive trend that led to the deposition of the Hammamiyat Member. Boucot et al. (1989) interpreted the depositional environment of the Subbat Member to be shallow-marine and nearshore, in a region of low relief; in most respects, it was deposited in an environment similar to the Sha'iba Member. Janjou et al. (1997a) interpreted the Subbat Member to be deposited in a siliciclastic lagoonal system of principally clayey sedimentation overrun by meandering channels, and characterized by weak hydrodynamics and tidal influence. This type of environment is represented by various types of sandstone facies: channel-fill, meander bar, crevasse and onlap. Progradation of this terrigenous lagoon sequence over the marine carbonates of the Qasr Member represents a regressive phase that succeeded the first transgressive episode at the base of the Jauf Formation.

According to Boucot et al. (1989), the depositional environment of the Hammamiyat Member was shallow-marine and distant from shore and sources of clastic debris; muds and rare sand bars accumulated quickly in quiet water below wave base. Janjou et al. (1997a) characterized the great facies diversity of the Hammamiyat in terms of environment ranging from carbonate lagoon (dominant) to siliclastic tidal complexes. According to Al-Husseini & Matthews (2006), the Hammamiyat Member is subdivided into 6 units which correspond to the six cycles of regression and transgression already identified by Janjou et al. (1997a). According to Al-Husseini & Matthews (2006), the two lower units are principally carbonate and indicate maximum distance from the terrigenous source. These facies are typical of shoreface or lagoon environments. Units 3, 4 and 5 are composed of sandstone facies predominant over clayey facies. The base of the final unit 6 indicates a strong hydrodynamic system and increasing terrigenous input, followed by a predominance of clayey facies, and then by a return to dolomitic sedimentation.

Finally, the Murayr Member was deposited in a brackish and estuarine environment and the sandstone beds may represent beach deposits and estuarine channels (Boucot et al., 1989). Janjou et al. (1997a) interpreted the facies of the lower part of the Murayr Member to define depositional sequences of estuarine channel fill. The middle dolomitic layers represent transgressive fluctuations that replaced estuarine sedimentation by more-lagoonal deposition.

The uppermost sandstone beds indicate an environment having a strong hydrodynamic system and considerable terrigenous input, but nevertheless under tidal influence. The deposits of the Murayr Member were deposited by a regressive siliciclastic estuarine complex.

In contrast to the sandstones of the underlying Tawil and overlying Jubah Formations, the limestones of the Jauf Formation reflect thus clearly an open-marine depositional environment in northwestern Saudi Arabia. However the Jauf Formation changes from marine in northwestern Saudi Arabia to marginal marine/continental in central and southern regions (Al-Hajri et al., 1999; Al-Hajri and Owens, 2000) (Fig. 2.3). In the subsurface of eastern Saudi Arabia, Rahmani et al. (2002) divided the Jauf Formation into a lower member or Sequence S1 and middle and upper members both forming Sequence S2. The D3B Subzone (Al-Hajri et al., 1999) occurs in a mainly dark-coloured marker shale at the top of the transgressive system tract of Sequence S2 (Rahmani et al., 2002). Wender et al. (1998) suggested a similar interpretation in which the D3B marker was considered as a possible condensed section and maximum flooding interval. Rahmani et al. (2002) interpreted each of the two sequences of the Jauf Formation as third-order. They identified 16 fourth-order sequences in Sequence S1 and 15 more in Sequence S2. Sequence S1 probably corresponds to the Sha'iba, Qasr and lower Subbat Members. Sequence S2 may represent the Hammamiyat and Murayr Members. Rahmani (2004) described Sequence S1 as dominated by a falling stage systems tract (forced regressive shoreface) which prograded from west to east over a distance of 150-200 km. Sequence S2 comprises transgressive and highstand system tracts.

Al -Husseini & Matthews (2006) demonstrated that the deposition of the Jauf Formation in outcrop corresponds to a second-order transgressive-regressive cycle and manifests several stratigraphic elements that can be interpreted in terms of third- and fourth-order orbital cycles (Fig. 2.5). Al-Husseini & Matthews (2005) calibrated a periodic second-order sequence stratigraphic framework for the Arabian Phanerozoic succession on the basis of a simplified orbital-forcing model of sea-level. In this framework, each second-order depositional sequence (denoted DS^2) was deposited during a constant period of approximately 14.58 million years (my). The Jauf Formation corresponds to the 28th sequence (DS^2 28) and was deposited between second-order sequence boundaries (denoted SB^2) that coincide with the Jauf/Tawil Formation boundary (SB^2 28 at 407.6 my) and Jubah/Jauf Formation boundary (SB^2 27 at 393.0 my). The second-order cycle can be characterized in terms of an initial flood (Qasr Member), followed by a more regional flood (Hammamiyat Member). The Hammamiyat flood is recognized across Saudi Arabia by the D3B Subzone (Al-Hajri et al., 1999). The 6 units of the Hammamiyat Member appear to be fourth-order cycles and could constitute a third-order deposition sequence according to Al-Husseini & Matthews (2006). The lower units 1 and 2, which are principally carbonate, represent maximum transgression in the Jauf Formation. The upper units 3-6 represent the start of the second-order regression that gave way to the final regression (Murayr Member). A first major sequence may be represented by the Sha'iba, Qasr and the lower part of the Subbat Members. It may be a double third-order sequence which corresponds probably in subsurface to Sequence S1 of Rahmani et al. (2002). The rest of the Jauf Formation may represent 4 third-order sequences and probably corresponds to the Sequence S2 of Rahmani et al. (2002).

2.3.2. Jubah Formation

Lithology

These strata were previously designated as the Sakaka sandstone (Bramkamp et al., 1963; Bahafzallah, 1981; Powers, 1968), Wasia Group (Powers, 1968) and the Wasia and Biyadh Formations (Lozej, 1983); ages as different as Devonian and Cretaceous were assigned to them. This lithostratigraphic unit appears in outcrop in northwestern Saudi Arabia. The formation is notably described in the explanatory notes of several geological maps where it crops out (e.g. Wallace et al., 1996, 1997; Janjou et al., 1997b). In eastern Saudi Arabia, the Jubah Formation is recognized only in the subsurface (e.g. Wender et al., 1998, Al-Hajri et al., 1999). Over many structures and palaeo-highlands the formation is absent because of Late Palaeozoic uplift and erosion, as the Jauf Formation (Wender et al., 1998; Konert et al., 2001).

The formation ranges in thickness in surface exposure from about 220 m (Meissner et al., 1989) to 250 m (Wallace et al., 1997), and thickens toward the northeast according to Meissner et al. (1986). Borehole S-462 penetrated, at least, more than 400 m of the Jubah Formation. The Jubah Formation overlies unconformably the Jauf Formation (Janjou et al., 1997a, Wallace et al., 1996, 1997). This erosional boundary between the Jauf and Jubah Formations reflects an abrupt change in the sedimentary environment. The disconformable top of the Jubah Formation is placed above the *Prototaxites*-bearing sandstones and above the uppermost occurrences of fish remains (Wallace et al., 1996, 1997).

In northwestern Saudi Arabia, this unit is drilled by boreholes JNDL-1 and S-462. In the Al-Jawf quadrangle and Ash Shuwahitiyah quadrangles (Wallace et al., 1996, 1997), the Jubah Formation in outcrop is mostly medium and coarse-grained sandstone composed of subrounded and rounded quartz grains, and rare beds of light green and yellowish-green-weathering shale and silty shale. The lower part of this unit is light grey, and contains light and dark minerals grains that give it a 'salt and pepper' appearance. The upper part consists of interbedded sandstone and some beds of silty shale and mudstone. The fresh surfaces of the sandstone are light-grey and the weathered surfaces are brown and reddish brown. The sandstone is fine to coarse-grained, and locally contains quartz-pebble conglomerate. Ferruginous and manganiferous cement and grain coatings are common and mica occurs on bedding planes. Most of the sandstone is medium- to thick-bedded, and medium- and small-scale planar and through crossbeds are common. At some levels, sandstone beds contain abundant animal burrows. Lenticular interbeds of grey, light-green, and greyish-lavender shale and mudstone contain matrix-supported silt and sand.

Palaeontological data

The most common fossil in the Jubah Formation is *Prototaxites*, but plates and bones of fish also occur locally (Forey et al., 1992). These are typical of fresh-water environment and suggest a Middle Devonian age (Forey et al., 1992; Wallace et al., 1996, 1997). According to Al-Hajri et al. (1999), D2 Palynozone occurs in the lower and middle Jubah Formation and includes palynoflora recovered from the base of Jubah Formation is considered as late Eifelian.

Depositional environment

Crossbedding and fish remains suggest that the Jubah Formation was deposited in brackish water of delta channels or in a fluvial environment near the strandline (Wallace et al., 1996, 1997).

2.4. Review of Devonian miospore palynological studies in Saudi Arabia

Fig. 2.6 compares Devonian miospore biozonations defined and/or applied in the different studies. Hemer & Nygreen (1967) were the first to report on spore assemblages from the Devonian of Saudi Arabia. These were from core and cutting samples of a 1341 ft Devonian sequence in borehole S-462 in northern Saudi Arabia. They assumed that this interval represented a non-marine extension of the Jauf Formation present in outcrops some 70 km away (but now considered as part of the Jubah Formation, see below). Based on spore assemblages they subdivided the strata into four zones: Zone I (1465-1670 ft, Upper Devonian assemblage); Zone II (1670-1940 ft, Upper Devonian); Zone III (1940-2300 ft, Middle Devonian); Zone IV (2700-2750 ft, probably Givetian, lower diversity assemblage in sandy facies).

Loboziak & Streel (1995b) examined Devonian cuttings from borehole TRBH-1 also in northern Saudi Arabia, with additional data from wells DMMM-45 and SDGM-211 from eastern Saudi Arabia. Based on taxa common to the Euramerican region, they applied the Devonian spore zonation developed in Western Europe by Streel et al. (1987). In all three wells, they assigned the spore assemblages from the uppermost Tawil and lower Jauf formations to the AB-FD Oppel Zone range (Emsian age). Higher in the sequence, in the Subbat Member of the Jauf Formation in TRBH-1 and DMMM-45, they recognized the FD (Min) and AP Oppel Zones (late Emsian age). Few characteristic spore taxa occurred above this latter zone in the Jubah Formation and Loboziak & Streel (1995b) considered these strata to belong to an undifferentiated AP-AD Oppel Zone range (latest Emsian to early Givetian). Stratigraphically above this, in TRBH-1, assemblages they assigned to the AD (Lem) and TA Oppel Zones (Givetian) occur.

Steemans (1995) published reports of Devonian spore assemblages from cuttings in wells DMMM-45 and UDYN-1. In DMMM-45, the miospores were recovered from the lower part of the Tawil Formation and assigned to the MN, BZ and PoW (W and Pa) Oppel Zones (Lochkovian to Pragian). Those recovered from the Jauf Formation were assigned to the AB Oppel Zone (Emsian). In UDYN-1, Steemans (1995) reported Lochkovian spore assemblages from the Tawil Formation (MN-R Interval Zone) and Givetian-Frasnian spore assemblages from the upper Tawil to lower Jauf Formations.

Al-Hajri et al. (1999) provided a detailed operational palynological zonation developed by Saudi Aramco for Devonian strata of Saudi Arabia. Because it was developed for oil industry application, and based largely on cutting samples, this zonation uses primarily first down-hole occurrences of taxa (i.e., extinctions), although it also considers first common down-hole occurrences/co-occurrences, and acme zones. The scheme consists of six zones and four subzones, from top to base: D0, D1, D2, D3A, D3B, D3/D4, D4A, and D4B. These were age-calibrated based on comparisons with the established spore zonation schemes of Richardson

& McGregor (1986) and Streel et al. (1987), that were both established in the Euramerican Old Red Sandstone Continent and the Ardenne-Rhenish region, respectively.

From the same sequence/borehole studied by Hemer & Nygreen (1967) (see above), Loboziak (2000) described spore assemblages from Jubah Formation cuttings of borehole S-462 from northern Saudi Arabia over the interval 1465 ft to 2806 ft. The oldest assemblages were interpreted to be of late early Eifelian age and the youngest of late early Frasnian age, based on comparisons with the spore biostratigraphy scheme developed by Streel et al. (1987).

Clayton et al. (2000) described latest Devonian-earliest Carboniferous spore assemblages from the uppermost Jubah Formation in wells of eastern Saudi Arabia. In HRML-51, Strunian assemblages characterized by *Retispora lepidophyta* were recovered (D0 Palynozone of Al-Hajri et al., 1999). Latest Famennian and earliest Tournaisian assemblages in ABSF-29 were referred to the '*Verruciretusispora famennensis* Assemblage' and the '*Indotriradites explanatus* Assemblage', respectively. This work clearly demonstrates that in places the Jubah Formation extends into the Carboniferous.

2.5. Palynological results in northwestern Saudi Arabia

Samples from BAQA-1, BAQA-2, JNDL-3 and JNDL-4 were prepared in the Palynological Research Facility of the University of Sheffield whereas these from JNDL-1 were processed in the laboratory of 'Paléobotanique, Palynologie et Micropaléontologie' of the University of Liège. All the 188 samples were prepared using standard palynological acid maceration techniques (see 1.3). The vast majority of samples were productive, yielding palynomorphs that are well preserved and of low thermal maturity (T.A.I. ca. 2). Because of the low thermal maturity, oxidation of the organic material was not required.

2.5.1. Borehole BAQA-1

Baq'a-1 (BAQA-1) was drilled by Saudi Aramco and is situated in northwestern Saudi Arabia in the Nafud Basin (Fig. 2.4). It is here studied between 416.6 ft and 169.1 ft, including 18 productive samples. The samples are shared between the Qasr and Subbat Members of the Jauf Formation. The boundary between the two members is situated at about 393 ft.

Palynological data

In all samples, the palynological material is well-preserved. Miospores or leiospheres predominate the assemblages. Acritarchs with appendages can locally be present in large amount. Rare scolecodonts, *incertae sedis* representing probably algal cysts for most of them and fungi spore also occur locally. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.1 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.7 to 2.11.

The samples 416.6' to 406.0' in the limestone Qasr Member are dominated by leiospheres, although sculptured acritarchs represent up to 40% of the whole palynological assemblage in the sample 408.3' (Fig. 2.8). In this interval, the characteristic of the miospore assemblage is difficult to interpret because miospore specimens are rare in the slides. The miospores become predominant from the sample 399.0' up to the top of the section. The total amount of acritarch rises once up to 36% of the whole palynological assemblage at 345.5' (Fig. 2.8). The dominant type of structure is the uniform thickness of the exine for the majority of miospores (Fig. 2.11). From the sample 399.0', the simple spores sculptured with discrete elements (mainly *Apiculiretusispora*) increase progressively whereas the simple laevigate spores (*Retusotriletes*), the reticulate/foveolate spores (e.g. *Brochotriletes* and *Dictyotriletes*) and the radial-patterned spores (*Emphanisporites*) show the opposite trend (Figs 2.9 and 2.11). Specimens of *Artemopyra* first occur from the sample 371.1'. *Biornatispora* are restricted from 399.0' to 345.5'. Specimens of *Verrucosisporites* become less common towards the top of the section. Another interesting characteristic feature of these assemblages is the large amount of *Synorisporites papillensis* (cingulate and papillate spore) between samples 376.4' and 366.9' (Fig. 2.8).

The diversity seems to be low in the leiosphere-rich assemblages (Figs 2.9, 2.10 and 2.11) and decreases towards the top of the section in miospore-rich palynofacies. The number of different miospore taxa recognized per sample varies from two in the leiosphere-rich assemblages to 39 for the richest sample at 395.2'. Trilete spores dominate the miospore assemblages. The cryptospores constitute a significant part of the miospore assemblages all along the section and have their acme in the sample 345.5' where they represent up to 22% of the whole miospore assemblage. The great proportion of cryptospore in the sample 408.3' may be caused by the paucity in miospore specimens and may not be representative (Figs 2.7 and 2.10).

The cosmopolitan species dominate the miospore assemblages. Except the sample 416.6' where the interpretation is biased by the low diversity, the abundance of the typical endemic Gondwanan species shows a decrease (Fig. 2.11).

Comparisons with other assemblages

The index species of Euramerica recognized in the section are *Dictyotriletes emsiensis*, *D. subgranifer* and *Verrucosisporites polygonalis* (Fig. 2.7), indicating the *polygonalis-emsiensis* Assemblage Zone of Richardson & McGregor (1986) and the Su Interval Zone of Streel et al. (1987). These spore assemblages are typical of a late Pragian-early Emsian age.

2.5.2. Borehole BAQA-2

Baq'a-2 (BAQA-2) was drilled by Saudi Aramco and is situated in northwestern Saudi Arabia in the Nafud Basin (Fig. 2.4). It is here studied between 134.4 ft and 50.2 ft, including 9 productive samples. All samples come from the Sha'iba Member of the Jauf Formation. The base of the Jauf Formation is located at 154.4 ft and the boundary of the Sha'iba and the Qasr Members at 45 ft.

Palynological data

In all samples, the palynological material is well-preserved. Miospores predominate the assemblages however acritarchs may be numerous locally. *Incertae sedis* representing probably algal cysts for most of them can also be found. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.2 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.12 to 2.16.

The palynological assemblages are dominated by miospores (Fig. 2.12). Sculptured acritarchs or leiospheres are locally abundant and even constitute almost half of the whole palynological assemblage in the sample 133.0' (Fig. 2.13). The miospores of this section are mainly simple laevigate spores (*Retusotriletes*), simple spores sculptured with discrete elements (mainly *Apiculiretusispora* and *Cymbohilates*) and papillate spores (mainly *Synorisporites papillensis*) (Fig. 2.14 and 2.15). These simple forms are mainly of uniform thickness or cingulate spores (Fig. 2.16). Zonate and cavate spores already occur with *Lycospora culpa*, *Cirratriradites diaphanus* and *Leiozosterospora* cf. *L. andersonii*. The abundance of numerous genera and morphological groups is more or less constant all along the section. On the contrary, specimens of *Gneudnaspora* and *Retusotriletes* increase towards the top of the Sha'iba Member whereas the simple spores sculptured with discrete elements which are dominated by *Apiculiretusispora* decreases to the top (Fig. 2.14 and 2.15).

The diversity, after decreasing, increases again in the upper part of the section (Figs 2.14, 2.15 and 2.16). The number of different miospore taxa recognized per sample varies from 15 to 33 for the richest samples at the top of the Sha'iba Member. Trilete spores dominate the miospore assemblages. The cryptospores (*Cymbohilates* and *Gneudnaspora*) constitute a significant part of the miospore assemblages all along the section and increase up to represent 21% of the whole miospore assemblage in the sample 50.2' (Figs 2.14 and 2.15). Monolete spores first appear in the upper part of the Sha'iba Member (Figs 2.12 and 2.15).

The cosmopolitan species dominate the miospore assemblages. Note that the typical endemic Gondwanan species show a slight increase towards the top of the Sha'iba Member (Fig. 2.16).

Comparisons with other assemblages

The oldest spore assemblages from the lower part of the Sha'iba Member are considered to belong to the *polygonalis-emsiensis* Assemblage Zone of Richardson & McGregor (1986) and the PoW Oppel Zone of Streel et al. (1987), based on the general characteristics of the assemblages and the presence of characteristic taxa such as *Brochotriletes foveolatus*, *Clivosispora verrucata*, *Dictyotriletes emsiensis*, *D. subgranifer* and *Verrucosisporites polygonalis* (Fig. 2.12). The presence of *D. subgranifer* may indicate that they belong to the uppermost interval zone (Su Interval Zone) of the PoW Oppel Zone. The PoW Oppel Zone is of Pragian-earliest Emsian age, with the Su Interval Zone straddling the latest Pragian-earliest Emsian. Since no taxa Emsian characteristic are recorded, the oldest spore assemblage from the Sha'iba Member is rather considered of late Pragian. The samples from 64.5' to 50.2' constitute a homogeneous assemblage with the first occurrence of *Dictyotriletes biornatus* Morphon, *Gneudnaspora divellomedia* var. *divellomedia* and the first simple monolete spore, *Latosporites ovalis*. This occurrence is particularly interesting as it represents one of the earliest reports of a monolete spore because the oldest monolete spores were not older than Emsian according to Traverse (2007).

2.5.3. Borehole JNDL-1

Domat Al-Jandal-1 (JNDL-1) was drilled by Saudi Aramco in the vicinity of Domat Al-Jandal in the Nafud Basin (Fig. 2.4). It is here studied between 495.0 ft and 153.8 ft, including 10 productive samples. All samples come from the Jubah Formation. Sample 495.0’ is situated just above the boundary between the Jauf and Jubah Formations.

Palynological data

In all samples, the palynological material is well-preserved. Miospores dominate the assemblages. Acritarchs with appendages, leiospheres, algal spores (*Quadrisporites*) and *incertae sedis* representing probably algal cysts occur locally in minority. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.3 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.17 to 2.21.

All palynological assemblages are predominated by miospores (Fig. 2.17). The lowermost sample at 495.0’ is dominated by simple laevigate spores (*Retusotriletes*) and simple spores sculptured with discrete elements (*Acinosporites*, *Apiculiretusispora* and *Dibolisporites*). The reticulate/foveolate (*Brochotriletes* sp. 2), cavate (*Geminospora* sp. 1 and *Rhabdosporites minutus*) and zonate spores (*Zonotriletes* sp. 1) are rare (Figs 2.19 and 2.20). The simple forms have generally an exine of uniform thickness (Fig. 2.21). A large gap in recovery follows, with the next spore assemblages being from the middle part of the Jubah Formation. There is a distinct change in the nature of the spore assemblages. The spore assemblages from the middle part of the Jubah Formation are distinctive and very different from those lower in the sequence. They include notably lots of *Emphanisporites* specimens and more diversified zonate-pseudosaccate (*Grandispora*, *Samarisporites*, *Zonotriletes*) and cavate spores (*Acinosporites* sp. 1, *Geminospora svalbardiae*) to the detriment of simple sculptured spores (e.g. *Acinosporites*, *Apiculiretusispora*, *Dibolisporites* and *Verrucosisporites*) (Figs 2.19 and 2.20).

The diversity is commonly high for the section except for the two uppermost samples (154.5’ and 153.8’) where it decreases strongly (Figs 2.19, 2.20 and 2.21). These are poorer in organic matter. The number of different miospore taxa recognized per sample varies from 15 to 42 for the richest sample at 174.6’. Trilete spores dominate the miospore assemblages. The cryptospores (mainly *Artemopyra* and *Gneudnaspora*) constitute only a significant proportion of the miospore assemblages in the uppermost part of the section where they may represent up to 22% of the whole miospore assemblage in the sample 155.6’ (Fig. 2.20).

The cosmopolitan species dominate the miospore assemblages in all assemblages. The typical endemic Gondwanan species are rare in the sample 495.0’ and are clearly more numerous in the uppermost assemblages where they may represent up to more than a quarter of the miospore assemblages (Fig. 2.21). Their decrease in the two uppermost samples (154.5’ and 153.8’) can be explained by a lower diversity of the assemblages coupled with paucity in specimens of the samples.

Comparisons with other assemblages

In the lowermost part of the Jubah Formation, *Acinosporites apiculatus* and *Grandispora protea* first appear (Fig. 2.17) and indicate the AP Oppel Zone (Pro Interval Zone) of Streel et al. (1987). This biozone is dated as latest Emsian to earliest Eifelian. A number of distinctive species the last occurrence of which are commonly restricted to Emsian strata in the literature make their last appearance in this sample such as *Amicosporites streelii*, *Clivosispora verrucata*, *Emphanisporites decoratus*, and *Verrucosisporites polygonalis*. Consequently the lowermost part of the Jubah Formation is likely latest Emsian in age. The assemblages from the middle part of the Jubah Formation contain the *Grandispora velata* (Fig. 2.17) which is the index species of the *velata-langii* Assemblage Zone of Richardson & McGregor (1986) and the Vel Interval Zone of Streel et al. (1987). In addition, many other zonate-pseudosaccate spores (e.g. *Grandispora douglastownense*, *Samarisporites eximius*, *Zonotriletes armillatus* and *Z. simplicissimus*) occur. *Geminospora svalbardiae* which was wrongly identified as *Geminospora lemurata* in Breuer et al. (2007) is also present. This type of assemblage is typical of a late early-middle Eifelian age.

2.5.4. Borehole JNDL-3

Domat Al-Jandal-3 (JNDL-3) was drilled by Saudi Aramco in the vicinity of Domat Al-Jandal in the Nafud Basin (Fig. 2.4). It is here studied between 499.5 ft and 225.7 ft, including 31 productive samples. All samples come from the Hammamiyat and Murayr Members of the Jauf Formation. The base of the Jubah Formation is situated just above the uppermost sample at about 225 ft.

Palynological data

In all samples, the palynological material is well-preserved. Miospores or leiospheres dominate alternatively the assemblages. Acritarchs with appendages, algal spores (*Quadrisporites*) and scolecodonts can also be found in minority. Large amounts of *incertae sedis* representing probably algal cysts occur locally. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.4 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.22 to 2.26.

The section is characterized by an alternation of leiosphere-rich and miospore-rich intervals (Figs 2.22 and 2.23). These leiosphere-rich assemblages are dominated by a single sphaeromorph taxon. The miospore assemblages comprise mainly simple laevigate spores (*Retusotriletes*), simple sculptured spores (*Apiculiretusispora*, *Cymbosporites* and *Dibolisporites*) and radial-patterned spores (*Emphanisporites*) (Figs 2.24 and 2.25). The main species represent simple spores of uniform thickness or patinate forms (Fig. 2.26). The other miospore groups are rarer and/or occur sporadically. *Cymbosporites* is mainly characteristic of the middle part of the section, whereas *Dibolisporites* increases from the middle part. Specimens of *Artemopyra* appear in the second part of the borehole whereas the cavate sculptured spores (*Rhabdosporites minutus*) is only present in the lower part as the reticulate/foveolate spores (e.g. *Brochotriletes* and *Dictyotriletes*) (Figs 2.24 and 2.25).

The mean diversity is not especially high for well-preserved organic matter. The number of different miospore taxa recognized per sample varies from four in the leiosphere-rich assemblages to 21 for the richest sample. The general trend of the diversity is more or less constant from base to top. It decreases momentarily with the occurrence of the leiosphere-rich assemblages (Figs 2.24, 2.25 and 2.26). Trilete spores dominate the miospore assemblages. The cryptospores dominated by *Gneudnaspora* specimens occur above all in the miospore-rich assemblages, notably between the samples 389.0’ to 341.0’. Monolete spores are rare as usually. The great proportion of cryptospore in the lowermost part of the borehole may be caused by the paucity in miospore specimens and may not be representative (Figs 2.22 and 2.25).

The typical endemic Gondwanan species displays the same trend as the cryptospores and thus are above all numerous in specimens in miospore-rich assemblages (Fig. 2.26).

Comparisons with other assemblages

An important inception is the first appearance of *Rhabdosporites minutus* at the base of this section (Fig. 2.22). In Euramerica this taxon first appears in the FD Oppel Zone (Min Interval Zone) of Streel et al. (1987). That corresponds to a middle-late Emsian age. Not far above this, in the sample 466.6’, the stratigraphically important spore *Camarozonotriletes sextantii* first appears (Fig. 2.22). In the spore biostratigraphic scheme of Richardson and McGregor (1986), *C. sextantii* is a nominal species for the *annulatus-sextantii* Assemblage Zone of early (but not earliest) to early late Emsian age. These authors note the sporadic occurrence of this taxon: in some sequences it is abundant but in others it is extremely rare. Its inception is variable and its occurrence is intermittent. Thus the presence of *C. sextantii* is consistent with an assignment to the Min Interval Zone and a middle-late Emsian age. The spore assemblages are essentially similar throughout the remainder of the sampled section. In addition, the D3B Subzone of Al-Hajri et al. (1999), which is marked by the sudden abundance of a monospecific leiospherid (sphaeromorph), is recognized all along the section. It appears here as a series of pulses regularly interrupted by a return to more continental palynofacies (miospore-rich assemblages).

2.5.5. Borehole JNDL-4

Domat Al-Jandal-4 (JNDL-4) was drilled by Saudi Aramco in the vicinity of Domat Al-Jandal in the Nafud Basin (Fig. 2.4). It is here studied between 499.1 ft and 37.1 ft, including 64 productive samples. All samples come from the Subbat and the Hammamiyat Members of the Jauf Formation. The base of the Subbat Member is not reached by the borehole. The Subbat/Hammamiyat boundary is situated at about 337 ft.

Palynological data

In all samples, the palynological material is well-preserved. Miospores or leiospheres dominate alternatively the assemblages. Acritarchs with appendages, algal spores (*Quadrisporites*) and scolecodonts are generally also found in minority. Large amounts of *incertae sedis* representing probably algal cysts occur locally. One chitinozoan-rich level occurs between 163.7 ft and 165.8 ft. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.5 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.27 to 2.31.

The Subbat Member is characterized by miospore-rich assemblage whereas the Hammamiyat displays an alternation of leiosphere-rich and miospore-rich intervals (Figs 2.27 and 2.28). The miospore assemblages comprise mainly simple laevigate spores (*Retusotriletes*), simple spores sculptured spores (mainly *Apiculiretusispora*, *Cymbosporites* and *Dibolisporites*) and radial-patterned spores (*Emphanisporites*) (Figs 2.29 and 2.30). The main species represent simple spores of uniform thickness or patinate forms and have constant trend all along the section (Fig. 2.31). The other miospore groups are rarer and/or occur sporadically. *Dibolisporites* show a net increase from the lower part of the Hammamiyat Member. First specimens of *Acinosporites* (*A. lindlarensis*) appear in the second part of the Subbat Member as the cavate sculptured spores (*Rhabdosporites minutus*) whereas the reticulate/foveolate (*Brochotriletes* and *Dictyotriletes*) and convolute/rugulate spores are more numerous in the lower part of the section (Figs 2.29 and 2.30).

The mean diversity is not very high for well-preserved organic matter. The number of different miospore taxa recognized per sample varies from 3 in the leiosphere-rich assemblages to 24 for the richest sample. The general trend of the diversity is a slight decrease from the base of the siliclastics to the limestones. In details, it decreases momentarily with the occurrence of the leiosphere-rich assemblages (Figs 2.29, 2.30 and 2.31). Trilete spores dominate the miospore assemblages. The cryptospores dominated are significantly present in the Subbat Member and in the miospore-rich assemblages of the Hammamiyat Member (Fig. 2.27). *Gneudnaspora* specimens occur above all in the miospore-rich assemblages, notably between the samples 389.0’ to 341.0’. Monolete spores are rare as usually. *Cymbohilates* seems to be preferentially more characteristic of the siliclastics from the Subbat Member whereas *Artemopyra* and *Gneudnaspora* are more numerous in the limestone interval of the Hammamiyat Member (Fig. 2.29).

The proportion of the typical endemic Gondwanan species is relatively constant along the section (Fig. 2.31).

Comparisons with other assemblages

In the Subbat Member, *Dictyotriletes subgranifer* is the only index species from Euramerican biozonations recognized here. However, the co-occurrence of some stratigraphically important spores such as *Apiculiretusispora brandtii and Acinosporites lindlarensis* (from the sample 404.8’) indicates an undifferentiated Emsian age. *Rhabdosporites minutus* first occurs from the sample 346.3’ just below the base of the Hammamiyat Member (Fig. 2.27). The Min Interval Zone of Streel et al. (1987) is consequently recognized up to top of the section and is characteristic of a middle-late Emsian age. The presence of *Camarozonotriletes sextantii* in the middle part of the Hammamiyat Member (Fig. 2.27) is consistent with an assignment to the Min Interval Zone and the *annulatus-sextantii* Assemblage Zone of Richardson & McGregor (1986). In addition, the D3B Subzone of Al-Hajri et al. (1999) is recognized from the base of the Hammamiyat Member to the top of the section. Like in borehole JNDL-3, it appears as a series of leiosphere-rich assemblage pulses alternating with normal spore-rich assemblages.

2.5.6. Borehole S-462

S-462 was drilled by Saudi Aramco in the Nafud Basin, 80 km northeast of the Jauf Formation type section (Fig. 2.4). This borehole was studied at first by Hemer & Nygreen (1967) and then by Loboziak (2000) (see 2.4). It is here re-studied from 2800 ft to 1475 ft, including 29 cutting samples. The base of the Jubah Formation is not reached by the borehole and the upper part is overlaid unconformably by the Cretaceous Wasia Group. All samples come from the Jubah Formation. New palynological slides were processed by using standard palynological acid maceration techniques.

Palynological data

In all samples, the palynological material is well-preserved. Miospores dominate totally the assemblages. Note that megaspores are abundant all along the section. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.6 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section is plotted in Fig. 2.32. The other types of charts illustrating the relative abundance of the different palynological group are not presented here. They are difficult to interpret, as samples of borehole S-462 are cuttings. Indeed, organic material can be caved during drilling implying disruption to the real succession of the different miospore forms (see 1.5.3).

The miospore assemblages are dominated notably by the cavate and zonate sculptured spores (*Geminospora*, *Grandispora*, *Rhabdosporites* and *Samarisporites*), and simple spores sculptured with discrete elements (*Acinosporites*, *Apiculiretusispora*, *Camarozonotriletes*, *Cymbosporites* and *Dibolisporites*). Some of the latter (*Acinosporites*, *Camarozonotriletes* and *Dibolisporites*) and the radial-patterned spores (*Emphanisporites* and *Scylaspora*) are rarer in the upper part of the section. Zonate laevigate spores are only present in 2615’ and cavate laevigate spores are above all characteristic of the uppermost part of the section. The number of different taxa recognized per sample varies from six to 22. Trilete spores dominate the miospore assemblages. The cryptospores appear from time to time. The studied megaspores *Contagisporites optivus* and *Verrucisporites ellesmerensis* are present from 2265’ to 1715’ (Fig. 2.32). Many unidentified megaspores are abundant all along the section but they have not been studied in this work.

Comparisons with other assemblages

Because of problems related to downhole caving, first occurrences of stratigraphically important taxa must be considered with caution; therefore the biozonation proposed herein must be regarded as still provisional.

Despite the absence of index species, the lowermost sample (2800’) could correspond to the *devonicus-naumovii* Assemblage Zone of Richardson & McGregor (1986) and the AD-pre Lem Oppel Zone of Streel et al. (1987) because no *Geminospora lemurata* is recognized. At the minimum the base of the Lem Interval Zone would be situated at 2765’, the TA Oppel Zone marked here by *Samarisporites triangulatus* at 2665’ and the TCo Oppel Zone recognized because of *Chelinospora concinna* at 2465’. The presence higher of taxa typical of their respective biozones proves the probable caving of the index species of Streel et al. (1987). *Scylaspora rugulata* which is known from the AD to TA Oppel Zone in the literature seems to indicate that the Lem Interval Zone is situated higher than 2765’. The short range here of *Contagisporites optivus* demonstrate that the base of TA Oppel Zone would rather placed at about 2265’. The presence of *Ancyrospora langii* from 1915’ could demonstrate that the base of the TCo Oppel Zone is situated at the minimum at about 1915’. As the uppermost part of the section is very poor in characteristic species, it could belong to the TCo Oppel Zone or another younger biozone. As conclusions, the base of the borehole would be late Eifelian and the rest could extend in the almost whole Givetian. Indeed, the uppermost part of the section could be late Givetian, as no Frasnian typical species occur.

In comparison with the results of Loboziak (2000), there are some minor differences. The common recognized species do not show exactly the same stratigraphic ranges, this author though that the investigated interval ranges from the late early Eifelian (AP/AD Oppel Zones of Streel et al., 1987) to the late early Frasnian (BJ/BM Oppel Zones of Streel et al., 1987). Indeed in the same investigated upper part of the section, he found the typical Frasnian species *Geminospora piliformis* and *Hystricosporites blessii*, which have not been identified in this work. He placed the base of the Lem Interval Zone and TA Oppel Zone of Streel et al. (1987) respectively, at 2440’ and 2120’ or 2020’. The base of the Frasnian would be situated at about 1900’.

2.6. Palynological results in eastern Saudi Arabia

All the 164 samples from eastern Saudi sections were prepared in the laboratory of ‘Paléobotanique, Palynologie et Micropaléontologie’ of the University of Liège by using standard palynological acid maceration techniques (see 1.3). Among them, 85 were productive, yielding palynomorphs that are moderately to poorly-preserved, and of higher thermal maturity. Indeed the eastern Saudi sections are markedly deeper than northwestern Saudi sections. Because of the high thermal maturity, oxidation of the organic material was sometimes required.

2.6.1. Well ABSF-29

Abu Safah-29 (ABSF-29) was drilled by Saudi Aramco in the Arabic Gulf, 530 km northeast of Riyadh (Fig. 2.4). Clayton et al. (2000) already studied this well from 15587.5 ft to 15289.5 ft in the upper part of the Jubah Formation where latest Devonian to Early Carboniferous miospore assemblages were recognized. ABSF-29 is here studied between 16794.3 ft and 16327.6 ft, including 12 productive samples. The lowermost samples come from the upper part of the Jauf Formation and the uppermost ones from the Jubah Formation. Consequently a sampling gap of about 400 ft in thickness separates the two groups of samples. The base of the Jauf Formation is located at 16983 ft. The boundary between the Jauf and Jubah Formations is situated at 16640 ft. The Jubah Formation is here overlaid unconformably by the Berwath Formation.

Palynological data

In all samples, the palynological material is poorly-preserved, and of high thermal maturity. Thus miospores are not easily determinable. Miospores or acritarchs dominate alternatively the assemblages. *Incertae sedis* representing possible algal cysts and scolecodonts occur locally in minority. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.7 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.33 to 2.37.

The oldest palynological assemblage (at 16794.3 ft) is dominated by simple miospores comprising laevigate (*Retusotriletes*) and sculptured simple spores (*Apiculiretusispora* and *Dibolisporites*) of uniform thickness or patinate (Fig. 2.35, 2.36 and 2.37). *Cymbosporites senex* is very abundant and represent one third of this palynological assemblage (Fig. 2.34). In the same level, cryptospores (*Cymbohilates* and *Gneudnaspora*) occur in minority. The palynological assemblages from the sample 16766.8' to 16752.5' of the Jauf Formation are dominated by monospecific leiospheres (Fig. 2.34). In the assemblages from the Jubah Formation, miospores dominate the palynological assemblages except in the sample 16356.7' where small sculptured acritarchs represent 95% of the whole palynological assemblage (Fig. 2.34). Cavate spores (*Geminospora* and *Grandispora*) first occur in the Jubah Formation and constitute a main component of the assemblages (Fig. 2.37). *Dibolisporites* and *Emphanisporites* become numerous in these levels whereas patinate spores (*Cymbosporites*) decrease in comparison with the lowermost assemblages. *Acinosporites*, *Rhabdosporites* and *Verrucosisporites* make their first inception in the upper assemblages (Fig. 2.35). In general simple spores are less common than in the Jauf Formation and the assemblages display more various forms of miospores.

The curve of diversity is logically lower in the acritarch-rich assemblages (Figs 2.35, 2.36 and 2.37). The number of different miospore taxa recognized per sample varies from 0 in some leiosphere-rich levels to 22 for the richest sample. This low diversity can be explained by the poor conservation state of the organic material. Trilete spores dominate the miospore assemblages. The cryptospores are mainly characteristic of the lowermost assemblage (Fig. 2.35).

Although the cosmopolitan species dominate the miospore assemblages along the section, the typical Gondwanan species are more numerous in the Jauf Formation than in the Jubah Formation (Fig. 2.37).

Comparisons with other assemblages

No index species from Euramerica appear in the oldest miospore assemblage. The co-occurrence of species such as *Biornatispora dubia* and *Cymbosporites senex* seems to correspond to an undifferentiated Emsian age for this sample. The D3B Subzone of Al-Hajri et al. (1999) appears in the upper part of the Jauf Formation. The first occurrence of *Geminospora lemurata* in the lowermost sample of the Jubah Formation marks the base of the AP-Lem Interval Zone of Streel et al. (1987). In the lowermost samples of the Jubah Formation, the most significant species for stratigraphy are *Camarozonotriletes*? *concavus*, *Grandispora permulta*, *Scylaspora rugulata* and *Verrucosisporites scurrus* and indicate an early Givetian age. The first occurrence of *Samarisporites triangulatus* marks the base of the TA Oppel Zone of Streel et al. (1987) in the uppermost sample. That corresponds to a late early-middle Givetian age.

2.6.2. Well FWRH-1

Fawwarah-1 (FWRH-1) was drilled by Saudi Aramco and is situated in eastern Saudi Arabia (Fig. 2.4). It is here studied between 15937.6 ft and 15886.3 ft, including 5 productive samples. The samples come from the lower part of the Jauf Formation. The Tawil/Jauf Formation boundary is situated at 16104 ft and the Jauf/Jubah Formation boundary at 15517 ft.

Palynological data

In all samples, the palynological material is moderately preserved. Miospores dominate the assemblages. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.8 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section is plotted in Fig. 2.38. The other types of charts illustrating the relative abundance of the different palynological groups are not presented here because no specimen counting has been carried out for this section. In addition, these charts would be difficult and probably unrepresentative to interpret the evolution of the palynological assemblages on the basis of so few samples. Nevertheless some general features can be defined.

Although all species do not occur at the base of the section (Fig. 2.38), these samples contain a same miospore assemblage because the few samples extend on a reduced thickness (about 50 ft). The palynological assemblages are dominated by simple miospores comprising laevigate spores (*Retusotriletes*), sculptured simple spores (*Apiculiretusispora*, *Cymbosporites* and *Dibolisporites*), reticulate/foveolate spores (*Biornatispora dubia*, *Brochotriletes*, *Camarozonotriletes filatoffii* and *Dictyotriletes*) and radial-patterned spores (*Emphanisporites* and *Scylaspora*). These forms are mainly of uniform thickness but can be cingulate or patinate. The zonate spores are only present with *Cirratriradites diaphanus* in the sample 15893.3’. The lowermost and uppermost samples are the least diverse. The number of different miospore taxa recognized per sample varies from 9 to 20 for the richest samples. Trilete spores dominate the miospore assemblages. The cryptospores (*Artemopyra* and *Gneudnaspora*) and monolete spores (*Latosporites ovalis*) are also present (Fig. 2.38). The cosmopolitan species dominate the miospore assemblages but typical Gondwanan species are significant and represent about 20 to 30 % of all the species recognized.

Comparisons with other assemblages

The section contains a unique assemblage and thus belongs probably to a unique biozone. The presence of index species from Euramerica, *Dictyotriletes emsiensis* and *Verrucosisporites polygonalis* (Fig. 2.38) indicate the Pragian-earliest Emsian *emsiensis-polygonalis* Assemblage Zone of Richardson & McGregor (1986). However, a unique specimen of *Brochotriletes bellatulus* is found in the sample 15919.7’ (Fig. 2.38); it is one of the index species of the AB Oppel Zone of Streel et al. (1987) and could give an undifferentiated Emsian age to the assemblage.

2.6.3. Well HWYH-956

Hawiyah-956 (HWYH-956) was drilled by Saudi Aramco and is situated in eastern Saudi Arabia (Fig. 2.4). It is here studied between 14220.8 ft and 14056.1 ft, including 25 productive samples. All the samples come from the upper part of the Jauf Formation. The base of the Jauf Formation is situated at 14427 ft and the boundary between the Jauf and Jubah Formation at 13973 ft.

Palynological data

In all samples, the palynological material is moderately to poorly-preserved. Miospores or acritarchs predominate the assemblages. Rare scolecodonts and *incertae sedis* representing possible algal cysts can also be found locally. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.9 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.39 to 2.43.

The oldest palynological assemblage is dominated by small sculptured acritarchs (Fig. 2.40). Miospores (trilete spores and cryptospores) are the main components of the samples from 14213.8’ to 14186.0’ (Fig. 2.39). In the lower part of this interval, *Cymbosporites senex* constitutes up to almost 60% of the palynological assemblages (Fig. 2.40). Cryptospores mainly with *Cymbohilates comptulus* also represent a significant percentage of the assemblage (Fig. 2.40). In the interval from 14213.8’ to 14186.0’, simple laevigate spores (*Retusotriletes*) and other simple spores sculptured with discrete elements (*Apiculiretusispora*, *Cymbohilates* and *Cymbosporites*) are dominant in the miospore assemblages (Figs 2.41 and 2.42). The dominant spores are of uniform thickness or patinate (Fig. 2.43). In the upper next interval from 14162.1’ to 14117.2’, monospecific leiospheres are predominant in the palynological assemblages except in the sample 14159.5’ (Fig. 2.40). During this interval *Biornatispora*, *Dibolisporites* and reticulate/foveolate spores become more numerous in the miospore assemblages whereas *Brochotriletes* and *Verrucosisporites* disappear (Figs 2.41 and 2.42). Zonate laevigate spores also first occur with *Cirratriradites diaphanus*. The miospore assemblages are still mainly composed of simple spores of uniform thickness or patinate (Fig. 2.43). The peak in cryptospores in the sample 14153.4’ (Fig. 2.42) is explained by the fact that only one specimen of *Gneudnaspora minor* var. *minor* has been recorded in the leiosphere-rich assemblage. The uppermost sample displays the first inception of *Acinosporites*. Simple laevigate or sculptured spores (*Apiculiretusispora*, *Cymbosporites* and *Dibolisporites*) and radial-patterned spores have the upper hand in this miospore assemblage (Figs 2.41 and 2.42). Most of them are of uniform thickness. *Cymbohilates* disappears to let *Gneudnaspora* as the unique remaining genus in the cryptospores (Fig. 2.41).

The curve of diversity is logically lower in the acritarch-rich assemblages (Figs 2.41, 2.42 and 2.43). The number of different miospore taxa recognized per sample varies from 1 to 36 for the richest sample. The diversity of miospore taxa remains relatively high in the lower part of the leiosphere-rich interval and then decrease in the upper part. Trilete spores constitute the main component of the miospore assemblages all along the section. The cryptospores show a decrease in the leiosphere-rich assemblage (Figs 2.40 and 2.42).

The abundance of the typical endemic Gondwanan forms is more or less constant along the well and lower than the cosmopolitan species which thus dominate the miospore assemblages (Fig. 2.43).

Comparisons with other assemblages

Dictyotriletes emsiensis and *Verrucosisporites polygonalis* (Fig. 2.39) seem to indicate the *emsiensis-polygonalis* Assemblage Zone of Richardson & McGregor (1986) and the PoW Oppel Zone of Streel et al. (1987) in the oldest assemblages. However, the occurrence of the stratigraphically important species, *Apiculiretusispora brandtii*, points out an undifferentiated Emsian at least from the sample 14195.2' (Fig. 2.39). The overlying interval from 14162.1' to 14117.2' reveals the presence of the D3B Subzone of Al-Hajri et al. (1999). It appears to be marked by a brief return to a more continental palynofacies at 14159.5'. The lowest level of the section where acritarchs dominate the whole palynological assemblage is not considered as belonging to D3B Subzone because leiospheres are far from dominating the assemblages what is not typical of the D3B interval. Although *Grandispora protea* is not recognized in this section, the first inception of *Acinosporites apiculatus* (Fig. 2.39) in the uppermost sample (14056.1') marks the base of the AP Oppel Zone of Streel et al. (1987) indicating of late Emsian age for this last sample.

2.6.4. Well KHRM-2

Kharma-2 (KHRM-2) was drilled by Saudi Aramco and is situated in eastern Saudi Arabia (Fig. 2.4). All the samples come from the upper part of the Jauf Formation. The boundary between the Tawil and Jauf Formations is situated at 16661 ft and the top of Jauf Formation at 16100 ft.

Palynological data

In all samples, the palynological material is moderately to poorly-preserved. Miospores or acritarchs dominate alternatively the assemblages. Rare scolecodonts, algal spores (*Quadrisporites*) and *incertae sedis* representing possible algal cysts also are found locally. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.10 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.44 to 2.48.

The samples 16316.6' and 16226.0' are dominated by small sculptured acritarchs and the samples 16228.0', 16223.0' and 16217.1' by leiospheres. The sample 16224.7' seems to be transitional since it is dominated jointly by both sculptured acritarchs and leiospheres (Fig. 2.45). The miospores represent the main component of the whole palynological assemblages in the middle part of the sampled section (samples 16278.0' to 16251.8') (Fig. 2.44). The trends of the different miospore groups are difficult to interpret because the curve of diversity is fluctuating. For example, the peak in *Emphanisporites* in sample 16228.0' may be explained by the low diversity due to the paucity in specimens of this sample (Fig. 2.46). However, the miospore assemblages are dominated by simple spores of uniform thickness (above all *Apiculiretusispora* and *Retusotriletes*) (Figs 2.46 and 2.48). We can also note that specimens of *Cymbosporites senex* are slightly more abundant in the sample 16269.0' than in the other miospore-rich assemblages (Fig. 2.45).

The diversity is very variable. The number of different miospore taxa recognized per sample varies from three to 34 for the richest sample (16273.0'). It is commonly low in the leiosphere-rich assemblages (Figs 2.46, 2.47 and 2.48). On the contrary, the diversity can be low or high in the sculptured acritarch-rich and miospore-rich assemblages (samples 16316.6’, 16226.0’ and 16224.7’). These changes in diversity could mean changes in sedimentary environments since the state of preservation seems to be constant all along the section. Trilete spores dominate the miospore assemblages. The cryptospores are also present but in minority in the lower part of the section (Figs 2.45 and 2.47). Their larger representation in the sculptured acritarch-rich assemblages of samples 16226.0’ and 16224.7’ is not caused by the low diversity in species since these samples contain more than 20 species (Fig. 2.47).

The abundance of the typical endemic Gondwanan species is very low and increases in the top of the section (Fig. 2.48).

Comparisons with other assemblages

The co-occurrence of typical Emsian species such as *Acinosporites lindlarensis*, *Apiculiretusispora brandtii*, *Camarozonotriletes sextantii*, *Emphanisporites decoratus* and the presence of the index species *Rhabdosporites minutus* seem to indicate the Min Interval Zone of Streel et al. (1987) from the sample 16273.0’ (Fig. 2.44). Consequently, this section is likely dated as middle-late Emsian. The D3B Subzone of Al-Hajri et al. (1999) appears from the sample 16228.0’ to the top of sampled section. A sculptured acritarch-rich level interrupts the dominance of the typical D3B leiospheres in sample 16226.0’. The lowermost sample (16316.0’) which is also dominated by sculptured acritarchs is not characteristic of the D3B Subzone.

2.6.5. Well NFLA-1

Nafla-1 (NFLA-1) was drilled by Saudi Aramco and is situated in eastern Saudi Arabia (Fig. 2.4). It is here studied between 16673.7 ft and 16631.7 ft, including three productive samples. All the samples come from the upper part of the Jauf Formation. The boundary between the Tawil and Jauf Formations is situated at 17088 ft and the top of Jauf Formation at 16520 ft.

Palynological data

In all samples, the palynological material is moderately preserved. Miospores dominate the assemblages. Rare sculptured acritarchs and leiospheres also occur. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.11 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section is plotted in Fig. 2.49. The other types of charts illustrating the relative abundance of the different palynological groups are not presented here because no specimen counting has been carried out for this section. In addition, these charts would be difficult and probably unrepresentative to interpret the evolution of the palynological assemblages on the basis of so few samples. Nevertheless some general features can be defined.

Although all species do not occur at the base of the section (Fig. 2.49), these samples are considered to contain a same miospore assemblage because the few samples extend on a reduced thickness (about 40 ft). The palynological assemblages are dominated by simple miospores comprising laevigate spores (*Retusotriletes*) and simple spores sculptured with discrete samples (*Apiculiretusispora*, *Cymbosporites* and *Dibolisporites*). Other types of form (reticulate/foveolate, radial-patterned, zonate and cavate spores) also occur but in minority. The samples are poor in specimens and species. The number of different miospore taxa recognized per sample varies from 6 to 11 for the richest samples. Trilete spores dominate the miospore assemblages. The cryptospores (*Gneudnaspora*) and monolete spores (*Latosporites ovalis*) are also present in the assemblages. The cosmopolitan species dominate the miospore assemblages.

Comparisons with other assemblages

The section represents a unique assemblage and thus belongs to a unique biozone. No index species from Euramerica is recognized. The co-occurrence of some significant species for stratigraphy such as *Biornatispora dubia*, *Clivosispora verrucata*, *Cymbosporites senex* and *Dibolisporites eifeliensis* (Fig. 2.49) indicates probably a Pragian or Emsian age to the assemblage.

2.6.6. Well SDGM-462

Shedgum-462 (SDGM-462) was drilled by Saudi Aramco and is situated in eastern Saudi Arabia (Fig. 2.4). It is here studied between 13775.6 ft and 13654.6 ft, including 12 productive samples. All the samples come from the upper part of the Jauf Formation, except the uppermost one from the base of the Jubah Formation. The base of the Jauf Formation is located at 14113 ft and the boundary between the Jauf and the Jubah Formations at 13661 ft. The Unayzah Formation overlies unconformable the Jubah Formation at 13540 ft.

Palynological data

In all samples, the palynological material is poorly-preserved, and of high thermal maturity. Thus miospores are not easily determinable. Miospores or leiospheres predominate alternately the assemblages. Acritarchs with appendages, *incertae sedis* representing possible algal cysts and scolecodonts can also be found but generally in small amount. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.12 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.50 to 2.54.

The oldest palynological assemblages are dominated by miospores comprising laevigate and sculptured simple spores. These are mainly dominated by patinate forms; indeed, *Cymbosporites senex* is very abundant in these levels (Fig. 2.51). The cryptospore *Cymbohilates comptulus* represents a significant percentage of the miospore assemblage. Acritarchs including leiospheres characterize about 25% of the whole palynological assemblage in the two lowermost samples (Fig. 2.51). *Retusotriletes* and *Apiculiretusispora* (spores of uniform thickness) become predominant from the sample 13755.3’ in miospore assemblages (Fig. 2.52). *Clivosispora* is characteristic of the lower part of the section (Fig. 2.52). The palynological assemblages from the sample 13710.2’ to the top of the Jauf Formation are dominated by monospecific leiospheres, often associated with few acritarch specimens, except in the sample 13690.8’ rich in miospores (Fig. 2.51). *Dibolisporites* and *Emphanisporites* are above all characteristic in the upper part of the section. Patinate spores after decreasing come back in numbers in the two uppermost samples. *Acinosporites* first occurs in the unique sample of the Jubah Formation (13654.6’) where miospores are dominant again. *Apiculiretusispora*, *Dibolisporites* and *Retusotriletes* are the main component of this last assemblage (Fig. 2.52).

The curve of diversity is logically lower in the acritarch-rich assemblages (Figs 2.52, 2.53 and 2.54). The number of different miospore taxa recognized per sample varies from 1 to 16 for the richest sample. This low diversity could be explained by the poor conservation state of the organic material. Trilete spores dominate the miospore assemblages. The cryptospores are above all present in leiosphere-poor assemblages (Figs 2.51 and 2.53).

The abundance of the typical endemic Gondwanan species is low and more or less constant from base to top; the cosmopolitan species thus dominate the miospore assemblages (Fig. 2.54).

Comparisons with other assemblages

No index species from Euramerica is identified from the samples 13775.6’ to 13721.9’, but the co-occurrence of miospore species such as *Biornatispora dubia*, *Cymbosporites senex* and *Dibolisporites eifeliensis* (Fig. 2.50) seems to indicate a Pragian or Emsian age for this interval. The D3B Subzone of Al-Hajri et al. (1999) appears as two pulses in the upper part of the Jauf Formation (Fig. 2.50). In the D3B Subzone, *Camarozonotriletes sextantii* makes its unique occurrence in this section and indicates the Emsian *annulatus-sextantii* Assemblage Zone of Richardson & McGregor (1986). The first occurrence of *Acinosporites apiculatus* in the uppermost sample (Fig. 2.50) marks the base of the AP Oppel Zone of Streel et al. (1987), although *Grandispora protea* is not recognized in this section. The base of the Jubah Formation is thus probably of late Emsian age.

2.6.7. Well UTMN-1830

Uthmaniyah-1830 (UTMN-1830) was drilled by Saudi Aramco and is situated eastern Saudi Arabia (Fig. 2.4). It is here studied between 13738.5 ft and 13592.3 ft, including 11 productive samples. All the samples come from the upper part of the Jauf Formation. The base of the Jauf Formation is situated at about 13970 ft. The Unayzah Formation overlies unconformably the Jauf Formation just above the uppermost sample. Thus, the uppermost part of the Jauf Formation is missing.

Palynological data

In all samples, the palynological material is moderately preserved. Miospores or leiospheres dominate alternatively the assemblages. Some algal spores (*Quadrisporites*) and rare acritarchs with appendages and scolecodonts occur locally. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.13 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 2.55 to 2.59.

The oldest palynological assemblages from 13738.5’ to 13670.8’ are dominated by miospores comprising simple laevigate spores (*Retusotriletes*), simple spores sculptured with discrete elements (*Apiculiretusispora*, *Cymbohilates* and *Cymbosporites*) and radial-patterned spores (*Emphanisporites*) (Figs 2.57 and 2.58). From a structural point of view, these forms are of uniform thickness or patinate (Fig. 2.59). *Cymbosporites comptulus* and *Emphanisporites rotatus* are particularly numerous in the lowermost sample. In the sample 13689.7’, leiospheres characterize about 20% of the whole palynological assemblage. The abundance of *Cymbosporites senex* displays a significant positive peak in the sample 13670.8’ and constitutes 32% of the whole palynological assemblage (Fig. 2.56). In the interval from 13614.6’ to 13592.3’, monospecific leiospheres become predominant (Fig. 2.56). In the lower part of the leiosphere-rich interval, *Apiculiretusispora* and the reticulate/foveolate (e.g. *Brochotriletes foveolatus*, *Biornatispora dubia*, *Camarozonotriletes filatoffii* and *Dictyotriletes emsiensis*) spores are significantly more common in the miospore assemblages whereas *Cymbosporites* decrease (Figs 2.57 and 2.58). In the meantime, the other morphological groups do not seem to show significant variations.

The curve of diversity decreases in the leiosphere-rich assemblages (Figs 2.57, 2.58 and 2.59). The number of different miospore taxa recognized per sample varies from 1 to 35 for the richest samples. Trilete spores dominate the miospore assemblages. The cryptospores are more numerous in miospore-rich assemblages (Figs 2.55 and 2.56).

The abundance of the typical endemic Gondwanan species is low and relatively constant from base to top; the cosmopolitan species thus dominate the miospore assemblages (Fig. 2.59).

Comparisons with other assemblages

The co-occurrence of cosmopolitan species such as *Acinosporites lindlarensis*, *Biornatispora dubia*, *Cymbosporites senex*, *Dibolisporites eifeliensis* and *Verrucosisporites polygonalis* indicate an undifferentiated Emsian age in the interval from 13738.5’ to 13670.8’. The D3B Subzone of Al-Hajri et al. (1999) appears from 13614.6’ to 13592.3’. In the D3B Subzone, the occurrence of *Camarozonotriletes sextantii* and *Verruciretusispora dubia* (Fig. 2.55) points out also an Emsian age for the rest of the section. Indeed, *C. sextantii* and *V. dubia* marks respectively the *annulatus-sextantii* Assemblage Zone of Richardson & McGregor (1986) and the FD Oppel Zone of Streel et al. (1987).

2.6.8. Well YBRN-1

Yabrin-1 (YBRN-1) was drilled by Saudi Aramco and is situated in eastern Saudi Arabia (Fig. 2.4). It is here studied between 16684.8 ft and 16642.0 ft, including 8 productive samples. All the samples come from the Jubah Formation. The boundary between the Jauf and the Jubah Formations may be situated at about 16700 ft. The Jubah Formation is overlaid unconformably by Unayzah Formation at 16360 ft.

Palynological data

In all samples, the palynological material is moderately to poorly-preserved. Thus miospores are sometimes not easily identifiable. Miospores dominate the assemblages. Some chitinozoan specimens occur in the sample 16647.3’ and 16649.3’. The identified miospore taxa are reported (in alphabetical order) in Appendix 2.14 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section is plotted in Fig. 2.60. The other types of charts illustrating the relative abundance of the different palynological groups are not presented here because no specimen counting has been carried out for this section. In addition, these charts would be difficult and probably unrepresentative to interpret the evolution of the palynological assemblages on the basis of so few samples. Nevertheless some general characteristics can be described.

These samples are not well distributed along the section and constitute two sample groups. The oldest palynological assemblages in the samples 16684.8' and 16684.3' are dominated by simple laevigate spores (*Retusotriletes*) and simple spores sculptured with discrete elements (e.g. *Apiculiretusispora*, *Dibolisporites* and *Verrucosisporites*). The cavate sculptured spores (*Geminospora* and *Grandispora*) constitute an important part of the assemblages of the uppermost group of samples. In the samples 16649.3' to 16642.0', radial-patterned (*Emphanisporites* and *Scylaspora*), cingulate (*Camarozonotriletes*), patinate (*Archaeozonotriletes* and *Cymbosporites*) and zonate spores (*Samarisporites*) occur. These younger assemblages are still dominated by spores of uniform thickness and cavate spores. The diversity is low and could be explained by the poor conservation state of the organic material. The number of different miospore taxa recognized per sample varies from 8 to 16 for the richest sample. The trilete spores dominate the miospore assemblages. The cryptospores are only present in the uppermost group of samples. In addition specimens of megaspore (*Verrucosisporites ellesmerensis*) occur in the sample 16649.3' indicating a continental or very nearshore environment.

Comparisons with other assemblages

The occurrence of *Geminospora lemurata* in the lowermost sample of the section (Fig. 2.60) marks the base of the *lemurata-magnificus* Assemblage Zone of Richardson & McGregor (1986) and the AP-Lem Interval Zone of Streel et al. (1987). The absence of younger species indicates an early Givetian age for the samples 16684.8' and 16684.3'. Species such as *Auroraspora minuta*, *Grandispora incognita* and *Verrucosisporites scurrus* are often found in this biozone. The uppermost interval from 16649.3' and 16642.0' belongs to the TA Oppel Zone of Streel et al. (1987) because *Samarisporites triangulatus* first occurs at its base (Fig. 2.60). Other typical taxa of this biozone are *Cymbosporites catillus*, *C. cyathus* and *Rhabdosporites langii*. Consequently, the uppermost sampled interval corresponds to a late early-middle Givetian age.

Chapter 3 – North Africa

3.1. Introduction

Two boreholes from North Africa (Libya and Tunisia) have been studied in order to compare them with the results from Saudi Arabia. These sections were already the subject of two papers (Loboziak & Streel, 1989; Loboziak et al., 1992a) but their current study, in the light of results presented above, allows us to have a more detailed view on Devonian palynology mainly on the northwestern Gondwana. According to Streel et al. (1990b), the Ardenne-Rhenish Devonian miospore zonation of Streel et al. (1987) can be used in western Gondwana. Indeed, subsequent works in Libya (Streel et al., 1988; Loboziak & Streel, 1989) and in Brazil (Burjack et al., 1987; Loboziak et al., 1988) showed the same sequence of first occurrences for many of the characteristic species of the miospore zonation developed in the Ardenne-Rhenish regions. At first, the miospore zonation of Streel et al. (1987) is thus applied to the results presented here.

3.2. Regional geological background

The North African Platform experienced a complex and polyphase history. Initially part of a regionally continuous clastic-dominated Gondwana passive margin, it was progressively segmented into broad forelands and intracratonic basins and swells during Late Devonian to Late Carboniferous collision with Laurussia. The North African Platform is boarded by the African Shield in the south, with its Eglab, Hoggar, Tibesti, Jebel Awaynat and Nubian Precambrian Massifs, and the Atlassic-Maghrebian fold belts and East Mediterranean Basin in the north (Fig. 3.1). The underlying Precambrian basement evolved as part of Pangaea, formed from the collision and suturing of several cratons and island-arcs during the Pan-African Orogeny. This subsequently evolved into a stable Gondwana during most of the Palaeozoic when a passive continental margin developed up to the Hercynian deformation in the Late Carboniferous (Boote et al., 1998).

In the late Silurian, the sedimentary sequence was terminated by a regionally extensive unconformity (Harland et al., 1990). Indeed, a significant Caledonian tectonic activity was initiated during the Pridoli-Lochkovian as a result of the collision between West Africa and North America. In the Ghadames Basin, a transgressive-dominated sequence succeeded with the development of a vast, regionally continuous, fluvial system, thinning regionally to the north and locally onto intra-platform structural arches. The sediments were derived from a southeastern source. Epeirogenic activity, reflecting the initial collision between Gondwana and Laurussia, increased in Middle to Late Devonian resulting as an increase in stratigraphic complexity. So Eifelian-earliest Givetian uplift and erosion terminated the previous sequence. It was followed by a widespread marine transgression, grading up into a series of stacked depositional cycles, each strongly influenced by intra-platform highs. The Middle and Upper Devonian cycles are made up of regressive, fluvial-dominated delta systems each with an erosional upper surface, in places incised and capped by extensive transgressive marine shales, limestones and iron oolithes (Boote et al., 1998).

3.3. Description of the studied sections

The two studied boreholes (A1-69 and MG-1) are located in the Ghadames Basin (Fig. 3.2) which is a large intra-cratonic basin covering portions of Algeria, Tunisia and Libya, and extending over 350 000 km². The basin contains up to 6000 m of Palaeozoic and Mesozoic sediments. It is bounded to the north by the Dahar-Nafussah High, to the south by the Qarqaf Uplift (Libya) and the Hoggar Shield, and its western limit is represented by the Amguid-El Biod Arch. The eastern margin is not well-defined, being overlapped by the western flank of the younger Sirt Basin. The Illizi Basin in Algeria is often considered as southwestern part of the Ghadames Basin (Echikh, 1998). The Caledonian tectonic activity caused the uplifting and erosion of the southwestern and southern flank of the Ghadames Basin, where the Lower Devonian (Tadrart Formation) overlies unconformably the Upper Silurian. Two additional unconformities are observed higher in the Devonian from the Ghadames Basin, particularly over the southern flank representing late Caledonian tectonic phases. These unconformities are observed at the top of the Emsian (Abdesselam-Rouighi, 1991; Echikh, 1992) and at the base of the Frasnian radioactive carbonate shale layer. In addition, biostratigraphic hiatuses occur in the Givetian and Frasnian according to Echikh (1987, 1992).

The two boreholes were drilled across, from base to top, the Ouan-Kasa, Awaynat Wanin I, Awaynat Wanin II and Awaynat Wanin III Formations. In the Ghadames Basin, these lithological units have been recently redescribed by Ben Rahuma et al. (2007) from outcrops of the Awaynat Wanin area (southern flank). Northwestward, along a dip section, correlation shows an overall thinning of the sandstone units and thickening and deepening of the shaly units. Nevertheless, these formations have been described by Massa (1988) from subsurface data as following.

3.3.1. Ouan-Kasa Formation

This unit is mainly siliciclastics and can be divided into two parts. Its lower part is composed of sands and/or limestones. This limestone facies is only known along the far northern flank of the Ghadames Basin and reflects a marine deposit environment with occurrence of brachiopods, bryozoa and corals. The upper part is clayey-silty and mainly made up of stacking up parasequences of several meters each. These parasequences are fining upward and were deposited under tidal conditions. At the base, sediments contain coquina beds indicating a subtidal environment. Then, bioturbated sand bars overlie previous sediments and become progressively richer in clay (intertidal environment). The end of the parasequences evolves toward lagoon clay with presence of algae and stromatolites (supratidal environment). Occurrence of ferruginous oolithes indicates emersions or sub-emersions within lagoon environments.

The Ouan-Kasa Formation is well-distinguished from the underlying Tadrart Formation which is composed of coarse sands. However, there are significant lateral variations of facies over the whole Ghadames Basin. This unit is thicker on the northern flank near the Libyan/Tunisian border where it can be 130-205 m thick. It may be difficult to distinguish well the boundary between the Tadrart and Ouan-Kasa Formations.

The present unit is considered as upper Early Devonian (Pragian-Emsian) according to macrofauna (Massa, 1988).

3.3.2. Awaynat Wanin I Formation

This unit is mainly clayey in its lower part whereas the upper part comprises multicoloured sands with a constant content in iron oxides. These sediments are considered as either sand bars or channel deposits related to fluvial-dominated delta systems.

As the underlying Ouan-Kasa Formation, this unit is thicker and reaches about 130 m in thickness on the northern flank of the Ghadames Basin.

Macrofauna is poor in the Awaynat Wanin I Formation but seems to indicate principally an Eifelian age (Massa, 1988).

3.3.3. Awaynat Wanin II Formation

On the southern flank of the Ghadames Basin, this unit is mixed with clay and well-isolated sand strata which progressively decrease in thickness up to disappear. On the northern flank, the clayey facies predominates with rare and thin marl-limestone strata. Black shale facies occurs sporadically. For the first time during the Devonian in North Africa, a large eustatic transgression developed with the deposit of the Awaynat Wanin II Formation. Sediments were deposited in deltaic to near-shore facies on the south whereas they were more distal on the north with open marine facies. According to pelagic organisms, bathymetry should vary, from north to south, from 10-20 m to 100-200 m.

In this Formation, Boucot et al. (1983) recognized post-Eifelian brachiopod assemblages. In sample 2304 m, Weynant in Massa (1988) identified a Givetian conodont fauna. Assemblages of microfossils such as ostracodes, tentaculites and conodonts indicate thus a Givetian age for the deposit of the Awaynat Wanin II Formation (Massa, 1988).

3.3.4. Awaynat Wanin III Formation

This unit is predominated by dark grey clays. Some thin very micaceous siltstones and thin limestones occur. The siliciclastic input from the continent is much reduced at this time. Indeed, the eustatic transgression overpasses the basin margins. The deltaic system is restricted to some tens km^2 at the outcrops of the Awaynat Wanin areas in the southwestern flank of the Ghadames Basin (Vos, 1981).

Macrofauna and microfauna are impoverished due to confined facies or even euxinic conditions. Small bivalves, tentaculites, foraminifera and ostracods are recognized and the age of the deposit of the Awaynat Wanin III Formation is estimated more or less as being Frasnian (Massa, 1988).

3.4. Review of Devonian miospore palynological studies in North Africa

The present paragraph summarizes the most important Devonian palynological studies carried out in the different Palaeozoic basins from North Africa. Fig. 3.3 compares Devonian miospore biozonations defined and/or applied in the different studies. Jardiné & Yapaudjian (1968) and Magloire (1968) were the first to report on spore assemblages from the Devonian of North Africa; these were from core samples of petroleum boreholes respectively drilled in the Illizi (Polignac) Basin (western Algeria) and in the Bechar Basin (eastern Algeria). These authors established biozonation based on acritarch, chitinozoan and spore assemblages in 'Gedinnian' to Givetian strata (Jardiné & Yapaudjian, 1968) and in Lochkovian and 'Siegenian' strata (Magloire, 1968). The two papers show stratigraphic ranges and illustrations of miospore species but description of those are not given.

Then Massa & Moreau-Benoit (1976) published a palynological synthesis of the Devonian of the Ghadames Basin (western Libya). Numerous deep boreholes drilled during oil prospection were studied. The authors assigned the spore assemblages from the Tadrart Formation to the Tahara Formation to a Pragian-late Famennian age. They subdivided this continuous sequence into 11 palynozones. Later, Moreau-Benoit (1979, 1980) described the miospore species cited in the previous synthesis (Massa & Moreau-Benoit, 1976). New considerations and additional data on systematics and stratigraphic distribution of Middle and late Devonian miospore taxa came out in Massa & Moreau-Benoit (1985) and Moreau-Benoit (1988, 1989). Moreau-Benoit (1989) reinterpreted the age of the biozonation previously established in Massa & Moreau-Benoit (1976). So far, this synthesis, which comprised some works from the same authors, constitutes the most important study on Devonian miospores from North Africa.

Paris et al. (1985) presented initial results of a project which illustrated all of the stratigraphically significant taxa encountered in a comprehensive study of Ordovician to Late Cretaceous sections in northeast Libya. They recorded Emsian-Famennian spore assemblages from cutting and core samples from exploration wells situated in Cyrenaica. This first article gave only a brief description of the different assemblages without figuring stratigraphic range of miospores. Secondly in the final phase of this project, Streel et al. (1988) compared these assemblages to the well-established Devonian Western European zonation of Streel et al. (1987). In addition, they proposed a re-calibration of the western Libyan Palynozones 4 to 8 of Massa & Moreau-Benoit (1976) with emphasis on the significance of the first occurrence of *Geminospora lemurata*. Streel et al. (1988) restricted to the Eifelian Stage the Palynozones 4-6, previously dated as Eifelian to the upper Givetian, and to the early Givetian, the Palynozones 7 and 8, previously dated as Frasnian by Massa & Moreau-Benoit (1976).

Boumendjel et al. (1988) examined core samples of borehole TRN 3 drilled in the Illizi Basin. Only 'Siegenian' and early Givetian spore assemblages were recognized. Consequently numerous sedimentary gaps were highlighted or estimated. Other data from the Illizi Basin were published on the Emsian to latest Famennian stratigraphic interval (Coquel & Latrèche, 1989; Moreau-Benoit et al., 1993). Besides, Moreau-Benoit et al. (1993) applied the biozonation developed by Richardson & McGregor (1986) to the results from the Illizi Basin. These last studies confirmed the numerous gaps recognized in this Basin due to tectonic episodes considered as Emsian.

Loboziak & Streel (1989) presented systematic results on the more important taxa encountered in four boreholes from the Ghadames Basin. The results were compared with the

Western European zonation of Streel et al. (1987). In borehole A1-69, the first occurrences of the characteristic miospores showed the same stratigraphic sequence as in the Ardenne-Rhenish reference biozonation. Chronostratigraphic correlations made through this biozonation gave an Emsian to late Frasnian age for the studied samples. From the 55 observed species, almost 90% were also found in Western Europe according to Loboziak & Streel (1989).

Streel et al. (1990a) reviewed miospores, faunas and megafloras of the Lower and Middle Devonian in Libya. They notably demonstrated the diachronism of the Tadrart and Ouan-Kasa Formations across the Ghadames Basin. In the northern margin of the basin, the lower part of the Tadrart Formation in borehole MG-1 is within the lowermost part of the Lochkovian not at its base. In the southern margin, the Tadrart and Ouan-Kasa Formations are probably not older than late Emsian, maybe early Eifelian. The Awaynat Wanin I Formation is often absent there or strongly reduced.

Devonian miospores of the Tunisian borehole MG-1 from the northern margin of the Ghadames Basin were compared to the available faunal data in Loboziak et al. (1992a). The age of the various formations drilled was revised. The authors concluded that the Emsian and the Eifelian are represented by a thicker sedimentation than the other stages. The Devonian stratigraphy in this area is more complex than was previously believed.

Rahmani-Antari & Lachkar (2001) is the unique palynological study on Devonian material from Morocco. The authors studied 4 wells and 1 outcrop section in order to inventory organic microfossils notably for Devonian series. Spores, acritarchs as well as chitinozoans allowed to subdivide the Devonian into 8 palynozones in spite of some sedimentary, erosion or observation gaps.

One of the last recent palynological studies was carried out by Rubinstein & Steemans (2002). It concerned borehole A1-61 situated on the northern margin of the Ghadamis Basin. The Silurian/Devonian boundary was recognized in the Tadrart Formation. Ludlow to Early Lochkovian spore assemblages were described, compared and correlated with miospore zonation schemes established for the type sequences of the Welsh Borderland, and those previously described from Libya.

3.5. Palynological results

3.5.1. Borehole A1-69

The cored borehole A1-69 (Lat. = 29° 03’ 50’’ N, long. = 13° 40’ 13’’ E) was drilled by SHELL in 1959. It is situated in Libya in the southern flank of the Ghadames Basin, about 120 km to the northeast from the Awaynat Wanin outcrops. It is here studied between 2109.5 ft and 971 ft, including 29 productive samples. The boundaries of the formations are difficult to place. However the comparisons with the gamma-ray log of others boreholes allows to place coarsely them (see Streel et al., 1990a). The top of the Ouan-Kasa and Awaynat Wanin I Formations may be respectively situated at about 2000 ft and 1575 ft. The top of the Awaynat Wanin II Formation occurs above the highest studied sample. This borehole was already published by Loboziak & Streel (1989) from a palynological point of view. Palynological slides processed for this paper have been re-studied.

Palynological data

In most samples, miospores are very abundant, very well-preserved and of low thermal maturity. Acritarchs, chitinozoans, prasinophycean cysts and scolecodonts are commonly present but in minority. However acritarchs can be much more numerous in the uppermost samples. The identified miospore taxa are reported (in alphabetical order) in Appendix 3.1 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 3.4 to 3.7.

The oldest spore assemblage from the Ouan-Kasa Formation comprises diverse and rather small-sized miospores. These include mainly retusoid forms (*Retusotriletes*), spinose forms (*Apiculiretusispora*, *Dibolisporites*), verrucate forms (*Verrucosisporites*), patinate forms with laevigate or variably sculptured exine (*Archaeozonotriletes*, *Chelinospora*, *Clivosispora*, *Cymbosporites*) and reticulate/foveolate forms (*Dictyotriletes*, *Brochotriletes*). Zonate and camerate spores (*Zonotriletes*, *Rhabdosporites*) are not very numerous. Cryptospores are also present (*Artemopyra*, *Gneudnaspora*). *Acinosporites* decreases from the base of the section and end up disappearing in the Awaynat Wanin II Formation. Spores characterized by proximal radial pattern (mainly *Emphanisporites* and *Scylaspora*) progressively decrease in importance from base to top (Figs 3.5, 3.6 and 3.7).

In the uppermost sample from the Ouan-Kasa Formation, the first large apiculate and spinose zonate-pseudosaccate spores (*Grandispora*) start to occur. They diversify quickly from the lower part of the Awaynat Wanin I Formation with taxa belonging to *Geminospora*, *Grandispora*, *Samarisporites* and *Zonotriletes*. These are going to be preponderant in the spore assemblages in younger samples up to top of the section. However zonate laevigate spores are more numerous in the Awaynat Wanin I Formation than in the Awaynat Wanin II Formation whereas zonate sculptured spores do not show this trend.

First megaspores (*Jhariatriletes emsiensis*) make a brief inception in the lower part of the Awaynat Wanin I Formation. Many other megaspore types, including *Contagisporites optivus*, appear later in the Awaynat Wanin II Formation but most of them are not described in this work. However, they were briefly reported in de Ville de Goyet et al. (2007), they will be the subject of a next more detailed manuscript. *Scylaspora rugulata* occurs only in the upper part of the Awaynat Wanin I Formation and the lower part of the Awaynat Wanin II Formation.

In the lower part of the Awaynat Wanin II Formation, an important morphon of spores characterized by an irregular spinose to verrucate sculpture first appears. It includes *Dibolisporites farraginis*, *Dibolisporites uncatus*, *Verrucosisporites scurrus* and *Verrucosisporites premnus* (*V. scurrus* Morphon). *Geminospora* become more important from the base of the Awaynat Wanin II Formation notably with the inception of *Geminospora lemurata*. Cavate laevigate spores first appear in the Awaynat Wanin II Formation.

From the middle of the Awaynat Wanin II Formation to the top of the section, *Cymbosporites* (*C. catillus*, *C. cyathus* and *Cymbosporites* sp. 4) and *Chelinospora timanica*, become main components of spore assemblages. Indeed, *Cymbosporites*, *Verrucosisporites* and convolute and rugulate (*Chelinospora timanica*, *Convolutispora* spp.) spores are above all present in the upper part of the section.

Some minor cases of reworking seem to be evident because some species (e.g. *Brochotriletes foveolatus*, *Dictyotriletes subgranifer*, *Latosporites ovalis* and *Retusotriletes maculatus*) are found either punctually in youngest isolated samples or regularly higher in comparison with their known stratigraphic range in the literature.

The following general trends among miospore genera and morphological groups can be deduced from the results (Figs 3.5 and 3.6). The *Acinosporites* disappear in the Awaynat Wanin II Formation. The *Ancyrospora* or spores characterized by anchor elements are present in the middle part with *A. nettersheimensis* and then disappear up to the first inception of *A. langii* in the uppermost sample (at 971'). *Archaeozonotriletes* shows a discontinuous presence along the section with *A. chulus* in the lower part and *A. variabilis* in the upper part. *Auroraspora* occurs only in the Awaynat Wanin II Formation with *A. minuta* and represent the first occurrence of the cavate laevigate spores which also comprises *G. punctata*. Rare three-layered spores occur punctually in the lower part of the Awaynat Wanin II Formation. The presence of *Brochotriletes* is discontinuous along the section. *Camarozonotriletes* is present at the base with *C. sextantii*, and in the Awaynat Wanin II Formation with *C.*? *concavus*. *Chelinospora* and *Cymbosporites* (or patinate spores) are above all characteristic of the top of the section notably with *Chelinospora timanica*, the *Cymbosporites catillus* Morphon and *Cymbosporites* sp. 4. *Dibolisporites* become an important component of the assemblages from the Awaynat Wanin I Formation. *Dictyotriletes* are mainly confined to the base of the borehole like reticulate/foveolate spores. *Emphanisporites* progressively decrease in importance from base to top. *Geminospora* appears in the lower part of the section with *G. svalbardiae* but becomes an important component in the Awaynat Wanin II Formation with *G. lemurata*. The *Grandispora* have their acme along the middle part of the section. *Samarisporites* which is included in the zonate sculptured spore is more or less constant from their first occurrence. *Scylaspora* occurs only in the middle part with *S. rugulata*. Papillate spores, *Synorisporites* and *Zonotriletes* which is included in the zonate laevigate spores are characteristic of the lower part. *Verrucosisporites* are above all typical of the Awaynat Wanin II Formation with the *V. scurrus* Morphon. Note that some genera (*Camarozonotriletes*, *Chelinospora*, *Cymbosporites* and *Verrucosisporites*) show an absence in the middle part of the section (Fig. 3.5) and reappear in the Awaynat Wanin II Formation. This feature is not probably caused by a decrease in diversity since the curve is constant during this interval. These forms are replaced by others (notably *Acinosporites*, *Emphanisporites*, *Samarisporites* and *Zonotriletes*) and this change in the assemblage composition can be due to lots of processes such as ecological or climatic changes, or the facies dependence of some miospore forms.

The curve of diversity is relatively constant along the sampled section. However a very slight decrease can be detected from base to top (Figs 3.5, 3.6 and 3.7). The number of different taxa recognized per sample varies from 11 to 37 for the richest samples. Trilete spores dominate the miospore assemblages. The cryptospores are above all present in miospore levels from the base of the section and in the lower part of the Awaynat Wanin II Formation but constitute a minor percentage of the whole miospore assemblages in the upper part of the section. Megaspores are frequent in terms of specimens and species in the Awaynat Wanin II Formation and appear briefly in the sample 1962' (Fig. 3.6).

The typical endemic Gondwanan species may show a slight decrease from base to top where cosmopolitan species are much more numerous (Fig. 3.7). The slight decrease, in the upper part of the section of the spores of uniform thickness, i.e. characterized by the simplest structure benefits above all patinate and cavate spores. However, the cavate spores are quite constant from the Awaynat Wanin I Formation. In the Awaynat Wanin I Formation, the cingulate spores stand back whereas the zonate spores seem to have their acme (Fig. 3.7).

Comparisons with other assemblages

The oldest spore assemblages from the Ouan-Kasa Formation are considered to belong to the Min Interval Zone of Streel et al. (1987), based on the general characteristics of the assemblages and the presence of typical taxa such as *Biornatispora dubia*, *Camarozonotriletes sextantii*, *Dibolisporites eifeliensis*, *Rhabdosporites minutus*, *Synorisporites papillensis* and *Verrucosisporites polygonalis*. In Euramerica, the FD Oppel Zone (including the Min Interval Zone) indicates a late Emsian age.

In the uppermost sample from the Ouan-Kasa Formation, the stratigraphically important spore *Acinosporites apiculatus* and *Grandispora protea* first appear and indicate the AP Oppel Zone (Pro Interval Zone). These index species and the last appearance of *Camarozonotriletes sextantii* suggest a latest Emsian age for the top of the Ouan-Kasa Formation. From this sample, large apiculate and spinose zonate-pseudosaccate spores start to occur and dominate in the spore assemblages.

At the base of the Awaynat Wanin I Formation, the first inception of *Grandispora velata* marks the base of the Vel Interval Zone. The common species *Geminospora svalbardiae* first appears. The large zonate-pseudosaccate spores are already well-diversified with *Grandispora protea*, *G. douglastownense*, *G. gabesensis*, *G. velata*, *Samarisporites eximius*, *Samarisporites* sp. 2, *Samarisporites* sp. 3, *Zonotriletes* sp. 5 and *Zonotriletes* spp. These spore assemblages are typical of those of early Eifelian age.

Higher in the Awaynat Wanin I Formation, the unique index species *Acinosporites acanthomammillatus* marks the base of the AD Oppel Zone. This biozone is undifferentiated up to the first appearance of *Geminospora lemurata* whose inception marks the base of the Lem Interval Zone. In this interval, note the successive first occurrence of the stratigraphically important spore *Scylaspora rugulata* and *Grandispora permulta*. These spore assemblages are already Eifelian in age.

Geminospora lemurata first occurs in the sample 1486' and indicate the Lem Interval Zone whose base is early Givetian. *Rhabdosporites langii* first appears here in this interval.

The first inception of *Contagisporites optivus* is recognized just below that of *Samarisporites triangulatus* which marks the base of the TA Oppel Zone. A middle Givetian age is suggested for this sequence up to the first appearance of *Chelinospora concinna* in the highest sample. As no typical Frasnian species are found in this sample, the lower part of the TCo Oppel Zone is identified and characteristic of a late Givetian age.

In comparison with the results of Loboziak & Streel (1989), there are some minor changes (Fig. 3.8). The Min Interval Zone is here recognized in the lowest sample of borehole A1-69. After detailed examination of palynological slides, the index species *Acinosporites apiculatus*, *Grandispora velata*, *Geminospora lemurata* are found lower whereas *Chelinospora concinna* appears 138 ft higher than alleged by Loboziak & Streel (1989). The Frasnian BM Oppel Zone is not formally recognized here, however one of its index species (*Lophozonotriletes media*) is found relatively low in comparison with the literature and the results of Loboziak & Streel (1989). This taxon shows a large morphological variability (see Volume III). According to Streel (pers. comm., 2007) the concept of *L. media* was more restrictive in Loboziak & Streel (1989); that may explain the difference in the results. However this difference raises the issue of the use of very variable miospore forms for index species which could be mixed up with other taxa. Finally, although these authors mentioned some taxa restricted to western Gondwana (Loboziak & Streel, 1995a), they focused mainly on characteristic species of Western Europe.

3.5.2. Borehole MG-1

The second studied borehole is Mechiguig 1 (MG-1). It was drilled on the northern flank of the Ghadames Basin in 1958-1959 by SEREPT in Tunisia near the Libyan border. Its most complete palynological analysis appeared in Loboziak et al. (1992a). It comprises here 55 productive samples and has been studied between 2741.4 m (8994.09 ft) and 2160.6 m (7088.58 ft). As the samples are expressed in meter in the previous studies on borehole MG-1, this convention is kept herein to allow easy comparisons between the different studies, while samples from other studied sections are expressed in feet. A table of conversion between samples expressed in meter and feet is established in Appendix 3.2 (Volume II). The top of the Ouan-Kasa and Awaynat Wanin I Formations are situated at about 2545 m and 2400 m. The Awaynat Wanin II Formation extends up to about 2200 m. Only the lower part of the Awaynat Wanin III Formation is crossed by the studied section. New palynological slides have been processed from old residue using standard palynological acid maceration techniques.

Other fossil groups were observed and studied in this borehole. In core 28, which includes samples 2728, 2713 and 2704 m, a very poor conodont assemblage occurs (Massa, 1988) but cannot be precisely interpreted from a stratigraphic point of view (Loboziak et al., 1992a). This same core revealed the occurrence of an Early Devonian tentaculite species from the Russian Platform (Hajlasz et al., 1978). In addition, Boucot et al. (1983) assigned a brachiopod fauna as 'Siegenian'-Emsian in non-specified levels from the Ouan-Kasa Formation. In core 15 (sample 2304 m), another conodont assemblage was removed from non-specified levels from the Awaynat Wanin II Formation and is of Givetian age (Massa, 1988). However, Weynant in Loboziak et al. (1992a) was not certain of this age because only broken specimens of index conodont species were collected.

Palynological data

Samples 2631.2 m and 2741.4 m are moderately well-preserved and contain brown material whereas in the other samples, miospores are very abundant, very well-preserved and of low thermal maturity. Acritarchs, chitinozoans, prasinophycean cysts and scolecodonts are often present but are never predominant. The darker spores of samples 2631.2 m and 2741.4 m may indicate reworking levels (see below). The identified miospore taxa are reported (in alphabetical order) in Appendix 3.3 (see Volume II). Stratigraphic range of each miospore taxon encountered in the section and relative abundance of the different palynological groups are plotted in Figs 3.9 to 3.12.

The oldest spore assemblage from the Ouan-Kasa Formation is not especially very diverse and includes mainly retusoid forms (*Retusotriletes*), spinose forms (*Apiculiretusispora*, *Dibolisporites*), reticulate/foveolate forms (*Dictyotriletes*, *Brochotriletes*) radial-patterned spores (*Emphanisporites*) and zonate spores (*Perotrilites*, *Samarisporites*). Cryptospores and monolete spores are absent.

Acinosporites and *Grandispora* first appear in the overlying sample where the large apiculate and spinose zonate-pseudosaccate spores seem to be already well-diversified (first inception of *Grandispora permulta*, *Grandispora protea*, *Grandispora* spp.) Then this morphological group, comprising *Geminospora*, *Grandispora*, *Samarisporites*, *Zonotriletes*, goes on diversifying during the deposit of the rest of the section. From the Ouan-Kasa Formation, the *Verrucosisporites scurrus* Morphon appears in significant quantity. In samples 2631.2 m, older forms than those from underlying samples first occur (e.g. *Ambitisporites asturicus*, *Cymbosporites dittonensis*, *Iberoespora cantabrica*, *Lycospora culpa*).

At the base of the Awaynat Wanin I Formation, the frequent typical taxa *Camarozonotriletes*? *concavus*, *Chelinospora timanica*, *Grandispora libyensis* and *Grandispora stolidotus* make their first inception.

The significant species such as *Geminospora lemurata*, *Rhabdosporites langii*, *Samarisporites triangulatus* and *Chelinospora concinna* successively appear in the Awaynat Wanin II Formation. The *Cymbosporites catillus* Morphon is well represented in the Awaynat Formation III where *Ancyrospora langii* and *Hystricosporites* sp. 1 characterized by anchor sculptural elements and *Camarozonotriletes parvus* occur.

In addition of the sample 2631.2 m where reworking process is obvious, other cases of reworking seem to be evident. Indeed some species (e.g. *Brochotriletes foveolatus*, *Dictyotriletes emsiensis*, *Latosporites ovalis*) are found punctually in youngest isolated samples or continue occurring too high in comparison with their known stratigraphic range in the literature (e.g. *Camarozonotriletes sextantii*, *Dictyotriletes subgranifer*, *Verrucosisporites polygonalis*).

The following most interesting general trends among miospore genera and morphological groups can be deduced from the results (Figs 3.10 and 3.11). The *Acinosporites* shows a constant presence along the borehole like many other genera (e.g. *Camarozonotriletes*, *Dibolisporites*, *Emphanisporites*, *Grandispora*, *Samarisporites*, *Verrucosisporites* and *Zonotriletes*). The *Ancyrospora* are only present in the Awaynat Wanin Formation III whereas first specimens (*Hystricosporites*) of spores sculptured with anchor elements occur from the lower part of the Awaynat Wanin II Formation. *Archaeozonotriletes* displays a discontinuous presence along the section. *Auroraspora* occurs only in the lower part of the Awaynat Wanin I Formation and from the upper part of the Awaynat Wanin III Formation. *Brochotriletes* and *Dictyotriletes* and more generally reticulate/foveolate spores are mainly found in the Ouan-Kasa Formation and rarely punctually in the upper part of the section. *Synorisporites* and papillate spores also are characteristic of the lowest Formation. Convolute/rugulate (*Chelinospora timanica*, *Convolutispora* spp.) spores are mainly found from the base of the Awaynat Wanin I Formation. *Cymbosporites* is above all characteristic of the top of the section notably with the *C. catillus* Morphon and *Cymbosporites* sp. 4. *Geminospora* appears from the Ouan-Kasa Formation with *G. svalbardiae* but becomes an important component in the Awaynat Wanin II Formation with *G. lemurata*. Rare three-layered spores (*Grandispora* sp. 1) occur punctually in the upper part of the borehole.

The curve of diversity increases slightly along the sampled section (Figs 3.10, 3.11 and 3.12). The number of different taxa recognized per sample varies from 9 to 36. Trilete spores dominate the miospore assemblages. The cryptospores constitute a minor percentage of the miospore assemblages all along the section. Megaspores are not found probably because of the more distal position of borehole MG-1 in the basin. Note that monolete spores seem to represent about 11% of the whole miospore assemblage of the sample 2557.5 m but that can be explained by the low diversity of this sample (Figs 3.11).

It is difficult to draw conclusions about the evolution of the miospore assemblages in terms of palaeogeographical affinity and exine structure since the curves do not show marked trends (Fig. 3.12).

Comparisons with other assemblages

The poor oldest spore assemblage from the Ouan-Kasa Formation has similarities with those from the *annulatus-sextantii* Assemblage Zone of Richardson & McGregor (1986) and the AB-FD Oppel Zones of Streel et al. (1987). It is not older than the AB Oppel Zone. The co-occurrence of *Brochotriletes foveolatus*, *Dibolisporites eifeliensis*, *Emphanisporites annulatus*, *Perotrilites caperatus* and *Retusotriletes maculatus* are typical of an Emsian assemblage.

In the overlying samples, some typical Pragian and/or Emsian species such as *Camarozonotriletes sextantii*, *Dictyotriletes subgranifer*, *Emphanisporites schultzii* and *Verrucosisporites polygonalis* first appear. They are not recorded in the underlying Emsian spore assemblage probably because of the poor state of preservation. In addition, *Acinosporites apiculatus*, *Densosporites devonicus*, *Grandispora permulta* and *Grandispora protea* also occur. The group of large spinose zonate-pseudosaccate miospores proliferates almost throughout the top of the section. These assemblages indicate the *douglastownense-eurypterota* Assemblage Zone of Richardson & McGregor (1986) and AP-Pro Interval Zone of Streel et al. (1987) and are late Emsian/early Eifelian in age. *G. permulta* is a common endemic species of western Gondwana and is the index species of the late early Eifelian Per Interval Zone of Melo & Loboziak (2003). It may occur a little bit earlier in North Africa.

D. devonicus which marks the base of the younger *devonicus-naumovii* Assemblage Zone of Richardson & McGregor (1986) and AD Oppel Zone of Streel et al. (1987) seems appear abnormally very early but Streel & Loboziak (1996) do not consider anymore this species as defining the base of the latter. Besides, *D. devonicus* is difficult to distinguish from other variant of the same genus (see Volume III). No *Acinosporites acanthomammillatus* (the other index species of the AD Oppel Zone) is found in these levels but it appear sporadically from sample 2527 m. The AD Oppel Zone could be recognized from this sample although *A. acanthomammillatus* is rare in this section. A markedly Eifelian age can be attributed for this interval.

As first *Geminospora lemurata* specimens appear from sample 2315 m, the base and lower part of the *lemurata-magnificus* Assemblage Zone of Richardson & McGregor (1986) or AD-Lem Interval Zone of Streel et al. (1987) is somewhere between sample 2375 m and 2315 m. Its base is dated as earliest Givetian. *Rhabdosporites langii* first appears in borehole MG-1 almost at the same time as *Geminospora lemurata*. This feature is similar to the *Geminospora lemurata-Chelinospora* ex gr. *ligurata* (LLi) Interval Zone of Melo & Loboziak (2003) in Brazil. *Lophozonotriletes media* from the Frasnian BM Oppel Zone of Streel et al. (1987) is found in this interval of borehole MG-1. It is earlier than in Euramerica. According to Streel (pers. comm., 2007), this difference may be explained by the use of a larger concept of *L. media* in this study (see Volume III).

Samarisporites triangulatus which marks the base of the TA Oppel Zone of Streel et al. (1987) and the Trg Interval Zone of Melo & Loboziak (2003) first occurs from sample 2258 m. A middle Givetian age is suggested for this sequence up to the first inception of *Chelinospora concinna* at the base of the Awaynat Wanin III Formation. As no typical Frasnian species are found in the highest samples, the lower part of the TCo Oppel Zone of Streel et al. (1987) is identified and characteristic of a late Givetian age.

Sample 2631.2 m contains lots of reworked early Devonian species and do not contain autochthonous material. This event could reflect late Caledonian tectonic phases from the top of the Emsian which are known to have affected parts of western Libya (Bellini & Massa, 1980; El-Rweini, 1991; Abdesselam-Rouighi, 1991; Echikh, 1992) and eastern Algeria (Boudjema, 1987; Ford & Muller, 1995).

In comparison with the results of Loboziak et al. (1992a), there are some changes and the differences in palynostratigraphic and chronostratigraphic charts are illustrated in Fig. 3.13. Although the collected faunas do not allow a precise dating (see above), they do not contradict the results given by miospore zonation. Massa (1988) allocated each formation to a unique stage. Loboziak et al. (1992a) considered the Ouan-Kasa and the lower part of Awaynat Wanin I Formations as Emsian in age. An Eifelian age was allocated from the rest of Awaynat Wanin I Formation to the upper part of the Awaynat Wanin II Formation. Givetian strata were considered as much reduced in thickness and occurred only in the upper part of the Awaynat Wanin II Formation. The Awaynat Wanin Formation III was dated as Frasnian. In Loboziak et al. (1992a), first inception of lots of species is alleged to occur higher in the sequence. For example, *Geminospora lemurata* first appears at the base of the Awaynat Wanin III Formation (sample 2205 m) according to Loboziak et al. (1992a) whereas specimens start to occur in sample 2315 m according to the present results; it means a difference of 110 m between the two studies. These differences may be partly caused by the use of different species concepts according to Streel (pers. comm., 2007). That may be certainly true for *Lophozonotriletes media* which is found markedly earlier than in Euramerica. However, for the other index species, the concept of species such as *Chelinospora timanica*, *Densosporites devonicus*, *Geminospora lemurata* and *Samarisporites triangulatus* seems similar as the specimens illustrated in both studies strongly resemble. In addition, the same remark may be done as for A1-69; Loboziak et al. (1992a) recognized above all characteristic species of the Western Europe zonation of Streel et al. (1987) and they took little notice of endemic taxa.

Chapter 4 – Biozonation & correlation

4.1. Previous miospore biostratigraphic scales

4.1.1. Introduction

The two main Devonian miospore zonations defined by Richardson & McGregor (1986) and Streel et al. (1987) from Euramerican material are commonly used in most of the palynological studies (see 1.6). Loboziak & Melo (2002) simplified the Western European biozonation of Streel et al. (1987) to apply it to western Gondwanan localities. In addition, they associated the ranges of some endemic miospores which could represent useful zonal markers for the regional biozonation (Loboziak & Streel, 1995a). In northwestern Gondwana, Massa & Moreau-Benoit (1976) and Moreau-Benoit (1989) established also a unique detailed biozonation (see 3.4).

The palynological analyses have shown here that the reference spore zones usually used in Euramerica are not all recognized in the Gondwanan coeval sections. This can be due to the absence or the rarity of several index species. The Euramerican index species such as *Acinosporites macrospinosus*, *Ancyrospora ancyrea* var. *ancyrea*, *A. eurypterota*, *A. kedoae*, *Cymbosporites magnificus*, *Emphanisporites foveolatus*, *Hystricosporites* cf. *corystus*, *H. reflexus*, and *Samarisporites praetervisus* among others are not observed here. In addition, some species in the studied sections first occur in different stratigraphic levels from those of Euramerica. For example, *Rhabdosporites langii*, which characterizes the *velata-langii* Assemblage Zone of Richardson & McGregor (1986), spans a part of the AP and AD Oppel Zones of Streel et al. (1987). Its first occurrence is thus considered as early Eifelian in many localities in Euramerica (see Volume III). However, *R. langii* which has a reliable first inception in the studied boreholes appears in Givetian strata more or less in the meantime as that of *Geminospora lemurata* which marks the base of the *lemurata-magnificus* Assemblage Zone of Richardson & McGregor (1986) or the Lem Interval Zone of Streel et al. (1987).

Since the Western European zonation of Streel et al. (1987) was used in the previous studies (Loboziak & Streel, 1989; Loboziak et al., 1992a) on the North African boreholes revised here, it has also been attempted to apply it in Chapter 3. Significant differences in the results are demonstrated between the two boreholes. The upper Oppel Zones (Lem, TA and TCo) can be easily applied and do not seem to show large lateral variations. On the contrary, the lower parts of the sections show greater differences. The Vel Interval Zone is not recognized in borehole MG-1. In the same section, *Grandispora protea* co-occurs with *Densosporites devonicus* which marks theoretically the base of the AD Oppel Zone (see 3.5.2). In short, some minor problems crop up with the application of biozonation from Euramerica to studied sections for accurate regional correlations.

4.1.2. Cosmopolitanism vs. endemism

In this study, 162 different species are found in all Saudi sections taken together. Among these, about 49% are found outside Gondwana (cosmopolitan species) and the remaining 51% are restricted to Saudi Arabia or Gondwana (endemic species). In North Africa, from the 110 and 117 species observed respectively in boreholes A1-69 and MG-1, about 60% are cosmopolitan species. The remaining 40% are taxa endemic to North Africa or Gondwana. In term of number of specimens, these endemic taxa may represent a greater again percentage of the whole miospore assemblages. Therefore, one of the main problems for miospore-based palynostratigraphy and biostratigraphy in general is provincialism. Almost since their origin, land plant taxa have not been cosmopolitan, and therefore the lateral extension of correlation by miospores is risky (Traverse, 2007). Precise transcontinental correlation is sometimes difficult, intercontinental correlation is again more difficult and sometimes impossible (except in very broad terms). A new biozonation based on the own characteristics of the miospore assemblages described here could allow more accurate local/regional correlations.

4.2. New biozonation applied for northwestern Gondwana

The ranges of the main species occurring in northwestern Gondwana have been plotted in a composite stratigraphic chart (Fig. 4.1). The plotted stratigraphic ranges of all taxa do not represent a mean based on their local range in each section but is their total stratigraphic range. The first and last occurrences of each taxon have been taken into account in all cored sections whereas only last occurrences in borehole S-462 have been used because first occurrences in drill section may be influenced by caving (see 1.5.3). Parts of the stratigraphic ranges of some species which showed inconsistent occurrences may indicate reworking of these specimens. Consequently, these inconsistent occurrences as the stratigraphic range of all taxa have been compared to the Devonian palynological literature (see Volume III) in order to determine if the suspected reworking is possible. If a cosmopolitan species is only known elsewhere in older levels, its upper occurrences are not plotted only if they are inconsistent, i.e. non continuous, because they result very likely from reworking processes. The upper limit of plotted stratigraphic range is thus based on their last consistent occurrence when it is possible to do. When a species is rare, it is difficult to assess the consistency of their occurrence. Note also that the coeval species plotted in Fig. 4.1 are not necessarily found always together. Some taxa are known only in North Africa and the reverse is true too. In addition, when several species are plotted as coeval it often means that it is difficult to rank their very close first inceptions according to their recording in the different sections. Fig. 4.1 is a schematic and simplified chart. As it is difficult to take into account each relative stratigraphic position of each species in comparisons with all other species to establish such a handmade chart, the successive occurrence of species may appear jerky. In reality, the species must likely appear more progressively. Finally, the thickness of each biozone is a mean of their local thickness in sections when biozones are entirely recognized and not condensed.

By studying, analyzing and comparing stratigraphic range of miospores species and composition of different assemblages of the studied boreholes/wells, a new biozonation can be defined. As each type of biozones has different advantages and disadvantages (see 1.5.2), different types of biozones have been combined to establish the most useful biozonation. The assemblage zones have been used to subdivide the stratigraphic column on a large scale. Firstly, their advantage is that they are probably the most easily applicable for long-distance (intercontinental) correlation to other studies. Secondly, some general characteristics or trends of the assemblages may be included in order to be also useful in a local/regional use. Finally, several index species may be designated for the recognition of the zone. Thus, in spite of the absence of one or two index species in a studied section, the assemblage zone might be recognizable. The assemblage zones are themselves divided into subzones when it is possible for a more accurate stratigraphy. These subzones are either interval or acme zones. The interval zones are not useful if their index taxon is absent for any reason but they can be very useful for local/regional correlations in a same phytogeographic province. However, a note of caution is expressed regarding the use of interval zones, because it is quite possible that the age of first occurrences may vary spatially due to immigration/migration or subtle biogeographical, ecological or facies effects (Wellman, 2006). Nevertheless, the use of interval zones is still the only way to correlate miospores with other palaeontological groups such as conodonts and foraminifera. As regards the acme or abundance zones, their use is tenuous and probably more of ecological significance than anything else but they are above all useful for local correlation. Lineage zones have not been applied here in spite of some possibilities. Lots of cases of morphological variation are probably due to ontogeny, i.e. different state of maturation of sporangia, and the different morphotypes from a same morphological lineage often co-occur all along their ranges. Few cases show morphological variation with time (see Volume III). The boundaries of such miospore lineage are commonly arbitrary and difficult to applicable at this stage of the work. In order to build a solid local/regional biozonation, it does not much matter that used index species are widespread (cosmopolitan) or endemic species. First and foremost, they must be easily recognizable but also uneasily confused with other possible taxa and numerous enough in these sections to define solid biozones. In addition, these index species have to show the same succession in the different studied sections.

The new proposed scheme based on a combination of diverse types of biozones consists of 9 assemblage zones, 8 interval zones and 2 acme zones (including the D3B Subzone based on leiospheres) spanning in age from late Pragian to late Givetian/?early Frasnian. Thanks to this new local/regional biozonation, the studied sections from the three distinct regions have been correlated (Fig. 4.2). Correlation within each region is also figured separately (Figs 4.3, 4.4 and 4.5). Generally in palynological studies, the base of biozones is located at the sample where the index species first appear. However, these species might occur in unsampled strata below their first observed occurrence. Thus, it is closer to reality to place the base of biozones between two samples although uncertainty still remains in biozonation. That is why the limits of biozones do not correspond to the samples. From base to top, the assemblages are defined and compared to biozones defined in the literature (Figs 4.6 and 4.7). The age of each assemblage is discussed. As few precise independent palaeontological dating is available for the studied areas, we have to keep in mind that the suggested ages are only based on the comparisons with reference spore biozones which themselves are dated independently. The use of the high-resolution conodont-based international Devonian stratigraphy allows to date the miospore zonation from Western Europe of Streel et al. (1987) (e.g. Streel & Loboziak, 1996; Streel et al., 2000).

4.3. Assemblage Zone 1 (A1)

Geographic and lithostratigraphic distribution

This assemblage is only recognized in the lower part of the Sha'iba Member from the Jauf Formation in Saudi Arabia, i.e. in borehole BAQA-2 (Fig. 4.2).

Biozone boundary definition

This assemblage is worth being defined because it seems easily distinguishable from the overlying assemblage. As this biozone is only recognized in two samples, its real extension and its lower boundary are not known and therefore it will need to be updated in the future.

Reference section

Borehole BAQA-2 is the only possible reference section, in the samples 133.0’ and 134.4’.

Characterization of the biozone

A1 contains above all small-sized simple spores. The most characteristic trilete spores are *Amicosporites streelii*, *Biornatispora dubia*, *Brochotriletes foveolatus*, *Camarozonotriletes filatoffii*, *Chelinospora cantabrica*, *Cirratriradites diaphanus*, *Clivosispora verrucata*, *Cymbosporites dammamensis*, *C. rarispinosus*, *Dibolisporites eifeliensis*, *Dictyotriletes emsiensis*, *D. subgranifer*, *Lycospora culpa*, *Retusotriletes maculatus*, *Scylaspora costulosa*, *Synorisporites papillensis* and *Verrucosisporites polygonalis*. Cryptospores are rather well-diversified with several species of *Cymbohilates* (e.g. *C. baqaensis* and *C. comptulus*) and *Gneudnaspora divellomedia* var. *minor* and constitute in term of specimens almost 10% of the whole miospore assemblage. All these species persist upwards in the succeeding Assemblage 2. The miospores of this section are mainly simple laevigate spores (*Retusotriletes*), simple spores sculptured with discrete elements (mainly *Apiculiretusispora* and *Cymbohilates*) and papillate spores (mainly *Retusotriletes maculatus* and *Synorisporites papillensis*). The simple forms are almost exclusively of uniform thickness or cingulate. However, the zonate spores already occur with *Cirratriradites diaphanus* and *Lycospora culpa*.

Comparison with reference biozones

The co-occurrence of *Verrucosisporites polygonalis* and *Dictyotriletes emsiensis* is the criterion to correlate this assemblage to the *polygonalis-emsiensis* Assemblage Zone of Richardson & McGregor (1986). Moreover, the presence of *Dictyotriletes subgranifer* indicates more precisely the Su Interval Zone of Streel et al. (1987) (Fig. 4.6). A1 corresponds to Palynozone 2 of Moreau-Benoit (1989) (Fig. 4.7).

Age

The Su Interval Zone according to Streel et al. (2000) straddles the Pragian/Emsian boundary. Since no Emsian miospores characteristic of the succeeding *annulatus-sextantii* Assemblage Zone of Richardson & McGregor (1986) or AB Interval Zone of Streel et al. (1987) are recorded, A1 is considered of late Pragian or earliest Emsian.

4.4. Assemblage Zone 2 (A2)

Geographic and lithostratigraphic distribution

This assemblage is present conformably in Saudi Arabia from the Sha’iba to the top of the Subbat Member from the Jauf Formation. It is recognized in boreholes BAQA-1, BAQA-2 and wells ABSF-29, FWRH-1, HWYH-956, KHRM-2, NFLA-1, SDGM-462, UTMN-1830 (Fig. 4.2). Characteristic species of this biozone are also recognized in a reworked level (sample 2631.2 m) from the Ouan-Kasa Formation in borehole MG-1 in North Africa.

Biozone boundary definition

Its lower boundary is based on the first (almost coeval) occurrence of *Cymbosporites senex*, *Dictyotriletes biornatus* Morphon, ?*Knoxisporites riondae* and *Latosporites ovalis*.

Reference section

No section recorded entirely A2 but the combination of boreholes BAQA-2 (from 64.5’ to 50.2’), BAQA-1 and the lower part of JNDL-4 (from 499.1’ to 411.5’) can serve as a reference section since these sections are easily correlated by lithostratigraphic and sedimentologic data.

Characterization of the biozone

The most characteristic species to appear in the assemblage are *Apiculiretusispora brandtii*, *Artemopyra inconspicua*, *Artemopyra recticosta*, *Cymbosporites asymmetricus*, the *Diaphanospora* sp. 1 Morphon, *Gneudnaspora divellomedia* var. *divellomedia*, *Emphanisporites schultzii*, *Reticuloidosporites antarcticus* and *Retusotriletes tenerimedium* appear. These characteristic species apart, almost those from the underlying assemblage A1 are still present. Several species of *Chelinospora* (e.g. *C. cantabrica*, *C. hemiesferica*, *C.* cf. *hemiesferica*, *Chelinospora* sp. 2) disappear within A2. The trilete spores are still dominated by simple forms (*Apiculiretusispora* and *Retusotriletes*) but are more and more diversified. They comprise diverse simple spores sculptured with discrete elements (mainly *Cymbosporites*, *Dibolisporites* and *Verrucosisporites*), reticulate/foveolate spores (*Biornatispora dubia*, *Brochotriletes*, *Camarozonotriletes sextantii*, and *Dictyotriletes*), convolute/rugulate spores (*Chelinospora*), radial-patterned spores (*Emphanisporites* and *Scylaspora*) and papillate spores (e.g. *Cirratriradites diaphanus*, ?*Knoxisporites riondae*, *Retusotriletes maculatus* and *Synorisporites papillensis*). Although the trilete spores are mainly of uniform thickness, cingulate or patinate, the zonate spores diversify and become more numerous and often larger (up to more than 130 µm) than in A1. *Zonotriletes* sp. 1, *Zonotriletes* sp. 2 and *Perotrilites caperatus* make their first inception in A2. Cavate spores are already present from the base of the assemblage with *Leiozosterospora* cf. *L. andersonii*. Although a unique specimen of sculptured monolete spore (*Devonomonoletes* sp. 1), which is a poorly-known species, is recorded in the underlying assemblage, A2 is characterized by the first significant inception of monolete spores. The simple laevigate monolete spores (*Latosporites ovalis*) first occurs at the base of A2 followed later by the short-ranged reticulate form *Reticuloidosporites antarcticus* apparently only known in Gondwana. The cryptospores still constitute a significant part with *Cymbohilates* genus and diversify with the first apparition in this study of *Artemopyra* genus and large laevigate hilate cryptospore specimens (*Gneudnaspora divellomedia* var. *divellomedia*). An interesting event characterizes the uppermost part of A2, below the lower boundary of the overlying assemblage and the D3B Subzone of Al-Hajri et al. (1999). It corresponds to a punctual significant increase of *Cymbosporites senex* specimens. These can constitute up to almost 60% of the whole palynological assemblages (see 2.6.3). This event is sometimes also accompanied by large amounts of cryptospores *Cymbohilates comptulus*, and recorded in all sections where A2 is recognized, however its intensity varies according to the sections. On this base, an acme zone can be defined (see below).

A2 is divided into 3 subzones which seem to be useful at local scale in Saudi Arabia (Figs 4.4 and 4.5). They are defined below.

Comparison with reference biozones

The only index species used in Euramerica and recognized all along A2 are *Dictyotriletes emsiensis*, *D. subgranifer* and *Verrucosisporites polygonalis*. However, the diversified composition of A2 seems to indicate a younger biozone than the *polygonalis-emsiensis* Assemblage Zone of Richardson & McGregor (1986) and the Su Interval Zone of Streel et al. (1987) (Fig. 4.6). Because of the absence of taxa characteristic of Palynozone 3 of Moreau-Benoit (1989), A2 corresponds still to Palynozone 2 of Moreau-Benoit (1989) (Fig. 4.7).

Age

The composition of the assemblage indicates at least a late Pragian but an early Emsian age may not be totally rejected. The occurrence of first monolete spores is interesting as they are not older than Emsian according to Traverse, 2007. However, Wellman (2006) found a unique specimen of monolete spores in an assemblage corresponding to the Su Interval Zone. In the literature, the earliest record of monolete spores to date appears to be that of *Reticuloidosporites antarcticus* in Kemp (1972) which is also found here but this Emsian assemblage from Antarctica is only dated by comparisons of spore assemblages. Moreau-Benoit (1966) figured 2 monolete species from the Emsian of Brittany (France). In Euramerica, first rare monolete spores occur from the Emsian *annulatus-sextantii* Assemblage Zone of Richardson & McGregor (1986). The very first appearance of monolete spores may be in late Pragian-?earliest Emsian. The Pragian/Emsian boundary may, therefore, lies somewhere in A2.

4.4.1. Interval Zone A2a

Geographic and lithostratigraphic distribution

A2a is present in Saudi Arabia from the Sha'iba to the lower part of the Subbat Member from the Jauf Formation. It is recognized in boreholes BAQA-1 and BAQA-2 (Fig. 4.2).

Biozone boundary definition

Its lower boundary corresponds to that of A2. It is based on the first occurrence of *Latosporites ovalis*, the first laevigate monolete spore. Although this species is not a main component of the miospore assemblages, it is easily distinguishable even in a poorly-preserved material. The upper boundary is marked by the first occurrence of the *Diaphanospora* sp. 1 Morphon (A2b).

Reference section

No section recorded A2a in its entirety but the combination of boreholes BAQA-2 (from 64.5’ to 50.2’), and the lower part of BAQA-1 (from 416.6’ to 366.9’) can serve as a reference section since these boreholes are easily correlated by lithostratigraphic and sedimentologic data.

4.4.2. Interval Zone A2b

Geographic and lithostratigraphic distribution

A2b is present in Saudi Arabia from the Sha’iba to the lower part of the Subbat Member from the Jauf Formation. It is recognized in boreholes BAQA-1 and BAQA-2 and wells FWRH-1, HWYH-956, KHRM-2, NFLA-1, SDGM-462, UTMN-1830 (Fig. 4.2).

Biozone boundary definition

Its lower boundary is based on the first occurrence of the *Diaphanospora* sp. 1 Morphon (see Volume III). These forms are common in Saudi Arabia and easily identifiable. The upper boundary is marked by either a punctual significant increase of *Cymbosporites senex* specimens (A2c) or A3.

Reference section

BAQA-1 (from 345.5’ to 169.1’) can serve as a reference section.

4.4.3. Acme Zone A2c

Geographic and lithostratigraphic distribution

A2c is present everywhere in Saudi Arabia. It is recognizable in the Subbat Member of the Jauf Formation in northwestern (JNDL-4) and eastern Saudi Arabia (ABSF-29, HWYH-956, KHRM-2, SDGM-462, UTMN-1830). *Cymbosporites senex* are markedly less numerous in northwestern Saudi Arabia.

Biozone boundary definition

Its lower boundary is defined by a significant increase of *Cymbosporites senex* specimens.

Reference section

As the acme zone of *Cymbosporites senex* is more easily distinguishable in eastern Saudi Arabia, well HWYH-956 (from 14213.8’ to 14205.4’) is chosen as reference section for A2c.

4.5. Assemblage Zone 3 (A3)

4.5.1 Assemblage Zone A3a

Geographic and lithostratigraphic distribution

This assemblage is present in Saudi Arabia in the upper part of the Subbat, Hammamiyat and Murayr Members from the Jauf Formation. It is recognized in boreholes JNDL-3, JNDL-4 and wells ABSF-29, HWYH-956, KHRM-2, SDGM-462, UTMN-1830 (Fig. 4.2). Its upper part is also recognized in North Africa in the Ouan-Kasa Formation but only in two samples.

Biozone boundary definition

Its lower boundary is based on the first occurrence (almost coeval) of *Acinosporites lindlarensis* and *Stellatispora multicostata*. The lower boundary of A3a in North Africa is not known.

Reference section

A3a is entirely recognized in some sections from eastern Saudi Arabia which are unfortunately condensed. So the reference section is the combination of boreholes JNDL-3 (from 499.5’ to 225.7’) and JNDL-4 (from 404.8’ to 37.1’). As the boreholes are distant from about 15 km, they are easily correlated by lithostratigraphic and sedimentologic data.

Characterization of the biozone

The most characteristic miospore species to appear in A3a are *Brochotriletes* sp. 2, *Camarozonotriletes sextantii*, *Cymbohilates heteroverrucosus*, *Diatomozonotriletes franklinii*, *Emphanisporites annulatus*, *Emphanisporites decoratus*, *Rhabdosporites minutus*, *Stellatispora multicostata* and *Verrucisporites dubia*. At the base of A3a, *Cymbosporites dittonensis*, *C. rarispinosus*, and the *Diaphanospora* sp. 1 Morphon disappear whereas *Cirratriradites diaphanus*, *Cymbohilates comptulus* and *Cymbosporites dammamensis* do it within A3a. In the upper part, *Brochotriletes hudsonii*, *Camarozonotriletes filatoffii*, *Dibolisporites eifeliensis*, *Latosporites ovalis*, *Scylaspora costulosa* and *Stellatispora multicostata* make their last occurrence. This miospore assemblage comprises mainly simple laevigate spores (*Retusotriletes*), simple sculptured spores (*Apiculiretusispora*, *Cymbosporites* and *Dibolisporites*) and radial-patterned spores (*Emphanisporites*). *Dibolisporite*s spp. increases in term of specimens in comparisons with the previous assemblages and *Iberoespora* genus disappears definitively at the base of A3a. The reticulate/foveolate (*Brochotriletes* and *Dictyotriletes*) and convolute/rugulate spores have decreased in number in comparisons with the previous assemblages. The most common species are simple spores of uniform thickness and patinate forms. The other structural miospore groups, i.e. cingulate, zonate and cavate spores are rarer and/or occur sporadically. The cryptospores are above all numerous in specimens in miospore-rich assemblages. *Gneudnaspora* and *Artemopyra* dominate the hilate cryptospores.

In Saudi Arabia, A3a includes the D3B Subzone of Al-Hajri et al. (1999). This biozone is an acme zone characterized by the sudden dominance of small leiospheres (*Leiosphaeridia jaufensis*) in the whole palynological assemblage. This monospecific leiospherid typifies the D3B Subzone that occurs in both eastern and northern Saudi Arabia. These leiospherid-rich, low-diversity assemblages occur in northwestern Saudi Arabia not as a unique event but a series of marine pulses that extends on a four hundred feet thickness. Moreover, the D3B Subzone is much thicker than in eastern Saudi Arabia where it is normally several tens of feet thick and appears as a more condensed and homogenous event. These leiospherid-rich assemblages alternate with normal miospore-dominated assemblages. No signs of the D3B Subzone are recorded in North Africa. The D3B Subzone is described in more details in Chapter 6.

Comparison with reference biozones

Camarozonotriletes sextantii, *Emphanisporites annulatus*, *Rhabdosporites minutus* and *Verrucisporites dubia* allow to partly relate A3a to *annulatus-sextantii* Assemblage Zone of Richardson & McGregor (1986) and the Min Interval Zone of Streel et al. (1987) that is comprised in the FD Oppel Zone (Fig. 4.6). A3a corresponds partly to Palynozone 3 of Moreau-Benoit (1989) (Fig. 4.7). The stratigraphically important species *Acinosporites lindlarensis is* known to appear from the Emsian.

Age

The reference biozones which can be correlated to A3a point out a middle-late Emsian age.

4.5.2. Assemblage Zone A3b

Geographic and lithostratigraphic distribution

This assemblage is present in Saudi Arabia from the upper part of Murayr Member and in the lowermost part of the Jubah Formation. The lack of samples in the lower part of the Jubah Formation does not allow an estimation of its real extension. Its lower part is thus only recognized in borehole JNDL-1 and wells HWYH-956, SDGM-4620 (Fig. 4.2). On the contrary, the whole A3b is present in North Africa in the Ouan-Kasa Formation.

Biozone boundary definition

Its lower boundary is marked by the first occurrence of the first large apiculate and spinose zonate-pseudosaccate spores (*Grandispora/Samarisporites* complex). *Samarisporites* sp. 1 which appears in A3a is small-sized and do not belong to the large apiculate zonate-pseudosaccate spores. Generally *Grandispora protea* appears at first but *G. permulta* is coeval in borehole MG-1 whereas elsewhere it appears in A5. The common species *Dibolisporites gaspiensis*, *Dibolisporites* sp. 1 and rare specimens of *Acinosporites apiculatus* and *Zonotriletes* sp. 4 make their first inception in the meantime. In Saudi Arabia, the lower boundary of A3b may be controlled by particular environmental conditions as it is located above the uppermost level of the marine algal bloom corresponding to D3B Subzone of Al-Hajri et al. (1999).

Reference section

Borehole A1-69 (sample 2040') is the reference section because it contains the entirety of A3b and does not seems influenced by reworking processes as in borehole MG-1.

Characterization of the biozone

Densosporites devonicus is only known in borehole MG-1. *Grandispora douglastownense* and *Samarisporites eximius* appear in the upper part of A3b. First specimens of the spinose-verrucate *Verrucosisporites scurrus* are already present in borehole MG-1. *Acinosporites lindlarensis*, *Apiculiretusispora brandtii*, *Brochotriletes* sp. 2, *Camarozonotriletes sextantii*, *Craspedispora ghadamisensis*, *Cymbosporites asymmetricus*, *C. senex*, *Diatomozonotriletes franklinii*, *Emphanisporites annulatus*, *Granulatisporites* sp. 1 and *Rhabdosporites minutus* appeared previously are still present. Several typical early Devonian taxa disappear within A3b; they are *Amicosporites streelii*, *Apiculiretusispora plicata*, *Biornatispora dubia*, *Clivosispora verrucata*, *Dictyotriletes subgranifer*, *Emphanisporites decoratus*, *Emphanisporites schultzii*, *Retusotriletes maculatus* and *Verrucosisporites polygonalis*. The simple miospores are mainly laevigate (*Retusotriletes*), sculptured (mainly *Acinosporites*, *Apiculiretusispora*, *Cymbosporites* and *Dibolisporites*) and radial-patterned (*Emphanisporites*). *Dibolisporite*s diversifies with the advent of several new taxa. The reticulate/foveolate and convolute/rugulate spores common in Early Devonian have again decreased and become rare. The most common species are still simple spores of uniform thickness but large zonate and pseudosaccate (cavate) spores become significant to the detriment of patinate forms. The cryptospores have decreased in number and seems to be still dominated by *Gneudnaspora* and *Artemopyra*.

Comparison with reference biozones

The first inception of the large zonate-pseudosaccate spores is known elsewhere all over the world and corresponds in Euramerica to the *douglastownense-eurypterota* Assemblage Zone of Richardson & McGregor (1986) and the AP Oppel Zone of Streel et al. (1987), the index species *Acinosporites apiculatus*, *Grandispora douglastownense* and *G. protea* of which are found in A3b. In Brazil, it corresponds to the *Grandispora-Samarisporites* spp. (GS) Interval Zone of Melo & Loboziak (2003). In Eastern Europe, the *Diaphanospora inassueta* (DI) Zone of Avkhimovitch et al. (1993) which includes *G. douglastownense* may be correlated to A3b (Fig. 4.6). Note that *Densosporites devonicus* which is a nominal species of the middle Eifelian-early Givetian *devonicus-naumovii* Assemblage Zone of Richardson & McGregor (1986) and the AD Oppel Zone of Streel et al. (1987) seems to appear earlier in North Africa than in Euramerica. After many years of palynological consulting, Streel (pers. comm., 2007) considers now the first inception of *D. devonicus* as unpredictable and consequently does not constitute a reliable criterion to mark the base of the AD Oppel Zone (see 3.5.2). *Grandispora permulta* which is also found in A3b marks the base of the Per Interval Zone of Melo & Loboziak (2003) which lies later in Brazil (Fig. 4.7). A3b corresponds partly to Palynozone 4 of Moreau-Benoit (1989).

Age

This renewal of the miospore assemblages occurred from the late Emsian to early Eifelian. The Emsian/Eifelian boundary is likely situated somewhere in A3b.

4.6. Assemblage Zone 4 (A4)

Geographic and lithostratigraphic distribution

This assemblage is present in North Africa in the upper part of the Ouan-Kasa Formation and the lower part of the Awaynat Wanin I Formation (Fig. 4.2). In Saudi Arabia, only its upper part occurs in the Jubah Formation from borehole JNDL-1 by comparing the two regions. The lack of productive samples both below and above the uppermost group of samples does not allow an estimation of its real extension in Saudi Arabia.

Biozone boundary definition

Its lower boundary is based on the first (almost coeval) occurrence of *Geminospora svalbardiae*, which is relatively abundant, *Grandispora gabesensis* and *G. velata*. *Jhariatriletes emsiensis* occurs briefly at the base of A4.

Reference section

Borehole A1-69 (from 1962’ to 1830’) is the reference section for A4.

Characterization of the biozone

Acinosporites acanthomammillatus, *Ancyrospora nettersheimensis*, *Auroraspora minuta*, *Camarozonotriletes rugulosus*, *Dibolisporites pilatus*, *Samarisporites angulatus*, *Squamispora arabica*, *Zonotriletes armillatus* and *Z. simplicissimus* first appear in the upper part of A4. In addition of these new taxa, *Acinosporites lindlarensis*, *Cymbosporites asymmetricus*, *Diatomozonotriletes franklinii*, *Dibolisporites* sp. 1, *Emphanisporites annulatus*, *Grandispora protea*, *G. douglastownense*, *Rhabdosporites minutus*, *Zonotriletes* sp. 1 and *Zonotriletes* sp. 4 are still common in A4. Other ancient taxa disappear in A4; these are *Brochotriletes* sp. 2, *Cymbohilates baqaensis*, *C. heteroverrucosus*, *Cymbosporites senex*, *Dictyotriletes emsiensis*, *Granulatisporites* sp. 1 and *Synorisporites papillensis*. The large apiculate and spinose zonate-pseudosaccate spores proliferate and are abundant throughout the assemblage. They diversify again more with new forms of *Grandispora* and *Samarisporites*. In addition, other pseudosaccate genera (*Auroraspora* and *Geminospora*) and make their first inception in this assemblage. The typical feature of grapnel-tipped spines (*Ancyrospora*) and three-layered spores (*Acinosporites* sp. 1) appears for the first time. The simple miospores are mainly of uniform thickness, laevigate (*Retusotriletes*), sculptured (mainly *Acinosporites*, *Apiculiretusispora* and *Dibolisporites*) and radial-patterned (*Emphanisporites*). Indeed, A4 includes lots of *Emphanisporites* specimens (*E. mcgregorii*, *E. rotatus* and *Emphanisporites* sp. 1) especially in Saudi Arabia. The zonate laevigate spores (*Zonotriletes*) as *Acinosporites* genus, which diversify here, have never been so numerous and seem to reach their acme in this assemblage. In Saudi Arabia, the cryptospores (*Artemopyra*, *Cymbohilates* and *Gneudnaspora*) constitute a significant part of the miospore assemblages in where they may represent up to about 20% of the whole miospore assemblage whereas they are almost exclusively represented by *Gneudnaspora* and much rarer in North Africa. Relatively small megaspores (*J. emsiensis*) first appear in this assemblage in North Africa.

A4 is here difficult to divide into subzones because it is only known in its entirety in North Africa. In addition, the main species which appear within A4 are either restricted to a unique region (e.g. *Acinosporites eumammillatus* and *Ancyrospora nettersheimensis*), or/and the real range of which are unknown so far (e.g. *Dibolisporites pilatus* and *Squamispora arabica*), or/and are not very common locally (e.g. *Acinosporites acanthomammillatus*, *Camarozonotriletes rugulosus*, *Zonotriletes armillatus* and *Z. simplicissimus*).

Comparison with reference biozones

In Euramerica *Ancyrospora nettersheimensis* possesses an acme zone (net) in the AP Oppel Zone of Streel et al. (1987) and is also known in the *douglastownense-eurypterota* Assemblage Zone of Richardson & McGregor (1986). *Grandispora velata*, present in this assemblage, marks the base of the *velata-langii* Assemblage Zone of Richardson & McGregor (1986) and the Vel Interval Zone of Streel et al. (1987). *Acinosporites acanthomammillatus* and *Densosporites devonicus* are the index species of the AD Oppel Zone of Streel et al. (1987) but Streel & Loboziak (1996) showed that the former appears earlier as in the biozonation of Richardson & McGregor (1986), i.e. the *velata-langii* Assemblage Zone (Fig. 4.6). In Eastern Europe, the *Elenisporis biformis* (Bi) Subzone of Avkhimovitch et al. (1993) which includes *A. acanthomammillatus* and *Grandispora velata* may be correlated to the upper part of A4. In North Africa, A4 corresponds to Palynozones 4 and 5 of Moreau-Benoit (1989) (Fig. 4.7). Consequently A4 straddles at least the *douglastownense-eurypterota* and *velata-langii* Assemblage Zones and may correspond eventually partly to the AD Oppel Zone.

Age

The reference biozones which can be correlated to A4 indicate an early-early late Eifelian age.

4.7. Assemblage Zone 5 (A5)

Geographic and lithostratigraphic distribution

This assemblage is present in North Africa in the Awaynat Wanin I Formation and the lower part of the Awaynat Wanin II Formations (Fig. 4.2). In Saudi Arabia, it is recognized in the Jubah Formation only at the base of borehole S-462, but in one sample at least. The lack of samples in the other studied sections does not allow to confirm its lateral extension in eastern Saudi Arabia.

Biozone boundary definition

Its lower boundary is based on the first occurrence of a series of common species which appear more or less coeval. It comprises *Camarozonotriletes*? *concavus*, *Chelinospora timanica*, *Corystisporites multispinosus*, *Grandispora libyensis*, *G.* ?*naumovii*, *G. stolidotus*, *Scylaspora rugulata* and *Verrucosisporites premnus*. Note that the first specimens of *G. libyensis* are morphotype with rather slender spines (see Volume III).

Reference section

As the lower boundary of A5 can be located easily enough in borehole MG-1, the latter is the reference section.

Characterization of the biozone

In addition to the new species, *Elenisporis* sp. 1 and *G. incognita* appear within A5. In the upper part of A5, the most common species to appear are *Archaeozonotriletes variabilis*, *Cristatisporites* sp. 2 and *Dictyotriletes* sp. 2 near the top. The other most characteristic previously known species are *Acinosporites lindlarensis*, *Auroraspora minuta*, *Craspedispora ghadamisensis*, *Diatomozonotriletes franklinii*, *Emphanisporites annulatus*, *Geminospora svalbardiae*, *Grandispora permulta*, *Rhabdosporites minutus*, *Samarisporites eximius* and *Zonotriletes* sp. 4. All members of the *Verrucosisporites scurrus* Morphon, some of which have already occurred previously, are henceforth present and are particularly characteristic of this interval and constitute a main component of the miospore assemblages. A5 also marks the vanishing of ancient common taxa such as *Ancyrospora nettersheimensis*, *Camarozonotriletes sextantii*, *Cymbosporites asymmetricus*, *Dibolisporites gaspiensis*, *Grandispora protea* and *Zonotriletes* sp. 1. The large apiculate and spinose zonate-pseudosaccate spores proliferate again and are still so abundant throughout the assemblage. They have reached their apogee in A5. The sculptured zonate spores are more or less constant whereas laevigate zonate spores have markedly decreased in comparisons with the underlying assemblage (A5). The simple miospores are mainly of uniform thickness, laevigate (*Retusotriletes*), sculptured (mainly *Acinosporites*, *Apiculiretusispora*, *Dibolisporites* and *Verrucosisporites*) and radial-patterned (*Elenisporis*, *Emphanisporites*, *Scylaspora*). The cingulate (*Camarozonotriletes*) and patinate spores (*Archaeozonotriletes* and *Chelinospora*) are rarer. The reticulate/foveolate (*Brochotriletes* and *Dictyotriletes*) are very rare or absent throughout the assemblage whereas the convolute/rugulate spores (*Chelinospora*) come back. The feature of grapnel-tipped spines (*Ancyrospora*) still occurs with rarer specimens of *Hystricosporites* (unplotted in Fig. 4.2) in addition in the upper part (see Volume III). Rare spores characterized by three-layers (*Grandispora* sp. 1) are also recorded. The cryptospores are much rarer in A5; *Gneudnaspora divellomedia var. divellomedia* is sometimes found whereas *Artemopyra* specimens have became very rare. The monolete spores are absent although rare specimens seems to be reworked.

A5 is divided into 2 interval zones which are useful at local scale in North Africa (Fig. 4.3). They are defined below.

Comparison with reference biozones

Grandispora ?naumovii, rare *Acinosporites acanthomammillatus* specimens and local *Densosporites devonicus* specimens found in A5 are the index species of the *devonicus-naumovii* Assemblage Zone of Richardson & McGregor (1986) and the pre Lem portion of the AD Oppel Zone of Loboziak & Melo (2002). This last biozone appear undifferentiated here up to the first appearance of *Geminospora lemurata* whose inception marks the base of the Lem Interval Zone of Streel et al. (1987). The stratigraphically important species *Scylaspora rugulata* appears in Euramerica within the *velata-langii* Assemblage Zone of Richardson & McGregor (1986). A5 could correspond to the upper part of the *velata-langii* Assemblage Zone and the AD-pre Lem Oppel Zone (Fig. 4.6). A5 could also be referred to the *Grandispora naumovii* (GN) Subzone of Avkhimovitch et al. (1993) and the *Rhabdosporites langii* (RL) because of some similar characteristics in the composition of the assemblages from Eastern Europe and North Africa. Although *R. langii* is not found in A5, *Densosporites devonicus*, *Grandispora protea*, specimens of different species of *Camarozonotriletes* and *Diatomozonotriletes*, and specimens of the *Verrucosisporites scurrus* Morphon occur in these Eastern European biozones. In North Africa, Palynozone 6 of

Moreau-Benoit (1989) could be the equivalent of A5. Finally, the composition of the assemblage corresponds to the Per Interval Zone of Melo & Loboziak (2003) in Brazil (Fig. 4.7).

Age

The comparisons with the references biozones demonstrate that A5 extends from the early late Eifelian through earliest Givetian. Loboziak et al. (1990) showed that the widespread *Geminospora lemurata* first occur above the Eifelian/Givetian boundary which is likely located in the upper part of A5 or at the A5/A6 boundary.

4.7.1. Interval Zone A5a

Geographic and lithostratigraphic distribution

A5a is only recognized in the Awaynat Wanin I Formation in North Africa.

Biozone boundary definition

Its lower boundary corresponds to that of A5. It is based on the first occurrence of *Scylaspora rugulata*. Although this species is not a main component of the miospore assemblages, it is easily distinguishable even in a poorly-preserved material. The upper boundary is defined by the first occurrence of *Grandispora incognita* (A5b).

Reference section

Borehole MG-1 (sample 2536.0 m to 2518.0 m) is the reference section for A5a.

4.7.2. Interval Zone A5b

Geographic and lithostratigraphic distribution

A5b is only recognized in the upper part of the Awaynat Wanin I and the lower part of Awaynat Wanin II in North Africa. A5b is the upper subzone of A5 but it is not recognized in its own in S-462. The sample in S-462 where undifferentiated A5 is recognized is very poor in miospores.

Biozone boundary definition

Its lower boundary is based on the first occurrence of *Grandispora incognita* which is a common species in the studied region. The upper boundary is based on the first occurrence of *Geminospora lemurata* (A6).

Reference section

Borehole A1-69 (from 1596’ to 1490’) is the reference section for A5b.

4.8. Assemblage Zone 6 (A6)

Geographic and lithostratigraphic distribution

This assemblage is present in the Jubah Formation in Saudi Arabia and in the Awaynat Wanin II Formation in North Africa (Fig. 4.2). It seems to be known in its entirety in North African sections and borehole S-462 whereas the few samples from wells ABSF-29 and YBRN-1 allow to recognize only a little part of it, probably the upper part.

Biozone boundary definition

Its lower boundary is only based on the first occurrence of *Geminospora lemurata*. The upper boundary is defined by the first occurrence of *Samarisporites triangulatus* (A7). Although the boundaries of A6 correspond in theory to an interval zone (see 1.5.2), this biozone is described as an assemblage zone because numerous species and general characteristics of the assemblages are included in the characterization of A6.

Reference section

Borehole A1-69 (from 1486’ to 1296’) is the reference section for A6 because its lower boundary is precisely located in it.

Characterization of the biozone

Geminospora punctata and *Rhabdosporites langii* make their first inception more or less in the meantime as *G. lemurata*. *Cymbosporites* sp. 4, then *Camarozonotriletes parvus*, *Corystisporites undulatus*, *Dibolisporites turriculatus*, and *Lophozonotriletes media* appear within A6. First specimens of *Contagisporites optivus* appear near the top of this interval. The other most common typical taxa, previously appeared, are *Archaeozonotriletes variabilis*, *Acinosporites lindlarensis*, *Auroraspora minuta*, *Camarozonotriletes*? *concavus*, *Chelinospora timanica*, *Craspedispora ghadamisensis*, *Cristatisporites* sp. 2, *Diatomozonotriletes franklinii*, *Dictyotriletes* sp. 2, *Elenisporis* sp. 1, *Emphanisporites annulatus*, *Grandispora incognita*, *G. libyensis*, *G. ?naumovii*, *G. permulta*, *G. stolidotus*, *Samarisporites eximius*, *Scylaspora rugulata*, *Zonotriletes* sp. 4 and the different forms of the *Verrucosisporites scurrus* Morphon. *Apiculiretusispora brandtii*, *Geminospora svalbardiae*, *Grandispora velata* and *Rhabdosporites minutus* are the most characteristic species to vanish in A6. The large apiculate and spinose zonate-pseudosaccate spores continue their apogee and are accompanied now by abundant smaller cavate spores (*Geminospora*). Besides, the cavate spores (*Auroraspora*, *Geminospora*, *Grandispora* and *Rhabdosporites*) in general with the simple spores of uniform thickness are the two main structures in the miospore assemblages. Cingulate (*Camarozonotriletes* and *Lophozonotriletes*), patinate (*Archaeozonotriletes*, *Chelinospora* and *Cymbosporites*) and zonate (*Zonotriletes*) spores are in minority, although patinate are more numerous than in A5 and A6. The simple miospores are still dominated by laevigate (*Retusotriletes*) spores but these have began to decline, sculptured (mainly *Acinosporites*, *Apiculiretusispora*, *Cymbosporites*, *Dibolisporites* and *Verrucosisporites*) and radial-patterned (mainly *Emphanisporites*) spores. The reticulate/foveolate spores remain still rare however new minor forms appear from time to time (e.g. *Brochotriletes* sp. 1, unplotted in Fig. 4.2). The three-layered cavate spores are represented by *Grandispora* sp. 1 and *Rhabdosporites streelii*. The cryptospores are uncommon, only specimens of *Gneudnaspora* and *Artemopyra* are found. The monolete spores seem to reappear discreetly after a distinct decline in the underlying assemblages. Monolete *Geminospora lemurata* are not so rare and first large cavate monolete spores (*Archaeoperisaccus* cf. *A. rhacodes*) first occur from A6 but remain very poorly known in this work. More and more megaspore specimens (including *Contagisporites optivus*) appears throughout A6. Most of them are unstudied in this work but described in de Ville de Goyet et al. (2007).

A6 is divided into 2 interval zones which are useful at local scale in North Africa (Fig. 4.3). They are defined below.

Comparison with reference biozones

This assemblage characterized above all by the widespread first occurrence of *Geminospora lemurata* equals the Lem Interval Zone of Streel et al. (1987) and the lower part of the *lemurata-magnificus* Assemblage Zone of Richardson & McGregor (1986) in Euramerica (Fig. 4.6). In Eastern Europe, these reference biozones are correlated to the lower part of the *Geminospora extensa* (EX) Zone of Avkhimovitch et al. (1993). A6 corresponds to Palynozone 7 of Moreau-Benoit (1989) (Fig. 4.7). The stratigraphically important species *Rhabdosporites langii* appears later here than in Euramerica. It is similar in the Amazon Basin, where *R. langii* is only characteristic from the *Geminospora lemurata-Chelinospora* ex gr. *ligurata* (LLi) Interval Zone of Melo & Loboziak (2003) (Fig. 4.7). *Lophozonotriletes media* which is the index species of the Frasnian BM Oppel Zone of Streel et al. (1987) is found earlier than in Euramerica. According to Streel (pers. comm., 2007), this difference is probably explained by the use of a larger concept of *L. media* in this work (see Volume III). As specimens attributed to *L. media* seem to be very variable in time and space, it could be an unreliable key species for precise biostratigraphy.

Age

Loboziak et al. (1990) consider the Lem Interval Zone of Streel et al. (1987) as early Givetian in age but not the earliest.

4.8.1. Interval Zone A6a

Geographic and lithostratigraphic distribution

A6a is recognized in the Awaynat Wanin II Formation in North Africa and partly in the Jubah Formation in Saudi Arabia (borehole YBRN-1).

Biozone boundary definition

Its lower boundary corresponds to that of A6 as it is based on the first occurrence of *Geminospora lemurata*. The upper boundary is defined by the first occurrence of *Corystisporites undulatus* (A6b).

Reference section

Borehole A1-69 (from 1486’ to 1416’) is the reference section for A6a.

4.8.2. Interval Zone A6b

Geographic and lithostratigraphic distribution

A6b is recognized in the Awaynat Wanin II Formation in North Africa and partly in the Jubah Formation in Saudi Arabia (borehole YBRN-1).

Biozone boundary definition

Its lower and upper boundaries are based respectively on the first occurrence of *Corystisporites undulatus* and *Samarisporites triangulatus* (A7).

Reference section

Borehole A1-69 (from 1416’ to 1296’) is the reference section for A6b.

4.9. Assemblage Zone 7 (A7)

Geographic and lithostratigraphic distribution

This assemblage is present in the Jubah Formation in Saudi Arabia and in the Awaynat Wanin II Formation in North Africa (Fig. 4.2). It seems to be known in its entirety in North African sections and borehole S-462 whereas the few samples from wells ABSF-29 and YBRN-1 allow to recognize only a small part in eastern Saudi Arabia.

Biozone boundary definition

Its lower boundary is only based on the first occurrence of *Samarisporites triangulatus*. The upper boundary is marked by the first occurrence of *Chelinospora concinna* (A8). Although the boundaries of A7 correspond in theory to an interval zone (see 1.5.2), this biozone is described as an assemblage zone because numerous species and general characteristics of the assemblages are included in the characterization of A7.

Reference section

Borehole A1-69 (from 1293’ to 1074’) is the reference section for A7 because its lower boundary is located very precisely in it.

Characterization of the biozone

The first inception of *Cymbosporites catillus*, *C. cyathus*, *Grandispora fibrilabrata* and *Verrucisporites ellesmerensis* are likely a little bit younger than that of *Samarisporites triangulatus*. The other most common typical taxa, previously appeared, are *Acinosporites lindlarensis*, *Archaeozonotriletes variabilis*, *Auroraspora minuta*, *Camarozonotriletes parvus*, *C.? concavus*, *Chelinospora timanica*, *Corystisporites undulatus*, *Cristatisporites* sp. 2, *Cymbosporites* sp. 4, *Diatomozonotriletes franklinii*, *Dibolisporites turriculatus*, *Emphanisporites annulatus*, *Geminospora lemurata*, *G. punctata*, *Grandispora incognita*, *G. libyensis*, *G. ?naumovii*, *G. permulta*, *Lophozonotriletes media*, *Rhabdosporites langii* and the different forms of the *Verrucosisporites scurrus* Morphon. Note that the specimens of *G. libyensis* possess rather slender spines as well as more massive bulbous biform elements (see Volume III). The two morphotypes intergrade and coexist mainly in A7 (see Volume III). *Contagisporites optivus*, *Craspedispora ghadamisensis*, *Dictyotriletes* sp. 2, *Elenisporis* sp. 1, *Grandispora douglastownense*, *Scylaspora rugulata* and *Zonotriletes* sp. 4 are the most characteristic species to disappear in A7. The general diversity of the miospore populations begins to decrease from the base of this assemblage. The large apiculate and spinose zonate-pseudosaccate spores show a quantitative decrease and announce their decline. They seem to be replaced with numerous small patinate specimens (mainly *Cymbosporites*). Indeed the *catillus* Morphon constitute one of the main components of the miospore assemblages. *Geminospora lemurata* and *Samarisporites triangulatus* are also abundant. The cavate spores (*Auroraspora*, *Geminospora*, *Grandispora* and *Rhabdosporites*) in general, the simple spores of uniform thickness and the patinate spores are the main structures shown by the miospores. The cingulate (*Camarozonotriletes* and *Lophozonotriletes*) and zonate (mainly *Samarisporites*) spores are less numerous. Besides, the laevigate zonate spores (Zonotriletes) are sporadic. As regards the simple miospores, they comprise above all laevigate (*Retusotriletes*), sculptured (mainly *Apiculiretusispora*, *Cymbosporites*, *Dibolisporites* and *Verrucosisporites*) and radial-patterned spores (*Emphanisporites*). *Acinosporites* specimens become rather infrequent. The convolute/rugulate (*Chelinospora timanica* and *Convolutispora*) spores become more common than previously whereas the reticulate/foveolate spores remain still very rare. Moreover, the last persisting species of *Dictyotriletes* disappear in A7. The cryptospores are very uncommon, *Artemopyra* vanish at the base of the assemblage and let *Gneudnaspora divellomedia* var. *divellomedia* as the last survivor of this group. The megaspores are very diverse in both Saudi Arabia and North Africa; they include notably *Contagisporites optivus* and *Verrucisporites ellesmerensis*.

A7 is divided into 2 interval zones (Fig. 4.3) which are defined below.

Comparison with reference biozones

Samarisporites triangulatus is a widespread species and seems to appear almost at the same time everywhere. In Euramerica, A7 corresponds to the TA Oppel Zone of Streel et al. (1987) in spite of the absence of *Ancyrospora ancyrea* var. *ancyrea* in the studied sections (Fig. 4.6). The co-occurrence of *Contagisporites optivus* and *Samarisporites triangulatus* could indicate in part the *optivus-triangulatus* Assemblage Zone of Richardson & McGregor (1986). Although it is generally correlated to the TCo Oppel Zone of Streel et al. (1987), *C. optivus* appears from the underlying TA Oppel Zone in Belgium (Steemans, pers. comm., 2007). Nevertheless, the use of megaspore species for correlation is little reliable since they are recovered from few types of deposit environments. The Eastern European equivalent of A7 is the *Samarisporites triangulatus-Corystisporites serratus* (TS) Subzone of Avkhimovitch et al. (1993). A7 is also comparable with the lower part of the *Samarisporites triangulatus* (Trg) Interval Zone of Melo & Loboziak (2003) defined in the Paraná and Parnaíba Basins. The latter is referred to both TA and TCo Oppel Zones (Fig. 4.7).

Age

The comparisons with the reference biozones suggest a middle-late Givetian age for A7.

4.9.1. Interval Zone A7a

Geographic and lithostratigraphic distribution

A7a is recognized in the Awaynat Wanin II Formation in North Africa but not in the Jubah Formation in Saudi Arabia because of the lack of samples (wells ABSF-29 and YBRN-1) or cutting samples (borehole S-462).

Biozone boundary definition

Its lower boundary is based on the first occurrence of *Samarisporites triangulatus*.

Reference section

Borehole A1-69 (from 1293.0’ to 1277.0’) is the reference section for A7a.

4.9.2. Interval Zone A7b

Geographic and lithostratigraphic distribution

A7b is recognized in the Awaynat Wanin II Formation in North Africa and partly in the Jubah Formation in Saudi Arabia (wells ABSF-29 and YBRN-1).

Biozone boundary definition

Its lower boundary is based on the first occurrence of specimens belonging to the *Cymbosporites catillus* Morphon.

Reference section

MG-1 (from 2252.1 m to 2212.5 m) is the reference section for A7b.

4.10. Assemblage Zone 8 (A8)

Geographic and lithostratigraphic distribution

This assemblage is recognized in the uppermost part of the Awaynat Wanin II Formation and in the Awaynat Wanin III Formation in North Africa and in the uppermost part of the Jubah Formation in borehole S-462 from northwestern Saudi Arabia (Fig. 4.2). Its upper boundary is not known.

Biozone boundary definition

Its lower boundary is only based on the first occurrence of *Chelinospora concinna*. A8 may correspond in theory to an interval zone (see 1.5.2), but this biozone is described as an assemblage zone because numerous species and general characteristics of the assemblages are included in the characterization of A8.

Reference section

MG-1 (from 2205 m to 2160.6 m) is the reference section because A8 extends on numerous samples in it.

Characterization of the biozone

In addition of the first occurrence of *Chelinospora concinna*, this assemblage is mainly distinguished from the underlying assemblage (A7) by the inception of the common species *Ancyrospora langii*, and *Emphanisporites* sp. 3. *Geminospora lemurata*, *Samarisporites triangulatus* and the *Cymbosporites catillus* Morphon is still well represented in large amounts. The other most characteristic previously appeared species are *Auroraspora minuta*, *Camarozonotriletes parvus*, *C.? concavus*, *Chelinospora timanica*, *Corystisporites undulatus*, *Cristatisporites* sp. 2, *Cymbosporites* sp. 4, *Dibolisporites turriculatus*, *Geminospora punctata*, *Grandispora fibrilabrata*, *G. incognita*, *G. ?naumovii*, *G. permulta*, *Lophozonotriletes media*, *Rhabdosporites langii*, and the diverse forms of the *Verrucosisporites scurrus* Morphon. *Diatomozonotriletes franklinii*, *Emphanisporites annulatus*, *G. libyensis*, *Samarisporites eximius* and *Verrucisporites ellesmerensis* disappear before the observed top of A8. The general diversity of the miospore populations is still decreasing. The large apiculate and spinose zonate-pseudosaccate continue their quantitative decline started in A8. The cavate spores (*Auroraspora*, *Geminospora*, *Grandispora* and *Rhabdosporites*) in general and the patinate spores (*Archaeozonotriletes*, *Chelinospora* and *Cymbosporites*) are the main structures shown by the miospores. The simple spores of uniform thickness seem to be a little bit in the background. The cingulate (*Camarozonotriletes* and *Lophozonotriletes*) and zonate (mainly *Samarisporites*) spores are markedly less numerous than the two main structure of spores. The laevigate zonate spores (*Zonotriletes*) are still sporadic. The simple miospores, they comprise above all laevigate (*Retusotriletes*), sculptured (mainly *Cymbosporites*, *Dibolisporites* and *Verrucosisporites*), radial-patterned (*Emphanisporites*), convolute/rugulate (*Chelinospora timanica* and *Convolutispora*) spores. The reticulate/foveolate spores become less rare than previously because of the inception of *Chelinospora concinna*. The feature of grapnel-tipped spines seems to be more and more frequent with the reappearance of *Ancyrospora* genus and the presence of rarer specimens of *Hystricosporites* (unplotted in Fig. 4.2). The cryptospores are still very uncommon, with a unique species, *Gneudnaspora divellomedia* var. *divellomedia*. The monolete spores are above all present with the monolete form of *Geminospora lemurata*. The megaspores are still present in number, including notably *Verrucisporites ellesmerensis*.

As few samples characterize A8 and its upper boundary is not known, this assemblage zone is not divided into subzones.

Comparison with reference biozones

This assemblage is the equivalent of the TCo Oppel Zone of Streel et al. (1987) since *Samarisporites triangulatus* and *Chelinospora concinna* are found together (Fig. 4.6). A8 also corresponds in part to the *optivus-triangulatus* Assemblage Zone of Richardson & McGregor (1986) where *Ancyrospora langii* first appears. Although *S. triangulatus* is present in Eastern Europe, it is difficult to refer A8 to the biozonation of Avkhimovitch et al. (1993) because of the too large differences between the two assemblages. Nevertheless, the *optivus-krestovnikovii* (OK) Zone of Avkhimovitch et al. (1993) is correlated with the upper portion of the *optivus-triangulatus* Assemblage Zone of Richardson & McGregor (1986). In the Amazon Basin, A8 equals more or less the upper part of the Trg Interval Zone of Melo & Loboziak (2003) (Fig. 4.7).

Age

The TCo Oppel Zone of Streel et al. (1987) straddles the Givetian/Frasnian boundary. But no typical Frasnian species are found in the uppermost samples of the studied sections, A8 would be consequently of a late Givetian age. However, an early Frasnian age cannot be totally rejected because there are very few typical species first occurring in early Frasnian. These could be absent for any reasons from northwestern Gondwanan regions.

4.11. Comparison between regional ranges of some cosmopolitan species

As Richardson & McGregor (1986) provided ranges of encountered species in their published stratigraphic chart in Euramerica, the ranges of the species in common with the present work can be compared in both palaeocontinents. As no independent palaeontological calibration is available between the two regions, the calibration of ranges is made on the basis of comparisons between the characteristics of miospore assemblage zones defined in Richardson & McGregor (1986) and those previously described (see above). Even if this reasoning is circular, only broadly compared age ranges of spores in the two regions can be plotted (Fig. 4.8).

Numerous species seem to show synchronous or slightly heterochronous first occurrences in the two distinct regions such as *Acinosporites acanthomammillatus*, *A. apiculatus*, *A. lindlarensis*, *Apiculiretusispora brandtii*, *Archaeozonotriletes variabilis*, *Chelinospora concinna*, *Geminospora lemurata*, *Grandispora protea* and *Scylaspora rugulata*. On the other hand many cases of heterochroneity are probably highlighted in Fig. 4.8. Indeed, the first occurrence of some species (e.g. *Chelinospora timanica*, *Contagisporites optivus*, *Densosporites devonicus*, *Grandispora velata*, and the *Verrucosisporites scurrus* Morphon) is clearly older in the northwestern Gondwanan assemblages defined here. On the contrary, *Ancyrospora nettersheimensis*, *Camarozonotriletes sextantii*, *Emphanisporites annulatus*, *E. decoratus*, *Rhabdosporites langii* and *Verruciretusispora dubia* first occur in older strata in Euramerica. In addition, the heterochroneity phenomenon may disturb the appearance order of some stratigraphically important species. For instance, *R. langii*, which appears earlier than the *V. scurrus* Morphon in Euramerica, occur largely later than the *V. scurrus* Morphon in northwestern Gondwanan assemblages. *Samarisporites triangulatus* appears before *C. concinna* in the new defined biozonation, whereas that is the reverse in Euramerica after Richardson & McGregor (1986). Nevertheless, Streel et al. (1987) showed in Western Europe the earlier occurrence of *S. triangulatus* by comparison with that of *C. concinna*.

In short, certain species and certain structural features seem to have attained widespread geographical distribution instantaneously in terms of geological time. On the other hand, there are some species that apparently do not make their first occurrence contemporaneously. Their first occurrence can be locally as well as regionally heterochronous. The seemingly heterochronous appearance of some species may be explained by significant ecological and hydrodynamic control, in addition to the large-scale palaeogeographical controls (Richardson & McGregor, 1986). In addition to the provincialism, the heterochroneity of some cosmopolitan species seem to make comparisons between coeval assemblages again more challenging. The phenomenon emphasizes the advisability of comparing whole assemblages comprising shared, characteristic species for long-distance correlation using miospores.

4.12. Correlation of lithostratigraphic units

Thanks to the new upward local/regional biozonation, the lithostratigraphic units are correlated (Fig. 4.2). It appears that the Jauf Formation which changes from marine in northwestern Saudi Arabia to marginal marine/continental in eastern regions (Al-Hajri et al., 1999) is isochronous. Indeed, the Assemblage Zone A3a and the D3B Subzone of Al-Hajri et al., 1999) are recognized in the upper part of the Jauf Formation from eastern regions (Fig. 4.5) and in the Hammamiyat and Murayr Members in the Nafud Basin (Fig. 4.4). In addition, the Jauf Formation is known to be less thick in eastern regions (see 2.3.1). Where the Jubah Formation overlies more or less conformably the Jauf Formation, the few samples from the base of the Jubah Formation indicate that it belongs to the Assemblage Zone A3b. There is likely an important unconformity in well YBRN-1 as its lower part shows Assemblage Zones A6 and A7. Although there are no samples from the upper Jauf Formation, several biozones seems to be lacking. The geology is very complex in eastern Saudi Arabia and the region is composed of a series of horst and tilted fault blocks arranged in a general north-south direction. The major faults were originated in the Late Carboniferous Hercynian Orogeny and have been rejuvenated in the Triassic and Late Cretaceous. Deep erosion occurred as a result of the Hercynian Orogeny, effectively removing partly the Devonian over much of this region (Al-Hajri et al., 1999).

In North Africa, the lower part of the Ouan-Kasa Formation is the equivalent of the upper part of the Jauf Formation and the lower part of the Jubah Formation. Therefore, the other lithostratigraphic units correspond to the rest of the Jubah Formation in Saudi Arabia. The Ouan-Kasa Formation and the lower part of the Awaynat Wanin I Formation are likely diachronic as this interval of strata is younger in borehole MG-1 (Fig. 4.3). In upper strata, isochroneity of sediments seems to develop from the upper part of the Awaynat Wanin I Formation as the biozone boundaries are more or less parallel to the lithostratigraphic boundaries.

Chapter 5 – Downward biozonation

5.1. Introduction

Usually the biostratigraphic studies rely on the temporal succession of the apparition points (i.e. first occurrence) of species. Consequently, biozonations are established from base to top, i.e. upwards. Although first occurrences are subject to heterochroneity (see 4.11), resulting from ecological, hydrodynamic and large-scale geographical controls, they tend to be inherently more reliable, and thus are better known than the extinction points, i.e. last occurrences or first down-hole occurrences (Al-Hajri et al., 1999). In addition, last occurrences remain often unused because they may be affected by diverse factors. They can represent persistence of relict floras or they can be artificially renovated by reworking of forms extracted by erosion from older sediments. The reworking processes can be frequent in the continental and coastal facies where miospores are abundant. Last occurrences give less weight in the definition of zonal boundaries (Richardson & McGregor, 1986).

In oil exploration, upward biozonation presents disadvantages in subsurface operations since caving in ditch cutting samples makes the first occurrences less reliable (see 1.5.3) and leads up to mistakes in stratigraphic interpretations. A zonation based on last occurrences (i.e. first down-hole occurrences) or downward biozonation, however, is more interesting as it circumvents contamination by caving. It provides palynostratigraphic data in a timely manner for operational decisions since only the top, and not the base, of a zone needs to be penetrated to confirm its identity. The application of a downward biozonation, however, requires vigilance because possible reworking remains.

5.2. Previous miospore downward biozonation

A downward biozonation is a concept commonly used within oil industry, but most of these biozonations have never been published. Only some few precise attempts were undertaken in Palaeozoic palynology.

To provide stratigraphic control for oil exploration in Saudi Arabia, Al-Hajri et al. (1999) devised an operational palynological zonation based primarily on first down-hole occurrences of some index miospore species (Fig. 5.1). This biozonation was calibrated with the standard Euramerican spore zonations of Richardson & McGregor (1986) and Streel et al. (1987), and further controlled by mega-fossil data from outcrops in northwestern Saudi Arabia (e.g. Boucot et al., 1989; Forey et al., 1992). Six palynozones and four subzones were recognized in the Devonian (see 2.4). Although the distribution and abundance of spores varies both stratigraphically and regionally throughout the Devonian System of Saudi Arabia, this downward biozonation has nevertheless proven to be an invaluable tool in furnishing stratigraphic control for exploration and development.

5.3. New provisional downward biozonation

In the case of downward biozonation, the assemblage zone concept seems attractive in theory (see 1.5.2), but the recognition of assemblage zones is more time-consuming to identify than the interval zones because there are more features to observe. Indeed in office routine, oil palynologists who scan slides from cutting samples in order to identify biozones cannot spend too much time on each slide to describe the characteristics of miospore assemblages. In the case of downward biozonation, the use of the interval zone concept (see 1.5.2) is preferred here to assemblage zones. The advantage to use interval zones in operational palynological zonation is that only some common index species are enough to recognize a succession of biozones during microscope office routine.

Ideally, such type of biozonation can be defined after a detailed miospore study in numerous long-ranging sections. Long-ranging sections reveal the succession of a maximum of species and enable to observe the potential index species for a downward biozonation. Unfortunately, the sections studied in eastern Saudi Arabia are short-ranging and are thus difficult to use for selection of index species. The most complete sections used here to determine the index species of the downward biozonation are boreholes A1-69, MG-1, S-462 and the composite section from northwestern Saudi Arabia. The chosen index species are common and seem to show the same downward succession in the long-ranging studied sections from North Africa and northwestern Saudi Arabia. From the composite stratigraphic chart of Fig. 4.1 (see 4.2), all main miospore species occurring in northwestern Gondwana are sorted according to their first down-hole occurrence (Fig. 5.2). This downward biozonation has above all a local/regional usefulness because it is based on common species in the studied region. The zonation is not presumed to be complete or final. It must be tested in the future on several drilled sections. Modifications will be needed as new data come to hand from continuing exploration and as other previously drilled sections are re-evaluated.

The downward interval zones defined below allow correlation of the studied sections in a relatively reliable way (Fig. 5.3). The correlations on the basis of the downward biozonation show comparable results with those from the upward biozonation (Fig. 5.4) and do not show great differences. The results for biozonation of S-462 are surely more precise with the downward biozonation as it is the only drilled section of the study. The lateral tracings of boundaries of the downward interval zones are consistent (i.e. parallel) with those from the upward biozonation, or show some minor crossovers. Indeed the DI0/DI1, DI1/DI2, DI2/DI3 and DI5/DI6 boundaries cross with the boundaries of the upward biozonation (Fig. 5.4). These crossovers, however, are not very significant as they occur in a reduced thickness and concern only two boundaries at the same time. At first, it can be explained by the fact that the last occurrences are likely less reliable than the first occurrences. Secondly, the downward biozonation is defined from the composite stratigraphic chart that represents the total stratigraphic range of species. Local stratigraphic ranges vary according to the sections. Finally, crossovers of bio-events are inherent in the fossil record and are due to numerous of uncertainty factors (see 1.5.3).

The new proposed provisional scheme based on first down-hole occurrences of several index species consists of 8 interval zones and 1 acme zone (D3B Subzone). In descending order, the biozones are defined, calibrated according to the new upward biozonation established here (Fig. 5.5) and compared to biozones of same type describe in Al-Hajri et al. (1999) (Fig. 5.6).

5.4. Downward Interval Zone (DI0)

DI0 is not considered as a true interval zone since its younger boundary is not known in this work. Its older boundary is characterized by the first down-hole occurrence of *Grandispora stolidotus*. DI0 is recognized in North Africa and in northwestern Saudi Arabia (borehole S-462) (Fig. 5.3). DI0 will need to be updated in the future to know its real range. It equals to the upper part or the entirety of the Assemblage Zone A8 of the new upward biozonation (Figs 5.4 and 5.5). Samples belonging here to DI0 are related to Palynozone D2 of Al-Hajri et al. (1999) (Fig. 5.6).

5.5. Downward Interval Zone (DI1)

DI1 is defined as the interval between the first down-hole occurrences of *Grandispora stolidotus* and *Scylaspora rugulata*. These two species seems common in northwestern Gondwana. Indeed, DI1 is recognized from North Africa to eastern Saudi Arabia (Fig. 5.3). This biozone is also characterized by the first down-hole occurrence of *Acinosporites lindlarensis*, *Brochotriletes foveolatus* and *Emphanisporites annulatus* which seems less reliable than the two previous ones. The younger boundary of this biozone is located within Assemblage Zone A8 of the new upward biozonation (Figs 5.4 and 5.5). DI1 is included in Palynozone D2 of Al-Hajri et al. (1999) (Fig. 5.6).

5.6. Downward Interval Zone (DI2)

DI2 is defined as the interval between the first down-hole occurrences of *Scylaspora rugulata* and *Geminospora svalbardiae*. *Contagisporites optivus* makes its first down-hole occurrence more or less meanwhile. DI2 is recognized from North Africa to eastern Saudi Arabia (Fig. 5.3). The younger boundary of DI2 is situated in the lower part of Assemblage Zone A7 or in the upper part of Assemblage Zone A6 of the upward biozonation (Figs 5.4 and 5.5). DI2 lies within Palynozone D2 of Al-Hajri et al. (1999) (Fig. 5.6).

5.7. Downward Interval Zone (DI3)

DI3 is defined as the interval between the first down-hole occurrences of *Geminospora svalbardiae* and *Synorisporites papillensis*. First specimens of *Camarozonotriletes sextantii* occur downward from DI3. The biozone is only recognized in North Africa as there are not any samples in coeval assemblages from Saudi Arabia (Fig. 5.3). The younger boundary of this biozone is located in the lower part of Assemblage Zone A6 or in the upper part of Assemblage Zone A5 of the upward biozonation (Figs 5.4 and 5.5). The lower part of Palynozone D2 of Al-Hajri et al. (1999) corresponds more or less to DI3 (Fig. 5.6).

5.8. Downward Interval Zone (DI4)

DI4 is defined as the interval between the first down-hole occurrences of *Synorisporites papillensis* and *Apiculiretusispora plicata*. Those two species are often abundant in studied samples. DI4 is recognized in North Africa and northwestern Saudi Arabia (Fig. 5.3). Several endemic taxa (e.g. *Cymbohilates baqaensis*, *C. heteroverrucosus*, *Dibolisporites pilatus* and *Squamispora arabica*) could make their first down-hole occurrence in DI4 in spite of a large sample gap higher in northwestern Saudi Arabia. The younger boundary of DI4 lies within Assemblage Zone A4 from the upward biozonation (Figs 5.4 and 5.5). DI4 could also be referred to Palynosubzone D3A of Al-Hajri et al. (1999) (Fig. 5.6).

5.9. Downward Interval Zone (DI5)

DI5 is defined as the interval between the first down-hole occurrences of *Apiculiretusispora plicata* and the diverse members of the *Dictyotriletes biornatus* Morphon. The younger boundary of this biozone is also characterized by the first down-hole occurrence of *Biornatispora dubia*, *Clivosispora verrucata*, *Emphanisporites decoratus*, *E. schultzii*, *Retusotriletes maculatus* and *Verrucosisporites polygonalis*. DI5 is recognized from North Africa to eastern Saudi Arabia (Fig. 5.3). Its younger boundary seems to lie within the newly defined Assemblage Zone A3b in upward biostratigraphy (Figs 5.4 and 5.5).

DI5 includes the D3B Subzone of Al-Hajri et al. (1999) which is marked by the sudden abundance of the monospecific leiospherid that typifies the D3B (Fig. 5.6). Although the top of the subzone is picked at the top of the acme the monospecific leiosphere appears to range, in low numbers, partly into the overlying subzone. According to Al-Hajri et al. (1999), the top of the D3B Subzone is not based on the leiospherid but the first down-hole occurrence of *Dibolisporites eifeliensis*. Other common taxa may be added now to characterize the top of this subzone; they are *Biornatispora dubia*, *Dictyotriletes subgranifer* and *Latosporites ovalis*. The D3B Subzone is described more in details in Chapter 6.

5.10. Downward Interval Zone (DI6)

DI6 is defined on the basis of the first down-hole occurrence of members of the *Dictyotriletes biornatus* Morphon. However a possibly reworked unique specimen of *Dictyotriletes biornatus* has been found within DI5. This downward interval zone is recognized in Saudi Arabia (Fig. 5.3). Its younger boundary is situated in Assemblage Zone A2 in the newly defined upward biozonation (Figs 5.4 and 5.5). Palynozone D3/D4 of Al-Hajri et al. (1999) which is defined as the interval zone from the first down-hole occurrence of *Dibolisporites eifeliensis* and to the first down-hole occurrence of *Dictyotriletes emsiensis* represents more or less the equivalent of DI6 (Fig. 5.6).

5.11. Downward Interval Zone (DI7)

The younger boundary of DI7 is defined on the first down-hole occurrence of *Lycospora culpa*. The older boundary of this biozone and its lateral distribution are currently unknown as DI7 is only recognized in northwestern Saudi Arabia (Fig. 5.3). The top of DI7 lies within the lower part of the newly defined Assemblage Zone A2 (i.e. Interval Zone A2a) in upward biostratigraphy (Figs 5.4 and 5.5). Palynosubzone D4A of Al-Hajri et al. (1999) seems to correspond in part to DI7 (Fig. 5.6). It has been documented in samples from the lower part of the Jauf Formation of northwestern Saudi Arabia and upper part of the Tawil Formation in eastern Saudi Arabia (Al-Hajri et al., 1999).

Chapter 6 – Palaeogeography & palaeoenvironments

6.1. Introduction

The heterogeneous geographic distribution of modern plant and animal taxa is the result of the complexly interrelated effects of many factors including evolution, migration, climatic patterns, physical, atmospheric, and tectonic movements. These processes have operated throughout the geological history. Consequently, floral and faunal provincialism is an expected characteristic of the fossil record. The earliest plant fossil records indicate that provinciality was characteristic of terrestrial vascular plant distributions probably right from the beginning of terrestrial colonization by vascular plants (Wnuk, 1996). Phytogeographic differentiation occurs in direct response to climatic gradients and palaeogeographic barriers (e.g. mountain ranges or ocean). As those gradients and barriers change, provincial boundaries expand, contract, fragment or reassemble. Phytogeographic units are dynamic through time (Wnuk, 1996).

6.1.1. Plant distribution

Large amount of palaeobotanical data from late Early Devonian strata enable to attempt to understand in part the world phytogeographic distribution at this time. In several studies (e.g. Ziegler et al., 1981; Raymond et al., 1985; Raymond, 1987), multivariate methods were applied to analyse the global plant distribution. These authors recognize three main realms in Early Devonian: the equatorial/low-latitude Euramerican Realm (including Euramerica, Siberia and South China), Gondwanan Realm (including the most part of Gondwana) and Angaran Realm (including Kazakhstan and northeastern Gondwana). These realms are themselves subdivided into subunits. Unfortunately, there are no recent analyses of Middle and Late Devonian phytogeography. Nevertheless, Gensel (1986) suggested that Middle Devonian floras were mostly uniform in composition though some endemism in Russian floras was noted. On the other hand, Edwards (1973) thought there were two distinct floral realms in the Middle Devonian, one that corresponded to the Gondwanan Realm and the other to the Euramerican Realm. Edwards & Berry (1991) agreed with Raymond et al. (1985) in recognizing a temperate Middle Devonian south Gondwanan subunit. It seems likely that the floristic divisions of the Middle Devonian persisted into the Late Devonian (Wnuk, 1996). Edwards (1973) and Edwards & Berry (1991) subscribed to the opinion that Late Devonian floras were cosmopolitan.

The interpretation of the global plant distribution in the Devonian remains, however, somewhat hazardous because of the scarcity of palaeobotanical data, problems of independent age dating of plant assemblages, misidentification of specimens and unidentified synonymies.

6.1.2. Miospore distribution

Palynology, thanks to its more abundant fossil record, has a higher potential to reveal phytogeographic pattern, and provide an analysis independent of the macrofossil plant results. From earliest Devonian Saudi miospore assemblages, Steemans et al. (2007a) discovered that the cryptospores are very similar to those from a coeval continental assemblage from southern Euramerica (Wellman & Richardson, 1996), whereas the trilete spores show a strong affinity with miospore assemblages from western Gondwana. According to Steemans et al. (2007a), at least two main phytogeographical provinces existed in earliest Devonian (Lochkovian): western Gondwana and Euramerica. Nevertheless, the high similarity of coeval cryptospore assemblages from Euramerica and Saudi Arabia implies absence of a significant palaeogeographic barrier between the palaeocontinents. Since migration of cryptospore-producing plants was most likely a progressive step-by-step process (see 6.3.1), they favour a Rheic Ocean already reduced from earliest Devonian with perhaps even periodic connection (Steemans et al., 2007a). These authors think that the differences of trilete spore assemblages between Euramerica and Gondwana relate to palaeoenvironmental (climatic) differences and not to endemism due to palaeogeographical barrier such as a large Rheic Ocean.

During the Early Devonian, Steemans & Lakova (2004) defined the *sinuosus-zavallatus* Phytogeographic Province which is a subprovince of Euramerica covering the eastern part of the Caledonian Mountains. This province is characterized by taxa belonging to the phylogenetic lineage of *Emphanisporites micrornatus* (Breuer et al., 2005a) that are exclusively present in this region.

As for plant distribution (see 6.1.1), Marshall (1996) applied also multivariate methods to analyse the global miospore distribution notably for Emsian and Givetian intervals. In the Emsian, the different regions where miospores have been encountered are linked at low levels and are quite distinct. The Emsian miospore assemblages are therefore characterized by a marked provincialism. The Givetian results demonstrate higher level linkage between regions, thus demonstrating an apparently progressive decrease in provincialism during the Devonian. McGregor (1979) agreed that Devonian miospores had a cosmopolitan distribution, but he indicated that detailed palynological records show evidence of provincialism during the Devonian. McGregor & Playford (1992) suggested also certain cosmopolitanism in the Devonian land vegetation during Middle through Late Devonian time to allow considerable floristic interchange, although some provincialism should exist (see 1.5.4). Streel et al. (1990b) noted that analyses of Euramerican miospore assemblages suggest vegetation differences between the northern and southern parts of Euramerica, The distribution of *Archaeoperisaccus* was believed to characterize a single major phytogeographic province: northern Euramerica. This province has an equatorial position and includes Arctic Canada and Russian Platform. Streel et al. (1990b), Loboziak & Streel (1995a) and Streel & Loboziak (1996) thought that southern Euramerica and western Gondwana constituted an other unique major phytogeographic province during the Middle and Late Devonian in spite of several endemic miospore species restricted to western Gondwana (see 1.5.4). Despite the nomenclatural problems that are still important between the two provinces of Euramerica (northern and southern), the palynofloras of northern Euramerica seem to contain many more species than those from southern Euramerica-western Gondwana within the latest Givetian to early-middle Famennian.

Finally, di Pasquo et al. (2007) defined the Afrosouthamerican Subrealm in South America and Africa from the Middle to early Late Devonian. This subrealm belongs to the western Gondwana-southern Euramerica Phytogeographical Province previously defined by Streel & Loboziak (1996) and embraces Argentina, Bolivia, Brazil, Paraguay, Uruguay and Ghana. It is characterized by *Grandispora pseudoreticulata*, other endemic species (e.g. *Acinosporites ledundae*, *Apiculatisporis grandis*, *Apiculiretusispora laxa*, *G. permulta*, *G. daemonii*, *Leiotriletes balapucensis* and *Retusotriletes paraguayensis*) that show a restricted palaeogeographical distribution. These palynofloras appear to have been developed around 55° and 75° S palaeolatitude. Nevertheless, the occurrence of some Euramerican species in the assemblages of the cooler Afrosouthamerican Subrealm can support the development of relatively similar climatic conditions (e.g. Streel & Loboziak, 1996). The Afrosouthamerican Subrealm seems to correspond to the temperate south Gondwanan subunit recognized on base of macrofossil evidence by Raymond et al. (1985) and Edwards & Berry (1991) (see 6.1.1).

6.1.3. Marine fauna distribution

Devonian marine biogeography changes from a highly provincial Early Devonian to a very cosmopolitan Late Devonian level (e.g. Boucot, 1988). There is a parallel trend from a globally high climatic gradient in the Early Devonian to a very low gradient in the Late Devonian. The causes behind changing levels of Devonian provincialism are poorly understood, but changing oceanic current circulation barrier positions, plus changing global climatic gradients may be the first order controls and they, in turn, may have been largely controlled by changing global geography. On the basis of marine fauna, three realms can be defined during the Devonian. Firstly, the warm Old World Realm is distinguishable and includes mainly Eurasia, South China and Australia. Then, the Eastern Americas Realm (including North Africa, North America and northern South America) has warm temperate conditions which are intermediate between the topical-subtropical warm water Old World Realm and the cooler water Malvinokaffric Realm (including southern South America, South Africa and parts of Antarctica) which is distinguishable only during Early and early Middle Devonian (Eifelian). According to Boucot (1988), a global, fairly abrupt warming event near the Eifelian/Givetian boundary caused the demise of the Malvinokaffric and Eastern Americas Realms and numerous marine fauna taxa. These three realms are themselves subdivided into a number of subunits according to different groups of organisms.

The Lower Devonian from Saudi Arabia shows Rhenish-Bohemian Region affinities (Boucot, 1984; Boucot et al., 1989). The Rhenish-Bohemian Region is a subunit of the Old World Realm. In Emsian-Eifelian, the Rheic Ocean did not act as a barrier as marine macrofauna show continuity in the surrounding area (Hladil & Bek, 1999).

6.1.4. Microphytoplankton distribution

The distribution of Palaeozoic acritarchs was most probably influenced by palaeoecological factors such as light, nutrient supply, temperature and salinity. However, it is difficult to assess the relative importance of these various factors as well as the effects of such larger scale influences as palaeobiogeography and palaeolatitude on the composition of preserved acritarch assemblages (Le Hérissé et al., 2000). Specific ecological conditions can be recognized thanks to individual acritarch morphotype and help to understand the palaeobiogeography of Palaeozoic microphytoplankton. Nevertheless, it is difficult to delimit clear provinces during the Devonian and more generally during the Palaeozoic because most acritarchs and related forms are planktonic organisms.

However, climatic realms can be recognized and correspond roughly to the latitudinal climatic belts that existed during the Devonian (Le Hérissé et al., 1997). In Early Devonian, differences in acritarch assemblages were pronounced between North America (Laurentia) and Gondwana, although Rubinstein et al. (submitted) suggest a cosmopolitan nature of numerous Early Devonian acritarchs. Therefore, the composition in acritarch assemblages from different regions is probably less clear-cut than previously suggested, even if some genera show a clear palaeogeographically-controlled distribution. Palaeogeographic reconstructions seem to indicate that the observed acritarch provincialism was not mainly caused by water temperature differences, but rather influenced by physical barriers as emerged land areas between the two regions. These barriers prevented dispersal and interchange of acritarchs and related forms (Le Hérissé et al., 1997). The level of endemism among acritarchs at generic and specific levels permits the recognition of at least two distinct acritarch biogeographic units: the eastern North American unit and the Gondwanan unit divided into the northwestern Gondwanan subunit and the high southern latitude subunit. The isolation of eastern North America on the basis of the spatial distribution of acritarchs is consistent with similar biogeographical differences between the North American and European provinces based on the distribution of faunal groups such as brachiopods, corals, or ostracodes (Le Hérissé et al., 1997). Unfortunately, based only on acritarch evidence, the duration of the units defined cannot be estimated because there is no indication whether this high level of endemism in acritarch assemblages persisted after the Early Devonian. Indeed, few Middle Devonian acritarch and prasinophycean floras have been reported; it is, therefore, difficult to assess the degree of provincialism and cosmopolitanism of numerous taxa. In Late Devonian, there are distinct differences between acritarch assemblages from Euramerica and Gondwana in spite of some widespread species (Vanguestaine, 1986; Streel et al., 1988). In summary, the contemporaneous studied assemblages were not separated enough to allow to understand the global Devonian acritarch distribution.

6.1.5. Chitinozoan distribution

As discussed by Paris (1996), chitinozoans, with their supposedly planktonic mode of dispersion, were sensitive to environmental parameters related to both the inshore-offshore and palaeolatitudinal trends. In a study on chitinozoans from Libya, Jaglin &Paris (2002) and Steemans & Lakova (2004) stated that the Rheic Ocean did not act as a hermetic barrier for transoceanic chitinozoan exchanges as soon as Late Silurian, as some species are also observed on its northern margin. However, evidence of faunal differentiation and endemism at genus and species levels is recorded by Paris et al. (2000) in Early Devonian chitinozoan assemblages from Australia and in Middle-Late Devonian chitinozoan assemblages from Brazil and Ghana. Unfortunately, no conclusions can be drawn about the global Devonian chitinozoan distribution because of too few available data in the considered interval.

6.2. From provincialism to cosmopolitanism

6.2.1. Generalities

Early Devonian was thus marked by provincialism of vegetation (e.g. Marshall, 1996; Wnuk, 1996) and marine fauna (e.g. Boucot, 1988). Progressively, the provincialism shaded off to the benefit of cosmopolitanism from Middle Devonian. The increase of cosmopolitanism of miospores assemblages during the Devonian is well illustrated in this work. The high provincialism of the Early Devonian results in far lower correlation reliability, whereas the high cosmopolitan of the Middle/Late Devonian results in the reverse. Indeed, it has been less reliable to use the reference biozonations from Euramerica (Richardson & McGregor, 1986; Streel et al., 1987) in Early Devonian and early Middle Devonian in northwestern Gondwana. On the contrary, it has been much easier to apply the Givetian biozones of Euramerica than older ones. Besides the newly defined assemblages A6, A7 and A8 correspond respectively to the reference biozones Lem, TA and TCo of Streel et al. (1987). The similarity of northwestern Gondwanan assemblages with Euramerican palynofloras increases in Middle Devonian. The slight global decrease of the ratio endemic/cosmopolitan species from late Pragian to Givetian/?early Frasnian, calculated on the basis of the composite stratigraphic chart of miospore taxa (Fig. 4.1), corroborates this increase in cosmopolitanism. It proves, once again, the homogenization of the vegetation of Euramerica and northwestern Gondwana from Middle Devonian. This homogenization of palynofloras from Emsian to early Frasnian is also shown by Hashemi & Playford (2005) in the Adavale Basin (Australia). A trend towards increasing floristic alliance between eastern Gondwana and Euramerica is demonstrated through Middle-Late Devonian time. In addition, the progressive global homogenization seems to be accompanied in northwestern Gondwana by a decrease in diversity in Givetian Assemblages Zones A7 and A8 (see 4.9 and 4.10), what is logical. The homogenization of the vegetation was likely due to a decrease of the latitudinal climatic gradient during the Devonian making easier floristic interchange between Euramerica and Gondwana. Steemans & Wellman (2007) assess that Rheic Ocean was already relatively narrow in earliest Devonian (see 6.1.2) to allow floristic interchange. Meyer-Berthaud et al. (2003) consider that the two continents are close to each other in Middle Devonian on the basis of the distribution of the lycopsid *Leclercqia complexa*. Its distribution was not cosmopolitan, although broad, and showed constraints. In addition, the lesser the splitting of tectonic plates, the lower the diversity of flora and fauna. Therefore, the western Gondwana-southern Euramerica Phytogeographical Province got to be formed from Middle Devonian (Streel & Loboziak, 1996).

6.2.2. Coefficient of similarity

A way to estimate most objectively the similarity between the miospore spore assemblages from different regions is the coefficient of similarity (CS) *sensu* Clark & Harteberg (1983) for bioprovincialism evaluation. Numerous Palaeozoic palynological studies have used CS (e.g. Le Hérissé et al., 1997; Samuelsson et al., 2002). This simple and straight-forward approach is expressed by the formula:

$$CS = 2v/a+b$$

With v: number of species in common between the two compared assemblages; a and b: total number of species in each assemblage, respectively. If CS is lower than 0.2, the similarity between the two compared assemblages is estimated as low. If CS is included between 0.2 and 0.55, the similarity is considered as moderate to high. If CS is higher than 0.55, the similarity is appraised as very high (Clark & Harteberg, 1983).

CS has been calculated between northern and southern Euramerica, western, northwestern and eastern Gondwanan localities on the basis of the palynological literature (Fig. 6.1). Other regions such as China are not considered here because of the different taxonomic concept used in those regions and/or too few data available, making the comparisons difficult. The analysis comprises species only documented in the range from the base of the Emsian to the top of the Givetian in order to compare them to the assemblages described here. Indeed the assemblages described in the present work are mainly from this range. Pragian is only represented by its upper part in northwestern Saudi Arabia.

Northern Euramerican miospore assemblages are described in Arctic Canada (Owens, 1971; McGregor & Camfield, 1982), Spitsbergen (Allen, 1965) and in Eastern Europe (Avkhimovitch et al., 1993) (Fig. 6.1). Although numerous studies have dealt with southern Euramerican miospores assemblages, only several substantial ones have been analysed. Miospore assemblages are found in Scotland (Richardson, 1965; Marshall, 1988; Marshall & Fletcher, 2002), in the Ardenne-Rhenish regions (Riegel, 1973; Tiwari & Schaarschmidt, 1975; Streel, 1987; Steemans, 1989) and in Poland (Turnau, 1986, 1996; Turnau et al., 2005) (Fig. 6.1). Beyond the Caledonian Range, Emsian-Givetian miospore assemblages occur in Gaspé and Ontario (McGregor, 1973; McGregor & Camfield, 1976) (Fig. 6.1). With the help of di Pasquo (comm. pers., 2007), species occurring in southwestern Gondwana from Emsian to Givetian have been listed from different papers (Daemon et al., 1967; Menéndez & Pöthe de Baldis, 1967; McGregor, 1984; Perez-Leyton, 1990; Loboziak & Streel, 1995a; Blieck et al., 1996; Ottone, 1996; Vavrdová et al., 1996; Dino, 1999; Grahn et al., 2003; Melo & Loboziak, 2003; Amenábar, 2007; di Pasquo, 2007; Mendlowicz Mauller et al., 2007; Rubinstein & Steemans, 2007). The southwestern Gondwanan localities where miospore assemblages are found are situated in Argentina, Bolivia, Brazil and Paraguay (Fig. 6.1). For the northwestern Gondwanan assemblages, the species from 7 important papers (Massa & Moreau-Benoit, 1976; Boumendjel et al., 1988; Moreau-Benoit, 1989; Moreau-Benoit et al., 1993; Loboziak & Streel, 1995b; Loboziak, 2000; Rahmani-Antari & Lachkar, 2001), and the present work have been listed. These localities are located from Morocco to Saudi Arabia eastwards (Fig. 6.1). In eastern Gondwana, Emsian-Givetian palynological records are from Antarctica (Kemp, 1972) and Australia (Grey, 1991, McGregor & Playford, 1992; Hashemi & Playford, 2005) (Fig. 6.1). Then, lists of Emsian-Givetian miospore species have been established for each region by taking synonymy of certain forms into account. The total number of species in each region and the number of species in common between two compared regions are summarized in Fig. 6.2.

6.2.3. Distorting factors

Caution is needed for the interpretation of these results because they may be distorted by some factors. Firstly, different teams of authors defined the analysed assemblages and so they might use different taxonomic concept (see Volume III). Consequently, the established lists of species can be biased because of cases of unsuspected synonymy, even if a lot of cases of synonymy have been discovered by editing the lists of species, in addition to the well-established synonymies. In general, confidence of taxonomic identification is directly proportional to the number of specimens found; it also is inversely proportional to the number of observers used to identify all taxa in an assemblage (Gradstein et al., 1985). For a same assemblage, the more numerous the authors, the larger the list of species. Secondly, lots of rare species are often not presented in the publications because there is too few information about them. Authors may not describe or illustrate all of the kinds of spores in an assemblage, preferring to omit rare forms or difficult to interpret. Thirdly, the taphonomy affects the apparent diversity. The most poorly-preserved assemblages are often less diverse. Fourthly, the dating of the assemblages described in the analysed publications has not been reappraised and thus possible mistakes may occur. There may be problems about independent age dating of miospore assemblages. Indeed, the age of some published miospore assemblages may be poorly constrained, not independently controlled, or even wrongly dated. Fifthly, only a small part of Devonian miospore literature for these two continents has been analysed even if the most substantial works have been used. Finally, the resulting CS are meant not to be very precise but only provide a rough approximation on the similarity between the two continents from the Emsian-Givetian interval.

6.2.4. Results

After an analysis of the Emsian-Givetian palynological literature (see 6.2.2), CS can be calculated between some different potential phytogeographic provinces (Fig. 6.3) for the interval considered. The most important results are plotted on a Middle Devonian palaeogeographic reconstruction of Scotese (2000) (Fig. 6.4). The most striking result is the low general values which correspond to a low to moderate similarity of miospore assemblages between the different considered regions according to criteria of Clark & Harteberg (1983).

As suggested by Streel et al. (1990b) (see 6.1.2), the vegetation differences between northern and southern Euramerica are confirmed by a CS equal to 0.34. On the other hand CS has also been calculated within Euramerica between the two regions separated by the Caledonian Range; Europe and Russia constituting the eastern part of Euramerica and North America representing its western part. CS between the two regions equals 0.33 (Fig. 6.3). This moderate similarity demonstrates that the Caledonian Range act as a physical barrier restricting miospore dispersion and, therefore, floristic interchange. In Euramerica, the Caledonian Range had an influence on the geographic plant distribution as well as the latitudinal gradient as North-South and East-West CS are almost similar. This mountain range already played a major part in phytogeography from Lochkovian by preventing plant migration and influencing climate (Steemans & Lakova, 2004; Breuer et al., 2005a).

The western Gondwana-southern Euramerica Phytogeographical Province (Streel et al., 1990b; Streel & Loboziak, 1996) seems to show important latitudinal differentiation. CS is lower between southern Euramerica and southwestern Gondwana than between southern Euramerica and northwestern Gondwana. Indeed the composition of miospore assemblages change and the diversity decreases southwards. In the Early Devonian, Steemans et al. (2007a) invoke climatic differences to explain the variations in the trilete spore assemblages between southern Euramerica and northwestern Gondwana as Euramerica showed probably already connections with Gondwana (see 6.1.2). The climatic gradient seems still to exist, at least, in the major part of Middle Devonian to elucidate the moderate CS between North and South of the western Gondwana-southern Euramerica Phytogeographical Province. Northwestern Gondwana constituted an intermediate region that shared mainly taxa with Euramerica in the North and southwestern Gondwanan localities (South America) in higher latitudes. Streel & Loboziak (1995a) have demonstrated that the miospore assemblages from western Gondwana are dominated, in Middle Devonian, by some endemic forms such as (e.g. *Camarozonotriletes*? *concavus*, *Craspedispora ghadamisensis*, *Grandispora libyensis* and *G. permulta*). This difference with southern Euramerican assemblages faded in Late Devonian. Except *G. permulta*, no characteristic species from the Afrosouthamerican Subrealm (di Pasquo et al., 2007) occur in the northwestern Gondwanan assemblages. In Middle Devonian, northwestern Gondwana was characterized by a warmer temperate climate than southwestern Gondwana (Scotese, 2000). The northern boundary of the Afrosouthamerican Subrealm is, therefore, likely situated somewhere between North Africa and Ghana.

As stated by McGregor & Playford (1992), enough similarities exist between Euramerican and Australian assemblages in Middle and Late Devonian to sustain long distance biostratigraphic correlation (see 1.5.4), but the low CS between eastern Gondwana and other regions may correspond to a single phytogeographic province as suggested by Streel & Loboziak (1996). Among the analysed regions, eastern Gondwanan localities (Fig. 6.1) are palaeogeographically the most isolated. Its assemblages include a lot of peculiar taxa that occur only there (see Hashemi & Playford, 2005). The low to moderate CS in the whole Gondwana seems to point out the existence of different climate in Gondwana as no physical barriers is known during the Emsian-Givetian interval.

The amount of Devonian palaeobotanical and palynological records remains quite unequal around the world. Mainly in Australia and South America, there are still very few detailed data in comparison with those from North America and Europe. Only few papers in Devonian palynofloras contain taxonomic descriptions and illustrations. Although the evaluation of provincialism from Emsian to Givetian need further refinement, CS calculated here gives a good enough global estimation of the miospore distribution for the considered period of time. The low to moderate similarity between the analysed regions could mainly due to the latitudinal climatic gradient. Indeed, the localities, where Emsian-Givetian miospore assemblages are recorded, are rather well-distributed from the Equator to polar regions of the southern hemisphere (Fig. 6.1). The different regions correspond to the climatic belts determined by Scotese (2000) for the Middle Devonian (Fig. 6.5). Northern Euramerica is situated in the tropical belt at the Equator. Southern Euramerica is more arid. However, there is likely a difference of climate between western and eastern Euramerica because of the Caledonian Range. Difference of rainfall should be marked between the two regions as expected from the consequence of a so huge mountain range, although, the latter was already partly eroded in Middle Devonian. Northwestern Gondwana lies in the warm temperate climatic belt. In the highest latitudes, southwestern Gondwana or Afrosouthamerican Subrealm corresponds to a cool temperate region. Eastern Gondwana is likely composed of different climatic regions as it is much extended in latitudes.

6.3. Palaeobiogeography of northwestern Gondwanan assemblages

6.3.1. Late Pragian-Emsian

Miospore species in Early Devonian samples studied here show a typical Gondwanan affinity. For instance, *Zonotriletes* spp. published in Jardiné & Yapaudjian (1968) and commonly occurring in this work are only known in western Gondwana. Species of *Iberoespora* are common in Brittany, Spain, and northwestern Gondwana but very rare in Euramerica according to Steemans (pers. comm., 2007). Besides, numerous species known in older strata from Brittany (e.g. Le Hérissé, 1983) and Spain (e.g. Rodriguez, 1983; Richardson et al., 2001) occur in the material studied here (e.g. *Chelinospora cantabrica*, *C. hemiesferica*, *C.* cf. *hemiesferica*, *Cymbosporites dammamensis* and ?*Knoxisporites riondae*). These two regions belong to the Armorican Plate (or Armorica), initially considered as part of northwestern Gondwana. Armorica is shown to detach and drift towards Euramerica during the Emsian (Cocks & Torsvik, 2002). Recently, Mendlowicz Mauller et al. (2007) have described late Pragian-early Emsian miospore assemblages from Brazil (southwestern Gondwana) which contain several species newly described from northwestern Gondwana (Breuer et al., 2007). The Early Devonian assemblages show also some similarities with those from eastern Gondwana. Hashemi & Playford (2005) found in the Emsian from Australia, *Scylaspora costulosa* and *Retusotriletes* cf. *R. crassus*. In Antarctica, Kemp (1972) described notably *Reticuloidosporites antarcticus* and specimens synonymous of ?*Knoxisporites riondae*. In addition, the Early Devonian samples present a lot of species unpublished so far (see Volume III), which are likely endemic to northwestern Gondwana. On the other hand, several widespread Early Devonian species such as *Acinosporites lindlarensis*, *Camarozonotriletes sextantii*, *Cirratriradites diaphanus*, *Dictyotriletes emsiensis*, *D. subgranifer*, *Synorisporites papillensis* and *Verrucosisporites polygonalis* occur in northwestern Gondwanan assemblages.

The studied Early Devonian samples contain also relatively diverse cryptospore assemblages. In some levels (see Chapter 2), cryptospores can be numerous and represent a significant part of the miospore assemblages. In the Middle Devonian, their diversity and number decrease strongly (see Chapter 4). Among the 11 cryptospore taxa, 6 are cosmopolitan. In earliest Devonian, cryptospore-producing plants were cosmopolitan and could tolerate a wide range of climates. They were environmentally restricted to damp habitats in confined environments, usually with no direct outlet to the sea (Wellman et al., 2000; Steemans & Wellman, 2004; Steemans et al., 2007a). That explains why cryptospores are uncommon in Devonian marine deposits. Cryptospores were produced by very small-sized plants that probably grew in wet habitats, thus limiting the likelihood of their spores being redistributed far by wind. It seems thus improbable that cryptospores could be effectively dispersed over long distances. Migration of cryptospore-producing plants was most likely a progressive step-by-step process (see 6.1.2). Trilete spore-producing plants were most likely more specialised as they colonized a wider spectrum of biotopes, and therefore were more sensitive to ecological variation. Trilete spores show more palaeoenvironmental and palaeogeographical variations than cryptospores (Steemans et al., 2007a).

Monolete spores first occur here in the late Pragian-?earliest Emsian Assemblage A2 (see 4.4). Monolete spores sometimes occur in modern ferns in the same sori as trilete spores, but they are never as numerous as trilete spores. Their appearance is, however, particularly interesting as it represents one of the earliest reports of monolete spores. Indeed the oldest monolete spores, known in the literature, are not older than Emsian according to Kemp (1972) and Traverse (2007). However, Wellman (2006) found a unique specimen of monolete spores in Scotland in a late Pragian-?earliest Emsian assemblage. Besides, this specimen may be similar to the first significant monolete form (*Latosporites ovalis*) described here, and, therefore, it could be coeval with Saudi specimens. *L. ovalis* occurs also in Brazil in late Pragian-early Emsian (Mendlowicz Mauller et al., 2007). *L. ovalis* is thus probably the oldest occurrence of monolete spores and may appear as soon as late Pragian. Monolete spores are rare especially before the Late Devonian where they are well represented in northern Euramerica by the cavate *Archaeoperisaccus* complex (e.g. McGregor & Owens, 1966; McGregor, 1969; Naumova, 1953; Pashkevich, 1964). In the literature, the earliest (Emsian) records of monolete spores are notably *Reticuloidosporites antarcticus* in Antarctica (Kemp, 1972) and two different forms from Brittany (Moreau-Benoit, 1966). De Jersey (1966) and Hashemi & Playford recorded rare laevigate monolete spores from Emsian (but not earliest) in the Adavale Basin (Australia). From late Emsian strata in the Russian Platform, Tchibrikova (1959, 1962) and Avkhimovitch et al. (1993) recorded several species of ornamented azonate monolete spores. The appearance of first monolete spores may be situated in late Pragian-?earliest Emsian. In addition, that hints at the possibility that monolete spores appeared on Gondwana, before their first appearance in Euramerica (Breuer et al., 2007). In Euramerica, first rare monolete spores occur in early Emsian after Richardson & McGregor (1986).

6.3.2. Eifelian

The similarity of northwestern Gondwanan assemblages with Euramerican palynofloras increases in Eifelian with the proliferation of the large spinose zonate-pseudosaccate, numerous species of which are widespread (e.g. *Grandispora douglastownense*, *G. incognita*, *G. protea*, *G. ?naumovii*, *G. velata* and *Samarisporites eximius*). Other type of cosmopolitan species make their first inception, such as *Archaeozonotriletes variabilis*, *Chelinospora timanica*, *Scylaspora rugulata* and the different forms belonging to the *Verrucosisporites scurrus* Morphon. Nevertheless species endemic to western Gondwana (e.g. *Camarozonotriletes*? *concavus*, *Grandispora gabesensis*, *Craspedispora ghadamisensis*, *Grandispora libyensis* and *Grandispora permulta*) still occur in Eifelian assemblages. In Middle Devonian, Loboziak & Streel (1995a) show in a quantitative study that these endemic species might represent significant part of the western Gondwanan miospore assemblages in Brazil and North Africa. Their relative frequencies decrease strongly in Frasnian. In addition to these endemic species to western Gondwana, the Eifelian samples contain other unpublished species (see Volume III) likely restricted to only northwestern Gondwana. Notable differences still exist between southern Euramerica and western Gondwana assemblages. For instance, *Hystricosporites* and *Ancyrospora* (hystricospores), i.e. miospores with grapnel-tipped processes, seem to proliferate from Eifelian in Euramerica whereas they are very rare and little diversified in northwestern Gondwana.

6.3.3. Givetian-?early Frasnian

The homogenization of northwestern Gondwanan palynofloras goes on in Givetian-?early Frasnian samples. Despite the occurrence of common endemic species (see Volume III), cosmopolitan forms are more and more present. The cosmopolitan species such as *Ancyrospora langii*, *Auroraspora minuta*, *Chelinospora concinna*, *Cymbosporites catillus*, *C. cyathus*, *Geminospora lemurata*, *Rhabdosporites langii* and *Samarisporites triangulatus* make their first inception. Most of them represent significant proportion of Givetian assemblages from northwestern Gondwana. *R. langii* seems to appear later in northwestern Gondwana and Gondwana in general (see 4.8 and 4.11). Indeed, it is not known before Givetian in eastern Gondwana (McGregor & Playford, 1992) and southwestern Gondwana (Loboziak et al., 1988; Melo & Loboziak, 2003). *G. lemurata* makes its inception in the lower part of Givetian and its widespread distribution attest to its efficiency for long distance transport. As noted by Marshall (1996), it is one of the most cosmopolitan species of Devonian miospores. *G. lemurata* has been attributed for a long time to the *Archaeopteris* major group of progymnosperms of Givetian to Famennian (e.g. Allen, 1980). The *Archaeopteris* plants had secondary wood and grew as extensive stands of tall trees (Beck, 1981), forming the first forest communities that possibly occupied an appreciable range of terrestrial habitats, including coastal and near-coastal environments. Some species of *Archaeopteris* were heterosporous, their megaspore being *Contagisporites optivus*, and others possibly homosporous (Marshall, 1996).

Megaspores begin to occur sporadically in Eifelian assemblages but they are above all numerous and diverse in the Givetian assemblages. In contrast to the numerous cosmopolitan microspore species, northwestern Gondwanan megaspore assemblages show very low similarity with coeval Euramerican assemblages (Steemans et al., 2007b). That reflects the fact that microspores are more easily transported by wind because of their smaller size. Indeed, heterosporous plants have less potentiality to be dispersed on long distances because of the large size of their propagules (megaspores) and the requirement of their microspores for cross fertilisation. That needs to be moderated by the presence of 4 megaspore species out of 20 which were known to be as restricted in Euramerica (Steemans et al., 2007b). Among these 4 megaspore species, *Contagisporites optivus* and *Verrucisporites ellesmerensis* are described and discussed in Volume III. They can be locally common in the studied samples. According to Marshall (1996), *C. optivus* was only restricted to Euramerica and he considered that records of *C. optivus* from South Africa, China, and Morocco (which are the previous localities outside Euramerica where *C. optivus* were recorded) are based on misidentifications. *V. ellesmerensis* occurs in both Arctic Canada (Chi & Hills, 1976) and Saudi Arabia (see also Marshall et al., 2007). Differences between Euramerica and northwestern Gondwana in the megaspore assemblages are probably mainly due to latitudinal climatic differences and not a palaeogeographic barrier as megaspores with their microspores can not be transported on long distances. The Rheic Ocean was probably narrow and terrestrial paths between Gondwana and Euramerica existed. This palaeogeography had existed at least since the Lochkovian (Steemans et al., 2007a). It shows that the megaspore-producing plants were able to achieve, step-by-step, dispersal over wide distances on continents. De Ville de Goyet et al. (2007) and Steemans et al. (2007b) have compared the megaspore assemblages from borehole A1-69 to those from a coeval south Euramerican locality (Belgium). Since the palaeoenvironments are very similar (continental to deltaic) and the climates different, comparison is interesting. Northwestern Gondwanan megaspores show larger sculptural elements than those from Euramerica. The presence of spinate or bifurcate processes on most of them (about 80% of all specimens) may corroborate the hypothesis regarding functional morphology proposed by Ditcher et al. (1992) for the processes of Devonian spores. They suggest that the morphological characters of megaspores may have been developed to provide buoyancy, movement or attachment for some plants living permanently, temporarily or for a particular phase of their life cycle in an aquatic environment. On the contrary, homosporous plants lived in many different biotopes ranging from dry to humid. The fact that megaspores are rarely transported by wind and that they may be produced by plants living in a restricted aquatic biotope might force a high level of endemism of heterosporous plants. Unlike cryptospore-producing plants that live also in restricted environments (see 6.3.1) most of heterosporous plants could not tolerate a wide range of climates.

Two specimens of cavate monolete spores occur in Givetian strata and have been assigned to *Archaeoperissacus* cf. *rhacodes*. Their presence is in accord with the earlier (pre-Frasnian) inception of *Archaeoperisaccus* in China (Lu Lichang, 1980), Algeria (Moreau-Benoit et al., 1993) and Australia (Hashemi & Playford, 2005), than in other northern hemisphere regions. According to Streel et al. (1990b), the *Archaeoperissacus* complex is restricted to the equatorial belt.

6.4. Palaeolatitudinal considerations

The Earth's climate is primarily a result of the redistribution of the sun's energy across the surface of the globe. It is warm near the Equator and cool near the Poles. Wetness, or rainfall, also varies systematically from the equator to the pole. It is wet near the equator, dry in the subtropics, wet in the temperate belts and dry near the poles (Scotese, 2000). As northern Euramerica, southern Euramerica, northwestern Gondwana and southwestern Gondwana are situated from the Equator to polar regions and correspond to different climatic belts determined by Scotese (2000) for the Middle Devonian (see 6.2.4), the analysis of the literature carried out in this work (see 6.2.2) allows to describe the distribution of the main different miospore types and their diversity according to a latitudinal gradient (Fig. 6.6). Although the palaeobotanical affinity of the most genera and spore types remain unknown so far, interesting trends on the composition, the diversity of miospore assemblages and the distribution of different types of spores can be described from this figure.

It appears that *Apiculiretusispora*, *Ancyrospora*, *Archaeozonotriletes*, *Convolutispora*, *Densosporites*, *Geminospora*, *Hystricosporites*, *Punctatisporites* and *Rhabdosporites* are produced by plants above all characteristic of tropical assemblages from northern Euramerica. They are more diversified there than in any other regions. *Ancyrospora* is considered as a lycophyte derivation (Wellman, 2002). Dilcher et al. (1992) and Kar & Dilcher (2002) discussed the functional morphology of hystricospores and hypothesized their derivation from plants that inhabited lowland paludal situations, even water itself. Several authors (e.g. Streel, 1967; Richardson, 1965, 1967) considered that the plants that produced *Ancyrospora* and *Rhabdosporites* occupied upper floodplain and lacustrine situations whereas the parental sources of *Geminospora* characterized lower floodplain and paralic environment. In contrast, Allen & Marshall (1981, 1986) and Marshall & Allen (1982) reported abundance of *Geminospora* in proximal fluvio-lacustrine facies of a true internal basin. Although, the monolete *Archaeoperissacus* complex is more diversified and numerous in the tropical belt, some species may occur in highest latitudes. *Kraeuselisporites* and *Perotrilites* is highly diversified as well as in northern Euramerica as southern Euramerica.

The arid assemblages from southern Euramerica are notably characterized by highly diversified simple miospores such as *Acinosporites*, *Aneurospora*, *Brochotriletes*, *Biornatispora*, *Dibolisporites* type, *Emphanisporites*, *Retusotriletes* and verrucate spores. In addition, more complex miospores such as *Grandispora*, *Hystricosporites* and *Perotrilites* are numerous.

The warm temperate assemblages in northwestern Gondwana contain also highly diversified simple spores such as *Biornatispora*, *Brochotriletes*, *Chelinospora*, *Cymbosporites*, *Dictyotriletes*, *Iberoespora*, *Synorisporites* and verrucate spores. The large apiculate zonate-pseudosaccate spores (*Grandispora* and *Samarisporites*) are numerous in these assemblages and are the most diversified in the warm temperate belt. Lots of laevigate zonate spores (e.g. *Zonotriletes*) are typical of these assemblages. Cryptospores (e.g. *Cymbohilates*) seems more diversified under these latitudes.

The cool temperate palynofloras from the subpolar to polar regions (southwestern Gondwana) appears as markedly less diversified in general. Indeed, miospore types occurring in these assemblages are less diversified than everywhere else. In addition, many miospore types do not occur. *Geminospora* and *Retusotriletes* are very little diversified by comparison with warmer assemblages.

6.5. The D3B event

6.5.1. Introduction

Al-Hajri et al. (1999) defined at first Palynosubzone D3B. It corresponds to an acme zone of a monospecific leiospherid (*Leiopshaeridia jaufensis*) endemic to the Arabian Peninsula. This species is a simple, laevigate sphaeromorph with a diameter range of 25-45 µm. Its somewhat thickened, rigid wall give rises to distinctive broad compressional folds, a feature that enhances recognition of the species. In eastern Saudi Arabia, the acme zone ranges from 5 to 60 feet in thickness (Al-Hajri et al., 1999). Breuer et al. (2005b, 2007) have shown that this event is represented in northwestern Saudi Arabia as a series of abundance pulses that range on about 400 feet thickness. The acme zone is remarkable for its lateral continuity in Saudi Arabia. The D3B event is isochronous as it is shown by the correlation of miospores assemblages between northwestern and eastern Saudi Arabia (see Chapter 4). The D3B event is preceded by an increase in *Cymbosporites senex* specimens (Acme Zone A2c) in both regions, although the acme zone is less marked in northwestern than eastern Saudi Arabia. In addition, *Camarozonotriletes sextantii* first occurs within the D3B interval in both regions. The age of the D3B event is middle-late Emsian because it corresponds in Western Europe likely to the Min Interval Zone of Streel et al. (1987) and the newly defined Assemblage A3a in northwestern Gondwana (see Breuer et al., 2005b, 2007). As noted earlier (see 2.3.1), invertebrate fossil evidence from nearby surface exposures support a late Emsian age for the equivalent stratigraphic interval.

In northwestern Saudi Arabia, the D3B interval is associated with the marine Hammamiyat and Murayr Members of the Jauf Formation. Their facies are typical of shoreface or lagoon environments (Al-Husseini & Matthews, 2006).Unusual monotypic assemblages amongst the marine invertebrate fauna were already noted in the same levels in northwestern Saudi Arabia by Boucot et al. (1989). According to these authors (p. 549), 'A remarkable feature, especially of the marine part of the Jauf Formation, is the repeated occurrence of faunally unique beds. The extreme of this situation is seen in the presence of numerous beds where the fossil content is monotypic (a single, low-diversity community, or even a single species community)… The fossil content of these peculiar, low diversity and single species beds may possibly reflect unusually subtle palaeoenvironmental fluctuations that are rarely seen in the geologic column. Extraordinary explanations seemed called for. An extraordinarily stable, extraordinarily gently-dipping, extraordinarily extensive platform area as the dominant palaeogeographic feature might be at least a partial clue to the control producing such fossil occurrences.'

6.5.2. Palynofacies throughout D3B

Thanks to palynomorph countings, evolution of general palynofacies throughout the D3B interval has been established (see Chapter 4). It appears that the leiosphere-rich assemblages typical of the D3B event alternate with miospore-rich levels in northwestern Saudi Arabia.

This feature is not discerned in eastern Saudi Arabia as the D3B event, there, is condensed in section. Nevertheless, a miospore-richer interval may be sometimes discerned within the D3B interval (e.g. wells HWYH-956 and SDGM-462). In the D3B interval, few spores and numerous types of algae or phycomata cysts (probably of green algae, classified in this work in *incertae sedis*) are associated with *Leiosphaeridia jaufensis*, probably reflecting peculiar environmental conditions associated with a marine transgression (see 2.3.1). The series of marine pulses in northwestern Saudi Arabia may correspond to the fourth-order cycles recognized by Al-Husseini & Matthews (2006) in the Hammamiyat and Murayr Members (see 2.3.1). Although more numerous peaks have been recorded in boreholes JNDL-3 and JNDL-4 (Fig. 6.7), 6 main peaks occur in the Hammamiyat Member like the 6 fourth-order cycles recognized by Al-Husseini & Matthews (2006).

A way to calculate concentration of palynomorphs involves adding a known quantity of exotic markers to a measured quantity of sediments and using the markers as a standard to which the indigenous taxa are compared. Exotic *Lycopodium* spores were introduced during the processing of palynological slides from eastern Saudi wells in order to know the absolute number of spores and other palynomorphs per gram of rock (i.e. concentration). During palynomorph counting, *Lycopodium* markers have also been counted to calculate concentration with a 95% of confidence intervals using the methodology of Maher (1981). Although the results have not been analysed here, some examples are given to have a rough idea about the concentration of palynomorphs in the distinctive palynofacies of the D3B event. For instance, the typical leiosphere-rich levels are characterized by a very high concentration that can reach 10 000 000 leiosphere specimens/g of sediments indicating maximum distance from the terrigenous source. To obtain such huge concentration in palynomorphs, it means a very low rate of sedimentation and/or a maximum of productivity in leiospheres (bloom?). In the underlying or overlying miospore-rich levels, concentration varies from 1000 to 50 000 miospore specimen/g indicating an increasing terrigenous input and a more proximal depositional environment of these levels.

6.5.3. Local correlation based on palynofacies

Evolution of general palynofacies throughout D3B allows correlation of the two most detailed sections (boreholes JNDL-3 and JNDL-4). In the Hammamiyat and Murayr Members, the most significant peaks in the relative abundance of leiospheres (classified here into acritarchs) are noted from 1 to 8. In these levels, leiospheres represent, at least, more than 25% of the whole palynological assemblage. Very accurate correlation is relatively easy on base of the palynofacies combined with the first occurrence of the important miospore species *Camarozonotriletes sextantii* (Fig. 6.7). Correlation by palynofacies may even be practical within a small area, but such precise correlation cannot be extended far laterally (Traverse, 2007). Indeed the correlated boreholes are distant from about 15 km and easy lithostratigraphic and sedimentologic correlation is also done by sedimentologists from Saudi Aramco.

The correlation between boreholes JNDL-3 and JNDL-4 can be done with the Graphic Correlation Method (e.g. Shaw, 1964; Edwards, 1984; Mann & Lane, 1995). Basically, it consists in comparing the common characteristics (e.g. fossil events and other types of events) of two total or partly time equivalent stratigraphic sections. They are plotted into a Cartesian coordinate system and the information in common is extrapolated in the field of the graph to obtain points of correlation. All the points obtained allow to draw a line of correlation (L.O.C.) in a way to cause minimum change of known ranges. As the time equivalent stratigraphic sections in boreholes JNDL-3 and JNDL-4 are short, there are few first and last occurrences of spores to plot. Therefore, the peaks in relative abundance of leiospheres can be plotted as they constitute isochronous events to make correlation between sections easier (Fig. 6.8). L.O.C. can be drawn between boreholes JNDL-3 and JNDL-4 on the basis of the D3B pulses. First occurrence (FO) of *Camarozonotriletes sextantii* and last occurrence (LO) of *Dictyotriletes emsiensis* are isochronous and, therefore, reliable as they are situated on L.O.C. However, last occurrences of species (LO) are generally less reliable for fine correlation. Indeed, some last occurrences of species (e.g. *Cymbosporites dammamensis* and *Synorisporites papillensis*) are diachronous as they are plotted far from L.O.C. (Fig. 6.8). Variation of the L.O.C. slope indicates a repeated change of the sedimentation rate between the two sections.

Chapter 7 – General conclusions

Devonian miospore assemblages from 16 sections in northwestern Gondwana have been studied in this work. The results are mainly of taxonomic, biostratigraphic and palaeogeographic nature.

7.1. Miospore taxonomy

Taxonomy is the base of any palynological study and needs a detailed work before analysing other palynological data. Palynologists must be rigorous and keep the same taxonomic concept all along a study and compare their results between each other by taking the possible difference of concept of the different authors into account. In this study, 204 rare to common species have been described and illustrated in details. Some were already defined in the literature, others seems new and endemic to northwestern Gondwana and have been defined in open nomenclature. These new forms have been compared with possible resembling forms from the literature. In addition, the vertical (stratigraphic) and lateral (palaeogeographic) ranges of all described species are noted.

This taxonomic work has revealed that lots of species are difficult to constrain because of their large morphological variability. Besides, some species show continuous intergrading morphological variation and, therefore, can be grouped into morphons. The morphological variability of each taxon is one of the major problems in any palynological study. It appears obvious that today the description of a new miospore species should be associated with numerous illustrated specimens and studies on variability and biometrics in order to make future comparisons easier. The morphological variations of miospores are caused by either a phylogenetic evolution, ontogeny (maturation of sporangia) or taphonomic factors. Palynologists must have in mind these problems of morphological evolution and their consequences on the definition of first real occurrence and the definition of biozones.

7.2. Upward biozonation

The two main standard biozonations defined by Richardson & McGregor (1986) and Streel et al. (1987) from Euramerican assemblages are commonly used in most of the palynological studies. Nevertheless, they are not always easily applicable in the studied sections because of the absence, the rarity or the heterochroneity of the index species. Indeed, one of the main problems for miospore-based palynostratigraphy is provincialism. Therefore, the establishment of a new local/regional biozonation based on the own characteristics of the miospore assemblages described here has appeared necessary for more accurate correlation. As each biozone concept has different advantages and disadvantages, different types of biozones have been combined to establish the most useful biozonation. The new upward biozonation consists of 9 assemblage zones, 8 interval zones and 2 acme zones (including the D3B Subzone based on leiospheres) spanning in age from late Pragian to late Givetian/?early Frasnian. The newly defined biozones have been compared to other coeval biozones defined in the literature. Thanks to this new local/regional biozonation, the studied sections from the three distinct regions (North Africa, northwestern Saudi Arabia and eastern Saudi Arabia) have been correlated.

7.3. Downward biozonation

After the establishment of the composite stratigraphic chart of the main miospore species, a biozonation based on the first down-hole occurrence of species has been developed. Indeed, this type of biozonation is mainly useful in oil exploration since only the top of a biozone needs to be penetrated to be identified. The interval zones have been preferred in the definition of this downward biozonation because their recognition is quick during microscope office routine. This provisional downward biozonation consists of 8 interval zones and has to be tested in the future on several drilled sections in order to improve and confirm its effectiveness. The vertical resolution of the downward biozonation is lower than the upward biozonation as it contains less biozones. However, it is difficult to increase the resolution by adding subzones because first down-hole occurrences are less reliable than real first occurrences of taxa. Nevertheless, correlation obtained from the downward biozonation seems to be relatively reliable by comparison with the upward biozonation.

7.4. Palaeogeography

An analysis of the palynological literature has allowed the calculation of the coefficient of similarity (CS) in the Emsian-Givetian interval between palynofloras from northwestern Gondwana and coeval miospore assemblages from 4 other regions (northern Euramerica, southern Euramerica, southwestern Gondwana, and eastern Gondwana). CS gives a good enough provincialism evaluation. The resulting low general values correspond to a low to moderate similarity of miospore assemblages between the different considered regions for this period of time. The provincialism could mainly due to the latitudinal climatic gradient as the proximity of Euramerican and Gondwanan land masses as soon as Lochkovian should not prevent plant migration. The studied miospore assemblages have a northwestern Gondwana palaeogeographic affinity. These warm temperate assemblages are differentiated from other assemblages by highly diversified simple spores and numerous large apiculate zonate-pseudosaccate spores from late Emsian to late Givetian. Many laevigate zonate spores seem to occur exclusively in these assemblages in Emsian and Eifelian. In Emsian, cryptospores seems more diversified in the warm temperate climatic belts than everywhere else. Despite this certain degree of provincialism, floristic interchanges exist. Indeed, northwestern Gondwana constituted an intermediate region that shared mainly taxa with more arid Euramerican localities in the North and cooler southwestern Gondwanan localities (South America) in higher latitudes.

The global calculation of CS should be moderated as it could not be calculated more precisely for each stage. However, it seems that a homogenization of the vegetation took place from Emsian to Givetian. Indeed, the standard Givetian biozones (Lem, TA and TCo) from Western Europe (southern Euramerica) of Streel et al. (1987) are easily recognizable in the studied material whereas it is less reliable to use standard biozonations in the Early Devonian and early Middle Devonian assemblages. The transition from provincialism to cosmopolitanism during the Devonian is not only shown by palynofloras but also by the palaeogeographic distribution of other fossil groups. It is likely due to a decrease of the latitudinal climatic gradient.

Finally, the moderate similarity calculated between Emsian-Givetian Euramerican and Gondwanan assemblages demonstrates also the usefulness to have established a new biozonation based on the own characteristics of the miospore assemblages described here from northwestern Gondwana.

References cited in Volumes I & II

Abdesselam-Rouighi, F., 1991. Biostratigraphie des spores, acritarches et chitinozoaires du Dévonien du Sahara oriental (Algérie). *IIème Séminaire de Géologie Pétrolière, Bourmerdès, Algeria*, 21-23 October, Sonatrach.

Al-Ghazi, A., 2007. New evidence for the Early Devonian age of the Jauf Formation in northern Saudi Arabia. *Revue de Micropaléontologie* 50, 59-72.

Al-Hajri, S.A., Filatoff, J., Wender, L.E., Norton, A.K., 1999. Stratigraphy and operational palynology of the Devonian System in Saudi Arabia. *GeoArabia* 4, 53-68.

Al-Hajri, S.A., Owens, B. (Eds.), 2000. Stratigraphic Palynology of the Paleozoic of Saudi Arabia. *GeoArabia, Special Publication* 1, 231 p. Bahrain.

Al-Hajri, S.A., Paris, F., 1998. Age and palaeoenvironment of the Sharawra Member (Silurian of northwestern Saudi Arabia). *Geobios* 31, 3-12.

Al-Husseini, M.I., Matthews, R.K., 2005. Arabian orbital stratigraphy: second-order sequence boundaries? *GeoArabia* 10, 165-184.

Al-Husseini, M., Matthews, R.K., 2006. Devonian Jauf Formation, Saudi Arabia: orbital second-order Depositional Sequence 28. *GeoArabia* 11, 53-70.

Al-Laboun, A.A., 1982. The subsurface stratigraphy of pre-Khuff formations in central and northwestern Arabia. Unpublished PhD thesis. Faculty of Earth Sciences, King Abdul Aziz University, Jeddah, 102 p.

Al-Laboun, A.A., 1986. Stratigraphy and hydrocarbon potential of the Paleozoic succession in both Tabuk and Widyan basins, Arabia. In: Halbouty, M.T. (Ed.), Future Petroleum Provinces of the World. *Memoirs of the American Association of Petroleum Geologists* 40**,** 373-397. Tulsa.

Al-Siyabi, H., Parington, M., Verstralen, I., 2001. Stratigraphy and hydrocarbon potential of the Devonian Misfar Formation of south Oman. In, International Conference on the Geology of Oman. *GeoArabia* 6**,** 282.

Allen, K.C., 1965. Lower to Middle Devonian spores of North and Central Vestspitsbergen. *Palaeontology* 8, 687-748.

Allen, K.C., 1980. A review of *in situ* Late Silurian and Devonian spores. *Review of Palaeobotany and Palynology* 29, 253-270.

Allen, K.C., Marshall, J.E.A., 1981. Depositional environments and palynology of the Devonian south-east Shetland Basin. *Scottish Journal of Geology* 17, 257-273.

Alpern, B., Streel, M., 1972. Palynologie et stratigraphie du Paléozoïque moyen et supérieur. *Bureau de recherches géologiques et minières, Mémoire* 77, 217-241.

Amenábar, C.R., 2007. New palynological assemblage from the Chigua Formation (Early Late-Middle Devonian), at Del Chaco creek, Volcán Range, Precordillera Argentina. *Field Meeting of the IGCP 499-UNESCO 'Devonian land-sea interaction: evolution of ecosystems and climate'*, *San Juan, Argentina*, May 14-22, Serie de Correlación Geológica, INSUGEO, Universidad Nacional de Tucumán, Special Volume, 92-96.

Avkhimovitch, V.I., Tchibrikova, E.V., Obukhovskaya, T.G., Nazarenko, A.M., Umnova, V.T., Raskatova, L.G., Mantsurova, V.N., Loboziak, S., Streel, M., 1993. Middle and Upper Devonian miospore zonation of Eastern Europe. *Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine* 17, 79-147.

Bahafzallah, A., Jux, U., Omara, S., 1981. Stratigraphy and facies of the Devonian Jauf Formation, Saudi Arabia. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 1, 1-18.

Beck, C.B., 1981. *Archaeopteris* and its role in vascular plant evolution. In: Niklas, K.J. (Ed.), Paleobotany, Paleoecology and Evolution. *Praeger* 1**,** 193-230. New York.

Bellini, E., Massa, D., 1980. A stratigraphic contribution to the Palaeozoic of the southern basins of Libya. In: Salem, M.J., Busrewil, M.T. (Eds.), The Geology of Libya. Volume I. *Academic Press***,** 3-56. London.

Ben Rahuma, M.M., Proust, J.N., Eschard, R., 2007. Stratigraphic architecture of the Devonian successions in Awaynat Wanin area - Ghadamis Basin, Western Libya. *EAGE , 3rd North African/Mediterranean Petroleum and Geosciences*, *Tripoli, Libya*, 26-28 february 2007.

Berberian, M., King, G.C.P., 1981. Towards a paleogeography and tectonic evolution of Iran. *Canadian Journal of Earth Science* 18, 210-265.

Beydoun, Z.R., 1991. Arabian Plate hydrocarbon geology and potential - A plate tectonic approach. *American Association of Petroleum Geologists, Studies in Geology* 33, 1-77.

Blieck, A., Gagnier, P.Y., Bigey, E.P., Edgecombe, G.D., Janvier, P., Loboziak, S., Racheboeuf, P.R., Sempere, T., Steemans, P., 1996. New Devonian fossil localities in Bolivia. *Journal of South American Earth Sciences* 9, 295-308.

Boote, D.R.D., Clark-Lowes, D.D., Traut, M.W., 1998. Palaeozoic petroleum systems of North Africa. In: McGregor, D.S., Moody, R.T.J., Clark-Lowes, D.D. (Eds.), Petroleum Geology of North Africa. *Geological Society, Special Publication* 132**,** 7-68. London.

Boucot, A.J., 1984. Old World Realm (Rhenish-Bohemian Region), shallow water, Early Devonian brachiopods from the Jauf Formation, Saudi Arabia. *Journal of Palaeontology* 58, 1196-1203.

Boucot, A.J., 1988. Devonian biogeography: an update. In: McMillan, N.J., Embry, A.F., Glass, D.J. (Eds.), Devonian of the World. *Canadian Society of Petroleum Geologists* 3**,** 211-228. Calgary.

Boucot, A.J., Massa, D., Perry, D.G., 1983. Stratigraphy and taxonomy of some lower and middle Devonian brachipods-bearing beds of Libya and northern Niger. *Palaeontographica, Abteilung A* 180, 91-125.

Boucot, A.J., McClure, H.A., Alvarez, F., Ross, J.P., Taylor, D.W., Struve, W., Savage, N.N., Turner, S., 1989. New Devonian fossils from Saudi Arabia and their biogeographical affinities. *Senckenbergiana Lethaea* 69, 535-597.

Boudjema, A., 1987. Evolution structurale du bassin pétrolier (triassique) du Sahara nord orientale (Algérie). Unpublished PhD thesis, Université de Paris Sud, Centre D'Orsay.

Boumendjel, K., Loboziak, S., Paris, F., Steemans, P., Streel, M., 1988. Biostratigraphie des miospores et des chitinozoaires du Silurien supérieur et du Dévonien dans le Bassin d'Illizi (S.E. du Sahara algérien). *Geobios* 22, 329-357.

Bramkamp, R.A., Brown, G.F., Holm, D.A., Layne, N.M., Jr., 1963. Geologic map of the Wadi As Sirhan Quadrangle, Kingdom of Saudi Arabia. Map I-200 A, scale 1:500,000. U.S. Geological Survey Miscellaneous Investigation Series Map.

Breuer, P., Stricanne, L., Steemans, P., 2005a. Morphometric analysis of proposed evolutionary lineages of Early Devonian land plant spores. *Geological Magazine* 142, 241-253.

Breuer, P., Al-Ghazi, A., Filatoff, J., Higgs, K.T., Steemans, P., Wellman, C.H., 2005b. Stratigraphic palynology of Devonian boreholes from northern Saudi Arabia. In: Steemans, P., Javaux, E. (Eds.), Pre-Cambrian to Palaeozoic Palaeopalynology and Palaeobotany. *Carnets de Géologie / Notebooks on Geology* Memoir 2005/02, Abstract 01. Brest.

Breuer, P., Al-Ghazi, A., Al-Ruwaili, M., Higgs, K.T., Steemans, P., Wellman, C.H., 2007. Early to Middle Devonian miospores from northern Saudi Arabia. *Revue de Micropaléontologie* 50, 27-57.

Burjack, M.I.A., Loboziak, S., Streel, M., 1987. Quelques données nouvelles sur les miospores dévoniennes du bassin du Paraná (Brésil). *Sciences Géologiques, Bulletin* 40, 381-391.

Chaloner, W.G., Hemsley, A.R., 1991. Heterospory: cul-de-sac or pathway to the seed? In: Blackmore, S., Barnes, S.H. (Eds.), Pollen and Spores, Pattern of Diversification. *Systematics Association, Special Volume* 44**,** 151-167. London.

Chaloner, W.G., Sheerin, A., 1981. The evolution of reproductive strategies in early land plants. In: Scudder, G.G.E., Reveal, J.L. (Eds.), Evolution Today. *Proceedings of the Second International Congress of Systematic and Evolutionary Biology***,** 93-100. Pittsburg.

Chi, B.I., Hills, L.V., 1976. Biostratigraphy and taxonomy of Devonian megaspores, Arctic Canada. *Bulletin of Canadian Petroleum Geology* 24, 640-818.

Clark, D.L., Harteberg, E.W., 1983. Palaeoenvironmental factors and the distribution of conodonts in Lower Triassic of Svalbard and Nepal. *Fossils and Strata* 15, 171-175.

Clayton, G., Owens, B., Al-Hajri, S.A., Filatoff, J., 2000. Latest Devonian and Early Carboniferous miospore assemblages from Saudi Arabia. In: Al-Hajri, S.A., Owens, B. (Eds.), Stratigraphic Palynology of the Paleozoic of Saudi Arabia. *GeoArabia, Special Publication* 1**,** 146-153. Bahrain.

Cocks, L.R.M., Torsvik, T.H., 2002. Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review. *Journal of the Geological Society of London* 159, 631-644.

Coquel, R., Latreche, S., 1989. Etude palynologique de la Formation d'Illerène (Devono-Carbonifère) du Bassin d'Illizi (Sahara algérien oriental). *Palaeontographica, Abteilung B* 212, 47-70.

Daemon, R.F., Quadros, L.P., Da Silva, L.C., 1967. Devonian palynology and biostratigraphy of the Paraná Basin. In: Bigarella, J.J. (Ed.), Problems in Brazilian Devonian Geology. *Boletim Paranaense de Geociências* 21/22**,** 99-132. Curitiba.

Dilcher, D.L., Kar, R.K., Dettmann, M.E., 1992. The functional biology of Devonian spores with bifurcate processes – a hypothesis. *The Palaeobotanist* 41, 67-74.

Dino, R., 1999. Palynostratigraphy of the Silurian and Devonian sequence of the Paraná Basin, Brazil. In: Rodrigues, M.A.C., Pereira, E. (Eds.), Ordovician-Devonian palynostratigraphy in Western Gondwana: update, problems and perspectives. *Faculdade de Geologia da Universidade Estatal do Rio de Janeiro, Resumos expandidos***,** 27-61. Rio de Janeiro.

Echikh, K., 1987. Geology and habitat of hydrocarbons in western Libya. *Third Symposium on Geology of Libya*, *Tripoli University, Tripoli, Libya*.

Echikh, K., 1992. Geology and hydrocarbon potential of Ghadamis basin. Internal Report, National Oil Company of Libya (NOC), Tripoli.

Echikh, K., 1998. Geology and hydrocarbon occurrences in the Ghadames Basin, Algeria, Tunisia, Libya. In: Macgregor, D.S., Moody, R.T.J., Clark-Lowes, D.D. (Eds.), Petroleum Geology of North Africa. *Geological Society, Special Publication* 132**,** 109-129. London.

Edwards, D., 1973. Devonian floras. In: Hallam, A. (Ed.), Atlas of Palaeobiogeography. *Elsevier***,** 105-115. Amsterdam.

Edwards, D., Berry, C.M., 1991. Silurian and Devonian. In: Cleal, C.J. (Ed.), Plants Fossils in Geological Investigation, the Paleozoic. *Ellis Horwood***,** 117-153. London.

Edwards, L.E., 1984. Insight on why graphic correlation (Shaw's method) works. *Journal of Geology* 92, 583-587.

El-Rweini, W.S., 1991. Geology of the Aouinet Ouenine and Tahara Formations, Al Hamadah Al Hamra area, Ghadamis Basin. In: Salem, M.J., Sbeta, A.M., Bakbak, M.R. (Eds.), The Geology of Libya. Volume VI. *Elsevier***,** 2185-2193. Amsterdam.

Ford, G.W., Muller, W.L., 1995. Potential Silurian and Devonian truncation traps across the Ahara Arch, southwest Ghadames Basin, Algeria. *First Symposium on the Hydrocarbon Geology of North Africa*, 28-30 November, Geological Society of London.

Forey, P.L., Young, V.T., McClure, H.A., 1992. Lower Devonian fishes from Saudi Arabia. *Bulletin of the Bitish Museum of Natural History Geology* 48, 25-43.

Gensel, P.G., 1986. Diversification of land plants in the Early and Middle Devonian. In: Gastaldo, R.A., Broadhead, T.W. (Eds.), Land Plants: Notes for a Short Course. *University of Tennessee, Department of Geological Sciences. Stuides in Geology* 15**,** 64-80. Knoxville.

Gradstein, F.M., Agterberg, F.P., Browe, J.C., Schwarzacher, W.S., 1985. Quantitative Stratigraphy. D. Reidel Publishing CO., Dordrecht, Holland, 393 p.

Grahn, Y., Loboziak, S., Melo, J.H.G., 2003. Integrated correlation of Late Silurian (Pridoli *s. l.*)-Devonian chitinozoans and miospores in the Solimões Basin, northern Brazil. *Acta Geologica Polonica* 53, 283-300.

Grey, K., 1991. A mid-Givetian miospore age for the onset of reef development on the Lennard Shelf, Canning Basin, Western Australia. *Review of Palaeobotany and Palynology* 68, 37-48.

Hajlasz, B., Massa, D., Bonnefous, J., 1978. Silurian and Devonian tentaculites from Libya and Tunisia. *Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine* 2, 1-37.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., Smith, D.G., 1990. A Geological Time Scale 1989. Cambridge University Press, Cambridge.

Hashemi, H., Playford, G., 2005. Devonian spore assemblages of the Adavale Basin, Queensland (Australia): descriptive systematics and stratigraphic significance. *Revista Española de Micropaleontología* 37, 317-417.

Hedberg, H.D. (Ed.) 1976. International Stratigraphic Guide. *John Wiley & Sons, Ltd.*, 200 p. New York.

Helal, A.H., 1965. General geology and lithostratigraphic subdivision of the Devonian rocks of the Jauf area, Saudi Arabia. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 9, 527-551.

Hemer, D.O., Nygreen, P.W., 1967. Devonian Palynology of Saudi Arabia. *Review of Palaeobotany and Palynology* 5, 51-61.

Hladil, J., Bek, J., 1999. Distances between the Early/Middle Devonian Gondwana and Laurussia: faunal and spore dispersals as compared with paleomagnetic data on paleolatitudes. *Exploration Geophyphics, Remote Sensing and Environment* 2, 29-33.

Hughes-Clarke, M.W., 1988. Stratigraphy and rock unit nomenclature in the oil-producing area of interior Oman. *Journal of Petroleum Geology* 11, 5-60.

Husseini, M.I., 1991. Tectonic and depositional model of the Arabian and Adjoining Plates during the Silurian-Devonian. *American Association of Petroleum Geologists, Bulletin* 75, 108-120.

Jaglin, J.C., Paris, F., 2002. Biostratigraphy, biodiversity and palaeogeography of late Silurian chitinozoans from A1-61 borehole (north-western Libya). In: Steemans, P., Servais, T., Streel, M. (Eds.), Palaeozoic Palynology: A Special Issue in Honour of Dr. Stanislas Loboziak. *Review of Palaeobotany and Palynology***,** 335-358. Amsterdam.

Janjou, D., Halawani, M.A., Al-Muallem, M.S., Robelin, C., Brosse, J.-M., Courbouleix, S., Dagain, J., Genna, A., Razin, P., Roobol, M.J., Shorbaji, H., Wyns, R., 1997a. Explanatory notes to the geological map of the Al Qualibah Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-135, scale 1:250,000, sheet 28C. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, 44 p.

Janjou, D., Halawani, M.A., Brosse, J.-M., Al-Muallem, M.S., Becq-Giraudon, J.F., Dagain, J., Genna, A., Razin, P., Roobol, M.J., Shorbaji, H., Wyns, R., 1997b. Explanatory notes to the geological map of the Tabuk Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-137, scale 1:250,000, sheet 28B. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, 49 p.

Jardiné, S., Yapaudjian, L., 1968. Lithostratigraphie et Palynologie du Dévonien-Gothlandien gréseux du Bassin de Polignac (Sahara). *Revue de l'Institut Français du Pétrole* 23, 439-469.

Jersey, N.J., de, 1966. Devonian spores from the Adavale Basin. *Geological Survey of Queensland* 334, *Palaeontological Papers* 3, 1-28.

Kar, R.K., Dilcher, D.L., 2002. An argument for the origins of heterospory in aquatic environments. *The Palaeobotanist* 51, 1-11.

Kemp, E.M., 1972. Lower Devonian palynomorphs from the Horlick Formation, Ohio range, Antarctica. *Palaeontographica, Abteilung B* 139, 105-124.

Kevan, P.G., Chaloner, W.G., Savile, D.B.O., 1975. Interrelationships of early terrestrial arthropods an plants. *Palaeontology* 18, 391-417.

Konert, G., Al-Afifi, A.M., Al-Hajri, S.A., 2001. Paleozoic stratigraphy and hydrocarbon habitat of the Arabian Plate. *GeoArabia* 6, 407-422.

Le Hérissé, A., 1983. Les spores du Dévonien inférieur du Synclinorium de Laval (Massif Armoricain). *Palaeontographica, Abteilung B* 188, 1-81.

Le Hérissé, A., Al-Ruwaili, M., Miller, M.A., Vecoli, M., 2007. Environmental changes reflected by palynomorphs in the early Middle Ordovician Hanadir Member of the Qasim Formation, Saudi Arabia. *Revue de Micropaléontologie* 50, 3-16.

Le Hérissé, A., Gourvennec, R., Wicander, R., 1997. Biogeography of Late Silurian and Devonian acritarchs and prasinophytes. *Review of Palaeobotany and Palynology* 98, 105-124.

Le Hérissé, A., Servais, T., Wicander, R., 2000. Devonian acritarchs and related forms. In: Bultynck, P. (Ed.), Subcommission on Devonian Stratigraphy. Fossil groups important for boundary definition. *Courier Forschungsinstitut Senckenberg* 220**,** 195-205. Frankfurt.

Lebret, P., Halawani, M.A., Memesh, A., Bourdillon, C., Janjou, D., Le Nindre, Y.-M., Roger, J., Shorbaji, H., Kurdi, H., 1999. Explanatory notes to the geological map of the Turubah Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-139, scale 1:250,000, sheet 28F. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, 46 p.

Lelièvre, H., Janvier, P., Janjou, D., Halawani, M.A., 1995. *Nefudina qalibahensis* nov. gen., nov. sp. un rhénanide (Vertebrata, Placodermi) du Dévonien inférieur de la Formation de Jauf (Emsien) d'Arabie Saoudite. *Geobios* 19, 109-115.

Loboziak, S., 2000. Middle to early Late Devonian miospore biostratigraphy of Saudi Arabia. In: Al-Hajri, S., Owens, B. (Eds.), Stratigraphic Palynology of the Palaeozoic of Saudi Arabia. *GeoArabia, Special Publication* 1**,** 134-145. Bahrain.

Loboziak, S., Caputo, M.V., Melo, J.H.G., 2000. Middle Devonian-Tournaisian miospore biostratigraphy in the southwestern outcrop belt of the Parnaíba, north-central Brazil. *Revue de Micropaléontologie* 43, 301-318.

Loboziak, S., Melo, J.H.G., 2002. Devonian miospore successions of Western Gondwana: update and correlation with Southern Euramerican miospore zones. *Review of Palaeobotany and Palynology* 121, 133-148.

Loboziak, S., Melo, J.H.G., Matsuda, N.S., Quadros, L.P., 1997. Miospore biostratigraphy of the type Barreinrinha Formation (Curuá Group, Upper Devonian) in the Tapajós River area, Amazon Basin, North Brazil. *Bulletin des Centres de Recherches Exploration-Production Elf Aquitaine* 21, 187-205.

Loboziak, S., Melo, J.H.G., Rodrigues, R., Streel, M., Quadros, L.P., Barrilari, I.M.R., 1996. Age and correlation of the Barreirinha Formation (Curuá Group, Amazon Basin): new evidence from the miospore biostratigraphy. *Anais da Academia Brasileira de Ciências* 68, 207-212.

Loboziak, S., Melo, J.H.G., Streel, M., 2005. Devonian palynostratigraphy in Western Gondwana. In: Koutsoukos, E.A.M. (Ed.), Applied Stratigraphy. *Springer***,** 73-99. Dordrecht.

Loboziak, S., Steemans, P., Streel, M., Vachard, D., 1992a. Biostratigraphie par miospores du Dévonien inférieur à supérieur du sondage MG-1 (Bassin d'Hammadah, Tunisie) - Comparaison avec les données des faunes. *Review of Palaeobotany and Palynology* 74, 193-205.

Loboziak, S., Streel, M., 1989. Middle-Upper Devonian miospores from the Ghadamis Basin (Tunisia-Libya): systematics and stratigraphy. *Review of Palaeobotany and Palynology* 58, 173-196.

Loboziak, S., Streel, M., 1995a. West Gondwanan aspects of the Middle and Upper Devonian miospore zonation in North Africa and Brazil. In: Le Hérissé, A., Owens, B., Paris, F. (Eds.), Palaeozic palynomorphs of the Gondwana-Euramerican interface. *Review of Palaeobotany and Palynology* 86**,** 147-155. Amsterdam.

Loboziak, S., Streel, M., 1995b. Late Lower and Middle Devonian miospores from Saudi Arabia. In: Owens, B., Al-Tayyar, H., Van der Eem, J.G.L.A., Al-Hajri, S. (Eds.), Palaeozoic palynostratigraphy of the Kingdom of Saudi Arabia. *Review of Palaeobotany and Palynology* 89**,** 105-114. Amsterdam.

Loboziak, S., Streel, M., Burjack, M.I.A., 1988. Miospores du Dévonien moyen et supérieur du Bassin du Parana, Brésil: Systématique et stratigraphie. *Sciences Géologiques, Bulletin* 41, 351-377.

Loboziak, S., Streel, M., Burjack, M.I.A., 1989. Déductions paléoclimatiques d'une comparaison entre les assemblages de miospores du Dévonien moyen et supérieur de Libye et du Brésil. *Geobios* 22, 247-351.

Loboziak, S., Streel, M., Caputo, M.V., Melo, J.H.G., 1992b. Middle Devonian to Lower Carboniferous miospore stratigraphy in the Central Parnaíba Basin (Brazil). *Annales de la Société Géologique de Belgique* 115, 215-226.

Loboziak, S., Streel, M., Weddige, K., 1990. Miospores, the *lemurata* and *triangulatus* levels and their faunal indices near the Eifelian/Givetian boundary in the Eifel (F.R.G.). *Annales de la Société Géologique de Belgique* 113, 1-15.

Lozej, G.P., 1983. Geological and geochemical reconnaissance exploration of the cover rocks in northwestern Hijaz. Open-file report RF-OF-03-2. Deputy Ministry for Mineral Resources, Jeddah, Saudi Arabia.

Lu Lichang, 1980. On the occurrence of *Archaeoperisaccus* in E. Yunnan. *Acta Palaeontologica Sinica* 19, 500-503 (in Chinese).

Magloire, L., 1968. Etude stratigraphique par la palynologie des dépôts argilo-gréseux du Silurien et du Dévonien inférieur dans la région du Grand Erg Occidental (Sahara algérien). *International Symposium on the Devonian System, Calgary* 2, 473-495.

Maher, L.J., Jr., 1981. Statistics fro microfossil concentration measurements employing samples spiked with marker grains. *Review of Palaeobotany and Palynology* 32, 153-191.

Mann, K.O., Lane, H.R. (Eds.), 1995. Graphic Correlation. *SEPM Society for Sedimentary Geology, Special Publication* 53, 263 p. Tulsa.

Marshall, J.E.A., 1988. Devonian miospores from Papa Stour, Shetland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 79, 13-18.

Marshall, J.E.A., 1996. Vegetational history of Devonian spores. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principles and Applications. *American Association of Stratigraphic Palynologists Foundation* 3**,** 1133-1141. Dallas.

Marshall, J.E.A., Allen, K.C., 1982. Devonian miospore assemblages from Fair Isle, Shetland. *Palaeontology* 25, 277-312.

Marshall, J.E.A., Fletcher, T.P., 2002. Middle Devonian (Eifelian) spores from a fluvial dominated lake margin in the Orcadian Basin, Scotland. *Review of Palaeobotany and Palynology* 118, 195-209.

Marshall, J.E.A., Miller, M.A., Filatoff, J., Al-Shahab, K., 2007. Two new Middle Devonian megaspores from Saudi Arabia. *Revue de Micropaléontologie* 50, 73-79.

Massa, D., 1988. Paléozoïque de Libye occidentale: stratigraphie et paléogéographie. PhD thesis, Université de Nice, 514 p.

Massa, D., Moreau-Benoit, A., 1976. Essai de synthèse stratigraphique et palynologique du Système Dévonien en Libye occidentale. *Revue de l'Institut Français du Pétrole* 41, 287-333.

Massa, D., Moreau-Benoit, A., 1985. Apport de nouvelles données palynologiques à la biostratigraphie et à la paléogéographie du Dévonien en Libye (sud du bassin de Rhadamès). *Sciences Géologiques, Bulletin* 38, 5-18.

Matthews, R.K., Frohlich, C., 2002. Maximum flooding surface and sequence boundaries: comparisons between observation and orbital forcing in the Cretaceous and Jurassic (65-190 Ma). *GeoArabia* 7, 503-538.

McGregor, D.C., 1969. Devonian plant fossils of the genera *Kryshtovichia*, *Nikitinsporites*, *Archaeoperisaccus*. *Geological Survey of Canada, Bulletin* 182, 91-106.

McGregor, D.C., 1973. Lower and Middle Devonian spores of Eastern Gaspé, Canada. I. Systematics. *Palaeontographica, Abteilung B* 142, 1-77.

McGregor, D.C., 1979. Spores in Devonian stratigraphical correlation. In: House, M.R., Scrutton, C.T., Bassett, M.G. (Eds.), The Devonian System. *Palaeontological Association, Special Paper* 23**,** 163-184. London.

McGregor, D.C., 1984. Late Silurian and Devonian spores from Bolivia. *Academia Nacional de Ciencias* 69, 1-57.

McGregor, D.C., Camfield, M., 1976. Upper Silurian? to Middle Devonian spores of the Moose River Basin, Ontario. *Geological Survey of Canada, Bulletin* 263, 1-63.

McGregor, D.C., Camfield, M., 1982. Middle Devonian miospore from the Cape de Bray, Weatherall, and Hecla Bay Formations of northeastern Melville Island, Canadian Artic. *Geological Survey of Canada, Bulletin* 348, 1-105.

McGregor, D.C., Owens, B., 1966. Devonian spores of eastern and northern Canada. *Geological Survey of Canada, Paper* 66-30, 1-66.

McGregor, D.C., Playford, G., 1992. Canadian and Australian Devonian spores: zonation and correlation. *Geological Survey of Canada, Bulletin* 438, 1-125.

Meissner Jr., C.R., Dini, S.M., Farasani, A.M., Riddler, G.P., van Eck, M., Aspinall, N.C., 1988. Preliminary geological map of the Al Jawf Quadrangle, sheet 29D, Kingdom of Saudi Arabia. Open-file report USGS-OF-09-1. Ministry of Petroleum and Minerals, Deputy Ministry for Mineral Resources, Jeddah, Saudi Arabia.

Meissner Jr., C.R., Dini, S.M., Farasani, A.M., Smith, A.G., Aspinall, N.C., 1989. Geological map of the Al Jawf Quadrangle, sheet 29D, Kingdom of Saudi Arabia. Open-file report USGS-OF-88. Ministry of Petroleum and Minerals, Deputy Ministry for Mineral Resources, Jeddah, Saudi Arabia.

Meissner Jr., C.R., Mytton, J.W., Riddler, G.P., van Eck, M., Aspinall, N.C., Farasani, A.M., Dini, S.M., 1986. Preliminary geologic map of the Ash Shuwayhitiyah Quadrangle, sheet 30D, Kingdom of Saudi Arabia. Open-file report USGS-OF-06-1. Ministry of Petroleum and Minerals, Deputy Ministry for Mineral Resources, Jeddah, Saudi Arabia.

Melo, J.H.G., Loboziak, S., 2003. Devonian-Early Carboniferous miospore biostratigraphy of the Amazon Basin, Northern Brazil. *Review of Palaeobotany and Palynology* 124, 131-202.

Mendlowicz Mauller, P., Machado Cardoso, T.R., Pereira, E., Steemans, P., 2007. Resultados Palinoestratigráficos do Devoniano da Sub-Bacia de Alto Garças (Bacia do Paraná - Brasil). In: Carvalho, I.S., Cassab, R.C.T., Schwanke, C., Carvalho, M.A., Fernandes, A.C.S., Rodrigues, M.A.C., Carvalho, M.S.S., Arai, M., Oliveira, M.E.Q. (Eds.), Paleontologia: cenários de Vida. *Interciência***,** 607-619. Rio de Janeiro.

Menéndez, C.A., Pöthe de Baldis, E.D., 1967. Devonian spores from Paraguay. *Review of Palaeobotany and Palynology* 1, 161-172.

Meyer-Berthaud, B., Fairon-Demaret, M., Steemans, P., Talent, J., Gerrienne, P., 2003. The plant *Leclercqia* (Lycopsida) in Gondwana: implications for reconstructing Middle Devonian palaeogeography. *Geological Magazine* 140, 119-130.

Moreau-Benoit, A., 1966. Etude des spores du Dévonien Inférieur d'Avrillé (Le Flechay), Anjou. *Revue de Micropaléontologie* 8, 215-232.

Moreau-Benoit, A., 1979. Les spores du Dévonien de Libye. Première partie. *Cahiers de Micropaléontologie* 4, 1-58.

Moreau-Benoit, A., 1980. Les spores du Dévonien de Libye. Deuxième partie. *Cahiers de Micropaléontologie* 1, 1-53.

Moreau-Benoit, A., 1988. Considérations nouvelles sur la palynozonation du Dévonien moyen et supérieur du Bassin de Rhadamès, Libye occidentale. *Comptes Rendus de l'Académie des Sciences de Paris, Série II* 307, 863-869.

Moreau-Benoit, A., 1989. Les spores du Dévonien Moyen et Supérieur de Libye Occidentale: Compléments-Systématique-Répartition stratigraphique. *Cahiers de Micropaléontologie* 4, 5-32.

Moreau-Benoit, A., Coquel, R., Latreche, S., 1993. Étude palynologique du Dévonien du bassin d'Illizi (Sahara Oriental Algérien). Approche biostratigraphique. *Geobios* 26, 3-31.

Naumova, S.N., 1953. Spore-pollen assemblages of the Upper Devonian of the Russian Platform and their stratigraphic significance. *Akademiya Nauk SSSR, Institut Geologii Nauk 143, Geological Series* 60, 203 p. (in Russian).

Ottone, G.E., 1996. Devonian palynomorphs from the Los Monos Formation, Tarija Basin, Argentina. *Palynology* 20, 105-155.

Owens, B., 1971. Miospores from the Middle and Early Upper Devonian rocks of the Western Queen Elizabeth Island, Arctic Archipelago. *Geological Survey of Canada*, *Paper* 70-38, 1-157.

Paris, F., 1996. Chitinozoan biostratigraphy and palaeoecology. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principles and Applications. *American Association of Stratigraphic Palynologists Foundation* 2**,** 531-552. Dallas.

Paris, F., Richardson, J.B., Riegel, W., Streel, M., Vanguestaine, M., 1985. Devonian (Emsian-Famennian) palynomorphs. In: Thusu, B., Owens, B. (Eds.), Palynostratigraphy of North-East Libya. *Journal of Micropalaeontology* 4**,** 49-81. London

Paris, F., Winchester-Seeto, T., Boumendjel, K., Grahn, Y., 2000. Toward a global biozonation of Devonian chitinozoans. In: Bultynck, P. (Ed.), Subcommission on Devonian Stratigraphy. Fossil groups important for boundary definition. *Courier Forschungsinstitut Senckenberg* 220**,** 39-55. Frankfurt.

Pashkevich, N.G., 1964. New Devonian species of *Archaeoperisaccus* (Gymnospermae) from North Timan. *Akademiya Nauk SSR, Paleontologicheskii Zhurnal* 4, 126-129.

Pasquo, M., di, 2007. Asociaciones palinológicas presentes en las Formaciones Los Monos (Devónico) e Itacua (Carbonífero Inferior) en el perfil de Balapuca, sur de Bolivia. Parte 1. Formación Los Monos. *Revista Geológica de Chile* 34, 98-137.

Pasquo, M., di, Amenábar, C.R., Noetinger, S., 2007. The palaeobiogeographical significance of the spore *Grandispora pseudoreticulata* (Menéndez and Pöthe de Baldis) Ottone in the Middle to Late Devonian of Gondwana. *Field Meeting of the IGCP 499-UNESCO 'Devonian land-sea interaction: evolution of ecosystems and climate', San Juan, Argentina*, May 14-22, Serie de Correlación Geológica, INSUGEO, Universidad Nacional de Tucumán, Special Volume, 91-101.

Perez-Leyton, M.A., 1990. Miospores du Dévonien Moyen et Supérieur de la coupe de Bermejo-La Angostura (Sud-Est de la Bolivie). *Annales de la Société Géologique de Belgique* 113, 373-389.

Powers, R.W., 1968. Asie: Arabie Saoudite. Lexique Stratigraphique Internationale. Edition du CNRS, Paris, 177 p.

Powers, R.W., Ramirez, L.F., Redmond, C.D., Elberg, E.L., Jr., 1966. Sedimentary geology of Saudi Arabia. In, Geology of the Arabian Peninsula. *United States Geological Survey, Professionnal Paper* 560D**,** 1-147. Washington.

Rahmani, R.A., 2004. Facies and sequences of Devonian Jauf Reservoir, Ghawar Field, Saudi Arabia. In, 6th Middle East Geosciences Conference, GEO 2004. *GeoArabia* 9**,** 118.

Rahmani, R.A., Steel, R.J., Al-Duaiji, A.A., 2002. High-resolution sequence stratigraphy of the Devonian Jauf gas reservoir: a shoreface and estuarine embayment succession, greater Ghawar area, eastern Saudi Arabia. In, 5th East Geosciences Conference, GEO 2002. *GeoArabia* 7**,** 288.

Rahmani-Antari, K., Lachkar, G., 2001. Contribution à l'étude biostratigraphique du Dévonien et du Carbonifère de la plate-forme marocaine. Datation et corrélations. *Revue de Micropaléontologie* 44, 159-183.

Raymond, A., Parker, W.C., Barrett, S.F., 1985. Early Devonian phytogeography. In: Tiffney, B.H. (Ed.), Geological Factors and the Evolution of Plants. *Yale University Press***,** 129-167. New Haven.

Raymond, A., 1987. Paleogeographic distribution of Early Devonian plant traits. *Palaios* 2, 113-132.

Richardson, J.B., 1965. Middle Old Red Sandstone spore assemblages from the Orcadian basin north-east Scotland. *Palaeontology* 7, 559-605.

Richardson, J.B., 1967. Some British Lower Devonian spore assemblages and their stratigraphic significance. *Review of Palaeobotany and Palynology* 1, 111-129.

Richardson, J.B., McGregor, D.C., 1986. Silurian and Devonian spore zones of the Old Red Sandstone Continent and adjacent regions. *Geological Survey of Canada, Bulletin* 364, 1-79.

Richardson, J.B., Rodriguez, R.M., Sutherland, S.J.E., 2001. Palynological zonation of Mid-Palaeozoic sequences from the Cantabrian Mountains, NW Spain: implications for inter-regional and interfacies correlation of the Ludford/Prídolí and Silurian/Devonian boundaries, and plant dispersal patterns. *Bulletin of the Natural History Museum, Geology Series* 57, 115-162.

Riegel, W., 1973. Sporenformen aus den Heisdorf-Lauch- und Nohn-Schichten (Emsium und Eifelium) der Eifel, Rheinland. *Palaeontographica, Abteilung B* 142, 78-104.

Rodriguez, R.M., 1983. Palinologia de las Formaciones del Silurico superior - Devonico inferior de la Cordillera Cantabrica. *Servicio de Publicaciones, Universidad de León*, 1-231.

Rubinstein, C., Le Hérissé, A., Steemans, P., submitted. Lochkovian (Early Devonian) acritarchs and prasinophytes from the Solimões Basin, northwestern Brazil. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*.

Rubinstein, C., Steemans, P., 2002. Miospore assemblages from the Silurian-Devonian boundary, in borehole A1-61, Ghadamis Basin, Libya. *Review of Palaeobotany and Palynology* 118, 397-421.

Rubinstein, C., Steemans, P., 2007. New palynological data from the Devonian Villavicencio Formation, Precodillera of Mendoza, Argentina. *Ameghiniana, Revista de la Asociación Paleontológica Argentina* 44, 3-9.

Salvador, A. (Ed.) 1994. International Stratigraphic Guide. 2nd edition. *International Union of Geological Sciences and Geological Society of America*, 214 p. Boulder.

Samuelsson, J., Vecoli, M., Bednarczyk, W.S., Verniers, J., 2002. Timing of the Avalonia-Baltica plate convergence as inferred from palaeogeographic and stratigraphic data of chitinozoan assemblages in west Pomerania, northern Poland. In: Winchester, J.A., Pharaoh, T.C., Verniers, J. (Eds.), Palaeozoic Amalgamation of Central Europe. *Geological Society, Special Publication* 201**,** 95-113. London.

Scotese, C.R., 2000. Atlas of Earth History. PALEOMAP Project, 52 p. Arlington. http://www.scotese.com/earth.html.

Sharland, P.R., Archer, R., Casey, D.M., Davies, R.B., Hall, S.H., Heward, A.P., Horbury, A.D., Simmons, M.D., 2001. Arabian Plate sequence stratigraphy. *GeoArabia, Special Publication* 2, 1-371.

Steemans, P., 1989. Palynostratigraphie de l'Eodévonien dans l'ouest de l'Europe. *Mémoires Explicatifs pour les Cartes Géologiques & Minéralogiques de la Belgique* 27, 453 p.

Steemans, P., 1995. Silurian and Lower Emsian spores in Saudi Arabia. *Review of Palaeobotany and Palynology* 89, 91-104.

Steemans, P., 1999. Paléodiversification des spores et des cryptospores de l'Ordovicien au Dévonien inférieur. *Geobios* 32, 341-352.

Steemans, P., Lakova, I., 2004. The Moesian Terrane during the Lochkovian - a new palaeogeographic and phytogeographic hypothesis based on miospore assemblages. *Palaeogeography, Palaeoclimatology, Palaeoecology* 208, 225-233.

Steemans, P., Wellman, C.H., 2004. Miospores and the emergence of land plants. In: Webby, B., Paris, F., Droser, M.L., Percival, I.G. (Eds.), The Great Ordovician Biodiversification Event. Critical Moments and Perspectives in Earth History and Paleobiology. *Columbia University Press***,** 361-366. New York.

Steemans, P., Wellman, C.H., Filatoff, J., 2007a. Palaeophytogeographical and palaeoecological implications of a miospore assemblage of earliest Devonian (Lochkovian) age from Saudi Arabia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 250, 237-254.

Steemans, P., Breuer, P., Gerrienne, P., Prestianni, C., Streel, M., Ville de Goyet, F., de, 2007b. Givetian megaspores from Libya and Belgium. In, Pereira, Z., Oliveira, J.T., Wicander, R. (Eds.), CIMP, Joint Meeting of Spores/Pollen and Acritarch Subcommissions, 79-81. Lisbon.

Steineke, M., Bramkamp, R.A., Sander, N.J., 1958. Stratigraphic relations of Arabian oil. In: Weeks, L.G. (Ed.), Habitat of oil. *American Association of Petroleum Geologists, Symposium Tulsa*, 1294-1329.

Streel, M., 1965. Techniques de préparation des roches détritiques en vue de l'analyse palynologique quantitative. *Annales de la Société Géologique de Belgique* 88, 107-117.

Streel, M., 1967. Associations de spores du Dévonien inférieur belge et leur signification stratigraphique. *Annales de la Société Géologique de Belgique* 90, 11-53.

Streel, M., Fairon-Demaret, M., Gerrienne, P., Loboziak, S., Steemans, P., 1990a. Lower and Middle Devonian miospore-based stratigraphy in Libya and its relation to the megafloras and faunas. *Review of Palaeobotany and Palynology* 66, 229-242.

Streel, M., Fairon-Demaret, M., Loboziak, S., 1990b. Givetian-Frasnian phytogeography of Euramerica and western Gondwana based on miospore distribution. In: McKerrow, W.S., Scotese, C.R. (Eds.), Palaeozoic palaeogeography and biogeography. *Memoirs of the Geological Society of London* 12**,** 291-296.

Streel, M., Higgs, K., Loboziak, S., Riegel, W., Steemans, P., 1987. Spore stratigraphy and correlation with faunas and floras in the type marine Devonian of the Ardenno-Rhenish regions. *Review of Palaeobotany and Palynology* 50, 211-229.

Streel, M., Loboziak, S., 1996. Middle and Upper Devonian miospores. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principles and Applications. *American Association of Stratigraphic Palynologists Foundation* 2**,** 575-587. Dallas.

Streel, M., Loboziak, S., Steemans, P., Bultynck, P., 2000. Devonian miospore stratigraphy and correlation with the global stratotype sections and points. In: Bultynck, P. (Ed.), Subcommission on Devonian Stratigraphy. Fossil groups important for boundary definition. *Courier Forschungsinstitut Senckenberg* 220**,** 9-23. Frankfurt.

Streel, M., Paris, F., Riegel, W., Vanguestaine, M., 1988. Acritarch, chitinozoan and spore stratigraphy from the Middle and Late Devonian of northeast Libya. In: El-Arnauti, A., Owens, B., Thusu, B. (Eds.), Subsurface Palynostratigraphy of Northeast Libya. *Garyounis University*. Benghazi, Libya.

Strother, P.K., Al-Hajri, S., Traverse, A., 1996. New evidence for land plants from the lower Middle Ordovician of Saudi Arabia. *Geology* 24, 55-59.

Stump, T.E., Al-Hajri, S.A., Van der Eem, J.G., 1995. Geology and biostratigraphy of the Late Precambrian through Palaeozoic sediments of Saudi Arabia. In: Owens, B., Al-Tayyar, H., Van der Eem, J.G. (Eds.), Palaeozoic Palynostratigraphy of the Kingdom of Saudi Arabia. *Review of Palaeobotany and Palynology* 89**,** 5-17.

Tchibrikova, E.V., 1959. Spores of the Devonian and older rocks of Bashkiria. Data on palaeontology and stratigraphy of Devonian and older deposits of Bashkiria. *Academy of Sciences of USSR, Bashkirian Branch*, 1-247 (in Russian).

Tchibrikova, E.V., 1962. Spores of Devonian terrigenous deposits of western Bashkiria and the western slopes of the southern Urals. *Academy of Sciences of USSR, Bashkirian Branch*, 353-476 (in Russian).

Tiwari, R.S., Schaarschmidt, F., 1975. Palynological studies in the Lower and Middle Devonian of the Prüm Syncline, Eifel (Germany). *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft* 534, 1-129.

Torsvik, T.H., Cocks, L.R.M., 2004. Earth geography from 400 to 250 Ma: a palaeomagnetic, faunal and facies review. *Journal of the Geological Society of London* 161, 555-572.

Traverse, A., 2007. Paleopalynology. Second Edition. Springer, 28, 814 p. Dordrecht.

Turnau, E., 1986. Lower to Middle Devonian spores from the vicinity of Pionki (Central Poland). *Review of Palaeobotany and Palynology* 46, 311-354.

Turnau, E., 1996. Miospore stratigraphy of Middle Devonian deposits from Western Pomerania. *Review of Palaeobotany and Palynology* 93, 107-125.

Turnau, E., Milaczewski, L., Wood, G.D., 2005. Spore stratigraphy of Lower Devonian and Eifelian (?), alluvial and marginal marine deposits of the Radom-Lublin area (central Poland). *Annales Societatis Geologorum Poloniae* 75, 121-137.

Vanguestaine, M., 1986. Late Devonian and Carboniferous acritarch stratigraphy and palaeogeography. *Annales de la Société Géologique de Belgique* 109, 93-102.

Vaslet, D., Kellogg, K.S., Berthiaux, A., Le Strat, P., Vincent, P.-L., 1987. Expanatory notes to the geologic map of the Baq'a Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-116C, scale 1:250,000, sheet 27F. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, 29 p.

Vavrdová, M., Bek, J., Dufka, P., Isaacson, P.E., 1996. Palynology of the Devonian (Lochkovian to Tournaisian) sequence, Madre de Dios Basin, northern Bolivia. *Bulletin of the Czech Geological Survey* 71, 333-349.

Ville de Goyet, F., de, Breuer, P., Gerrienne, P., Steemans, P., Streel, M., 2007. Middle Devonian (Givetian) megaspores from Belgium (Ronquières) and Libya (A1-69 borehole). In: Steemans, P., Javaux, E. (Eds.), Pre-Cambrian to Palaeozoic Palaeopalynology and Palaeobotany. *Carnets de Géologie / Notebooks on Geology*, Brest, Memoir 2007/01, Abstract 11.

Vos, R.G., 1981. Deltaic sedimentation in Devonian of western Libya. *Sedimentary Geology* 29, 67-88.

Wallace, C.A., Dini, S.M., Al-Farasani, A.A., 1996. Explanatory notes to the geological map of the Ash Shuwahitiyah Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-

126C, scale 1:250,000, sheet 30D. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, 27 p.

Wallace, C.A., Dini, S.M., Al-Farasani, A.A., 1997. Explanatory notes to the geological map of the Al Jawf Quadrangle, Kingdom of Saudi Arabia. Geoscience Map GM-128C, scale 1:250,000, sheet 29D. Deputy Ministry for Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, 31 p.

Wellman, C.H., 2002. Morphology and wall ultrastructure in Devonian spores with bifurcate-tipped processes. *International Journal of Plant Science* 163, 451-474.

Wellman, C.H., 2006. Spore assemblages from the Lower Devonian 'Lower Old Red Sandstone' deposits of the Rhynie outlier, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 97, 167-211.

Wellman, C.H., Habgood, K., Jenkins, G., Richardson, J.B., 2000. A new assemblage (microfossil and megafossil) from the Lower Old Red Sandstone of the Anglo-Welsh Basin: its implications for the palaeoecology of early terrestrial ecosystems. *Review of Palaeobotany and Palynology* 109, 161-196.

Wellman, C.H., Richardson, J.B., 1996. Sporomorph assemblages from the 'Lower Old Red Sandstone' of Lorne Scotland. In: Cleal, C.J. (Ed.), Studies on early land plant spores from Britain. *Special Papers in Palaeontology* 55**,** 41-101.

Wender, L.E., Bryant, J.W., Dickens, M.F., Neville, A.S., Al-Moqbel, A.M., 1998. Paleozoic (pre-Khuff) hydrocarbon geology of the Ghawar area, eastern Saudi Arabia. *GeoArabia* 3, 273-302.

Wnuk, C., 1996. The development of floristic provinciality during the Middle and Late Paleozoic. In: Wnuk, C., Pfefferkorn, H.W. (Eds.), Palaeozoic Phytogeography. *Review of Palaeobotany and Palynology* 90**,** 5-40. Amsterdam.

Ziegler, A.M., Bambach, R.K., Parrish, J.T., Barrett, S.F., Gierlowski, E.H., Parker, W.C., Raymond, A., Sepkoski, J.J., Jr., 1981. Paleozoic biogeography and climatology. In: Niklas, K.J. (Ed.), Paleobotany, Paleoecology and Evolution. *Praeger* 2**,** 231-266. New York.

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