

The Gondwana–Laurussia convergence process: evidence from the Middle Mississippian (Viséan) palynostratigraphic record

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Abstract – The Gondwana–Laurussia convergence process can be explored by studying the Middle Mississippian (Viséan) palynoflora of northwest Africa. Statistical analysis of the Viséan miospore assemblages reported from Morocco defines two populations, one with clear Laurussian affinity from the northern margin of the Western Meseta, and the other, more Gondwanan in composition, from the southern part of the Western Meseta and Anti-Atlas. Moreover, no transitional assemblages have been described from the region. These palynofloral variations are a consequence of the complex palaeogeography of the northwest African margin, which was controlled by the Variscan Orogeny during Viséan times. Taking into consideration the palynofloral affinity of the miospore assemblages reported throughout the entire North African margin and the Middle East, it is possible to envisage a Late Carboniferous Pangaea amalgamation process initially evolving from the west, while in the east the ocean separating Gondwana and Laurussia persisted as an effective barrier to floral migration.

Keywords: Viséan palaeogeography, palynomorphs, Morocco, Gondwana, Laurussia.

1. Introduction

The convergence between Gondwana and Laurussia to form the Pangaeian supercontinent is one of the most momentous and intriguing events in Late Palaeozoic history. Palaeogeographic reconstructions involving both megacontinents have been based mainly on palaeomagnetic, palaeoclimatic, lithological and biogeographic data. The distribution of land-derived palynomorphs recovered from various Western Laurussian and Northern Gondwanan localities has played an important role in biogeographic interpretations (McKerrow *et al.* 2000; Clayton, Wicander & Pereira, 2002), insofar as two distinctive palynofloristic provinces are recognizable in the Middle/Late Mississippian. The Laurussian *Grandispora* Microflora occupies Western Europe and North America, whereas the Gondwanan *Aratrisporites saharaensis* Microflora has been recognized in North Africa, the Middle East and northern Brazil (Sullivan, 1965, 1967; Clayton, 1985; Clayton *et al.* 1991; Loboziak, Melo & Streel, 2000). Mixed palynological associations containing miospore representatives of both provinces have been described in Western Gondwana, particularly in northern Brazil (Loboziak *et al.* 1991, 1992; Loboziak, Melo & Streel, 1998, 2000; Melo & Loboziak, 2000, 2003). However, in northwestern Africa and southwestern Europe, where the palaeocontinents were evidently in close proximity, assemblages transitional between the *Grandispora* and *Aratrisporites saharaensis* Microfloras are as yet unreported.

The absence of mixing has been suggested as consequential on palaeolatitudinal (climatic) control,

or on a large seaway separating North Africa and Western Europe during Viséan time (Clayton, Wicander & Pereira, 2002). However, most palaeogeographic reconstructions (e.g. Matte, 1986, 2001; Kent & Keppie, 1988; Neugebauer, 1988; Ziegler, 1989; Van der Voo, 1993; McKerrow *et al.* 2000; Scotese, 2004; Scotese & McKerrow, 1990) indicate the unlikelihood that, during the Viséan (close in time to the initiation of Pangaeian amalgamation), the distance separating Gondwana and Laurussia would have been sufficient to induce strong latitudinal climate variations and thus to prevent or restrict the possibility of plant migration.

Analysing the palynological content of the Viséan of Morocco is critical to constraining the palaeogeography and evolution of the megacontinental borders and the inter-megacontinental areas. The northwestern African margin is the area of Northern Gondwana that first converged with Laurussia (Matte, 1986) and the only African region affected by the Variscan Orogeny. Hence, the structural and palaeogeographic differences between Morocco and elsewhere in Northern Gondwana remain significant since the Mississippian. In contrast to the extensive and stable intra- and pericratonic basins that occupied most of the North African region, Morocco was a tectonically active and palaeogeographically complex area. The unequivocal similarity in the miospore assemblages reported from other Gondwanan regions (from Algeria to Iran) is not shared by Morocco, where the different assemblages published thus far reveal important variations in terms of palynofloral affinity.

A better understanding of the compositional variability of the Moroccan palynofloras, and their relationship to the pre-collisional tectonic settings in which they were deposited, is a prime purpose of this study.

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This is appropriately based on statistical comparison between the published Viséan miospore assemblages from Morocco and those documented from Western Europe and other North African and Middle Eastern areas.

This comparison is intended to provide further insights into the Mississippian palaeogeography of Morocco, the relationship between Southern Laurussia and Northern Gondwana, and the role of the northwest African margin in the ultimate Pangaeon amalgamation.

2. Palaeogeographic evolution of the North African Variscan Belt

Since the Early Cambrian to Middle Devonian, North Africa has been tectonically stable and has experienced a generally uniform depositional history. In the Late Devonian, however, its northwestern corner was affected by the earliest stages of the Variscan Orogeny (Piqué, 1975). Thereafter, northwest Africa was primarily controlled by the orogenic evolution, developing depositional and structural patterns markedly different from those prevailing in the remaining passive margin of Northern Gondwana.

The Early Palaeozoic palaeogeography of North Africa was dominated by a shallow marine epicontinental platform that developed over a basement consisting of Late Precambrian post-collisional volcanic rocks and molassic red deposits of the Panafrican Orogeny. This platform, extending over other Western European and northeastern American regions (Piqué, 1989, 2001; Piqué & Michard, 1989), received mainly siliciclastic sediments during the Cambrian, Ordovician and Silurian. Sediment distribution and locally significant thickness variations were controlled by the moderate extensional tectonic regime that prevailed in North Africa during the Middle Cambrian (Cornée, Destombes & Willefert, 1987; Bernardin *et al.* 1988; Michard *et al.* 2008), by reactivation of pre-existing fault systems (Craig *et al.* 1999), and also through synsedimentary faulting associated with epeirogenic movements (Echikh, 1998).

During the Early Devonian, the graptolitic black shales that had dominated Silurian sedimentation transmuted into continental facies in eastern and central North Africa, whereas in the northwest, extensive carbonate platforms and deep troughs were covered respectively by reef limestones and pelagic and turbiditic sediments (Piqué *et al.* 1993; Michard *et al.* 2008). In the Late Devonian, the sedimentary continuity was interrupted, and the advent of the Variscan Orogeny caused the dislocation of the platform in northwest Africa (Piqué, 1975, 1989; Piqué & Michard, 1989). In response to the orogenic activity, new structural domains with disparate evolutionary histories developed in this marginal zone (Hoepffner, Soulaïmani & Piqué, 2005).

The rocks affected by the Variscan Orogeny occupy, in Africa, a wide NE–SW band extending from north-

ern Algeria to western Mauritania (Fig. 1). They are more extensively exposed in Morocco, in the so-called Meseta Domain, which is subdivided by the Mesozoic mountains of the Atlas Range into the Western and Eastern Meseta (Gentil, 1918). The Western Meseta comprises three major outcrops: the Central, Rehamna and Jebilet massifs; several other minor disconnected inliers constitute the Eastern Meseta. To the south, the Moroccan Meseta is delimited by the Anti-Atlas (Fig. 1). This domain, weakly affected by the Variscan deformation, is transitional between the North African Variscan Belt and the West African Craton (Piqué *et al.* 1993).

During Late Devonian time, the Western Meseta was influenced by extensional tectonism that gave rise to the opening of several basins bounded by NE–SW transcurrent shear zones generally corresponding to ancient reactivated fractures (Piqué, 2001; Hoepffner, Soulaïmani & Piqué, 2005). At that time, the largest and most subsiding basin was that of Sidi-Bettache, located at the northwestern margin of the Central Meseta. Bordered by chaotic facies including conglomerates, olistostromes and mud flows (Piqué, 1979), this basin was filled mainly by fine-grained turbiditic sediments and localized volcanic deposits (Kharbouch *et al.* 1985). The Eastern Meseta experienced a significant reduction in sediment supply and compressive tectonic activity with intensive folding related to regional ENE–WSW shortening (Piqué *et al.* 1993; Hoepffner, Soulaïmani & Piqué, 2005). The Anti-Atlas Domain remained tectonically stable in its western part, but normal faulting and tilting of platform blocks along its northeastern margin resulted in the opening of relatively small basins (Wendt, 1985).

During the Early Mississippian (Tournaisian), the Moroccan Palaeozoic was well differentiated palaeogeographically. It was characterized by continuous deposition in the subsiding Sidi-Bettache Basin and other subsidiary basins of the Western Meseta, the virtual lack of sedimentation in the presumably uplifted Eastern Meseta, and successive transgressive–regressive cycles in the Anti-Atlas (Piqué & Michard, 1989; Piqué, 2001).

In the Middle Mississippian (Viséan), increasing transtensional activity occurred in the Western Meseta. Further deepening of the Sidi-Bettache Basin was coeval with the opening of new, strongly subsiding basins, notably the Azrou-Khénifra and Jebilet basins (Fig. 1). These basins, also controlled by NE–SW dextral strike-slip shear zones, were rapidly infilled by fine- to coarse-grained detrital sediments, subordinate limestones, and local volcanic and subvolcanic rocks (Huvelin, 1977; Beauchamp & Izart, 1987; Berkli, Vachard & Paicheler, 2001; Bamoumen, Aarab & Soulaïmani, 2008; Moreno *et al.* 2008). The environmental and magmatic conditions characterizing some of these basins during the orogenic process favoured the generation and preservation of large massive sulphide deposits (Moreno *et al.* 2008). At this time, the Eastern Meseta was characterized by the formation of small

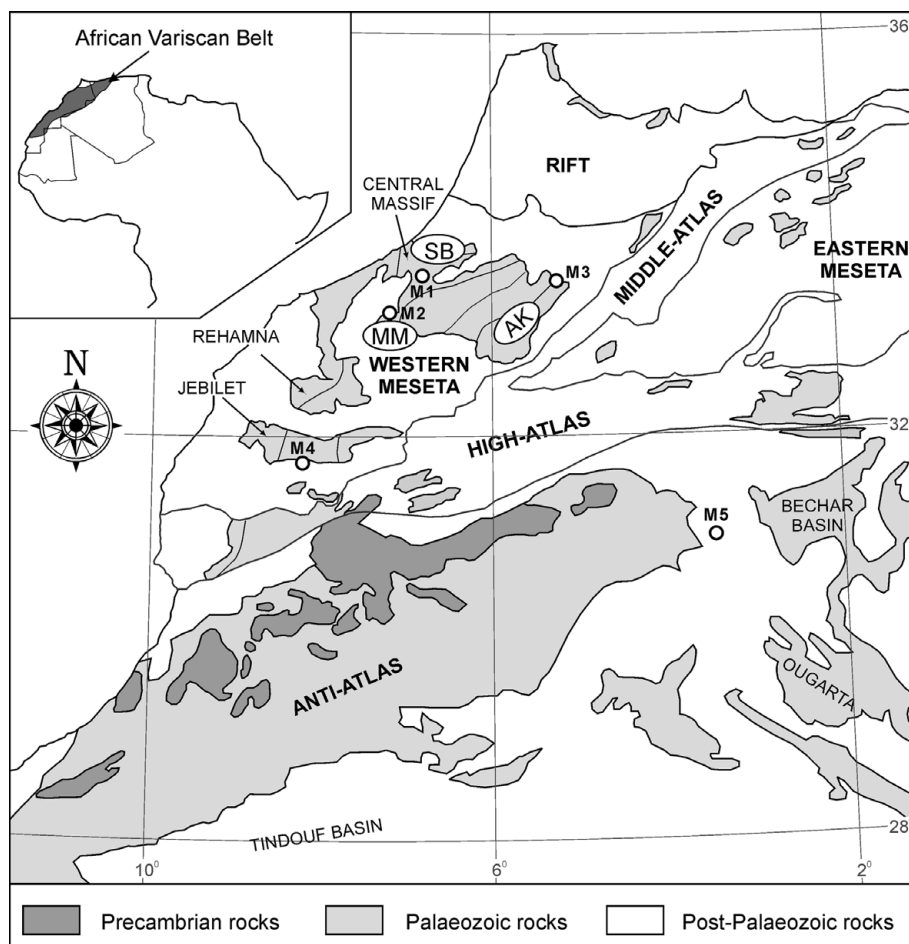


Figure 1. Location of the African Variscan Belt (upper left corner); and geological sketch map of the main Palaeozoic and Precambrian outcrops in northwest Africa showing the locations of the Moroccan Viséan palynofloras referred to in this study. M1-assemblage studied by Marhoumi, Doubinger & Piqué (1984); M2-assemblage, Loboziak *et al.* (1990); M3-assemblage, Ouarhache *et al.* (1991); M4-assemblage, Playford *et al.* (2008); M5-assemblage, Rahmani-Antari & Lachkar (2001). AK – Azrou-Khénifra Basin; SB – Sidi-Bettache Basin; MM – Mokra Massif.

basins filled with detrital, carbonate and volcanoclastic deposits (Hoepffner, Soulimani & Piqué, 2005), while the Anti-Atlas was dominated by widespread marine clastic deposition to the south and by reef building to the east (Piqué & Michard, 1989; Piqué, 2001).

The Palaeozoic rocks of Morocco were folded during the major compressive phase of the Variscan Orogeny in northwest Africa (Michard, 1976), dated as late Westphalian–Early Permian. In the Western and Eastern Meseta the effects of deformation varied considerably. Large, weakly deformed areas were delimited by strongly deformed shear zones, commonly accompanied by intrusive and extrusive magmatic rocks (Lagarde, Omar & Roddaz, 1990; Michard *et al.* 2008). The shear zones usually coincided with pre-existing faults like those responsible for the opening of the Devonian–Mississippian strike-slip basins (Piqué & Michard, 1989). Southward, in the Anti-Atlas, the deformation was generally weak, attenuating progressively toward the south, where this domain connects with the pericratonic, undeformed Tindouf Basin (Fig. 1).

From a broader palaeogeographic perspective, the tectonic complexity of northwest Africa is clearly a

manifestation of the high oblique convergence between Gondwana and Laurussia (Houari & Hoepffner, 2003; Simancas *et al.* 2005). Space–time evolution of the prolonged dextral transpressive regime affecting this region since the Late Devonian was critical for the rupture and compartmentalization of the pre-orogenic platform, for the infill and evolution of the syn-orogenic basins, and for the distribution of the different post-orogenic deformational patterns that characterize northwest Africa.

3. Statistical analysis

The statistical analysis developed here is based on the quantitative comparison between the Middle Mississippian (Viséan) miospore floras of Morocco and those from Southern Laurussia and other Northern Gondwanan regions. This comparison is plausible because, although the Viséan palynofloral assemblages reported in these two regions include relatively short-ranged and hence chronostratigraphically significant miospore species, they are mostly characterized by species whose stratigraphic ranges are not strictly confined to the Viséan. This permits assessment of

the palynofloral affinity by comparison of Viséan assemblages even including species having disparate stratigraphic ranges.

The method of comparison is the cluster analysis of a data matrix constructed with the similarity coefficients among the palynofloral assemblages of Morocco, and those selected from Western Europe, elsewhere in North Africa, and the Middle East. Cluster analysis has proven useful in studying the relationships between Northern Gondwana and Southern Laurussia palynological assemblages (see, for example, Clayton, Wicander & Pereira, 2002).

The numerous palynological publications based in these regions show significant differences in terms of taxonomic documentation. Those including comprehensive systematic descriptions and illustrations of the assemblages are in the minority. By contrast, most of the studies simply provide an inventory of the miospores identified or, more commonly, merely a summary listing of species deemed important stratigraphically. Accordingly, from this disparate database, selection criteria of both data analysis (statistical comparison method) and data source (previous literature) are clearly critical for the integrity of the comparative analysis.

The clustering method is by means of agglomerative, unweighted pair-groups with arithmetic averages, adopting normalized squared Euclidean distances as measurements. This method was selected from among various other options because it produced the highest cophenetic correlation coefficient ($r_{\text{coph}} = 0.96$). The clustering procedure was performed using the software SPSS 15.0.

The data matrix was constructed via a selection of published palynological assemblages considered representative of each given region. The potentially misleading effect produced by comparison of 'complete' and 'selective' lists of taxa was solved by using the similarity index of Simpson (1960), because this coefficient minimizes the effects of unequal population size and species diversity, and, furthermore, reduces the effect of discrepancies in sampling procedures (Simpson, 1960; Rowell, McBride & Palmer, 1973; Campbell & Valentine, 1977; Fallaw, 1979). Simpson's coefficient is given by: $Sc = c/N_1$, where c represents the number of shared species between two populations and N_1 represents the total number of species in the smaller assemblage.

The rectangular data matrix includes Moroccan Viséan assemblages in the left column, and selected Viséan assemblages from Western Europe, the rest of North Africa and the Middle East in the top row. The Moroccan assemblages were published by Marhoumi, Doubinger & Piqué (1984); Loboziak *et al.* (1990); Ouarhache *et al.* (1991); Rahmani-Antari & Lachkar (2001) and Playford *et al.* (2008). Those from Western Europe refer to Love (1960); Doubinger & Rauscher (1966); Sullivan & Marshall (1966); Smith & Butterworth (1967); Neves *et al.* (1973); Neves & Ioannides (1974); Brindley & Spinner (1989); Mahdi & Butterworth (1994); Turner, Spinner & Dorning (1995);

Owens *et al.* (2005); Pereira, Oliveira & Oliveira (2006) and Rodríguez *et al.* (2007). The North African and Middle Eastern assemblages are those documented by Coquel *et al.* (1977); Coquel, Doubinger & Massa (1988); Attar *et al.* (1980); Massa *et al.* (1980); Clayton & Loboziak (1985); Loboziak & Clayton (1988); Grignani, Lanzoni & Elatrash (1991); Kora (1993); Ravn *et al.* (1994); Clayton (1995); Abdesselam-Rouighi & Coquel (1997); Coquel & Abdesselam-Rouighi (2000) and Clayton *et al.* (2000). The location of these assemblages is shown in Figure 2.

The number of Viséan palynological assemblages documented in Southern Laurussia is clearly larger than that in Northern Gondwana. However, in order to preserve the equanimity of the cluster analysis and the weight given to each palynofloristic province, the numbers of assemblages selected from both regions were equalized. Several attempts were made to substitute assemblages in the constructed data matrix with others also considered representative (that is, Sullivan, 1964; Butterworth & Spinner, 1967; Neville, 1968; Hibbert & Lacey, 1969; Pereira, 1999; Jäger, 2002). In all instances, the final result proved virtually identical to that illustrated in Figure 3.

The list of species from Morocco reported also in other West European, North African and Middle Eastern assemblages is given in Appendix Figure A1. The published assemblages discarded for comparative purposes are: (1) those characterized by very low diversity (and would thus produce an unrealistic or detrimental effect on the statistical analysis); and (2) those that classified the miospores under an informal taxonomic system and hence proved difficult or impossible to compare with assemblages expressed via conventional taxonomy. Where a species has been assigned to different genera by different authors, we have chosen what we judge to be the more appropriate binomen. Where individual species within a genus (e.g. *Punctatisporites*) were not identified per se, the designation 'Genus spp.' (e.g. *Punctatisporites* spp.) is adopted.

4. Results and discussion

The regional and global palaeogeographic inferences expressed herein are based on comparison of the Moroccan Viséan palynofloras with those from Western Europe, the rest of North Africa, and the Middle East (Fig. 3). The values in Figure 3 represent the 'signature' of each Moroccan assemblage in terms of its affinity with the Laurussian and Gondwanan palynofloras. The clustering analysis of these data (Fig. 3) presents two distinctive groups: one containing the assemblages reported from the northern part of the Western Moroccan Meseta (samples M1, M2 and M3 from Marhoumi, Doubinger & Piqué, 1984; Loboziak *et al.* 1990 and Ouarhache *et al.* 1991, respectively); and the other comprising assemblages from the southern part of the Western Meseta and Anti-Atlas (samples M4 and M5 from Playford *et al.* 2008 and Rahmani-Antari & Lachkar, 2001, respectively). The average

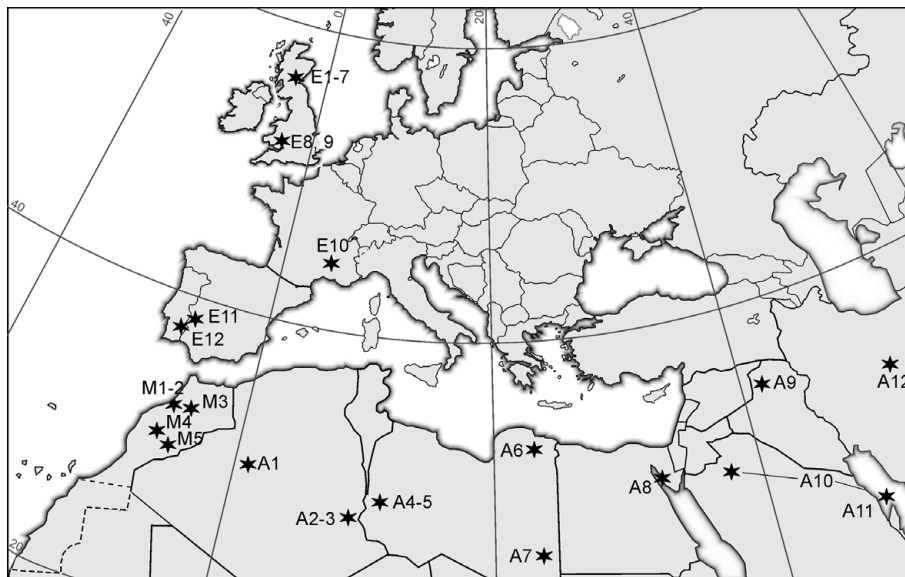


Figure 2. Location of the Viséan miospore assemblages from Morocco, Europe, the Middle East, and the rest of North Africa referred to in this study. The Moroccan assemblages (M1 to M5) are located more precisely in Figure 1. Authors/locations of the European assemblages are: E1, Love (1960); E2, Sullivan & Marshall (1966); E3, Neves *et al.* (1973); E4, Neves & Ioannides (1974); E5, Brindley & Spinner (1989); E6, Mahdi & Butterworth (1994); E7, Owens *et al.* (2005); E8, Smith & Butterworth (1967); E9, Turner, Spinner & Dorning (1995); E10, Doubinger & Rauscher (1966); E11, Rodríguez *et al.* (2007); E12, Pereira, Oliveira & Oliveira (2006). Authors/locations of the North African and Middle East assemblages are: A1, Coquel & Abdesselam-Rouighi (2000); A2, Attar *et al.* (1980); A3, Abdesselam-Rouighi & Coquel (1997); A4, Massa *et al.* (1980); A5, Coquel, Doubinger & Massa (1988); A6, Clayton & Loboziak (1985) and Loboziak & Clayton (1988); A7, Grignani, Lanzoni & Elatrash (1991); A8, Kora (1993); A9, Ravn *et al.* (1994); A10, Clayton (1995); A11, Clayton *et al.* (2000); A12, Coquel *et al.* (1977).

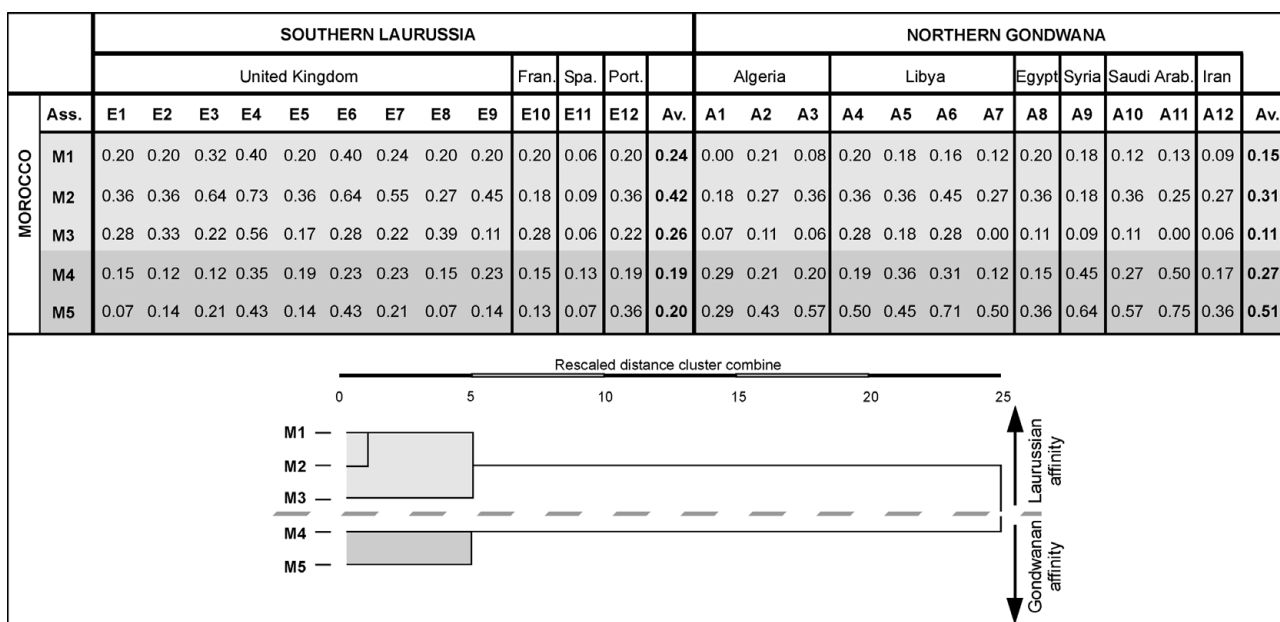


Figure 3. Simpson similarity matrix between the Viséan miospore assemblages of Morocco and those of Western Europe, the rest of North Africa and the Middle East. The resultant dendrogram shows two distinct groups, one Laurussian and the other Gondwanan in character.

Simpson similarity between the northern Moroccan assemblages and the Laurussian assemblages ranges between 0.24 and 0.42 (mean, 0.30), whereas values between the Laurussian assemblages and the southern Moroccan assemblages are 0.19 and 0.20. By contrast, the similarity between the northern assemblages of Morocco and the Gondwanan correlatives ranges

between 0.11 and 0.31 (mean, 0.19), and the values between the southern Moroccan assemblages and that of the rest of Gondwana are 0.27 and 0.51 (Fig. 3). In palaeogeographic terms this means that, whereas the Viséan spore assemblages of northern Morocco (M1, M2 and M3) are more akin to the Laurussian assemblages, those reported further south in the Variscan

Domain (M4, M5) reveal an unmistakable Gondwanan affinity. In addition, common to all the Moroccan palynological assemblages analysed in this study is the conspicuous absence of transitional assemblages, that is, containing species representative of the two palynofloristic provinces involved (the *Grandispora* and *Aratrisporites saharaensis* microfloras).

The likelihood that the results illustrated in Figure 3 could be influenced by preservational differences among the five Moroccan assemblages analysed merits consideration. However, it is extremely unlikely that only typical Northern Gondwanan species were selectively destroyed in those assemblages from the northern part of the Western Moroccan Meseta, and only characteristic Southern Laurussian miospores were eliminated from those assemblages from the southern part of the Western Meseta and Anti-Atlas.

In order to enhance understanding of the palaeogeographic significance of these trends, both locally and regionally, it is important to view them vis-à-vis the geotectonic settings in which the selected palynological assemblages were deposited. Assemblages M1–M4 are all from the Western Meseta (Fig. 1): M1 was reported by Marhoumi, Doubinger & Piqué (1984) from the lower Viséan of the northwestern Sidi-Bettache basin; M2 by Loboziak *et al.* (1990) from the middle Viséan of the Mdkra Massif, a southwesterly prolongation of Sidi-Bettache; M3 by Ouarhache *et al.* (1991) from an upper Viséan olistolith on the northeastern margin of Azrou-Khénifra Basin, northeastern Western Meseta and M4 by Playford *et al.* (2008) from the upper Viséan of the central zone of the Jebilet Massif. During the Late Devonian/Mississippian, Variscan tectonism resulted in the palaeogeographic complexity of the Western Meseta. The distribution, composition and affinity of the palynofloras seem to be markedly controlled by this highly tectonized setting. This is evidenced by the varied affinities of the miospore assemblages from the northern (Laurussian-influenced) and southern (Gondwanan-influenced) basins of the Western Meseta. Assemblage M5, studied by Rahmani-Antari & Lachkar (2001), derived from the lower Viséan of the eastern margin of the Tafilalt Basin, eastern Anti-Atlas Domain (Fig. 1). This basin, only weakly affected by the Variscan Orogeny, correlates to the north with the Jebilet Basin and to the south with the pericratonic Tindouf Basin. The Gondwanan affinity of this assemblage is clearly compatible with the proximity and influence of the emergent land masses of the West African Craton.

Palynofloral variations within the Western Meseta have regional palaeogeographic implications. It is generally accepted that the Late Devonian/Mississippian transtensional deformation affecting the Moroccan Meseta resulted in a complex palaeogeography with several basins showing comparable tectonic evolution (Beauchamp & Izart, 1987). The original extension and relationship between such basins are often masked by tectonic overprints derived from the Variscan and post-Variscan shortening, and also by the subsequent, extensive Mesozoic and Cenozoic cover deposits.

That notwithstanding, the northern Sidi-Bettache and Azrou-Khénifra basins may well be contiguous southward with the Rehamna and Jebilet basins (see, for example, Piqué & Michard, 1989; Piqué, 1989, 2001; Hoepffner, Soulaïmani & Piqué, 2005; Hoepffner, Houari & Bouabdelli, 2006; Moreno *et al.* 2008). This is supported by the genetic relationship of these basins; they exhibit a common set of major shear zones responsible for their opening and development, and pronounced similarities in their depositional, magmatic and structural evolution. However, their disparate palynological signatures and their lack of mixed assemblages point to the existence of a physical barrier impeding free connection of the Jebilet Basin with its northern counterparts. This is more likely a consequence of the complex palaeogeography of the Moroccan Meseta rather than the existence of a broad seaway separating its northern and southern parts. For Viséan time, such a seaway would scarcely be conceivable. Elements of the palynofloras characteristic of the southern regions of Western Europe are clearly represented in the northern Moroccan basins. To the south, the Gondwanan palynoflora occurs in the slightly deformed platform immediately north of the West African Craton, and also in the southern margin of the Western Meseta (the Jebilet massif), but never reached the northern Moroccan basins (Fig. 4). This interpretation is compatible with the structural evolutionary model proposed by Bouabdelli & Piqué (1996, fig. 5a), in which the Moroccan Variscan domain collapsed during the latest Devonian/Early Mississippian to form several individual pull-apart basins that were bordered by stretched and/or longitudinally equivalent transcurrent strike-slip shear zones.

The Late Palaeozoic palaeogeographic situation of the Moroccan Meseta represents a nexus between Northern Gondwana and Southern Laurussia. Understanding the distribution of its Viséan palynoflora may well provide further details regarding the pre-collisional relationship between these megacontinents. The evolution of Gondwana and Laurussia has been inferred from numerous studies. These show limited consensus on the drift pattern of Gondwana, on the motion and amalgamation of the different Gondwana-derived terranes that joined Laurussia, and on the location, nature and age of the suture zones (e.g. Tait *et al.* 1997, 2000; McKerrow *et al.* 2000; Weil, Van der Voo & van der Pluijm, 2001; Stampfli & Borel, 2002; Stampfli, Von Raumer & Borel, 2002; Robardet, 2003; Simancas *et al.* 2009; Keppie *et al.* 2010; Nance *et al.* 2010; Tahiri *et al.* 2010). However, the models proposed for the Late Devonian/Carboniferous interval mostly do not envisage any substantial separation between Gondwana and Laurussia. The Laurussian affinity of the palynoflora reported from the northern margin of the Moroccan Meseta is not only in good agreement with such a scenario, but also suggests very close Gondwana–Laurussia proximity during the Viséan.

Clayton, Wicander & Pereira (2002) detected strong dissimilarities, particularly in Viséan time, between the

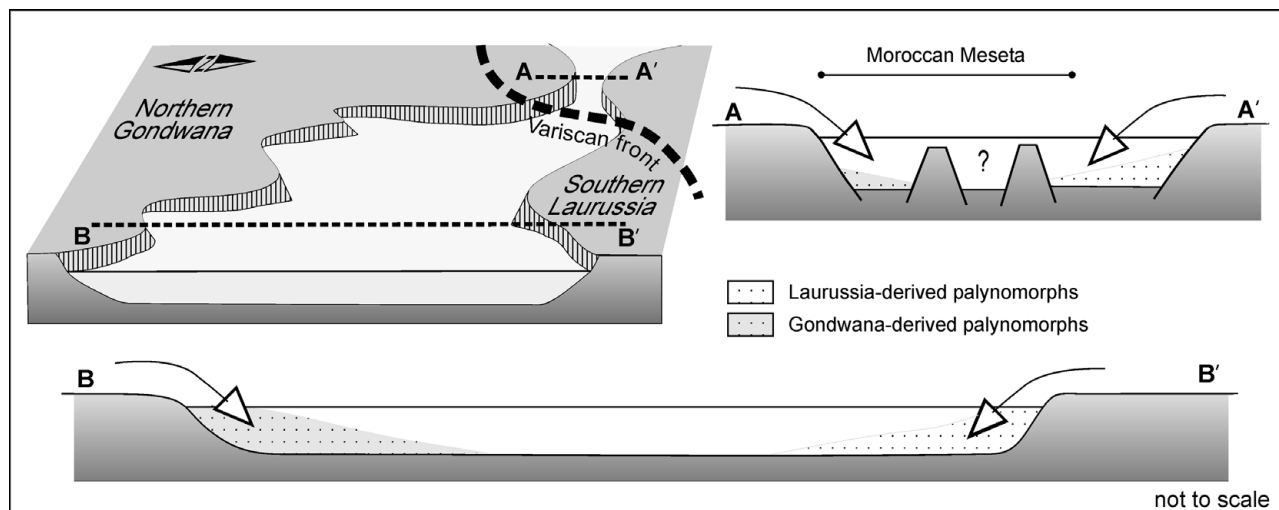


Figure 4. Proposed schematic depiction of the Southern Laurussian and Northern Gondwanan margins during Viséan times, and hypothetical cross sections illustrating the inferred relatively short distance but complex palaeogeography separating Gondwana and Laurussia from the west (A–A’); and the existence of an extensive seaway separating them from the east (B–B’).

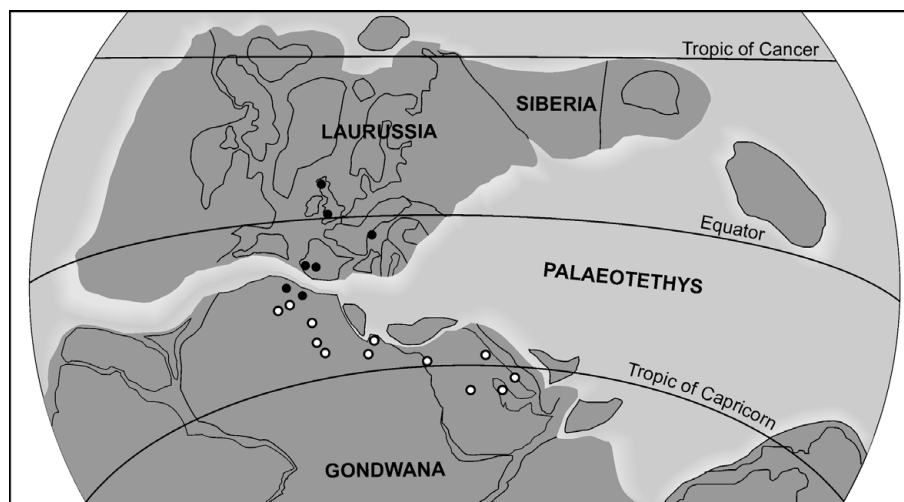


Figure 5. Mississippian palaeogeographic map (modified from Stampfli, 2000) showing the inferred position of the Laurussia-influenced (black dots) and Gondwana-influenced (white dots) miospore assemblages used in this study.

miospore assemblages of Western Europe and North Africa. Accordingly, they suggested that, in the absence of transitional assemblages, the two continents were separated by a large oceanic distance. This conjecture apparently disagrees with our results. However, the fact that our study is focused on the northwestern border of Gondwana (Morocco), and that of Clayton, Wicander & Pereira (2002) analysed assemblages from its northern and northeastern margins (Algeria, Libya and Saudi Arabia), makes both studies complementary and not incompatible. Thus, by taking the two studies jointly into account, it is possible to provide a more comprehensive palaeogeographic scenario of this northern margin of Gondwana, that is, extending from northern Morocco to Saudi Arabia. During the Late Devonian, the convergence between Laurussia and Gondwana was initiated in northwest Africa. Here, the development of a transpressive–transtensive geodynamic regime resulted in the final collapse of the Moroccan Platform,

with ensuing formation of several subsiding pull-apart basins, principally in the Western Moroccan Meseta (Piqué, 2001; Hoepffner, Houari & Bouabdelli, 2006). The northwestern margin of Gondwana was in close proximity to Laurussia in the Viséan (Fig. 5), and the northern basins of the Western Meseta clearly received a southerly influx of Laurussian terrestrial palynofloras (Fig. 4). The strong tectonic control and compartmentation of the Meseta Domain precluded the further southerly migration of such palynofloras and their potential mixing with those characterizing the Gondwanan realm. Further east, the oceanic separation of Laurussia from the central and eastern border of Northern Gondwana evidently remained much wider (Fig. 5) and, as suggested by Clayton, Wicander & Pereira (2002), this was probably the principal factor impeding plant migration and consequential miospore mixing (Fig. 4).

The interpretation proposed here, based on the composition and distribution of the Viséan palynofloras of

Northern Gondwana, is fully consistent with the clockwise rotational movement of Gondwana with respect to Laurussia that has been invoked by virtually all the pre-collisional palaeogeographic models. Furthermore, because northern Morocco is the only region in Africa featuring Viséan miospore assemblages of Laurussian character, the present palaeogeographic interpretation is consonant with reconstructions depicting very close proximity between the northwest margin of Gondwana and Southern Laurussia during Viséan time (e.g. Kent & Keppie, 1988; Ziegler, 1989; McKerrow *et al.* 2000; Matte, 2001; Robardet, 2003; Scotese, 2004).

In the later syn-collisional stage, the land connection between North Africa and Western Europe is indicated by, among other things, the mixed palynofloras preserved in uppermost Carboniferous and Lower Permian continental basins of Spain, Algeria, Nigeria and Oman (Doubinger & Fabre, 1983; Broutin, 1986; Broutin & Doubinger, 1985; Broutin *et al.* 1990, 1995). In view of the efficacy of palynomorphs as palaeogeographic indicators, further palynological analysis of Northern Gondwana and Southern Laurussia would clearly be important. For instance, knowledge of the Viséan palynoflora of the Rehamna Massif, located in the central part of the Western Meseta, would enhance understanding of the Palaeozoic palaeogeography of northwest Africa. Additionally, the Late Mississippian, and particularly the Pennsylvanian palynological sequence of Southern Laurussia and the remaining northern passive margin of Gondwana, could provide further information on the timing of the Pangaea amalgamation.

5. Conclusions

The statistical analysis of the Viséan miospore assemblages reported from Morocco reveals two distinct groups allied to the palynofloras reported from Western Europe on the one hand, and to the remaining areas of North Africa and the Middle East on the other. The assemblages defined from the northern margin of the Western Meseta signify a clear Laurussian affinity, whereas those known from the southern part of the Western Meseta and the Anti-Atlas are more Gondwanan in composition. On the other hand, no transitional assemblages have been described so far in the Viséan of northwest Africa. Both the differences in terms of Gondwanan/Laurussian affinity manifested by the Western Meseta miospore assemblages, and the notable absence of transitional assemblages in this area, appear to be consequential on the pronounced palaeogeographic variations that occurred within a confined area. In this regard, the Jebilet Basin, characterized by the Gondwanan signature of its palynoflora, evolved apparently separately from the northern Sidi-Bettache and Azrou-Khénifra basins, where the miospore assemblages are distinctly Laurussian in character. The differing evolution of these basins occurred despite them sharing the same structural trend.

In a broader palaeogeographic context, the disparate complexion of the Mississippian palynofloras reported along the North African margin is in good agreement with the generally accepted scenario in which the Late Carboniferous amalgamation of Pangaea initially evolved from its western margin, while, in the east, a large ocean still separated Southern Laurussia from Northern Gondwana. As the Viséan palynofloras of these margins appear to have been highly sensitive to the geodynamic changes related to the Pangaea accretion, further palynological data from the Carboniferous of Northern Gondwana and Southern Laurussia would facilitate an improved understanding of the amalgamation process.

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Moroccan Viséan spores reported in other Northern Gondwana and Southern Laurussia localities	SOUTHERN LAURUSSIA						NORTHERN GONDWANA																						
	United Kingdom						France	Spain	Portugal	Morocco					Algeria		Libya			Egypt	Syria	Saudi Arabia	Iran						
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	M1	M2	M3	M4	M5	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
<i>Acanthotriletes rigidispinosus</i> (Luber) Ishchenko 1956																													
<i>Anaplanisporites baccatius</i> (Hoffmeister et al.) Smith & Butterworth 1967	✓	✓	✓		✓								✓																
<i>Apiculatisporis aculeatus</i> (Ibrahim) Smith & Butterworth 1967				✓																									
<i>Aratrisporites saharaensis</i> Loboziak et al. 1986													✓	✓				✓	✓			✓	✓	✓			✓	✓	
<i>Auroraspora macra</i> Sullivan 1968			✓	✓		✓	✓	✓					✓	✓											✓				✓
<i>Auroraspora solisorta</i> Hoffmeister et al. 1955				✓	✓	✓	✓	✓																					
<i>Biannulatisporites simplex</i> Neville 1973			✓		✓								✓																
<i>Densosporites anulatus</i> (Loose) Smith & Butterworth 1967				✓									✓																
<i>Densosporites claytonii</i> Ravn et al. 1994				✓														✓	✓	✓		✓	✓	✓			✓	✓	
<i>Densosporites spitsbergensis</i> Playford 1963																													
<i>Densosporites triangularis</i> Kosanke 1950													✓																
<i>Endosporites micromanifestus</i> Hacquebard 1957	✓	✓		✓		✓		✓				✓	✓						✓			✓							
<i>Granulatisporites granulatus</i> Ibrahim 1933			✓																			✓	✓						
<i>Granulatisporites microgranifer</i> (Ibrahim) Potonié & Kremp 1956				✓		✓						✓	✓									✓							
<i>Knoxisporites gilletii</i> Doubinger & Rauscher 1966													✓																
<i>Knoxisporites literatus</i> (Waltz) Playford 1963	✓	✓	✓	✓	✓	✓							✓																
<i>Knoxisporites stephanephorus</i> Love 1960	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓															
<i>Laevigatosporites vulgaris</i> (Ibrahim) Ibrahim 1933																													
<i>Leiotriletes adnatus</i> (Kosanke) Potonié & Kremp 1956				✓																									
<i>Leiotriletes inermis</i> (Waltz) Ishchenko 1952				✓				✓	✓																				
<i>Leiotriletes ornatus</i> Ishchenko 1956													✓																
<i>Lycospora noctuina</i> Butterworth & Williams 1958	✓	✓	✓	✓		✓		✓											✓										
<i>Lycospora pellucida</i> (Wicher) Schopf et al. 1944				✓				✓														✓	✓						
<i>Lycospora pusilla</i> (Ibrahim) Schopf et al. 1944	✓		✓	✓	✓	✓	✓	✓														✓	✓	✓					
<i>Monoletes ellipsoides</i> (Ibrahim) Schopf 1938																													
<i>Pilososporites verutus</i> Sullivan & Marshall 1966			✓																										
<i>Plicatispora quasilabrata</i> (Higgs) Higgs et al. 1988																													
<i>Punctatisporites</i> spp.	✓	✓		✓	✓	✓	✓	✓					✓	✓	✓	✓	✓												
<i>Radiizonates arcuatus</i> Loboziak et al. 2000																						✓	✓	✓				✓	✓
<i>Raistrickia clavata</i> Hacquebard emend. Playford 1964																						✓	✓	✓					
<i>Retusotriletes crassus</i> Clayton 1980																													
<i>Retusotriletes incohatus</i> Sullivan				✓	✓	✓	✓																						
<i>Schulzospora</i> spp.	✓	✓	✓	✓	✓	✓	✓	✓	✓																				
<i>Spelaeotriletes arenaceus/triangulus</i> Neves & Owens 1966					✓		✓	✓														✓	✓	✓				✓	✓
<i>Spelaeotriletes pretiosus</i> (Playford) Utting 1987					✓																	✓	✓	✓					
? <i>Tholisporites decoratus</i> Gueinn 1973				✓		✓																							
<i>Tricidarisporites fasciculatus</i> (Love) Gueinn et al. 1973	✓	✓	✓	✓	✓	✓	✓	✓					✓																
<i>Tricidarisporites serratus</i> (Playford) Playford & Satterthwait 1986					✓																								
<i>Vallatisporites agadesensis</i> Loboziak & Alperm 1978																													
<i>Vallatisporites ciliaris</i> (Luber) Sullivan 1964			✓	✓	✓	✓	✓						✓	✓								✓	✓	✓				✓	✓
<i>Vallatisporites galearis</i> Sullivan 1964					✓																								
<i>Vallatisporites vallatus</i> Hacquebard 1957					✓		✓						✓	✓															
<i>Vallatisporites verrucosus</i> Hacquebard 1957																													
<i>Verrucosporites mesogrumosus</i> (Kedo) Byvsheva 1985																													
<i>Waltzisporea lobophora</i> (Waltz) Staplin 1960																													
<i>Waltzisporea planiangularata</i> Sullivan 1964			✓	✓		✓	✓	✓					✓	✓					✓										
<i>Waltzisporea polita</i> (Hoffmeister et al.) Smith & Butterworth 1967	✓	✓	✓	✓									✓	✓	✓							✓	✓						

Figure A1. List of Moroccan Viséan miopore species also reported in other West European, North African and Middle Eastern assemblages. Taxonomic names updated. For authors/locations of miopore assemblages see Figures 1 and 2.