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GEOLOGY

Correlation of Visean Floral Successions from the Equatorial Belt

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Elucidation of the most important evolutionary events, which involve the largest regional floras in the major climatic belts of the Earth, is useful for interregional correlation based on megafossil remains. These events are reflected in synchronous directed changes in the major plant groups (divisions and classes). The establishment of such a change in the development of terrestrial floras of the equatorial belt in the mid-Visean allowed us to divide their Visean history into two stages (early and late Visean) [1]. We revealed that different parts of the belt are characterized by specific evolutionary changes. The character of middle Visean floral changes from different regions of the East European Platform is considered in [1]. The present communication reports the results of a more detailed analysis of Visean floral successions from the equatorial belt.

As a whole, the vegetation of the equatorial belt experienced the following evolutionary reorganization in the mid-Visean: (1) appearance of bundle alternation in adjacent internodes of sphenopsid axes (genus *Mesocalamites*); (2) increase in the share of arborescent forms among Lycopodiales and replacement of the small leaf-cushion lepidophytes, which dominated in the Tournaisian–early Visean, by the large leaf-cushion forms; (3) substantial and, probably, simultaneous changes in the morphology of fronds among ferns, progymnosperms, and archaic gymnosperms and the consequent increase in their diversity and complexity of structure; and (4) increase in the diversity and quantity of seeds and male fructifications in plants from the orders Lagenostomales and Trigonocarpales, indicating the higher role of gymnosperms in vegetation. These changes serve as indicators of the mid-Visean boundary in floral successions in different regions of the equatorial belt. Therefore, this feature can be used to correlate local megafloral zones and assemblages of plant remains.

In the Visean, the equatorial belt comprised the following main land masses (from west to east): the spacious Euramerican continent (Laurussia), Kazakhstan microcontinent, and the group of small Cathasian continents separated from each other by marine and oceanic basins [2]. The protracted geographic isolation of these continents stimulated the development of endemic floras and specific evolutionary changes in the mid-Visean within each continent.

Laurussia. Visean floras of this continent are known from present-day Europe and Greenland, where the late Tournaisian–early Visean assemblage dominated by small leaf-cushion lepidophytes *Archaeosigillaria, Lepidodendropsis, Lepidodendron spetsbergense, L. losseni*, primitive sphenopsids *Archaeocalamites radiatus*, and plants with fernlike foliage (*Adiantites, Triphyllopteris*, and others) was replaced in the mid-Visean by the late Visean–early Serpukhovian (Namurian A, Table 1) assemblage. This assemblage was characterized by the predominance of large leaf-cushion lepidophytes (*Lepidodendron obovatum, L. volkmannianum*, and *Sigillaria*), the first appearance of sphenopsids *Mesocalamites*, and an increased share of gymnosperms (primarily lagenostoms and trigonocarps). At the same time, fronds of progymnosperms, ferns, and archaic gymnosperms acquired substantial morphological diversity (*Lyginopteris, Neuropteris, Pecopteris*, and others). It should be noted that different areas of Europe were characterized by local floral distinctions related to specific features of landscape–geographic environments, the geological history, and florogenesis. For example, many taxa are confined to local floras or small regions. In some areas, characteristic late Visean species appeared in the early Visean, or, on the contrary, the development of archaic early Visean forms continued in the late Visean (Table 1).

In Wagner's megafloral zonation [3], which reflects floral succession in central and southern areas of Europe, the mid-Visean boundary coincides with the boundary between the *Triphyllopteris* Zone and the

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Table 1. Changes in main plant groups of Europe at the early–late Visean boundary

Substage	Southern East European Platform (Dnieper–Donets, Lvov–Volyn, and Pripyat depressions)	Southern Europe (France, Germany, East Europe, Italy, and Spain)	Wales and Gloucestershire	Scotland	Northern Europe (Spitsbergen, Moscow, and Kizel basins), eastern Greenland
Upper Visean	**Sphenopsids**				
	Mesocalamites roemeri, M. haueri, M. ramifer, M. cistiformis, Archaeocalamites radiatus	*Mesocalamites roemeri, M. ramifer, Archaeocalamites radiatus*	*Archaeocalamites radiatus*	*Calamites approximatiformis, Mesocalamites roemeri, Archaeocalamites radiatus*	*Archaeocalamites radiatus*
	Lycopsids				
	Lepidodendron obovatum	*Lepidodendron obovatum, L. acuminatum, L. lossenii, Sigillaria eugenii, Sublepidodendron robertii*		*Lepidodendron obovatum, L. spetsbergense, Sigillaria taylori, Bothrodendron wiikianum, B. depereti, B. kidstoni, B. wardiense*	*Sublepidophloios sulphureus, Wittbergia zalesskii*
	Ferns, progymnosperms, and archaic gymnosperms				
	Lyginopteris bermudensiformis, L. stangeri, L. falkenhainii, L. fragilis, L. bamleri, Neuropteris antecedens, N. schlehanii, N. bulupalganensis, Archaeopteridium tschermaki, Adiantites tenuifolius, Triphyllopteris rombifolius	*Lyginopteris bermudensiformis, Neuropteris antecedens, N. antiqua, N. opatovicensis, N. gothanii, N. loshii, Archaeopteridium tschermaki, Sphenopteridium desfoursii, S. silesiacum, S. transversale, S. pachyrrhachis, S. crassum, S. dissectum, S. speciosum, Adiantites tenuifolius, A. bellidulus, Triphyllopteris collombiana, Pecopteris aspera*	*Lyginopteris bermudensiformis, Neuropteris antecedens, Archaeopteridium tschermaki, Sphenopteridium capillare, S. pachyrrhachis*	*Neuropteris antecedens, Archaeopteridium tschermaki, Sphenopteridium macconochiei, S. capillare, S. pachyrrhachis, S. crassum, S. dissectum, S. speciosum, Adiantites tenuifolius*	*Sphenopteridium* sp., *Adiantites* sp.
Lower Visean	**Sphenopsids**				
	Archaeocalamites radiatus	*Mesocalamites* sp., *Archaeocalamites radiatus*	*Archaeocalamites radiatus*	*Archaeocalamites radiatus*	*Archaeocalamites radiatus*
	Lycopsids				
	Lepidodendron spetsbergense, L. acuminatum, L. heeri	*Lepidodendron losseni, Sublepidodendron* sp., *Cyclostigma zafrenzis*	*Archaeosigillaria stobbsi, Lepidodendropsis (?) jonesi, L. recurvifolia, Lepidodendron (?) perforatum, Clwydia decussata*	*Bothrodendron wiikianum*	*Lepidodendron spetsbergense, L. acuminatum, L. heeri, Gryzlovia meyenii, Sublepidodendron robertii, Archaeosigillaria vanuxemii*
	Ferns, progymnosperms, and archaic gymnosperms				
	Adiantites antiquus, A. machanekii, Sphenopteridium flexibile, S. bifidum	*Adiantites* sp., *Sphenopteridium dissectum, S. noeldekei, S. schimperi, S. densifolium, S. nobile, S. ginkgoides, S. silesiacum, Triphyllopteris collombiana, T. gothanii, T. rhombifolius, Neuropteris broilii, N. antecedens*		*Adiantites antiquus, Sphenopteridium pachyrrachis, S. crassum*	*Adiantites geinitzii, A. longifolius, A. bellidulus, A. bredyana, Sphenopteridium flexibile, S. bifidum, S. kidstonii*

Table 2. Correlation of Visean megafloral successions from main regions of the equatorial belt

Dnieper-Donets Basin

Horizon	Megafloral zones [13]
Mezhevian	*Presigillaria jongmansii–Lyginopteris fragilis* (1A zone)
Donetsian	
Stylian	
Sukhian	
Glubokian	
Kos'vian	

West Europe

Stage	Megafloral zone [3]
Brigantian	*Lyginopteris bermudensiformis* – *Neuropteris antecedens*
Asbian	
Holkerian	
Arundian	*Triphyllopteris*
Chadian	

Moscow Basin

Horizon	Megafloral zones [1]
Venevian	*Sublepidodendron shvetzovii*
Mikhailovian	
Aleksinian	
Tulian	
Bobrikian	*Gryzlovia meyenii*

Kazakhstan

Horizon	Megafloral assemblages [8]
Dal'nenian	*Sphenophyllum tenerrimum*, *Archaeocalamites radiatus*, *Mesocalamites cistiiformis*, *M. ramifer*, *M. bespalovii*, *Ivanodendron obovatiforme*, *Lepidodendron kirghizicum*, *Caenodendron primaevum*, *Neurocardiopteris asiatica*, *Cardioneura microphylla*, *Sphenopteris* spp., *Aulocotheca*, *Trigonocarpus*, *Samaropsis*
Yagovkian	
Ishimian	*Lepidodendron pseudokirghizicum*, *Caenodendron primaevum*, *Dzungarodendron novikae*, *Archaeocalamites radiatus*, *Sphenophyllum tenerrimum*, *Neuburgia karatauensis*

South China

Stage	Formation	Megafloral assemblages [10]
Tatangian	Shangsian	***Cardiopteridium spetsbergense–Triphyllopteris collombiana*** (*Sublepidodendron mirabile*, *Lepidodendron shanyangense*, *L. volkmannianum*, *Spenophyllum tenerrimum*, *Archaeocalamites radiatus*, *Adiantites gotanii*, *Neuropteris* cf. *antecedens*, *Cardiopteridium spetsbergense*, *Triphyllopteris colombiana*, *Rhodeopteridium hsianghsianense*, *Paripteris gigantea*, etc.)
	Juisian	***Sublepidodendron mirabile–Adiantites*** (*Sublepidodendron mirabile*, *Eolepidodendron wusihense*, *Archaeocalamites* sp., *Adiantites* sp., *Rhodeopteridium* sp., etc.)

Lyginopteris bermudensiformis–Neuropteris antecedens Zone (Table 2), which passes near the boundary between the Go_{α} and Go_{β} goniatite zones [4].

In Scotland, the replacement of the early Visean plant assemblage by the late Visean assemblage occurs at the boundary between the Cementstone and Oil Shale groups [5]. According to palynological data, this boundary passes inside the Holkerian regional stage (Great Britain) that is correlated with the middle part of the Visean [6].

The most complete Visean succession of floral assemblages in Eastern Europe is known from the Moscow Basin. Here, the early and late Visean phases in floral evolution correspond to the *Gryzlovia meyeni* and *Lepidodendron shvetzovi* megafloral zones. The boundary between them is placed inside the Tulian Horizon [1]. Based on foraminifers and conodonts, the Tulian Horizon is correlated with the middle part of the Visean Stage [7] (Table 2).

Kazakhstan microcontinent. Table 2 presents the succession of Lower Carboniferous megafloral assemblages developed over a large area of the Kazakhstan territory [8]. In this region, the middle part of the Lower Carboniferous Yagovkian Horizon is marked by changes in vegetation similar to those in the middle part of the Visean in Europe: the appearance of *Mesocalamites*, diverse forms of fernlike fronds (*Neurocardiopteris, Cardioneura, Sphenopteris*), and representatives of trigonocarp gymnosperms (*Aulacotheca, Rtigonocarpus*). Based on the foraminiferal fauna, the Yagovkian Horizons of Kazakhstan correlates with the Tulian and Bobrikian Horizon of the East European Platform [9].

Cathasian continents. The Visean floral succession of these continental blocks is established in the South China Platform. It consists of two successive megafloral assemblages: *Sublepidodendron mirabile–Adiantites* and *Cardiopteridium spetsbergense–Triphyllopteris collombiana* [10] (Table 2). The boundary between these assemblages is placed inside the Juisian Stage representing the basal part of the Tatangian Stage (China), which correlates with the lower half of the Visean based on the coral remains [10]. The upper assemblage contains the first lycopodes forms with large, closely spaced leaf cushions (*Lepiddendron shanyangense, L. volkmannianum*) and gymnosperms of the endemic family Parispermaceae (*Paripteris gigantea*), which subsequently occupied the entire Chinese territory [11]. There are indications that the *Cardiopteridium spetsbergense–Triphyllopteris collombiana* assemblage contains the first *Mesocalamites* [12]. Fronds of *Triphyllopteris collombiana* known in southern Europe since the early Visean appeared and became typical of this area only in analogues of the upper Visean.

Thus, notable evolutionary changes defined in the largest regional floras of the Earth make it possible to correlate Carboniferous plant-bearing sediments within the major climatic belts. Based on these paleobotanical data, we could correlate for the first time the Visean continental sequences of Europe, Kazakhstan, and South China (Table 2). These correlations are consistent with schemes based on the marine fauna.

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