Latest Viséan–Early Namurian (Carboniferous) foraminifers from Britain: Implications for biostratigraphic and glacioeustatic correlations

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Article

Latest Viséan–Early Namurian (Carboniferous) foraminifers from Britain: implications for biostratigraphic and glacioeustatic correlations

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With 4 figures

Abstract. Foraminiferal studies on late Mississippian (Serpukhovian) limestones from northern England allow a well-constrained correlation between the western European regional substages for the early Namurian (Pendleian, Arnsbergian and Chokierian) with the Russian regional substages for the international Serpukhovian (Tarusian, Steshevian, Protvian and Zapaltyubian). The correlation presented here demonstrates closer correspondence between both regional scales, since the base of the traditional Serpukhovian in England is now likely located below the Three Yard Limestone Member and probably within the Five Yard Limestone Member, and the base of the late Serpukhovian is located at the base of the Crag Limestone. These newly recognized lower stratigraphic horizons differ quite significantly from the previously accepted levels of correlation for the base of the Pendleian (Great Limestone Member) and the base of the Arnsbergian (Lower Fell Top Limestone) in the Pennine region. These changes in the positioning of the boundaries helps resolve problems recognized in previous correlations. The new boundaries are now consistent with the conodont biostratigraphy which is currently being used to establish the GSSP boundary of the Serpukhovian. Previously, the FAD of *Lochriea ziegleri* in Britain was apparently much earlier than records elsewhere in the European basins. Some other mismatches arise now in recent publications owing to the erroneous correlation between these late Mississippian rocks in England and elsewhere in Europe and North America.

Key words. Foraminifers, early Namurian, Serpukhovian, Britain

Introduction

In Britain, and elsewhere in western Europe, the main biostratigraphic divisions for the early Namurian (which includes all of the Serpukhovian Stage) are the ammonoid zones of *Eumorphoceras* (E_1 and E_2) and *Homoceras* (H) (Bisat 1924, Ramsbottom et al. 1978, Waters et al. 2011). These zones correspond to the regional substages Pendleian (E_1), Arnsbergian (E_2) and Chokierian (H_1). In turn, owing to the rapid evolution of the ammonoids, those zones have been subdivided into numerous subzones and marine bands within the cyclothemic intervals (Ramsbottom 1977, 1979, Ramsbottom et al. 1978, Waters and Condon 2012).

The Serpukhovian Stage was defined by Nikitin (1890) in the southern part of the Moscow Basin, where it is represented by the Tarusian, Steshevian and Protvian substages. In the northern part of the Basin, a more complete succession is recorded, where the Pestovo beds (Fomina 1977) occur above the Protvian

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Substage. As those beds comprise poorly fossiliferous shales, the younger substages of the Serpukhovian were selected in the parastratotype section in the Donets Basin, Ukraine, and the Zapaltyubian and Voznesenskian substages were also included in the Serpukhovian (Aizenverg et al. 1979). However, the Voznesenskian Substage is now considered as the basal part of the Bashkirian Stage since Nemirovskaya (1987) recorded the conodont *Declinognathodus noduliferus*, which is the marker for the Mississippian/Pennsylvanian boundary (Lane et al. 1999).

Traditionally, the base of the Pendleian has been equated with the base of the Tarusian (e.g., Aizenverg et al. 1979, Einor 1996, Vdovenko 2001, Lane and Brenckle 2005, Davydov et al. 2010, Waters and Condon 2012). However, the correlation of the E_1/E_2 boundary with the Russian substages remains more controversial, and several positions have been suggested, one of which is equated with the early/late Serpukhovian boundary and another within the late Serpukhovian (see Cózar et al. 2011).

The upper boundary of the Serpukhovian is more clearly defined in several countries, as a result of numerous studies seeking potential stratotypes for establishing the Mississippian/Pennsylvanian boundary, which finally settled on the Arrow Canyon section in Nevada, USA (Lane et al. 1999). The global stratotype section and point (GSSP) for the Viséan/Serpukhovian boundary is currently under investigation, although, following the pioneer study on conodonts by Skompski et al. (1995), *Lochriea ziegleri* is considered to be the best candidate to mark that boundary (see e.g., Richards 2010). The selection of this taxon implies a lower horizon for the base of the Serpukhovian, lower than the current base of the Tarusian Substage in the Russian Platform (Skompski et al. 1995, Gibshman et al. 2009). One of the main problems concerning this conodont taxon is the apparent mismatch of its first occurrence in Britain, which is much earlier than elsewhere in Europe (see Cózar et al. 2011). In northern England (Pennines), this conodont was recorded from the Middle Limestone of the Askrigg Block (Skomp-

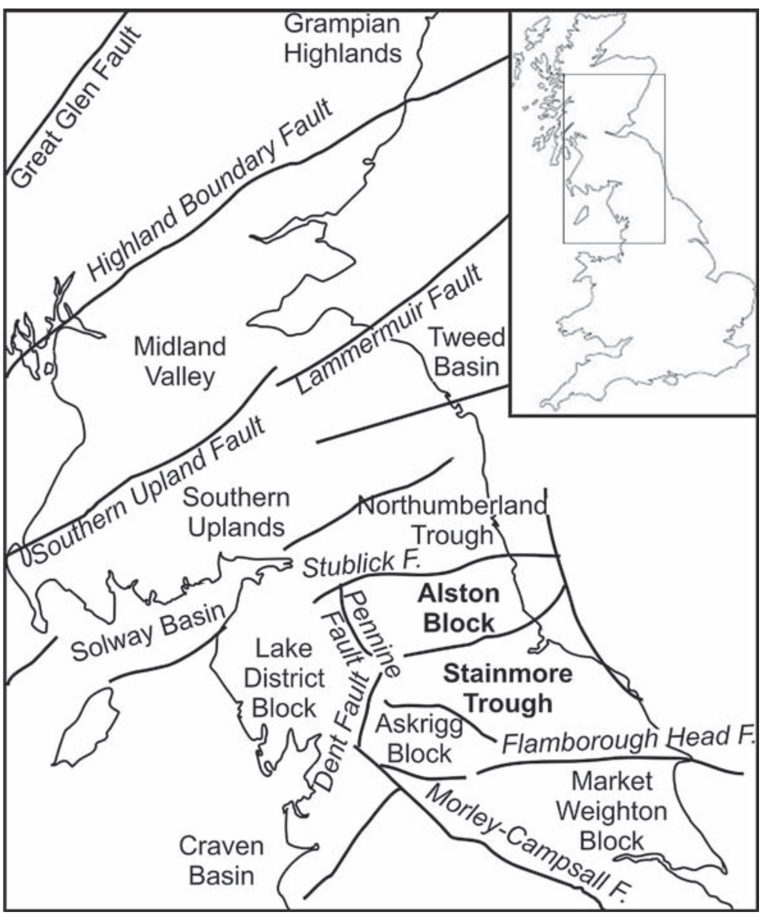

Fig. 1. Principal structural features and basins of the northern Britain (simplified from Dean et al. 2011).

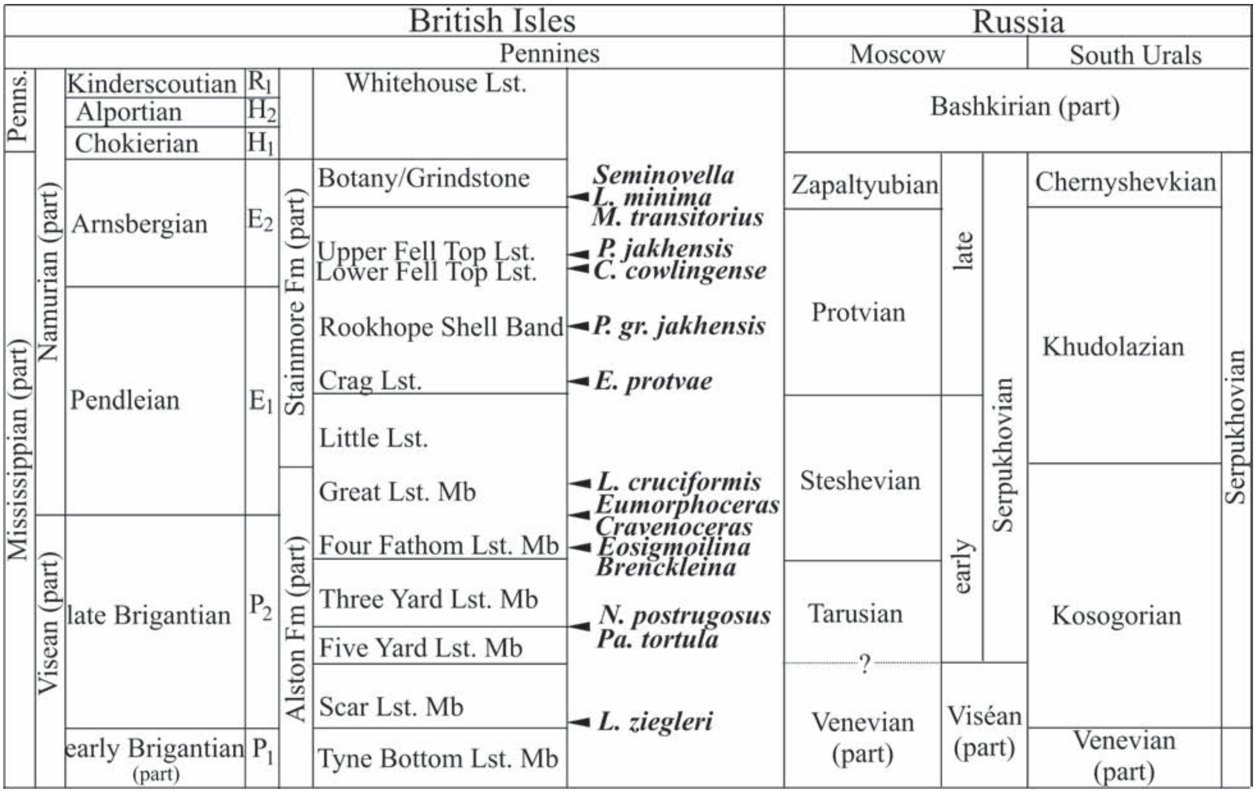

Fig. 2. Correlation of the British and Russian Carboniferous substages. In the Pennines column, a standard succession with the members and limestone beds is included, as well as the first occurrence of the main foraminifers, ammonoids and conodonts. Substages in the South Urals are used sensu Nikolaeva et al. (2009), with the base of the Kosogorian defined by the first occurrence of *Lochriea ziegleri*. Penns. = Pennsylvanian (part), *C.* = *Cravenoceras*, *E.* = *Eostaffellina*, *L.* = *Loeblichia*, *Lo.* = *Lochriea*, *M.* = *Monotaxinoides*, *N.* = *Neoarchaediscus*, *P.* = *Plectostaffella*, *Pa.* = *Paramillerella*.

ski et al. 1995), which is laterally equivalent to the Scar Limestone Member (Fig. 1) of the Alston Formation in the Stainmore Trough and Alston Block (George et al. 1976). That member contains the ammonoid *Lusitanoceras granosus* (P_{2a}), which is considered as the base for the late Brigantian Substage (see Riley 1993). Its occurrence from the base of the late Brigantian or equivalent levels is certainly at a much lower level than the first appearance datum (FAD) of *Cravenoceras leion*, the traditional marker for the base of the Namurian in England, and a level supposed to be laterally equivalent of the base of the traditional Serpukhovian.

Most studies dealing with the base of the Serpukhovian also contain foraminiferal and ammonoid data owing to their biostratigraphic potential for shallow- and deep-water facies, respectively (e.g., Gibshman 2003, Gibshman et al. 2009, Nikolaeva et al. 2009, Groves et al. 2012).

Since the pioneer study by Bisat (1924), and subsequent studies, ammonoid biostratigraphy in Britain is well-established in shaley deep-water facies of the Craven Basin, whereas they are extremely rare in shallow-water facies in the Stainmore Trough and Alston Block. In contrast, analyses of early Namurian foraminifers have been never undertaken comprehensively in shallow-water carbonates. Some of the classical limestone beds at the base of cyclothems of Pendleian and Arnsbergian age in the Stainmore Trough and Alston Block (Fig. 1) of northern England have been sampled now in natural outcrops and boreholes, including the Brigantian (late Viséan) Four Fathom Limestone Member and the basal Kinderscoutian (Bashkirian) Whitehouse Limestone (Cózar and Somerville 2004, Stephenson et al. 2010; Fig. 2). A recent revision of the lithostratigraphy in the Carboniferous of Great Britain by Dean et al. (2011) and Waters et al. (2011) has defined formal formations and members (mostly for Tournaisian and Viséan limestones), of which, all the studied succession is included in the upper part of the Alston Formation and lower part of the Stainmore Formation (Fig. 2).

Problems on the definition of the early Namurian substages

The base of the Pendleian was defined at the first occurrence of the ammonoid *Cravenoceras leion* and *Eumorphoceras medusa* (E_{1a}), which were recorded in shales above the Great Limestone Member in the Northumberland Trough (Ramsbottom et al. 1978). However, the latter authors noted the occurrence of *Cravenoceras* sp. and *Eumorphoceras pseudobilingue* in shales below the Great Limestone. More recently, Arthurton et al. (1988) recorded *C. leion* in shales below the Great Limestone at Fountain Fell (Askrigg Block, south of the Stainmore Trough; Fig. 1). Waters et al. (2011) considered the base of the Pendleian to lie within shales below the Great Limestone (thus, within the Four Fathom Limestone Mb cyclothem). A similar problem arose in defining the base of the Pendleian in the Midland Valley of Scotland (Fig. 1), where the ammonoid index, *Cravenoceras scoticum*, was recorded in shales below the conventional base of that substage therein, the Top Hosie Limestone (see Cózar et al. 2008, 2010). As a result of this paucity in the ammonoid records, the main tool for the correlation of those areas in Great Britain was the recognition of the Great Limestone Member and its lateral equivalents (Top Hosie Limestone in Scotland and the Main Limestone in the Askrigg Block).

The base of the Arnsbergian is defined at the first occurrence of the ammonoid *Cravenoceras cowlingense* (E_{2a}). This event was recorded in the Mirk Fell Ironstone of the Askrigg Block by Ramsbottom et al. (1978). This level was correlated with the Lower Fell Top Limestone further to the north in the Stainmore Trough and Alston Block (Fig. 2). Unfortunately, ammonoids in northern England are scarce north of the Craven Basin and lithostratigraphic correlation of limestone beds is thus, in part, based on indirect evidence (Stephenson et al. 2008). No biostratigraphic data supported those correlations. The main criteria for those correlations were related to glacioeustatism and their relative position below the Great Limestone Mb, the thickest and most continuous limestone in northern England.

The base of the Chokierian is defined by the first occurrence of *Isohomoceras subglobosum* (H_{1a}) within the *Homoceras* Genozone, although its base does not coincide exactly with the base of the Bashkirian, and the subzone H_{1a1} was still considered as Mississippian in Stonehead Beck (Riley et al. 1993).

New foraminiferal data from northern England and its biostratigraphical correlation with Russian substages

Foraminiferal assemblages are recorded in most limestone members and individual beds. However, this richness is not uniformly distributed, and depending on the outcrops, limestone units can be entirely dolomitized and devoid of foraminifers. In this study, only those biostratigraphically significant foraminifers are discussed, whereas, other components of the assemblages will be published elsewhere.

A diverse suite of foraminiferal species of the genera *Monotaxinoides* [*Monotaxinoides* sp., *Monotaxinoides priscus* Brazhnikova and Yartseva 1956, *Monotaxinoides* cf. *subplana* (Brazhnikova and Yartseva 1956) (Fig. 3A–3D)], *Eosigmoilina* (*Eosigmoilina*? sp.; Fig. 3F, 3J) and *Brenckleina* [*Brenckleina* aff. *tenuissima* (Brazhnikova 1964), *Brenckleina rugosa* (Brazhnikova 1964) and *Brenckleina* aff. *rugosa* (Fig. 3I, 3K, 3N–3P)] has been recorded from the Four Fathom Limestone Mb (uppermost late Brigantian). The Great Limestone Mb (lowermost Pendleian) can be also highlighted by the first occurrence of *Eostaffellina decurta* (Rauser-Chernousova 1948) (Fig. 3Q) and *Eosigmoilina* [*E. explicata* (Ganelina 1956) and *E. robertsoni* (Brady 1876); Fig. 3G–3H]. Species of *Monotaxinoides* and *E. decurta* may occur from horizons equivalent to the Tarusian Substage in the Urals (Kulagina et al. 2009), Kazakhstan (Brenckle and Milkina 2003) and Donets (Poletaev et al. 1991, Vdovenko 2001). *Brenckleina* is only known from the Protvian Substage in the Moscow Basin, and *Eosigmoilina* is not recorded at all (Gibshman 2003). In Tien Shan, *Eosigmoilina* is first recorded from the base of the Khudolazian (Fig. 2) and *Brenckleina* in younger parts of this regional substage (e.g., Kulagina et al. 1992). In the Donets, the occurrence of those genera is also assigned to the top of the Steshevian Substage (Poletaev et al. 1991), although Vdovenko (2001) reassigned them to the late Serpukhovian. Reitlinger et al. in Einor (1996) considered *Eosigmoilina* as occurring only from the Protvian Substage. Herein, the first occurrence of the eosigmoilinids in the upper part of the Steshevian Substages is considered probable. Thus, the Four Fathom Limestone and Great Limestone members cannot be older than the upper part of this Steshevian Substage (Fig. 2).

The Crag Limestone is highlighted by the first occurrence of large and evolved *Eostaffellina protvae*

Fig. 3. **A–B.** *Monotaxinoides priscus*, **A** – Four Fathom Limestone Member, Woodland Borehole; **B** – Great Limestone Mb, Bollihope Quarry. **C–D.** **C** – *Monotaxinoides* cf. *subplana*, Four Fathom Limestone Mb, Woodland Borehole; **D** – *Monotaxinoides* aff. *subplana*, Great Limestone Mb, Forsett Quarry. **E.** *Monotaxinoides transitorius*, Botany Limestone, Greenhill Quarry. **F, J.** *Eosigmoilina*? sp. **F** – Four Fathom Limestone Mb, Browson Bank Farm; **J** – Four Fathom Limestone Mb, Smeltmill Beck. **G.** *Eosigmoilina robertsoni*, Rookhope Shell Band, Woodland Borehole. **H.** *Eosigmoilina explicata*, Botany Limestone, Fier Cote Bolton Close Quarry. **I.** *Brenckleina* aff. *tenuissima*, Great Limestone, Brunton Quarry. **K, N.** *Brenckleina rugosa*, **K** – Four Fathom Limestone Mb, Smeltmill Beck; **N** – Botany Limestone, Greenhill Quarry. **L.** *Seminovella* sp., Botany Limestone, How Beck Head. **M.** *Loeblichia minima*, Botany Limestone, Greenhill Quarry. **O–P.** *Brenckleina* aff. *rugosa*, **O** – Botany Limestone, Fier Cote Bolton Close Quarry; **P** – Four Fathom Limestone Mb, Browson Bank Farm. **Q.** *Eostaffellina decurta*, Great Limestone Mb, Forsett Quarry. **R–T.** *Eostaffellina* "*paraprotvae*"?, **R** – Great Limestone Mb, Forsett Quarry; **S** – Little Limestone, Borrowdale Beck; **T** – Great Limestone Mb, Brunton Quarry. **U.** *Eostaffellina protvae*, Top Crag Limestone, Crag Bridge. **V.** *Eostaffellina* "*paraprotvae*", Top Crag Limestone, Crag Bridge. **X.** *Eostaffellina characteris*, Upper Fell Top Limestone, Rowlands Gill Borehole. **Y–Z.** *Plectostaffella* ex gr. *jakhensis*; **Y** – Rookhope Shell Band, Winston Bridge; **Z** – Upper Fell Top Limestone, Rowlands Gill Borehole.

(Rauser-Chernousova, 1948) and *E.* "*paraprotvae*" (Rauser-Chernousova, 1948), (Fig. 3U–3V). In addition, some specimens that could be also possibly attributed to *E.* "*paraprotvae*" and recorded from an older level, from the Great Limestone Mb, but their identification is questionable because of slightly obliquely oriented sections (Fig. 3R, 3T). However, this species is certainly present from the Little Limestone (Fig. 3S). *E. protvae* is restricted to the Protvian (Gibshman 2003, Kulagina et al. 1992, 2009). In the Donets, both species were recorded from the top of the equivalent horizon to the Steshevian, in C_4 and C_5 limestones (Aizenverg et al. 1979, 1983), although considered only as Protvian by Vdovenko (2001). Taking into consideration those records, the Crag Limestone is considered herein as defining the base of the late Serpukhovian, and equivalent to the Protvian Substage (Fig. 2).

Other more evolved species of *Eostaffellina* are recorded in the Rookhope Shell Band (*E. characteris* Reitlinger in Reitlinger and Mel'nikova 1977; Fig. 3X). Eosigmoilinids become also common in the Rookhope Shell Band. This horizon also records the first appearance of the genus *Plectostaffella*, although it is not common until higher levels (Upper Fell Top and Botany limestones). Most species of the genus *Plectostaffella* were described from substages laterally equivalent to the Zapaltyubian and Voznesenskian in Tien Shan (e. g., Kulagina et al. 1992), but the genus has been documented throughout the Serpukhovian (Vdovenko 2001, Brenckle and Milkina 2003). The most significant species recorded in northern England is *P.* "*jakhensis*" (Reitlinger 1971) (rare from the Rookhope Shell Band; Fig. 3Y; and more common from the upper Fell Top Limestone; Fig. 3Z). Some authors distinguished this species from *P. varvariensis* (Brazhnikova and Potievskaya 1948) (e. g., Kulagina et al. 1992, Gibsman and Akhmetshina 1991), and consider *P. jakhensis* as exclusively Bashkirian. However, slightly less skewed coiled specimens and less angular peripheries are also observed in the types of Reitlinger (1971). This led Groves (1988) and Groves et al. (1994) to consider them in synonymy, and van Ginkel (2010) who included both taxa in the group of *P.* ex gr. *jakhensis*. Thus, the species can be found in the literature from the late Serpukhovian in the Donetz Basin, eastern Russian Platform, southern Urals (Groves et al. 1994) and Kazakhstan (Brenckle and Milkina 2003). The Rookhope Shell Band and the Fell Top Limestone are also assigned to the Protvian Substage (Fig. 2).

The impoverished assemblages of the Grindstone Limestone (Alston Block) as well as the Botany Limestone (Stainmore Trough) are the highest limestones of the Arnsbergian, which were considered by Ramsbottom et al. (1978) as laterally equivalent. At this horizon, the occurrence of *Loeblichia minima* Brazhnikova 1962, *Monotaxinoides transitorius* Brazhnikova and Yartseva 1956, and *Seminovella* are noteworthy (Fig. 3M, 3E, 3L, respectively). In the Donets and Urals, *M. transitorius* is the nominal species for the youngest foraminiferal zone in the Serpukhovian, equivalent to the Zapaltyubian Substage (Aizenverg et al. 1979, 1983, Poletaev et al. 1991, Nikolaeva et al. 2009, Kulagina et al. 2009). In the Donets, *L. minima* is only recorded at equivalent levels to the Zapaltyubian (Aizenverg et al. 1983), although *Seminovella elegantula* is only recorded in Bashkirian rocks (Einor et al. 1979). In Tien Shan, both species are only recorded in the Chernyshevkian (Kulagina et al. 1992). The only discrepancy is documented by Reitlinger et al. in Einor (1996), who considered that *M. transitorius* might rarely occur from the Protvian Substage, and possibly in Brenckle and Milkina (2003) from Kazakhstan. The record of *L. minima* in the Steshevian of the Moscow Basin (Gibshman, 2003, Gibshman et al. 2009) is rather questionable, because they might be oblique and juvenile sections of *L. paraammonoides*, common taxa for this period. The Botany and Grindstone limestones are considered as representatives of the Zapaltyubian Substage (Fig. 2).

Biostratigraphic implications

These new foraminiferal data have implications for, in particular, the correlation of the base of the Pendleian with the base of the Serpukhovian. Thus, the base of the Tarusian Substage (Serpukhovian) in northern England has been located at a lower level in the succession, between the Four Fathom Limestone Mb and the Scar Limestone Mb, where *Lochriea ziegleri* was first recorded (Skompski et al. 1995). This conodont occurs in the "middle" part of the Venevian Substage of Russia (Skompski et al. 1995, Gibshman et al. 2009), and at the base of the re-interpreted Kosogorian Substage in the South Urals (Nikolaeva et al. 2009) (Fig. 2). To look for the equivalent of the Tarusian in England, the first occurrence of the following taxa should be carefully considered *Neoarchaediscus parvus* (Rauser-Chernousova 1948), *N. postrugosus* (Reitlinger 1949), *Eostaffella pseudostruvei* (Rauser-Chernousova and Beljaev in Rauser-Chernousova et al. 1936), *Janischewskina delicata* (Malakhova 1956), *Paramillerella tortula* (Zeller 1953), *Tubispirodiscus cornuspiroides* (Brazhnikova and Vdovenko in Brazhnikova et al. 1967) and *Eolasiodiscus*? *muradymicus* Kulagina in Kulagina et al. 1992, as well as *E. donbassicus* Reitlinger 1956. These foraminiferal species have been used to define the base of the Serpukhovian in the U.S.S.R. and the Ukraine (e. g., Poletaev et al. 1991, Einor 1996, Gibshman 2003, Gibshman et al. 2009, Nikolaeva et al. 2009). In recent studies, emphasis has focused on the first appearance of *N. postrugosus*, *P. tortula* and *Eolasiodiscus* species, which seem to occur at equivalent levels as *L. ziegleri* (Gibshman et al. 2009, Kabanov et al. 2009, Nikolaeva et al. 2009). *Eolasiodiscus* has not been recorded in England in the Brigantian Substage or in lower Namurian rocks. *N. postrugosus* and *P. tortula* have been recorded in the late Brigantian of the Solway Basin, southern Scotland (Fig. 1). The oldest records of *N. postrugosus* and *P. tortula* is situated in Limestone X and Buccleuch Limestone in the Archerbeck Borehole (= Three Yard Limestone Mb; Holliday et al. 1975, Dean et al. 2011, Cózar and Somerville 2012). In the Midland Valley of Scotland (Fig. 1), those taxa are recorded from Assemblage 8 (Cózar et al. 2008, 2010), also laterally equivalent to the Three Yard Limestone Mb in N. England, but unfortunately, those taxa were not recorded in the Brigantian there (see Cózar and Somerville 2004). Limestone X located below the Buccleuch Limestone, could lie in an intermediate position between the laterally equivalent Three Yard and Five Yard Limestone members, or could be part of the Five Yard Limestone, which splits into two units in some areas of the Pennines (Holliday et al. 1975). It is not clear enough yet concerning the first occurrence of those taxa in northern England. Thus, the Three Yard Limestone Member can be readily assigned to the Tarusian (Fig. 2), and possibly the shales and thin limestone lenses below, and the Five Yard Limestone Mb should be further investigated, as being probably equivalent to the lower part of the Tarusian Stage.

If the base of the Tarusian is situated within the Five Yard Limestone cyclothem, that would coincide with the approximate relative position where the conodont *Lochriea ziegleri* is first recorded in slightly older levels than the base of the Tarusian (in the case of northern England, the Scar Limestone Mb). This relationship between the first occurrence of *L. ziegleri* slightly below the base of the Serpukhovian was also observed in the Rheinische Schiefergebirge (Germany), near Lan'shino Village (Moscow Basin) (Skompski et al. 1995), as well as in the Novogurovsky Quarry (Moscow Basin; Gibshman et al. 2009), and thus, foraminiferal and conodont biozonations would represent a robust correlation between the Russian Platform and Britain.

Foraminifers documented from northern England also help in resolving the correlation between the Pendleian/Arnsbergian and early/late Serpukhovian boundaries, although with less significant implications. They confirm that the early/late Serpukhovian boundary can be correlated with the Crag Limestone, in a intermediate position within the Pendleian, as previously suggested by some authors (e.g., Vachard and Berkhli 1992, Vdovenko 2001, Nikolaeva and Kullmann 2001, Krainer and Vachard 2002, Alekseev et al. 2004). Unfortunately, the current resolution of the foraminiferal biostratigraphy does not allow a higher precision of that correlation. Similarly, the base of the Arnsbergian (Fell Top Limestone) does not seem to contain foraminifers significant enough as to be correlated with a precise horizon within the Russian substages.

The rate of evolution in the foraminifers is not rapid enough as to subdivide the Serpukhovian into more biozones, and a more precise correlation cannot be proposed as yet. In contrast, ammonoids have a much higher rate of evolution, and numerous biozones and subbiozones have been published (e.g. Waters and Condon 2012). It is also noteworthy, the exceptional record of *Cravenoceras* and *Eumorphoceras* below the base of the Pendleian in Alston and south Askrigg blocks (Ramsbottom et al. 1978, Arthurthon et al. 1988), in shales between the Four Fathom and Great Limestone members.Those shales have been considered as Steshevian, and thus, no typical Namurian/Serpukhovian ammonids has been recorded in England in equivalent horizons to the Tarusian. However, ammonoids are often quite restricted to certain basins, and their use for international correlations is based on inferred equivalencies (e.g., Nikolaeva and Kullman 2001), and as already published by Stephenson et al. (2008), ammonoids are scarce north of the Craven Basin in England (Fig. 1). Thus, correspondance of some limestones in England is based on lithological markers and relative position within stratigraphic successions. Owing to the results with foraminifers and conodonts, ammonoid biostratigraphy from England needs to be recalibrated.

Implications for glacioeustatic correlations

In order to compare with other basins, a good geochronology and precise biostratigraphy is necessary. In this respect, Eros et al. (2012a, 2012b) published a correlation between the succession in the Donets (Ukraine), the Midcontinent (U.S.A.) and the Pennines (England), attributing all the cycles recognized in those regions as to be an effect of glacioeustatism. Although some concerns were raised by Ruban (2012) about the presence of lowstands in the eustasy curve of the Donets Basin, distinct from those in Haq and Schutter (2008), and, as a secondary consideration, the tectonic influence in that sector of the Variscan Belt. The apparent differences with the global eustasy curve by Haq and Schutter (2008) was argued by Eros et al. (2012b) on the basis of similar lowstands in the Midcontinent and Pennines.

The similar lowstands and highstands between the Donets and Midcontinent highlighted by Eros et al. (2012b), and the main argument for a glacioeustatic origin, might be even stronger than suggested by those authors with a better biostratigraphic calibration referred to the Viséan/Serpukhovian boundary. Eros et al. (2012b) based the Viséan/Serpukhovian boundary on the new geochronologic data of Davydov et al. (2010) and Gradstein et al. (2012), which positioned this boundary according to the proposal in progress of the Task Group in the Subcommission for Carboniferous Stratigraphy (Richards, 2010), which favoured the first appearance of the conodont *Lochriea ziegleri*. The first appearance of this conodont is not precisely defined yet, and as Davydov et al. (2010) recognized, it is situated in the middle to upper part of the Venevian Russian Substage. On the other hand, ornamented *Lochriea* do not occur in the American Realm, which complicate, notably, its correlation with the American Realm. This level is more precise in the Pennines (Middle Limestone = Scar Limestone Mb according to George et al. 1976). Considering the rest of the foraminiferal and conodont assemblages, most probably, the base of the Venevian might be located somewhere within the middle to upper parts of the early Brigantian (Fig. 4). However, the use of this potential Viséan/Serpukhovian boundary by Eros et al. (2012a, 2012b) in the Donets was not consistently used, and the correlation with its counterparts in the Pennines and Midcontinent did not consider that modification in the base of the Serpukhovian. For the Donets Basin, they considered the first occurrence of *L. ziegleri* as the base of the Serpukhovian, whereas for others regions, they only considered the traditional basal Serpukhovian/Pendleian boundaries.

In the case of northern England, the new data documented herein of the Tarusian Substage as probably equivalent to the Five Yard Limestone Mb (or at least the Three Yard Limestone Mb) might imply that at least three high-frequency sequences included in the latest Viséan by Eros et al. (2012a) should be considered also as Serpukhovian sequences (Five Yard Limestone, Three Yard Limestone and Four Fathom Limestone members), as well as an additional cycle considering the first occurrence of *L. ziegleri* (Scar Limestone Mb). Other minor cycles are recognized in northern England (e.g. Iron Post) although they do not seem to be of the same magnitude, because an equivalent unit in the Askrigg Block is not recognized between the Underset and Main limestones (= Four Fathom and Great Limestone respectively, sensu George et al. 1976).

Eros et al. (2012b) used the sequences and ammonoid dispersion levels of Waters and Condon (2012) for the comparison with the Pennines. The former authors highlighted the interval with scarce or absent dispersion of ammonoids, as well as the similarities in the number of high-frequency sequences, 17 for the Serpukhovian in both regions. However, Waters and Condon (2012) defined these 17 sequences in a conventional subdivision of the Pendleian/Arnsbergian (Fig. 4F), and using the Great Limestone and the first appearance of *Cravenoceras leion* as the base for the Pendleian. The Alston Formation in the Pennines contains at least 4 main members for the late Brigantian (Holliday et al. 1975, Johnson and Nudds 1996, Cózar and Somerville 2004, 2012, Cózar et al. 2010, Dean et al. 2011, Fig. 2), which most probably also correspond to fourth-order glacioeustatic sequences. Most or all of them, should be added to the sequences included in the new sense of the Serpukhovian sensu Eros et al. (2012b), thus making a total of 21 cycles, and hence detracting from the apparent cycle by cycle comparison in both regions, and thus, 17 by 21 respectively. However, similarly to the Iron Post Limestone cycle of the Alston Block, it should be clarified that not all of the cycles recognized in the Pennines seem to be of the same magnitude, because it is quite likely that fifth-order cycles can be masked within the fourth-order sequences. Mesothems described by Ramsbottom (1977, 1979) do not solve the problem (Fig. 4E), as they correspond to third-order sequences, but as in the Moscow Basin (Fig. 4D), resulted in more difficulties when attempting to compare between the basins.

On the other hand, Eros et al. (2012b) used the Menard Limestone as the base of the Serpukhovian in the Midcontinent, USA, as earlier proposed by Brenckle et al. (1977) and Baxter and Brenckle (1982) and more recently by Lane and Brenckle (2005). The boundary has been placed at different levels in the Mississippi River Valley sequence (Brenckle et al. 2005), higher up than the above-mentioned Menard Limestone, but as low as the Fraileys Shale (Fig. 4C) based on ammonoids (Manger and Sutherland 1984). Recently, Kulagina et al. (2008) proposed that the Beech Creek Limestone should be considered as the base for the Serpukhovian (Fig. 4C), including similar foraminifers recorded in the upper part of the FU 10 which Lane and Brenckle (2005) used to define the base of the Serpukhovian. Foraminifers of the Vienna

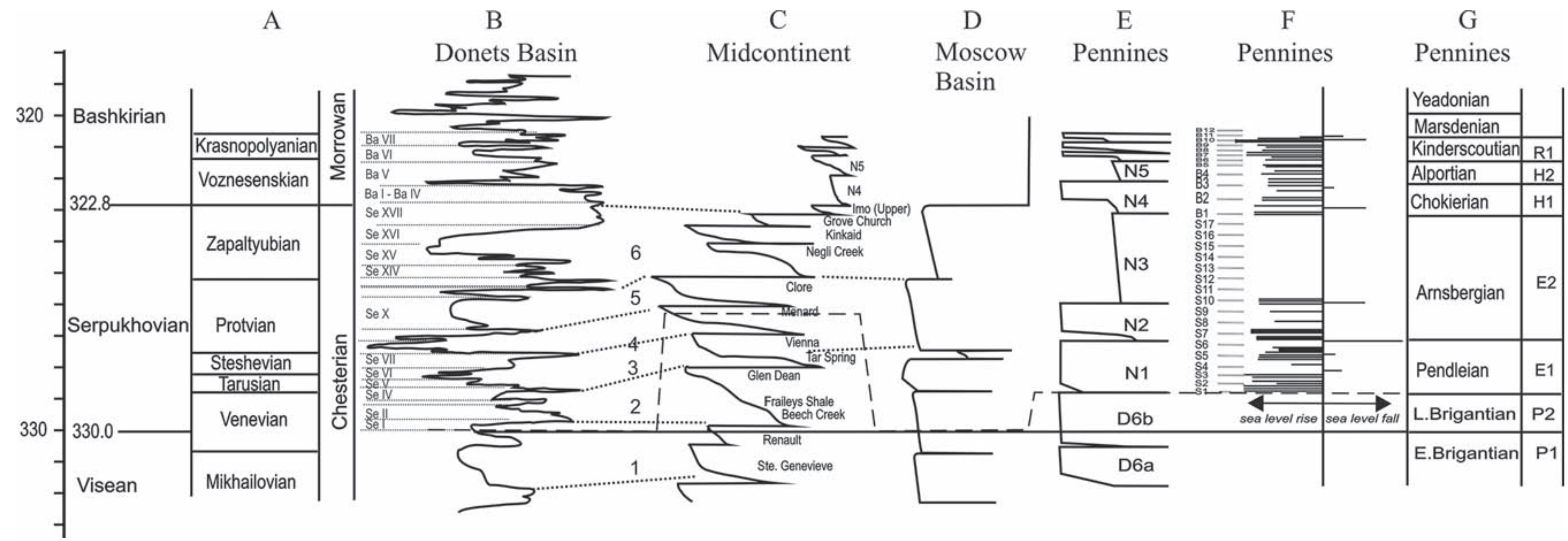

Fig. 4. Correlation of the Serpukhovian Stage (A) with the onlap curve in the Donets Basin (B) (modified from Eros et al. 2012b), Midcontinent USA (C) (modified from Ross and Ross, 1987), Moscow Basin (D) (modified from Alekseev et al. 2004), mesothems of Ramsbottom (E) (1977, 1979) and ammonoid bands (F) (from Waters and Condon, 2012) in the Pennines (northern England). Mississippian and Pennsylvanian Regional Substages and ammonoid zones for the Pennines (G). Dashed line is the correlation published in Eros et al. (2012b); solid line is the new correlation; dotted line is the correlations of some important levels.

Limestone are typically recorded from the Steshevian Substage. The traditional equivalent to the base of the Serpukhovian in the Midcontinent, the Menard Limestone (FU 11 of Lane and Brenckle, 2005), contains typical foraminiferal assemblages that were correlated with the Protvian Substage (Kulagina et al. 2008) (Fig. 4C).

The implications for the new base of the Serpukhovian in the Midcontinent, using the Beech Creek Limestone, is a much stronger correlation than that described by Eros et al. (2012b). During the latest Viséan and the entire Serpukhovian, six major offlap-onlap sequences can be markedly correlated (1 to 6 in Fig. 4B–4C). This correlation stronger supports the glacioeustatism on the Donets succession as the main controlling factor (as Eros et al. 2012b suggested), at least, for this part of the succession. However, this scenario is more complicated in the comparison between the Donets and northern England and invalidated by the previously published correlations. The four late Brigantian cycles seem to correspond to 4th-order magnitude, but the magnitude of the additional 17 Pendleian-Arnsbergian cycles should be further investigated.

Conclusions

On the basis of new foraminiferal data collected from Mississippian limestones in the Pennine region of N. England, the base of the Tarusian Substage (base of the traditional Serpukhovian) can now be located below the Three Yard Limestone Member and within the Five Yard Limestone Member (within the late Brigantian). The base of the Pendleian has no clear counterpart in the Russian stratigraphic scheme, because it corresponds to an intermediate position within the Steshevian Substage. The base of the Protvian Substage (base of the late Serpukhovian) is correlated with the Crag Limestone, whereas the base of the Arnsbergian was situated above (Lower Fell Top Limestone), but without any precise correspondence within the Protvian Substage. The Zapaltyubian Substage is recorded at levels equivalent to the Botany and Grindstone limestones in N. England. Unfortunately, shales above the latter limestone contain a reduced Chokierian and probably a missing Alportian Substage (Ramsbottom et al. 1978), up to the Kinderscoutian Whitehouse Limestone (Fig. 2). Thus, the transition to the Bashkirian cannot be studied by mean of foraminifers in Britain.

The base of the Serpukhovian highlights the unusual earlier record of the conodont *Lochriea ziegleri* in England, from the base of the late Brigantian, which now is substantially more consistent with the record of that conodont elsewhere in Europe. This repositioning of the base of the Serpukhovian has also implications for international correlations based on glacioeustatic cycles (e.g., Eros et al. 2012b). Correlation between Donets and the Pennines seems to be less consistent than previously published by other authors, but correlation with the Midcontinent is now more consistent.

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