Irish Serpukhovian revisited

P. Cózar¹ I. D. Somerville²

¹ Instituto de Geociencias (CSIC, UCM), Ciudad Universitaria, 28040 Madrid, Spain. E-mail: p.cozar@igeo.csic-ucm.es

² UCD School of Earth Sciences, University College Dublin, Belfield, Dublin 4, Ireland. E-mail: ian.somerville@ucd.ie

Correspondence

P. Cózar, Instituto de Geociencias (CSIC, UCM), Ciudad Universitaria, 28040 Madrid, Spain. E-mail: p.cozar@igeo.csic-ucm.es

Abstract

In this study of Mississippian rocks in Ireland, it is now recognised, based on faunal evidence, that several upper Viséan limestone formations which were previously excluded from the Serpukhovian now belong, in part, to the lower two substages of the Serpukhovian. A reassessment of previous foraminiferal determinations, together with new foraminiferal data, has confirmed that rocks equivalents to the Tarusian and Steshevian substages are present in several sections. In the Slievenaglasha Formation and Magowna Formation (County Clare) and Deer Park Formation (County Meath), Tarusian and Steshevian foraminiferal assemblages are thus recorded. In the Clogrenan Formation (County Carlow), Carganamuck Limestone Formation (County Armagh) and Rockdale Limestone Formation (County Tyrone), Tarusian foraminiferal assemblages are recorded in the upper beds of thick limestone successions. Key foraminiferal and algal taxa characterise each assemblage, which have been correlated with equivalent Serpukhovian strata in the north of England and Scotland. A three-stage evolution is

recognised in archaedisid foraminifers: from *Neoarchaediscus gregorii*, followed by *Neoarchaediscus postrugosus* form 1, and *Neoarchaediscus postrugosus* form 2, with *Neoarchaediscus postrugosus* form 1 used to define the base of the Serpukhovian. The recognition of Tarusian and Steshevian foraminiferal assemblages implies that areas of shallow-water platform carbonate sedimentation in Ireland during the upper Viséan (Brigantian) persisted into the early Serpukhovian.

Keywords: ammonoids, Arnsbergian, biostratigraphy, Brigantian, foraminifers, Pendleian

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1 INTRODUCTION

The Serpukhovian Stage is currently under investigation, as part of the research on establishing a Global Stratotype Section and Point (GSSP) between the Viséan and Serpukhovian (e.g., [Richards & Task Group, 2017](#)), that also marks the boundary between the Middle and Upper Mississippian. For nearly two decades, researchers have considered the conodont *Lochriea ziegleri* as the best candidate as a marker for the new GSSP of the basal Serpukhovian ([Richards & Task Group, 2003](#)). This implies that the base of the Serpukhovian should be relocated in slightly older levels, within the upper Viséan, than in the former parastratotype of the Serpukhovian in the Zabori'e Quarry of the Moscow Basin ([Gibshman, 2003](#); [Skompski et al., 1995](#)). In the last few years, numerous publications have been dedicated to the search for *Lochriea ziegleri* around the world (see references in [Cózar, Vachard, Aretz, & Somerville, 2019](#); [Nikolaeva et al., in press](#)). However, the supposed synchronous first occurrence of this taxon is still a matter of discussion (e.g., [Barham, Murray, Sevastopulo, & Williams, 2015](#); [Cózar et al., 2019](#); [Herbig, 2017](#); [Nikolaeva et al., in press](#); [Sevastopulo & Barham, 2014](#)). A significant problem which complicates the study of the first appearance datum (FAD) of this taxon, is the lack of calibration in the international correlations of biozones and regional stages (now recognized as regional substages), used in many countries/basins, compared to the standard chronostratigraphic scale (see [Davydov, Korn, Schmitz, Gradstein, & Hammer, 2012](#)). This calibration is progressing, but slowly, and yet, comparison of the FAD of different species is strongly controlled by traditional biozone/stage correlations, using very diverse types of fauna/flora. Furthermore, not well-constrained biozone correlations are dependent on inferred synchronous faunal dispersion/migrations. Within the studied late Viséan-Serpukhovian interval, one of the biggest mismatches in Europe is observed between the base of the Namurian and the base of the Serpukhovian. For many decades, the base of the Namurian was equated with the base of the Serpukhovian (see [George & Wagner, 1972](#); [Wagner & Higgins, 1979](#)), and even more recently, this correlation has been widely used ([Davydov, Crowley, Schmitz, & Poletaev, 2010](#); [Einor, 1996](#); [Lane & Brenckle, 2005](#); [Vdovenko, 2001](#); [Waters & Condon, 2012](#)). As a result, paradoxically,

significant parts of the Serpukhovian are not included in studies dealing with the Serpukhovian, but using it as equivalent to the Pendleian and Arnsbergian regional substages for Western Europe (e.g., [Brand, 2011](#); [Sevastopulo, 2009](#)).

Another conflicting point for a well-constrained calibration and correlation of the regional biozones/substages, is the definition of the stratotypes for the Serpukhovian substages. This did not follow a uniform criterion in terms of facies and fauna, being frequently based, unevenly, on deep-water versus shallow-water facies, or nektonic/pelagic versus benthic faunas, and hence of questionable national correlation, even moreso, for worldwide correlation.

The Serpukhovian Stage was originally defined by [Nikitin \(1890\)](#) in the Moscow Basin, and was divided into five substages: Tarusian, Steshevian, Protvian, Zapaltjubian and Voznesenskian. The lower three substages (Tarusian, Steshevian and Protvian) were defined in the Moscow Basin region ([Shvetsov, 1932](#); [Khimenkov, 1934](#)), based on shallow-water platform facies. However, because of poor preservation or absence of the upper part of the Serpukhovian, the Zapaltjubian and Voznesenskian substages were defined elsewhere, in the Donbass Basin of Ukraine ([Aizenverg et al., 1979](#)). Subsequently, the Voznesenskian was considered as part of the Bashkirian ([Nemirovskaya, 1987](#)) and hence the lowest part of the Pennsylvanian.

In Britain, the stratigraphic interval inferred to be laterally equivalent to the Serpukhovian, is approximately composed of the Brigantian (upper part), Pendleian, Arnsbergian and basal Chokierian substages. The Brigantian Substage was proposed by [George et al. \(1976\)](#) in shallow-water facies from the Stainmore Trough; in Belgium it corresponds to the upper part of the Warnantian ([Poty & Hance, 2006](#)). The Pendleian was defined by [Ramsbottom \(1981\)](#) at Light Clough, Pendle Hill, in deep-water facies of the Craven Basin, whereas the Arnsbergian was proposed by [Ramsbottom \(1969\)](#) in Arnsberg (Westphalia, Germany), also in deep-water facies (with a representative parastratotype for Britain and Ireland in Stony River, County Leitrim, Ireland). The Pendleian and Arnsbergian are widely recognized substages for Western Europe zonations (see [Davydov et al., 2012](#)). Correlation between shallow-water and deep-water facies in Britain is mostly based on ammonoids, although the occurrence of this

fossil group north of the Craven Basin (in the shallow-water platform successions of the Askrigg and Alston blocks) is rather scarce (Waters & Condon, 2012). This uneven facies distribution and use of different fossil groups for the recognition of these substages, leads to conflicting data between deep- and shallow-water facies in some periods, a feature highlighted by Czar and Somerville (2014, 2016) for northern England, and subsequently, correlations and comparisons with the international zonal schemes can induce significant errors (Czar & Somerville, 2014).

The aims of this study are firstly, the revision of middle and upper Mississippian rocks in Ireland (including both the Republic of Ireland and Northern Ireland) which could be correlated with the Serpukhovian stage (Figure 1). These rocks were previously assigned to the regional substages in England (Brigantian, Pendleian and Arnsbergian) and thus, of a low value for international correlation. The second aim, is the revision of faunal assemblages and inclusion of new foraminiferal data, to help date sections more precisely, and to enable biostratigraphic correlations to be made with upper Visan-Serpukhovian successions in northern England.

2 CRITERIA FOR THE DEFINITION OF THE SERPUKHOVIAN STAGE AND SUBSTAGES IN IRELAND

The base of the Serpukhovian Stage adopted here, in principle, is the FAD of the conodont *Lochriea ziegleri*. This taxon is rarely documented in Britain and Ireland, and it is first recorded from the Middle Limestone of the Askrigg Block in northern England (Varker in Skompski et al., 1995), and in the Magowna Formation in the Kilnamona/Magowna and St Brendan's Well sections in south central Ireland (Barham et al., 2015; Meischner in Skompski et al., 1995) and Lugasnaghta stream section in Northern Ireland (Sevastopulo & Barham, 2014; Barham et al., 2015). In sections from Ireland, the FAD of *L. ziegleri* is clearly younger than in Britain, and in sections in south central Ireland, it even occurs in the same beds as those containing the ammonoid *Cravenoceras leion* of the E₁ zone (Hodson & Lewarne, 1961).

The data from the sections in northern England were also revised in [Sevastopulo and Barham \(2014\)](#), and those authors confirmed that the FAD of *L. ziegleri* is from “the lower part of the Middle Limestone”. The Middle Limestone is a composite carbonate unit in the Askrigg Block of northern England, which represents the amalgamation of the Single Post, Cockleshell and Scar limestones, known from the Stainmore Trough, Alston Block and Northumberland Trough farther to the north ([Holliday, Burgess, & Frost, 1975](#); [Rose & Dunham, 1977](#)). Thus, [Sevastopulo and Barham \(2014\)](#) interpreted that the FAD of *L. ziegleri* should be correlated with levels equivalent to the Single Post Limestone, assigned by [Ramsbottom \(1974\)](#) to the P_{1d} ammonoid subzone, but according to the revised ammonoid zones in [Korn and Titus \(2011\)](#), this level should be considered as the P_{1c} subzone (see details in [Sevastopulo & Barham, 2014](#)). However, it is worth highlighting that (i) the FAD of *L. ziegleri* in the Single Post Limestone is based on an imprecise “lower part”, because the Middle Limestone can be subdivided into the three limestone units observed further to the north; (ii) the FAD of *L. ziegleri* in the Single Post Limestone is based on an indirect correlation, because the stratigraphic details of the section(s) were never published; (iii) the assignment to the P_{1d} subzone is based on an indirect correlation, assuming ammonoids recorded further to the north in England, but not present in the Askrigg Block; and (iv) the reinterpretation of the P_{1c} subzone is equally based on an indirect correlation of the ammonoid zone by comparison with ammonoids in the basins in Germany.

The separation of the Single Post, Cockleshell and Scar limestones is more easily recognisable in the Alston Block and Stainmore Trough, but further south they become thinner, and eventually are amalgamated as one limestone unit in the Askrigg Block. Nevertheless, thin shale partings can be used to distinguish the three individual limestones within the amalgamated Middle Limestone (e.g., [Dunham, 1990](#); [Rose & Dunham, 1977](#); [Strank, 1981](#)). The extreme amalgamation is observed in the Pateley Bridge region, included as part of the southern Askrigg Block succession, and situated between the North and Middle Craven Faults. There, the so-called Toft Gate Limestone, is the lateral equivalent of the combined Simonstone, Single Post, Cockleshell and Scar limestones ([Dunham & Stubblefield, 1945](#)). Thus, if the limestones equivalent within the Middle Limestone are not well established, and the FAD of

Lochriea zieglerei is not precisely located, to assume that this taxon first occurs in the Single Post Limestone needs further supporting evidence. Therefore, the first point to clarify is, if the FAD of *L. zieglerei* in any given section corresponds to the Single Post Limestone, it should be desirable to demonstrate the same event in sections north of the Askrigg Block, where limestones are much more clearly separated by thick clastic intervals. On the other hand, considering the stratigraphical reinterpretation of the ammonoids above the Single Post Limestone as typical of the P_{1c} subzone, it is not clear if that means that the P_{1d} subzone of N England does not exist, or if the ammonoids are not representative of the P_{1d} subzone of England (because this zone is recognized from shales above the Hardraw Limestone), or if the P_{1d} subzone should be restricted to shales between the Cockleshell and Scar limestones.

Apart from conodonts and ammonoids, [Hallett \(1971\)](#) and [Strank \(1981\)](#) studied the foraminifers of the Middle Limestone and Single Post/Cockleshell/Scar limestones. Subsequent studies of those limestones have shown them to be barren or with very limited foraminiferal assemblages (e.g., [Cózar & Somerville, 2004](#); [Johnson, Somerville, Tucker, & Cózar, 2011](#)). The Scar Limestone and younger limestone beds were studied in detail by [Cózar and Somerville \(2016\)](#).

Unfortunately, [Hallett \(1971\)](#) did not distinguish the three individual limestone units which comprise the Middle Limestone, and thus he considered it as a single unit. The only relevant foraminifer first occurring from the Middle Limestone is *Neoarchaediscus gregorii*, although the specimen he illustrated ([Hallett, 1971, pl. 5, fig. 12](#)) is from the Three Yard Limestone, and is considered herein as *Planospirodiscus* aff. *taimyricus* (in contrast to the nominal species, this form contains some inner skew-coiled whorls). Thus, it is not clear what was the diagnosis used by [Hallett \(1971\)](#) in identifying *N. gregorii*.

[Strank \(1981\)](#) studied these limestones at Birkett Cutting (Askrigg Block), Whitfield Gill (Askrigg Block) and Trout Beck (Alston Block). The main foraminiferal features for this interval were the reduction in the number of large *Archaediscus* at angulatus stage (cf. Conil, Longerstaey, & Ramsbottom, 1980; Pirlet & Conil, 1977), and an increase in the number of small asteroarchaediscinae, including the first occurrence of

Asteroarchaediscus bashkiricus and *A. rugosus*. These features are noted from the Single Post Limestone, but they are more accentuated in the Cockleshell Limestone. These foraminiferal characteristics also coincide with a major change in the coral and brachiopod fauna between the Single Post and Cockleshell limestones, which led [Strank \(1981\)](#) to propose that the base of the late Brigantian P₂ zone should be located at the base of the Cockleshell Limestone. Furthermore, at Birkett Cutting, “*Millerella*” *tortula* occurs in the Cockleshell Limestone ([Strank, 1981, pl. 73, fig. 24](#), as cf. *Planoendothyra* sp.), and at Whitfield Gill, it is noteworthy for the first occurrence of *Neoarchaediscus gregorii* from the Single Post Limestone. With the available data, the occurrence of *N. gregorii* from levels of the uppermost early Brigantian might be the best candidate in the British Isles to recognize horizons that might be equivalent to the FAD of *Lochriea ziegleri*, although further studies focused on the Single Post and Cockleshell limestones are needed to increase the knowledge of their foraminiferal assemblages. *Neoarchaediscus gregorii*, together with clearer basal Serpukhovian (Tarusian) markers, such as *Neoarchaediscus postrugosus* and “*Millerella*” *tortula* are recorded from the Scar Limestone ([Cózar & Somerville, 2016](#)), whereas, as mentioned above, “*M.*” *tortula* has been recorded from the Cockleshell Limestone. However, the first occurrence of those taxa can show important delays in Britain. For instance, the best Serpukhovian foraminiferal marker, *N. postrugosus*, is first recorded in the Midland Valley of Scotland from younger levels, correlated with the Three Yard Limestone of northern England ([Cózar, Somerville, & Burgess, 2010](#)). “*Millerella*” *tortula* is, so far, unknown in the Midland Valley, whereas *N. gregorii* is recorded from the levels immediately below the Lower Limestone Formation (late Brigantian to Pendleian) in limestones at Kirkcaldy and Catcraig (East Fife and East Lothian, respectively) ([Karubub, 1993](#)), which have been correlated with the Single Post Limestone ([Cózar & Somerville, in press](#)). Well-constrained regional markers of the Single Post Limestone or equivalent levels are *Asteroarchaediscus bashkiricus* and *A. rugosus*, although more simple and small forms, such as *Asteroarchaediscus pustulus* has been recorded from the top of the Tynebottom Limestone ([Cózar & Somerville, 2004](#)).

Younger Serpukhovian substages are recognized on the basis of the foraminifers recorded in the Alston Block and Stainmore Trough, as described in [Cózar and Somerville \(2014, 2016\)](#), and their associated ammonoid/miospore biozones. Thus, levels correlated with the Steshevian Substage include the following main limestones: Three Yard Limestone (oldest), Four Fathom Limestone, Great Limestone and Little Limestone ([Figure 2](#)). The main criteria for this correlation are the occurrence of *Eostaffellina* from the Three Yard Limestone and *Eosigmoilina/Brenckleina* from the Four Fathom Limestone, although the Three Yard Limestone might be considered also as part of the Tarusian. The Protvian Substage was restricted to the Crag Limestone, due to the first occurrence of large and rounded *Eostaffellina*, such as *Eostaffellina protvaeensis*, new name proposed by [Gibshman \(2019\)](#) for *E. protvae*. The Zapaltjubian might be present from the Rookhope Shell Band, Lower Fell Top Limestone and Coalcleugh Limestone, based on the occurrence of common *Plectostaffella*, including *Plectostaffella varvariensis* and *P. jakhensis*. However, classical markers of the Zapaltjubian (*Loeblichia minima*, *Monotaxinoides transitorius* and *Seminovella elegantula*) do not occur up to the Botany/Grindstone Limestone. [Cózar and Somerville \(2014\)](#) suggested that the possible level of correlation with the Voznesenskian (Bashkirian) was the Botany/Grindstone Limestone. However, [Cózar and Somerville \(2016\)](#) recorded the possible occurrence of *Plectostaffella bogdanovkensis* and *Eostaffellina?* sp. A from the Upper Fell Top Limestone. This species of *Plectostaffella* is mostly restricted to the Bashkirian and the plausible species of *Eostaffellina* has differentiated layers in the wall, a feature typical of *Pseudostaffella* and *Varistaffella*, both genera restricted to the Bashkirian (see discussion in [Cózar & Somerville, 2016](#)). Both taxa suggested that the possible level of correlation with the Voznesenskian is the Upper Fell Top Limestone ([Figure 2](#)). However, the conodont *Declinognathodus noduliferus*, the marker for base of the Bashkirian, has been only recorded from the H_{1a2} subzone of the Chokierian Substage in Stonehead Beck section ([Riley, Varker, Owens, Higgins, & Ramsbottom, 1987](#); [Varker, 1994](#)). This upper part of the succession in Britain and Ireland needs to be further investigated.

For the correlation with the ammonoid and miospore zones, the biozones of those fossil groups recognized in the Alston Block are adopted here, based on data in [Owens,](#)

McLean and Bodman (2004), Brand (2011), Waters, Somerville, Stephenson, Cleal, and Long (2011), Waters, Millward, and Thomas (2014), and McLean, Owens, Bodman, and McLean (2018). As mentioned above, many shaley facies in the upper part of the studied succession could be only dated using miospore zones, and hence, there is an important issue concerning the correlation of the base of the NC zone. For some authors, the base of this zone should be correlated with the P_{2b} ammonoid subzone (e.g., George et al., 1976; Owens et al., 2004; Waters et al., 2011), whereas for others, it should be correlated with intermediate levels of the P_{1a} subzone (Sevastopulo & Wyse Jackson, 2009), or its base should be correlated with the base of the P_{2a} subzone (McLean et al., 2018). Miospore details in Owens et al. (2004) and Owens, McLean, Simpson, Shell, and Robinson (2005) suggest that the NC zone occurs in shales associated with the St Monans Little Limestone and Second Abden Limestone in Fife, Scotland and the Five Yard Limestone in northern England, and thus, the correlation with the P_{2b} zone is followed here (Figure 2).

2.1 Faunal constraints for the Irish Mississippian zonation and correlation

A significant problem to acknowledge is the particularities of the fauna in Ireland, in that some foraminiferal taxa do not show, apparently, the same stratigraphic range as in northern England.

The best foraminifer to recognize the Single Post Limestone in northern England is *Asteroarchaediscus*, but in Ireland, its first occurrence is located in basal levels of the Brigantian (Cózar & Somerville, 2005; Cózar, Somerville, & Somerville, 2005a; Cózar, Somerville, Aretz, & Herbig, 2005b; Cózar, Somerville, Mitchell, & Medina-Varea, 2006; Somerville & Cózar, 2005), or even from the latest Asbian (Jones & Somerville, 1996). The first occurrence of *Neoarchaediscus gregorii* is also a problematic taxon, because in rare cases, it is present within the early Brigantian (Cózar & Somerville, 2005), although, generally, it is associated to levels recognized as close to the base of the late Brigantian (e.g., Cózar et al., 2006). Within the continuous carbonate successions in

Ireland, archaediscids show a three-stage evolution. In the first stage, *Neoarchaediscus gregorii* first occurs, together with primitive forms, assigned to the genus *Planospirodiscus* (Figure 3a-b, 3f, 3h-l). In the second stage, *Neoarchaediscus postrugosus* first occurs, although those specimens are more similar to the paratype defined by Reitlinger (1949), with a more compact shape, and less evolute final whorl (Figure 3j-m). In addition, evolved forms of *Planospirodiscus* co-occur with the latter (e.g. *Planospirodiscus* aff. *taimyricus*). In the final stage, *Neoarchaediscus postrugosus*, similar to the holotype first occurs, marked by a narrower test, and more clearly evolute final whorl (Figure 3n-o). In this higher level, more evolved *Planospirodiscus taimyricus* and *Tubispirodiscus* are also recorded, together with “*Millerella*” *tortula*. The two morphotypes of *N. postrugosus* are distinguished, herein, as form 1 (for the paratype) and form 2 (for the holotype). The difference between both types of the species was discussed by C3zar and Somerville (2016), although the species recorded from the base of the Scar Limestone in northern England, contain both morphotypes from the base. Taking into consideration the poverty in foraminiferal data from the Single Post and Cockleshell limestones, it is plausible, that at least, form 1 should occur in those horizons (or perhaps even both). Further detailed foraminiferal research is necessary in the Single Post and Cockleshell limestones to confirm the first occurrences of those taxa compared to the first occurrence of *Lochriea ziegleri*. In contrast to Kulagina (2017), *Neoarchaediscus gregorii* is considered, herein, to be derived from other discoidal primitive forms, such as *N. incertus* (= *N. probatus*; Brenckle & Grelecki, 1993), with more open whorls in the lumen. The progressive occlusion of the lumen as well as incipient development of evolute final whorls in *N. postrugosus*, seems to be culminated with more evolute final whorls in specimens such as *N. shugorensis*, completing a phylogenetic lineage. This lineage is characterized by an aligned arrangement of the final whorls. On the other hand, *Asteroarchaediscus* seems to be derived from wider species of *Neoarchaediscus*, also with a progressive occlusion of the lumen, such as *N. parvus*. The holotype of *N. parvus* shows oscillating coiling (see reillustration of the types in Kulagina, 2017), however, one of the paratypes described by Rauser-Chernousova (1948) shows an aligned coiling (it looks like *N. shugorensis*), a fact that led some authors to consider the species as being characterized by an aligned coiling (e.g., Vachard, 1988).

Owing to its occlusion, *N. postrugosus* has been considered as *Asteroarchaediscus* by some authors (e.g., Vachard, 1988; Brenckle & Grelecki, 1993). However, to accept this genus identification for the species, that would imply that *Asteroarchaediscus* is a polyphyletic genus, when really, a clear independent lineage can be recognized for the discoidal forms. On the other hand, Brenckle, Ramsbottom, and Marchant (1987) and Brenckle and Grelecki (1993) considered *Planospirodiscus* as a senior synonym of *Tubispirodiscus*, because they interpreted that there is no occlusion of the lumen in the types of *Planospirodiscus* (interpreted as cements). However, occluded and non-occluded forms with more or less parallel flanks occur readily in the geological records (e.g. C3zar & Somerville, 2013), and thus, both genera are considered valid (Vachard, 1988).

The conodonts *Lochriea nodosa* and *L. mononodosa* were considered to be restricted to the late Brigantian in Ireland (Aldridge, Austin, & Husri, 1968; Austin, Conil, & Husri, 1970; Austin & Husri, 1974; Somerville, 1999), and both species have been widely used as markers for this substage. In fact, this stratigraphic record was rather similar to that in England (e.g., Bowden, 2001; Metcalfe, 1981), although Varker (1964), Davies, Austin and Moore (1993) and Varker in Skompski et al. (1995) recorded these species from the Gayle Limestone in the Askrigg Block. In Ireland, all the records of these species seems to be restricted to the late Brigantian, except in the Cuilcagh Mountains, where Kelly (1989) recorded *L. nodosa* from the Meenymore Formation in the Aghagranian River section (Table 1), which is considered here as early Brigantian (see C3zar et al., 2006; Figure 2).

The ammonoid records in the lower part of the studied successions from Ireland are very limited, due to a higher predominance of shallow-water platform carbonates. Thus, data on ammonoids are rather sparse, except for the successions in northwest Ireland, where thin limestones are interbedded with thicker shales (e.g., Brandon, 1972, 1977; Brandon & Hodson, 1984; Hodson & Moore, 1959; Korn, 1990; Moore, 1958). However, even there, there is an apparent conflict between the ammonoids and the foraminiferal and conodont distributions (compare Barham et al., 2015; C3zar et al., 2006; Kelly, 1989; Sevastopulo & Barham, 2014). Ammonoids in the shales in the

upper part of the studied successions are relatively common ([Ramsbottom et al., 1978](#)).

3 SERPUKHOVIAN IN IRELAND

The upper Viséan-Serpukhovian rocks in Ireland occur in six major basins/regions: South Munster Basin, North Munster Shelf, Shannon Basin, Dublin Basin, NW Carboniferous Basin, and Northern Ireland (similar to those documented in [Waters et al., 2011](#)), which will be described in geographical sequence, from south to north ([Figures 1, 2](#)).

3.1 South Munster Basin

In the South Munster Basin, the macrofauna of the Lispatrick Formation suggests a Brigantian age ([Sleeman & Pracht, 1994](#)), from the lower levels ([Figure 2](#)), based on the occurrence of the bivalve *Posidonia becheri*. Ammonoids recorded from the middle part of the formation in Old Head were assigned to the P_{1d} goniatite subzone, whereas *Eumorphoceras* (not identified at species level, and thus, only suggesting a Pendleian or Arnsbergian age) was recorded 3 m above the base of the White Strand Formation ([Naylor, Sevastopulo, & Sleeman, 1985](#)). In Galley Head, goniatites of the P_{1b}-P_{1c} subzones were recorded ([Graham, 1975](#)), and [Naylor et al. \(1985\)](#) reported ammonoids of the P_{1c} subzone, 6 m above the base of the Lispatrick Formation, and approximately 18 m higher up, ammonoids of the P_{2a} subzone. [Sevastopulo and Wyse Jackson \(2009\)](#) first proposed a Serpukhovian age for the uppermost 10 metres of the Lispatrick Formation, although they only considered as plausible, Serpukhovian rocks of the P₂ zone. Assuming the previously discussed equivalence of the ammonoid subzones is correct, at least the upper half of the Lispatrick Formation corresponds to the Serpukhovian. Owing to a predominance of mudrocks and the rarity of ammonoids for a precise subdivision, and taking into consideration the thicknesses of each interval,

it seems that strata equivalent to the Tarusian Substage might be complete, but younger rocks might be absent, or extremely condensed, due to the thinner occurrence of rocks above the well-constrained Tarusian assemblages (Figure 2). The White Strand Formation is supposed to range from the Pendleian to the Chokierian (Sleeman & Pracht, 1994), although as mentioned above, the datings are of low resolution, because the *Eumorphoceras* ammonoid did not allow a more precise dating (Naylor et al., 1985), and the succession can be eroded in some sections, as in Old Head, and at Seven Heads (Naylor, Higgs, Reilly, & Sevastopulo, 1988). Miospores recorded by Naylor et al. (1988) from the base of the lower member belong to the NC miospore zone and the upper part to the Arnsbergian TK biozone (Naylor et al., 1988) (Figure 2). Similarly, Somerville, Jones, and Philcox (1996a) also reported the NC miospore zone from the base of the formation in the Cloyne Syncline. These data led Sevastopulo (2009) and Waters and Somerville (2011) to consider that the White Strand Formation extends from the base of the Pendleian up to the Bashkirian, although the miospore zone from the base of the formation might be restricted to late Serpukhovian, or Pendleian E_{1c} subzone (Figure 2). In Whiddy Island, there are also record of shales, where the East Point Member of the Reenydonagan Formation contain ammonoids of the E_{2b} subzone (Naylor, Jones, & Clayton, 1978), and higher up, the Middle Battery and Kilmore formations are supposed to contain higher levels of the Arnsbergian to Chokierian, although they are not dated (Sevastopulo, 2009) (Figure 2). Compared to sections in Seven Heads, it might be suggested that the lower part of the Reenydonagan Formation ranges down to similar levels as the White Strand Formation. However, all the above-mentioned outcrops were included within the Kinsale sub-basin of Naylor, Sevastopulo, and Sleeman (1989), whereas Whiddy Island belongs to the Bantry sub-basin (Figure 2). It is difficult to extrapolate between both sub-basins, since they both had strong differences from the Lower Viséan (Arundian) upwards (Sevastopulo & Wyse Jackson, 2009). In both shaley successions of the Kinsale and Bantry sub-basins, further work is required to precisely date the lower extension of the formations, as well as to confirm a rather plausible hiatus in part of the early Serpukhovian.

3.2 North Munster Shelf/South Central Ireland

In the Buttevant area of north County Cork, the Liscarroll Limestone Formation was attributed to the Brigantian (Gallagher, 1992, 1996; Gallagher & Somerville, 1997), and Somerville, Waters, and Collinson (2011) considered the Liscarroll Limestone Formation extending from the early Brigantian to the P_{2a} subzone, and thus, supposedly late Brigantian. Rugose corals recorded in this formation were assigned to the H zone (sensu Mitchell, 1989), representative of the early Brigantian (see Gallagher & Somerville, 1997). Foraminifers of the formation are typically early Brigantian (see Gallagher, 1996; Gallagher & Somerville, 1997), and the most evolved forms are those of *Loeblichia paraammonoides* and *Howchinia* trans. *Monotaxinoides*. *Loeblichia paraammonoides* is first recorded from the Gayle Limestone (Askrigg Block) in northern England, in the foraminiferal assemblage 5 of Cózar & Somerville (2004), of early Brigantian age. The so-called *Howchinia* trans. *Monotaxinoides* is reinterpreted herein as *Hemidiscopsis declivis*, a taxon described from the late Viséan in Russia (Mikhailovian Substage; Cózar, Sanz-López, & Blanco-Ferrera, 2015; Ganelina, 1956). However, the only other occurrence of this taxon in Ireland has been reported from the upper part of the Clogrenan Formation in County Carlow (see below) (Somerville & Cózar, 2005, as cf. '*Monotaxinoides*' sp.) in upper Brigantian rocks. It is necessary to note here, that Gallagher (1996) and Gallagher and Somerville (1997) correlated the upper part of the Liscarroll Limestone Formation with the upper part of the Clogrenan Formation (corresponding to the Serpukhovian) (see below). Nevertheless, the rapid lateral facies changes of the Clogrenan Formation (see Cózar & Somerville, 2005), does not allow to confirm that similar facies between the upper member of the Liscarroll Limestone Formation and the Clogrenan Formation are coeval. Thus, there is no clear evidence of the presence of the Serpukhovian in the Liscarroll Limestone Formation, and the succession is probably restricted to the upper Viséan (Figure 2).

In east County Limerick, the Dromkeen Limestone Formation is, in part, the lateral equivalent of the Liscarroll Limestone and Clogrenan formations, which also extends from the early Brigantian up to the late Brigantian P_{2a} subzone (Somerville et al., 2011).

The attribution to the younger subzone is based on the finding of a single element of the conodont *Lochriea mononodosa* (Somerville, Strogon, & Jones, 1992). In previous publications, the occurrences of *L. nodosa* or *L. mononodosa* were considered as guides for the late Brigantian (e.g., Austin et al., 1970; Austin, 1973; Jones & Somerville, 1996; Somerville, 1999). However, as discussed previously, in England, these species occur in intermediate positions of the early Brigantian, and thus, the restriction of both species to the late Brigantian is usually the rule, but some exceptions exist in England and Ireland. Rugose corals and foraminifers from the Dromkeen Limestone Formation do not suggest the occurrence of the late Brigantian. Thus, the Dromkeen Limestone Formation, like the Lisscarroll Limestone Formation, probably does not extend to basal levels of the Serpukhovian stage (Figure 2).

The Lisscarroll Limestone Formation passes northeastwards, to Counties Kilkenny and Carlow, where it is called the Clogrenan Formation (Archer, Sleeman, & Smith, 1996; Tietzch-Tyler & Sleeman, 1994; Figure 2). The lower part of the Clogrenan Formation is well exposed in several quarries in the eastern flank of the Castlecommer Syncline, as at Clogrenan Quarry, whereas the upper part of the formation is more complete in the northern part of the region, in County Laois, such as in Guileen-1 Borehole and Dunamase Quarry (Table 1). The Clogrenan Formation ranges through the early and late Brigantian (Cózar & Somerville, 2005). The late Brigantian age was recognized by the co-occurrence of *Janischewskina typica* and *Endothyranopsis sphaerica*. These taxa are typically recorded from the Five Yard Limestone from northern England in foraminiferal assemblage 7 (Cózar & Somerville, 2004). On the other hand, the early Brigantian interval was subdivided in three units (3-5) by Somerville and Cózar (2005). In the middle part of the unit 3, is the FAD of *Neoarchaediscus gregorii*, with *Neoarchaediscus postrugosus* form 1, a few metres above (Figure 3). These horizons are interpreted here as equivalent to the Single Post-Cockleshell limestones in England, and thus considered to mark the base of the Serpukhovian, laterally equivalent to the Tarusian. The upper part of unit 3 contains the FAD of *Planospirodiscus taimyricus*, *P. minimus* and rare *Climacammina*. In unit 4 are recorded the FAD of *Neoarchaediscus postrugosus* form 2 and “*Millerella*” *tortula* (as *Millerella?* sp.). This horizon of unit 4 is correlated with the Scar Limestone Member of northern England, whereas the upper

part of the Clogrenan Formation (units 5 and 6) is considered equivalent to the Five Yard Limestone Member ([Figure 4](#)). Younger Serpukhovian strata in the region are composed of the Luggacurren Shale Formation, which disconformably overlies the Clogrenan Formation, has been dated as Arnsbergian (E_{2c}). However, the basal levels, comprise cherts and black shales (Coonbeg Chert and Glenview Shale members, respectively) that could not be dated. [Higgs \(1986\)](#) assigned the Coonbeg Chert to the Arnsbergian E_{2b} subzone due to the lithological similarities with cherts in County Limerick. [Sevastopulo \(2009\)](#) and [Somerville et al. \(2011\)](#) interpreted these cherts as belonging to the E_{2b} subzone.

In south County Wexford, the Viséan carbonate succession recorded from boreholes was revised by [Nagy et al. \(2005\)](#). The youngest strata of the Wexford Formation are of late Asbian age. [Clayton, Sevastopulo, and Sleeman \(1986\)](#) attributed the Park Formation, which unconformably overlies the Asbian strata, to the Namurian (E_{1c} to R_{2c} subzones), which [Somerville et al. \(2011\)](#) interpreted as Pendleian to Marsdenian. However, there is no biostratigraphic dating from this mudstone formation.

3.3 Shannon Basin

In northwest County Limerick, close to Foynes, there is a deep-water succession that extends through the Brigantian into the Pendleian (Parsonage, Corrig Lodge and Clare Shale formations; [Figure 2](#)). The upper 10 metres of the Parsonage Formation contain calcilutite wackestone with rare thin grainstones, which contain Brigantian foraminifers ([Sleeman & Pracht, 1999](#)). Late Asbian conodonts were recorded through the formation, and thus, the formation is interpreted not to reach the Serpukhovian. The overlying Corrig Lodge Formation contains conodonts of the *Lochriea nodosa* Zone, at 15 m above the base of the formation, which was considered as late Brigantian in [Sleeman and Pracht \(1999\)](#), [Somerville et al. \(2011\)](#) and [Somerville \(2016a\)](#). Ammonoids of this formation are only representative of the B₂ subzone ([Hodson & Lewarne, 1961](#)), but productid brachiopods and foraminiferal assemblages

recorded by [Shephard-Thorn \(1963\)](#) were attributed to the upper D2 zone or equated with the V3c foraminiferal zone of Belgium (= Brigantian). [Waters et al. \(2011\)](#) extended the formation from the early Brigantian to the lower part of the late Brigantian. [Sevastopulo and Wyse Jackson \(2009\)](#) only considered the Clare Shale Formation as Serpukhovian. Assuming, as previously stated, that the first occurrence of *Lochriea nodosa* in Ireland is usually at levels within the P₂ zone (although, exceptionally, it has been recorded from the P₁ zone), the Corrig Lodge Formation is considered here (at least in part) as the lower part of the early Serpukhovian ([Figure 2](#)). [Shephard-Thorn \(1963\)](#) inferred a plausible break in the deposition, involving parts of the D2 zone, P₂ and E₁ zones in some areas, because in the southern Foynes area, the first ammonoids in the Clare Shale Formation were assigned to the E₂ zone. Nevertheless, this formation further to the west contains ammonoids of the E₁ zone ([Hodson & Lewarne, 1961](#); [Sevastopulo, 2009](#); [Wignall & Best, 2000](#); [Wignall, Somerville, & Braithwaite, 2016](#)), although the basal E_{1a} subzone is not present, which confirms the hiatus between the Viséan limestones and the Namurian shales. This hiatus suggests that the Viséan limestones could not reach the late Brigantian in the region, because all the foraminiferal/ammonoid/conodont markers suggest an age compatible with the P₁ zone passing into the E_{1b} subzone. This also confirms that the late Serpukhovian is present, but only represented as shales ([Figure 2](#)). However, [Sleeman and Pracht \(1999\)](#) and [Sevastopulo \(2009\)](#) considered that the Clare Shales Formation is in continuity with the underlying limestone in some regions, although palaeontological evidences were not provided for each locality.

In the southwestern part of the Shannon Basin, at Ballybunnion, 40 km west of Foynes ([Figure 1](#)), the formations are the same as those described above, although this area is less-well dated than the Foynes region, but the formations do not seem to be synchronous. The only available dating of the Corrig Lodge Formation records ammonoids of the P_{1d} zone in the upper part of the Formation ([Sleeman & Pracht, 1999](#)). In the Clare Shale Formation, [Kelk \(1960\)](#) recorded ammonoids of the P₂ zone from the lower levels of the formation (up to H₁ Chokierian). Thus, in this region, the succession appears to be continuous, and the base of the Clare Shale Formation seems to be older than in the Foynes area. This difference in age within the Shannon Basin

was already recognised by [Hodson and Lewarne \(1961\)](#). More recent works in the region did not investigate in detail this diachronism (e.g. [Wignall et al., 2016](#)) or they focused their research on the youngest beds of the Clare Shale Formation (e.g., [Braithwaite, 1993, 1995](#); [Fallon & Murray, 2015](#)).

In the Burren region, north County Clare, forming the southern part of the Galway-Roscommon Shelf ([Pracht & Somerville, 2015](#); [Sevastopulo & Wyse Jackson, 2009](#)), are recorded the upper Viséan shallow-water carbonate platform facies of the Shannon Basin. This comprises the Burren Formation (Asbian) and overlying Slievenaglasha Formation ([Figure 2](#)). The latter extends throughout the Brigantian, although only the uppermost part of the formation, the Lissylisheen Member, was previously considered as late Brigantian ([Gallagher, 1996](#); [Gallagher, MacDermot, Somerville, Pracht, & Sleeman, 2006](#)). This was due to these authors recording a foraminifer identified by them as “close to *Archaediscus at tenuis* stage”, which is likely, a transitional form between the angulatus and tenuis stages (cf. Conil, Longerstaey, & Ramsbottom 1980; Pirlet & Conil, 1977) or an evolutus stage (cf. Vachard, 1988) or angulatus-tenuis stage (cf. Zandkarimi, Vachard, Najafian, Hamdi, & Mosaddegh, 2017). Furthermore, [Clarke \(1966\)](#) described the rugose coral *Orionastraea* from the top of the formation in Lisdoonvarna, which is representative of the late Brigantian coral zone J of [Mitchell \(1989\)](#), although revision of the genus in Ireland by [Nudds \(1979\)](#) restricted it to the P_{1d} subzone. Succeeding the Slievenaglasha Formation, in stratigraphic continuity, is the Magowna Formation, which records the transition into the Pendleian ([Sleeman & Pracht, 1999](#)), with ammonoids of the E₁ zone. Thus, it seems that much of the Serpukhovian is well represented in this region. [Meischner \(in Skompski et al., 1995\)](#) recorded common conodont assemblages from the Kilnamona Stream section, including *Lochriea commuta*, *L. mononodosa*, *L. cruciformis*, *L. ziegleri* and *L. senckenbergica*. The same beds were also studied by [Barham et al. \(2015\)](#), and they also found similar rich conodont assemblages. However, none of them sampled the thick massive limestone of the Slievenaglasha Formation, except for the top bed, from which similar assemblages were recorded, which implies that the first occurrence of these conodonts has to be at a lower level in this formation.

The Ballyelly Member [the third member (of 4 members), in the upper part of the Slievenaglasha Formation, [Gallagher et al., 2006](#); [Figures 2, 4](#)] has been resampled in the N 67 roadside quarry, 3 km northeast of the town of Lisdoonvarna. This 6-m-thick section, near the base of the member, contained the following foraminifers: *Archaediscus* at angulatus stage (common), *A. chernousovensis*, *Asteroarchaediscus bashkiricus* (common), *A. rugosus*, *Endothyra spira*, *Howchinia bradyana* (common), *H. gibba* (common), *Janischewskina?* sp., “*Millerella*” *tortula*, *Neoarchaediscus gregorii* (common), *N. karreriformis*, *N. occlusus*, *N. parvus* (common), *N. postrugosus* forms 1 and 2, *N. spp.* (common), *Omphalotis minima*, *Pseudoammodiscus* spp., *Pseudolituotuba gravata*, *Pseudotaxis eominima*, *Tetrataxis* spp. (common), *Tubispirodiscus* sp. and *Valvulinella youngi* (common) ([Figure 5](#)). This rich assemblage allows us to assign the Ballyelly Member to the early Serpukhovian, since it contains markers of the Tarusian Substage. The occurrence of both forms of *N. postrugosus*, at 1 m above the base of the quarry, suggest that the likely base of the Serpukhovian is located in slightly older levels than the base of the member, i.e. within the top of the underlying Fahee North Member ([Figures 2, 4](#)).

The uppermost part of the Slievenaglasha Formation (the Lissylisheen Member, only 2 m thick) has been sampled in the Gowlaun River section in Lisdoonvarna (see [Somerville, 2016b](#), fig 5.2.11), and Vigo Cave and Vigo Pothole (Kilfenora). They contain the foraminifers: *Archaediscus* at angulatus stage (common), *A. at angulatus stage* transitional to *tenuis* stage (common), *A. at tenuis stage*, *Asteroarchaediscus bashkiricus* (common), *A. rugosus*, *Cepekia cepeki*, *Eosigmoilina cf. robertsoni*, *Howchinia gibba*, *Neoarchaediscus gregorii* (common), *N. postrugosus* form 2, *N. shugorensis*, *N. spp.* (common), *Planospirodiscus* sp., *P. taimyricus* (common), *Tetrataxis* spp., *Tubispirodiscus cornuspiroides* (a species included in *Tubispirodiscus* as discussed in C3zar, Somerville, & Burgess, 2008), *T. simplissimus* and *T. spp.* ([Figure 6](#)). This rich and diverse assemblage is representative of the Steshevian Substage, and correlatable with the Four Fathom Limestone in northern England (assemblage 9 in [C3zar et al., 2010](#); [Figure 4](#)). Moreover, indirectly, the upper part of the Ballyelly Member is considered to include also the Three Yard Limestone ([Figures 2, 4](#)).

The transition into the Pendleian of the Magowna Formation (about 3 m thick) has been sampled in Magowna Waterfall and the Kilnamona stream section, as well as from the upper metre of the Lissylisheen Member. The assemblages in the Magowna Formation are very similar to those from the Lissylisheen Member, with abundant *Asteroarchaediscus*, *Planospirodiscus*, discoidal *Neoarchaediscus*, *Tubispirodiscus*, and rare eosigmoilinids (*Eosigmoilina robertsoni*). However, in addition is recorded a different eosigmoilinid, *Brenckleina* cf. *rugosa*, and *Brownediscus*? (Figure 7). The latter taxon is a form very close to the nominal genus, although the inner whorls are not at tenuis stage. It is similar to specimens recorded in the Tramaka Encrinite of Belgium (Austin, Conil, Groessens, & Pirlet, 1974; Brenckle, Ramsbottom, & Marchant, 1987), of upper late Serpukhovian (Zapaltjubian Substage) age. The only comparable specimens in Britain were recorded from the Blae Pot Limestone of the Archerbeck Borehole in the Solway Basin (Scotland), a limestone correlated with the Little Limestone in northern England (Cózar & Somerville, 2013), corresponding to the upper part of levels correlated with the Steshevian Substage (Figure 2). Thus, the assemblages are also assigned to the Steshevian Substage, and taking into consideration the occurrence of *Cravenoceras leion* in those beds, as well as *Brownediscus*?, it should be correlated with the Great Limestone of northern England (and the foraminiferal assemblage 10 in Cózar et al., 2010). No foraminiferal evidence of the late Serpukhovian has been recorded. The supposed lateral equivalence of the Magowna and Corrig Lodge formations, as proposed by Sleeman and Pracht (1999), is not supported by the biostratigraphical data. Above the uppermost shales of the Magowna Formation, the succession is capped by the St Brendan's Well Phosphate Bed, which Wignall and Best (2000) and Wignall et al. (2016) considered to span the E_{2a2} to E_{2c2} interval. Thus, the late Serpukhovian (Protvian) corresponds to a hiatus (Figure 2), and the lower part of the phosphates and Clare Shale Formation represents the uppermost late Serpukhovian.

3.4 Dublin Basin and Kingscourt Outlier

In the Dublin Basin, deep-water basinal facies extend throughout the Viséan, which is flanked on the northern margins by shallow-water platform facies (Nolan, 1986; Pickard, Jones, Rees, Somerville, & Strogon, 1992; Pickard, Rees, Strogon, Somerville, & Jones, 1994; Strogon, Somerville, Jones, & Pickard, 1995; Strogon, Somerville, Pickard, Jones, & Fleming, 1996). In the north County Dublin area at Loughshinny, Brigantian deep-water facies are represented by the Loughshinny Formation (Nolan, 1986; Pickard et al., 1994; Strogon et al., 1996). Precise foraminiferal data are documented in Nolan (1986), who recorded primitive *Planospirodiscus* from the lower part of the Loughshinny Formation, suggesting an uppermost early Brigantian age. Also, evolved *Planospirodiscus taimyricus* were recorded from the Ballustree Member (as gen. nov., Nolan, 1986, pl. 14, figs. 17-18), and *Howchinia* cf. *subconica* from the upper 4th member. In addition, *Brenckleina* might be also present from the upper member (recorded by Nolan, 1986, pl. 16, fig. 28, as *Asteroarchaediscus* sp.). Pickard et al. (1992) recorded *Lochriea mononodosa* from intermediate positions in the formation. These taxa suggest that the Ballustree Member should be considered as equivalent to the Tarusian in age, and the Member 4 might correspond to the lower part of the Steshevian (Figure 2). The succeeding Donore Shale Formation contains *Cravenoceras leion* (Nevill, 1957), representing the upper part of the Steshevian. There are no biostratigraphical data from the overlying Balrickard Sandstone Formation, whereas the succeeding Walshestown Shale Formation contains ammonoids of the E_{1c} to E_{2b} subzones (Ramsbottom et al., 1978; Sevastopulo, 2009; Smyth, 1950), including the upper part of the late Serpukhovian. Therefore, the Balrickard Sandstone Formation, on stratigraphical grounds, must represent the lower part of the late Serpukhovian.

In the Ardagh/Kingscourt outlier in north County Meath, 60 km NW of Dublin (Figure 1), shallow-water platform facies of Brigantian age is represented by the Deer Park Formation. The late Brigantian age was based on the occurrence of the conodonts *Lochriea nodosa* and *L. mononodosa* in the upper part of the succession in Barley Hill Quarry, Poulmore Scarp Quarry and in the Almush Stream section (Somerville, 1999; Somerville & Somerville, 1999). Strogon et al. (1995) distinguished a laterally equivalent facies (the Almush Shale Member of the Loughshinny Formation), which record ammonoids of the P_{1c} to the P_{2c} subzones (Jackson, 1965). Thus, the early

Serpukkhovian can be inferred to represent the upper part of the Deer Park Formation, as well as part of the Almush Shale Member (Figure 2). Foraminifera obtained from the uppermost part of the Deer Park Formation at Poulmore Scarp Quarry (Cózar, Somerville, & Somerville, 2005a; and new data), include *Howchinia subconica*, *Eolasiodiscus* sp. (as *Monotaxinoides*? sp.), *Tubispirodiscus attenuatus*, *T.* cf. *cornuspiroides*, *Planospirodiscus* cf. *taimyricus* from the lower part of the quarry (lower 6 m) and *Archaediscus* at tenuis stage, *Cepekia cepeki*, *Brenckleina* sp., *Brenckleina rugosa*, *Eosigmoilina robertsoni*, *Neoarchaediscus shugorensis*, *Eostaffellina decurta*, *E.* ex gr. *paraprotvae* (from 6.8 m and higher beds), as well as common incertae sedis *Algospongia Calcifolium okense* throughout the quarry section (Figure 8). Most of the *Howchinia* species contain umbilical structures, a feature observed from advanced early Serpukhovian times (Cózar et al., 2015). The forms attributed to *Eolasiodiscus* in Britain were only known previously in the late Serpukhovian (Cózar & Somerville, 2014; Stephenson et al., 2010), although it has been recorded from the Upper Skateraw Limestone in East Lothian (Scotland), at a level correlated with the Three Yard Limestone in northern England (Alston Block), whereas, *Howchinia subconica* was recorded from the younger Four Fathom Limestone (Cózar & Somerville, 2016). *Brenckleina*, *Eosigmoilina* and *Archaediscus* at tenuis stage was also recorded from the Four Fathom Limestone, although recent discoveries have identified the presence of *A.* at tenuis stage in the Three Yard Limestone (Cózar & Somerville, in press). On the other hand, the *Eostaffellina* species have been recorded from the Three Yard Limestone. In the Alston Block, the acme of *Calcifolium okense* is located between the Three Yard Limestone Member and the Great Limestone Member (Cózar & Somerville, 2004, 2016), although its first occurrence is from the Five Yard Limestone (Cózar & Somerville, 2004). All those members were considered as equivalent to the Steshevian, although the upper part of the Poulmore Scarp Quarry yielding *Eosigmoilina* and *Brenckleina* is correlated with the Four Fathom Limestone, and the lower part of the quarry should be correlated with the Three Yard Limestone Member, and thus, it might be the lower part of the Steshevian (Figures 2, 4). This interval is also represented by the basinal Almush Shale Member, laterally equivalent to the platform Deer Park Limestone Formation. Younger strata are represented by the Ardagh Shale Formation, ranging from the E_{1a} to E_{1c} subzones (Jackson, 1965). Although there is a continuous

succession between the Deer Park and Ardagh Shale formations, a small hiatus between both formations had been previously suggested (Somerville, Strogon, Jones, & Somerville, 1996b; Strogon et al., 1995), although it is now considered of lesser importance (Figure 2). The Carrickleck Shale Formation which succeeds the Ardagh Shale Formation ranges in age from the E_{2a} to H_{2c} (Somerville & Waters, 2011c). Thus, the upper part of the early Serpukhovian up to the lower part of the late Serpukhovian corresponds with the Ardagh Shale Formation, and the upper part of the late Serpukhovian is included within the lower part of the Carrickleck Shale Formation.

3.5 Northwest Carboniferous Basin and Slieve Carna Outlier

In the Slieve Carna outlier (County Mayo), a shaley succession is recorded. It comprises the Tooromin Shale and Craggagh Shale formations (Long, McConnell, & Philcox, 2004). According to ammonoids listed by Ramsbottom et al. (1978), the Tooromin Shale includes the P₂ zone, and the Craggagh Shale contains the E_{1a} to E_{1c} subzones, and thus, most of the early Serpukhovian seems to be present and only the lower part of the late Serpukhovian (Figure 2). The lack of any limestones in the succession does not allow the confirmation of these biostratigraphic ages using foraminifers and conodonts. No other putative Serpukhovian rocks are known in Western Ireland (see Pracht & Somerville, 2015; Somerville & Waters, 2011b).

In the Northwest Carboniferous Basin (counties Sligo, Leitrim, and western Fermanagh) there is a relatively uniform succession (Leitrim Group), and the Brigantian-Arnsbergian interval is well exposed around the Cuilcagh Mountains, close to Lough Allen (Legg, Johnston, Mitchell, Smith, 1998; Somerville & Waters, 2011a; Figure 1). The lower part of the Leitrim Group (upper Viséan) is composed of the Meenymore, Glenade Sandstone, Bellavally and Carraun Shale formations (Brandon & Hodson, 1984; Legg et al., 1998), ranging from the B_{2a} to P_{2c} ammonoid subzones (Brandon, 1977; Brandon & Hodson, 1984) (Figure 2). Aldridge et al. (1968) recorded *Lochriea nodosa* and *L. mononodosa* from the middle part of the Carraun Shale Formation, and

Barham et al. (2015) recorded *L. nodosa*, *L. mononodosa*, together with *L. cruciformis*, *L. ziegleri* and *L. senckenbergica* from similar levels, in the Ardvarney Limestone Member and Sranagross Dolomite Member (Carraun Shale Formation). Sevastopulo and Wyse Jackson (2009) considered the Meenymore and Glenade Sandstone formations as Asbian in age, and the Bellavally and Carraun Shale formations as Brigantian. However, Kelly (1989) recorded *L. nodosa* from the basal Meenymore Formation. Somerville and Waters (2011a) considered the Meenymore and Bellavally formations as early Brigantian in age, with the boundary between the early Brigantian and late Brigantian located in the middle part of the Carraun Shale Formation. On the other hand, as Czar et al. (2006, 2019) mentioned, the Tullysheherny Member, at the base of the Bellavally Formation, contains *Neoarchaediscus postrugosus* form 2, *N. gregorii* and *Planospirodiscus* aff. *taimyricus* (Figure 9a-h), which allow us to establish that the base of the Serpukhovian is located at or below the base of the Bellavally Formation (Figure 4). The assemblage is similar to that recorded in upper positions of the unit 3 in the Clogrenan Formation, and similarly, it is correlated with levels equivalent to the Scar Limestone of northern England. A similar assemblage is recorded near the top of the Bellavally Formation, Sheena Shale Member, where more evolved *Planospirodiscus* first occur (Figure 9i-l). At the base of the succeeding Carraun Shale Formation, within the Derreens Limestone Member, *Neoarchaediscus* with some whorls at tenuis stage, *Tubispirodiscus* and *Archaediscus* at tenuis stage are recorded. (Figure 9i-u). These taxa can be compared to other outcrops in Ireland and Britain, suggesting a probable Steshevian foraminiferal assemblage for the Carraun Shale Formation, in particular, the lower part of this substage, equivalent to the Three Yard Limestone (Figures 2, 4). This substage extends up to the Dergvone Shale Formation (upper part of the Leitrim Group), which includes the first occurrence of *Cravenoceras leion* (Brandon & Hodson, 1984). The overlying Briscloonagh Sandstone Formation does not contain any palaeontological records, and it is assumed to represent the rest of the Pendleian, because the succeeding Gowlaun Shale Formation contains faunal markers of the Arnsbergian E_{2a} subzone (MacDermot, Long, & Harney, 1996). Above, the Lackagh Sandstone Formation has no faunal records (Legg et al., 1998), and the veneering Bencroy Shale Formation, which only crops out in Co. Leitrim, contains

ammonoids of the E_{2b1} subzone (Brandon & Hodson, 1984; Ramsbottom et al., 1978) (Figure 2).

3.6 Northern Ireland

In Northern Ireland, apart from the Cuilcagh Mountains area which contains the Leitrim Group (see section 3.5), there are other regions where Serpukhovian rocks are present. In the south, in County Armagh, close to the Kingscourt outlier (Figure 1), in the Armagh Platform succession, the youngest Viséan strata comprise the Carganamuck Limestone Formation (Figure 2), ranging in age from early to late Brigantian (Mitchell & Somerville, 2011). However, Cózar et al. (2005a) established that most of the > 35-m-thick unit is late Brigantian, with only the lower 7 metres of the formation assigned to the early Brigantian. The late Brigantian age was based on the FAD of *Janischewskina typica* and *Endothyranopsis sphaerica*, and thus, this interval can be correlated with the Five Yard Limestone in the early Serpukhovian (Figure 2). A remarkable first occurrence is that of *Calcifolium okense* (rare) and *Neoarchaediscus shugorensis*. These taxa in the upper part of the formation suggest a level equivalent to the basal level of the Steshevian, equivalent to the Three Yard Limestone in northern England (Figure 4) (similar to the upper beds of the Deer Park Formation in the Kingscourt outlier, 40 km to the south). Unfortunately, younger Mississippian strata are not preserved, as the top of the succession is eroded beneath Triassic rocks.

In the centre of Northern Ireland, in Cookstown, County Tyrone (Figure 1), the upper part of the Rockdale Limestone Formation contains the base of the late Brigantian (Mitchell & Somerville, 2011), and Brigantian-aged rocks are also present in the succeeding Rossmore Mudstone Formation (Figure 2), with ammonoids of the P_{2a} subzone in its lower part (Robbie, 1955). The upper part of the Rockdale Limestone Formation was studied in Cookstown Quarry and in the Ballytrea Borehole (Cózar et al., 2005a; Somerville, 1999; Somerville & Somerville, 1999). Although the borehole

contains very poor foraminiferal assemblages, the upper part of the quarry yields *Janischewskina typica* and *Biseriella parva*, as well as the conodonts *Lochriea nodosa* and *L. mononodosa*, which can be correlated with the early Serpukhovian. Older levels in the quarry also include *Neoarchaediscus gregorii*, *Neoarchaediscus postrugosus* form 1 and *Climacamina*, which can be correlated with the Single Post/Cockleshell limestone interval at the base of the Serpukhovian (Figure 4). A single occurrence of *Calcifolium okense* might suggest equivalence to the Five Yard Limestone Member (Cózar & Somerville, 2004), although its acme occurs from the Three Yard limestone upward (see above). Similarities with the top of the Carganamuck Limestone Formation, including also the first occurrence of *Biseriella parva*, suggest that the top part of the Rockdale Limestone is most probably equivalent also to the Three Yard Limestone Member (Figure 4). There is no biostratigraphic dating of the upper part of the Rossmore Mudstone Formation, but the succeeding Millstone Grit Group contains NC-TK miospore zones, equivalent to the E_{1b} to E_{2b} (Ramsbottom et al., 1978). Thus, the Rossmore Mudstone Formation is also considered to be of early Serpukhovian age, whereas the Millstone Grit Group extends from the upper part of the early Serpukhovian to most of the late Serpukhovian (Figure 2).

The Fintona Block in Kesh-Omagh is the only succession in Ireland which is exclusively composed of continental alluvial sediments (Mitchell & Owens, 1990). The NM and VF Miospore biozones were recorded from the Topped Mountain Sandstone, whereas most of the early Brigantian Ballyreagh Conglomerate Formation is not dated, and the NC biozone was recognized in the succeeding Ballinamallard Mudstone Formation, which extends upwards to the Pendleian (Mitchell & Somerville, 2011). This suggests that the base of the Serpukhovian lies within the Ballyreagh Conglomerate Formation, and the Ballinamallard Mudstone Formation represents the rest of the early Serpukhovian (Figure 2). The biostratigraphy in this region cannot be more precise, because of the generalized absence of fauna. In parallel, the Greenan Sandstone Formation was also dated as VF biozone, but from the lower part of the formation, and thus, its upper range is unknown, possibly ranging into the Serpukhovian. Mitchell and Owens (1990), and Sevastopulo (2009) considered that the upper part of the formation extended through the Pendleian.

On the north coast, in County Antrim ([Figure 1](#)), the Ballycastle Group is rather poorly studied, but contains the early Brigantian VF biozone in the lower levels, and ammonoids of the P_{2b} biozone from the upper part ([Mitchell, 2004](#); [Mitchell & Somerville, 2011](#)), which allow to infer the occurrence of the Serpukhovian in this group. Foraminiferal assemblages in the upper part of the group, from the Main Limestone Member ([Mitchell, 2004](#)), contain numerous *Asteroarchaediscus*, *Neoarchaediscus*, *Archaediscus*, *Planospirodiscus* and *Tubispirodiscus*. This assemblage typically occurring in the early Serpukhovian levels equivalent to the Tarusian, but samples near the top of the member also contain *Planospirodiscus taimyricus*, *P. minimus*, *Neoarchaediscus gregorii*, as well as *Eostaffellina* aff. *decurta* ([Figure 10](#)). This latter taxon suggests that the group reaches the lower part of the Steshevian, and the foraminiferal assemblage is typical of the Three Yard Limestone in northern England. This succession was interpreted by [Sevastopulo \(2009\)](#) as the Ballyvoy Sandstone Formation of [Mitchell \(2004\)](#), and of late Brigantian and Pendleian age. [Sevastopulo \(2009\)](#) based the lithological correlation on the so-called Main Coal with horizons also located nearly at the base of the Millstone Grit Group ([Wilson & Robbie, 1966](#)).

4 SUMMARY AND IMPLICATIONS

One of the main implications arising from this study, is that Serpukhovian rocks in Ireland are ‘not almost exclusively terrigenous, with rare limestones’, as claimed by previous authors (e.g., [Sevastopulo, 2009, p. 269](#)), but that they include the upper part of the thick platform limestones successions throughout much of Ireland, previously referred to as upper Viséan in age. It is agreed, though, that the change from carbonate to siliciclastic sedimentation was not synchronous, and not always coincident with the base of the Pendleian. It is evident from the foraminiferal data, that rocks of Serpukhovian age are present in County Carlow (Clogrenan Formation), County Clare (Slievenaglasha and Magowna formations), County Meath (Deer Park Formation), County Armagh (Carganamuck Limestone Formation) and County Tyrone (Rockdale Limestone Formation), in areas where there occurred continuous shallow-

water platform limestone sedimentation. In these thick limestone units (typically 50-100 m thick), Tarusian (and in some cases Steshevian) foraminiferal assemblages are recorded (Figure 4).

The assemblage in the lower part of the Clogrenan Formation (County Carlow) is characterised by the presence of primitive *Planospirodiscus* and *Neoarchaediscus gregorii*, followed immediately by *Neoarchaediscus postrugosus* form 1, which are considered representative of the Single Post Limestone and Cockleshell Limestone in the Alston Block in northern England (assemblage 6), equivalent to the latest Venevian age (Figure 4). The higher beds in the Clogrenan Formation, and in the Ballyelly Member of the Slievenaglasha Formation in the Burren, record *Neoarchaediscus gregorii*, *Neoarchaediscus postrugosus* form 2, *Planospirodiscus taimyricus*, “*Millerella tortula*” *Janischewskina typica* and *Endothyranopsis sphaerica*. These foraminiferal assemblages can be correlated with similar assemblages in the Scar-Five Yard limestones (Alston Block) in northern England (Cózar & Somerville, 2004, 2014, 2016, in press; Figures 2, 4) and possibly representing a late Tarusian age. Other successions in south central Ireland, such as the Liscarroll Limestone Formation and Dromkeen Limestone Formation, do not have any representatives of Serpukhovian foraminiferal assemblages, with the youngest taxa present being of late Viséan age.

In Northern Ireland within the Carganamuck Limestone Formation (County Armagh), although this succession has been eroded beneath the unconformity with the overlying Triassic strata, early Serpukhovian foraminiferal assemblages with *Janischewskina typica* and *Endothyranopsis sphaerica* are recorded from the lower beds. Furthermore, the rare presence of *Calcifolium okense* and *Neoarchaediscus shugorensis* establish that the highest beds are equivalent to the Three Yard Limestone in the Alston Block (Figure 4). The youngest beds of the Rockdale Limestone Formation (County Tyrone) contain *Janischewskina typica* and *Biseriella parva*, as well as rare *Calcifolium okense*, suggesting equivalence to the Five Yard Limestone Member, and the top of the formation equivalent to the Three Yard Limestone (Figure 4).

The youngest beds of the Deer Park Formation (County Meath) record *Archaediscus* at tenuis stage, *Eolasiodiscus*, *Brenckleina*, *Eosigmoilina*, *Cepekia cepeki*, *Eostaffellina*,

Neoarchaediscus shugorensis and abundant *Calcifolium okense*. This foraminiferal assemblage can be correlated with similar assemblages in the Three Yard Limestone (Alston Block) in northern England (Cózar & Somerville, 2004, 2014, 2016, in press; Figures 2, 4) of the upper part of the early Serpukhovian.

In County Clare the youngest beds of the Slievenaglasha Formation (Lissylisheen Member) have recorded late Steshevian foraminiferal assemblages, with the presence of *Archaediscus* at tenuis stage, *Cepekia cepeki*, *Eolasiodiscus*, *Eosigmoilina*, *Neoarchaediscus shugorensis* and *Tubispirodiscus simplissimus*. These beds can be correlated with the Four Fathom Limestone in northern England (Cózar & Somerville, 2004, 2014, 2016, in press; Figures 2, 4). In the thin overlying Magowna Formation, a similar assemblage is recorded, together with *Brownediscus?*, *Brenckleina* and *Eosigmoilina*, of late early Serpukhovian age, and correlated with the assemblage 10 in northern England (Great Limestone and Little limestones).

The most important foraminifers recorded from the Main Limestone in Ballycastle (County Antrim) are *Planospirodiscus taimyricus*, *Neoarchaediscus gregorii* and *Eostaffellina* aff. *decurta* which are of likely late early Serpukhovian age.

The shallow-water platform limestones of late Viséan-Serpukhovian age in Ireland have prolific foraminiferal faunas and record important evolutionary changes, especially within the archaediscid group. In several sections, notably the Clogrenan Formation, a succession of distinct evolutionary events can be recognised, with the FAD of *Neoarchaediscus gregorii*, followed by *Neoarchaediscus postrugosus* form 1, and *Neoarchaediscus postrugosus* form 2. In Russia *N. postrugosus* is currently used as the marker taxon to define the base of the Serpukhovian (Gibshman, 2003; Kulagina et al., 2011, Nikolaeva et al., in press). What is particularly unique about most of the upper Viséan-Serpukhovian successions in Ireland (except Cuilcagh Mountains and Ballycastle), is that they are represented by thick continuous limestone units, unlike most other coeval successions in northern Europe which are cyclothemic, with thin limestone beds alternating with thick clastic units, e.g. Moscow Basin, Urals, Ukraine, Poland, northern England and Scotland. Thus, in Ireland, evolutionary lineages can be

recorded, whereas in most other successions, only discrete foraminiferal events are preserved in the cyclothemic limestones.

Another major implication of the above faunal data concerns the palaeogeography. The recognition of Tarusian and in some cases Steshevian foraminiferal assemblages in the limestones, implies that many of the shallow-water platform areas in Ireland during the upper Viséan (Brigantian substage) persisted into the Early Serpukhovian.

5 CONCLUSIONS

One of the main conclusions arising from this study on Mississippian rocks in Ireland, is that limestone formations which were previously excluded from the Serpukhovian are now recognised, in part, on faunal grounds, as belonging to the lower two substages of the Serpukhovian. A reassessment of previous foraminiferal determinations, together with new foraminiferal data, has confirmed that rock equivalent to the Tarusian and Steshevian substages are present in several sections. In the Slievenaglasha Formation and Magowna Formation (County Clare) and Deer Park Formation (County Meath), Tarusian and Steshevian foraminiferal assemblages are recorded. In the Clogrenan Formation (County Carlow), Carganamuck Limestone Formation (County Armagh) and Rockdale Limestone Formation (County Tyrone), Tarusian foraminiferal assemblages are recorded in the upper beds of thick limestone successions. Key foraminiferal and algal taxa characterise each assemblage, which have been correlated with equivalent Serpukhovian strata in the north of England and Scotland. A three-stage evolution is recognised in archaediscid foraminifers: from *Neoarchaediscus gregorii*, followed by *Neoarchaediscus postrugosus* form 1, and *Neoarchaediscus postrugosus* form 2, with *Neoarchaediscus postrugosus* form 1, used to define the base of the Serpukhovian. The recognition of Tarusian and Steshevian foraminiferal assemblages, implies that areas of shallow-water platform carbonate sedimentation in Ireland during the upper Viséan (Brigantian) persisted into the Early Serpukhovian.

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STATEMENT OF CONFLICT OF INTEREST

The authors of the paper declare that there are no potential sources of conflict of interest.

ORCID

Pedro Cózar <https://orcid.org/0000-0002-4669-8702>

Ian Somerville <https://orcid.org/0000-0001-8379-9097>

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Figure Captions

Table 1 Location of selected stratigraphic sections mentioned in the text and illustrated material.

Figure 1 Map of Serpukhovian outcrops in Ireland with the location of the main Carboniferous basins and important sections mentioned in the text.

Figure 2 Lithostratigraphical correlation of Serpukhovian Irish rocks. Some highlighted members are in italics font. Horizontal striped bands correspond to hiatuses or absence of strata. Abbreviation Lissyl. = Lissylisheen.

Figure 3 Selected archaedisks from the unit 3 of the Clogrenan Formation (scale bar 100 microns). a-b, f, i sample Pc889, bed 15, Clogrenan Quarry; c-d, r-t sample Pc893, bed 20, Clogrenan Quarry; e, g-h sample Pc951, top of bed 1, Bannagogle Quarry; j-m, p-q sample Pc1383, bed 8, Guileen-1 Borehole; n bed 44 and o bed 53, Clogrenan Quarry (location of bed in [Cózar & Somerville, 2005](#)). [Thin-sections containing all the illustrated foraminifers in Figs. 3 to 9 are housed in the P. Cózar's palaeontological collection in the Geology Faculty, Universidad Complutense de Madrid, Spain]. (a-d) *Neoarchaediscus gregorii*. (e) *Neoarchaediscus gregorii acutiformis*? (f) *Planospirodiscus* aff. *minimus*. (g) *Planospirodiscus minimus*. (h-i) *Planospirodiscus* sp. (j-k) *Neoarchaediscus postrugosus* form 1. (l-m) *Neoarchaediscus postrugosus*? form 1. (n-o) *Neoarchaediscus postrugosus* form 2. (p) *Planospirodiscus* sp. (q) *Planospirodiscus taimyricus*, Pc1383. (r) *Planospirodiscus* aff. *taimyricus*. (s) *Tubispirodiscus* cf. *simplissimus*. (t) *Tubispirodiscus* sp. 1.

Figure 4 Diagram to show FAD of key foraminiferal and algal taxa in shallow-water platform limestone successions in Ireland containing Serpukhovian assemblages and their correlation with foraminiferal assemblages in northern England (Alston Block) (note that scale is half than that for the Irish sections) and the Russian substages (after [Cózar & Somerville, 2004, 2013, 2014, 2016](#)). Well-established correlations are in solid lines, and inferred position of the correlations are in dotted lines. Clogrenan Formation

is a composite section of the Clogrenan Quarry and Guileen-1 Borehole (after [Cózar & Somerville, 2005](#)); Slievenaglasha is a composite section of the Slievenaglasha and Clooncloose sections for the Balliny and Fahee North Member ([Gallagher et al., 2006](#)) Lisdoonvarna Quarry for the Ballyelly Member, Gowlaun River for the Lissylisheen Member, and Kilnamona section for the Magowna Formation; Deer Park Formation is a composite section of the Barley Hill Quarry, Deer Park South and Poulmore Scarp Quarry ([Somerville & Somerville, 1999](#); [Cózar et al., 2005a](#)); Carganamuck Limestone Formation is based on Carganamuck Quarry ([Cózar et al., 2005a](#)); Rockdale Limestone Formation is based on Cookstown Quarry ([Cózar et al., 2005a](#)); the Leitrim Group is a composite section of the Aghagrania River section (Meenymore Fm), Sruh Croppa River section (Bellavally and Carraun Shale formations, and Altvenagh River section (Sheena Shale Member) in County Fermanagh ([Cózar et al. 2006](#)). Lithological abbreviations: P.- Pendleian; Tu- Tullysheherny Member; Sr - Sraduffly Member; Lu - Lugasnaghta Shale Member; Sh - Sheena Shale Member; Co - Corry Member; De - Derreens Limestone Member; DT - Doagh Limestone and Tawnyunshinagh Limestone members; Ar - Ardvarney Limestone Member; Sn - Sranagross Member; Ca - Camderry Member. Foraminiferal abbreviations: At - *Archaediscus at tenuis* stage; Bp - *Biseriella parva*; Br - *Brenckleina*; Bw - *Brownediscus*; Cc - *Cepekia cepeki*; Co - *Calcifolium okense*; Cl - *Climacammina*; Ef - *Eostaffellina*; Eg - *Eosigmoilina*; Es - *Endothyranopsis sphaerica*; Jt - *Janischewskina typica*; Mt - "*Millerella*" *tortula*; Ng - *Neoarchaediscus gregorii*; Np1 - *Neoarchaediscus postrugosus* form 1; Np2 - *Neoarchaediscus postrugosus* form 2; Ns - *Neoarchaediscus shugorensis*; Pm - *Planospirodiscus minimus*; Pt - *Planospirodiscus taimyricus*; Pa - *Planospirodiscus* aff. *taimyricus*; Ta - *Tubispirodiscus attenuatus*; Ts - *Tubispirodiscus simplissimus*.

Figure 5 Selected foraminifers from the Ballyelly Member, Slievenaglasha Formation, Lisdoonvarna Quarry. Specimens b, c, f, 5 m below the top, specimens a, d, h, 4.7 m below the top, and specimen g at the top of the member (scale bar 100 microns). (a-b) *Neoarchaediscus parvus*. (c-d) *Asteroarchaediscus rugosus*. (e) *Neoarchaediscus postrugosus*? form 1 (oblique section). (f) *Neoarchaediscus postrugosus* form 1. (g) *Neoarchaediscus postrugosus* form 2. (h) *Tubispirodiscus* sp. (primitive form).

Figure 6 Selected foraminifers from the Lissylisheen Member Slievenaglasha Formation, Gowlaun river section (scale bar 100 microns). (a) *Neoarchaediscus shugorensis*. (b) *Neoarchaediscus postrugosus* form 2. (c) *Neoarchaediscus gregorii acutiformis*. (d) *Neoarchaediscus* sp. 1. (e-f) *Planospirodiscus* aff. *taimyricus*. (g-h) *Planospirodiscus taimyricus*. (i) *Tubispirodiscus* cf. *cornuspiroides* (juvenile). (j-k) *Tubispirodiscus* sp. 1. (l) *Tubispirodiscus simplissimus*. (m) *Tubispirodiscus* aff. *simplissimus*. (n) *Cepekia cepeki*. (o) *Eosigmoilina* cf. *robertsoni*.

Figure 7 Selected foraminifers from the Magowna Formation at Kilnamona section, a-g, bed 2; h-m, bed 3; n-aa, bed 4 of [Skompski et al. \(1995\)](#) (scale bar 100 microns). (a) *Tubispirodiscus* sp. 1. (b) *Tubispirodiscus simplissimus*. (c) *Neoarchaediscus postrugosus* form 1. (d) *Planospirodiscus* sp. 2. (e) *Planospirodiscus* sp. 3. (f) *Planospirodiscus minimus*. (g) *Neoarchaediscus shugorensis*. (h) *Tubispirodiscus simplissimus*. (i) *Brownediscus?* sp. 1. (j) *Neoarchaediscus gregorii acutiformis*. (k) *Asteroarchaediscus rugosus*. (l) *Planospirodiscus* sp. 1. (m) *Archaediscus* sp. with some final whorls at tenuis stage. (n) *Tubispirodiscus* sp. 1. (o) *Planospirodiscus* sp. 1. (p) *Brownediscus?* sp. 2. (q) *Planospirodiscus minimus*. (r) *Tubispirodiscus attenuatus*. (s) *Planospirodiscus* sp. 3. (t) *Neoarchaediscus?* sp. (u) *Planospirodiscus* sp. 4. (v) *Tubispirodiscus* sp. (w-x) *Brenckleina* cf. *rugosa*. (y-z) *Eosigmoilina?* sp. (aa) *Eosigmoilina robertsoni*.

Figure 8 Selected foraminifers from Poulmore Scarp Quarry (Deer Park Formation). (scale bar 100 microns). c, f at 3.1 m above the base of the quarry, j-k at 3.8 m, g, m, n at 6.8 m, h, l, o, at 7.4 m, a, d at 9.1 m, and b, e, i at 10.8 m above the base of the quarry. Sample number means metres above the base of this disused quarry. (a-b) *Planospirodiscus* aff. *taimyricus*. (c) *Neoarchaediscus postrugosus* form 2. (d-e) *Neoarchaediscus shugorensis*. (f) *Tubispirodiscus cornuspiroides?* (g) *Eosigmoilina robertsoni*. (h) *Brenckleina* sp. (i) *Brenckleina rugosa*. (j-l) *Archaediscus* sp. at tenuis stage. (m) *Eostaffellina* ex gr. *paraprotvae*. (n) *Eostaffellina* sp. (o) *Eostaffellina decurta*.

Figure 9 Selected archaediscids from Cuilcagh Mountains. a-h sample Pc2453, Tullysheherny Member of the Bellavally Formation (scale bar 100 microns). i-l sample Pc2467, Sheena Shale Member of the Bellavally Formation, m-n, p-q, t-u, sample

Pc2458 and o, r-s, sample Pc2459, Derreens Limestone Member of the Carraun Shale Formation (see location of samples in [Cózar et al., 2006](#)). (a) *Planospirodiscus* sp. (b-c) *Planospirodiscus* aff. *taimyricus*. (d-e) *Neoarchaediscus gregorii*. (f-h) *Neoarchaediscus postrugosus* form 2. (i) *Planospirodiscus minimus*. (j) *Neoarchaediscus postrugosus* form 2 (oblique section). (k-l) *Planospirodiscus taimyricus*. (m) *Neoarchaediscus postrugosus?* - note that flanks of the test are more similar to *Planospirodiscus*. (n-o) *Neoarchaediscus postrugosus* form 2. (p-q) *Tubispirodiscus attenuatus*. (r) *Neoarchaediscus shugorensis*. (s-t) Evolved form of *Tubispirodiscus* with 3-4 whorls at tenuis stage. (u) *Archaediscus* sp. at tenuis stage.

Figure 10 Selected foraminifers from the Main Limestone (Ballycastle Group), sample Pc2300 (scale bar 100 microns). (a) *Neoarchaediscus* aff. *postrugosus* form 2. (b) *Neoarchaediscus postrugosus* form 2. (c) *Planospirodiscus* cf. *taimyricus*. (d) *Planospirodiscus* sp. 1. (e) *Eostaffellina* aff. *decurta*.

Stratigraphic section	Lithological unit	Irish Grid coordinates
Aghagrania River	Meenymore Formation	[M 996 120]
Almush Stream	Almush Shale Member (Deer Park Fm)	[N 788 871]
Altvenagh River	Sheena Shale Member (Bellavally Fm)	[H 119 298]
Ballytrea Borehole	upper Rockdale Limestone Formation	[N 870 744]
Bannagogle Quarry	upper Clogrenan Formation	[S 661 645]
Barley Hill Quarry	lowermost Deer Park Formation	[N 827 965]
Carganamuck Quarry	Carganamuck Formation	[H 878 498]
Clogrenan Quarry	lower Clogrenan Formation	[S 688 720]
Clooncloose	lower Slievenaglasha Formation	[R 2835 9506]
Cookstown Quarry	upper Rockdale Limestone Formation	[H 801 748]
Deer Park South	Deer Park Formation	[N 823 962]
Dunamase Quarry	upper Clogrenan Formation	[S 542 993]
Gowlaun River (= St Brendan's Well)	Lissylisheen Member (Slievenaglasha Fm)	[R 1450 9840]
Guileen-1 Borehole	upper Clogrenan Formation	[S 572 915]
Kilnamona	Magowna Formation	[R27821 80339]
Lisdoonvarna Quarry (N67)	Ballyelly Member (Slievenaglasha Fm)	[R 1540 9950]
Magowna Waterfall	Magowna Formation	[12890 18220]
North Star Dyke at Ballycastle	Main Limestone (Ballycastle Group)	[D148 419]
Poulmore Scarp Quarry	uppermost Deer Park Formation	[N 823 959]
Pollasumera River	Meenymore Formation	[H 129 323]
Slievenaglasha	lower Slievenaglasha Formation	[R 3126 9835]
Sruh Croppa River	Tullyshehery Member (Bellavally Fm)	[H 104 317]
Sruh Croppa River	Derreens Limestone Member (Carraun Shale Fm)	[H 098 307]
Vigo Cave (W of Inchiquin Lough)	Lissylisheen Member (Slievenaglasha Fm)	[R 260 905]
Vigo Pothole	Lissylisheen Member (Slievenaglasha Fm)	[R260 907]

MISSISSIPPIAN (pars)													PENN.		
Viséan			Serpukhovian										Bashkirian		
Venevian		Tarusian	?	Steshevian			Protvian	?	Zapaltjubian			Voznesenskian			
early Brigantian			late Brigantian			Pendeian			Arnsbergian				H1a		
P1c	P1d	P2a	P2b	P2c	E1a	E1b	E1c	E2a	E2b	E2c	H1a				
VF			NC					TK		SO					
Jew	Cockleshell Single Post Tynebottom	Scar	Five Yard	Three Yard	Four Fathom	Great Iron Post	Little	Crag	Rookhope Shell	Lower Felltop	Coaldough	Upper Felltop	Botany/Grindstone		
													Whiddy Island (Bantry sub-basin)		
									?	Reenydonagan Fm <i>East Point</i>	Middle Battery Fm	Kilmore			
Lispatrick Fm				?	?	White Strand Fm							Kinsale sub-basin		
Liscarroll Limestone Fm		?											Buttevant		
Dromkeen Limestone Fm		?											East Limerick		
Clogrenan Fm										Leggacurren Shale Fm		Carlow/ Kilkenny			
Parsonage Fm	Corgrig Lodge Fm	Clare Shale Fm										Ballybunnion			
Parsonage Fm		Corgrig Lodge Fm					Clare Shale Fm						Foynes		
Slievenaglasha Fm					Magowna Fm					St Brendan's Well Phosphate Bed		Clare Shale Fm	Burren		
<i>Fahee North</i>		<i>Ballyelly</i>		<i>Lissyll</i>											
Loughshinny Fm				Donore Shale Fm		Bairickard	Walshestown Shale Fm						Dublin Basin		
		<i>Ballustree</i>	<i>4th Member</i>												
Deer Park Fm							Ardagh Shale Fm			Carricleck Shale Fm			Kingscourt/ Ardagh		
		<i>Almush Shale</i>													
			Tooromin Shale Fm		Craggagh Shale Fm								Slieve Carna		
Meenymore Fm		Glenade	Bellavally Fm		Carraun Shale Fm		Deryvone	Briscoonagh Fm		Gowlaun Shale Fm		Lackagh	Bencroy	NW Ireland	
Carganamuck Limestone Fm													Armagh		
Rockdale Limestone Fm			?	Rossmore Mudstone Fm		Millstone Grit Group								Cookstown	
Ballyreagh Conglomerate Fm			Ballinamallard Mudstone Fm												Fintona Block
Greenan Sandstone Fm			?											Fintona Block	
Ballycastle Group													Ballycastle		
hemipelagic outer shelf inner shelf peritidal, deltaic alluvial