# Comparisons of rugose corals from the Upper Visean of SW Spain and Ireland: implications for improved resolution in Late Mississippian coral biostratigraphy

Sergio RODRÍGUEZ[1], Ian D. SOMERVILLE[2]

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**Abstract:** Rugose corals have been used in biostratigraphic studies mainly for local zonations. Their utility as index fossils has been undervalued because of problems in identification and overemphasis on facies control on coral distribution. Problems of identification may be solved using only well-defined and well-known species and genera, and by using the species group concept. The Late Viséan transgression created extensive shallow-water carbonate shelves producing an abundance of corals and widespread distribution of the main taxa. For these reasons, the upper Viséan is a very good interval for comparing distribution of rugose coral assemblages from different regions and assessing their value as index fossils.

Approximately 35 species are considered important for coral biostratigraphy in the Upper Viséan in terms of their broad geographical distribution, their occurrence in shallow-water platform facies and their continuous distribution in the Upper Viséan. Their distribution in all regions within the western Palaeotethys subprovince is consistent, with only minor variation. The stratigraphical distribution of rugose coral species in Southwest Spain and Ireland shows similar patterns and is consistent with the distribution in most areas of Western Palaeotethys. Five coral assemblage zones can be recognised in Sierra Morena; zones 1 and 2 combined could be Early Asbian in age, zone 3 is Late Asbian and zones 4 and 5 combined are Brigantian. The Upper Viséan in Ireland comprises four coral zones, zone F is Early Asbian in age, zone G is Late Asbian and zones H and I are Brigantian.

**Key-words:** Ireland, Spain, Visean, Asbian, Brigantian, Rugosa, biostratigraphy

## Contents



[1] Departamento y U.E.I. de Paleontología, Facultad de Ciencias Geológicas e Instituto de Geología Económica, Ciudad Universitaria, 28040 Madrid, Spain, e-mail: sergrodr@geo.ucm.es

[2] UCD School of Geological Sciences, University College Dublin, Belfield, Dublin 4, Ireland, e-mail: ian.somerville@ucd.ie

## 1. INTRODUCTION

Biostratigraphic zonations using rugose corals in the Mississippian (Lower Carboniferous) are numerous, but almost always are considered to be of too local a scale, and hence not useful in long distance correlations. Some examples are that of VAUGHAN (1905) in

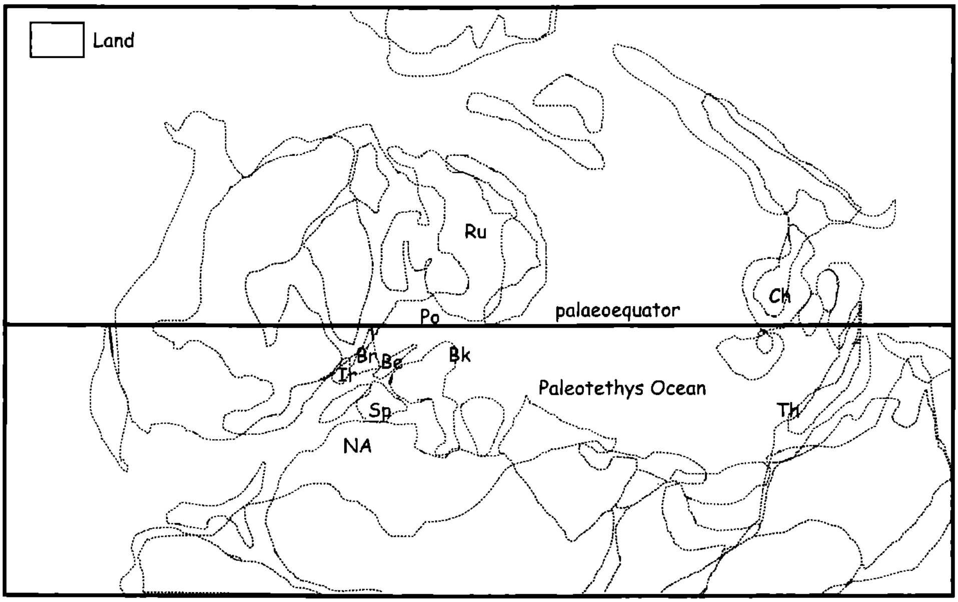


Fig. 1: Viséan palaeogeographic reconstruction with location of the cited areas. Sp = Spain, Ir = Ireland, Br = Britain, Be = Belgium, Bk = Balkans, PO = Poland, Ru = Russia + Ukraine, NA = North Africa, Th = South Asia (Thailand, Laos, Vietnam, Cambodia), Ch = China (Modified from SCOTESE, 2000).

Britain, Yu (1934) in China, Dobrolyubova (1958) in Russia, Vassilyuk (1975) in Ukraine, Sando (1977) in western USA, Kachanov (1979) in the Urals, Kato (1979) in Japan, Wu & Zhao (1984) in South China, Sando & Bamber (1985) in North America, Poty (1985, 1994) in Belgium, Mitchell (1989) in Britain, and Hecker (2001) in Moscow Basin, Donets Basin and Urals. A global zonation was proposed by Sando (1990), but its degree of precision is low.

The infrequent use of coral biostratigraphic zones is closely related to taxonomic problems. Most species have broad intraspecific variations and homeomorphism is common in corals. Additionally, distribution of corals is controlled by facies variations. Nevertheless, rugose corals are relatively abundant, they are easily sampled and their preparation for study is not complex. Problems of identification may be solved using only well-defined and well-known species and genera (Hecker, 2001), and by using the species group concept.

The primary aim of this paper is to compare the stratigraphic distribution of Upper Visean rugose corals in Southwest Spain and Ireland. Such a comparison may confirm the utility of corals for biostratigraphic studies and could form the basis for a coral biostratigraphic chart that may be useful in the Western Palaeotethys region. Consequently, we will focus our study and comparison in the best-known areas in this region, from Russia to North Africa and from Ireland to Ukraine (Donetz). In addition, this study could be also useful for some areas outside this geographical area, such as Thailand and

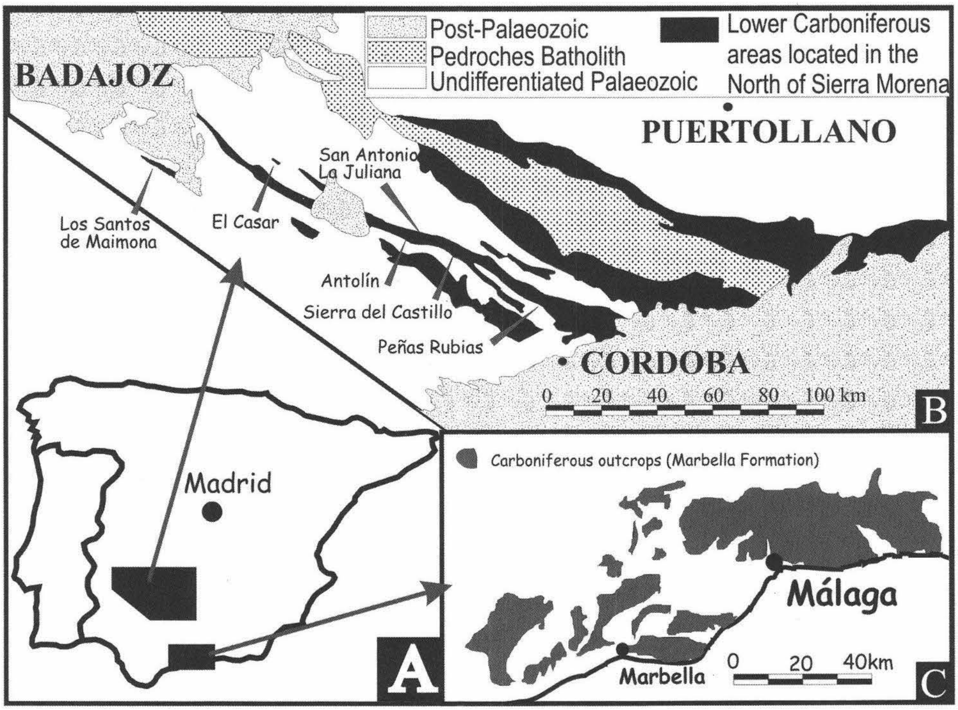


Fig. 2: Location of the main Carboniferous outcrops in SW Spain.

China (Eastern Palaeotethys), because of the close similarity of many taxa, which flourished in equatorial areas and were probably connected by seaways (Fig. 1).

One of the main reasons for the abundance and widespread distribution of Upper Viséan corals is the occurrence of a major transgression that created extensive shallow-water carbonate shelves and thus provided many new ecological niches. That implies also a good communication between basins (FEDOROWSKI, 1981; HECKER, 2001). An additional factor for the abundance of corals in the Western Palaeotethys region is its position in the equatorial belt during the late Mississippian. The Upper Visean (Asbian + Brigantian) was selected for this study because of the maximum abundance of corals in this interval, related to the major transgression.

## 2. DATA BASE

This study is based on distribution analysis of rugose corals collected in SW Spain (RODRÍGUEZ & FALCES, 1992, 1996; RODRÍGUEZ et al., 2001a,b, 2002; and unpublished data) (Figs. 2 and 3) and Ireland (STROGEN et al., 1995; GALLAGHER & SOMERVILLE, 1997; SOMERVILLE, 1997, 1999; and unpublished data; SOMERVILLE et al., 1992, 1996, 2001; ARETZ, 2002; COZAR & SOMERVILLE, 2005) (Figs. 4 and 5). The species considered to be important for

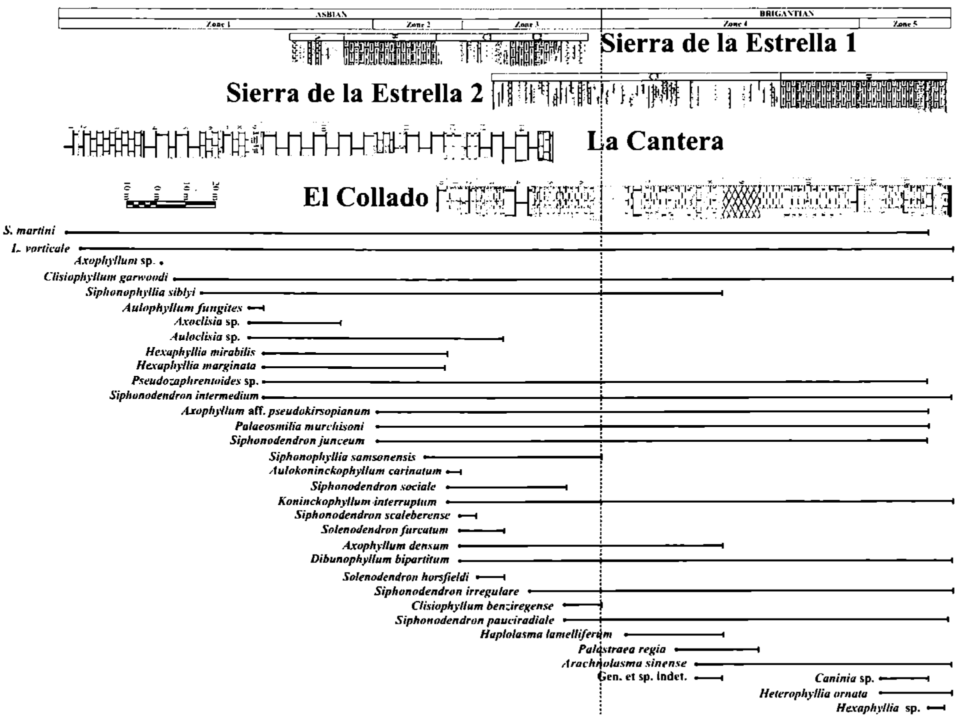


Fig. 3: Coral distribution in the Sierra del Castillo Block (Guadiato Area, SW Spain).

biostratigraphic purposes are included in Table 1. The ages of Upper Visean (Asbian to Brigantian) stratigraphic units containing corals were determined and corroborated independently using foraminifera (Cf6α-δ subzones of CONIL et al., 1990; JONES & SOMERVILLE, 1996; or zones 15–16 of MAMET, 1974; CÓZAR, 2003), and conodonts (*Lochriea commutata, Gnathodus bilineatus* and *Lochriea nodosa/mononodosa* zones of METCALFE, 1981; VARKER & SEVASTOPULO, 1985). Thus, the distribution of corals is well constrained in the successions.

Comparison was made with Upper Visean coral genera collected in other areas of Western Palaeotethys and adjacent regions (Table 2). The areas considered are: Belgium (POTY, 1981, 1983, 1985) including the Boulonnais in North France (POTY, 1994; POTY & HANNAY, 1994); Great Britain (MITCHELL, 1989; HILL, 1938–1940, SOMERVILLE & STRANK, 1984; JOHNSON & NUDDS, 1996); Poland (FEDOROWSKI, 1968, 1970, 1971; KHOA, 1977); Balkans (mostly Slovenia and Croatia) (KOSTIC-PODGORSKA, 1954, 1957, 1958, 1964) Russia + Ukraine (DOBROLYUBOVA, 1958; FOMITCHEV, 1953; VASSILJUK, 1960; HECKER, 2001) and

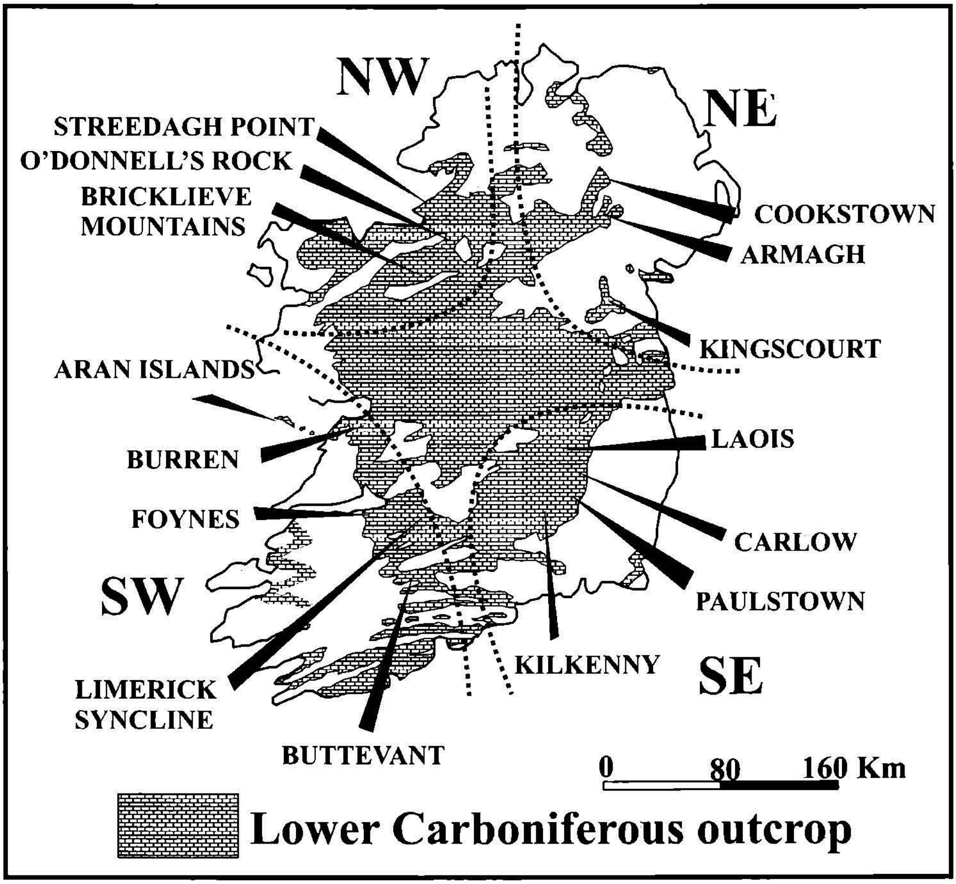


Fig. 4: Location of the main Lower Carboniferous outcrops in Ireland.

North Africa (Semenoff-Tian-Chansky, 1974; Termier & Termier, 1950; and unpublished data). Data provided by Fontaine (1961) and Fontaine et al. (1991) from Indochina (Laos and Vietnam) and data provided by Chi (1931), Yu (1933), Wu (1964), Yu et al. (1983), Wu & Zhao (1989) and Lin et al. (1995) from South China were also included for comparison with Eastern Palaeotethys.

Undissepimented mostly ahermatypic corals are not taken into account, because of difficulties with their taxonomy and the scarcity of descriptions in some areas. Tabulate corals and Heterocorallia have been studied and compared in Ireland and Spain, but they are not included in the general comparison because they were not described in some of the areas. Rugose corals from Ireland and Spain were considered to the species level. In some cases we applied a pragmatic approach, using species groups where two or more species are similar, have identical stratigraphic distribution and may be misidentified.

Emphasis is placed on genera in the general comparison, because species concepts are in some cases controversial. Some revision of published generic taxonomy was necessary to make the genera and species consistent with concepts endorsed by both authors of this paper. Usually, the generic concept proposed by Fedorowski (1981) in his compilation paper has been applied to specimens which have not been seen.

More than 50 species were analysed, but only 35 are considered important for coral biostratigraphy in the Upper Visean (Table 1). The criteria for selecting species were (1) their broad geographical distribution, (2) their occurrence in shallow-water platform facies and (3) their complete or almost complete distribution in the Upper Visean.

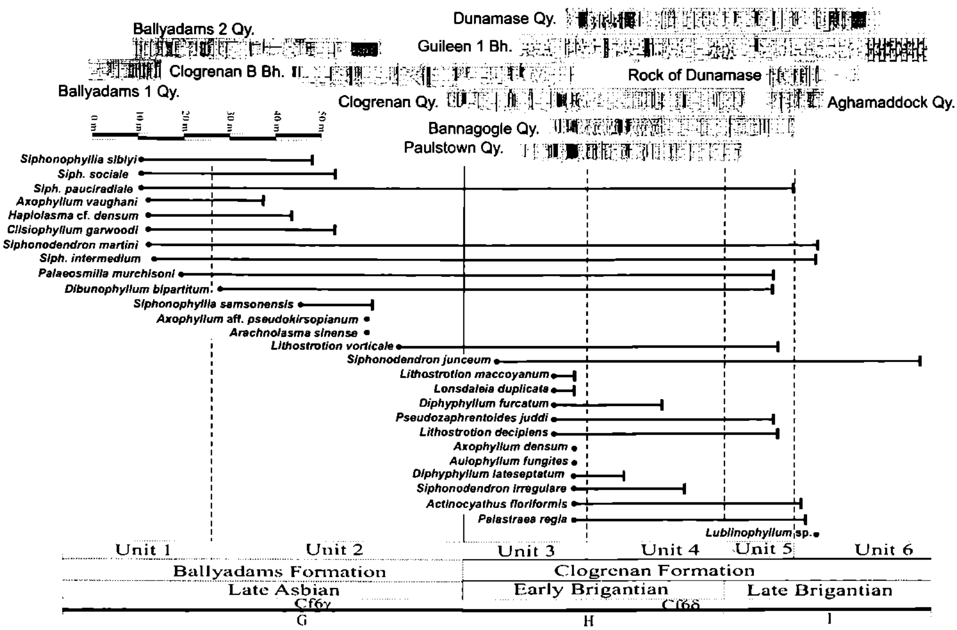


Fig. 5: Coral distribution in SE Ireland.

| Species | RCA | Stages | Sp | Ir | Br | Be | Bk | Po | RU | NA | Th | Ch |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Actinocyathus floriformis* | LC | B | X | X | X | X | | X | X | | X | X |
| *Arachnolasma cylindrica* | R | A | | | | | | X | X | X | X | X |
| *Arachnolasma sinense* | R | UAB | X | X | | | | X | X | X | X | X |
| *Aulokoninckophyllum carinatum* | R | UAB | X | X | X | | | | X | | X | X |
| *Aulophyllum fungites* | LC | AB | X | X | X | X | | X | X | X | | |
| *Axophyllum pseudokirsopianum* Group | LC | UAB | X | X | X | X | | X | X | X | X | X |
| *Axophyllum vaughani* Group | LC | HAB | X | X | X | X | | X | X | | X | X |
| *Clisiophyllum garwodi* | A | HAB | X | X | X | X | X | X | | X | | X |
| *Clisiophyllum keyserlingi* Group | R | UAB | X | X | X | X | X | X | X | X | | X |
| *Dibunophyllum bipartitum* | A | UAB | X | X | X | X | X | X | X | X | | X |
| *Diphyphyllum fasciculatum* | R | UAB | | X | X | X | | | X | X | X | |
| *Diphyphyllum furcatum* | RC | UAB | X | X | X | X | | X | X | X | | X |
| *Diphyphyllum lateseptatum* | R | UAB | | X | X | X | | X | X | X | | |
| *Gangamophyllum boreale* | R | UAB | X | | | X | X | | X | X | | X |
| *Haplolasma densum* Group | RC | UAB | X | X | X | X | | X | X | X | | X |
| *Kizilia concavitabulata* | R | B | X | | | X | | | X | | X | X |
| *Koninckophyllum interruptum* Group | LC | UAB | X | X | X | X | X | X | X | X | | X |
| *Lithostrotion araneum* | A | HA | X | X | X | X | | X | X | X | | |
| *Lithostrotion decipiens* | A | AB | X | X | X | X | | X | X | X | X | X |
| *Lithostrotion maccoyanum* | LC | UAB | | X | X | X | | X | | X | | X |
| *Lithostrotion vorticale* | A | HAB | X | X | X | X | | X | X | X | | X |
| *Lonsdaleia duplicata* | LC | B | X | X | X | X | | | X | | X | X |
| *Nemistium edmondsi* | R | BS | | | X | | | | X | | | |
| *Orionastraea* spp. | R | B | | X | X | | | X | X | | X | X |
| *Palaeosmilia murchisoni* | A | HAB | X | X | X | X | X | X | X | X | X | X |
| *Palastraea regia* | RC | B | X | X | X | X | | X | X | X | | X |
| *Pseudozaphrentoides juddi* | RC | UA | X | X | X | X | | X | X | X | | X |
| *Siphonodendron intermedium* | A | UAB | X | X | X | X | | X | X | X | | X |
| *Siphonodendron irregulare* | LC | UAB | X | X | X | X | | X | X | X | X | X |
| *Siphonodendron junceum* | A | AB | X | X | X | X | | X | X | X | X | |
| *Siphonodendron pauciradiale* | A | AB | X | X | X | X | | X | X | X | X | X |
| *Siphonodendron scaleberense* | LC | HA | X | X | X | X | | | | | | |
| *Siphonophyllia samsonensis* Group | A | AB | X | X | X | X | | | | X | | X |
| *Siphonophyllia siblyi* | RC | ALB | X | X | X | X | | X | | X | X | X |
| *Solenodendron furcatum* | LC | UAB | X | X | X | | | | | X | X | |

Tab. 1: Occurrence of species in selected areas during the Viséan.
**RCA** = Rare-Common-Abundant. R = rare (1–3 specimens in each area), RC = Relatively common (4–10 specimens in most areas), LC = Locally common (more than 10 specimens in individual horizons, but less than 4 specimens in most areas, C = Common (4–10 specimens in different levels of most areas), A = Abundant (more than 10 specimens in different levels of most areas).
**Stages** = Stratigraphical distribution in the Upper Visean. H = Holkerian, A = Asbian, UA = upper Asbian, B = Brigantian, LB = lower Brigantian, S = Serpukhovian.
**Countries** = **Sp** = Spain, **Ir** = Ireland, **Br** = Britain, **Be** = Belgium (plus Boulonnais), **Bk =** Balkans (Slovenia and Croatia), **Po** = Poland, **RU** = Russia + Ukraine, **NA** = North Africa, **Th =** South Asia (Thailand, Laos, Vietnam, Cambodia), **Ch** = China.

| Genera | SW Spain | Ireland | Britain | Belgium | Balkans | Poland | Russia | N Africa | Thailand | China |
|---|---|---|---|---|---|---|---|---|---|---|
| *Palaeosmilia* | • | • | • | • | • | • | • | • | • | • |
| *Palastraea* | • | • | • | • | • | • | • | • | | • |
| *Clisiophyllum* | • | • | • | • | • | • | • | • | | • |
| *Axoclisia* | • | • | | | | • | • | • | | |
| *Neoclisiophyllum* | • | • | | | | • | | | | • |
| *Carruthersella* | | | | | | • | | • | | |
| *Amygdalophyllum* | • | | | • | | • | • | • | | • |
| *Aulophyllum* | • | • | • | • | | • | • | • | | |
| *Auloclisia* | • | • | • | | | • | • | • | | •? |
| *Arachnolasma* | • | • | | | | • | • | • | • | • |
| *Haploplasma* | • | • | • | • | | • | • | • | | • |
| *Corwenia* | | • | • | | | • | • | • | | • |
| *Koninckophyllum* | • | • | • | • | | • | • | • | | • |
| Colonial *"Koninck."* | | • | | | | | • | | | |
| *Dibunophyllum* | • | • | • | • | • | • | • | • | | • |
| *Caninophyllum* | • | • | • | • | | | • | • | | • |
| *Siphonophyllia* | • | • | • | • | | • | • | • | • | • |
| *Kizilia* | • | | | • | | | • | | | • |
| *Pseudozaphrentoides* | • | • | • | • | | • | • | • | | • |
| *Solenodendron* | • | • | • | • | | • | • | • | • | |
| *Aulina* | | • | • | • | | | | • | | • |
| *Aulokoninckophyllum* | | • | | • | | • | • | • | • | • |
| *Orionastraea* | • | • | • | | | • | • | | | • |
| *Lithostrotion* | • | • | • | • | | • | • | • | • | • |
| *Siphonodendron* | • | • | • | • | | • | • | • | • | • |
| *Nemistium* | | | • | • | | | • | | | |
| *Diphyphyllum* | • | • | • | • | | • | • | • | • | • |
| *Actinocyathus* | •* | • | • | • | | • | • | | • | • |
| *Axophyllum* | • | • | • | • | • | • | • | • | • | • |
| *Pareynia* | | | | • | | | | • | | |
| Axophyllid gen. nov. | • | | | | | | | | | |
| *Gangamophyllum* | •* | | | • | • | • | • | • | | • |
| *Lonsdaleia* | •* | • | • | • | | • | • | | • | • |
| *Lublinophyllum* | | • | | | | • | | • | • | |

Tab. 2: Distribution of genera in selected areas during the Late Viséan. * Occurrence in boulders from Marbella Formation.

- *Palaeosmilia murchisoni* Milne-Edwards & Haime, 1848 – ubiquitous, long stratigraphical and wide geographical range; occurs mainly in massive pale grey limestones.
- *Palastraea regia* (Phillips, 1836) – typical indicator of Brigantian; same ecological preferences as *P. murchisoni*, from which it evolved.
- *Clisiophyllum keyserlingi* M'Coy, 1849 Group – *C. benzigerense* Semenoff-Tian-Chansky, 1974 (from North Africa) included here, because both species have similar features and identical stratigraphic range.
- *Clisiophyllum garwoodi* (Salée, 1913) – ubiquitous, long stratigraphical and wide geographical range; occurs mainly in massive pale grey limestones.
- *Axoclisia cuspiforma* Semenoff-Tian-Chansky, 1974 – present only in North Africa and Spain, rare in both areas; of low stratigraphical value in our opinion.
- *Amygdalophyllum* spp. – genus present in several countries, but identification is in some cases difficult; could be confused with some species of *Spirophyllum* present only in Poland; both genera discarded.
- *Aulophyllum fungites* (Fleming, 1828) – common in many areas, but usually restricted to muddy (soft bottom) environments.
- *Auloclisia mutata* Lewis, 1927 – described only in Spain, Britain and North Africa; also restricted to soft bottom environments.
- *Arachnolasma sinense* (Yabe & Hayasaka, 1920) – uncommon, but present in most areas; local absence may result from identification as juvenile *Dibunophyllum*.
- *Arachnolasma cylindricum* Yu, 1934 – scarce, present in few areas.
- *Haplolasma densum* (Lewis, 1930) Group – *H. lamelliferum* Semenoff-Tian-Chansky, 1974 is also included, species could be synonymous if unknown microstructure of holotype of *H. densum* is also lamellar; both species relatively common with same stratigraphical distribution.
- *Corwenia rugosa* (M'Coy, 1849) – only in some areas and always rare.
- *Koninckophyllum interruptum* (Thomson & Nicholson, 1876) Group – *K. magnificum* (Thomson & Nicholson, 1876) and *K. interruptum* considered together because of similar distribution and the presence of impersistent columella in both; occur usually in pale grey massive limestones.
- *Dibunophyllum bipartitum* (M'Coy, 1849) – abundant, widespread, and first occurrence typically in upper Asbian (muddy limestones).
- *Caninophyllum archiaci* (Milne-Edwards & Haime, 1852) – secondary importance, because not widespread and uncommon.
- *Siphonophyllia siblyi* Semenoff-Tian-Chansky, 1974 – very useful species because widespread, long-ranging and easily identified.
- *Siphonophyllia samsonensis* (Salée, 1913) Group – includes *S. benburbensis* (Lewis, 1927) (here regarded as junior synonym of *S. samsonensis*); same importance as *S. siblyi*.
- *Pseudozaphrentoides juddi* (Thomson, 1893) – same importance as species of *Siphonophyllia*.
- *Solenodendron furcatum* (Smith, 1925) – widespread and locally common; usually associated with *Siphonodendron*.
- *Aulokoninckophyllum carinatum* (Carruthers, 1909) – rare, geographically and stratigraphically restricted.

- *Orionastraea* spp. – same as *Aulokoninckophyllum*; no species selected because they are apparently restricted to particular areas, but possibly useful because of short stratigraphical ranges, especially in the Brigantian.
- *Lithostrotion* spp. – all species widespread, common or abundant; stratigraphical value varies because of wider or narrower stratigraphical distribution; smallest species *L. maccoyanum* MILNE-EDWARDS & HAIME, 1851, apparently most important because of shorter stratigraphical distribution, having evolved from larger species in the late Asbian; *L. araneum* (M'COY, 1844) and *L. vorticale* (PARKINSON, 1808) less important – also occur in the Holkerian.
- *Siphonodendron* spp. – same as *Lithostrotion*, even more abundant; *S. martini* not included in useful species because of much longer stratigraphical range; *S. irregulare* (PHILLIPS, 1836) sometimes difficult to distinguish from *S. pauciradiale* (M'COY, 1844) and, according to POTY (1983), not restricted to upper Asbian- Brigantian; *S. scaleberense* NUDDS & SOMERVILLE, 1987 also less important because of first occurrence in Holkerian (with acme in upper Asbian); smaller species *S. pauciradiale* and *S. junceum* (FLEMING, 1828) restricted to Asbian and Brigantian, evolved from larger species in early and late Asbian, respectively; *S. junceum* may have evolved in late Asbian from *S. pauciradiale.*
- *Nemistium edmondsi* SMITH, 1928 – very localized in Brigantian, small geographical distribution, identification difficult because of impersistent columella; nevertheless, used as index fossil in the Lower Carboniferous zonation of Russia (HECKER, 2001).
- *Diphyphyllum* spp. – all species have widespread geographical distribution and short stratigraphical range, but only *D. furcatum* HILL, 1940 common.
- *Actinocyathus floriformis* (MARTIN, 1809) – very important index species, restricted to the Brigantian; locally common.
- *Axophyllum vaughani* Group and *Axophyllum pseudokirsopianum* Group – *A. vaughani* Group includes species having well developed lonsdaleoid dissepiments and thin structures (*A. vaughani* (SALÉE, 1913), *A. lonsdaleiforme* (SALÉE, 1913), *A. expansum* MILNE-EDWARDS & HAIME, 1850); *A. pseudokirsopianum* Group includes species with thickened structures, scarce lonsdaleoid dissepiments and more or less twisted axial structure (*A. kirsopianum* (THOMSON, 1880), *A. pseudokirsopianum* SEMENOFF-TIAN-CHANSKY, 1974, *A. densum* (RYDER, 1930), *A. mendipense* (SIBLY, 1906)); both groups widespread, locally common, relatively easy to identify.
- *Gangamophyllum boreale* GORSKY, 1938 – relatively low value because rare, although stratigraphical range short;. absence in some areas may be related to difficulties in distinguishing it from *Axophyllum pseudokirsopianum* Group.
- *Lonsdaleia duplicata* (MARTIN, 1809) – very important index species for Brigantian; locally common.
- *Kizilia concavitabulata* DEGTJAREV, 1965 – of secondary importance because of restricted geographical distribution and scarcity.

Many other dissepimented rugosans have been analysed, but they were discarded because they have too long a stratigraphical range (*Bothrophyllum*), or they occur in only one or two geographical areas (*Melanophyllum*, *Lublinophyllum*, colonial *"Koninckophyllum"*) or occur mainly in deeper-water facies (*Rylstonia*).

## 3. BIOSTRATIGRAPHIC ZONATIONS IN SOUTHWEST SPAIN AND IRELAND

Descriptions of the stratigraphic distribution of corals in Ireland and southwest Spain follow. Successions of coral assemblages are consistent in both countries, but the distribution of species and genera differ in different areas for several reasons. Facies changes, migrations and local tectonic movements produce differences in the first occurrence of taxa in several areas. In addition, the sampling is not complete in many localities, so that the stratigraphic range or distribution of some taxa may well be extended in the future. In some areas the absence of carbonates in the sequences produce gaps in the distribution of some taxa.

The quality of data is highly variable. In Spain and Ireland most studied sections are located in disused quarries. In Ireland, some sections are located in large working quarries which continually expose new faces, so that the richness of coral faunas from sections can be further supplemented, others occur in boreholes which, although providing excellent continuous vertical sections, have no lateral expression. Although colonial corals are usually intersected in drillcore from boreholes, solitary corals may be missed or only oblique sections produced. In Spain, some sections are located in exposed outcrops that provide rare corals, but detailed search in some of them may also provide new finds. Additionally, many Visean outcrops in Sierra Morena are located in isolated blocks corresponding to olistoliths. Corals located in those blocks may be well preserved, but their precise stratigraphic position is sometimes uncertain.

Zonations are based on coral assemblages, in preference to individual ranges of species. Acmes have not been used for zonations because there are strong variations in different areas. They can be used only as a complementary datum. For instance, *S. junceum* has a clear acme in the Brigantian in SW Spain, Ireland, Belgium and Britain (associated with well-bedded dark grey argillaceous limestones). The high abundance of *S. junceum* may be used as an indicator of the Brigantian, but not with any greater precision.

### 3.1. Southwest Spain

The most complete succession of Upper Visean carbonate rocks in Southwest Spain is located in the Sierra del Castillo Unit (Guadiato Area; Fig. 3). Other outcrops in the Guadiato Area are discontinuous and measured sections reach less than 60 m. Some notable sections containing corals are located in the Antolín zone, south from Peñarroya, where debris flow masses are included in turbiditic successions.

On the other hand, other Visean limestones in the Guadiato area are located in olistolites within the younger San Antonio-La Juliana Unit. The latter is composed of siliciclastic and calcareous Serpukhovian rocks and Visean limestone blocks commonly containing corals.

Los Santos de Maimona Basin is an isolated Carboniferous area containing siliciclastic, volcanic and calcareous rocks more than 700 m thick. Corals are common in several calcareous units.

#### *3.1.1. Sierra del Castillo*

From a sedimentary point of view, two areas can be distinguished within the Sierra del Castillo Unit (structural block), shallow water sediments occur in the Sierra del Castillo

(La Cantera and El Collado sections) and deeper ramp facies occur in the Sierra de la Estrella (Sierra de la Estrella 1 and 2 sections). These sections were described and their age established with foraminifera by Cózar (1996, 1998, 2003). Conodonts are currently being studied by D.D. Bermúdez, whose preliminary results agree very closely with foraminiferal data. The distribution of corals in these sections is shown in Figure 3.

The lower part of the 130 m thick La Cantera quarry section in Sierra del Castillo Unit comprises crinoidal limestones with interbedded microbial limestones (units 1–5). They yielded a poor coral assemblage. *Siphonodendron martini*, *Lithostrotion vorticale*, *Clisiophyllum garwoodi* and *Axophyllum* sp. (undetermined species of the *A. vaughani* group) are scarce there. All species have a long stratigraphical range, with ranges beginning lower in the Visean in other regions. Thus, this assemblage does not provide much biostratigraphic information. The data provided by foraminifers and algae indicate that these rocks belong to the Asbian, but the data cannot be used precisely to ascertain if they are lower or upper Asbian.

There is a change to marls and marly limestones higher in the section (units 6–10). Corals are more common here and changes in the assemblage are noticeable. *Siphonophyllia siblyi*, *Aulophyllum fungites*, *Auloclisia* sp., *Axoclisia* sp. and the heterocorals *Hexaphyllia mirabilis* and *Heterophyllia marginata* are common there. This assemblage has a strong ecologic control, being typical for soft, muddy substrates. The first occurrence of all these corals is also lower than upper Asbian in other regions, so the complete assemblage of lower beds in the Sierra del Castillo (units 1–10 from the La Cantera section) seems to have survived from lower substages.

More important, however, is the first occurrence of *Axophyllum* aff. *pseudokirsopianum*, *Pseudozaphrentoides juddi* and *Siphonodendron junceum* in unit 11 of the La Cantera section, together with *Palaeosmilia murchisoni* and most species recorded in lower beds. The first three cited species have their first occurrence typically in upper Asbian in other regions, so the complete assemblage could be regarded as typical for upper Asbian.

The richest and most diverse assemblages from the Sierra del Castillo Unit occur in units 12–14 from La Cantera Section and in units 1–5 from El Collado Section. The first occurrences of *Siphonodendron sociale*, *S. scaleberense*, *S. irregulare*, *Solenodendron horsfieldi* (a taxon more typical of the lower Visean), *So. furcatum*, *Axophyllum densum*, *Dibunophyllum bipartitum*, *Koninckophyllum interruptum*, and *Siphonophyllia samsonensis* are recorded in these beds. Lithology is similar to that of units 10 and 11 from La Cantera section, so no ecological factors can be invoked to explain such a notable change in the coral assemblage.

Equivalent first appearances of several species (including some in common with El Castillo) occur in unit C1 from Sierra de la Estrella (Fig. 3): *Siphonodendron sociale*, *S. scaleberense*, *Aulokoninckophyllum carinatum*, *Dibunophyllum bipartitum* and *Palaeosmilia murchisoni*. In this case, the faunal change may be due to ecological factors, because the lithology changes strongly from massive microbial limestones to well-bedded marly limestones. However, the stratigraphical position is approximately the same as in the Sierra del Castillo Unit.

Coral assemblages become impoverished in units 6 and 7 of El Collado section. Some fasciculate species such as *Siphonodendron sociale*, *S. scaleberense*, *Solenodendron horsfieldi* and *So. furcatum* have their last occurrence in unit 5 and some solitary corals such as *Dibunophyllum bipartitum, Koninckophyllum interruptum* and *Pseudozaphrentoides* sp. are absent, but reappear above in units 12–14. This may be related to environmental factors, because common palaeokarst and rare stromatolites occur in units 5–8. Nevertheless, *Palastraea regia, Arachnolasma sinense, Haplolasma lamelliferum* and an endemic form (nov. gen.) first occur in the upper levels of unit 7 and units 8 and 9. This seems to coincide with the beginning of the Brigantian, because *Palastraea regia* is a good marker of this stage in many areas (Belgium, British Isles, Russia, etc; see SOMERVILLE, 1979; POTY, 1981; MITCHELL, 1989; JONES & SOMERVILLE, 1996; HECKER, 2001).

A similar occurrence of *Palastraea regia* in the upper part of unit C3 in Sierra de la Estrella (Fig. 3) also marks the base of the Brigantian for this unit. The assemblage is dominated by colonial rugosans (*Lithostrotion* and *Siphonodendron*) with peculiar features and contains scarce solitary rugosans identified as *Clisiophyllum garwoodi* and *Koninckophyllum interruptum*. Some specimens of *Palastraea* sp. and *Siphonodendron martini* are reworked and may have come from shallower water environments.

The upper beds (units 12–14) in Sierra del Castillo contain abundant and diverse rugose corals. No new species are recorded, but the acme of *Siphonodendron junceum* and *Lithostrotion vorticale* are located there. In addition, the heterocoral *Heterophyllia ornata* has its first occurrence in these beds.

From the distribution data given above, five coral assemblage zones were recognised in the Sierra del Castillo Unit and referred to as informal zones 1–5 (Fig. 6):

Zone 1 – The lowest zone of Sierra del Castillo is not clearly defined because most species recorded in units 1–10 of the La Cantera section and unit A from the Sierra de la Estrella section first occur in older rocks in other areas. So, the taxa recorded in this zone have long stratigraphical ranges, and their first occurrence corresponds to the lowest occurrence of suitable facies. This zone is characterised by the presence of *Siphonodendron martini, Lithostrotion vorticale, Clisiophyllum garwoodi, Siphonophyllia siblyi, Aulophyllum fungites, Auloclisia, Axoclisia*, and the heterocorals *Hexaphyllia mirabilis* and *Heterophyllia marginata*.

Zone 2 – characterised by the first occurrence of *Axophyllum* aff. *pseudokirsopianum, Siphonodendron junceum* and *Palaeosmilia murchisoni*. Most species recorded in zone 1 are also common in this zone. It comprises units 11 and 12 from La Cantera section and unit 1 from El Collado section. This zone is not identifiable in Sierra de la Estrella, because of the dominance of massive microbial limestones completely lacking dissepimented corals.

Zone 3 – base of zone characterised by the first occurrences of *Dibunophyllum bipartitum, Siphonodendron sociale, S. scaleberense* and *Solenodendron furcatum*. In this zone *Siphonodendron irregulare, Solenodendron horsfieldi, Siphonophyllia samsonensis, Koninckophyllum interruptum* and *Axophyllum densum* are also typically recorded. Some corals that are common in lower zones, such as *Clisiophyllum garwoodi* and *Palaeosmilia murchisoni*, are most abundant in zone 3. This zone corresponds to a maximum of coral abundance and diversity, which in other areas of Eurasia and Africa occurs in the Upper Asbian. It comprises units 13 and 14 from the Cantera section, units 2–6 of the El Collado section and unit C1 from the Sierra de la Estrella section.

Zone 4 – characterised by the first occurrence of the genus *Palastraea*; other corals recorded here include *Arachnolasma sinense* and *Haplolasma lamelliferum*. An en-

| Stages | | Foraminifers: Conil et al (1990) | Foraminifers: Mamet (1974) | Corals: England (Mitchell 1989) | | Corals: Belgium (Poty 1984) | | Corals: East Europe (Hecker 2001) | | SW Spain | | Ireland | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Brigantian | | | 16 sup | I | Orionastraea<br>Co. rugosa | | | | **Pa. regia**<br>**Ac. floriformis**<br>**Nemistium** | 5 | Acme S. junceum<br>L. vorticale<br>Ho. ornata | I | **Orionastraea rete**<br>Lublinophyllum<br>K. cf. volgense |
| | | δ | 16 inf | H | **Pa. regia**<br>**Ac. floriformis**<br>Di. lateseptatum<br>Lo. duplicata<br>Di. furcatum<br>etc. | 8 | Pa. regia<br>Ac. floriformis | VIII | Corwenia<br>Acme of many species | 4 | H. lamelliferum<br>**Pa. regia**<br>Ar. sinense<br>Gen. nov. | H | **Pa. regia**<br>**Co. rugosa**<br>**Ac. floriformis**<br>**Lo. duplicata**<br>Di. lateseptatum |
| Asbian | upper | Cf6 γ | 15 | G | **H. cf. densa**<br>So. furcatum<br>Di. fasciculatum<br>L. maccoyanum<br>**D. bipartitum** | 7 | Di. furcatum<br>S. junceum<br>S. pauciradiale | VII | D. bipartitum<br>Diphyphyllum<br>A. fungites<br>L. maccoyanum<br>S. pauciradiale<br>S. intermedium<br>S. junceum | 3 | **K. interruptum**<br>**D. bipartitum**<br>Sp. samsonensis<br>Ax. densum<br>**So. furcatum**<br>**S. irregulare**<br>S. sociale<br>S. scaleberense<br>S. pauciradiale | G | **D. bipartitum**<br>**H. cf. densum**<br>S. irregulare<br>**S. junceum**<br>**L. maccoyanum**<br>So. furcatum<br>Ax. aff. pseudokirsopianum<br>C. garwoodi<br>Ps. juddi |
| | lower | α–β | 15 | F | **D. bourtonense**<br>Ax. vaughani<br>Ps. juddi<br>**S. pauciradiale**<br>**S. junceum**<br>S. scaleberense<br>A. redesdalense<br>C. keyserlingi<br>Sp. benburbensis | 6 | L. araneum<br>S. martini | VI | **Acrocyathus**<br>**Dorlodotia**<br>Ca. archiaci<br>P. murchisoni<br>L. ex. gr. araneum<br>S. martini<br>Ps. juddi | 2<br>1 | **Ax. aff. pseudokirsopianum**<br>**S. junceum**<br>P. murchisoni<br>Sp. siblyi<br>Hx. mirabilis<br>Hx. marginata<br>Axoclisia<br>Auloclisia<br>A. fungites<br>S. martini<br>L. vorticale<br>C. garwoodi | F | Di. bourtonense<br>**S. pauciradiale**<br>S. martini<br>S. scaleberense<br>**L. decipiens**<br>**L. vorticale**<br>**So. furcatum**<br>**Sp. samsonensis**<br>Sp. siblyi<br>P. murchisoni<br>Ax. vaughani<br>Ca. archiaci |

Fig. 6: Comparative table with zonations in the main Carboniferous areas from Europe. A = *Aulophylllum*, Ac = *Actinocyathus*, Ar = *Arachnolasma*, Ax = *Axophyllum*, C = *Clisiophyllum*, Ca = *Caninia*, Co = *Corwenia*, D = *Dibunophyllum*, Di = *Diphyphyllum*, H = *Haplolasma*, Ho = *Heterophyllia*, Hx = *Hexaphyllia*, K = *Koninckophyllum*, L = *Lithostrotion*, Lo = *Lonsdaleia*, O = *Orionastraea*, P = *Palaeosmilia*, Pa = *Palastraea*, Ps = *Pseudozaphrentoides*, S = *Siphonodendron*, So = *Solenodendron*, Sp = *Siphonophyllia*. Species names in bold font are key zonal taxa.

demic genus, only recorded in the Sierra del Castillo Unit occurs in this zone. Some long-range species such as *Siphonodendron martini, S. irregulare, Siphonophyllia siblyi, Axophyllum* aff. *pseudokirsopianum, A. densum* and *Clisiophyllum garwoodi* are also recorded here. The zone comprises units 7–11 from the El Collado section and unit C3 of the Sierra de la Estrella section.

Zone 5 – characterised by the highest abundance of *Lithostrotion vorticale, Siphonodendron junceum* and *Koninckophyllum interruptum. Dibunophyllum bipartitum, Clisiophyllum garwoodi, Axophyllum* aff. *pseudokirsopianum* and *Heterophyllia ornata* are also common here.

### *3.1.2. Antolín*

The Sierra del Castillo Unit is represented in the Antolín area (Fig. 2) by turbiditic shales and sandstones with interbedded masses of carbonate debris containing abundant corals (RODRÍGUEZ et al., 2002). The limestone debris yielded rugose corals coming from different areas and probably of different ages (RODRÍGUEZ & RODRÍGUEZ-CURT, 2003). Thus, the biostratigraphic data from this locality are not precise. Nevertheless, these resedimented rocks represent a short geological time interval, because only foraminifers of Zone 15 (upper Asbian) of MAMET have been recorded (CÓZAR, 1998). These data are provisional because foraminiferal studies in this area involved few samples.

The common occurrence of *Axophyllum* aff. *pseudokirsopianum* in Antolín suggests correlation with zones 2–5 of Sierra del Castillo. The occurrence of *Siphonodendron sociale* indicates equivalence to zones 2 and 3. This assemblage is also dominated by lithostrotionids and axophyllids, as developed in zone 3 of Sierra del Castillo. Further comparisons are not possible, however, because the coral assemblage from Antolín is very unusual. Many species are not common in other areas. In fact, the most common species are those of *Siphonodendron* with thickened structures and very numerous septa at a diameter similar to that of *S. martini* and an endemic axophyllid.

#### *3.1.3. San Antonio-La Juliana Unit*

This structural unit is composed of Serpukhovian rocks containing limestone olistoliths from tens of metres to kilometres in size. These olistoliths contain Visean rugose corals, and some limestone beds reach up to 170 m. Nevertheless, no detailed biostratigraphy has been done in most of the olistoliths because of the discontinuous outcrops. Coral assemblages of most olistoliths are typically Upper Visean; they are dominated by *Siphonodendron martini*, *Axophyllum* aff. *pseudokirsopianum* and *Palaeosmilia murchisoni*. *Clisiophyllum garwoodi*, *Siphonophyllia siblyi*, and a primitive geyerophyllid are also common in the olistoliths. This assemblage (recorded in Adelfilla 1 Olistolith) can be related to the assemblage of zone 3 from the Sierra del Castillo.

At least two sections in olistoliths (Peñarroya 1 and Peñarroya 2; Fig. 2) show an unusual assemblage containing *Siphonodendron pauciradiale*, *Diphyphyllum gracile* HILL, 1940 and *Gangamophyllum boreale*. This assemblage well exposed in Peñarroya 2 could be related to the assemblage of zone 4 from Sierra del Castillo, because of the presence of *S. pauciradiale*, but the two other species have been not recorded elsewhere in Sierra Morena. The coral assemblage from autochthonous sediments differs largely from these and it is composed of *Melanophyllum*, endemic axophyllids and aulophyllids and small lithostrotionids. This assemblage is not yet completely studied.

#### *3.1.4. Los Santos de Maimona*

Los Santos de Maimona Basin (Fig. 2) contains more than 700 m of shales, limestones and volcanoclastic rocks. It is divided into 8 stratigraphic units numbered from 0 to 7 (RODRÍGUEZ et al., 1992, 1994). Dissepimented corals are common only in units 1, 3, 4, 5 and 6. Unit 1 is composed of coral biostromes (*Siphonodendron* limestones), containing an assemblage dominated by *Siphonodendron martini*. Also present are *Siphonodendron irregulare*, *Syringopora* sp., *Siphonophyllia samsonensis*, *Si. siblyi*, *Axophyllum vaughani*, *A. pseudokirsopianum*, *Clisiophyllum garwoodi*, *Caninia* sp., *Solenodendron horsfieldi* and *Corwenia? maimonensis* (RODRÍGUEZ & FALCES, 1992). This assemblage is similar to that in zone 3 of Sierra del Castillo, but is distinguished mainly by the absence of *Palaeosmilia murchisoni* and the large species of *Siphonodendron* (*S. scaleberense* and *S. sociale*).

Units 3 and 4 are contemporaneous; unit 3 represents shallow water environments (shallow platform and shoals) and unit 4 represents deeper water facies (calcareous turbidites), the contact between them being transitional. The coral assemblage is dominated by *Lithostrotion vorticale* and *L. araneum*; the first occurrences of *Siphonodendron sociale* and of *Diphyphyllum furcatum* are recorded. *S. sociale* is present only in zone 3 of the Sierra del Castillo and *D. furcatum* is absent there. Other components of the assemblage are *Siphonodendron martini, S. irregulare, Siphonophyllia siblyi* and *Axophyllum densum*. All of these taxa are also common in zone 3 of the Sierra del Castillo Unit. Consequently, we consider units 1 to 4 in Los Santos to be included in that zone.

Units 5 and 6 are mixed siliciclastic-carbonate turbidites containing very few dissepimented corals. The top of unit 5 contains *Lithostrotion decipiens* and unit 6 contains *Siphonodendron pauciradiale*. These two species are absent from the shallow water facies in Sierra del Castillo, but *S. pauciradiale* is common in the deeper water facies of Sierra de la Estrella, occurring only in the equivalent to zone 4. Thus, units 5 and 6 in Los Santos de Maimona may be equivalent to Zone 4 of the Sierra del Castillo area, but this is not conclusively established, because this correlation is based only on the occurrence of one species, which occurs stratigraphically lower in other areas of Europe (zone F of MITCHELL, 1989; Zone VII of HECKER, 2001, Zone RC7 of POTY, 1985).

### *3.1.5. Other areas in Sierra Morena*

Other outcrops in Sierra Morena have yielded rugose corals, but they are mainly isolated blocks or they have been not studied in detail:

El Casar (Fig. 2) is an isolated outcrop lying north of the Guadiato Area between major faults. It yielded an assemblage lacking colonial rugose corals, but having abundant specimens of *Axophyllum* aff. *pseudokirsopianum* and rare specimens of *Palaeosmilia murchisoni* and a primitive geyerophyllid. This outcrop seems to be equivalent in age to the assemblage of zone 3 in Sierra del Castillo.

Peñas Rubias is also an isolated block included in massive limestone debris located in the southeastern extension of the Guadiato area (Fig. 2). It comprises more than 25 m of limestones and marls containing very abundant rugose corals, mainly *Siphonodendron martini* and *Solenodendron furcatum*, but also some specimens of *Dibunophyllum bipartitum, Clisiophyllum garwoodi*, etc. This outcrop is not yet completely studied, but the assemblage is very similar to that in zone 3 of Sierra del Castillo.

### *3.1.6. Betic Cordillera (Southeast Spain)*

Coral assemblages from the Marbella Formation in Malaga Province (Fig. 2) have been described by HERBIG (1984, 1986). They occur in olistolites and limestone boulders of Asbian and Brigantian age. The complete assemblage is: *Kizilia concavitabulata, Clisiophyllum garwoodi, Dibunophyllum bipartitum, Koninckophyllum interruptum, Palae-*

*osmilia murchisoni, Pseudozaphrentoides juddi, Siphonodendron "irregulare", S. pauciradiale, Axophyllum densum, A. latevesiculosum, A.* aff. *pseudokirsopianum, A.* sp., *Actinocyathus floriformis crassiconus, Actinocyathus* sp., *Gangamophyllum boreale, Lonsdaleia corbariensis, Heterophyllia* aff. *ornata and Hexaphyllia mirabilis.* In terms of the Sierra del Castillo zonation, this assemblage comprises many species in common with zone 3 (*K. interruptum, D. bipartitum, A. densum, S. irregulare*), but also species typical of zone 1 (*Hexaphyllia mirabilis*) and typical of zone 5 (*Heterophyllia ornata*). Therefore, the stratigraphical distribution of these boulders and olistolites seems to encompass at least the entire interval represented in Sierra del Castillo. In addition, there are some species typical of higher levels in the Brigantian and Serpukhovian, such as *A. floriformis crassiconus* and *L. corbariensis*, indicating the presence of younger rocks in the recorded interval.

On the other hand, some species are absent from the assemblage, such as the most common species in the Visean, *Siphonodendron martini*. We have no explanation for its absence at present. Other important genera not represented are *Siphonophyllia, Solenodendron* and *Diphyphyllum*.

## 3.2. Ireland

The rugose coral faunas from the Upper Visean rocks of Ireland are described under four separate geographical regions: SE, SW, NW and NE Ireland (Fig. 4).

### *3.2.1. Southeast Ireland*

Recent investigations in SE Ireland have documented rich Upper Visean rugose coral assemblages from the Ballyadams (Asbian) and Clogrenan (Brigantian) formations in quarries and boreholes from the Carlow–Kilkenny district (Figs. 4 and 5; Cózar & Somerville, 2005). In the Ballyadams Quarry, Co. Laois, 70 m of upper Asbian shelf limestones are exposed showing palaeokarstic surfaces and palaeosols which have been assigned to units 1 and 2 (Cózar & Somerville, 2005). In unit 1 (lower bench) are recorded *Siphonodendron sociale, S. pauciradiale, S. martini, Siphonophyllia siblyi* and *Axophyllum* sp. This assemblage is joined by *Siphonodendron intermedium* and *Palaeosmilia murchisoni* in the lower part of the middle bench. In unit 2 (upper part of middle bench and all of the top bench) several solitary corals occur in addition to the colonial *Siphonodendron* species. These include *Axophyllum vaughani, Clisiophyllum garwoodi, Haplolasma* cf. *densum, Siphonophyllia samsonensis* (= *S. benburbensis*) and *Dibunophyllum bipartitum.* The latter species is abundant in the uppermost beds of the quarry along with *Axophyllum* aff. *pseudokirsopianum* and *Arachnolasma sinense* -assemblage zone G of Mitchell (1989) and Jones & Somerville (1996) and Rugose Coral subzone RC7β of Poty (1985) and Poty (in Conil et al., 1990).

In Clogrenan Quarry the top of the Ballyadams Formation and the contact with the overlying Clogrenan Formation is exposed. *Lithostrotion vorticale* is recorded at the top of the Ballyadams Formation. The same species is present in the lower beds of the Clogrenan Formation (unit 3) together with *Siphonodendron pauciradiale* and *S. junceum.* These species form biostromes at the top of unit 3 in Clogrenan, Bannagogle and Paulstown quarries in the Carlow area (Somerville et al., 2007). They all record rich and diverse Brigantian assemblages. These include *Diphyphyllum furcatum, Dibunophyllum bipartitum, Pseudozaphrentoides juddi* (Clogrenan Quarry), *Lithostrotion maccoyanum* and *Actinocyathus floriformis* (Bannagogle Quarry), and *Lonsdaleia duplicata, Lithostrotion decipiens, Aulophyllum fungites* and *Siphonodendron irregulare* (Paulstown Quarry). The same rich assemblage has been recovered from a biostrome at the base of Dunamase Quarry with most of the taxa present, with the addition of *Palastraea regia, Axophyllum densum* and *Siphonodendron intermedium* – assemblage zone H of Mitchell (1989) and Jones & Somerville (1996) and Rugose Coral Zone RC8 of Poty (1985) and Poty (in Conil et al., 1990).

*Palastraea regia* is present in unit 4 in Clogrenan Quarry together with *Actinocyathus floriformis, D. lateseptatum, Siphonodendron martini* and *Lithostrotion decipiens.* The fauna recovered from unit 5 in Dunamase Quarry contains *D. bipartitum, S. junceum, Pseudozaphrentoides juddi*, and in the Rock of Dunamase, silicified colonies of *A. floriformis, L. decipiens* and *L. vorticale* are conspicuous. The youngest Brigantian rocks (unit 6) occur at the Rock of Dunamase and in the top bench of Dunamase Quarry. In the former locality silicified colonies of *S. junceum* and *A. floriformis* are common and *Lublinophyllum* is rare. The latter colonial genus, which is new to Ireland, is recorded only at the top of the scarp, below the castle ruins. Also at Black Castle quarry, NW of Kilkenny (Fig. 4), the uppermost beds of the Clogrenan Formation contain *Orionastraea rete* (Nudds, 1979), which probably indicates a later early Brigantian to late Brigantian age -zones I-K of Mitchell (1989) and Jones & Somerville (1996).

### *3.2.2. Southwest Ireland*

In the Limerick Syncline (Fig. 4), Upper Visean coral assemblages have been documented from the Herbertstown Limestone and Dromkeen Limestone formations (Somerville et al., 1992). *Lithostrotion decipiens* and *Siphonodendron scaleberense* are both recorded in the upper part of the Herbertstown Limestone Formation (of early Asbian age). Beds lower in the formation yielded a Holkerian fauna including *Siphonodendron sociale, S. martini* and *Lithostrotion vorticale.* In the overlying Dromkeen Limestone Formation a more diverse rugose coral assemblage of late Asbian age has been recorded: *Dibunophyllum bipartitum, Palaeosmilia murchisoni, Siphonodendron pauciradiale, S. sociale, S. martini, S. intermedium, Axophyllum vaughani, Haplolasma* cf. *densum* and *Pseudozaphrentoides juddi.* An upper faunal band in the formation yielded the first occurrence of *Siphonodendron junceum, S. irregulare* and *Diphyphyllum lateseptatum.* The coral assemblages from the two formations are equated with the RC 6 and 7α–β Zones, respectively, of Poty (1985, in Conil et al. 1990), and assemblage zones E-G of Mitchell (1989) and Jones & Somerville (1996).

In the Foynes section (Fig. 4) and in the Foynes Borehole 97/147 early Asbian corals have been recorded from the Durnish Formation including: *Caninia cornucopia, Caninophyllum archiaci, Clisiophyllum garwoodi, Palaeosmilia murchisoni, Siphonodendron martini, S. sociale, Siphonophyllia benburbensis (= S. samsonensis), Solenodendron furcatum* (Shephard-Thorn, 1963; Sleeman & Pracht, 1999; Somerville, unpublished data). The overlying Shanagolden Formation has sparse *S. samsonensis*, but the presence of the zonal conodont *Gnathodus bilineatus* and foraminifera in the upper part of the formation establishes a late Asbian age (Sleeman & Pracht, 1999).

In the Burren, Co. Clare and the offshore Aran Island of Inishmore, western Ireland (Fig. 4), Upper Visean rocks are represented by the Burren and Slievenaglasha Formations (Gallagher, 1992; Gallagher & Somerville, 1997; Pracht et al., 2004). An early Asbian coral assemblage is identified in the lower part of the Burren Formation with *Lithostrotion araneum, Siphonodendron pauciradiale, Siphonophyllia samsonensis* and *Solenodendron furcatum* (Gallagher, 1992). A rich late Asbian rugose coral assemblage has been recorded from near the top of the cyclic member (upper part of the Burren Formation) on Inishmore island (Somerville, 1999), in which palaeokarsts and palaeosols are well developed. Taxa recovered include: *Lithostrotion araneum, L. vorticale, Palaeosmilia murchisoni Siphonodendron junceum, S. pauciradiale* and, at the very top of the formation, *L. maccoyanum* (Somerville, 1999; Pracht et al., 2004). Corals are rare in the Slievenaglasha Formation with occasional colonies of *Siphonodendron martini* and the solitary species *Dibunophyllum bipartitum*, but rare silicified colonies of the diagnostic Brigantian species *Actinocyathus floriformis* and *Palastraea regia* have been recorded (Somerville, 1999; Pracht et al., 2004). The coral assemblages from the two formations are equated with the RC 7β and 8 Zones, respectively, of Poty (1985; in Conil et al., 1990), and assemblage zones G and H of Mitchell (1989) and Jones & Somerville (1996).

In the Ballyclogh-Buttevant area, north Co. Cork, southern Ireland (Fig. 4), Upper Visean rocks are represented by the Ballyclogh and Liscarrol Limestone formations (Gallagher, 1992; Gallagher & Somerville, 1997). Asbian coral taxa recorded from the Ballyclogh Limestone Formation include: *Lithostrotion vorticale, L. decipiens, L. maccoyanum, Siphonodendron junceum, S. pauciradiale, S. intermedium, S. martini* and the solitary corals *Axophyllum vaughani, Dibunophyllum bipartitum,* and *Clisiophyllum garwoodi* (Gallagher, 1992; Gallagher & Somerville, 1997). Brigantian coral taxa recorded from the Liscarrol Limestone Formation include: *Actinocyathus floriformis, Diphyphyllum lateseptatum, Lithostrotion decipiens, Lonsdaleia duplicata, Siphonodendron irregulare, S. junceum, S. pauciradiale, S. sociale* and the solitary corals *Dibunophyllum bipartitum,* and *Palaeosmilia murchisoni* (Gallagher, 1992; Gallagher & Somerville, 1997).

### *3.2.3. Northwest Ireland*

In Counties Sligo and Roscommon, north and south of the Curlew Mountains (Fig. 4), Upper Visean rocks rich in rugose corals have been assigned to the Bricklieve Limestone Formation (Caldwell, 1959; MacDermot et al., 1996; Morris et al., 2003). *Siphonodendron* biostromes are laterally extensive in this formation and have been used as marker horizons throughout the Bricklieve Mountains (Caldwell, 1959; Caldwell & Charlesworth, 1962; Dixon, 1972). The lower biostrome ("*pauciradiale* reef"), 30–50 m thick, is dominated by *Siphonodendron pauciradiale* with, in addition, *Lithostrotion decipiens, Haplolasma* cf. *densum, Solenodendron furcatum, Siphonophyllia samsonensis* and *S. siblyi* (Caldwell & Charlesworth, 1962; Dixon, 1972; Aretz, 2002; Cozar et al., 2005a). The middle biostrome ("*martini* reef"), 40–60 m thick, although dominated by *Siphonodendron martini*, is more diverse in the number of species recorded. They include *S.*

*pauciradiale, S. scaleberense, S. sociale, Axophyllum* cf. *pseudokirsopianum, Caninophyllum archiaci, Clisiophyllum* sp., *Haplolasma* cf. *densum, Palaeosmilia murchisoni* and *Siphonophyllia siblyi* (CALDWELL & CHARLESWORTH, 1962; DIXON, 1972; ARETZ, 2002; COZAR et al., 2005a). Much higher in the succession are several thin (1 metre thick) biostromal developments of *Siphonodendron junceum* together with *Pseudozaphrentoides juddi* and *Lithostrotion maccoyanum* of late Asbian (Cf6γ subzone) age (COZAR et al., 2005a). Also from the equivalent-aged Glencar Limestone Formation at O'Donnell's rock, Co. Leitrim (Fig. 4) has been recorded *Solenodendron furcatum* (DIXON, 1972; ARETZ, 2002; COZAR et al., 2005a). At Streedagh Point, Co. Sligo within the Glencar Limestone Formation are recorded very abundant *Siphonophyllia samsonensis*, with rare *Lithostrotion decipiens* and *Siphonodendron paucidradiale* (COZAR et al., 2005a). The coral assemblages recorded from both formations are equated with the RC7 α and β zones of POTY (1985; in CONIL et al., 1990), and assemblage zones F and G of MITCHELL (1989) and JONES & SOMERVILLE (1996).

### *3.2.4. Northeast Ireland*

In Cookstown Quarry, Co. Tyrone (Fig. 4), a 140 m-thick section in Upper Viséan limestones and sandstones (Rockdale Limestone Formation) is confirmed as Early Asbian-Brigantian in age (SOMERVILLE, 1999). Colonial rugose corals are abundant in the lower beds (0–30 m) including: *Lithostrotion vorticale, L. araneum, Siphonodendron sociale, S. pauciradiale, S. intermedium, S. martini* and the solitary corals *Axophyllum vaughani, Caninophyllum archiaci* and *Clisiophyllum keyserlingi*. This assemblage is characteristic of the early Asbian (Rugose Coral zone F of MITCHELL, 1989; JONES & SOMERVILLE, 1996). Colonial corals are rare in the rest of the Asbian section, with only the solitary coral *Palaeosmilia murchisoni* present. A well-bedded grey limestone and shale unit (101–109 m above the base) has yielded abundant solitary corals including *Dibunophyllum bipartitum, Aulophyllum fungites,* and *Siphonophyllia samsonensis,* together with *Siphonodendron junceum*. This combined assemblage is of late Asbian to early Brigantian age (Rugose Coral zone G of MITCHELL, 1989; JONES & SOMERVILLE, 1996). Both cerioid and fasciculate corals are present between 110–113 m, with *Lithostrotion decipiens, L. maccoyanum, Siphonodendron junceum* and *S. irregulare*. The youngest beds (3 m below the top of the section) contain a rich coral fauna including: *Lonsdaleia duplicata, Diphyphyllum lateseptatum, Koninckophyllum magnificum* and *K. interruptum*. This assemblage is diagnostic of the Brigantian (Rugose Coral zone H of MITCHELL, 1989; JONES & SOMERVILLE, 1996).

In the Wilson's Bridge borehole WB3 and in nearby quarries in Co. Armagh (Fig. 4), Upper Visean rocks are represented by the Wilson's Bridge, Loughgall and Carganamuck Limestone formations (SOMERVILLE et al., 2001). The basal beds of Wilson's Bridge Limestone Formation are sandy and poor in corals with rare *Siphonodendron martini* and *Axophyllum* sp., but higher in the formation abundant colonial corals occur. These include *Lithostrotion decipiens, L. vorticale* and *Siphonodendron sociale*. Rare solitary corals recorded are *Haplolasma* cf. *densum* and *Pseudozaphrentoides juddi*. This assemblage indicates a late Asbian age for the Wilson's Bridge Limestone Formation (see JONES & SOMERVILLE, 1996). Similar late Asbian coral assemblages have been recorded at Kingscourt (STROGEN et al., 1995; SOMERVILLE, 1997), Limerick (SOMERVILLE et al., 1992) and north Co. Cork (GALLAGHER & SOMERVILLE, 1997). The type section for the Carganamuck Limestone Formation is in Cargananmuck Quarry. The limestones in the formation yield early Brigantian corals *Actinocyathus floriformis, Aulophyllum fungites, Dibunophyllum bipartitum, Diphyphyllum lateseptatum, Palastraea regia, Pseudozaphrentoides juddi, Siphonodendron junceum* and *S. pauciradiale* (SOMERVILLE et al., 2001; CÓZAR et al., 2005b).

In the Kingscourt area, Co. Meath (Fig. 4), a rich collection of Upper Viséan colonial and solitary rugose corals has been obtained from the Mullaghfin Formation in Mokeeran Quarry (STROGEN et al., 1995; SOMERVILLE, 1997). They include the colonial species: *Lithostrotion araneum, L. decipiens, L. vorticale, Siphonodendron intermedium, S. martini, S. pauciradiale, S. scaleberense* and several species of solitary corals *Axophyllum* sp., *Dibunophyllum bipartitum, Siphonophyllia samsonensis* and *Pseudozaphrentoides juddi*. This assemblage is typical of the late Asbian Rugose Coral zone G (MITCHELL, 1989; JONES & SOMERVILLE, 1996). In Bridge Farm Quarry, and Brittas Demesne quarry, Co. Meath, sections close to the top of the Mullaghfin Formation yielded in addition to *Siphonodendron martini, S. pauciradiale, Palaeosmilia murchisoni, Lithostrotion araneum* and *Axophyllum* sp. also, *Dibunophyllum bipartitum* and *Siphonodendron junceum* (STROGEN et al., 1995; SOMERVILLE, 1997, 1999). In the mud-mound facies in Ardagh Quarry, near Kingscourt, late Asbian taxa recorded in the lower part include the solitary corals *Axophyllum vaughani, Dibunophyllum bipartitum* and *Siphonophyllia siblyi* with occasional *Siphonodendron* and *Lithostrotion*. However, in the upper part of the mud-mound, fasciculate corals can be locally abundant: *Siphonodendron martini, S. sociale, Corwenia rugosa,* and *'Koninckophyllum'* cf. *volgense* (DOBROLYUBOVA, 1958) forming large *in situ* colonies, together with *Koninckophyllum magnificum* and *K. interruptum* (SOMERVILLE et al., 1996; SOMERVILLE, 1997). This assemblage is typical of the Brigantian Rugose Coral zone H (MITCHELL, 1989; JONES & SOMERVILLE, 1996). In Rathgillen Quarry, Co. Meath, basinal limestones of the Loughshinny Formation have yielded a Brigantian coral assemblage including *Actinocyathus floriformis* and *Dibunophyllum bipartitum* (STROGEN et al. 1995; SOMERVILLE, 1997).

A Dinantian rugose coral zonation for Ireland was proposed by JONES & SOMERVILLE (1996). It is based on the zonation of MITCHELL (1989) and is here slightly modified (Fig. 6). The Upper Visean comprises zones F-K. Zone F is identified by the first occurrence of *Siphonodendron pauciradiale, Solenodendron furcatum* and *Dibunophyllum bourtonense.* Zone G is identified by the first occurrence of *Dibunophyllum bipartitum, Haplolasma* cf. *densum* and *Siphonodendron junceum.* In addition, the data presented above show that this zone also contains the first occurrence of *Siphonodendron irregulare, Lithostrotion maccoyanum, Pseudozaphrentoides juddi* and *Axophyllum* cf. *pseudokirsopianum.* Zone H is identified by the first occurrence of *Actinocyathus floriformis, Corwenia rugosa, Palastraea regia,* and *Lonsdaleia duplicata.* The endemic species *Koninckophyllum?* cf. *volgense* is also typical in this zone. Upper zones are not easy to identify in Ireland. The index species from Mitchell in Britain do not occur or appear together with index species of zone H. The uppermost Brigantian beds in Ireland are characterised by the occurrence of *Siphonodendron junceum, Orionastraea rete* and *Lublinophyllum*. The latter two taxa are not recorded earlier and the rocks containing them could be equated with zone I of MITCHELL (1989).

### 3.3. Similarities and differences

In comparing the complete assemblages and zonations from Ireland and SW Spain, the following facts are relevant:

- High similarity in first occurrences and markers of lower and upper Asbian. The most remarkable difference is the earlier first occurrence of *Siphonodendron pauciradiale* in Ireland.
- Differences in the abundance of some colonial corals. *Diphyphyllum* is common in Ireland and very rare in SW Spain, whereas *Solenodendron* is common in SW Spain and comparatively rare in Ireland. Nevertheless, the most common species of both genera have their acme in the upper Asbian.
- Lower Brigantian is characterised in both areas by first occurrence of *Palastraea regia*. The other markers in Ireland (*Actinocyathus floriformis, Corwenia rugosa* and *Lonsdaleia duplicata*) are absent from Sierra Morena.
- Total absence in SW Spain and scarcity in Ireland of index species of *Orionastraea* in upper Brigantian.

## 4. COMPARISON TO OTHER AREAS

SANDO (1990) proposed the only global Mississippian zonation using rugose corals. It has unfortunately a very low degree of precision for the Upper Visean, because that interval occurs completely within his Zone 4A, which is characterised by the presence of axophyllids, aulinids, *Palaeosmilia, Dibunophyllum*, lithostrotionids and heterophyllids. The attempt by SANDO to find taxa common for all regions impeded the use of species or genera with shorter ranges to define more precise zones. Most genera and species used by SANDO are common in Spain and Ireland; guidelines of occurrence in both countries are similar to those described by SANDO.

POTY (1985; in CONIL et al., 1990) established a more precise zonation for Belgium and neighbouring areas defined in conjunction with foraminiferal and conodont biozones. He divided the Dinantian into 8 rugose coral zones (RC1–8), with the Upper Viséan corresponding to the upper part of zones RC6, 7 and 8 (Fig. 6). Zone RC6 is defined by the presence of *Lithostrotion araneum* and the maximum development of *Siphonodendron martini*. The first occurrence of *Siphonodendron pauciradiale* and *Diphyphyllum furcatum* defines the beginning of subzone RC7α. *Siphonodendron junceum* occurs in the upper part of this zone (RC 7β) and in zone RC8. The latter zone is defined by occurrence of *Actinocyathus floriformis* and *Palastraea regia*. This zonation is more precise, but it has some problems for application in Spain as *A. floriformis* is absent from Sierra Morena, but it occurs in boulders from the Marbella Formation in Betic Cordillera (HERBIG, 1986). The first occurrence of *Siphonodendron pauciradiale* is most useful for recognising the base of the Asbian in Ireland. Unfortunately it appears to be absent in Sierra del Castillo and Los Santos de Maimona. The occurrence of *S. junceum* in these countries begins below that level or in the same beds as the maximum development of *S. martini*. *Diphyphyllum furcatum* is scarce in Spain, but it seems to have a distribution similar to that in Belgium.

MITCHELL (1989) divided the Visean of Britain into 11 rugose coral zones (A-K), with the highest 6 zones (F-K) corresponding to the Upper Visean. He used 68 species for this zonation. Most zones are assemblage zones although he proposed index taxa for each one. Some further taxa have been added to these assemblage zones in a modified version of his table (see RILEY, 1993). The distribution of taxa seems to be consistent with occurrence of most species in Ireland and Spain. The main problem for application of this zonation is the absence in Sierra Morena of index taxa for zones I-K. As stated in the comparison with POTY's (1985) zonation, it is probably due to absence of these zones in Sierra Morena. Nevertheless, the index taxa for these upper zones are present in boulders from the Marbella formation; thus the zonation of MITCHELL (1989) could be useful in southern Spain. JONES & SOMERVILLE (1996) applied this zonation in Ireland, but they also had problems finding the index taxa of higher zones. The additional data from Ireland presented above also fit well with MITCHELL's zonation.

A coral zonation of the East-European Platform by HECKER (2001) is the most recent attempt. The Mississippian is divided into 9 zones using both assemblage zones and interval zones. Zones VI to VIII correspond to the Upper Visean (Fig. 6). The occurrence of taxa in Eastern Europe seems to be consistent with the occurrence in Spain and Ireland with some minor discrepancies that can be explained by migrations and facies variations. The main index taxa of HECKER (op. cit.) are scarce (*Dorlodotia, Nemistium*) or absent (*Acrocyathus*) in SW Spain and Ireland. Nevertheless, zones VII and VIII approximately coincide with zone 3 and 4–5 from the Sierra del Castillo area and with zones G and H-I from Ireland (JONES & SOMERVILLE, 1996).

## 5. CONCLUSIONS

The utility of rugose corals in biostratigraphic studies has been commonly undervalued mainly because of problems of identification and overemphasis of facies control on coral distribution. Problems of identification may be solved by using only well defined and well known species and genera, and by using the species group concept.

Approximately 35 species are considered important for coral biostratigraphy in the Upper Visean because of their broad geographical distribution, their occurrence in shallow-water platform facies and their stratigraphic continuity in the Upper Visean.

The stratigraphical distribution of rugose coral species in Southwest Spain and Ireland show similar patterns and is consistent with the distribution in most areas from Western Palaeotethys.

The additional data from Ireland presented in this paper fit well with the zonation proposed by JONES & SOMERVILLE (1996). Zones F and G correspond to the Asbian and zones H and I correspond to the Brigantian. Five coral assemblage zones can be recognised in Sierra Morena; zones 1 and 2 combined could be Early Asbian in age, zone 3 is Late Asbian and zones 4 and 5 combined are Brigantian. There are some small differences between these areas in the first occurrences of some markers, but the two zonations are analogous. They are consistent with those proposed previously in Belgium (POTY, 1985), Britain (MITCHELL, 1989) and Russia (HECKER, 2001).

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**Plate 1**

Typical Upper Asbian corals

Fig. 1: *Dibunophyllum bipartitum*, upper Asbian, Sierra del Castillo, Spain; x 2

Fig. 2: *Siphonodendron junceum*, upper Asbian, Sierra del Castillo, Spain; x 3

Fig. 3: *Solenodendron furcatum*, upper Asbian, Sierra del Castillo, Spain; x 3

Figs. 4, 5: *Axophyllum* aff. *pseudokirsopianum*, upper Asbian, Sierra del Castillo, Spain; x 2

Figs. 6, 7: *Siphonodendron scaleberense*, upper Asbian, Sierra de la Estrella, Spain; x 2

Fig. 8: *Siphonodendron pauciradiale*, upper Asbian, Sierra de la Estrella, Spain; x 2

Fig. 9: *Aulophyllum fungites*, upper Asbian, Sierra del Castillo, Spain; x 2

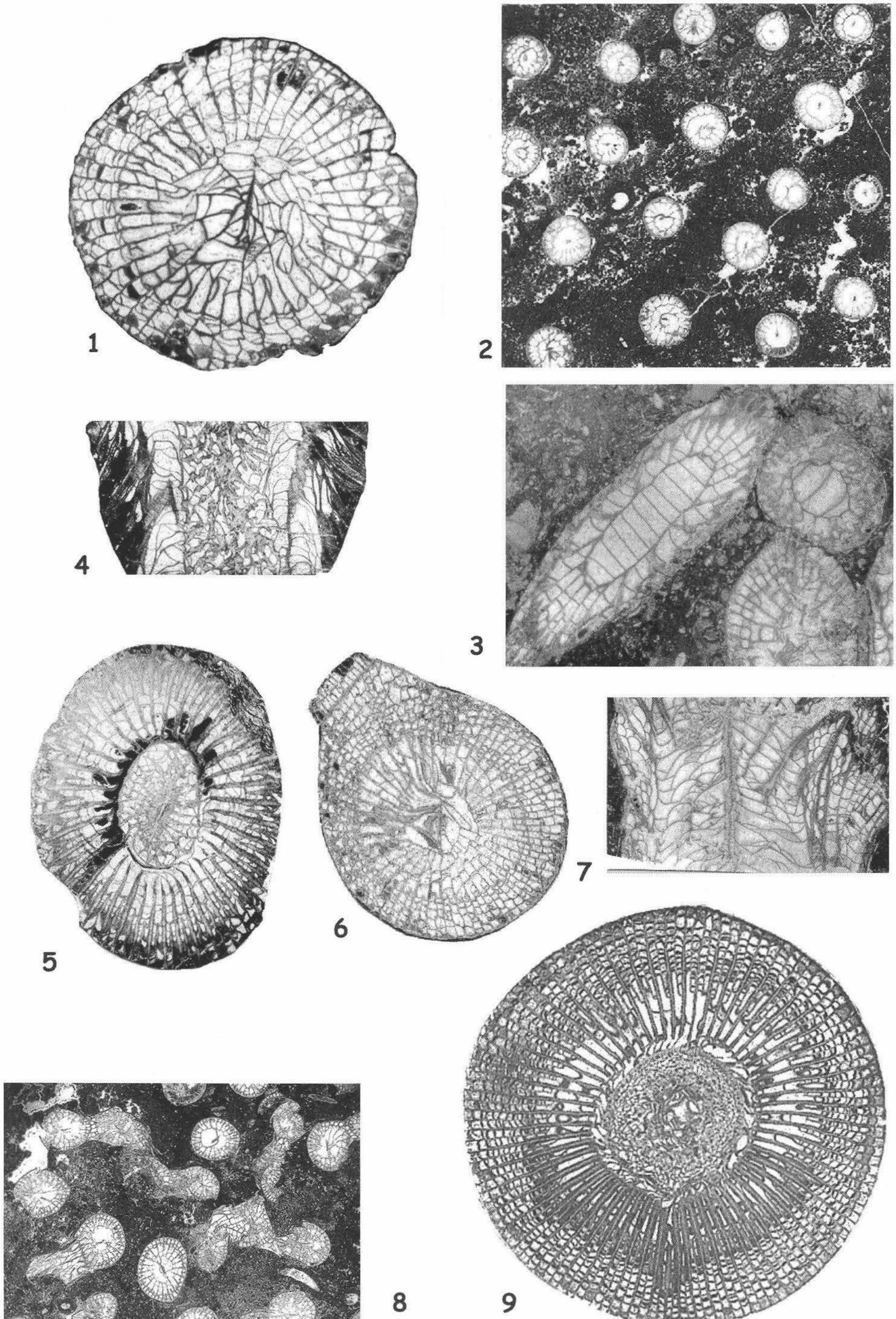
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**Plate 2**

Typical Brigantian corals

Fig. 1: *Palastraea regia*, Brigantian, Sierra del Castillo, Spain; x 1

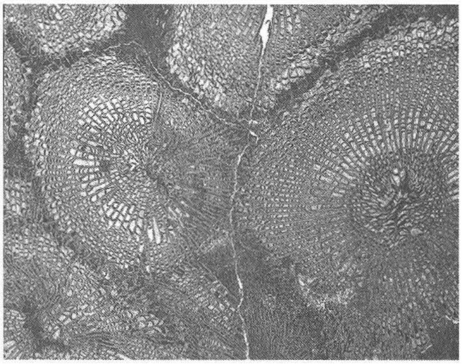
Figs. 2–3: *Arachnolasma sinense*, Brigantian, Spain; x 2

Fig. 4: *Lonsdaleia duplicata*, Brigantian, Dunamase Quarry, Ireland; x 2

Fig. 5: *Diphyphyllum furcatum*, Brigantian, Paulstown Quarry, Ireland; x 2

Fig. 6: *Actinocyathus floriformis*, Brigantian, Paulstown Quarry, Ireland; x 2

Fig. 7: *Corwenia rugosa*, Ardagh Quarry, Co. Meath, Ireland; x 2



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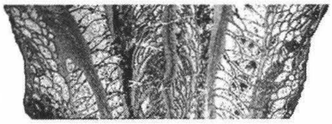

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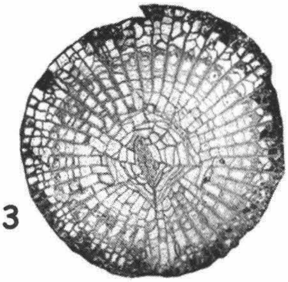

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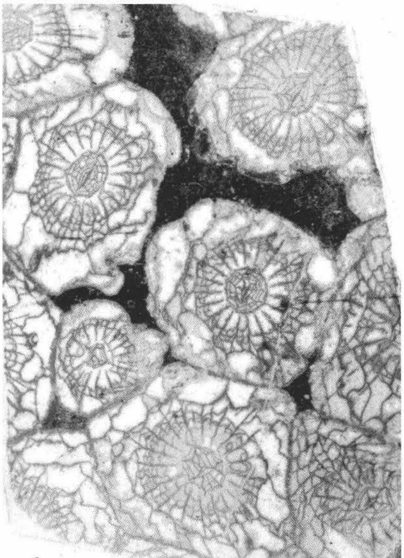

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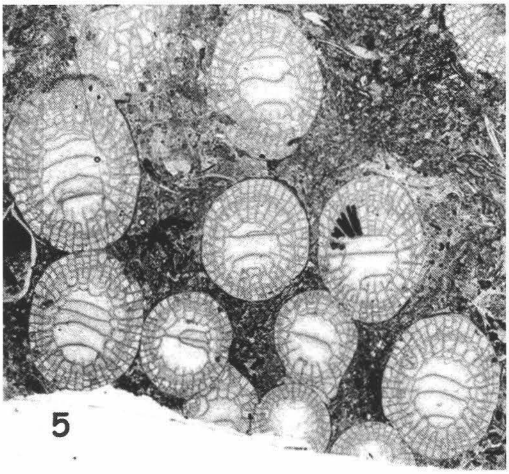

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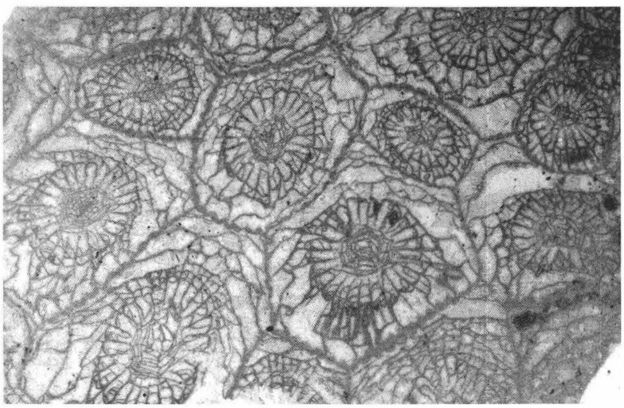

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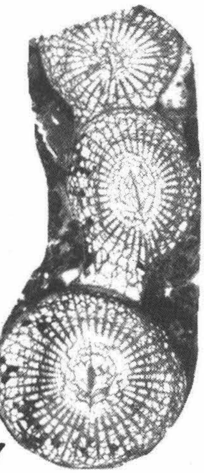

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