PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Synchronology [and Discussion]

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Phil. Trans. R. Soc. Lond. B 1985 **309**, 11-27
doi: 10.1098/rstb.1985.0068

Phil. Trans. R. Soc. Lond. B **309**, 11–27 (1985) [11]
Printed in Great Britain

Synchronology

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Radiometric dating cannot as yet approach the resolution obtainable in Silurian and Devonian biostratigraphy. Progress towards achievement of a global standard for the Wenlock and Emsian interval (against which evolution and environment must be seen) is reviewed. In biostratigraphical correlation with this standard certain groups are especially useful. Correlation between marine Upper Silurian and Lower Devonian rocks and their equivalents in the Old Red Sandstone magnafacies presents particular problems and yet the latter provides significant evidence of plant and vertebrate evolution at this time. The recognition of widespread physical events such as volcanic episodes may sometimes prove useful. Sea level curves seldom provide a precise synchronology not achievable through biostratigraphy. Quantitative methods of correlation are so far of theoretical rather than practical interest.

Introduction

The later part of the Silurian Period and the earlier part of the Devonian Period were times of great palaeogeographical change. The Proto-Atlantic Ocean closed and the Old Red Sandstone Continent was brought into being. The cosmopolitanism of Silurian faunas gave way to the provincialism of the Devonian. Plants colonized the continental areas, producing organic material in the fresh waters, supportive of the vertebrate faunas transferring from marine environments into the rivers and lakes. These various events overlapped in detail in time as well as in space. The palaeobiological, sedimentological, palaeogeographical and tectonic evidence that builds this splendid scenario is fully meaningful only if the events, the evidence for which is available in the rocks, can be related with appropriate accuracy in time. Our interpretations must be based upon a sound stratigraphy. We need to be able to build a *synchronology* – an arrangement of events such that those of the same date are treated together.

Radiometric dates

Since Arthur Holmes provided his inspirational and influential geological time scale in years (Holmes 1937), radiometric dating laboratories have developed and multiplied and there has been a succession of revised chronometric scales, some of them reviewing those that have gone before. Estimates of the beginning, end, and duration of the Silurian and Devonian periods and their subdivisions, thus provided, are confusingly varied. In any case, as Harland *et al.* (1982) have remarked, it is only to be expected that such scales will continue to improve and can never be final.

A range of dates for the Silurian–Devonian boundary starting with the figure provided in the Geological Society of London's *Phanerozoic time scale* of 1964 is given in table 1. Two more comprehensive lists for the subdivisions relevant to the present symposium are given in table 2. From these various data two important conclusions emerge. The first is that, in terms of a broad view of earth history with its patterns of inorganic and organic evolution, we are here

TABLE 1. RANGE OF DATES FOR THE SILURIAN–DEVONIAN BOUNDARY

McKerrow *et al.* 1984	Harland *et al.* 1982	Gale *et al.* 1980	McKerrow *et al.* 1980	Spjeldnaes 1978	Boucot 1975	Lambert 1971	Geol. Soc. Lond. 1964
412	408	400	411	410	405	415	395

Radiometric dates in millions of years.

TABLE 2. DATES FOR SILURIAN AND DEVONIAN SUBDIVISIONS

			McKerrow *et al.* 1984	duration	Harland *et al.* 1982	duration
Devonian		Emsian	391–401	10	387–394	7
Devonian		Siegenian	401–406	5	394–401	7
Devonian		Gedinnian	406–412	6	401–408	7
Silurian	Přídolí		412–414	2	408–414	6
Silurian	Ludlow		414–420	6	414–421	7
Silurian	Wenlock		420–425	5	421–428	7

Radiometric dates in millions of years.

concerned with an episode about 410 Ma ago and of perhaps about 35 Ma duration. Secondly, the six subdivisions from Wenlock to Emsian listed in table 2 are mostly about 6 or 7 Ma in individual duration. The Přídolí alone seems to be rather shorter. Boucot's (1975) estimates of the 'relative palaeontological duration' of subdivisions of the Silurian similarly gave 44% for the Llandovery, 21% for the Wenlock, 23% for the Ludlow, but only 12% for the Přídolí. In some cases the dates in years themselves have been assigned to these subdivisions on the basis of interpolation. Nevertheless they suffice to demonstrate that chronostratigraphy, in which a global standard scale based upon marker points in rocks is correlated with, particularly by biostratigraphical methods, allows closer subdivision and, above all, a much more accurate *correlation* than does geochronometry. In other words, as will be seen in what follows, synchronology in the later part of the Silurian and early Devonian is not yet normally to be achieved by radiometric dating.

Chronostratigraphy

Although an attempt was made to establish an internationally agreed standard for the Pliocene–Pleistocene boundary in 1964, modern procedures in chronostratigraphy effectively were initiated by the activities of the Silurian–Devonian Boundary Committee (Martinsson 1977). The successive publications of the Stratigraphy Committee of the Geological Society of London (the latest being *A guide to stratigraphical procedure*, Holland *et al.* 1978) have also played their part in emphasizing the critical matter of defining the base of each chronostratigraphical unit at a marker point ('golden spike') in a standard boundary stratotype section. An extensive international framework now exists within the International Union of Geological Sciences comprising the Commission on Stratigraphy, its constituent subcommissions for the various systems, and its working groups or committees established to settle particular boundary and other problems. The Silurian and Devonian subcommissions grew to some extent out of the Boundary Committee referred to above. The Subcommission on Silurian Stratigraphy was constituted from an *ad hoc* body at a meeting held in the University of Birmingham in 1974. The Subcommission on Devonian Stratigraphy was organized at a meeting in Marburg at the end of 1973. The activities of these bodies are of crucial, some would emphasize *urgent*, importance if there is to be an internationally agreed and accepted stratigraphical language, which is needed if we are ever to have sensible discussion of synchronology.

Silurian System

Through an eight-year programme, initiated at the International Geological Congress held in Sydney in 1976, the Subcommission on Silurian Stratigraphy has already reached substantial agreement that the Silurian System shall be divided into Llandovery, Wenlock, Ludlow and Přídolí series. The Wenlock and Ludlow are each subdivided into, respectively, Sheinwoodian plus Homerian and Gorstian plus Ludfordian stages. The time is not thought to be ripe for possible subdivision of the Přídolí. The basal boundaries of all these divisions and subdivisions are defined at marker points in boundary stratotype sections (Holland 1982). Decisions concerning names and definitions for the Wenlock and Ludlow and their subdivisions have already been agreed and are ratified by the Commission on Stratigraphy. For the Přídolí the international process nears completion. All the basal boundaries have been related to graptolite biozones, which are also indicated in table 3.

TABLE 3. SUBDIVISIONS OF THE SILURIAN

chronostratigraphy				location of basal boundary stratotype	graptolite biostratigraphy
					uniformis
Silurian System	Upper Silurian	Přídolí Series		Barrandian (Pozary section)	*transgrediens* *ultimus* *parultimus*
		Ludlow Series	Ludfordian Stage	Ludlow district (Sunnyhill Quarry)	*leintwardinensis*
			Gorstian Stage	Ludlow district (Pitch Coppice)	*tumescens* (= *incipiens*) *nilssoni* s.l.
	Lower Silurian	Wenlock Series	Homerian Stage	Wenlock district (Whitwell Coppice)	*ludensis* *lundgreni*
			Sheinwoodian Stage	Wenlock district (Hughley Brook)	*ellesae* *centrifugus*
		Llandovery Series			

Devonian System

The Subcommission on Devonian Stratigraphy has concentrated its activities so far in attempting to standardize series boundaries, respectively between the Lower and Middle Devonian and between the Middle and Upper Devonian (Ziegler & Klapper 1982). The base of the system is already established at a boundary stratotype at Klonk in Czechoslovakia and at an horizon marked by the first appearance of the graptolite *Monograptus uniformis*. Of the two boundaries presently coming under decision, we are concerned in the present context only with the lower one which provides a top for the Lower Devonian. Partly because rocks about the middle of the Devonian tend to be in carbonate facies, partly because the graptolites, which have proved so useful in Lower Palaeozoic biostratigraphy, are here in the last episode of their long range, partly because of the vagaries of research activity, there has been a tendency to pay particular attention to conodont lineages and to choose boundaries corresponding to conodont horizons.

Although the decision has not yet been ratified by the Commission on Stratigraphy, the Subcommission has agreed by a vote taken in 1980 to place the Lower–Middle Devonian boundary at the base of the *Polygnathus costatus partitus* Biozone, with a boundary stratotype chosen in 1981 at the Wetteldorf Richtechnitt in the Prüm Syncline, Eifel Mountains (West Germany). This trench section is to be protected. Subdivision of the Lower Devonian has presented problems, though the Subcommission appears now to have agreed to the three stage names: Lochkovian, Pragian and Emsian, thus switching at the base of the Emsian from the Barrandian (Czechoslovakia), with its Hercynian facies, to the Rhenish facies of the Ardennes and Rhenish Schiefergebirge. The widespread use of the Rhenish facies trio of Gedinnian, Siegenian and Emsian had become familiar, and indeed is to be found in the contributions that follow in the present volume.

The correlation of the Rhenish and Hercynian divisions (table 4) is in any case a matter of fundamental importance. It is referred to in Ziegler's (1979) historical account of subdivision of the Devonian System. The base of the *Monograptus uniformis* Biozone in the boundary stratotypic section at Klonk must also provide definition of the base of the first stage of the Devonian. This gives one good reason for using the name Lochkovian for this stage. It seems

Table 4. Subdivisions of the Devonian

<table>
<tr><th>Series</th><th>Standard Stages</th><th>Hercynian equivalents</th><th>Rhenish equivalents</th></tr>
<tr><td>Middle Devonian</td><td>Eifelian</td><td rowspan="2">Dalejan</td><td>Eifelian</td></tr>
<tr><td rowspan="6">Lower Devonian</td><td rowspan="3">Emsian</td><td rowspan="3">Emsian</td></tr>
<tr><td>Zlíchovian</td></tr>
<tr><td rowspan="3">Pragian</td></tr>
<tr><td rowspan="2">Pragian</td><td>Siegenian</td></tr>
<tr><td rowspan="2">Gedinnian</td></tr>
<tr><td>Lochkovian</td><td>Lochkovian</td></tr>
<tr><td>Přídolí</td><td></td><td></td><td></td></tr>
</table>

that the basal horizon does also correlate with the base of the Gedinnian. Thus the trilobite *Warburgella rugulosa rugulosa* and the conodont *Icriodus woschmidti* both occur at the base of the Gedinnian in the Rhineland and both have proved diagnostic of the base of the Devonian elsewhere in the world.

The base of the Siegenian in the Ardennes is not well defined. There has been uncertainty as to whether the Schistes de Saint-Hubert, with their upper Dittonian fish should be included in the Siegenian (House 1975), though these have been taken to be the approximate correlative of the Siegener Schichten in the Rhineland (House 1977). The diachronous sparse marine fauna that follows may appear higher still in the Rhineland (Ziegler 1979).

Things are better in the Emsian with its extensive assemblages of brachiopods, trilobites, corals, conodonts, ostracodes, vertebrates and spores. The base of the stage is recognized by the disappearance of *Acrospirifer primaevus* and the appearance of the *Arduspirifer* lineage, together with other brachiopod and trilobite elements. Ziegler reviews the gradual refinement of correlation of the base of the succeeding Eifelian Stage (Middle Devonian) with the Hercynian facies, in particular by the use of conodonts. The newly selected boundary at the base of the *partitus* Biozone involves moving the horizon 1.9 m below the Heisdorf–Lauch lithological boundary level traditionally used in the Eifel.

Erben's (1964) three magnafacies of the Devonian: Rhenish, Hercynian and Old Red Sandstone are all significantly developed in the Lower Devonian and, whatever boundary stratotypes are eventually selected and their choice ratified, it is essential that an accurate web of correlation is established that will relate such diverse developments as the Lower Devonian graptolitic sequences of the Canadian Arctic (see for example Jackson *et al.* 1978), the varied carbonate and other facies (see for example Chlupác 1983) of Bohemia, the clastic successions of the Ardennes and Rhineland, the continental deposits of the Lower Old Red Sandstone and many other developments across the world.

The choice of the two lowest stages as being in the Hercynian facies makes correlation with the Old Red Sandstone more difficult. It is easier to relate the Rhenish and Old Red Sandstone magnafacies, which do actually interfinger in places along the southern border of the Old Red Sandstone continent. However, in other respects, the Hercynian stages are more helpful for correlation outside Europe.

The Lower Old Red Sandstone of Wales and the Welsh Borderland has long been divided into Downtonian, Dittonian and Breconian, though the status of these subdivisions has tended to remain unclear. The Downton is of course Silurian rather than Devonian in age. Its correlation as *approximately* coextensive with the Přídolí has been reviewed by Kaljo (1978) and by Bassett *et al.* (1982). Vertebrate faunas have allowed correlation of the Dittonian (see above) with at least upper Gedinnian and lower Siegenian of Rhenish facies of the Lower Devonian. These and other Old Red Sandstone correlations are given in the Geological Society of London's *A correlation of Devonian rocks in the British Isles* (House *et al.* 1977).

At its meeting in Montpellier in September 1983, the Subcommission on Devonian Stratigraphy agreed to set up a working group to be convened by Professor D. L. Dineley to study marine–non-marine facies correlation. Continental Devonian rocks occur not only in the lands around the North Atlantic but also as far afield as Antarctica, Australia, China and Siberia. Critical ranges of palynomorphs, macroplants and vertebrates will be assembled.

Silurian stratigraphy has benefited from the largely cosmopolitan faunas of the time. With the advent of Devonian provincialism things were considerably more complex, and this complexity is reflected in what has been said above. There is still much to be done, but in the meantime it is important that we say what we mean by the divisions we use. The present Chairman of the Subcommission on Devonian Stratigraphy, Professor W. Ziegler, seeking a sense of urgency, commented in a circular issued in 1979 upon the very varied use of stratigraphical terms by contributors to the International Symposium on the Devonian System held in Bristol the previous year. According to his notes, during the last day four out of five speakers delivering keynote papers used nine different versions of a Lower Devonian–Middle Devonian boundary, some of them even in the same paper.

A firmly established boundary stratotypic arrangement will at least provide stable anchoring points as refinement of correlation continues. I have elsewhere reviewed the crucial significance of the marker point ('golden spike') in the boundary stratotype section (Holland 1978, 1984) and illustrated it by successive versions of a diagram.

Biostratigraphy

For a proper appreciation of the course of evolution of plants and animals and the changing environment we need a veritable web of world-wide correlation, this essentially being tied firmly to the global standard stratigraphical scale. This is achieved largely through biostratigraphical methods. More and more groups of fossils gradually come into effective use for this purpose, though some remain better than others and some are appropriate only in particular facies. It would be possible to write a book on Silurian and Devonian biostratigraphy, so that what follows must be a highly selective commentary.

Graptolites

In the Silurian the graptolites remain the most effective of all biostratigraphical tools. It is not just that their use is classically based upon the early researches of Lapworth, Elles and Wood, followed much later by the substantial contributions of Bouček and other Central European workers. When present, even in small numbers, if reasonably preserved they provide a clear and decisive answer. Unfortunately, the problem created by undue admiration of the graptolites has been failure to recognize that many other groups of fossils also have good biostratigraphical potential, and that the presence of a true graptolitic shale facies may well imply the absence of other fossils needed in the correlation of the widespread platform carbonates of the time.

Rickards (1976) has surveyed the Silurian graptolite biostratigraphy of the British Isles. This does not, of course, take care of the higher Ludlow and Přídolí forms. There are nine Wenlock graptolite biozones: *centrifugus*, *murchisoni*, *riccartonensis*, *rigidus*, *linnarssoni*, *ellesae*, *lundgreni*, *nassa* and *ludensis*. Referring back to our apportionment of radiometric dates (table 2), this means that an average Wenlock graptolite biozone occupies less than one million years, a remarkable degree of resolution.

In the case of the Ludlow it is not easy to find agreement on the designation of the highest graptolite biozones. A possible arrangement is of *nilssoni/colonus*, *scanicus/chimaera*, *tumescens/incipiens*, *leintwardinensis*, *bohemicus*, *kozlowskii* and *formosus*. In the Přídolí, both Pedder *et al.* (1978) and Koren' (1983), to give examples, list *ultimus* (a subdivision of which may be recognized in the Barrandian), *lochkovensis*, *bouceki*, *perneri* and *transgrediens* biozones.

The recognition of Devonian graptoloids *as such* has come only in the past 25 years. They range from Gedinnian to the lower part of the Emsian (Pragian and possibly lowest Zlichkovian), occur widely across the world, but are found only in the appropriate facies. Their cosmopolitanism makes them stratigraphically particularly useful. Jaeger (1979, 1983) who has done much to record their nature and distribution, distinguishes at least six biozones, these being *uniformis*, *praehercynicus* and *hercynicus* in the Lochkovian and *falcarius*, *thomasi* and *yukonensis* above.

Dr Tatyana Koren' has in preparation a paper for the International Geological Congress in Moscow (August 1984) in which she attempts to group Silurian graptolite biozones into an internationally recognizable and useful standard zonation. A further possible step would be to define a set of *chronozones*, the lowest category of the chronostratigraphical hierarchy, each with its basal boundary stratotype. Bassett *et al.* (1975) have already defined two such chronozones within the Homerian Stage of the Wenlock Series, the relevant sections being in the type Wenlock area of the Welsh Borderland. Their ranges as so defined correspond to those of the *lundgreni* Biozone (Whitwell Chronozone) and the *nassa* plus *ludensis* biozones (Gleedon Chronozone).

A good example of the importance of graptolite biostratigraphy in correlating significant evolutionary events with the chronostratigraphical standard is provided by Garratt & Rickards (1984) in their assessment of the age of the *Baragwanathia* flora of Victoria (Australia). There have been discussions of the supposed Silurian age of the earliest *Baragwanathia* assemblage in contrast to that of the higher local assemblage of the same genus, which is unquestionably Devonian on the evidence of *Monograptus thomasi* present on the same slabs as the fossil plants. At one of the localities for the lower assemblage the plants are known *in situ* but the graptolites occur with more of the plants in debris which it is reasonable to assume comes from the same source. *Bohemograptus bohemicus bohemicus*, clearly illustrated in the authors' drawings, provides a firm Ludlow age. At the other locality graptolitic material and plant-bearing beds are interbedded. Here the graptolites are assigned to *Monograptus* aff. *uncinatus uncinatus*. There is more possibility of confusion here with *M. thomasi*, but the designation *aff.* is provided only because the material is slightly distorted. In any case the two localities are mapped as at almost the same horizon.

At present the earliest record of erect fertile land plants, of the genus *Cooksonia*, is from the Wenlock of Ireland (Edwards, Feehan & Smith 1983). Here again graptolites provide the vital evidence of age, *Monograptus ludensis* occurring together with *M. auctus* both above and below the plant bearing beds.

Brachiopods

Of the various groups of invertebrate shelly macrofossils present in the late Silurian and early Devonian, the brachiopods have so far proved to be the most useful biostratigraphically. Holland & Hughes (1980) noted the recent historical pattern of their study 'in which Arthur Boucot's unique world-wide attack on brachiopod genera is now giving way in various places to exceedingly detailed specific studies'. Thus the identification of the 'lost series' (Přídolí), between the Silurian and Devonian (as then understood) was made possible partly by Boucot's recognition that the brachiopod fauna of the Skala of Podolia (Boucot & Pankiwskyj 1962) is post-Ludlow, pre-Gedinnian in aspect and thus falls into place immediately before the Lower Gedinnian fauna of Belgium (Boucot 1960). Within the Silurian also, for example, the Wenlock stages (Sheinwoodian and Homerian) first defined by Bassett *et al.* (1975) each has its own broad brachiopod assemblage. Within the Devonian much use has been made of detailed spiriferid lineages (for example, Jahnke 1971; Ziegler 1979). Johnson (1979) has attempted integration of brachiopod zonal schemes with Devonian conodont chronology. Much has been made of brachiopod 'communities' (associations) and it is refreshing to find Pickerill & Hurst (1983) embarking upon a series of studies 'attempting to incorporate faunal associations within the framework of detailed lithofacies analysis', though actually in the Llandovery clastic rocks of Arisaig, Nova Scotia.

Trilobites

Though other groups of invertebrate macrofossils such as the cephalopods have undoubted *potential* for biostratigraphy, the trilobites alone rival, and in some circumstances surpass, the brachiopods in importance. Thomas *et al.* (1984) have compiled an excellent review of trilobites in British and Irish stratigraphy, charting the distribution of all known species and subspecies. They note in their introductory comments that 'particular problems arise from the diachronous occurrence of environmentally controlled generic assemblages. Generic associations therefore provide only a general indication of age but specific identity gives more compelling evidence of age-equivalence because species generally persist for much shorter intervals of time than do genera. Particular grounds for correlation exist when a consistent sequence of species of the same genus is encountered in different successions'. Within the Silurian, these authors reproduce trilobite zonal schemes from the Altai Mountains, Soviet Union (upper Llandovery to Přídolí), Bohemia (upper Wenlock and Ludlow) and Poland (top Ludlow to Přídolí). However the distribution of British Wenlock trilobites is very closely related to lithofacies and the Ludlow, and more especially Downton, faunas are restricted. Species of *Acastella* and *Warburgella* are of international significance about the Silurian–Devonian boundary (Ormiston 1977). Alberti (1979) has reviewed the international biostratigraphical value of Devonian trilobites and Chlupác (1983) has recently described the successive trilobite assemblages in the Devonian carbonate facies of the Barrandian area.

Vertebrates

The late Silurian and Devonian evidence is critical to our understanding of vertebrate evolution. To those who are not vertebrate palaeontologists these fossils may be difficult to find and to identify. They do occur widely and are common at some localities. White's (1950) account of the vertebrate faunas of the Lower Old Red Sandstone of the Welsh Borderland was part of the long continued discussion on the placing of the Silurian–Devonian boundary. It provided details of localities and ranges and showed that the vertebrates could be used to zone the Downton and Dittonian. Later the same author (White 1956) published a preliminary note on the ranges of pteraspids in Western Europe. Stressing their importance in Lower Devonian stratigraphy, he noted that 'by reason of their wide geographical range and apparently brief specific duration, they seem to offer a sound means of dividing and correlating the troublesome continental and sub-continental strata'. A useful correlation table shows the Dittonian as extending from the middle of the lower Gedinnian up to the base of the middle Siegenian.

Turner's work on thelodonts of the Welsh Borderland and other areas has demonstrated the potentiality of scale assemblages (microvertebrates) in correlation. They become significant in the Wenlock and very useful in the Ludlow, Downton and Dittonian. They are, of course, abundant constituents of the various bone beds at these levels. Turner (1973) compares the Welsh Borderland thelodont succession with those in Scotland, the Baltic region (including the Beyrichienkalk), Spitsbergen, the Soviet Union, Canada, etc.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Micropalaeontology

There has been great growth in Silurian and Devonian micropalaeontology. The very volume of the information is itself a problem to be faced, though it is not insoluble. A recent review (Ellison 1984) finds that more than 200 papers on conodonts are now being published every year. Of all the references to conodonts, 80% have appeared in the last 20 years. The advantages of micropalaeontology in biostratigraphy are obvious. A single sample of relatively small size may yield a very large number of fossils. Judicious use of various groups allows for the crossing of facies boundaries. A disadvantage is that quick stratigraphical age determinations are not readily made in the field, except perhaps in the case of the ostracodes which are relatively large as microfossils go.

Silurian and Devonian ostracodes have been extensively studied by Martinsson in Sweden, Abushik in the Soviet Union, Copeland in Canada, David Siveter in the United Kingdom, and others. Siveter's (1978) review of British Silurian ostracode stratigraphy notes the significance of the group in the marine to quasi-marine conditions of the Downton series. The species *Frostiella groenvalliana*, for example, is a useful index for the basal part of the Downton and allows correlation throughout the Baltic region, in Podolia, and even to Nova Scotia. Bassett *et al.* (1982) make use of the ostracodes in their correlation across facies from the base of the Downton to a level at or slightly above the base of the *ultimus* Biozone.

The conodonts are of particular importance in international correlation, especially in carbonate facies. Walliser's pioneering treatment of the Silurian forms (Walliser 1964, 1971) has been followed by Schonlaub's studies in the Carnic Alps and Bohemia. Klapper (1977) summarizes occurrences about the Silurian–Devonian boundary. The significance of the conodonts in Devonian biostratigraphy has already been emphasized. Knowledge to the summer of 1978 was brought together by Klapper & Ziegler (1979).

The chitinozoa show increasing promise in biostratigraphical work. According to Laufeld (1979) all chitinozoa are bathymetrically controlled. Nevertheless the Silurian forms are cosmopolitan with provincialism arising again in the Devonian. An earlier paper by Laufeld (1971) demonstrated how only two samples from the basal Silurian beds in the Kitaygorod section, in a tributary valley of the Dnestr River in Podolia, were sufficient to indicate the presence of a very thin middle Llandovery above the local Ordovician and followed by the Wenlock. Dorning (1981 *a*) recorded chitinozoa from the type Wenlock and Ludlow. Paris has used these microfossils in biostratigraphical correlation of the Přídolí and Lochkovian rocks of the Massif Amoricain with those of the standard sections in the Barrandian area (Paris 1981; Kříž & Paris 1982).

In palynology, the acritarchs continue to prove especially useful in areas of Lower Palaeozoic rocks not readily dateable by other means. A good example is Dr David Smith's work on the Lower Palaeozoic inliers of central and southern Ireland, the understanding of which has been substantially improved by this means. Smith (1981) has summarized a decade of progress in Irish Palaeozoic palynology as a whole. Dorning (1981 *b*) recorded acritarchs from the type Wenlock and Ludlow. In Old Red Sandstone stratigraphy and in correlation between the Old Red Sandstone and the marine Devonian, spores are exceedingly important. Richardson & Lister (1969) described the spore sequence from Wenlock to Dittonian in the Welsh Borderland and South Wales, finding significant changes at the Ludlow–Downton boundary and between the Downton and Dittonian. Richardson (1974) attempted a synthesis of the stratigraphical distribution of Silurian and Devonian miospores in the Northern Hemisphere and McGregor (1979) has extended the treatment on a world wide basis. Richardson *et al.* (1981) used palynomorphs for international correlation of the Ludlow–Downton and Silurian–Devonian boundaries. Edwards & Richardson's (1974) treatment of Dittonian plants from the Welsh Borderland, as in the case of these other publications, touches upon the relationship between the Old Red Sandstone stratigraphical subdivisions and the marine Devonian stages of the Rhenish facies. Most of the Dittonian is generally equated with the Gedinnian but its upper part is correlated with the early Siegenian. The highest beds of the Breconian may reach the Emsian (Allen 1977).

In conclusion, an ideal example of the way micropalaeontological studies may be used to increase the correlative potential of properly defined boundary stratotype sections is Mabillard & Aldridge's (1984) treatment of microfossil distribution across the base of the Wenlock Series. Rich assemblages of acritarchs, chitinozoans, conodonts and ostracodes, were collected bed by bed from two localities. The base of the Wenlock does not itself correspond to any microfossil biozonal boundary, but a detailed pattern of ranges emerges which can be employed as a whole or in part elsewhere.

Other methods of stratigraphical correlation

Event stratigraphy becomes significant in a few special situations. Thus, for example, Allen & Williams (1981) have recognized a distinctive group, 2–4 m thick, of three almost superposed graded ash-fall tuffs widely distributed in South Wales and the Welsh Borderland. This so-called Townsend Tuff Bed lies not far below the '*Psammosteus*' Limestone or its equivalent and thus seems to provide a useful local marker for the base of the Dittonian. It occurs in an interval of barren strata between the Silurian marine-brackish vertebrate fauna with *Hemicyclaspis*, *Sclerodus* and *Didymaspis* and the incoming freshwater fauna of *Traquairaspis* and *Pteraspis* which is found in the upper part of the Ledbury Formation.

Bentonites, each indicating an isochronous volcanic event, have long seemed promising in Lower Palaeozoic correlation. They are common, for example, in the type Wenlock area and in the Wenlock rocks of the Ludlow Anticline. They were first described from Gotland. The Llandovery and pre-*ludensis* Biozone Wenlock of Estonia alone contain more than 50 bentonites (Laufeld & Jeppsson 1976). Tsegelnjuk *et al.* (1983) have documented their occurrence in the Ludlow and Přídolí sequence of Podolia. Laufeld and Jeppsson noted the difficulty of correlating some of the 40 thin bentonites in two boreholes from southern Gotland only 20 km apart, and yet remained 'confident that, when the biostratigraphic studies of the cores have been completed, the subsurface bentonite beds will be of the utmost value for a refinement of the correlation with the eastern Baltic area...and with the supramarine bedrock of Gotland...'. This is the crucial point: that bentonites are likely to be useful when used *in conjunction* with biostratigraphy. In fact they are often numerous when they are not needed because the biostratigraphy is so good. This is the case, for example, in the higher Silurian rocks of Podolia.

Sea level curves can be used in effective graphical depiction of a sequence of palaeogeographical events. Brouwer (1983) has used them in a very broad way to demonstrate global control of the Phanerozoic sedimentry record by changing rates of sea floor spreading. The attempted matching of smaller-scale sea level curves across the world is a hazardous undertaking.

House (1983) has reviewed Devonian eustatic events. He recognizes that important orogenic events appear to control major Devonian facies shifts, but that the lesser scale rhythms that he has described 'seem inescapably eustatic if the dating of the events internationally is accepted'. The larger scale control of these is again seen as related to activity of plate margins, but the interpretation of the finer rhythms, be it climatic or something else, remains elusive. Concerning these finer-scale rhythms, House concludes 'whatever the final interpretation which is accepted their precise documentation in time will, again, depend on refinement in techniques of international biostratigraphic correlation'.

One example of the actual usefulness of sea level curves in special circumstances is to be found in Johnson & Colville's (1982) study on the regional integration of evidence for evolution in the *Pentamerus–Pentameroides* lineage. They seek to demonstrate independence from geographical variation. They find that gaps in sample testing for gradualism in this lineage from the lower Silurian Hopkinton Dolomite of eastern Iowa occur stratigraphically where pentamerid associations are succeeded by deeper water stricklandiid associations or by shallow coral–algal associations. Specimens were collected from different horizons and show signs of gradual change in the spacing and orientation of the outer plates. These samples could represent sudden changes in a series of geographically isolated populations. It seemed to be a classic case of Darwin's 'imperfection' in the geological record. However, the use of sea level curves allowed these authors an ingenious theoretical framework into which to integrate samples on a temporal basis from two or more widely separated regions. The result shows gradualistic change in *Pentamerus oblongus* from widely spaced and divergent outer plates to a narrowly spaced and more parallel arrangement, followed by an approach to the ultimately convergent configuration of *Pentameroides subrectus*.

Since the appearance of Shaw's seminal book on the subject (Shaw 1964), there has been an uneasy flirtation with quantitative methods in stratigraphy. A synthesis of quantitative stratigraphical correlation has recently appeared (Cubitt & Rayment 1982). Professor Hallam's review of this in *Sedimentology* (volume **31**, pp. 134–135) puts matters so effectively in perspective that quotation is justified. Having reminded us that biostratigraphical analysis is by its nature qualitative in character, he notes that 'a single Jurassic ammonite identifiable to generic level is usually more valuable stratigraphically than any number of specimens of foraminiferal or brachiopod species, or indeed the species of any other group. By relying upon the most diverse and abundant macrofauna, the Bivalvia, it would be easy in the absence of ammonites to miscorrelate the Lower Lias of South America with the Middle Jurassic of Europe. In other words, playing the numbers game with fossil assemblages may prove to be the wrong strategy even using the most sophisticated mathematical techniques available'. He concludes his review: 'probably quantitative stratigraphers would not wish to claim that at present their proposed techniques offer more than the *promise* of improved correlation...'. Hallam himself 'still awaits demonstrated *achievement*'.

Discussion of other methods of correlation and of the possible refinement of techniques will continue and it is healthy that this should be so. In Cretaceous palynology Hughes & Moody-Stuart (1969) found stratigraphical zones 'unacceptable as tools' and proposed instead to employ 'biorecords' and 'events'.

Smith & Fewtrell (1979), citing examples from the Lower Carboniferous and Mesozoic, suggest the use of network diagrams in depicting stratigraphical temporal correlation. However, in spite of it all, the abiding impression remains that biostratigraphy, though it does date back to William Smith, continues to be used and is used with increasing rigour. It continues to deserve support.

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Discussion

J. B. Richardson (*British Museum* (*Natural History*), *Cromwell Road*, *London SW7 5BD*, *U.K.*). Miospore studies during the last decade have enabled considerable progress to be made in the zonation of continental deposits (Old Red Sandstone magnafacies). For example miospore sequences in the Anglo-Welsh area of the British Isles can be correlated with graptolite-bearing sections in Podolia and marine subsurface sections in Libya (Richardson *et al.* 1981) as well as Gedinnian rocks in the type area (Steemans 1982). But it is not possible to correlate directly with the section for Silurian–Devonian boundary at Klonk, Czechoslovakia, which is in distal sediments of Bohemian magnafacies. While the writer agrees with Professor Holland that well-defined stratotype sections are a pre-requisite for progress in stratigraphy it is important to mention that there are difficulties with the Klonk stratotype and discrepancies between the Podolian and Czechoslovakian sequences in the appearance of the varieties of the key graptolite species *Monograptus uniformis*. In Czechoslovakia the boundary occurs in bed 20 where *M. uniformis uniformis* and *M. uniformis angustidens* 'appear suddenly and in great abundance in the upper part of bed 20' (Chlupáč & Kukal 1977). In contrast, in Podolia the base of the Devonian System is placed at the first appearance of *M. uniformis angustidens*, at the base of the Tajna Beds, and *M. uniformis uniformis* occurs at the top of the Tajna Beds 53 m above. So while the designation of the Klonk sequence for the Silurian–Devonian boundary represented a working consensus among subcommission members it should be stated that it is a compromise which has raised serious problems not least of which is that direct correlation with the continental sequences of the Old Red Sandstone magnafacies is now impossible. In future stratotypes should be chosen from sections in Rhenish magnafacies as such sections are intermediate between, and often interdigitate with, Old Red Sandstone and Bohemian magnafacies and from the Palynological viewpoint sections Rhenish magnafacies have the greatest correlation potential.

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T. S. Westoll, F.R.S. (*Department of Geology*, *The University*, *Newcastle upon Tyne*, *NE1 7RU*, *U.K.*). The succession in the Welsh Borderland and South Wales is important for the sequence of both plant and fish fossils during the geological interval here considered. Some important points need to be made.

(i) Wickham King defined the base of the Dittonian both in a lithological and a palaeontological sequence in the 'Cephalaspis Sandstone–Cornstone' where *Pteraspis* and *Cephalaspis* made their first recorded appearance. White and Toombs found *Pt. leathensis* and *Cephalaspis* at the very top of the 'Psammosteus Limestones', and were justified in lowering the base to this level. Then Allen and Tarlo extended the Psammosteus Limestone group downwards, and referred this extended group to the Ditton Series. The important fauna of the Psammosteus Limestone group is varied and abundant, particularly marked by *Traquairaspis* and, as shown by Susan Turner, by the thelodont *Turinea*. The transference of the 'Psammosteus Limestone Group' to the Dittonian cannot be justified by palaeontology.

	Bohemia	Podolia	Lithuania	Ardennes	Artois	Welsh Borderland
Emsian	Prag					Clee
Siegenian	Lochkov			Anor St Hubert	Matringhem	
Gedinnian	②	Dniepr Czortkow ③ Borszczow ②	Tilže ③ Jūra ②	Oignies Gdoumont Mondrepuits ? ②	Vimy Pernes Ps. de Liévin Méricourt	Dittonian ③ Ps. L. Downtonian
Infra-Gedinnian	Přídolí ①	Skała	Minija ①	Haybes Fépin	Drocourt Angres Calc. de Liévin F	L.B.B. ①
Lud.	Kopanina	Malinovets	Pagegiai			Ludlovian

(ii) This last faunal assemblage is fully represented in the lower part of the Czortkow of Podolia; in the upper part, and in the succeeding Dniepr, is a sequence of pteraspid faunas closely comparable with those of the Dittonian. Below the Czortkow is the Borszczow, some 250 m thick, at the base of which *M. uniformis*, defining the new base of the Devonian, appears. Thus the Psammosteus Limestone assembly is nowhere near that base. The correlation between the Podolian and Lithuanian columns is well established. The horizon marked (1) is the base of the *M. ultimus* zone, which Martinsson thinks to be close to the Ludlow Bone-Bed Horizon; (2) is the base of the *M. uniformis* zone, which some workers have suggested may be close to the lowest fossiliferous layers of the type Gedinnian (Mondrepuits). This may not be quite accurate, but it seems reasonable to use the informal term 'InfraGedinnian' for those strata intervening between the level of the lowest fossiliferous beds of the Mondrepuits and the equivalent of the base of the *M. ultimus* zone.

(iii) The Downtonian of S Wales (the Psammosteus Limestone equivalent is well above its base) oversteps successively Ludlow, earlier Silurian and onto Ordovician. The Downtonian is thus structurally the lowest element in a new stratigraphic and depositional regime, and the Silurian regime in the type area of that System lies below it. The new usage for the base of the Devonian will place that horizon well below the Psammosteus Limestone at some level that is highly unlikely to be defined on fossil evidence.

C. H. Holland. Professor Westoll refers to the re-definition of the base of the 'Dittonian' by Allen and Tarlo. These authors referred to their proposed boundary as 'based on lithology'. There has been continued confusion between lithostratigraphy, biostratigraphy and chronostratigraphy in the Old Red Sandstone rocks of Wales and the Welsh Borderland. We do require a properly agreed and defined set of mappable lithostratigraphical divisions in these areas and it does not matter where the bases of these lie in relation to the biostratigraphy. The proposed informal term 'Infra-Gedinnian' is perhaps unnecessary as there is already substantial international agreement that the chronostratigraphical division between the Ludlow and the base of the Gedinnian (or rather Lochkovian) shall be called the Přídolí.

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