*Geol. Mag.* **135** (*4*), *1998, pp. 447–471. Printed in the United Kingdom* *© 1998 Cambridge University Press* 

# Early Silurian sea-level changes

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(*Received* 2 September 1997; *accepted* 19 January 1998)

**Abstract** – Global sea-level fluctuated markedly during the early Silurian, probably as a result of the waxing and waning of ice-sheets in the South American portion of Gondwana. The highest sea-levels of the Silurian are recorded by the Telychian upper *crispus*–lower *griestoniensis* and *spiralis*–lower *lapworthi* biozones. Other highstands occurred in the early Aeronian, during the *convolutus* Zone (mid Aeronian), *guerichi* Zone and late *turriculatus* Zone (early Telychian), and early Sheinwoodian. Low sea-levels characterized much of the *argenteus* and *sedgwickii* zones (Aeronian), the *utilis* Subzone (late *guerichi*–early *turriculatus* zones, early Telychian), the late Telychian (commencing in the mid *lapworthi* Zone) and, after a period of apparently only small amplitude sea-level fluctuations in the late Sheinwoodian and earliest Homerian, the mid–late Homerian, in particular the early *nassa* Zone. Facies (and faunal) changes in the Lower Silurian do not support the P and S model of Jeppsson and others, but are consistent with the sea-level changes proposed herein. Mid Telychian marine red beds appear to have been deposited during a minor sea-level fall immediately after a period of very high sea-levels, rather than during a transgressive episode as previously suggested. Comparison of the sea-level curve presented herein with those constructed in the past is hampered by the lack of precision currently possible in the correlation of early Silurian deep water (graptolitic) and shallow water (shelly) sequences. Improving the precision of this correlation should be a priority for future research.

## 1. Introduction

The timing and magnitude of Silurian sea-level fluctuations have been subjects of considerable recent and ongoing research interest (see, e.g. Johnson, 1996; Ross & Ross, 1996). This paper presents a new sea-level curve for the Silurian up to the early Ludlow, based on facies changes on a number of palaeocontinents. These have been dated, primarily using graptoloids, with a precision to zonal and in some cases subzonal scale. This new curve differs markedly from those previously published, in terms of both the number of fluctuations recognized and in their timing.

### 1.a. Biostratigraphy

The graptolite zonation used herein (Fig. 1) is significantly more detailed than those used previously for constructing sea-level curves (e.g. Johnson, Kaljo & Rong, 1991; Johnson, 1996; Ross & Ross, 1996) and that recommended recently by the IUGS Subcommission on Silurian Stratigraphy (see Koren' *et al.* 1995) for the palaeogeographical reconstructions presented at the James Hall Meeting (Rochester, New York, August 1996).

For the purposes of this paper, graptolite zones are treated as chrons (note that the biostratigraphical term 'biozone' is also used herein, for 'a body of rock strata characterized by its fossil content that distinguishes and differentiates it from adjacent strata'; Boggs, 1995, p. 592).

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For the Llandovery, it is unlikely that the graptolite zonal scheme will be significantly modified in the near future; the majority of the zones shown in Figure 1 can be recognized by graptolite specialists world-wide. However, for parts of the Wenlock (particularly the upper Sheinwoodian and lower Homerian), some problems have been experienced in international correlation (see, e.g. Lenz & Melchin, 1991, fig. 3; Štorch, 1994*a*, fig. 9) and ongoing taxonomic and biostratigraphical studies may result in a refinement or revision of the existing graptolite zonation. Herein, the late Sheinwoodian is referred to simply as the mid Wenlock.

### 1.b. Cause and magnitude of Silurian sea-level changes

Of the various mechanisms suggested (Donovan & Jones, 1979), that most likely to be responsible for the eustatic sea-level changes in the early Silurian is variation in the amount of water incorporated in land-based ice-sheets. This conclusion is based first on the apparent rapidity of many of the sea-level changes (see, e.g. Loydell, 1994) and secondly on the direct evidence of glacial deposits present in the Silurian sequences of Brazil (Grahn & Caputo, 1992) and elsewhere in South America (see Hambrey, 1985).

Obviously, the third (and possibly fourth) order cycles being discussed here are superimposed upon the longer term second order and first order cycles (Haq, Hardenbol & Vail, 1988) linked to global tectonic processes. It is likely, for example, that the particularly high sea-levels of the Telychian and early Sheinwoodian reflect the coincidence of interglacial 'greenhouse' conditions with an increase in the volume of oceanic ridges.

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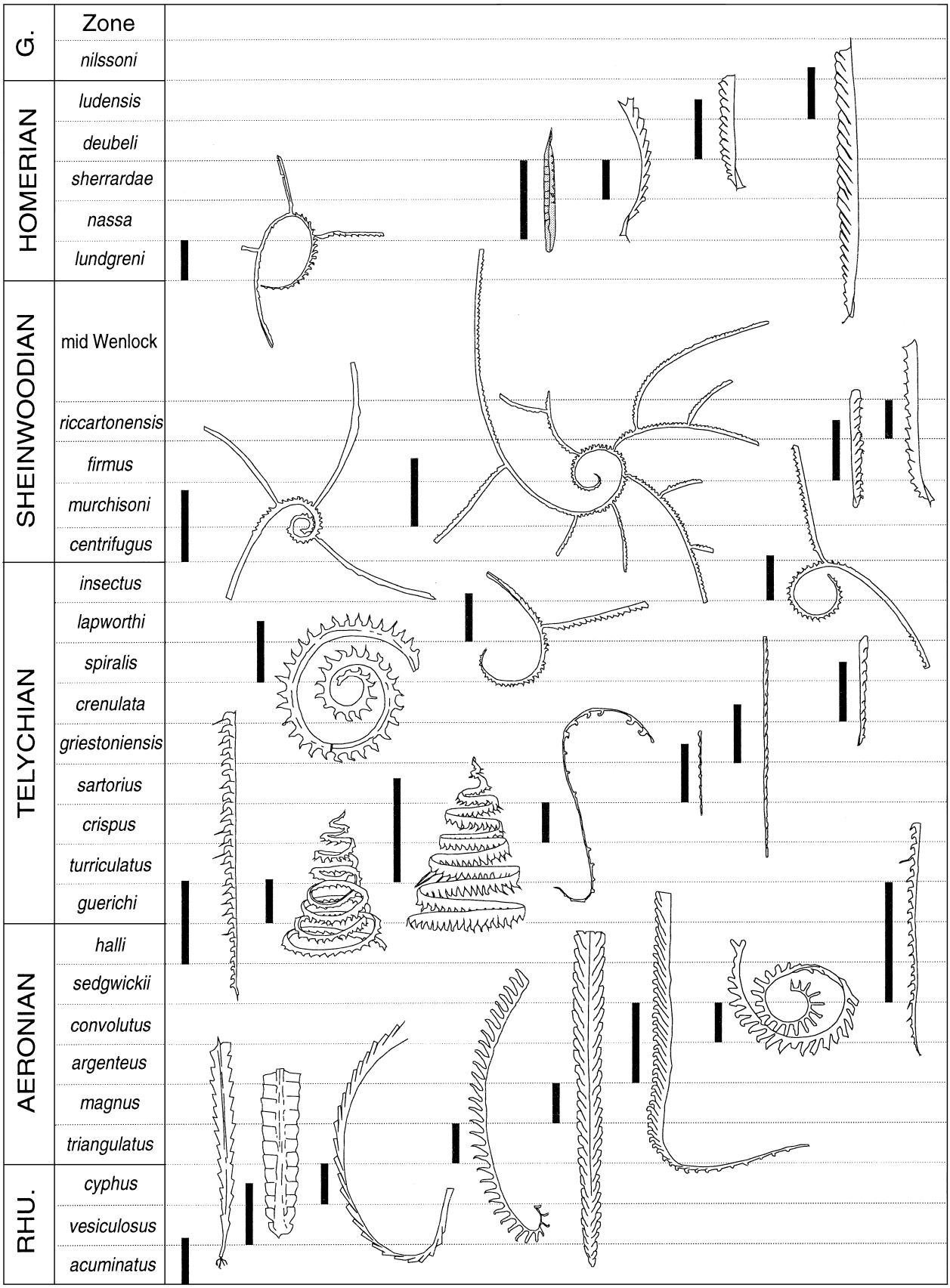



Figure 1. Early Silurian graptolite zones, with illustrations of zonal index species (×2, except for *Cyrtograptus* species which are ×1), and their stratigraphical ranges.

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Determination of the magnitude of sea-level change is dependent upon one's ability to gauge water depth at the time of deposition. This is exceedingly difficult to do precisely, particularly where deposition was occurring below storm wave base, which appears to be the case for many of the graptolitic shale occurrences documented herein. It is for this reason that the sea-level curve in Figure 3 lacks an absolute scale.

Those sea-level curves presented previously which have indicated in absolute terms the magnitude of sea-level change (e.g. in Ross & Ross, 1996, > 60 m difference between lowest and highest Silurian sea-levels) were based on estimates of the depth ranges of benthic assemblages (Ross & Ross used the depth range estimates of Johnson, 1987). Although Brett, Boucot & Jones (1993, p. 37) have suggested that 'The absolute depths suggested by diverse lines of evidence are remarkably accordant' and that, with very few exceptions, 'all prior depth estimates for particular benthic assemblages are within a few meters of each other', other authors (e.g. Aldridge, Jeppsson & Dorning, 1993; see Section 1.d.4) have questioned the validity of using benthic assemblages as indices of water depth.

Recently, Rong & Johnson (1996) and Johnson, Rong & Kershaw (in press) have used evidence from the marine submergence of palaeotopographical features of known relief to demonstrate that sea-level rises in the Rhuddanian and Aeronian were greater than 70 m and 65 m respectively.

### 1.c. Time-scale

Whichever of the published Silurian time-scales is used (see, e.g. Holland, 1989; Harland *et al.* 1990; Tucker *et al.* 1990; Fordham, 1992; Hughes, 1995), the duration of each graptolite zone (Fig. 1) is, on average, considerably less than one million years. Some of the sea-level changes recognized herein have been dated with subzonal precision, perhaps to the nearest (very) few hundred thousand years. This, of course, is still very imprecise when one considers the magnitude and frequency of sea-level changes in the Quaternary (see, e.g. Goudie, 1992).

### 1.d. Methodology

#### *1.d.1. Sea-level rises*

The methodology used is basically very simple. To quote Leggett (1980, p. 139), 'carbon preservation in sediments, both in deep marine and shelf environments, occurs preferentially during phases of eustatic transgression.' Herein, eustatic rises in sea-level are recognized largely on the basis of the contemporaneous appearance of graptolitic dark grey laminated shales and mudstones in the shelf sequences of different palaeocontinents; because of the presence of graptolites, precise dating is often possible.

Offshore, periods of transgression commonly gave rise to condensed sequences and thus it is important that sections are sampled at closely spaced intervals. For example, in the Ohesaare core (Saaremaa, Estonia) the thickness of strata represented by the *proteus* Sub-biozone (penultimate sub-biozone of the *turriculatus* Biozone) through to the lower *griestoniensis* Biozone (that is, approximately three biozones) is less than two metres (fortunately, in the study of Loydell, Kaljo & Männik (in press) this interval was covered by eight graptolitic samples). The condensed nature of sequences deposited during rises in sea level enhances the likelihood of their obliteration by erosion and/or bioturbation during subsequent regressions. For this reason, some sea-level rises may have been overlooked in the past (and in the account below).

Leggett (1978, p. 168) highlighted a means of recognizing short-duration sea-level rises during periods of generally low sea-levels: 'thin seams of carbonaceous shale may represent relatively short phases of interglacial melting, enhanced productivity, density stratification and pelagic-carbon preservation in much the same way as the thin basin-wide sapropel seams that were deposited in the Mediterranean during the glacial Pleistocene.'

The pronounced differences in graptoloid diversity between shallower shelf environments (low diversity faunas, dominated by stratigraphically long ranging taxa) and deeper shelf environments (high diversity faunas, often including stratigraphically short-ranging taxa) has long been recognized (see, e.g. Elles, 1939), although it has been explained in different ways: Berry (1962), Berry & Boucot (1972) and Kaljo (1978) invoked depth zonation; others (e.g. Watkins & Berry, 1977; Loydell, 1993*a*) have provided convincing evidence for water mass specificity being the major control on local graptoloid distribution patterns in the Silurian. Whatever the explanation, it is clear that where a graptolitic stratum bearing a high diversity of graptolites occurs in a shelf sequence, the indication is that water depth was considerable (probably many tens to more than one hundred metres). (Rong, Johnson & Yang, 1984, used graptoloid diversity as one of their depth indices in their study of Llandovery sea-level changes in China.)

#### *1.d.2. Sea-level falls*

The precise dating of regressions in shallow water facies is not easy: graptolite faunas are sparse and usually comprise stratigraphically long-ranging taxa (Loydell, 1994). Integration of the graptolite biozonation with those based on conodonts, chitinozoans, brachiopods, etc. (traditionally used for shallower water facies) is at an early stage (see Loydell, Kaljo & Männik, in press), and thus for a considerable part of the Silurian it remains essentially impossible to correlate precisely from shallow water (shelf/shelly) facies into deep water (basinal/graptolitic facies). A further difficulty with the dating of regressions is that in shallow water sequences a regression may result in erosion and/or emergence and thus the removal of previously deposited

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strata and/or a period of non-deposition. In the Ohesaare core, for example, most of the Aeronian and the lower part of the Telychian is not represented (beds yielding *proteus* Sub-biozone faunas directly overlie latest Rhuddanian or early Aeronian strata; Loydell, Kaljo & Männik, in press). Thus there is no record of the various mid Aeronian to early Telychian sea-level changes (see below). Reliance in the past primarily on data from shelly, shallow-water sequences is perhaps one reason why previously constructed sea-level curves in general show fewer fluctuations than the sea-level curve presented herein (see Section 3.1 below).

Deeper water sequences can, however, prove useful in the dating of regressions, where predominantly graptolitic shales are interbedded with coarser, turbiditic and/or bioturbated beds. The former indicate transportation, erosion and redeposition of shelf-derived sediments, and the latter indicate oxygenation of bottom waters; both are characteristic of glacial periods, of lowered sea-level.

#### *1.d.3. Distinguishing tectonic from climatic signals*

Distinguishing tectonic, as opposed to climatic, signals in sedimentary sequences is an essential component of any study of eustatic sea-level changes. During the Silurian, some regions, particularly those bordering the closing Iapetus Ocean, were tectonically active. At times, the influence of local tectonism was greater than, and worked in opposition to, that of global sea-level change (e.g. throughout much of the Silurian after the early Telychian in South China (Johnson, Rong & Yang, 1985); in the Welsh Basin, during the Rhuddanian (Davies & Waters, 1995) and *gemmatus* Subzone (*guerichi* Zone, early Telychian; Loydell, 1994)). At other times the effects of local tectonism may have been to amplify those attributable to eustatic sea-level change (e.g. during the *utilis* Subzone (late *guerichi*–early *turriculatus* Zone) in the Welsh Basin; Dobson, 1995). Tectonism was often accompanied by volcanic activity (e.g. in the Prague Basin, particularly from the mid Sheinwoodian onwards; Štorch, 1994*a*).

#### *1.d.4. Benthic communities*

In part because of uncertainties with regard to the precise correlation of graptolite biozones with the divisions of the Silurian based on brachiopod evolutionary lineages (e.g. Johnson *et al.* 1991, p. 319; Johnson, Kaljo & Rong, 1991, p. 151; Loydell, 1994, p. 363), the extensive benthic community data collected by Markes Johnson and co-workers, used to generate previous sea-level curves for the Silurian (see Johnson, Kaljo & Rong, 1991, and Johnson, 1996, for summaries), is not included in the present work. Some authors (e.g. Jeppson, 1990; Aldridge, Jeppsson & Dorning, 1993, p. 501) have urged considerable caution 'in inferring sea-level fluctuations directly from changes in benthic communities', suggesting that the distribution of these communities could 'have been affected by many environmental parameters, including energy state, nutrient supply, clastic input, oxygen concentration, and light penetration, all of which can vary in response to climatic change without any variation in sea-level.'

#### *1.d.5. Temporal graptoloid diversity changes*

Loydell (1994) highlighted the inverse relationship between global sea-level and total world-wide graptoloid diversity, using the nutrient-supply models of Valentine (1971) and Hallock (1987) to explain this. To avoid any possible circularity in the arguments presented previously and below, temporal graptoloid diversity changes are not used herein as evidence for the timing and/or magnitude of specific sea-level fluctuations. It is clear, however, that there is a good correlation between sea-level and graptoloid diversity: e.g. in the early *sedgwickii* Zone, *utilis* Subzone, mid *lapworthi* Zone, late *firmus* Zone and early *nassa* Zone, all periods of falling or low sea-level (Fig. 3), graptoloid diversity declined (Štorch, 1995). Similarly, the *convolutus*, early *guerichi*, and *spiralis* zones and the early Sheinwoodian were all times of both high graptoloid diversity (Štorch, 1995) and rising or high sea-level (Fig. 3).

#### *1.d.6. Dating of sequences*

Such has been the extent of graptolite taxonomic revision in recent years that the majority of published unillustrated faunal lists cannot be taken at face value. The evidence presented below is based, therefore, almost entirely on sections the faunas of which have been either studied by the author or have been illustrated well enough for verification of identifications without recourse to examination of the original specimens. Evidence from unillustrated faunal lists has been accepted only where the likelihood of misidentification of the graptoloid reported (e.g. *Cephalograptus cometa* (Geinitz)) is extremely slim.

#### *1.d.7. Construction of the sea-level curve*

As note above (Section 1.b), the absolute magnitude of sea-level changes in the Silurian is not known precisely and is difficult to estimate. The sea-level curve presented in Figure 3 portrays an estimate of the relative magnitude of Silurian sea-level changes. Those changes which had a pronounced effect on the nature of contemporaneous deposition on several palaeocontinents have been accorded greater magnitude than those for which facies changes were less pronounced or more limited in their palaeogeographical extent.

## 2. Sea-level changes

Evidence for the various early Silurian sea-level changes is given below. The palaeocontinents are dealt with separately. Data from Pearya, which collided with Laurentia

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during the early Silurian, is included with that for Laurentia. Figure 2 illustrates the palaeogeographical extent of the 'database' used for producing the new sea-level curve.

### 2.a. Rhuddanian to early Aeronian sea-level rise

The Rhuddanian to early Aeronian has been depicted as a period of rapidly rising sea-level (Johnson, Kaljo & Rong, 1991; Johnson, 1996) resulting from melting of Gondwanan ice sheets. As the fact that sea-level rose at this time seems to be universally accepted, all that is recorded below is a representative selection of data first regarding the timing of onset and duration of deposition of graptolitic shales in shallow marine settings on the various palaeocontinents, and secondly suggesting temporary reversals in this transgressive trend. The latter have been recognized before by, for example, Johnson *et al.* (1991) in Estonia (Baltica), based on brachiopod community displacements, and by Ross & Ross (1996) in North America (Laurentia), based on lithofacies analysis. Sea-level reached a maximum in the early Aeronian *triangulatus* to (?early) *magnus* zones.

#### *2.a.1. Laurentia*

In the Craighead inlier, northeast of Girvan, the Rhuddanian formations demonstrate a progressive diminution in grain-size and increase in palaeo-water depth of deposition. The lowest formation, the Lady Burn Conglomerate 'was deposited in shallow water' and is probably of mid Rhuddanian age (Cocks & Toghill, 1973, p. 213). The overlying Mulloch Hill Formation contains a diverse shelly fauna and is dominated by sandstones, with interbedded shales and siltstones. The succeeding Glenwells Shale Formation consists of sparsely graptolitic, laminated grey shales assigned to the upper *cyphus* Biozone by Cocks & Toghill (1973, p. 214). Similarly, in the 'Main Outcrop' (Cocks & Toghill, 1973) in the Girvan area, the basal layers of the Tralorg Formation (the lowermost formation of the Silurian), consisting of greyish brown concretionary mudstones, with echinoderm fragments and rare brachiopods, are overlain by 'black pyritic graptolitic mudstones with thin grey mudstones' (Cocks & Toghill, 1973) of *cyphus* Zone age.

The lower Aeronian in the Girvan area is represented by coarser-grained formations: in the Criaghead inlier these are the Glenwells Conglomerate Formation ('probably not deposited under shallow water': Cocks & Toghill, 1973, p. 215) and the Newlands Formation (calcareous siltstones and occasional sandstones); in the 'Main Outcrop' the approximately equivalent strata form the turbiditic Saugh Hill Grits Formation. Given the evidence from elsewhere for high sea-levels in the early Aeronian it is suggested that the presence of these coarse-grained formations in the Girvan area is a result of local tectonic activity.

In the Craighead inlier, the Newlands Formation is overlain by the Glenshalloch Shale Formation, the upper part of which has yielded a rich graptolite fauna, assigned to the *magnus* Biozone by Cocks & Toghill (1973, p. 216). This suggests a cessation of the earliest Aeronian tectonism and a reversion to deposition of fine-grained sediment during a period of high sea-level.

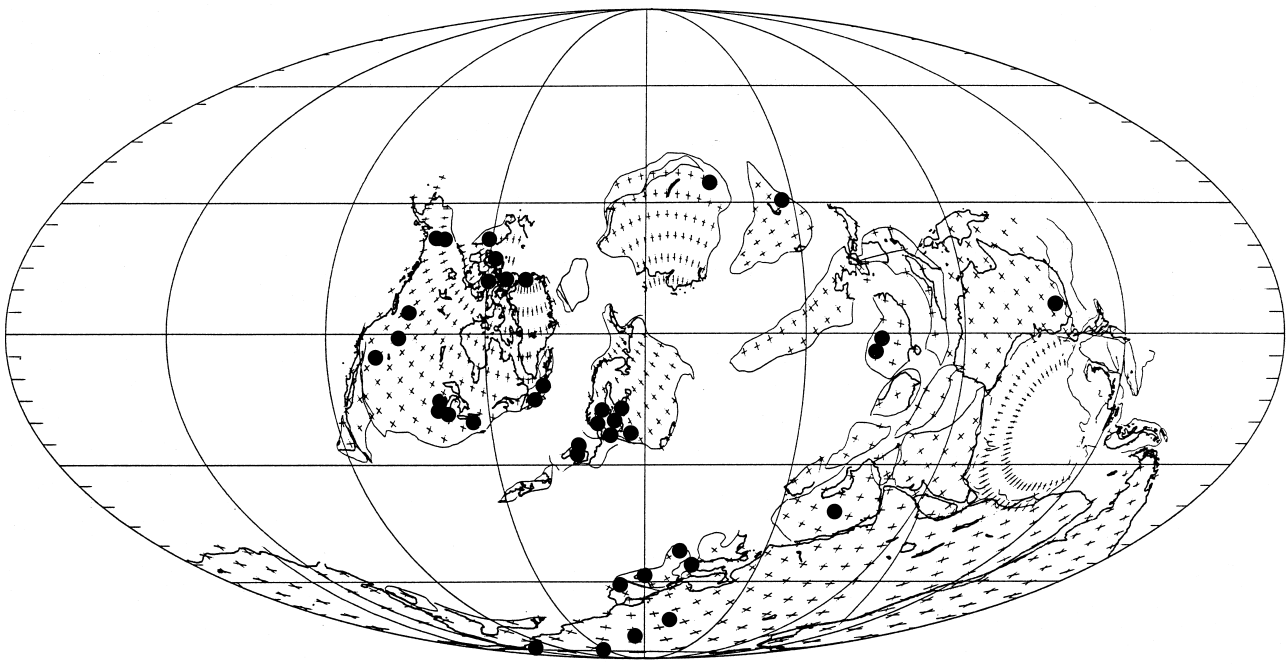


Figure 2. Llandovery world palaeogeography (after Scotese & McKerrow, 1990), with locations (black circles) of sections used in the construction of the new global sea-level curve for the Early Silurian.

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*2.a.2. Baltica*

In the Silvberg section (Dalarna, Sweden), the Rhuddanian is predominantly 'mudstone and limestone with rather scarce brachiopods' (Waern, 1960, p. 127). Graptolitic shales appear in the upper part of the Rhuddanian; these shales become increasingly darker in the lower Aeronian (*triangulatus* and *magnus* biozones). At Gulleråsen-Sanden (also in Dalarna), the lowermost graptolitic shales are, similarly, latest Rhuddanian in age (Waern, 1960, p. 129).

On the island of Malmøya, south of Oslo, Norway, the 'shale-dominated sequence of the Solvik Formation reflects the rapid early Silurian transgression' (Worsley *et al*. 1983, p. 15). Graptolites are very sparse except for close to the base of the Silurian, where the diplograptoid assemblages are predominantly monospecific, and in the uppermost Rhuddanian/lowermost Aeronian (Howe, 1982; based on the presence of *Pseudorthograptus obuti* (Rickards & Koren')).

*2.a.3. Gondwanan periphery*

A possible mid or late Rhuddanian fall in sea-level is suggested by some sections in the Prague Basin, e.g. Loděnice (Štorch, 1986, p. 73), where early Aeronian strata unconformably overlie *acuminatus* Biozone graptolitic shales.

The Silurian of the Carnic Alps of southern Austria is dealt with under this heading for convenience, despite Schönlaub's (1994*a*) suggestion that this area lay midway between Gondwanaland and Baltica (cf. Scotese & McKerrow, 1990). In the Oberbuchach 1 section (Jaeger & Schönlaub, 1980; Schönlaub, 1994*b*) the only pre-Telychian dark grey graptolitic shales are of *triangulatus* Zone age; they yield a rich fauna including the index species. The graptolitic beds are both underlain and overlain by quartzites. This is consistent with an early Aeronian sea-level highstand, both preceded and succeeded by periods of lower sea-levels.

*2.a.4. Gondwana*

In the Panuara area of central New South Wales, Australia, the oldest graptolitic mudstones (Avon Lea Mudstone Member of the Cadia Coach Shale Formation) are of early Aeronian age. The Cadia Coach Shale Formation overlies the interbedded limestone-clastic Bagdad Formation (Jenkins, 1978; Jell & Talent, 1989).

**2.b. Mid Aeronian sea-level changes**

The mid Aeronian is defined herein as the *argenteus* and *convolutus* zones. In many cratonic areas, non-sequences span much of the Aeronian. In part this may be a result of *sedgwickii* Zone and/or *utilis* Subzone (late *guerichi*–early *turriculatus* zones) erosion/emergence, but it also reflects a significant pre-*convolutus* Zone sea-level fall. Evidence, given below, from those sequences in which the middle Aeronian *is* represented indicates that the highest sea-levels of the mid Aeronian occurred late in the *convolutus* Zone, immediately prior to the major sea-level fall of the *sedgwickii* Zone. Although low sea-levels characterized the *argenteus* Zone, thin beds of dark grey graptolitic mudstone in the otherwise barren mudstones of this biozone in sections in Laurentia and Eastern Avalonia, suggests at least one (and probably more) brief sea-level rise(s) during the zone.

*2.b.1. Laurentia*

The Dob's Linn sequence is remarkably similar to those of Eastern Avalonia (see below) with regard to the level in the Aeronian at which the sequence ceases to be dominated by black graptolitic mudstones. Toghill's (1968) horizon 30 bears a *magnus* Biozone fauna. This balck shale marks the end of the early Aeronian sea-level highstand. Above horizon 30, non-graptolitic mud- and claystones predominate, with thin, interbedded black graptolitic mudstones, supporting the suggestion of a mid Aeronian fall in sea-level, punctuated by minor reversals. The beds of black shale become more frequent in the *convolutus* Biozone, marking a sea-level rise.

For the northern Yukon, Lenz (1982, p. 1923) noted that 'a middle Llandovery restriction in graptolitic lithofacies and biofacies suggests a mild regression.'

In the Trail Creek area, central Idaho, graptolitic shales of *convolutus* Zone age unconformably overlie late Ordovician strata (Carter & Churkin, 1977).

In parts of northeastern Russia, *convolutus* Biozone graptolitic shales unconformably overlie Ordovician strata (see, e.g. Obut, Sobolevskaya & Nikolayev, 1967, sections XII and XIV).

*2.b.2. Baltica*

Johnson, Kaljo & Rong (1991, p. 154) expressed their concern about the reported age of the uppermost dark grey to nearly black graptolitic shales of the Aeronian of Bornholm. Graptolites from these shales were assigned to the uppermost part of the *convolutus* Biozone by Bjerreskov (1975). Johnson, Kaljo & Rong noted, however, that the fauna included *Cephalograptus extrema*, a species described originally from the *sedgwickii* Biozone of Bohemia and Germany (Bouček & Přibyl, 1941). On this basis they stated: 'It may be that the mid-Aeronian high stand in sea-level bridges the top of the *M. convolutus* Biozone and the bottom of the *M. sedgwickii* Biozone.' *Ce. extrema* has, however, been recorded also from the uppermost part of the *convolutus* Biozone in the English Lake District (Hutt, 1974), Poland (Tomczyk, 1962) and Bohemia (P. Štorch, pers. comm., 1997); in the absence of typical lower *sedgwickii* Biozone taxa (e.g. *Lagarograptus tenuis* (Portlock), *Stimulograptus sedgwickii* (Portlock)) from Bornholm, there seems no reason to doubt Bjerreskov's (1975) original assignation of the fauna to the *convolutus* Biozone. It is of course possible, however, that high sea-levels did continue into the earliest

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*sedgwickii* Zone and that the graptolitic strata deposited then were subsequently bioturbated when the sea-bottom became oxygenated later in the *sedgwickii* Zone (see below).

In the Kullatorp (Kinnekulle, Vestergötland, Sweden) core the strata of the *convolutus* Biozone consist 'almost entirely of black laminated shale' (Waern, 1948). This shale is underlain by unfossiliferous interbedded limestones and mudstones.

In the Silvberg section (Dalarna, Sweden), Waern (1960) reports the presence of a thin conglomerate between dark shales yielding triangulate monograptids (*triangulatus* and/or *magnus* biozone(s)) and dark grey graptolitic shales of the *convolutus* Biozone. A conglomerate occurs at a similar level in the Gulleråsen-Sanden section (also in Dalarna; Waern, 1960, p. 129), where it is overlain by dark graptolitic shales of the *convolutus* Biozone.

In the Dębniak core (near Nowa Słupia, Poland: Tomczyk, 1962), the lower Aeronian is absent. Above an unconformity and overlying late Rhuddanian strata is a thin sequence (approx. 5 m) of mid Aeronian claystones and siltstones, with an intercalated black graptolitic shale horizon yielding *Cephalograptus cometa* (Geinitz), a species indicating the upper part of the *convolutus* Biozone. This sequence is in turn terminated by another unconformity. This is consistent with an *argenteus* Zone sea-level fall, followed by a *convolutus* Zone sea-level rise, in turn followed by a *sedgwickii* Zone sea-level fall (see below). In most of the other sections illustrated by Tomczyk (1962, fig. 4) the middle Aeronian is largely or completely absent (probably eroded away during the *sedgwickii* Zone, assuming that deposition had occurred at times during the mid Aeronian).

#### *2.b.3. Eastern Avalonia*

In Shropshire, *convolutus* Biozone graptolites occur in a transgressive sequence, in the 'Pentamerus Beds' of the Hamperley borehole (Cocks & Rickards, 1969).

In the Llangollen area of northeastern Wales, where Rhuddanian–Aeronian sequences are dominated by bioturbated and unfossiliferous or sparsely fossiliferous strata, the *convolutus* Biozone is conspicuous in being represented by black and dark grey graptolitic mudstones and shales (Wills & Smith, 1922).

Between Llangollen and Hamperley lie the Berwyn Hills, in the western part of which Llandovery strata of pre-mid Telychian age are absent or largely absent (Cave in Bassett *et al*. 1992). This suggests that tectonic uplift in this area was of greater significance than eustatic sea-level changes.

At Llanystumdwy, northwest Wales (Baker, 1981), graptolitic mudstones of *magnus* Zone age are overlain by 3 m of generally barren grey mudstones, in the midst of which lies a silty and calcareous mudstone band which has yielded a trilobite fauna. This is highly suggestive of a late *magnus* Zone or early *argenteus* Zone sea-level fall. Black graptolitic mudstones, yielding an *argenteus* Biozone fauna overlie the barren mudstones. The *convolutus* Biozone at Llanystumdwy is unusual in being identified in only one thin, black graptolitic mudstone within otherwise barren mudstones.

In the Howgill Fells the nature of the mudstones changes above (or in?) the *magnus* Biozone (Rickards, 1970). Whilst the Rhuddanian and lower Aeronian consist entirely of graptolitic mudstones there is only one thin (150 mm) graptolitic band (containing an *argenteus* Biozone fauna) in the succeeding 9 m of mudstones. Lake District sections are very similar (Hutt, 1974), as indeed are those in mid Wales (e.g. Jones, 1909), and at Dob's Linn (Laurentia, see Section 2.b.1, above).

#### *2.b.4. Gondwanan periphery*

In the Carnic Alps a post-*triangulatus* Zone sea-level fall is suggested by the early Aeronian graptolitic strata in the Oberbuchach 1 section being overlain by quartzites (Jaeger & Schönlaub, 1980; Schönlaub, 1994*b*).

In the Frankenwald (northeast Bavaria) a paucity of mid Aeronian graptolitic strata is apparent in the sections described by Stein (1965).

Štorch (1986, p. 73) noted that in the Řeporyje area of the Prague Basin graptolitic strata of *convolutus* Zone age unconformably overlie earliest Silurian black shales.

In eastern Serbia sandstones overlie graptolitic shales; the latter yielded early Aeronian graptolites to Mihajlović (1974).

In the Orihuela del Tremedal section in the Tremedal massif of the Western Iberian Cordillera, Spain, the only Aeronian graptolitic shale is of *convolutus* Zone age. This lies within the Los Puertos Quartzite Formation, which is dominated by sandstones and breccias, the latter immediately underlying the graptolitic shale (Gutiérrez-Marco & Štorch, 1998).

#### *2.b.5. Gondwana*

It is noteworthy that the lower part of the Qusayba Member of the Tabuk Formation of central Saudi Arabia is a graptolitic shale of *convolutus* Zone age (McClure, 1978; El-Khayal, 1985, 1986, 1987*a*,*b*,*c*). This is the only graptolitic shale recorded from either the Rhuddanian or Aeronian of central Saudi Arabia.

In the Panuara area of central New South Wales, Australia, Telychian limestones unconformably overlie the early Aeronian Cadia Coach Shale Formation (Jenkins, 1978; Jell & Talent, 1989). The uppermost member of the formation, the 'Upper Sandstone Member' of Jenkins (1978) was suggested by Jenkins to indicate regression (the continuation of which is indicated by the unconformity). Graptolites from the underlying member include *Coronograptus gregarius* (Lapworth).

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### 2.c. *Stimulograptus sedgwickii* Zone sea-level fall

A eustatic fall in sea-level during the *sedgwickii* Zone is indicated from facies changes on many palaeocontinents. The precise timing of this sea-level fall remains problematical, however, and it may be that there were several rapid fluctuations in sea-level during this zone. The widespread occurrence of dark grey graptolitic shales of early *sedgwickii* Zone age in Great Britain (and at localities in Sweden) suggests a continuation of the high sea-levels of the late *convolutus* Zone, with regression occurring in the mid–late *sedgwickii* Zone. In other areas, however, evidence for early *sedgwickii* Zone high sea-levels is generally lacking, with most sequences indicating regression. The question remains as to whether the lower *sedgwickii* Biozone of Eastern Avalonia (and, to a lesser extent, Baltica) is recording high sea-levels of global extent (with the record of this period having been destroyed elsewhere by subsequent erosion or bioturbation) or whether these otherwise anomalous records of graptolitic shales in the *sedgwickii* Biozone are the consequence of local bottom water anoxicity caused by factors such as increased isolation (from oceans) of marginal basins, resulting from eustatic sea-level fall.

#### *2.c.1. Laurentia*

The Pencleuch Shale (*convolutus* Biozone) in the Girvan area is overlain, above a tectonically induced hiatus, by the Lower Camregan Grits Formation which, in turn, is overlain by the Wood Burn Formation; both are sandstone-dominated formations. The latter has yielded only *Stimulograptus sedgwickii* (Portlock), indicating the *sedgwickii* Biozone (examination of the Gray Collection in The Natural History Museum has shown that, contrary to Cocks & Toghill's (1973, p. 226) observation, *Stimulograptus halli* (Barrande), the presence of which would indicate the *halli* Biozone, is not present: Loydell, 1992, p. 16). The Wood Burn Formation fines upwards, perhaps reflecting the beginning of the sea-level rise which culminated in the *guerichi* Zone (early Telychian), and which succeeded the *sedgwickii* Zone sea-level fall, although because of the tectonic activity in the area (see also Section 2.e.1), some caution should be exercised in interpreting the facies changes in the Girvan area as resulting from eustatic sea-level change alone.

At Dob's Linn (Toghill, 1968), immediately above black mudstones with a diverse graptoloid fauna including *Cephalograptus cometa* (Geinitz), are grey mudstones and claystones, without graptolites. Above this lie approximately 2 m of dominantly graptolitic mudstones. These in turn are overlain by approximately 4 m of mostly non-graptolitic mud- and claystones, with layers of calcareous nodules towards the top. This sequence can be interpreted as indicating generally lowered sea-levels in the *sedgwickii* Zone, but with intervals (interglacials?) during which sea-level rose and dark grey graptolitic muds were deposited.

At Huff Ridge, on Ellesmere Island in the Canadian Arctic, between graptolitic strata of *convolutus* and *guerichi* Zone age are several thick limestone beds (total thickness 23 m). At Trold Fiord, Ellesmere Island and Twilight Creek, Bathurst Island, there is a similar non-graptolitic limestone interval between the *convolutus* and *guerichi* biozones; at these two localities it is only 1.5–2 m thick (Melchin, 1989).

#### *2.c.2. Baltica*

Johnson, Kaljo & Rong (1991) cited evidence from the work of Bjerreskov (1975) for a sea-level fall during the *sedgwickii* Zone. Bjerreskov (1975, p. 11) recorded 'a sudden change in lithology', 'within a vertical distance of 1 cm [from the top of the 'dark grey to nearly black' richly graptolitic shales of the upper part of the *convolutus* Biozone – the *cometa* band] the shales change to light grey, argillaceous and silty mudstone'; these mudstones are heavily bioturbated. As they are sandwiched between graptolitic shales of late *convolutus* Zone and early *guerichi* Zone age, it can be safely assumed that they were deposited during the late Aeronian *sedgwickii* and *halli* zones. Likewise, in the Kullatorp (Kinnekulle, Vestergötland, Sweden) core the black graptolitic shales of the *convolutus* Biozone are overlain by greyish green mudstones with a sparse coral and brachiopod fauna (Waern, 1948). However, in the Silvberg and Gulleråsen-Sanden sections of Dalarna (Sweden), Waern (1960, p. 129) records finely laminated black shales bearing *Stimulograptus sedgwickii* (Portlock) above those of the *convolutus* Biozone.

#### *2.c.3. Eastern Avalonia*

The belief that the black, laminated hemipelagites of the *sedgwickii* Biozone of the Welsh Basin were deposited during a period of widespread marine transgression stems from Cave (1979; see also Davies & Waters, 1995; Woodcock *et al.* 1996). An alternative interpretation was proposed by Loydell (1994, p. 364) who explained the occurrence of graptolitic black mudstones in the lower part of the *sedgwickii* Biozone as a consequence of increased isolation of the semi-enclosed Welsh Basin from the remnant Iapetus Ocean. A similar explanation had been provided for the presence of black shales in the Ludlow of the Welsh Basin by Leggett *et al.* (1981).

In the Llangollen area of northeast Wales (Wills & Smith, 1922), there is a non-sequence above the graptolitic mudstones and shales of the *convolutus* Biozone suggesting post-*convolutus* Zone non-deposition/erosion/?emergence. Sedimentary deposition appears not to have resumed until the Telychian.

At Llanystumdwy, northwest Wales (Baker, 1981), between graptolitic *convolutus* Biozone and Telychian strata, occur 10.35 m of generally barren grey mudstones. Within these mudstones there is one horizon of trilobitic calcareous nodules, and only one thin black graptolitic mudstone. In the Spengill section of the Howgill Fells the

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*sedgwickii* Biozone is in part represented by limestones (Rickards, 1970), the only occurrence of this lithology in the Llandovery of this section. Underlying strata are mudstones, both non-graptolitic and graptolitic, the latter yielding a *convolutus* Biozone assemblage. A *sedgwickii* Zone fall in sea-level is suggested by both the Llanystumdwy and Spengill sequences.

#### *2.c.4. Gondwanan periphery*

In the northwest part of the Prague Basin barren green or yellow mudstones and claystones (locally with thin black graptolitic shale intercalations) overlie the graptolitic shales and cherts (*convolutus* Biozone) of the Želkovice Formation (Štorch, 1994*a*). In the Řeporyje area, these bioturbated yellow-grey claystones unconformably overlie the graptolitic laminites and shales of the *convolutus* Biozone (Štorch, 1986, p. 73); the claystones here are overlain by dark grey shales of the *turriculatus* Biozone. The indication here is of a post-*convolutus* Zone sea-level fall.

#### *2.c.5. Gondwana*

El-Khayal (1985) described the beds overlying the graptolitic shales of the Qusayba Member, Saudi Arabia (see Section 2.b.5, above). These are gypsiferous and contain thin beds of red, haematitic siltstone coarsening upwards into poorly sorted, grey, medium-grained, thin-bedded sandstones. El-Khayal (1987*a*) noted that these beds are also ripple-marked and have a variety of horizontal and vertical burrows. This upper part of the Qusayba Member has not been dated, but clearly indicates regression following the transgression responsible for the deposition of the *convolutus* Biozone graptolitic shales. The Qusayba Member in the sections studied by McClure (1978) and El-Khayal is unconformably overlain respectively by Devonian and Permian strata, and a Quaternary duricrust, so no evidence for later Silurian sea-level changes is available from this area.

#### *2.c.6. South China*

Loydell (1992, p. 17) noted that there appear to be no graptolitic strata of *sedgwickii* or *halli* Zone age in the sections in southern Shaanxi described by Chen (1984), with collections from successive beds yielding respectively *convolutus* Biozone and *guerichi* Biozone graptoloid faunas. If confirmed, this would be consistent with a late Aeronian sea-level fall.

#### *2.c.7. Siberia*

Yolkin *et al.* (1997) analysed the cyclic nature of Silurian sedimetation in southwest Siberia. They identified (fig. 5) a major sea-level fall at the *convolutus–sedgwickii* zone boundary. This was followed by transgression (the Syrovatiy event).

### 2.d. *Spirograptus guerichi* Zone sea-level rise

Sea-level rose early in the Telychian (early *guerichi* Zone; see Loydell, 1994), but transgressive facies have not yet been recorded from all palaeocontinents. In some cases this may be because the thin transgressive deposits were obliterated by *utilis* Subzone regression. In the past, there has been some confusion of this earliest Telychian sea-level rise with that of the late *turriculatus* Zone (see Sections 2.e and 2.f, below).

#### *2.d.1. Laurentia*

At Irene Bay, in the most nearshore of the Ellesmere Island (Canadian Arctic) sections described by Melchin (1989), the oldest Silurian strata are of *guerichi* Zone age. They are laminated argillaceous dolostones with thin shaly interbeds. They unconformably overlie late Ordovician dolostones. The oldest Silurian graptolitic strata (laminated argillaceous limestones with thin shaly interbeds) of Middle Island (a small island north of Melville Island (see Melchin, 1989, fig. 1)) are similarly of *guerichi* Zone age.

#### *2.d.2. Baltica*

Graptolitic shales of *guerichi* Zone age are known from central Sweden (see, e.g. Hutt, Rickards & Skevington, 1971; Loydell, 1991; Loydell, Štorch & Melchin, 1993), Lithuania (Paškevičius, 1979) and from core samples from 33 km northeast of the island of Rügen, in the Baltic Sea (Maletz, 1997).

On Bornholm (Bjerrskov, 1975), light grey and finely laminated graptolitic mudstones of early *guerichi* Zone age overlie the bioturbated beds of the upper Aeronian (see Section 2.d.2).

#### *2.d.3. Gondwanan periphery*

In many sections in Spain and Portugal, the widespread early to mid Llandovery sandstones (e.g. the ‘Criadero Quartzite’ and ‘Los Puertos Quartzite’) are overlain by black graptolitic shales of the *guerichi* Biozone (Garcia Palacios, Gutiérrez-Marco & Herranz Araújo, 1996; Gutiérrez-Marco & Štorch, 1998), indicating earliest Telychian transgression.

#### *2.d.4. Gondwana*

Graptolitic shales and siltstones of *guerichi* Zone age occur in the Forbes district of New South Wales, Australia (Sherwin, 1974).

#### *2.d.5. South China*

Transgression across the Yangtze platform is recorded by the Nanjiang Formation of northern Sichuan (Johnson, Kaljo & Rong, 1991, p. 155). At Qiaotin, the formation disconformably overlies the upper Ordovician and is

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richly graptolitic, the faunas having been studied originally by Chen (1984) and restudied by Loydell (1992, pp. 20–1; 1993*a*, pp. 334–5). The lower part of the Nanjiang Formation bears a *Spirograptus guerichi* Biozone fauna.

#### 2.e. *Stimulograptus utilis* Subzone sea-level fall

A *utilis* Subzone (late *guerichi*–early *turriculatus* zones) sea-level fall was proposed by Loydell (1994), who suggested that it might be equivalent to the early Telychian sea-level fall of Johnson, Kaljo & Rong (1991). However, as it is now clear that Johnson, Kaljo & Rong had assumed that the *guerichi* Zone and late *turriculatus* Zone sea-level rises were one and the same (see below), this direct correspondence seems less likely.

The brief period of lowered sea-level seems to have lasted into the *johnsonae* Subzone (early *turriculatus* Zone), at some point in which sea-level began to rise again (see Section 2.f.1, below).

##### *2.e.1. Laurentia*

In the Trold Fiord section on Ellesmere Island the transition from *guerichi* to *turriculatus* biozones is marked by limestones. Strata above and below are dominantly calcareous shales and mudstones (Melchin, 1989). Less confidently dated argillaceous limestones are present at a similar level at Huff Ridge, also on Ellesmere Island.

In the Girvan district (Scotland) turbidites of the Upper Camregan Grits Formation lie in between the argillaceous Maxwellston Mudstones (*guerichi* Biozone) and Penkill (upper *turriculatus* and *crispus* biozones) formations. The single graptolitic horizon in the Upper Camregan Grits bears a *johnsonae* Subzone fauna, dominated by *Streptograptus johnsonae* Loydell. This turbiditic influx is consistent with a sea-level fall, as interpreted from other regions, but, given the significant Telychian tectonic activity in the region and the anomalous age of the subsequent turbidite-dominated formation (the Protovirgularia Grits Formation, deposition of which commenced during a global sea-level rise in the late *crispus* Zone), it is accepted that the onset of deposition of the Upper Camregan Grits need not have been prompted by contemporary eustatic sea-level change alone.

##### *2.e.2. Eastern Avalonia*

At Buttington Brick Pit, eastern mid Wales, a thin sandstone less than 1 m above the base of the Tarannon Shales Formation was shown by Loydell & Cave (1993) to be of *johnsonae* Subzone age. The underlying Cefn Formation, of silty mudstones and micaceous sandstones, and containing bryozoans and small compound corals (Loydell & Cave, 1993, p. 95), was deposited in shallower water than the Tarannon Shales and is almost certainly at least in part of *utilis* Subzone age.

Within the Aberystwyth Grits Formation, the coarsest and thickest turbidites are of late *utilis* Subzone age. Dobson (in Dobson, 1995, p. 47) interpreted this period as one of 'fan build-out... when the shelf was exposed'. Loydell (1994, p. 364) had previously noted that for the *gemmatus* Subzone of the *guerichi* Zone 'The extent to which local tectonic activity can mask eustatic sea-level change is demonstrated well by the Welsh Basin' where 'the influence... of uplift and erosion... far outweighed that of rising global sea level.' During the *utilis* Subzone, I suggest that local tectonism and eustatic sea-level fall *combined* to make this the time of maximum early Telychian clastic input into the Welsh Basin.

##### *2.e.3. Gondwanan periphery*

In the Prague Basin of Bohemia (Kříž, 1991) the transition from the Želkovice Formation (dominated by dark siliceous shales) to the overlying Litohlavy Formation is marked by green calcareous shales and clayey limestones, locally containing iron ooliths, termed the Basal Green Shale by Kříž. In the southwestern part of the basin the underlying and overlying graptolitic units have yielded upper *guerichi* and *turriculatus* biozone faunas respectively.

##### *2.e.4. South China*

In the Qiaotin section, Nanjiang, Sichuan, the black, richly graptolitic shales of the lower part of the Nanjiang Formation comprise horizons Ba031–Ba036 of Liu, Chen & Zhang (1964) and Chen (1984, pp. 8–9). This part of the formation is 24.6 m thick and is of *guerichi* Zone age (Loydell, 1992, 1993*a*). Horizon Ba037 marks the transition to more sparsely graptolitic grey-green and yellow green shales. Horizons Ba037–Ba054 lie within these shales. All were assigned to the upper part of the *utilis* Sub-biozone (that is, lowermost *turriculatus* Biozone) by Loydell (1992, 1993*a*). The thickness represented by these beds is more than 100 metres. Thus the late *utilis* Subzone in this area witnessed a sudden and significant increase in the volume of sediment being deposited.

#### 2.f. Late *Spirograptus turriculatus* Zone sea-level rise

A lengthy period of generally high, but fluctuating, sea-levels commenced in the late *turriculatus* Zone. Not until the mid *lapworthi* Zone was there a *major* fall in sea-level.

##### *2.f.1. Baltica*

In the Ohesaare core (Saaremaa, Estonia) the dark grey claystones of the basal Velise Formation contain graptolites indicating the *proteus* Sub-biozone of the upper *turriculatus* Biozone (Loydell, Kaljo & Männik, in press). Johnson *et al.* (1991, p. 329) considered that in the Ohesaare core, 'The unconformity below shales with *M. turriculatus* indicates that the early Telychian highstand involved a major transgression.'

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In the Oslo region of Norway, the lower of the two *turriculatus* Biozone graptolitic horizons in the Ek Formation has yielded *Streptograptus exiguus* (Lapworth), *Monograptus marri* Perner and *Pristiograptus huttae* Loydell (assigned incorrectly by Howe, 1982 to *Pristiograptus nudus* (Lapworth) – see illustrations in M. Howe, unpub. Ph.D. thesis, Univ. Cambridge, 1982). This assemblage suggests the upper part of the *turriculatus* Biozone (that is, post-*Streptograptus johnsonae* Sub-biozone). Worsley *et al.* (1983, p. 49) and Worsley (1989, p. 114) were incorrect in their assignment of these horizons to the *maximus* Biozone (=lower part of the *guerichi* Biozone). Johnson, Kaljo & Rong (1991) considered the deepening event recorded in the Oslo region to have been the same as that recorded in South China. It is now clear, however, that this is not the case. The early Telychian witnessed two sea-level rises, one in the *guerichi* Zone and one in the *turriculatus* Zone. These were separated by the sea-level fall of the *utilis* Subzone.

#### *2.f.2. Eastern Avalonia*

The lowest graptolitic horizon in the Tarannon Shales Formation in the Llanfyllin area of eastern mid Wales was assigned tentatively to the *carnicus* Sub-biozone (uppermost *turriculatus* Biozone) by Loydell & Cave (1996). The onset of deposition of this formation represented an early stage in the transgression. Other biostratigraphical data from eastern mid Wales is provided from Buttington Brick Pit (Loydell & Cave, 1993), in which a sandstone near the base of the formation yielded *Streptograptus johnsonae* Loydell, indicating the *johnsonae* Sub-biozone.

In the English Lake District, Hutt (1974, 1975) recorded *Torquigraptus proteus* (Barrande) from thin graptolitic beds within green mudstones in the lower part of the Browgill Formation. The age is clearly late *turriculatus* Zone (Loydell, 1992, p. 18).

Even in deep basinal turbidite-dominated settings, the influence of the late *turriculatus* Zone sea-level rise *may* be apparent (although a diversion of detrital supply to feed the Rhuddnant Grits Fan to the east is an alternative explanation; R. Cave, pers. comm., 1997). The *johnsonae* and *proteus* sub-biozones of the Aberystwyth Grits Formation record a decline in detrital supply, being represented by thinner and less coarse turbidites than those of the underlying *utilis* Sub-biozone (see sedimentary logs by A. A. Cullum in Dobson, 1995; Dobson & Loydell in Dobson, 1995, p. 97). Dobson (in Dobson, 1995, p. 47) described the late *turriculatus* Zone through to early *crispus* Zone as a period of maximum transgression (as recorded by the Aberystwyth Grits Formation), with the turbidites deposited at this time being 'shale prone and locally anoxic'.

#### *2.f.3. Gondwanan periphery*

In the Silurian of the Synclinorium du Ménez-Bélair (Massif Armoricain, France) the lowest graptolitic mudstones in the Formation de la Lande Murée (at La Lande Murée and at Le Rocher) contain a diverse and well preserved graptolite fauna including *Streptograptus storchi* Loydell, *Pristiograptus schucherti* Bjerreskov and *Torquigraptus proteus* (Barrande), indicating the upper part of the *turriculatus* Biozone (see Paris, Rickards & Skevington, 1980, for illustrations of fauna, and Loydell, 1993*b*, for revised identifications). Below the graptolitic mudstones the formation is composed of massive quartz arenites.

In the Prague Basin, deposition of the dark grey graptolitic shales of the Litohlavy Formation (above the 'Basal Green Shale'; see Section 2.e.3) resumed in the *turriculatus* Zone (Kříž, 1991).

### 2.g. Mid Telychian sea-level changes

Widespread occurrences of graptolitic, dark grey, laminated hemipelagite record high sea-levels during the late *crispus* through to early *griestoniensis* zones. The late *griestoniensis* and *crenulata* zones represent a period of lowered sea-level, although not as dramatically lowered as in the *argenteus* and *sedgwickii* zones (Aeronian) and *utilis* Subzone and mid *lapworthi* Zone (Telychian).

#### *2.g.1. Laurentia*

The Williamson Shale of New York State is stated by Grasso & Liebe (1996, p. 48) to have 'accumulated at a time when sea level was at its highest point in the Silurian Period of North America'. Both Johnson, Kaljo & Rong (1991; see Johnson, Rong & Yang, 1985, fig. 5, for sea-level curve for New York) and Ross & Ross (1996) indicate that sea-level rose to its highest point during the Silurian during deposition of this formation, but offer different dates for this sea-level highstand (*griestoniensis–crenulata* Zone boundary in Johnson, Kaljo & Rong, 1991; Llandovery–Wenlock boundary in Ross & Ross, 1996). It may be that past biostratigraphical imprecision has resulted in the combination of two sea-level rises, that is, those of the mid Telychian and the *spiralis* Zone (see Section 2.h), in the sea-level curves of Johnson, Kaljo & Rong (1991) and Ross & Ross (1996). With regard to dating, graptolites from low in the Williamson Shale at Tryon Park, Rochester (see Brett & Goodman, 1996, for locality details and Lin & Brett, 1988, fig. 1A, for photograph of exposure) are undoubtedly mid Telychian. Although the fauna is of low diversity (comprising only *Retiolites*, *Monograptus priodon* (Bronn) and *Stimulograptus clintonensis* (Hall)), *S. clintonensis* has been shown to have a restricted stratigraphical range in the middle of the Telychian (it has been recorded with certainty only from the *crispus*, *sartorius* and lower *griestoniensis* biozones: Zalasiewicz, 1994; Loydell & Cave, 1996). It thus provides firm evidence of the age of the graptolitic lower part of the Williamson Shale. Rickard (1975, pl. 2) indicated that the entire Williamson Shale was of *Pterospathodus amorphognathoides* conodont Zone age (that is, latest

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Telychian–?earliest Sheinwoodian; see Loydell, Kaljo & Männik, in press). However, the basal Williamson Shale at Tryon Park has yielded a *Pterospathodus celloni* Biozone conodont fauna (M. Kleffner, pers. comm., 1996), which is consistent with the mid Telychian age derived from the graptoloid biostratigraphical data.

Lin & Brett (1988) described the Williamson Shale (and its inferred lateral equivalent, the Willowvale Shale) in detail. On the basis of litho- and biofacies evidence, Lin & Brett (p. 251) suggested that 'two transgressive maxima occurred within the Williamson'. The earlier of these is that dated as mid Telychian on the basis of the presence of *Stimulograptus clintonensis*; the later is yet to be dated precisely, but may correlate with the *spiralis* sea-level rise described below.

In the Girvan district, Scotland, the two graptolitic horizons in the Protovirgularia Grits Formation were assigned to the *crispus* and *griestoniensis* biozones respectively by Cocks & Toghill (1973, p. 228). The lower, a '7.5 cm band of dark grey pyritic mudstone, weathering orange and crowded with graptolites' is undoubtedly of *crispus* Zone age (the index species is common); the higher horizon lacks biozonal index species, but has yielded several *Stimulograptus clintonensis* (Hall). Its age is therefore *crispus*, *sartorius* or lower *griestoniensis* Zone. Above this horizon lies the Lauchlan Formation, 'a conspicuous sequence of red and purple flaggy shales and thin sandstones.' This formation lacks graptolitic mudstones until 9 m below its top (total formational thickness is approx. 50 m), these being attributable to the *spiralis* Biozone (see Section 2.h.1). Thus, graptolitic shales are not known in this area from the upper part of the *griestoniensis* Zone and the *crenulata* Zone. Despite the undoubted tectonism in the Girvan area during the Telychian, the stratigraphical distribution of graptolitic mudstones is therefore in accord with the suggested sea-level highstand in the early mid Telychian, followed by lowered sea-level in the late *griestoniensis* and *crenulata* zones, and a sea-level rise in the *spiralis* Zone.

#### *2.g.2. Baltica*

Samples from the Velise Formation in the Ohesaare (Saaremaa, Estonia; Loydell, Kaljo & Männik, in press) core include dark grey graptolitic shale at 371.0 m (upper *crispus* Biozone), at 370.70 m (*sartorius* Biozone), and at 370.45–370.50 m and 370.35–370.37 m (both lower *griestoniensis* Biozone). There are no graptolitic horizons of either late *griestoniensis* Zone or *crenulata* Zone age.

In the Oslo region, Norway, Howe (1982) recorded *Mcl. griestoniensis* (Nicol) and *Streptograptus sartorius* (Törnquist) in a graptolite assemblage from Bed IV (black graptolitic shales within green siltstones) in the Ek Formation of Storskjæringa, Hadeland. These indicate the lower part of the *griestoniensis* Biozone, and the presence of this graptolitic mudstone at this level is consistent with the high sea-levels of the *crispus* and *sartorius* zones being maintained into the early part of the *griestoniensis* Zone.

On Bornholm, a 2 m thickness of unfossiliferous strata underlies the grey graptolitic shales of the *spiralis* Biozone (Bjerreskov, 1975). The unfossilferous beds comprise light grey, burrowed, mudstones, interbedded with three thin limestone bands and suggest a pre-*spiralis* Zone fall in sea-level.

#### *2.g.3. Eastern Avalonia*

Dark grey graptolitic mudstones occur sparsely in the lower and middle Telychian of the Banwy River section of eastern mid Wales. They cluster, however, in the upper part of the *crispus* Biozone and *sartorius* Biozone (Loydell & Cave, 1996), above which lie non-graptolitic, bioturbated red and green mudstones. The next horizon with biostratigraphically useful graptolites is assignable to the *spiralis* Biozone. The Banwy River section was deposited in an outer shelf/slope setting (Loydell & Cave, 1996, figs 3–4). Farther to the east, at Buttington Brick Pit, in a more nearshore setting, only one thin black graptolitic shale is present in the middle Telychian (Loydell & Cave, 1993); this presumably correlates with one of the Banwy graptolitic beds, perhaps that which has a fauna also dominated by *Stimulograptus clintonensis* (Hall).

In the Howgill Fells, Wilson (D. W. R. Wilson, unpub. Ph.D. thesis, Univ. Birmingham, 1954) identified graptolitic horizons yielding *Streptograptus sartorius* (Törnquist) and *Monoclimacis directa* Zalasiewicz, Loydell & Štorch (identified by Wilson as *Mcl.* cf. *griestoniensis*) underlying non-graptolitic mudstones (which are red in some sections).

Evidence for a brief, probably minor, sea-level rise in the *crenulata* Zone comes from the Cross Fell area (Burgess, Rickards & Strachan, 1970) and the Llanidloes area of mid Wales (Jones, 1945), where very thin beds of graptolitic shale occur within otherwise barren pale grey-green mudstones.

#### *2.g.4. Gondwanan periphery*

In the Velká Ohrada section of the Prague Basin, Štorch (1994*b*, p. 164) records breccias, considered to have originated 'by rapid sedimentation', in the upper part of the *griestoniensis* Biozone and lower *tullbergi* (= *crenulata*) Biozone. These overlie black graptolitic shales.

In the Rauchkofel Bodentörl section of the Carnic Alps, Austria, only one dark grey graptolitic mudstone is recorded. This was assigned to the upper part of the *crenulata* Biozone by Jaeger & Schönlaub (1970) and Schönlaub (1994c). The rich graptolite fauna, however, includes *Stimulograptus clintonensis* (Hall), *Monoclimacis griestoniensis* (Nicol) and *Mcl. directa* Zalasiewicz, Loydell & Štorch, indicating the lower part of the *griestoniensis* Biozone (Zalasiewicz, 1994; Zalasiewicz, Loydell & Štorch, 1995).

In the Silurian of the Synclinorium du Ménez-Bélair

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(Massif Armoricain, France), Paris, Rickards & Skevington (1980) dated dark grey graptolitic shales in the Formation de la Lande Murée to the late *crispus* Zone and early *griestoniensis* Zone. These graptolitic horizons are interbedded with massive quartz arenites indicating the generally shallow water environment of deposition here; the graptolitic shales represent deposition during periods of raised sea-level.

#### *2.g.5. South China*

Rong, Johnson & Yang (1984, fig. 4–(6)) and Johnson, Rong & Yang (1985, fig. 7) presented sea-level curves for the Dazhongba section, Yichang, Hubei Province showing marked shallowing in the *crispus* Zone, represented by the lower part of the Shamao Formation. The graptolite biostratigraphical evidence presented for the age of the lower (and middle) part of the Shamao Formation was the presence of *Retioclimacis typica* NIGP. This species was considered, however, to indicate the upper part of the *turriculatus* Biozone (Ni, 1978, cited in Rong, Johnson & Yang, 1984, p. 691), so the text and figures in these papers are inconsistent. Loydell (1993*a*,*b*) synonymized *R. typica* with *Metaclimacograptus undulatus* (Kurck), a species characteristic of the Aeronian, and known only very rarely from the lowest Telychian (*gemmatus* Subbiozone of Wales; Loydell 1993*b*). Loydell (1993*b*, p. 58) suggested that the *R. typica* 'level' probably correlated with the upper Aeronian *halli* Biozone (cf. Rong, Johnson & Yang, 1984, and Johnson, Rong & Yang, 1985, who assigned the lower and middle parts of the Shamao Formation to the *crispus* and *griestoniensis* biozones). Clearly, the sea-level curves presented by these authors do not apply to the Telychian graptolite zones quoted.

Johnson, Rong & Yang (1984, p. 1392) noted that graptolitic formations in the formation underlying the Hanchiatien Formation at Hangjiadan (Tongzi, northern Guizhou) 'contain elements referable to the upper part of the *Spirograptus turriculatus* Zone and the *Streptograptus crispus* Zone'. The only graptolites recorded from the Shihniulan Formation of Hangjiadan (Chen & Lin, 1978) are species of *Neodicellograptus* Mu & Wang. This genus is characteristic of the Aeronian, not the Telychian (Melchin & Mitchell, 1991; Melchin, 1998). Thus, here also the Telychian part of the sea-level curve presented by Rong, Johnson & Yang (1984, fig. 4-(1)) does not apply to the zones indicated in the original work.

Rong *et al*. (1990) showed that many of the biostratigraphical assumptions that had underpinned the sea-level curves for other areas on the South China plate (Johnson, Rong & Yang, 1985; Rong, Johnson & Yang, 1984) were incorrect and they redated virtually all of the Silurian formations of South China.

None of the sea-level curves of Johnson, Kaljo & Rong (1991), Johnson & McKerrow (1991, fig. 3e) and most recently Johnson (1996, fig. 2e) incorporates any of the above biostratigraphical revisions.

### 2.h. *Oktavites spiralis* Zone sea-level rise

Overall, the *spiralis* Zone was a period of high global sea-level, with perhaps the highest sea-level of the Silurian as a whole occurring during this zone. Minor fluctuations in sea-level are suggested by the intercalation of bioturbated non-graptolitic units in the well-dated sequences of Eastern Avalonia and Baltica.

#### *2.h.1. Laurentia*

Laminated argillaceous dolomite within the lower half of the Brandon Bridge Formation of Wisconsin bears a graptolite assemblage indicative of the *spiralis* Biozone (Mikulic, Briggs & Kluessendorf, 1985; pers. obs.). Deposition took place 'during transgression across a karstified surface within a localized area of water circulation' (Kluessendorf, 1994, p. 338; see also Kluessendorf & Mikulic, 1996).

In the Roberts Mountains of Nevada, the lowest laminated graptolitic shale in the Pete Hanson Creek Section I yielded *Oktavites spiralis* (Geinitz) to Berry & Murphy (1975). Underlying strata are chertified dolomites and limy siltstones.

In the Western Ranges of the Rocky Mountains of British Columbia, Canada, 'Recessive limy shale and argillaceous limestone of the Tegart Formation overlie resistant limestone of the Beaverfoot Formation. The contact is conformable but represents an abrupt, substantial rise in sea-level...' (Norford, 1994, p. 15). The graptolite fauna of the Tegart Formation indicates the *spiralis* Biozone [N.B. the specimen illustrated by Norford, pl. 2.5, fig. 4, as *Stomatograptus grandis* (Suess) is the stratigraphically older species *Stomatograptus longus* (Obut)].

The graptolitic fauna of the dark grey, laminasted Benbeg Mudstone at the base of the Lettergesh Formation (Doyle, Harper & Parkes, 1990) of the Doon Rock area, Kilbride Peninsula, Co. Mayo, Ireland, indicates the middle part of the *spiralis* Biozone. The fauna includes '*Streptograptus*' *nodifer* (Törnquist) and *Monograptus parapriodon* Bouček, together with longer-ranging taxa such as *M. priodon* (Bronn) and *Retiolites*. Rickards (1973) had previously suggested a *crenulata* Zone age for this fauna. The underlying Tonalee Formation consists of predominantly red mudstones with green mudstones and siltstones developed locally. It bears a sparse brachiopod fauna (Doyle, Harper & Parkes, 1990).

Some of the biostratigraphical data in Cocks & Toghill's (1973) study of the Silurian of Girvan is in need of revision. Cocks & Toghill suggested a *griestoniensis* Zone age for the 'dark grey pyritic mudstones... crowded with graptolites' in the upper part of the Lauchlan Formation. The remainder of the formation consists of a 'conspicuous sequence of red and purple flaggy shales and thin sandstones.' The fauna of the graptolitic mudstone includes *Oktavites spiralis* (Geinitz) and *Monograptus parapriodon* Bouček indicating the *spiralis* Biozone.

Bjerreskov (1986*a*) noted that the '*spiralis* Zone is the most extensively and frequently recorded graptolite zone

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and is found in every major area throughout N Greenland'; she recorded high diversity graptolite faunas from this biozone.

#### *2.h.2. Baltica*

In the Ohesaare core (Saaremaa, Estonia) the *spiralis* Biozone is represented by at least 5.2 m of strata, including at least 20 graptolitic levels (Loydell, Kaljo & Männik, in press). Graptoloids are abundant and diverse, particularly in the middle part of the biozone. Johnson & McKerrow (1991, p. 156) had noted that 'shale lenses bearing *Monoclimacis griestoniensis* confirm a bathymetric change from BA5 to BA6 [i.e. a deepening] in late Llandovery time'. The revison of the Ohesaare core graptoloid fauna by Loydell (in Loydell, Kaljo & Männik, in press) has revised the dating of this 'bathymetric change' to the *spiralis* Zone.

It is clear from the work of Howe (M. Howe, 1982, unpub. Ph.D. thesis, Univ. Cambridge, 1982) that the *Oktavites spiralis* Biozone is represented (at least in part) by laminated graptolitic shales in the northern Oslo region, Norway.

#### *2.h.3. Eastern Avalonia*

Three thin bands of graptolitic shale attributable to the *spiralis* Biozone were recognized by Loydell & Cave (1993) in Buttington Brick Pit, eastern mid Wales. In the Banwy River section (Loydell & Cave, 1996), four *spiralis* bands were identified, the lowest containing a fauna characteristic of the middle part of the biozone. The underlying green and red mudstones and shales of the Tarannon Shales Formation are bioturbated and lack graptolites.

#### *2.h.4. Gondwanan periphery*

In the Velká Ohrada section and elsewhere in the Prague Basin the base of the Motol Formation is placed low in the *spiralis* Biozone, at the point where alternating graptolitic shales and pale mudstones are succeeded by graptolitic shales alone (Štorch, 1994*b*). Above this level, lithological variation in the section is minor until the *dubius* Zone (mid Sheinwoodian), suggesting that the sea-level fall recorded elsewhere in the late Telychian was of insufficient magnitude to affect deposition in the Prague Basin or that the rate of tectonic subsidence here was approximately keeping pace with that of sea-level fall.

#### *2.h.5. South China*

The Ningqiang Formation of southern Shaanxi is characterized by interbedded limestones (with diverse benthic faunas) and graptolitic shales. Lin (1989) recognized two graptolitic horizons, the higher of which yielded *Oktavites spiralis* (Geinitz) (identified by Lin, explanation to pl. 2, fig. 4, as '*Oktavites tullbergi spiraloides* Pribyl').

### 2.i. Late Telychian sea-level changes

Following a late *spiralis* Zone minor sea-level fall, sea-level rose again in the early part of the *lapworthi* Zone. This was followed by a major sea-level fall in the mid *lapworthi* Zone with high global sea-levels not restored until the early Wenlock (see below).

#### *2.i.1. Baltica*

On Bornholm (Bjerreskov, 1975), richly graptolitic dark grey shales (lower *lapworthi* Biozone) are succeeded by grey-greenish mudstones interbedded with oolitic limestones with an impoverished graptoloid fauna (these in turn are overlain by earliest Wenlock graptolitic strata, yielding both *Cyrtograptus centrifugus* Bouček and *C. insectus* Bouček). In the mistaken belief that the *lapworthi* Biozone is of basal Wenlock age, Johnson & McKerrow (1991, p. 156) claimed that the sea-level fall responsible for this facies change took place early in the Wenlock. This is not the case: the *lapworthi* Zone is the penultimate Llandovery graptolite zone; the stratigraphical ranges of *C. lapworthi* Tullberg and *C. centrifugus* Bouček do not overlap (Fig. 1).

Graptolitic shales of early *lapworthi* Zone age occur in the Ohesaare core (Saaremaa, Estonia; Loydell, Kaljo & Männik, in press). This facies does not reappear until the lower Wenlock. Intervening strata are pale greenish grey marlstones; graptolites are very sparse indeed.

The uppermost Telychian of Lithuania records a transition from the graptolitic strata of the *spiralis* Biozone to non-graptolitic or very sparsely graptolitic, calcareous lithologies (Paškevičius, 1979). Deposition of graptolitic shales did not resume until the Wenlock.

All three areas are thus consistent in showing a late Telychian sea-level fall.

#### *2.i.2. Eastern Avalonia*

The same drop in sea-level is recorded in Eastern Avalonia by the pale olive-grey calcareous silty mudstones of the Butterley Mudstone Member of Buttington Brick Pit (Loydell & Cave, 1993), the Banwy Burrowed Member (above its basal graptolitic mudstone) of the Banwy River section (Loydell & Cave, 1996) and the Hafod yr Ancr Member of the Builth Mudstones Formation (J. Harris, unpub. Ph.D. thesis, Univ. Cambridge, 1987). The base of the Banwy Burrowed Member can be dated precisely as mid *lapworthi* Zone; the member consists of bioturbated mudstones with occasional thin interbedded graptolitic horizons. Approximately 2 m from its top graptolitic hemipelagite, yielding *Cyrtograptus centrifugus* Bouček, becomes the dominant lithology (see below).

#### *2.i.3. Siberia*

Yolkin *et al.* (1997) recognized a major sea-level fall late in the Telychian reflected in facies changes in southwest Siberia.

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### 2.j. Early Sheinwoodian sea-level rise

Sea levels rose again at the end of the Telychian, with the highest Sheinwoodian sea-levels occurring in the *murchisoni* Zone.

#### *2.j.1. Baltica*

In the Ohesaare core (Saaremaa, Estonia) the earliest Wenlock graptolitic strata (dark grey and brownish grey argillaceous marlstones) bear graptolites indicating either the *Cyrtograptus centrifugus* or the *C. murchisoni* Biozone. Definite *murchisoni* Biozone assemblages occur from 2.1 metres above the lowest Wenlock graptolitic strata (Loydell, Kaljo & Männik, in press).

On Bornholm low *centrifugus* Biozone strata are graptolitic (Bjerreskov, 1975), bearing both *Cyrtograptus insectus* Bouček and *C. centrifugus* Bouček, suggesting that the sea-level rise had begun by the earliest Wenlock.

Kaljo, Nestor & Einasto (1991, p. 211) stated: 'At the beginning of the Wenlock Epoch there was a maximum of transgression of the Baltic Silurian sea, when the deepest water facies with argillaceous deposits covered very large areas.' This contrasts with the statement of Johnson, Kaljo & Rong (1991, p. 159): 'The most reliable data from the Baltic region suggests that... a period of relatively high sea-levels was initiated with deposition of the *M. riccartonensis* Biozone'. Data presented below indicates rather that the sea-level highstand was in the *murchisoni* Zone, with minor regression indicated for the early *riccartonensis* Zone.

#### *2.j.2. Eastern Avalonia*

In the Builth Wells area laminated graptolitic hemipelagites of the *centrifugus* Biozone are present near Newbridge-on-Wye (J. Harris, unpub. Ph.D. thesis, Univ. Cambridge, 1987; Bassett, 1993; Loydell & Cave, 1994), whilst at Pencerrig Lake (Elles, 1900; Loydell & Cave, 1994) closer to the Silurian shoreline, the earliest Wenlock graptolitic shales are of the *murchisoni* Biozone. A similar situation pertains farther north in east Wales, in the Welshpool area, where laminated graptolitic strata appear two-thirds of the way through the *centrifugus* Biozone in the Banwy River section (outer shelf/slope: Loydell & Cave, 1996), but not until the *murchisoni* Biozone at Buttington Brick Pit (nearer shore: Loydell & Cave, 1993). Both areas (Builth and Welshpool) thus show progressive shoreward encroachment of graptolitic hemipelagite deposition with rising sea-level in the early Sheinwoodian.

### 2.k. Mid Sheinwoodian sea-level fall

A minor fall in sea-level appears to have occurred during the *firmus* Zone and early part of the *riccartonensis* Zone.

#### *2.k.1. Baltica*

On Gotland, the calcareous mudstones of the Upper Visby Formation are overlain by the limestones of the Högklint Formation. The latter are considered to represent a marine shallowing and thus sea-level fall. Skoglund (in Jaanusson, Laufeld & Skoglund, 1979, pp. 214–15) recorded (but unfortunately did not illustrate) two fragments of *Monograptus* cf. *riccartonensis* from 5 m above the base of the latter formation.

#### *2.k.2. Eastern Avalonia*

In the Banwy River section, Wales, the passage from the *murchisoni* to the *firmus* Biozone is marked by a minor lithological change, the strata becoming siltier; graptolites are sparser and the faunas are of low diversity.

In northern England, Rickards (1989, pp. 118, 128) shows thin sandstones of *riccartonensis* Zone age in otherwise monotonous Sheinwoodian mudstone/siltstone-dominated sequences.

In the English Midlands, grey, graptolitic mudstones, assigned to the *murchisoni* Biozone by Butler (1937), are succeeded by a 'prominent 10-m thick calcareous horizon known as the Barr Limestone' which 'probably correlates with all or part of the *riccartonensis* Zone' (Bassett, 1974, p. 756). The presence of the limestone suggests post-*murchisoni* Zone shallowing over the Midland Platform.

### 2.l. Mid Wenlock sea-level changes

As noted in the introduction, it is less easy to correlate late Sheinwoodian and early Homerian graptolitic strata across and between different palaeocontinents than it is older and younger Silurian strata. The 'mid Wenlock' portion of the sea-level curve presented herein is therefore likely to be inaccurate in detail.

The impression gained from most mid Wenlock sections is that sea-level changes at this time were not as great as those earlier in the Silurian and during the later Homerian and early Ludlow. The evidence available suggests that there was a sea-level rise early in the 'mid Wenlock' (during the *rigidus* Zone).

#### *2.l.1. Baltica*

From their investigations on Gotland (and in southern Britain), Jeppsson, Aldridge & Dorning (1995) concluded that 'middle Wenlock episodes and events were less strongly marked than those at the beginning and end of the epoch.'

On mainland Sweden dark graptolitic shales of *rigidus* Zone age were recorded by Bjerreskov (1986*b*) from Maglarp 1 core, Scania.

#### *2.l.2. Eastern Avalonia*

The upper Sheinwoodian of northern England is characterized by a monotonous sequence of mudstones with calcareous nodules (Rickards, 1989).

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In Shropshire, the Coalbrookdale Formation (with the exception of the Farley Member, at the top of the formation) 'comprises a monotonous sequence of ... silty mudstones' (Bassett *et al.* 1975, p. 3).

#### *2.l.3. Gondwanan periphery*

A late mid Sheinwoodian sea-level rise is suggested by the presence of dark grey graptolitic mudstones within the shelly limestones of the Kok Formation in the Cellon section, Austria. Jaeger (1975) recorded *Cyrtograptus rigidus* Tullberg from this level (see also Schönlaub, Kreutzer & Priewalder, 1994).

#### *2.l.4. Gondwana*

Legrand (1994, p. 271) noted that a transgression 'affecting a large area of the Algerian Sahara has been known for the last thirty years.' This is dated to the *Cyrtograptus rigidus* Zone.

### 2.m. Mid Homerian sea-level fall and late Homerian sea-level changes

Abundant evidence exists for a late Wenlock sea-level fall. Much of this evidence is summarized in the works of Lenz (1982), Johnson & McKerrow (1991) and, particularly, Kaljo *et al.* (1995). Kaljo *et al.* (1995, p. 214) stated: 'The global character of the latest Wenlock sea-level lowering has been advocated by many authors... and can be taken as proved.' There is evidence from some areas (e.g. Wales, Welsh Borderland, Gotland) to suggest two regressive episodes during the mid to late Homerian, with an intervening minor sea-level rise. Lithological changes suggest that the onset of the first regression occurred late in the *lundgreni* Zone with the lowest sea-level in the early part of the *nassa* Zone.

#### *2.m.1. Baltica*

In Latvia, Ulst (1974, p. 106) records a laminated dolomite (Ancia member of the Riga Formation) in the lower part of the *nassa* Biozone (*parvus* Biozone of Jaeger, 1991), within a sequence of graptolitic mudstones (see Koren' & Urbanek, 1994, for a possible alternative interpretation of the palaeoenvironmental factors responsible for the presence here of this dolomite).

Laufeld, Bergström & Warren (1975) described the transition from the Cyrtograptus Shales to the Colonus Shales in Skåne, southern Sweden: laminated graptolitic mudstones are overlain by 'olive grey, calcareous and slightly silty mudstone', interpreted as representing deposition during a regression resulting probably from a eustatic sea-level fall caused by glaciation. The regression was dated to the *ludensis* Zone on the basis of the presence of *Pristiograptus jaegeri* Holland, Rickards & Warren in the olive grey mudstones. Warren (p. 217 in Laufeld, Bergström & Warren, 1975) noted that the Swedish specimens of *P. jaegeri* 'fall consistently in the narrower end of the size range of the species.' Previously, Holland, Rickards & Warren (1969, p. 677) had indicated that *P. jaegeri* is present in pre-*ludensis* Zone strata and (p. 669) noted that the 'more slender forms seem to occur at lower stratigraphical levels.' On this basis, it seems more likely that the regression responsible for the facies changes in Sweden took place before the *ludensis* Zone.

On Gotland, two limestone-dominated units (upper part of the Slite Group and the stratigraphically higher Klinteberg Formation) are separated by the Mulde Formation (soft calcareous shales grading up into argillaceous limestones: Jeppsson, Aldridge & Dorning, 1995; see also Jeppsson, 1997, p. 314). The base of the Klinteberg Formation may lie within the *sherrardae* Biozone (see graptolite data given in Jeppsson, Aldridge & Dorning, 1995).

#### *2.m.2. Eastern Avalonia*

A considerable amount of biostratigraphical and lithological data has been accumulated from shelf sequences in Wales and the Welsh Borderland. Important references are those of Holland, Rickards & Warren (1969), Bassett (1974, 1989) and Bassett *et al.* (1975). The presence of *Monograptus flemingii* (Salter) low in the Much Wenlock Limestone Formation (Butler, 1939) indicates an age of no younger than *lundgreni* Zone. Widespread deposition of graptolitic siltstones in the Welsh Borderland did not resume until the early Ludlow (see below). Within the Much Wenlock Limestone Formation is a more argillaceous, nodular unit (see, e.g. Ratcliffe, 1988; Jeppsson, Aldridge & Dorning, 1995, fig. 2), perhaps indicative of a slight rise in sea-level.

In North and mid Wales, major facies changes indicating regression occur immediately above and below the *nassa* Biozone. Laminated hemipelagite with intercalated turbidites both underlie and overlie the massive, silty, bioturbated, calcareous mudstones of the Mottled Mudstone Member of the Nantglyn Flags Formation (Warren *et al.* 1984; Kemp, 1991, pp. 270–1; Cave, Hains & White, 1993). In places the member is separated into two (the Lower- and Upper Mottled Mudstones) by laminated hemipelagite, suggesting a minor sea-level rise in mid *nassa* Zone. Similarly, in northern England (Rickards, 1989; Kemp, 1991, p. 270) there are two 'prominent, bioturbated pale grey calcareous mudstones' (the Middle and Upper Coldwell Beds) in the upper Homerian, separated by laminated hemipelagites (locally slumped).

#### *2.m.3. Gondwanan periphery*

In Bohemian and Iberian sections, the *lundgreni–nassa* biozone boundary is marked by a lithological change, but to volcanic and possibly volcanic deposits, respectively (Kříž *et al.* 1993; Gutiérrez-Marco *et al.* 1996). No sea-level changes can be inferred.

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#### *2.m.4. Gondwana*

In the Anti-Atlas of Morocco, Hollard & Willefert (in Destombes, Hollard & Willefert, 1985, p. 243) record 'a thin horizon of black or rusty ferruginous limestone' bearing graptolites, including *Gothograptus nassa*. In western Morocco a similar lithology occurs (described as an 'ochreous ferruginous limestone' by Hollard & Willefert (in Destombes, Hollard & Willefert, 1985, p. 267)); underlying and overlying strata are graptolitic shales yielding *lundgreni* Biozone and latest Wenlock graptolite faunas, respectively.

Legrand (1994, p. 271) noted that 'a late Wenlock regression is observed' in many areas of the Sahara.

#### *2.m.5. Kazakhstania*

In the lower part of the Kursala Formation in the Alay Range, South Kirghizstan, calcareous turbiditic sandstones are present only at the *lundgreni–nassa* biozone boundary in the section in the Tul' village area (Koren' & Suyarkova, 1994, fig. 3). The remainder of the section (*lundgreni–ludensis* biozones) is entirely mudstones. In the Peshkaut Valley section (Koren' & Suyarkova, 1994, fig. 4), similar calcareous sandstones occur at only two levels, again in a sequence of mudstones: one is low in the *nassa* Biozone, the other being in the *sherrardae* Biozone, suggesting that the two shallowing phases recognized in Eastern Avalonia are reflected here too.

### 2.n. Early Ludlow sea-level rise

That the early Ludlow represented a time of eustatic sea-level rise has long been recognized. Whether this sea-level rise was rapid or more gradual has been the subject of some debate (e.g. Hurst, 1975; Bassett, 1976). The *nilssoni–scanicus* biozones record the highest late Silurian sea-levels (Johnson, Kaljo & Rong, 1991; Johnson, 1996).

#### *2.n.1. Laurentia*

Laminated, graptolitic shales of early Ludlow age are quite widely distributed in the American Midwest (Ross, 1962) and in Nevada (Berry & Murphy, 1975). Assemblages examined by the author, from the Lechthaylus Shale of northern Illinois and the Mississinewa Shale of Indiana include *Monoclimacis*? *micropoma* (Jaekel) indicating the upper part of the *nilssoni* Biozone (*progenitor* Biozone of Teller, 1969) or lower part of the *scanicus* Biozone (Teller, 1969; Rickards, 1976). This evidence of sea-level rise contrasts with Copper & Brunton's (1991, p. 249) statement that there 'is no record of... a marked relative sea level rise in North America at this time [i.e. at the beginning of the Ludlow]'.

#### *2.n.2. Baltica*

Bassett (1976, p. 216) noted that on Gotland 'the sedimentary evidence... indicates a deepening at the top of the Klinteberg Beds, i.e. close to the Wenlock–Ludlow boundary.'

#### *2.n.3. Eastern Avalonia*

Hurst, Hancock & McKerrow (1978) stated that a synchronous period of 'deepening' in the Welsh Borderland could be dated as 'very close to the base of the *N. nilssoni* zone in those areas where zonal graptolites are present.' Bassett (1976, p. 208) noted that 'there is an upward stratigraphical change from relatively onshore carbonates to relatively offshore silts at the Much Wenlock Limestone–Elton Beds boundary, presumably with a concomitant increase in depth'. In the Ludlow area, the brachiopod-dominated Lower Elton Formation is overlain by the Middle Elton Formation with abundant graptolites of the *nilssoni* Biozone and an impoverished benthic fauna (Holland, Lawson & Walmsley, 1963).

#### *2.n.4. Gondwana*

An early Ludlow transgression is recognized over much (but not all) of the Algerian Sahara (see Legrand, 1994, fig. 12).

## 3. Discussion

### 3.a. Comparison with previously published sea-level curves for the Silurian

Figure 3 illustrates the global sea-level curve derived herein from the correlated facies changes described in Section 2 above. Sea-level curves proposed previously are shown also, for comparison.

It is interesting, and perhaps surprising, that the sea-level changes that McKerrow (1979, p. 142) referred to as being 'confined to a single continent' appear to be those recognized as eustatic herein, whilst the eustatic sea-level curve of Leggett *et al.* (1981; Fig. 3), which was based on a synopsis of McKerrow's data, bears little relation to the curve presented herein. I can offer no explanation for this.

The sea-level curve of Ross & Ross (1996) was based on 'the study of lithofacies changes'. They used 'the concepts of depositional sequences and interpretations of sea-level fluctuations to establish a physical stratigraphic framework into which the *limited occurrences of zonal index faunas* are placed [my italics].' Without the necessary biostratigraphical framework it is difficult to use Ross & Ross's sea-level curve and to compare it meaningfully with that presented herein. (N.B. There are some significant miscorrelations presented in Ross & Ross's fig. 2, e.g. the base of the Williamson Shale of New York, of late *crispus* to early *griestoniensis* zone age, is correlated with the base of the Riga Formation of Estonia (which lies close to the Llandovery–Wenlock boundary)

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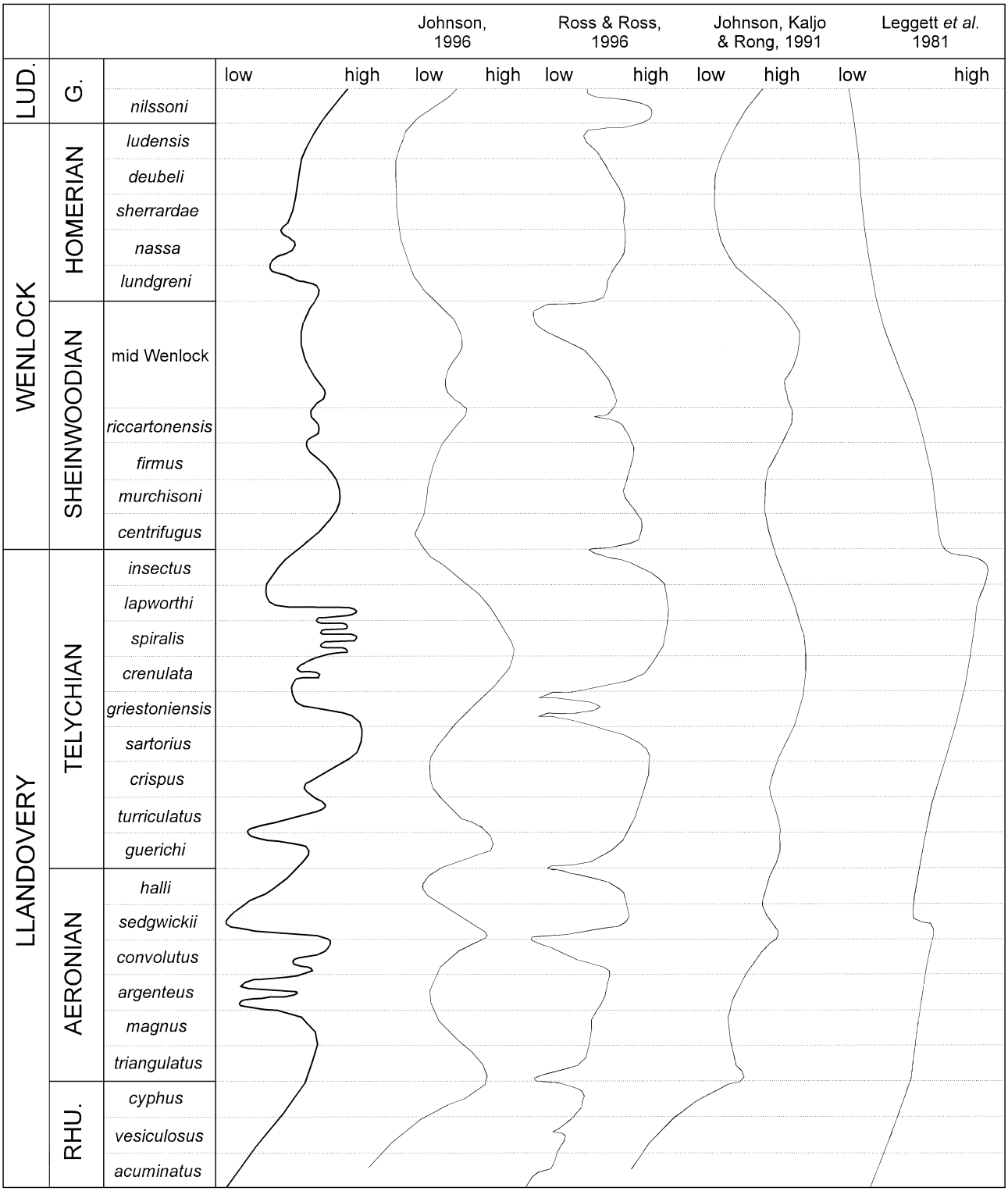



Figure 3. New global sea-level curve for the Early Silurian (left), compared with those proposed in the past. Zones are shown as of equal duration although this is extremely unlikely to have been the case.

with both placed by Ross & Ross at the *griestoniensis–crenulata* biozone boundary.)

The sea-level curves proposed by Johnson, Kaljo & Rong (1991) and Johnson (1996), both shown in Figure 3, were derived largely by analysis of correlated changes in benthic assemblages from different palaeocontinents. The curves were tied to the graptolite zonal scheme for the Silurian, despite both the absence of graptolites from most of the sections studied and the admitted inadequacy of existing attempts to correlate between graptolite biozones

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and the biostratigraphical divisions based on evolving brachiopod lineages. This may account for some of the differences between the sea-level curves (but see also comments in Sections 2.b.2, 2.e, 2.f.1, 2.g.1, 2.g.5, 2.i.1 and 2.j.1). In addition, the relative coarseness of brachiopod biostratigraphy, compared with that based on graptolites, may have prevented the previous recognition of some of the shorter duration sea-level fluctuations recognized herein. This, of course, is assuming that the benthic assemblage-based technique is valid for deriving sea-level curves (see objections of Aldridge, Jeppsson & Dorning, 1993, Section 1.d.4, above). Only by integrated biostratigraphical (and perhaps chemostratigraphical) studies, enabling precise correlation between the various Silurian facies (particularly those of the graptolite-rich 'basins' and the brachiopod-rich 'shelves'), will it be possible to test whether the facies (and interpreted sea-level) changes recognized herein correlate with the changes in benthic assemblages (and interpreted sea-level changes) recognized previously.

### 3.b. The P and S model

Jeppsson's (1990) model (see also Aldridge, Jeppsson & Dorning, 1993; Jeppsson, Aldridge & Dorning, 1995) relates lithological and faunal changes in the Silurian to climatic and oceanic changes, without the need for significant global sea-level change. Aldridge, Jeppsson & Dorning (1993, pp. 502–3) stated that 'the episodes and events can be defined only by reference to oceanic changes and not by their effects on local sequences.' This makes their model somewhat difficult to test!

My major concerns with the P and S model relate to the proposed relationship between planktic diversity and productivity and have been expressed already (Loydell, 1994). As the present paper is not concerned with temporal planktic diversity changes (see Štorch, 1995, for a recent review of Silurian graptolite diversity changes recognized in the Prague Basin, but probably global in extent), a further lengthy discussion of this aspect of Jeppsson's model is not presented here. However, comment is needed on Jeppsson's (1997) recent modification of his model to explain the *utilis* Subzone graptolite extinction (Loydell, 1994). This Jeppsson describes as the first identified secundo–primo event, occurring between the Malmøykalven Secundo Episode and the Snipklint Primo Episode. The P and S model predicts that the Malmøykalven Secundo Episode would be a time of low planktic diversity. Graptolite diversity data for the *guerichi* Biozone shows that this is clearly *not* the case (Loydell, 1994). Similarly, much of the Rhuddanian to early Aeronian Spirodden Secundo Episode is characterized by high (*not* the P and S model-predicted low) graptolite diversity (see, e.g. Koren' & Rickards, 1980).

From the point of view of observed *lithological* changes, many of those detailed above (Section 2), particularly for the Llandovery, are *not* those predicted by the P and S model. For example, of the deeper water sediments deposited in the Aeronian, those of the *triangulatus* and *magnus* biozones occur in the Spirodden Secundo Episode and fit Jeppsson's (1990) prediction in being dominated by graptolitic shales. However, the *argenteus* Biozone (still within the Spirodden Secundo Episode) is dominantly barren grey mudstones deposited under oxic conditions (*contra* Jeppsson's prediction), whilst the *convolutus* Biozone, deposited in the Jong Primo Episode is predominantly graptolitic shales (*contra* Jeppsson's prediction). The deep water deposits of the *sedgwickii* Zone (within the Malmøykalven Secundo Episode) are variable, but are predominantly oxic mudstones, particularly in the upper part of the zone (this again is *contra* Jeppsson's prediction). Similar observations could be made about the Snipklint Primo Episode which, according to Aldridge, Jeppsson & Dorning's (1990) scheme, must encompass most of the Telychian (Loydell, Kaljo & Männik, in press, demonstrate that the *celloni–amorphognathoides* conodont zone boundary correlates approximately with the *spiralis–lapworthi* graptolite zone boundary; the Snipklint Primo Episode comprises the whole of the *celloni* zone and the lower part of the *amorphognathoides* Zone). See above (Section 2) for details of Telychian sections.

Observed faunal and lithological changes do not support Jeppsson's (1990) oceanic model, but the latter are consistent with the eustatic sea-level changes detailed in Figure 3.

### 3.c. Silurian marine red beds

Ziegler & McKerrow (1975) reviewed the widespread occurrence of marine red beds, predominantly in late Llandovery sequences from the palaeocontienents Laurentia, Baltica and Eastern Avalonia. Ziegler & McKerrow correlated the occurrence of these red beds with four factors: (1) transgression; (2) high sedimentation rates; (3) quiet, generally outer shelf and deeper marine environments; and (4) availability of a suitably oxidized source area. Kemp (1991, p. 292) similarly suggested that the red beds 'probably originated from incorporation of oxidized material from land at the height of the Llandovery transgression'.

A detailed examination of Silurian marine red beds is beyond the scope of this paper, but I include below observations on the age of the main development of mid Telychian red beds in Eastern Avalonia and part of Laurentia (Scotland and Ireland only) and on the timing of marine red bed deposition in relation to sea-level changes.

In the Banwy River section (Loydell & Cave, 1996), red beds occur in the Tarannon Shales Formation, predominantly between graptolitic mudstones of the *sartorius* and *spiralis* biozones. In the Howgill Fells graptolitic mudstones underlying red beds are of *sartorius* Zone age (D. W. R. Wilson, unpub. Ph.D. thesis, Univ. Birmingham, 1954). In the Cross Fell area the red beds commence in the *griestoniensis* Biozone (Burgess, Rickards & Strachan, 1970). In western Ireland, the

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graptolitic Benbeg Mudstone (see Section 2.h.1), of *spiralis* Zone age, overlies red beds of the Tonalee Formation (Doyle, Harper & Parkes, 1990). In the Girvan district the red beds of the Lauchlan Formation (more than 50 m thick) lie above the Protovirgularia Grits Formation (early *griestoniensis* Zone at youngest; see Section 2.g.1, above). The graptolite band 9 m from the top of the Lauchlan Formation has yielded a fauna indicative of the lower part of the *spiralis* Biozone.

In all these areas, therefore, red beds were deposited predominantly during a period interpreted herein as of lower sea-level than the prior and subsequent highstands of the late *crispus*–early *griestoniensis* zones and *spiralis*–early *lapworthi* zones. This contrasts with Ziegler & McKerrow's and Kemp's suggested correlation of marine red bed deposition with transgression, but agrees with Ziegler & McKerrow's requirement of high sedimentation rates, which would be unusual during a period of transgression.

A possible scenario for mid Telychian red bed deposition is as follows. Sea-level during the late *crispus*–early *griestoniensis* zones was probably at (or near) its highest in the Silurian. This may have been associated with the climatic conditions necessary for formation of continental red beds in tropical and subtropical latitudes. Minor regression in the late *griestoniensis–crenulata* zones resulted in the transport into and subsequent deposition of the weathered material in various marine environments. Only in some quieter, outer shelf or deeper water palaeoenvironments has the red coloration been retained (Ziegler & McKerrow, 1975; Rickards, 1989); elsewhere, the iron was reduced and the coloration altered (often to grey-green). During the *spiralis*–early *lapworthi* zones rising sea-levels resulted in widespread deposition of graptolitic muds. The subsequent sea-level fall appears to have been fairly sudden and of considerable magnitude. Few latest Telychian sedimentary rocks are red; if this coloration was originally present (which is reasonable if one assumes that climatic conditions during the *spiralis*–early *lapworthi* zones were similar to those of the late *crispus*–early *griestoniensis* zones) it has generally not survived the collective processes of transport, deposition and diagenesis (one exception being the latest Telychian red beds of the Cross Fell area: Burgess, Rickards & Strachan, 1970).

It will be interesting to see whether precise dating of marine red beds elsewhere supports the above model of deposition during minor regression following major transgression.

## 4. Conclusions

Although more detailed and more tightly stratigraphically constrained than previously published global sea-level curves, the curve presented herein will undoubtedly be further refined as research on Silurian sequences continues. The highest priority for future Silurian stratigraphical research, however, should perhaps be the further integration of the various Silurian biostratigraphical schemes so that it may be possible to correlate precisely between different palaeoenvironments (in particular from deep water, 'graptolitic' facies to shallow water 'shelly' facies). Only when this has been achieved will it be possible to assess the influence of eustatic sea-level changes on, for example, overall Silurian biodiversity and to propose substantiated and testable explanatory models.

**Acknowledgements.** This paper could not have been written without the help of many individuals, in discussion and in providing access to collections and guidance/assistance in the field. I offer my considerable gratitude to the following: Carlton Brett (Rochester), Richard Cave (Aberystwyth), Chen Xu and Xu Yang (Nanjing), Mike Dorling (Sedgwick Museum, Cambridge), Dim Kaljo and Peep Männik (Tallinn), Joanne Kluessendorf and Don Mikulic (Illinois), Stuart McKerrow (Oxford), Claire Mellish and Richard Fortey (The Natural History Museum, London), Gary Mullins (Portsmouth), Peter Osborne and Paul Smith (Lapworth Museum, Birmingham), E. Pietrzeniuk (Berlin), Hans-Peter Schönlaub (Vienna) and Petr Štorch (Prague). I am indebted to Simon Brookes for his assistance in the production of Figures 1 and 3. Research funding has been provided by the University of Portsmouth and University of Wales, Aberystwyth, the Royal Society and Academia Sinica (Transhemisphere Telychian Project) and the N.E.R.C. (Small Grant GR9/1129). I am very grateful to these bodies for their support.

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