SILURIAN EUSTASY

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ABSTRACT. Despite rationales contrary to the concept of fully global sea-level changes, data are both abundant and consistent enough to demonstrate Silurian eustasy on a practical intercontinental scale. Beyond a rich endowment of Silurian strata on all the major palaeocontinents, progress in this area requires close international agreement on a common model for bathymetric change with respect to a unified time scale. The Llandovery Series has attracted the most successful collaboration in this regard. Bathymetric change is keyed mainly to stratigraphical replacement patterns in brachiopod-dominated communities bracketed by shallower coral-stromatoporoid and deeper high-diversity graptolite assemblages. At least four co-ordinated high stands in sea level occurred during Llandovery time. Full to partial corroboration of these events has been shown for Laurentia (North America), Baltica (Norway and Estonia), Avalonia (Wales and England), Siberia, South China (Yangste Platform), and the Australian sector of Gondwana. High stands cluster at the transition from Rhuddanian to Aeronian time, in mid Aeronian time (lowest *Monograptus sedgwickii* or *Stricklandia lens progressa* biozones), in early Telychian time (*M. turriculatus* or *S. laevis* biozones), and in late Telychian time. Each of these four cycles may have lasted 2·5 m.y.

Post-Llandovery strata yield some comparable patterns as found by independent parties not necessarily testing for eustatic patterns. Cycles in the development and demise of coral bioherms or shoal systems constitute a well-used technique for tracking Wenlock and Ludlow sea-level events. Data are available from North America, the British Isles, the Gotland and Saaremaa areas of the Baltic region, Siberia, China, and Australia. High stands in sea level were typical during mid Wenlock, early Ludlow, and late Ludlow times. Notable low stands in sea level occurred at the beginning and conclusion of Wenlock and during mid Ludlow (*Saetograptus leintwardinensis* Biozone) times. Many authors stress orogenic or more local tectonic explanations for changing bathymetric patterns. Experience with Llandovery data indicates that diastrophic patterns overprinted by eustatic signals are possible to distinguish from one another. Other cyclic features involving salt beds or sand peaks are more common in the upper Silurian (Ludlow-Přídolí) but their relationship to eustatic sea-level fluctuations remains controversial.

AN unmistakable aspect of the Silurian Period was shaped by vast platform seas that expanded across low relief on many palaeocontinents. Carbonate deposition was dominant in North America, extending from Anticosti Island in Quebec to the Great Basin of Utah and Nevada in one direction, and from Southampton Island in Hudson Bay to West Texas in another. Carbonates and marls also are well developed in northern Europe from the Shropshire district in England to the Oslo region of southern Norway, and to the islands of Gotland and Saaremaa in the Baltic region. Episodes of extensive carbonate deposition also occurred in Siberia and on the Yangtze Platform of South China. The Yass area of New South Wales in Australia and India's Spiti region likewise accumulated prominent carbonates representing deposition on the fringes of Gondwana. What factors raised these and associated marine sediments to so pervasive an epicontinental setting? What is the significance of recurrent community patterns recorded so clearly in the succession of stable platform carbonates? The purpose of this review is to explore the likelihood of Silurian eustasy as a key explanation for such phenomena.

The first comprehensive interpretation of Palaeozoic eustasy was offered by Grabau (1936), who drew on his direct knowledge of North American, European, and Asian stratigraphy. Use of seismic stratigraphy by Vail *et al.* (1977) later rekindled enthusiasm for a Phanerozoic time scale based on global sea-level patterns (Text-fig. 1). This approach also generated a strong measure of scepticism (e.g. Summerhays 1986). Continental shelf strata scrutinized through abundant unconformities have permitted recognition of a refined picture of Mesozoic and Cenozoic events attributed to

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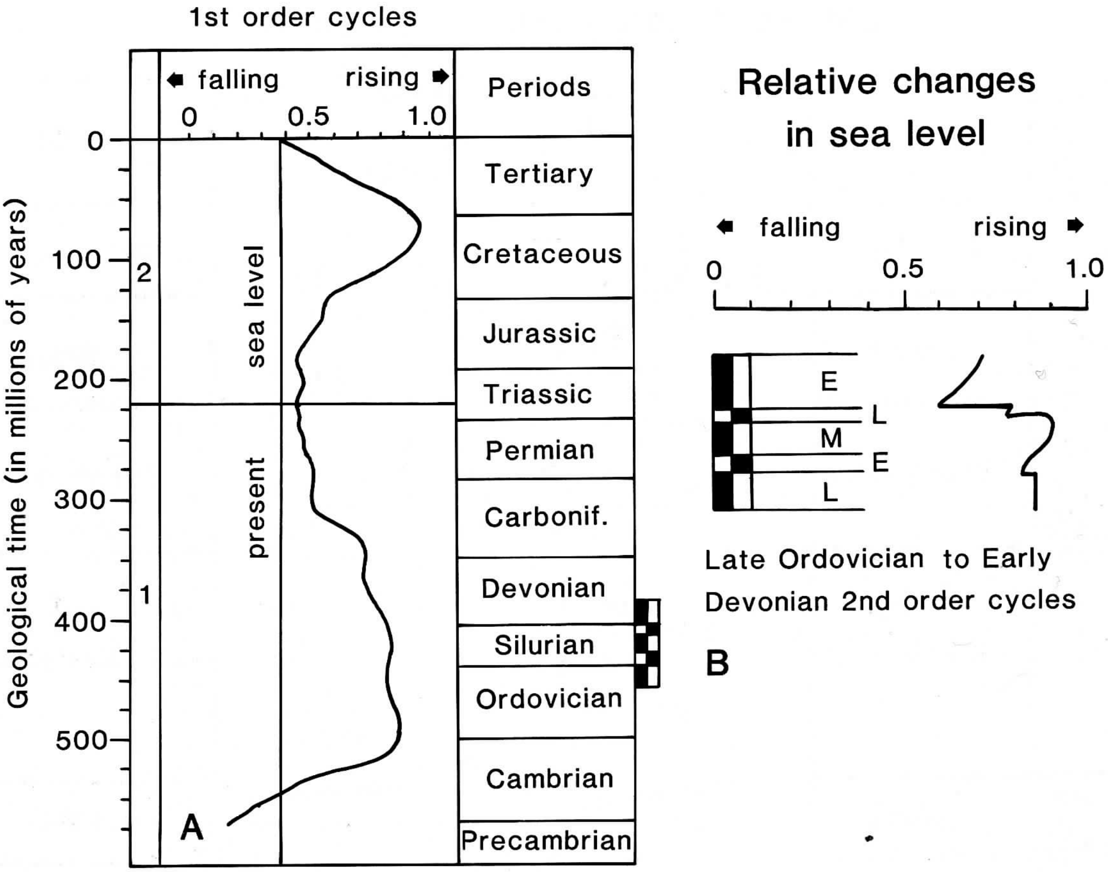


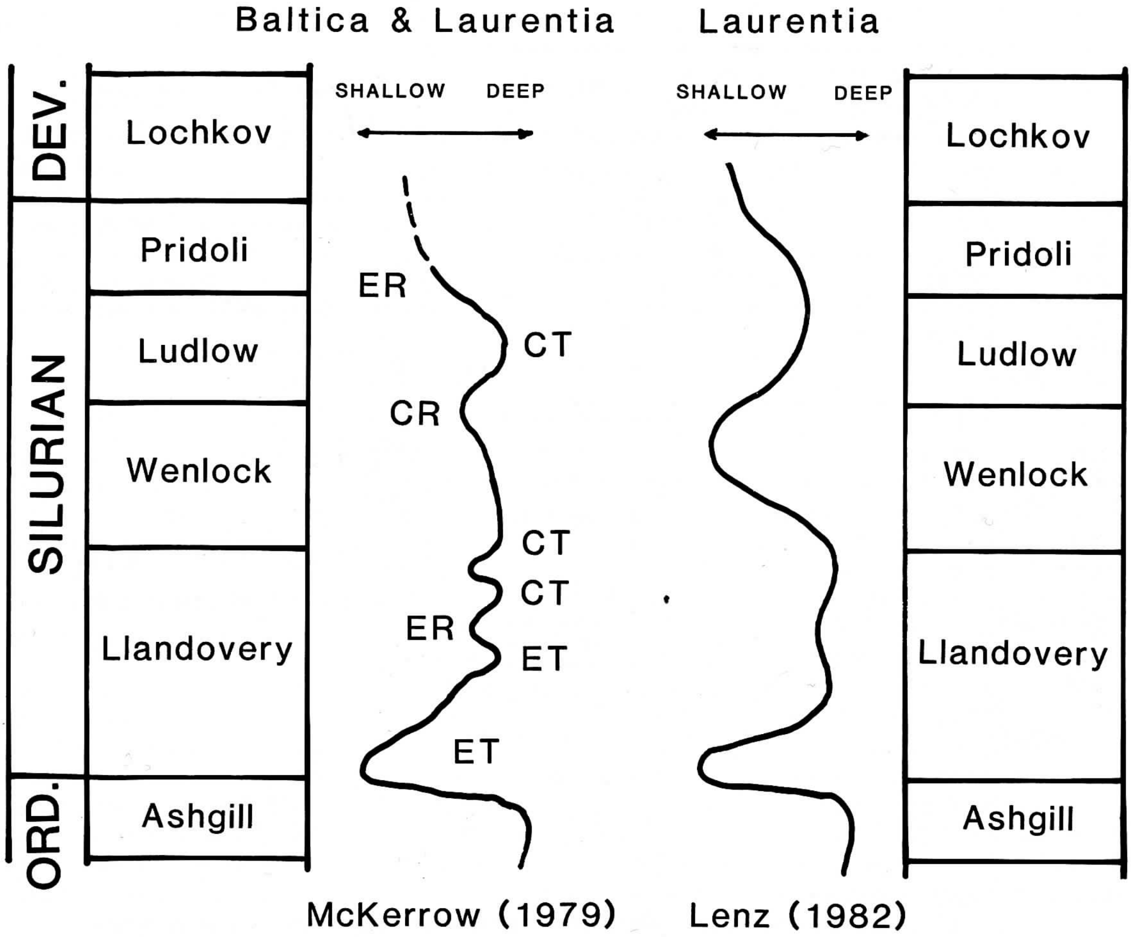
TEXT-FIG. 1. Relative sea-level curves after Vail *et al.* (1977). A, large scale, first order cycles for the Phanerozoic. B, magnification of smaller second order cycles for the late Ordovician to early Devonian.

eustasy (Haq *et al.* 1987), but the widely cited summaries of Palaeozoic events by Vail *et al.* (1977) and Hallam (1984) remain comparatively crude. Their general treatment of the middle Palaeozoic is in contrast to the more detailed analyses by McKerrow (1979) and Lenz (1982) as shown in Text-figure 2.

Some serious rationales mitigate against the concept of eustasy as a fully global process. Mörner (1976) pointed out that the shape and irregularities in the geoid insure regions of local regression while transgressive conditions may prevail elsewhere. Bond (1978) drew attention to the fact that the present continents express variable hypsometry, Africa being affected strongly by late Tertiary uplift on a continental scale. Under such limitations, it is likely that major exceptions to strict eustasy will be identified for any interval of geological time under investigation. Given a cluster of continental platforms with similar hypsometries, however, it is possible theoretically to demonstrate practical eustasy.

CAUSES OF EUSTATIC CHANGE

Three effective causes of eustatic change reviewed by Donovan and Jones (1979) are flux in the volume of ocean ridges (±300 m), flux in the volume of land ice (±150 m), and desiccation of isolated ocean basins (±15 m). The Silurian Period was a propitious time for practical eustasy due



TEXT-FIG. 2. Comparison of Silurian sea-level curves produced by McKerrow (1979), based on data from parts of Europe and North America, and by Lenz (1982) based on data from western and northern Canada.

to all these and other possible factors. Representing a time midway between dispersal of a Precambrian proto-Pangea and assembly of the Permian Pangea, Silurian rates of sea-floor spreading were relatively high. The volume of standing mid-oceanic ridges had to be correspondingly high to facilitate displacement of oceanic waters onto continental platforms. This effect is illustrated in Text-figure 1A by the lower bulge in the first-order global sea-level curve of Vail *et al.* (1977).

The main glacioeustatic drop in sea level during latest Ordovician time and subsequent rise during earliest Silurian time was first given wide credence by Berry and Boucot (1973). Hambrey (1985) offered a more recent summary of this glacial period. Glaciation of one kind or another on Gondwana apparently lasted from Caradoc to Wenlock time, gradually shifting focus from present day North Africa to South America. Some African strata indicate a succession of different tillites, strongly suggesting multiple glacial events. The result of glaciation negated the tectono-eustatic effect of sea-floor spreading; most palaeocontinents were drained thoroughly of epeiric seas during maximum glaciation near the close of Ordovician time. Both glacioeustatic and tectono-eustatic mechanisms operated in tandem to recharge Silurian epeiric seas.

Salt deposition was a prominent occurrence in North America, the Baltic region of Europe, and in Siberia during middle to late Silurian time (Kozary *et al.* 1968). One model for late Wenlock evaporites in the Michigan Basin of North America (Cercone 1988) calls for the local drawdown of saline waters below normal sea level. Evaporation of isolated basin waters and their outside precipitation had only a trivial effect on Silurian sea level.

A possible source of significant sea-level fluctuation was hypothesized by Cloetingh (1986), with respect to sediment loading on passive continental margins and its effect on intraplate stress and the reorganization of lithospheric stress fields. According to this tectono-eustatic model, even small variations in lithospheric stress could account for coeval sea-level changes up to 50 m at passive margins and intracratonic basins. Given the progressive closure of the Iapetus and Rheic oceans during Silurian time, oceanic expansion occurred elsewhere with requisite alterations to intraplate stress fields. Whether due to this mechanism or the sporadic decay of the Gondwanan ice cap, small scale fluctuations in Silurian sea level are widely recorded by the presence of cratonic carbonates and their related facies.

DETECTION OF EVENTS

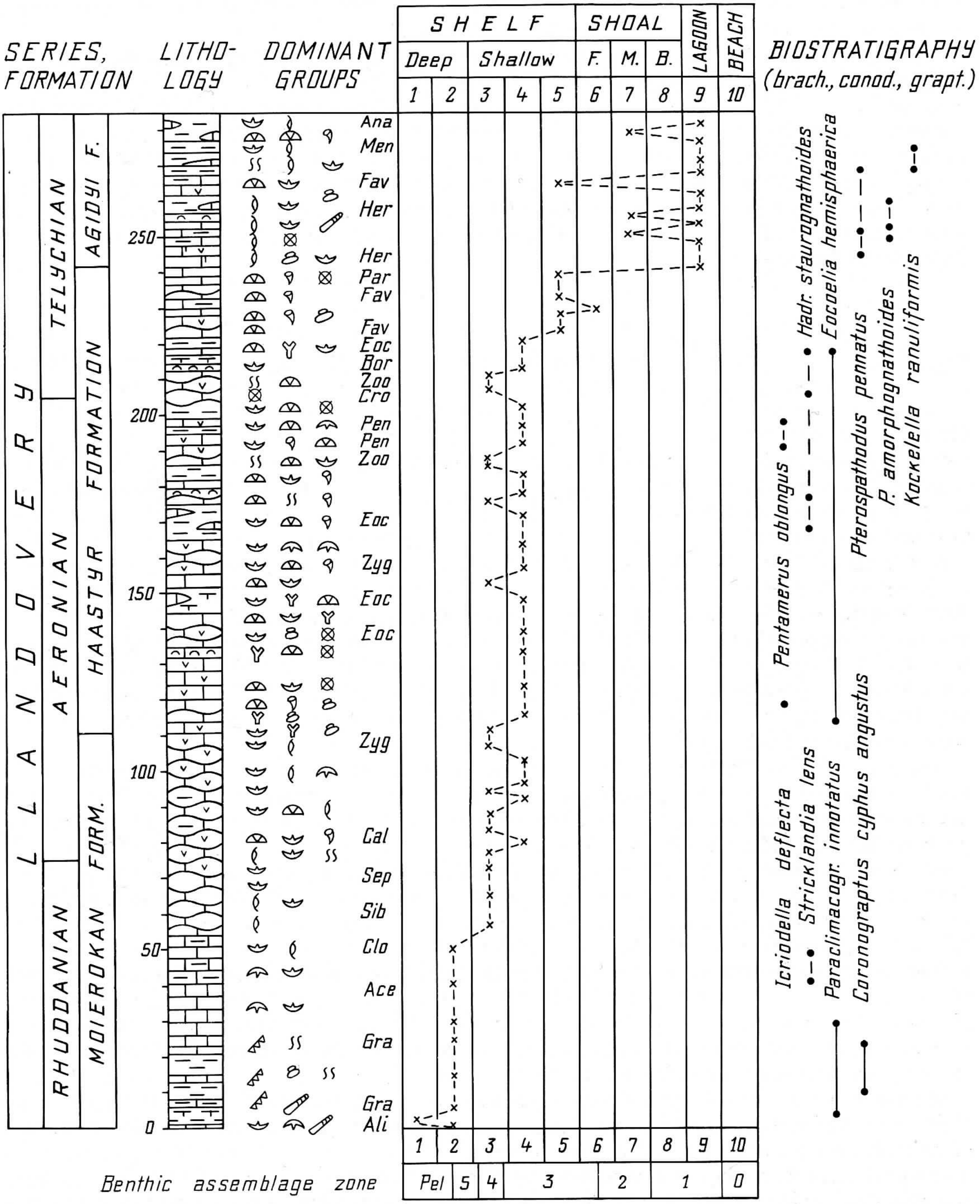
Bathymetric models applied to the lower Silurian of Wales, the Baltic region, North America, Siberia, and the Yangtze Platform of China are directly or closely related. Comparable community replacement patterns are the key to detecting sea-level events on a global scale. Ziegler (1965) set the stage for standard analysis of bathymetric variables from lower Silurian strata with his pioneering work in the Welsh Basin. The *Lingula*, *Eocoelia*, *Pentamerus*, *Stricklandia*, and *Clorinda* communities were defined by him as an onshore–offshore array of intergrading brachiopod associations whose distributions were controlled by multiple factors related to water depth. Graptolitic shales accumulated in the deepest part of the basin.

Subsequently, Rubel (1970) recognized the *Pentamerus*, *Stricklandia*, and *Clorinda* communities in the lower Silurian of Estonia. Kaljo (1978, p. 526) expanded the Baltic model by showing that these brachiopod associations are bracketed bathymetrically by shallower reef or lagoonal facies and deeper graptolitic shales. The *Pentamerus* community was interpreted as living below wave base. Acknowledging that wave base differs from basin to basin, Kaljo (1978, p. 528) suggested that wave base occurred at a depth of 25 m in the Baltic region. Kaljo and Rubel (1982) further refined the Baltic model by showing the relationship of brachiopod communities to distinct lithofacies zones dominated by carbonates and marls.

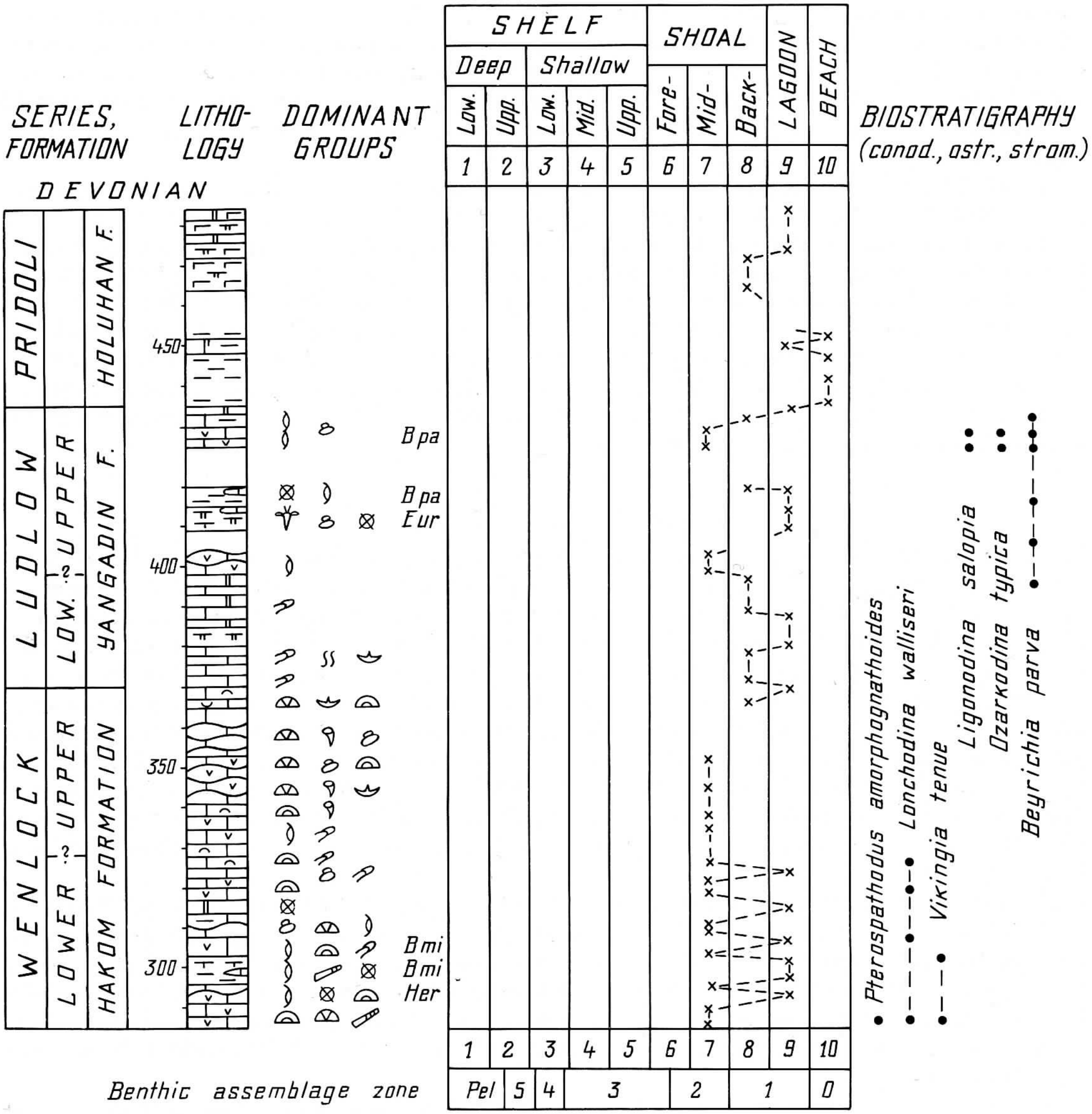
Johnson (1980, p. 208; 1987, p. 188) developed a somewhat similar bathymetric model for the lower Silurian carbonates of North America. A true *Clorinda* community is absent from the core of the North American platform, but an intergrading array of progressively shallower stricklandiid, pentamerid, coral-stromatoporoid, and stromatolite communities is well represented. The *Pentamerus* community was interpreted as living at or below effective wave base, estimated at a depth of 30 m. Beadle and Johnson (1986) used ecotypic size variation in the dasycladacean alga *Cyclocrinities* to confirm that North American pentamerid communities lived in shallower, more brightly lit waters than stricklandiid communities.

Size variation in this alga was noted also in the lower Silurian of the British Isles and Norway (Beadle and Johnson 1986). In a study of tempestites derived from *Pentamerus* shells in Norway (Johnson 1989), it was possible to demonstrate that the *Pentamerus* community lived within a range of depths below normal wave base still affected by storms of varying intensity and frequency. Just as today, water turbulence and light filtration were two important physical factors controlling the depth zonation of benthic palaeocommunities. Thus, the prolific and environmentally stable *Pentamerus* community makes a convenient bio-bathymetric marker readily available in lower Silurian strata all around the world.

In their detailed study of the Moiero River section of Siberia, Tesakov *et al.* (1986) utilized a complex ten-fold lithofacies model reflecting changes in water depth through time (Text-figs 3 and 4). Although this model was not inspired by the five-fold biofacies model of Ziegler (1965), pentamerid brachiopods including *Pentamerus oblongus*, *Virgiana moyeroensis*, and *Borealis borealis* are assigned to a comparable bathymetric setting (a 'middle shallow shelf' environment



TEXT-FIG. 3. Llandovery sea-level curve for Siberia modified from the data of Tesakov *et al.* (1986).



TEXT-FIG. 4. Wenlock to Přídolí sea-level curve for Siberia modified from the data of Tesakov *et al.* (1986).

roughly midway below lagoonal, shoal, and upper shallow shelf environments, but above the lower shallow shelf and deep shelf environments).

In their study of lower Silurian brachiopod faunas from the Yangtze Platform, Rong and Yang (1981, p. 258) mapped the Baisha facies with its low diversity *Paraconchidium–Virgianella* community in a shallower, more near-shore position relative to the Yinjian facies with its high-diversity *Stricklandia–Merciella* community. Rong *et al.* (1984) later recognized a wide range of communities comparable with Ziegler's original model, and used them to reconstruct the history of sea-level changes across the region.

The concept of depth-associated brachiopod communities was extended to the rest of the Silurian by Cocks and McKerrow (1973, p. 293), Boucot (1975, pp. 14–15), and Wang *et al.* (1987, pp.

13–15). No concerted attempt has been made, however, to track post-Llandovery sea-level events on the basis of stratigraphical replacement patterns in these brachiopod communities. Instead, Droste and Shaver (1987) combined reef generation cycles and conodont biostratigraphy to detect possible eustatic sea-level changes of Wenlock to Přídolí age in North America. A similar approach has been keyed to cycles of algal shoal generation by Radionova and Einasto (1986) in the Baltic region and by Ratcliffe (1988) in the English Midlands.

Process oriented sedimentology offers an auxiliary path to sea-level studies. As outlined by Aigner (1985), proximality trend analysis works on the premise that the effects of storms in forming tempestites diminish gradually with distance from shore and increasing water depth. Easthouse and Driese (1988) were the first to apply this concept to Silurian strata with their study of the Rockwood Formation in eastern Tennessee. In her study of the Solvik Formation in the Oslo Region, Baarli (1988) was the first to coordinate the method with the use of traditional lower Silurian brachiopod communities. This sensitive technique has much potential for testing bathymetric patterns in fossiliferous strata, as well as extending trends to relatively unfossiliferous sequences. Silurian applications have been restricted so far to the Llandovery Series, but the method is certainly relevant to other parts of the system.

CORRELATION OF EVENTS

Whatever criteria are used to track local sea-level trends, eustatic patterns are impossible to discern without recourse to a well defined time scale of global application. Interpolation of shelly and graptolitic facies is a long-standing problem for the Silurian System. Redescription of the Llandovery Series in the type area by Cocks *et al.* (1984) is still less than ideal. The boundary between the Aeronian and Telychian stages is equated, for example, with the lineage-zone boundaries between *Stricklandia lens progressa* and its descendant *S. laevis* and between *Eocoelia intermedia* and its descendant *E. curtisi*; it is also said to correspond to the boundary between the *Monograptus sedgwickii* and *M. turriculatus* graptolite biozones (Cocks *et al.* 1984, p. 173). As noted by Temple (1988), evidence is scant for occurrence of the *M. turriculatus* Biozone graptolites in the upper part of the Wormwood Formation defining the base of the Telychian Stage in the type area. Until additional graptolite data are provided, we cannot be fully confident about this Stage boundary.

Similarly, the transition from *Stricklandia lens intermedia* to *S. lens progressa* is not fixed in the type area, nor is its precise relationship to the boundary between the *Monograptus convolutus* and *M. sedgwickii* graptolite biozones. Both *S. lens progressa* and *M. sedgwickii* occur near the base of the Rhydings Formation (Cocks *et al.* 1984) but the presence of one or other of these important index fossils at a lower stratigraphical level remains an open issue. This example does not infringe on the choice of a Stage boundary but it is significant in terms of specific correlation problems explored below.

Integration of graptolite and shelly data for the Wenlock Series is better by comparison, with firm evidence for six out of nine possible graptolite biozones in the type area (Bassett *et al.* 1975, p. 6). Establishment of eustatic trends depends on the definitional rigor of series, stages, and biostratigraphical zones but a Silurian time scale based on practical eustasy clearly has the potential to become a powerful tool in correlation.

SUMMARY OF SILURIAN EVENTS

McKerrow (1979) recognized four Silurian eustatic sea-level events based on data from North America and Europe (Text-fig. 2): a transgression at the beginning of Llandovery time, a high stand followed immediately by a regression during later Llandovery time (within the *M. sedgwickii* graptolite biozone), and a regression at the end of Ludlow time. He also drew attention to sea-level events of limited continental effect. Unknown to McKerrow, the transgressive–regressive peak that he linked to the *M. turriculatus* Biozone in North America corresponds with an event defined by

Grabau (1936) in South China (see Rong *et al.* 1984). An early Ludlow 'continental transgression' also was thought by McKerrow (1979) to be restricted to northern Europe. Lenz (1982) recognized the same initial Llandovery transgression and late Ludlow regression in western and northern Canada, but he also identified a broad transgression of early Ludlow age (Text-fig. 2).

Much new research has been completed on the Silurian System since the attempts by McKerrow (1979) and Lenz (1982) to distil a middle Palaeozoic sea-level curve. A review of progress is divided into sections on the Llandovery and post-Llandovery series. Text-figure 5 gives a summary sea-level curve for the Silurian, showing regional conformity on parts of several palaeocontinents.

Llandovery Series

Research cooperation by M. E. Johnson (USA), Rong Jia-yu and Yang Xue-chang (China), B. G. Baarli and D. Worsley (Norway), as well as by M. Rubel, H. Nestor, and D. Kaljo (Estonia), has been particularly successful in tracking sea-level events on three different early Silurian continents. These are referred to as Laurentia (North America), Baltica (northern Europe), and Cathaysia (Yangtze Platform of south China). Complementary data from other regions including Avalonia, Siberia, and Gondwana are also reviewed here.

Laurentia. Bathymetric data from stratigraphical successions in 22 widespread parts of North America limited to the palaeocontinent Laurentia were correlated by Johnson (1987). Four high stands in sea level based primarily on community replacement patterns in platform carbonates cluster at the transition from Rhuddanian to Aeronian time, in mid Aeronian time (as marked low in the *S. lens progressa* Biozone), in early Telychian time (as marked by the *S. laevis* Biozone), and in late Telychian time (as marked by the *Costistricklandia* Biozone) near the Llandovery–Wenlock boundary (Text-fig. 5). Subsequently, Easthouse and Driese (1988) used proximality trend analysis in Tennessee to suggest coeval sea-level changes in a purely clastic setting bordering the tectonically active landmass Taconica.

Baltica. Johnson *et al.* (1991) co-ordinated bathymetric research in southern Norway's Oslo region and Estonia's Baltic region, representing two large sectors of the palaeocontinent Baltica. On the basis of community-replacement patterns through similar shelly faunas, they identified the same four Llandovery sea-level events in Baltica as in Laurentia (Text-fig. 5). Use of proximality trend analysis by Baarli (1988) in Norway provides corroborating evidence for the first two events from a different perspective. Graptolite data from Estonia indicate that the first of these events occurred near the transition between the *Coronograptus cyphus* and *C. gregarius* biozones and the third occurred within the *Monograptus turriculatus* Biozone. Graptolite data from Norway indicate that the last event occurred near the Llandovery–Wenlock boundary. A major disconformity below the Rumba Formation in Estonia corresponds to the well marked shallowing sequence in the Rytteråker Formation of Norway. This interval fits between the second and third transgressive events.

Graptolitic mudstones and shales deposited in southern Sweden and Denmark also belong to the palaeocontinent Baltica. Independent work by Bjerreskov (1975) on the Danish island of Bornholm provides tantalizing clues to shifts in bathymetry, but also illustrates some of the frustrations in trying to correlate trends between shelly and graptolitic facies. All Llandovery graptolite biozones are well represented on Bornholm except for the *Monograptus sedgwickii* Biozone, which is apparently absent despite continuous stratification. Bjerreskov (1975) observed that the graptolitic shales reach their maximum darkness and widest Scandinavian extent within the thin *Cephalograptus cometa* Biozone, commonly included within the upper part of the *M. convolutus* Biozone. Locally, the '*cometa* band' is succeeded by a light grey silty mudstone rich in trace fossils. This ungraptolitic interval is followed by darker mudstones bearing graptolites that are diagnostic of the lower *M. turriculatus* Biozone.

Apparently, graptolites of the *M. sedgwickii* Biozone were ecologically occluded. It is logical to believe that such conditions involved an interim drop in sea-level. The later rise in sea-level is

SERIES	STAGE	GRAPTOLITE ZONES	United States	Canada	Ireland	Wales	England	Norway	Sweden	Denmark	Estonia	Siberia	N. China	S. China	Australia
PRIDOLI															
		C. lochkovensis		S		S	S					S	S	S	
LUDLOW	Ludfordian	*M. ultimus - M. formosus*	D								D	D		D	D
		Neocucullograptinae													
		S. leintwardinensis				S	S		S		S				S
	Gorstian	*P. tumescens*													
		L. scanicus	D	D		D	D		D		D	D			D
		M. nilssoni													
WENLOCK	Homerian	*P. ludensis*	S	S		S	S		S		S	S			S
		C. lundgreni													
	Sheinwoodian	*C. ellesae*	D		D		D		D		D	D			
		C. linnarsoni							S		S				
		C. rigidus													
		M. riccartonensis													
		C. murchisoni	S	S	S		S	S	S	S		S		S	S
		C. centrifugus													
LLANDOVERY	Telychian	*M. crenulata*	D	D	D	D		D	D	D	D	D		D	D
		M. griestoniensis													
		M. crispus	S	S	S	S		S			S	S		S	S
		M. turriculatus	D	D		D	D	D		D	D	D		D	D
	Aeronian	*M. sedgwickii*	S D	S D		S D	S D	S D	D	S D	S D	S D		S	
		M. convolutus													
		C. gregarius	S	S		S		S			S	S		S	S
	Rhuddanian	*C. cyphus*	D	D		D		D			D	D		D	D
		C. vesiculosus													
		A. acuminatus													

TEXT-FIG. 5. Global Silurian sea-level curve showing geographical conformity on several different palaeocontinents. The United States, Canada, and Ireland represent Laurentia; Wales and England represent Avalonia; Norway, Sweden, Denmark, and Estonia represent Baltica; Siberia, North China, South China, and Australia each represent parts of other palaeocontinents. Entries below each country signify a recognized deepening (D) or shallowing (S).

consistent in timing with the *M. turriculatus* Biozone but the preceding high stand linked to the *M. convolutus* Biozone by way of the '*cometa* band' conflicts with the assumption that an eustatic peak must correspond to the lower *M. sedgwickii* Biozone. Put another way, there is widespread evidence for an eustatic peak correlative with the lower part of the *S. lens progressa* Biozone, but whether or not that shelly interval is fully synchronous with the *M. sedgwickii* Biozone is unclear in the Llandovery type area or elsewhere.

On Bornholm, the '*cometa* band' is 50 cm thick, the upper 10 cm of which are dominated by the subspecies *C. cometa extrema* (Bjerreskov 1975, p. 11). When *C. c. extrema* was defined by Bouček and Přibyl (1941) in Bohemia, it was assigned to the lower *M. sedgwickii* Biozone. Thus according to original designation, the '*cometa* band' straddles the zonal boundary between the *convolutus* and *sedgwickii* biozones where *C. c. extrema* is present. More work is needed on the correlation of critical graptolite and shelly faunas. 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.

Another bathymetric curiosity on Bornholm is the occurrence of an oolitic limestone capping mudstones containing an impoverished graptolite fauna of the *Cyrtograptus lapworthi* Biozone (Bjerreskov 1975). This relationship suggests that the final eustatic high stand during Llandovery time was followed by a lowstand in the early Wenlock (Text-fig. 5).

Avalonia. This microcontinent included parts of England, Wales, Ireland, Newfoundland, Nova Scotia, and a sliver of New England. McKerrow (1979) originally concentrated on data from many of these areas. Fortey and Cocks (1986, p. 158) provide some revisions for North and South Wales that confirm the second, third, and fourth high stands in sea level now recognized in Baltica and Laurentia. The first event known elsewhere to peak near the Rhuddanian–Aeronian transition is more subtle in Wales as recently detected in the Crychan Forest area (Siveter *et al.* 1989, p. 88).

Ancient rocky shores offer a particularly good reference point for the detection of transgressive and regressive events. A classic locality recognized in Shropshire as long ago as 1846 is the Silurian island or peninsula called the Longmynd (Johnson 1988). Cocks and Rickards (1969) studied an important set of palaeontological data recovered from five boreholes flanking the present south-eastern side of this landmass. The community replacement pattern from borehole number 5 at Hamperley, for example, was found to follow from the *Lingula* community to the '*Eocoelia*', *Pentamerus*, *Stricklandia*, *Pentamerus*, and *Clorinda* communities. This sequence was attributed originally by Cocks and Rickards (1969) to a normal transgression up to the *Stricklandia* community, but various imbalances in depositional and subsidence rates were invoked to explain the reversal to a *Pentamerus* community followed by the sudden skip to a *Clorinda* community. The relative position of abundant stricklandiid brachiopods falls between strata bearing *M. convolutus* and *M. sedgwickii* (Cocks and Rickards 1969, p. 228). The brachiopods in question were assigned to the subspecies *Stricklandia lens intermedia* with the qualification that 'the specimens probably fall outside the morphological limits of the lower forms of the subspecies' because its age is estimated as late as 'C_1' (Cocks and Rickards 1969, p. 221).

This means, in effect, that the specimens studied are near an early *S. lens progressa*, both in form and age. A different interpretation adopted by McKerrow (1979) is that the reversal from a *Stricklandia* community to a *Pentamerus* community reflects an actual drop in sea level. This event conforms to the mid Aeronian fluctuation noted farther to the south in the Welsh Borderland at May Hill. Here we have a good example of the kind of biostratigraphical problem that needs to be addressed if the mid Aeronian high stand in sea-level is to be defined more rigorously. Close association of *Clorinda* communities with strata bearing *M. turriculatus* in some of the other boreholes also suggests that the Longmyndian coast experienced a rapid early Telychian rise in sea level.

Siberia. Silurian seas of the Siberian platform were bounded on most sides by lowlands, with a connection to the open ocean only in the direction of the present north-west. The Moiero River sections described by Tesakov and Predtechensky (1979) and Tesakov *et al.* (1986) occupied a central platform position. More normal marine conditions prevailed during Llandovery time than during the Wenlock to Přídolí intervals. Facies patterns generally reflect the shrinkage and disappearance of these enclosed seas.

Tesakov and Predtechensky (1979) presented a facies model including quiet water lagoonal facies (gypsiferous to terrigenous layers), littoral facies (algal limestones or dolomites), sublittoral facies (coral- or brachiopod-rich nodular limestones), and quiet water eulittoral facies (trilobite- or graptolite-rich argillites). A more detailed revision of the Moiero sections in the context of a ten fold facies model was made by Tesakov *et al.* (1986). Pentamerid brachiopods are a common faunal element defining a mid bathymetric reference point in this scheme.

At least 10 or 11 cycles of Llandovery sea-level fluctuation can be interpreted on the basis of the bed-by-bed data collected by Tesakov *et al.* (1986) and summarized in Text-figure 3. When these data are smoothed by the consolidation of faunal information in 10 m intervals, four or five sea-level cycles become more prominent. The highest levels are represented by beds in the Moierokan Formation bearing *Coronograputus cyphus angustus* or *Stricklandia lens* (Rhuddanian–Aeronian boundary). Two peaks in the overlying Haastyr Formation fall within the lower range of the conodont *Hadrognathus staurognathoides* and the brachiopod *Eocoelia hemisphaerica* (mid Aeronian age). A subsequent peak in that formation falls within the upper range of the same conodont, but above *Pentamerus oblongus* (early Telychian age). Two peaks in the overlying Agidyi Formation fall squarely within the range of the conodont *Pterospathodus amorphognathoides* (a late Telychian age for the first is reasonable). These correlations agree with the timing of Llandovery sea-level changes noted elsewhere (Text-fig. 5).

Cathaysia. The Yangtze region of South China was a separate Silurian continent, with a marginal landmass called Cathaysia. Stratigraphical sections in six areas of adjoining Guizhou, Sichuan, and Hubei provinces were studied by Rong *et al.* (1984) for sea-level patterns and the results were compared with North American patterns by Johnson *et al.* (1985). Carbonate facies in South China and North America bear a striking resemblance to one another, but the extensive platformal shales rich in graptolites are a unique feature of South China. These are not exclusively deep water shales, as in the examples of the Welsh, Danish, and Estonian graptolitic shales. Chinese graptolite diversity data suggest that the initial Silurian transgression peaked mainly after the *Pristiograptus cyphus* Biozone, which is correlative roughly with the local emplacement of a shelly *Borealis* fauna (about at the Rhuddanian–Aeronian transition).

The mid Aeronian event registered in North America, Baltica, and Avalonia, and probably in Siberia, has not been detected yet in South China (Text-fig. 5). An event originally referred to by Grabau (1936) is well documented both by shelly and graptolite faunas as early Telychian in age (Rong *et al.* 1984). Additional information comes from northern Sichuan at Qiaoting, where the graptolitic shales of the Nanjiang Formation belonging to the lower *M. turriculatus* Biozone sit disconformably on the upper Ordovician 'Kuanyinchiao Bed'. Interpretation of a rapid transgression across this upland area fits the eustatic pattern recognized previously in China and elsewhere.

The geographically extensive *Salopinella–Coronocephalus–Sichuanoceras* fauna in the middle part of the Xiushan Formation was attributed by Johnson *et al.* (1985) to a high stand in sea-level at about the Llandovery–Wenlock boundary. Further investigation indicates that this distinctive fauna spans the boundary between the *Monoclimacis griestoniensis* and *M. crenulata* biozones (Yu *et al.* 1988), and also is restricted to the upper part of the *Spathognathodus celloni* conodont Biozone (Zhou *et al.* 1985). Although these biostratigraphical determinations draw the Xiushan Formation down more into the Llandovery Series, conformity with the latest Telychian eustatic event is not excluded (Text-fig. 5).

Gondwana. Llandovery strata are uncommon in Australia, but some graptolite and shelly (*Pentamerus* and *Stricklandia*) faunas are indicative of cyclic trends. Jenkins (1978) described an important sequence in the vicinity of Angullong, New South Wales, where the Cadia Group is separated by a major disconformity from upper Ordovician rocks and the Wangoola Group is separated from the Cadia Group by another disconformity spanning much of the *M. convolutus* and *M. sedgwickii* biozones. Both groups begin stratigraphically with conglomeratic to coralline and shelly limestones followed by graptolitic shales.

The Avon Lea Mudstone bears graptolites from the *M. triangulatus* Biozone. If this unit is taken as the transgressive climax of the Cadia Group, then it corresponds to a eustatic high stand near the Rhuddanian–Aeronian transition (Text-fig. 5). The second expected eustatic high stand is excluded by the 'Panuara Hiatus'; this exclusion necessarily invokes local tectonic uplift. But if two transgressive peaks are represented in the Wangoola Group by the *Pentamerus* beds of the Cobbler's Creek Limestone and the Ashleigh member of the overlying Glendalough Formation, respectively, then the third and fourth eustatic high stands known elsewhere in the Silurian world were registered in Australia (Text-fig. 5). These units are separated from each other by conglomeratic sandstones and red beds of a probable regressive character. The sandstones are correlated with the *M. griestoniensis* Biozone (Jenkins 1978).

Elsewhere on Gondwana, 'oscillatory' changes in shelf carbonates are reported below the Muth Quartzite in the Pin Valley of Spiti, India (Das Gupta 1982). The range of bio-bathymetric indicators there includes beds containing a diverse fauna of trilobites, solitary rugose and tabulate corals, bulbous stromatoporoids, and laminated dolomites with desiccation cracks and ripple marks. Das Gupta (1982) refers these strata to the upper Ordovician and lower Silurian. Although the precise Silurian age of the Muth Quartzite is disputed, it is rich in pentamerid brachiopods (Goel *et al.* 1987). Clearly, the Silurian of the Spiti area has great potential for more detailed sea-level studies.

Wenlock to Přídolí Series

Diastrophism has appealed to many authors who have studied post-Llandovery changes in sea-level (including the present authors). Stratigraphical variations in terrigenous content were used by Kaljo (1971) to establish transgressive–regressive patterns in the Baltic region, and he accounted for local differences in their timing by means of local tectonic movements. Continental scale uplift was cited by Rong *et al.* (1984) and Johnson *et al.* (1985) to explain the widespread early Wenlock emergence of China's Yangtze region, which persisted for the remainder of the Silurian Period. Bassett (1985) employed the gradually increasing tectonism of the Caledonides to explain the diachronous spread of shallow water and continental red-bed deposits across Scandinavia. We are not opposed to the notion of co-existing tectonic controls, but mounting evidence suggests that at least three eustatic high stands in sea level occurred during later Silurian times. Mid Wenlock, early Ludlow, and late Ludlow events are recognized in many areas.

Laurentia. On the basis of many years of research in the southern Great Lakes region of the U.S.A., Droste and Shaver (1987) summarized a model for sea-level cyclicity linked to repetitive salt beds and generations of coral-stromatoporoid bioherms. Their model correlates basinal salt beds and nearby reef terminations on interbasin platforms with marine regressions. Transgressions halted salt deposition and permitted renewal of bioherm development. Proposed high stands in sea-level include early to middle Wenlock, approximately middle Ludlow, late Ludlow to early Přídolí, and multiple Přídolí events (Droste and Shaver (1987, p. 215). Dating of these events was mainly by conodonts and brachiopods from the inter-basin arches.

Independent evidence for an early Wenlock regression followed by a transgression was given by LoBue (1982) on the basis of a laterally extensive palaeosol bracketed by tidal flat deposits in the Williston Basin of North Dakota. Other corners of Laurentia, such as the now detached Galway region of Ireland, also underwent an early Wenlock regression and subsequent transgression ending in mid Wenlock time (Williams and Harper 1988). A sea-level curve assembled by Bourque *et al.* (1986, p. 480), however, shows some discrepancies based on the timing of reef cyclicity in the Gaspé Basin of Quebec. They found that the early Wenlock regression was prolonged locally until a late Wenlock–early Ludlow transgression. In turn, this high stand in sea-level was prolonged through most of the Ludlow. Regional tectonics may have played a more dominant role in Quebec than in the midwestern United States.

In their study of thick limestones of the Leopold Formation in the Canadian Arctic, Dixon *et al.* (1981) described multiple sand peaks of Přídolí age, which they treated as time markers. Although unstated, the emplacement of detrital sediments within carbonates of intertidal origin probably involved brief relative changes in sea level.

Avalonia and Baltica. The work of Ratcliffe (1988) supports a general regression from middle to late Wenlock time in the English Midlands, on the basis of oncoids as bathymetric indicators. McKerrow (1979) cited evidence for a subsequent early Ludlow transgression in Wales, May Hill, and Shropshire. Across much of the Welsh Borderland, Cherns (1988, p. 498) established that the offshore migration of facies and faunas comprising upper Leintwardine strata (middle Ludlow) resulted from 'regression rather than tectonic controls on sediment supply'. These relationships are supported by a more recent compilation of data in the Ludlow area (Siveter *et al.* 1989, p. 40).

Despite the complex facies relationships within the carbonate succession of Gotland (Laufeld and Bassett 1981), phases of the Slite and Hemse beds incorporate similarly robust reef generations and may represent mid Wenlock and early Ludlow high stands in sea-level. Conversely, the Tofta and Eke beds appear to represent early Wenlock and mid Ludlow falls in sea-level. The Eke facies on Gotland correlate in part with the Leintwardine Formation of the Welsh Borderland (*Saetograptus leintwardinensis* graptolite Biozone). Jeppsson (1987) argues that the extinctions following after the *Pterospathodus amorphognathoides* (lower Wenlock) and *Polygnathoids siluricus* (middle Ludlow) conodont biozones were influenced by anomalous oceanic conditions, including possible drops in sea-level. His plot of limestones versus graptolitic marls (Jeppsson 1987, p. 133) on Gotland is consistent with the interpretation of high stands in sea-level during mid Wenlock and early Ludlow times (Text-fig. 5).

More detailed data are available from the nearby Estonian island of Saaremaa. Radionova and Einasto (1986, p. 168) compiled information on the succession of onshore, shoal-related algal communities that indicate marked transgressions in the mid Wenlock Maasi Beds, the earliest Ludlow Sauvere Beds, and the latest Ludlow Kudjape Beds. Conversely, maximum regression is indicated by the latest Wenlock Soeginina Beds and the upper part of the mid Ludlow Himmiste Beds (equivalent to Eke Beds).

Märss (1986) provides many additional stratigraphical logs for the Baltic region, plotting detailed curves based on a five-fold lithofacies system. As noted above, this system has been calibrated by Kaljo and Rubel (1982) to include brachiopod data. The sequences of offshore facies at Ohesaare (southern tip of Saaremaa) and Ventspils (in Latvia) is summarized by Märss (1986, p. 77), and they show a general similarity to the trends recorded by Radionova and Einasto (1986). In particular, the Ohesaare and Ventspils curves agree in suggesting late Wenlock regression, and the Ohesaare core confirms a regression at the K_2H level (*S. leintwardinensis* Biozone). On the other hand, the Ohessaare and Ventspils cores confirm that maximum Wenlock transgression occurred in the *Monograptus riccartonensis* Biozone, but the Ohesaare core also reflects the same subsequent transgression at the J_2M level in the *Cyrtograptus ellesae* Biozone at noted by Radionova and Einasto (1986). Furthermore, the Ohesaare curve indicates three Ludlow transgressions. The outer peaks correlate precisely with the prominent early and late Ludlow transgressions detected by Radionova and Einasto (1986), while the inner peak matches a minor fluctuation also recorded by Radionova and Einasto (1986). Unfortunately, the Ohesaare and Ventspils curves emphasize this middle peak.

Overall, the many similarities expressed by these data are compelling evidence for coeval sea-level events in the Baltic region (Text-fig. 5). The differences still may be explained by local tectonic movements as suggested by Kaljo (1971).

Siberia. Oscillating middle to back-shoal and lagoonal facies in the Moiero River sections of Siberia (Tesakov and Khromych 1986) specify a long late Wenlock transgression ending in a marked regression at the Wenlock–Ludlow boundary. Three transgressive peaks also are assigned to the Ludlow and a main transgressive peak is suggested as Přídolí in age (Text-fig. 4). Placement of the Wenlock–Ludlow and Ludlow–Přídolí boundaries, however, is not backed up by firm biostratigraphical data.

China. Excluding parts of western Sichuan and eastern Yunnan provinces, virtually no Wenlock, Ludlow, or Přídolí strata have been found in South China. Not enough is known about the succession of strata bearing Wenlock shelly faunas in Yunnan to describe accurately relative sea-level variations.

Upper Silurian to Lower Devonian strata are well developed, however, along a narrow belt from Qujing to Yuanjiang in eastern Yunnan. There the Kuanti and Miaokao formations are considered to be late Ludlow in age, and the Yulungssu Formation early Přídolí on the basis of brachiopods (Rong and Yang 1980). A pronounced drop in brachiopod diversity occurs through the Miaokao Formation and a restricted, very shallow water environment is represented by the sparsely fossiliferous mudstones of the overlying Yulungssu Formation. The main part of the Přídolí is represented by the sandstones and red beds of the lower part of the Cuifengshan Formation, which bears a shallow-water *Lingula* and bivalve fauna. Community succession in this sequence indicates a clear drop from a transgressive peak in the Late Ludlow, through a prolonged regression in the Přídolí (Rong 1986).

Upper Silurian to Devonian strata in both the Lesser Khingan Mountains of extreme north-eastern China in Heilongjiang Province and the Western Qinling Mountains of southern Gansu Province indicate regressive Přídolí conditions, followed by transgressive early Devonian environments.

Australia. An interesting regressive–transgressive episode of late Wenlock to early Ludow age was reported by Jones *et al.* (1987) from the Willow Glen Formation in the Cudgegong region of New South Wales. Fluvial sediments are bracketed by oolitic beds bearing minor gypsum crystals. The oolitic beds are bracketed in turn by algal limestones reflecting deeper water faunas.

Farther south is the famous Yass region of New South Wales, which features a continuous basal Ludlow to Devonian succession of carbonates, clastics, and tuffs (Link 1970; Strusz 1986). Transgressing the Hawkins Volcanics, the intertidal to supratidal O'Briens Creek Sandstone (exhibiting mud cracks and ripple marks) gives way to the Cliftonwood Limestone (bearing a sparse fauna of corals, brachiopods, and ostracodes). An early Ludlow age for this event is based on conodonts belonging to the *Neoprioniodus excavatus* Biozone. The overlying Hattons Corner Group begins with a thick tuff deposited under shallow marine to very shallow marine conditions and 'passes up into progressively deeper water marine mudstones and carbonates, though at no stage was deposition much below the photic zone' (Strusz 1986, p. 41). Shales containing a *Clorinda*-like community are succeeded by a rich coral–stromatoporoid community in the Hume Limestone which marks a significant drop in sea-level at the top of this unit. A mid Ludlow age for part of the Hume Limestone is shown by conodonts in the *Belodella triangularis – Polygnathoids siluricus* Biozone (Link 1970). Partial overlap with or close approximation to the *S. leintwardinensis* graptolite Biozone is implicit. Thus, this part of the Yass succession may conform to the same low stand in sea level recorded in northern Europe (Text-fig. 5).

The succeeding Booroo Ponds Group is composed mostly of graptolitic shales, bearing *Monograptus formosus* which indicates a late Ludlow age near the top. Transition to these shales is marked by the Yarwood Siltstone, which contains a diverse brachiopod fauna including *Aegiria* and *Dicoelosia* (Strusz 1986, p. 43). The late Ludlow transgression suffered a brief, minor reversal during deposition of the Rainbow Hill Marl, which bears shallow water brachiopods such as *Spirigerina*, *Nucleospira*, and *Salopina*. A similar regressive pulse at about this level was recorded also in the Baltic region.

According to Strusz (1986, p. 43), depositional conditions for the mostly Přídolí Barambogie Group 'were not markedly different from those of the preceding rocks'. A change in source area may have involved tectonism. A shallowing trend is not shown until the occurrence of algal limestones belonging to the Elmside Formation at the top of the group. A transitional Silurian–Devonian age for this unit is based on graptolites and conodonts.

CONCLUSIONS

The combined evidence is substantially in favour of at least four globally coordinated high stands in sea-level during Llandovery time (Text-fig. 5). An early event close to the Rhuddanian–Aeronian transition is now recognized in the United States, Canada, Norway, Estonia, Siberia, South China, and Australia (New South Wales). In terms of graptolite biostratigraphy, this falls near the boundary between the *Coronograptus cyphus* and *C. gregarius* biozones. A subsequent event of mid Aeronian age corresponds to the basal parts of the *S. lens progressa* and the *M. sedgwickii* biozones. Future work may prove that this event is related to the uppermost part of the *M. convolutus* Biozone as well. The mid Aeronian event was recorded in many parts of the United States, Canada, Wales, England, Norway, Sweden, Denmark, Estonia, and probably Siberia.

The third, early Telychian event is tied to the *S. laevis* and *M. turriculatus* biozones. It is widely established in the United States, Canada, Wales, England, Norway, Denmark, Estonia, Siberia, South China, and probably New South Wales. A fourth event took place before the end of Telychian time, as correlated with the lower parts of the *Costistricklandia lirata* and *M. crenulata* biozones. This final event is confirmed broadly in the United States, Canada, Wales, Norway, Denmark, Estonia, South China, and probably Siberia and New South Wales.

Standard geochronology suggests that these transgressive–regressive cycles had a duration of about 2·5 m.y. Community replacement patterns generally are symmetrical, suggesting gradual as opposed to punctuated changes in sea level.

The foregoing conclusions regarding Llandovery eustasy are based on a long period of international collaboration among the authors and various colleagues. Three important factors helped to facilitate the present outcome of our project. We are able to agree on a common model for scaling bathymetric change (in this case, keyed mainly to brachiopod communities). Direct visits have allowed us to judge field data for ourselves and thus to eliminate the possibility of reading too much into the stratigraphical literature. And finally, and most critically, we adhere to a unified time scale that is understood mutually to have certain deficiencies.

We appreciate the fact that strict eustasy is impossible as a fully global phenomenon, and we expect more contradictory evidence to surface from neglected quarters of the Llandovery world. With these qualifications, however, documentation of coeval sea-level fluctuations on three or more independent palaeocontinents strongly credits the concept of *practical* Silurian eustasy. By no means do we disregard the significance of local or regional tectonics as an agent of relative sea-level change. Rather, we are somewhat surprised at the persistent overprint of eustatic signals in regions of well known tectonic influence (such as the American Taconics and Scandinavian Caledonides).

The second part of this survey, concerning Wenlock–Přídolí eustasy, was undertaken strictly as a library study. Only one of us (D.K.) has had extensive field experience with upper Silurian strata. Disadvantages in assembling such independent data involve risks in which different authors might have gathered the primary information according to variable criteria and using possibly inconsistent time scales. Several of the authors we consulted based their bathymetric observations on similar concepts of reef cycles or shoal migrations (Bourque *et al.* 1986; Droste and Shaver 1987; Jones *et al.* 1987; LoBue 1982; Radionova and Einasto 1986; Ratcliffe 1988; and Tesakov and Khromych 1986). There is little certainty, however, that any of these authors would have processed the same field evidence in just the same way as the others. Nevertheless, the following useful conclusions can be drawn regarding the likelihood of global Wenlock–Přídolí changes in sea-level (see Text-fig. 5). A mid Wenlock high stand is reported widely in the United States, Ireland, England, Sweden, Estonia, and Siberia. The most reliable data from the Baltic region suggests that such a period of relatively high sea-levels was initiated with deposition of the *M. riccartonensis* Biozone and may have persisted through deposition of the *C. ellesae* Biozone. A late Wenlock drop in sea-level is recognized in the United States, England, Estonia, Siberia, and Australia (New South Wales).

Perhaps most significantly, a mid Ludlow regression is equated commonly with or approximately with the *S. leintwardinensis* graptolite biozone in England, Sweden, Estonia, and New South Wales. If this event was eustatic in nature, then there is a strong probability that at least one eustatic high stand in sea-level preceded it in early Ludlow time and another followed it in the late Ludlow. Various sources commonly cite two or even three major Ludlow transgressions. Very early and very late high stands appear to be the most widely agreed on.

The least persuasive evidence for eustasy comes from the Přídolí data. Available information from New South Wales indicates a prolonged period of high sea-levels; scattered points in China indicate a prolonged period of low stands; the Siberian story is presented as one simple transgression and regression, and multiple fluctuations are interpreted in the United States and Canada. Arguments that cyclicity in Přídolí salt beds or sand peaks might be eustatic appear to lack a broad geographical base of support.

At this point therefore, there is reasonable evidence in favour of at least three transgressive-regressive cycles in Wenlock-Ludlow time. There may be others. Standard geochronology suggests that these cycles were stretched over much longer periodicities than the earlier Llandovery cycles. It is more likely, however, that these post Llandovery trends are very general. They probably mask shorter term superimposed events that are yet to be studied fully and correlated on an international basis.

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