Thus one cannot speak of dinosaurs living in the Jurassic System, but rather that they lived in the Jurassic Period.

Geochronometry achieved through radiometric dating is a different matter, though a connection between this and biostratigraphy is indicated on the figure as biochronology. The term *biochronology* is appropriate in those as yet rare cases in which a most detailed event stratigraphy allows the precise coupling of radiometric dates with biostratigraphy. E.G. Kaufmann and his colleagues have achieved this in the Western Interior Basin of North America, where within the Cretaceous some 400 bentonites or other volcanic related layers provide a succession of isochronous surfaces which have been dated by the potassium–argon method to give a resolution of fractions of a million years. This chronology is linked with a most detailed ammonite and bivalve biostratigraphy. Such fine tuning is unlikely to be frequently achieved, even at this particular level, and thus it remains important that an internationally agreed global standard stratigraphy is maintained.

Concluding comments

In summary, *biostratigraphic units* are bodies of strata characterized by their fossil content. As Arkell (1956b) put it: 'without the fauna a zone is nothing: a will-o'-the-wisp, without substance, unrecognisable'.

Global standard stratigraphic divisions (chronostratigraphic divisions) are bodies of strata representing divisions of the internationally agreed hierarchy including era, system, series, stage, and chronozone. Their definition depends upon selected marker points (golden spikes) in basal boundary stratotype sections (Section 5.10), the choice having been ratified by the International Union of Geological Sciences (IUGS) acting through its Commission on Stratigraphy (Section 5.8). In few cases as yet have international procedures achieved completion. The Subcommission on Silurian Stratigraphy has a fully agreed scheme and in some other systems, such as the Devonian, matters are well advanced. In the meantime the names for the various systems are generally accepted. It is important that once the horizons for boundaries between global standard divisions are chosen, and once the golden spikes in boundary stratotype sections are agreed and the whole matter ratified by the International Union of Geological Sciences, these decisions are accepted for the reasonable future, so that stability is assured and fundamental work can move ahead against a rational and clear background. It is important to recognize that no boundary stratotype is likely to be perfect in all respects. It is too much to expect that sections will be found which have all the desirable attributes. It is also important to recognize that there is some urgency about the matter and, above all, that nationalism has no place in stratigraphy.

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5.7 Zone Fossils

M. G. BASSETT

The practical application of biostratigraphy (Section 5.6) in correlating rock units carries with it the implication that the fossils used in any particular exercise have a time significance. In reality, the local time ranges of all fossils are likely to vary from section to section across the extent of their geographical distribution because of different evolutionary and ecological factors that controlled origins, rates and extent of distribution, and extinctions (Fig. 1). Thus the ranges of fossils across a given area may well be diachronous in detail, but nevertheless, by careful collecting from accurately logged sections, it is possible to plot out the limits of successive faunas and/or floras that are representative of successive intervals of time. Biostratigraphic units built up in this way remain the primary tools for dating and correlating Phanerozoic sedimentary rocks throughout the world.

The fundamental unit is the *biozone*, which is defined solely on the basis of its fossil content, without regard to either thickness or lithology. Fossils that characterize a particular biozone are termed *zone fossils*, or index fossils, and the names of such taxa are then used for the name of the biozone itself; e.g. the *Monograptus ludensis* Biozone in the Silurian Period (based on a single index graptolite), the *Geminospora lemurata–Cymbosporites magnificus* Biozone in the Devonian Period (based on a combination of spore taxa), and the *Quenstedtoceras lamberti* Biozone in the Jurassic Period (based on an ammonite species). In general, the finer the taxonomic precision of the zonal index, the finer will be the degree of stratigraphic resolution in correlation, so that, for example, a biozone identified on the basis of a species will normally give a greater degree of accuracy than one based on genera or higher taxonomic groups.

Since different organisms evolve at different rates and are subject to different environmental constraints, their potential as biozonal indicators will also differ considerably. Ideally, for use in accurate and refined biostratigraphy, zone fossils should have a number of well defined characters: (1) a short vertical range resulting from rapid evolution; (2) a wide horizontal distribution, preferably intercontinental; (3) independence of facies control, as, for

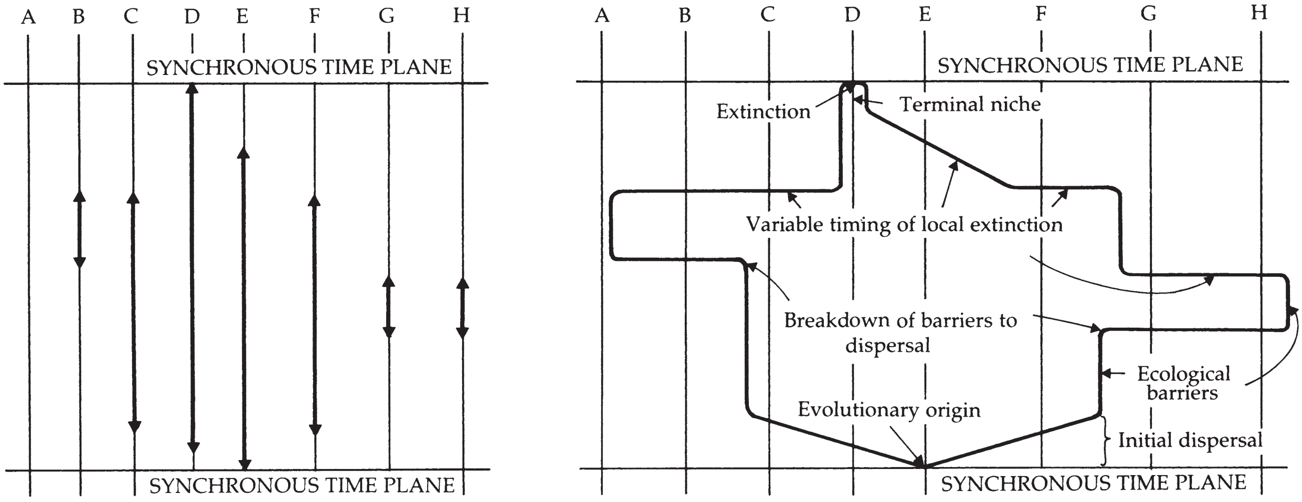

Fig. 1 Left, Hypothetical vertical ranges of a fossil species through eight measured stratigraphical sections A–H. Right, Geographical distribution of the same species illustrating some of the factors responsible for its stratigraphical expression. (After Taylor 1987.)

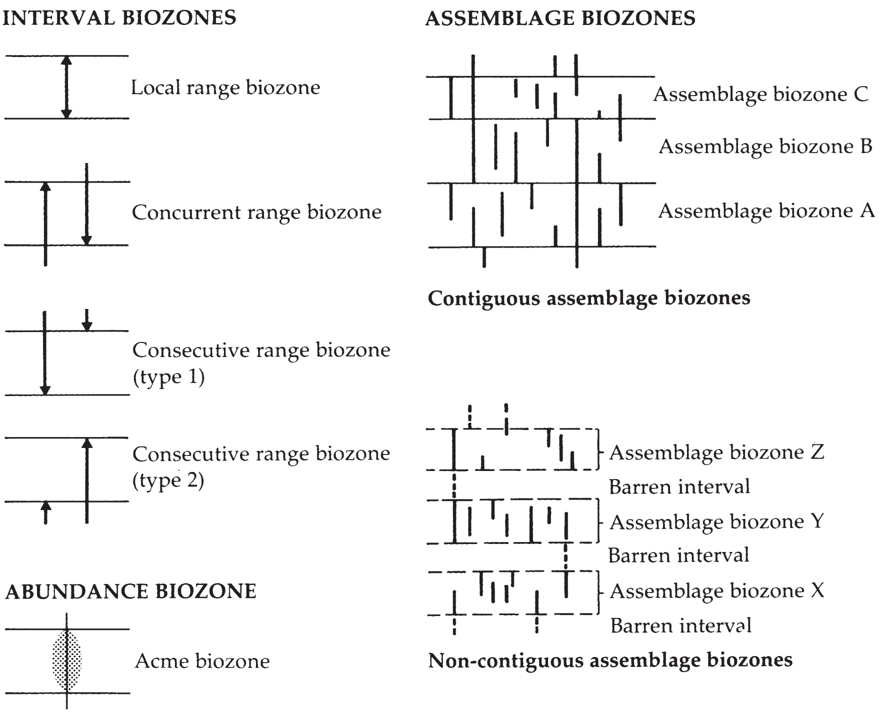

Fig. 2 Categories of biozones. (After Taylor 1987.)

example, in wind-borne spores and in free-swimming as opposed to benthic organisms; (4) distinctive morphological characteristics to ensure accurate identification; and (5) a high preservation potential, as in animals with hard shells or skeletons. It is rare for all these conditions to be met fully, but good examples of fossil groups that satisfy most criteria are the graptolites, ammonites, conodonts, planktic foraminifera, and spores.

Fig. 2 illustrates some of the various categories of biozones that can be constructed using different data sets of vertical ranges of fossils (see, for example, Holland *et al.* 1978; North American Commission on Stratigraphic Nomenclature 1983; Taylor 1987). In the *local range biozone* the total known range of the zone fossil defines the limit of the unit. The co-occurrence of overlapping taxa is used to define *concurrent range biozones*, in contrast to the *consecutive range biozone* where one (or more) of the zone fossils ranges through an interval unaccompanied by taxa that overlap with it at other levels. An *acme biozone* relies for definition on the recognition of a maximum occurrence of a fossil that might otherwise range both higher and lower in the succession. In *assemblage biozones* the recognition of different taxa with varying vertical ranges forms the basis for definition, and in such cases the name of the biozone itself is generally based on one of the more common members. It is clear that a zone fossil is not necessarily confined to the particular biozone that bears its name (Fig. 2).

The time-intervals represented by biozones, and thus their degree of accuracy in biostratigraphy, vary considerably throughout the geological column. Among the optimum levels of refinement currently available in Palaeozoic rocks are some graptolite biozones, which may give a resolution of correlation within one million years or less, whilst in the Mesozoic the time-span of some ammonite biozones and subzones may be as short as 200 000–250 000 years.

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5.8 International Commission on Stratigraphy

M. G. BASSETT

The International Commission on Stratigraphy (ICS) is the largest scientific body within the International Union of Geological Sciences (IUGS). It is also the *only* organization concerned with the co-ordination of stratigraphy on a global scale. One of its major statutory objectives (Cowie *et al*. 1986) is the establishment of a standard, globally applicable stratigraphic scale, which it seeks to achieve through the co-ordinated contributions of a network of Subcommissions, Working Groups, and Committees. It also organizes a number of conferences each year, and the results of these conferences are usually published. The precise definition of stratigraphic boundaries and their accurate correlation is a prerequisite of this work, particularly between divisions of System, Series, and Stage rank, as a means of constructing an internationally agreed framework within which geological events can be plotted both laterally and successively through time. In Phanerozoic rocks, fossils provide the chief means of correlating the sub-divisions of geological time and the boundaries between them.

In practice, chronostratigraphic boundaries are defined at a unique point in a rock sequence at a specific locality, thus representing a unique instant in time and a standard against which other sequences can be correlated; this unequivocal method of definition is often called 'golden spike' stratigraphy (see Holland 1986; Section 5.6). Such a unique point defined within a rock section is now referred to as a Global Boundary Stratotype Section and Point (GSSP; Cowie *et al*. 1986), providing an immutable time signal within a globally standard stratigraphic scale, and the only place at that level in the scale where *by definition* time and rock coincide (Sections 5.6, 5.10.1).

The first inter-System boundary to be defined and agreed internationally in this way was between the Silurian and Devonian systems (Martinsson 1977); in this case, and after considerable discussion of possible levels and appropriate sections throughout the world by an international Working Group of the ICS, a point was selected in a succession at Klonk in Czechoslovakia which coincides with the first appearance in that section of the graptolite *Monograptus uniformis*, taken to mark the base of the *uniformis* Biozone (Section 5.10.4); the strict definition of the GSSP is at a specific point within the rock sequence to mark the fixed point in time, and the base of the *uniformis* Biozone is not the defined level but is the datum used to correlate that point elsewhere. Similar subsequent decisions have been made for the Ordovician–Silurian (Section 5.10.3) and Pliocene–Pleistocene boundaries and for boundaries between Stage divisions within the Silurian and Devonian (Bassett 1985); fossils involved so far as a main basis for correlation include graptolites, conodonts, and ostracodes.

Within the ICS there are Subcommissions of international experts that monitor the latest specialized disciplines within each geological System, Working Groups to consider the formal definition of remaining inter-System boundaries, and Committees that carry out a variety of other standard-making stratigraphical work. This complex working organization has evolved in the long history of the ICS since its origins in 1878 (Martinsson & Bassett 1980; Cowie *et al*. 1986, p. 4). Most International Geological Congresses have had commissions and committees, with various names and with various durations, that have been concerned with international co-operation in stratigraphy, stratigraphic classification, and stratigraphic terminology. At the 11th Congress, Stockholm, 1910, a Commission on a Lexicon of Stratigraphy was created. This Commission functioned modestly through many subsequent Congresses. At the 19th Congress, Algiers, 1952, however, its name was changed to Commission on Stratigraphy and it was reorganized to include two Subcommissions: a Subcommission on the Lexicon of Stratigraphy and a Subcommission on Stratigraphic Nomenclature. Since that time the Commission on Stratigraphy has functioned continuously and many new Subcommissions have been added. In May 1965, the Commission applied formally for admission to the IUGS and was accepted as a commission of the IUGS. At that time the membership of the Commission was reduced drastically from 150–200 members to consist only of its officers and the presidents of its Subcommissions.

In its overall objective to clarify and co-ordinate principles of stratigraphic procedure, and to produce a unified nomenclature for a standard stratigraphic scale as a means of documenting global events unambiguously, the ICS also incorporates data from all other branches of stratigraphy, such as quantitative stratigraphy, magnetostratigraphy, chemostratigraphy, and geochronometry, to integrate with the biostratigraphic methods emphasized here and together they form the embracing discipline of *holostratigraphy*.

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5.9 International Geological Correlation Programme

J. W. COWIE

Introduction

In its life of over 15 years this joint programme of the International Union of Geological Sciences (IUGS), an independent non-governmental scientific body, and the United Nations Educational, Scientific and Cultural Organization (UNESCO) have sponsored a considerable body of geological research. This has been achieved in a number of ways (Skinner & Drake 1987):

1 Through the creation of a professional advisory secretariat with permanent headquarters in Paris and with, more recently, regional offices in various parts of the world to serve particularly remote (from Paris) and/or developing regions.

2 By means of grants to International Geological Correlation Programme (IGCP) projects whose scientific programmes and logistics have been reviewed and submitted through a Scientific Committee of volunteer, unpaid geologists from many parts of the world. (Finance comes to the IGCP from national government subscriptions on a codified basis.) These project grants are relatively small but are valuable 'pump-primers' or 'seed-money' serving as a validating and commendatory mechanism to attract other funds from national funding bodies, learned societies, geological surveys, commercial companies, and universities.

3 The individual IGCP projects are required, if they wish to continue to receive annual grants, to report in good time each year to the IGCP Secretariat which briefs the Scientific Committee and the Board of IGCP for their respective annual meetings in February. At these meetings decisions are made regarding overall policy, guidance for projects (through their project leaders), and level of funding for the coming year.

The IGCP arose from a conference in Czechoslovakia in 1967 to meet the need for a more concerted international effort to solve some of the fundamental geological problems with which the IUGS is concerned. Through 1968 and 1969 the proposal moved forward. A final draft, completed in 1971, was adopted by the Council of the IUGS and the General Conference of UNESCO; this launched the IGCP as a co-operative venture, and its statutes were approved in 1972. In May 1973 the IGCP Board held its first session at the UNESCO headquarters in Paris with Sir Kingsley Dunham (U.K.) as Chairman. W.B. Harland (U.K.) had acted as Secretary of the IUGS Co-ordinating Panel during the formative period and F. Ronner was appointed as Secretary of the 1973 Board.

Aims and scope

The principal goal of the IGCP is to encourage international research on geological problems related to the identification and assessment of natural resources and the improvement of man's environment. Continuing IGCP aims have been to stress the scientific achievements of the projects, improving man's environment, access to mineral resources, assistance in co-operation and communication between scientists from different regions, and the transfer of knowledge to developing countries. Assessments of the IGCP have been published by Reinemund & Watson (1983) and Skinner (1987).

The scientific scope of the IGCP has varied little since 1973; changes in emphasis have been subtle and have largely reflected changes in global geological policy and aims, with a slight shift, perhaps, from more academic, basic science to more applied, man-orientated aspects. Pure palaeobiology has not really been a part of the IGCP, but stratigraphy (including biostratigraphy) has played a significant role. The following projects are worthy of note in this context:

1 *Precambrian–Cambrian boundary* (Project 29).
2 *Ecostratigraphy* (Project 53).
3 *Biostratigraphic datum-planes of the Pacific Neogene* (Project 114).
4 *Upper Precambrian correlations* (Project 118).
5 *West African biostratigraphy and its correlations* (Project 145).
6 *Phosphorites of the Proterozoic–Cambrian* (Project 156).
7 *Early organic evolution and mineral and energy resources* (Project 157).
8 *Stratigraphic methods as applied to the Proterozoic record* (Project 179).
9 *Rare events in geology* (Project 199).
10 *Global biological events in Earth history* (Project 216).
11 *Floras of the Gondwanic continents* (Project 237).
12 *Stromatolites* (Project 261).

The range of topics with a palaeobiological emphasis is illustrated by those listed 10–12. New projects will probably be added by the IGCP, but there may be no new palaeobiological projects *per se* coming forward and this is a gap which palaeobiologists may wish to see filled — 12 out of 264 Projects in 15 years with only varying commitment may be considered too small a proportion of this international key programme.

Examples of palaeobiological projects

Project 261 on *Stromatolites* was started in 1987 with a meeting in Cardiff, U.K. Its full title is 'The biostratigraphical and environmental significance of stromatolites and other microbially derived organosedimentary structures through space and time'. The aim is to understand microbial evolution and the factors affecting stromatolite morphogenesis, to establish their classification, biostratigraphic potential, and role in forming mineral and petroleum deposits. The approach is multidisciplinary.

Project 237 on *Floras of the Gondwanic continents* was started in 1986 and held a key meeting in São Paulo, Brazil at the 7th Gondwana Symposium in July 1988. The primary objective is to produce a general, up-to-date summary of the Upper Silurian to Lower Tertiary flora of the Gondwanic continents. An interesting aspect of IGCP work is the exploitation of training opportunities in developing countries via international co-operation of experienced scientists from many countries. In 1986 at the University of São Paulo a four-month training session was mounted in paleobotany and paleophytogeography. Further courses in 1987 and 1988 also involved African participants.

Project 216 on *Global biological events in Earth history* has, in its activities in 1986 and 1987, aroused very wide interest indeed and is probably the IGCP Project which holds the most interest for palaeobiologists in general. The project arose from a programme of the International Palaeontological Association (IPA) and is concerned with world-wide, traceable, exceptional changes ('events') within the biosphere. It aims at a better understanding of the dependence and interdependence of processes and extraordinary events in the biosphere, geosphere, and atmosphere. Global bioevents fall into several categories of pattern: innovation-events (especially important in the Precambrian and Early Phanerozoic), radiation events, spreading events, and extinction events (which may not be extremely short-term but may occur stepwise). Cyclic and acyclic processes are given special attention in their possible overlap. Probable causes are either cosmic (revolution of the Solar System within the Galaxy and impact of cosmic bodies; Section 2.12.2) or biological and abiotic (sea-level, oceanic physical and chemical composition, climate, oceanographic parameters; Section 2.12.1). Some causes may be catastrophic but resulting from combination with unstable or perturbed conditions. In 1988 an international meeting of Project 216 entitled 'Abrupt changes in the global biota' was held in Boulder, U.S.A. Already the Project's 15 or so pages of bibliography indicate the opportune and seminal aspect of this successful palaeobiological IGCP activity.

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5.10 Global Boundary Stratotypes

5.10.1 Overview

J. W. COWIE

The most basic property of rocks which is utilized in stratigraphy is lithology; *lithostratigraphy* is concerned with the organization of rock strata into units based on their lithological character. Stratigraphy is also concerned with the organization of strata into two other types of units, however: (1) *biostratigraphy*, based on fossil content; and (2) *chronostratigraphy*, based on age relations. The latter, because of the nature of time, is the most abstract. Chronostratigraphic major boundaries have in recent decades been studied mainly by international working groups and projects (Lafitte *et al.* 1972; Harland 1973; Hedberg 1976; Bassett 1985). The different properties of rocks give rise to other branches of stratigraphy such as magnetostratigraphy, chemostratigraphy, stable isotope chemostratigraphy, and seismostratigraphy. This splitting of the subject into branches can lead to considerable complexity because the changes in a rock stratal succession based on one property may not coincide with those for another; different sets and types of units may be needed to assemble a unified time-scale. The newer term *holostratigraphy* covers the study of all aspects together and the general unity of stratigraphic studies should not be overlooked.

There is no consensus view of the principles and practice of stratigraphy. The position outlined here is that currently adopted by the International Commission on Stratigraphy of the International Union of Geological Sciences, which, in the true spirit of science, will probably evolve or change radically in the next few decades.

The most reliable systems of stratigraphy deal with global processes which are universal, unidirectional in the sense of irreversible (time sequences can only be read one way) and non-recurrent, and non-repeatable. Included here, most significantly, is the evidence from biological evolution (sequential) and nuclear decay (metric). Biological evolution interacts through geological time with other factors, but is the main indicator of the direction of the arrow of time, of prime polarity. The evidence available so far shows that it cannot be stopped and reset. Nuclear decay also has polarity, but, unlike biological evolution, it can be stopped and reset; additionally, it has the great virtue of numeracy. Geochronometry has particular attraction for geoscientists working in unfossiliferous or sparsely fossiliferous rocks, but biostratigraphy gives the most useful and, at the present stage of research, generally the most accurate framework.

Those who work mainly with the earlier part of the Proterozoic Eon rocks and the Archaean Eon rocks find little help from the stratigraphic methods frequently used in the Phanerozoic Eon — in particular with respect to palaeobiology and biostratigraphy. In attempting to establish a global Precambrian chronostratigraphy current ideas favour a chronometric subdivision based upon intervals of 'geological convenience'. Such a chronometric approach does not rule out the possibility of separate thematic time-scales — biostratigraphic, magnetostratigraphic, chemostratigraphic. This applies especially to the later part of the Proterozoic where palaeobiological evidence is available. The Archaean–Proterozoic Boundary is placed at 2500

Ma. A tripartite subdivision of the Proterozoic in eras with boundaries at 1600 Ma and 900 Ma is widely recommended.

Today, stratigraphy is a subject in a dynamic phase of development, with diverse emphases on aspects like unique or recurrent cyclic events (event stratigraphy), such as ash falls, eustatic changes, glacial deposits, appearance or disappearance of a particular biota, and evidence of impacts of extraterrestrial bodies. If these events can be shown to have global and isochronous effects, so that they are not merely parochial and diachronous masquerades, then they can be uniquely valuable in elucidating Earth history. Cyclicity is still being sought in the modern search for the 'pulse of the Earth'. Adjectives attached to stratigraphy proliferate, indicating renewed interest and involvement with stratigraphy as the keystone of the geological sciences — ecostratigraphy, seismic stratigraphy, chemostratigraphy, event stratigraphy, biostratigraphy, magnetostratigraphy, sequence stratigraphy, and others (Berry 1984).

International stratigraphy is much concerned with efforts to correlate standard global Series, Stages, and Systems, and a major part of this work has been to define boundaries between them (Fig. 1). Accurate communication without definition is impossible. A *Boundary Definition* utilizing a unique point in a rock sequence represents (if correctly selected), as nothing else in geology can, a unique instant of time; it defines unequivocally a standard against which other sequences can be correlated by the analysis of all available data. Biological/palaeontological species are subjective and the full range is unknown — because of incomplete research, or incompleteness of the geological record. This shortcoming can be overcome by using several independent groups of fossils to correlate faunal/floral assemblages (Glaessner 1984). It is salutary to recall that matters of *positive* science, which concern 'nature', require discovery, and apply some test of truth, should be distinguished from matters of *normative* science, which are regulated by man as part of his method of understanding nature and which apply tests of correctness and utility. The global stratigraphic scale (chronostratigraphy) is a norm which can be legitimately established by international agreement through an agreed voting procedure. It can be argued that choices in international stratigraphy should violate historical priority as little as possible, but this consideration can often be overridden by the higher priority of going for the best and making progress. Confusing historical precedents may need to be set aside by an authoritative international decision (which is very likely to violate some established usage).

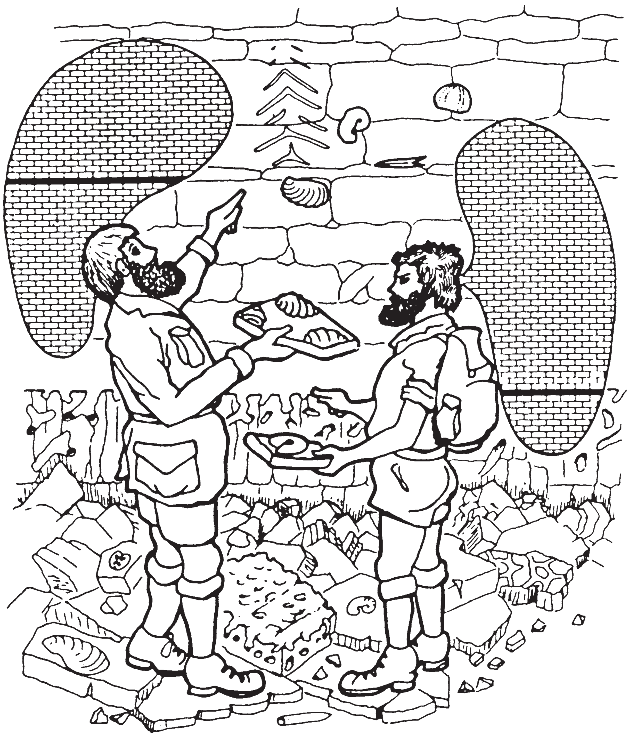

Fig. 1 The cover of a publication produced by the Subcommission on Cretaceous Stratigraphy.

Historical geology depends on positional relationships of rock and mineral bodies and identification of the Earth's evolutionary trends. The importance of the boundary stratotype lies in its role as a future anchor to which all subsequent correlations can be tied, even if new palaeobiological or physical methods become available, because it is the only place where we actually know (by definition) that time and rock coincide within our classification.

A *Boundary Stratotype Point* defines, without doubt, an instant of geological time. A horizon will, at the *Global Stratotype Section and Point* (GSSP) locality, contain the Point, but the horizon may, traced laterally, be diachronous (cutting across time-planes) and may drift away from the instant of time defined by the point. The GSSP is the standard and is unique. The correctly selected GSSP gives an actual point in rock and is therefore not an abstract concept — all other methods can prove to be diachronic. It will be expected to remain fixed in spite of discoveries stratigraphically above and/or below. The main criterion is that any horizon and point selected must be capable of being correlated over wide areas by any or all available methods. In a world which is not ideal, it is most unlikely that all selected stratotype points can meet all the ideal requirements; stratigraphy must therefore be a practical subject which responds to the needs of working geologists (Holland 1986).

GSSPs allow maximum flexibility with the use of multiple hypotheses to give minimum ambiguity and the greatest likelihood of stability. It is necessary to emphasize that each GSSP is the designated type of a stratigraphic boundary identified in published form and marked in the section as a specific point, constituting the standard for the definition and recognition of the stratigraphic boundary between two named global standard chronostratigraphic units. The type locality of a GSSP is the specific geographical locality in which the stratotype is situated.

Aspects to consider in the selection of a GSSP

Of great importance is the relationship of a stratotype section and point sequence to globally significant marker horizons in the immediate and accessible region, e.g. faunal or floral zone assemblages stratigraphically above or below the stratotype point, climatic markers such as tillites, and other factors assisting long-range (preferably global) correlation. Correlation must precede, accompany, and follow definition of a boundary. The choice of an appropriate boundary level for the point is only possible where a marker horizon has proved to be isochronous within the limits of precision attainable by stratigraphic methods. Auxiliary marker horizons as close as possible to the boundary level will give good approximate stratigraphic positioning where and when the primary marker is missing.

Other aspects to be considered include:

1 Continuity of sedimentation through the boundary interval — preferably a marine succession without major facies change. A continuous monofacial succession (or one with only rapidly alternating and repeating facies changes) will reduce possible errors resulting from stratigraphic gaps. It will also limit the occurrence of facies fossils and appearances and disappearances associated with environmental change rather than biological evolution of lineages.

2 Completeness of exposure: not in an isolated position but with a succession which can be followed easily — above and below the GSSP, and preferably laterally as well.

3 Adequate thickness of sediments.

4 Abundance and diversity of well preserved fossils: appearances and disappearances of single fossil species may be diachronous and therefore a bad guide for the location of a GSSP. Multispecies fossil zones (e.g. faunal assemblages) may be preferable. Taxa which are palaeoecologically tied to facies should be excluded from consideration (although all fossils are to some extent facies fossils). In order to minimize possible effects of environmental controls on different fossil groups, recognition of the boundary level should preferably be based on all available faunal and floral data.

The selection of appropriate fossils will vary greatly in different parts of the geological column. Ideally, selection of a point within an evolutionary lineage is desirable but recognition of such lineages can be subjective and not necessarily more accurate than the recognition of a particular assemblage zone. Such decisions must be left to the experts in each case. *Autochronology*, i.e. a single species taken out of a phylogenetic lineage (with its predecessor and successor known in detail) as the biological way of approaching a boundary free of ecological, facial, or sedimentary disturbing effect, may be a powerful tool when available.

5 Favourable facies for the development of widespread, reliable, and time-significant correlation horizons: this requires that the GSSP should not be in or close to conglomerates, breccias, olistostromes, turbidites, or remanié deposits. This should, as far as possible, eliminate variation of chronostratigraphic or chronometric age within the stratotype section near the stratotype point. Even if, for example, fossils in derived blocks and surrounding matrix appear to be of the same species and age, the danger exists that new techniques or new finds (palaeobiological or physical, such as magnetostratigraphy) might discriminate between the blocks and matrix, introducing an unacceptable imprecision.

6 Freedom from structural complication, metamorphism, or other alteration: currently the question of exotic accreted terrains is pressing, but the problem of the relationship between present and past position may not adversely affect global stratigraphy.

7 Freedom from unconformities: an *obvious* boundary should be suspect. Either it is too obvious because there is a marked change in lithology or because there is a marked change in fauna or flora. In either instance the change may imply a time-break, and consequently an unsuitable horizon at which to fix any time definition; no disconformities, unconformities, cryptic paraconformities, or time-breaks in sedimentation any longer than a brief diastem can be tolerated close to a GSSP.

8 Amenability to magnetostratigraphy and geochronometry: these factors are probably the most important for future work and some would argue that no GSSP should be accepted without one or both.

Boundary stratotype procedure

One of the main aims of the *Boundary stratotype procedure* is to attain a common language of stratigraphy that will serve geologists world-wide and avoid petty argument and unproductive controversy. Development of a standard global stratigraphic scale which is stable for a considerable period of time is the objective. Testing can then proceed. If new developments demand revision, this can be considered in exceptional circumstances such as: (1) permanent destruction or inaccessibility of an established stratotype; or (2) violation of accepted stratigraphic principles.

In the overwhelming majority of cases in the Phanerozoic Eon, correlation must precede the definition of a boundary. Unless preliminary choices are made, however, progress may be slow as the process of testing a candidate or the competition between candidates may be the stimulus required for improvement of needed correlation techniques and of the correlation itself. Correlation must precede the selection of boundary stratotype candidates to a considerable extent, but in practice the procedure may be complex. The finding of the best stratigraphic level and best geographical site may have to proceed in tandem for a time. Correlation to a satisfactory degree is necessary but improvements in correlation should continue after a boundary stratotype has been selected. In the Phanerozoic Eon, where the prime polarity factor is biological evolution, boundaries will normally be guided in their definition by chronostratigraphy (led by biostratigraphy), but in the Proterozoic and Archean Eons guidance will be chronometric at the present stage of research. Chronostratigraphy can be expected to be used increasingly for boundaries late within the Precambrian successions.

It would be unwise (or impossible) to specify which criteria are essential and which are desirable up and down the geological time-scale, because of the multiplicity of criteria involved, and the variation in circumstances. Only a brief preliminary checklist can be suggested:

1 Explicit motivation for the preference.
2 Correlation on a global scale.
3 Completeness of exposure.
4 Adequate thickness of sediments.
5 Abundance and diversity of well preserved fossils.
6 Favourable facies for widespread correlation.
7 Freedom from structural complication and metamorphism.
8 Amenability to magnetostratigraphy and geochronometry.

Accessibility and conservation. These two topics are contrasting but complementary factors. Recent experience has shown that if access to an important outcrop is too easy and unrestricted then excessive collecting (even vandalism and plunder) may destroy the outcrop. Conservation and some restriction is therefore necessary in developed regions. Conservation in more remote regions may be easier but this depends on regional geological activity by outsiders.

A problem for access/conservation may be weathering, e.g. heavy rainfall can form rapid mud flows from a marly sequence, frost can form screes which soon cover an outcrop, and outcrops on sea coasts may be particularly subject to rapid erosion.

There must be no insuperable physical and/or political obstacles to access by geologists of any nation, and access should preferably be afforded without great expense and ideally without much bureaucracy. At the International Geological Congress in Moscow (1984) it was agreed that a reasonable amount of collecting must be possible at a stratotype section. Although it is difficult for any group of geologists to commit any nation or organization to guarantee access and conservation for the indefinite future, total accessibility must assume considerable importance. If a GSSP were found to be inaccessible in the future, this would be a very powerful argument for a reassessment of the geographical location.

There is a metamorphosis once a GSSP has been ratified by the International Union of Geological Sciences:

1 Beforehand, all methods of correlation are enlisted to define a globally valid GSSP and to distinguish between what belongs to System X and what belongs to System Y.

2 After the decision the GSSP can be used to indicate without ambiguity what constitutes earliest System X and latest System Y. Correlation has in any case to precede the definition of a GSSP. Possibilities of correlation should be tested simul-

taneously, of course, at different levels close to the boundary.

There is no conflict between the global boundary stratotype concept and global, isochronous, event stratigraphy. The combination of global environmental change and major biotic changes (which may be caused by biological evolution) brings together lithostratigraphy and biostratigraphy to provide event stratigraphy. Stratotypes bring stability by an agreed point in rock representing a unique instant of time. The ultimate reference is to rock and not to abstractions.

In this work during the past decade or two, much inspiration and guidance has been derived by the international geological community from the brilliantly-expressed published results of the Silurian–Devonian Boundary Committee which have the great virtue of being based on practical experience in actually defining a GSSP (McLaren 1977; see also Section 5.10.4).

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5.10.2 Precambrian–Cambrian

J. W. COWIE

Historical background

The base of the Cambrian System, which is perhaps better termed the 'Precambrian–Cambrian Boundary' to emphasize the role of Precambrian studies as well as Cambrian research, is proving a difficult major geological horizon for which to establish a global standard. Interest was somewhat muted in the nineteenth century when so many enthralling problems concerning the younger parts of the geological column engaged attention. The relatively abrupt appearance of skeletalized fossils near the base of the Cambrian system is perhaps the greatest palaeobiological enigma, and this did not escape the attention of early geologists. It was not until the twentieth century, however, that much progress was made, as a consequence of the acceleration in exploration of the Earth's surface and the examination of sedimentary successions spanning the Precambrian–Cambrian transition (equivalent in age for most geologists to the Proterozoic Eon–Phanerozoic Eon transition).

In 1835 A. Sedgwick named the 'Cambrian Series' but his Lower Cambrian succession was largely without a fossil basis and would now be considered to include some Precambrian rocks as well. From the time of Cuvier in the eighteen-thirties it was assumed that natural breaks divided rocks in a world-wide pattern and that the 'Cambrian' rested unconformably on 'Archaean and Precambrian basement series'. Thus the base of the Cambrian was stratigraphically coincident with the unconformity first seen below the 'Cambrian' transgression. Vestiges of these ideas still persist and may yet be rejuvenated in event stratigraphy. Even as late as the nineteen-forties it was a tradition to regard, in the absence of other evidence, rocks without fossils at this level as Cambrian in age. Three decades ago workers equated the first horizon with trilobites ('Olenellus Zone') with the base of the Cambrian. The Archaean and Proterozoic Eons were grouped into rock units limited by unconformities that were thought to have a world-wide validity and occurrence. In recent decades, more and more successions have been described with apparently continuous sequences ranging from fossiliferous Cambrian rocks down into unfossiliferous strata of a lithological facies which could be expected to yield fossils but do not. A 'Symposium on the Cambrian System and its Base' at the 1956 International Geological Congress in Mexico was followed by a conference in Paris on the Precambrian–Cambrian Boundary in 1957. Further discussion took place in Copenhagen at the International Geological Congress in 1960. Research by Soviet geologists published in the nineteen-sixties was responsible largely for the establishment in 1972 (through stimulus from V.V. Menner, W.B. Harland, M.F. Glaessner, C.J. Stubblefield, and J.W. Cowie) of the Working Group on the Precambrian–Cambrian Boundary by the IUGS's International Commission on Stratigraphy (ICS) (Section 5.8).

Precambrian–Cambrian Boundary Working Group

At the first meeting in Yakutia, eastern Siberia, U.S.S.R., it was agreed that the Working Group should seek international agreement on the definition of the Precambrian–Cambrian Boundary in litho-, bio-, and chronostratigraphic terms based on a point in a standard rock sequence (Global Stratotype Section and Point — GSSP; Section 5.10.1) coupled with elucidation of the significant palaeobiological transitions occurring at, or about, this stage in the Earth's history. Selection of the GSSP would be based on biostratigraphy but all possible methods of correlation should be enlisted (Cowie 1985).

Up to 100 members from 20 countries have been involved in the Working Group, all recruited as individuals with relevant expertise, and at present there are 24 Voting Members. All serve as individual scientists and not as delegates of any nation or institution. From 1974 to 1988 the Working Group also functioned as IGCP Project 29: 'Precambrian–Cambrian Boundary'.

From 1972 to 1987, a series of meetings was organized to examine and discuss Precambrian–Cambrian Boundary sections. Plenary sessions and workshops were held in Montreal, Canada (1972), Paris, France (1974), Moscow, U.S.S.R. (1975), Leningrad, U.S.S.R. (1976), Sydney, Australia (1976), Beijing, China (1978), Paris, France (1980), Golden, Colorado, U.S.A. (1981), Kunming, China (1982), Bristol, U.K. (1983), Moscow, U.S.S.R. (1984), Uppsala, Sweden (1986), St. John's Newfoundland Canada (1987), and south China (1987).

Field meetings were also held, involving both examination of sections and discussions leading to subsequent research with local geologists. The following areas were visited: east Siberia, U.S.S.R. (1973 and 1981), Normandy and Brittany, France (1974), Ural Mts., U.S.S.R. (1975), Georgia, U.S.S.R. (1975), Anti Atlas Mountains of Morocco (1975 and 1976), Flinders Ranges in South Australia (1976), Iberian Peninsula of Spain and Portugal (1976), central and south China (1978 and 1982), eastern Newfoundland, Canada (1979), Mackenzie Mountains, Canada (1979), Nevada–California, U.S.A. (1981), Wales and England (1983), south Sweden (1986), Newfoundland (1987), and south China (1987) (Fig. 1).

The Precambrian–Cambrian transition is not signalled only by the skeletalization of fossil hard parts but is part of a major physical-chemical-biological changeover (possibly an 'explosion') shown also by the following (and other) changes and signals:

1 Decrease in dolomite accumulation.
2 Sharp drop in stromatolite formation and change of morphology.
3 First widespread appearance of red biogenic limestones.
4 Global accumulation of large phosphorite deposits (especially in the U.S.S.R., People's Republic of Mongolia, and China, but also elsewhere).
5 Considerable changes in the morphology and biological 'programming' of trace fossils.

At the 1983 Bristol meeting, candidates for the Global Stratotype Section and Point were discussed in some detail, and three were selected for further consideration: Ulakhan-Sulugur on the Aldan River in east Siberia, U.S.S.R.; on the Burin Peninsula, of eastern Newfoundland, Canada; and at Meishucun in Yunnan Province, southern China. At that time it was decided that the boundary stratotype should be placed as close as practicable to the lowest known appearance of diverse shelly fossils with a good potential for correlation (Luo Huilin *et al.* 1984; Rozanov 1984; Narbonne 1987).

These three candidates remain as prime choices in 1989 but new areas may well present important stratotype candidates in the future. They include the Olenek uplift region of northern Siberia (near the Anabar massif) and the Elburz mountains of Iran; the latter, in particular, has rich fossiliferous strata near the putative boundary and the former has great potential for correlation globally.

In 1987 a new GSSP candidate was presented by the Canadian and U.S. members of the Working Group at a slightly different level to the former Newfoundland candidate and guided by trace fossils as well as body fossils. It was claimed that

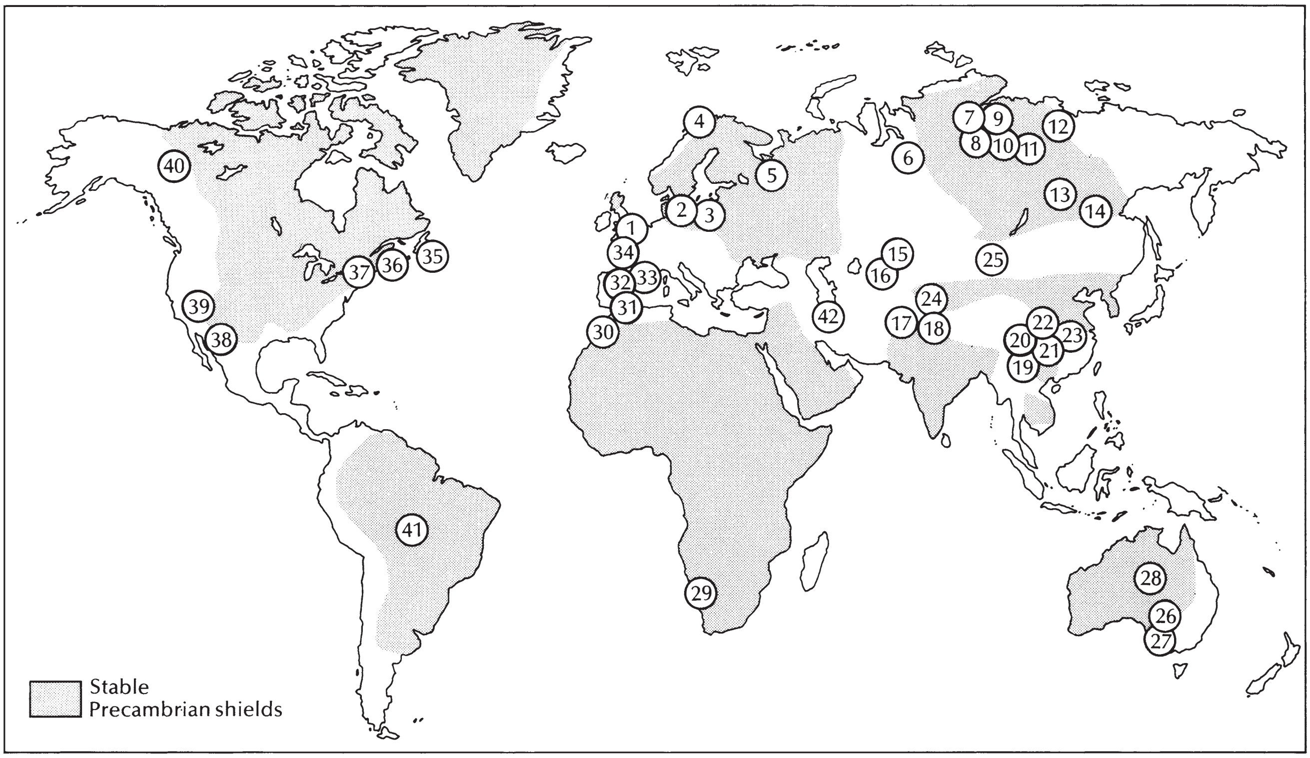

Fig. 1 Current geography of some important Precambrian–Cambrian boundary sections (circled) and Precambrian cratons (stippled). 1, North Wales, Shropshire and Nuneaton, England. 2, Bornholm and southern Sweden. 3, Northern Poland. 4, Troms, Norway, and Finnmark. 5, Onega Peninsula. 6, Sukharika river, Igarka region. 7–10, Anabar region: 7, Eriechka river; 8, Kotui river; 9, Fomitch and Rassokha rivers; 10, Kotuikan river. 11, Olenek uplift. 12, Chekurovka, lower reaches of Lena river. 13, middle reaches of Lena river. 14, Aldan river. 15, Kuznetask Alatau and northeastern Sayan. 16, Karatau, southern Kazakhstan. 17, Salt Range and Hazara district, Pakistan. 18, Mussoorie, Lesser Himalaya of India. 19, Meishucun, near Kunming, eastern Yunnan. 20, Maidiping, near Emei, southwestern Sichuan. 21, Northwestern Guizhou. 22, Southwestern Shaanxi. 23, Eastern Yangtze gorges, western Hubei. 24, Western Xinjiang. 25, Salanygol, Mongolian People's Republic. 26, Ediacara, Flinders Range, South Australia. 27, Mount Lofty and Yorke Peninsula, South Australia. 28, Amadeus and Georgina Basins, Northern Territory. 29, Nama Group, Namibia. 30, Anti Atlas and High Atlas, Morocco. 31, Sierra Morena and Montes de Toledo, Spain. 32, Cantabria and Asturia, northern Spain. 33, Montagne Noire, Hérault, France. 34, Brioverian of Normandy and Brittany, France. 35. Fortune Bay, Burin, Bonavista, and Avalon Peninsulas, southeastern Newfoundland. 36. St John, New Brunswick. 37, Nahant and North Attleborough, Massachusetts. 38, Carborca, Sonora, Mexico. 39, Mount Dunfee, Nevada and White Inyo Mountains, eastern California. 40, Mackenzie, Selwyn, and Wernecke Mountains of Yukon and Northwest Territories, northwestern Canada. 41, Corumba Group, State of Matto Grosso, Brazil. 42, Elburz Mountains, northern Iran. Localities 5–16 are in the U.S.S.R. and 19–24 are in the People's Republic of China. (After Brasier *in* Cowie & Brasier 1989.)

although the Precambrian–Cambrian boundary marks a fundamental change in Earth history with the first development of abundant skeletal and bioturbating organisms, and there is general agreement with the principle of placing the boundary '... as close as practical to the first appearance of abundant shelly fossils ...', marked provincialism of the earliest skeletal fossils and their virtual restriction to carbonate facies have hampered global correlation in the boundary interval. Trace fossils are especially common in siliciclastic facies, in which shelly fossils typically are rare and poorly preserved. Correlation in siliciclastic facies is critical, as these deposits comprise nearly 70% of exposed rocks in the boundary interval. Crimes (*in* Cowie & Brasier 1989) has outlined three globally-correlatable trace fossil zones that occur below the lowest trilobites.

Future research

It is clear that much research remains to be done on the palaeobiology of the Precambrian–Cambrian (Proterozoic–Phanerozoic) transition. Future work should include:

1 Integration of a global table of correlation by further documentation of stratotype sections using all available techniques.
2 Calibration of trace fossil data with the earliest

skeletalized body fossils, particularly in Asia, with revision and updating of range charts. These tables also should incorporate First Appearance Datum (FAD) and Last Occurrence Datum (LOD) of the main skeletal fossils, ichnofossils, and acritarchs, and evidence from sea-level curves, geochemistry (including stable isotopes), and magnetostratigraphy.

3 While not departing greatly from previous criteria regarding the stratigraphic level chosen for the Global Stratotype Section and Point, it seems agreed: (i) the level should be traceable into carbonate platform successions in Asia through the early skeletal fossil sequence and/or by chemostratigraphy, magnetostratigraphy, or sequence–event stratigraphy; (ii) the level should also be traceable into clastic platform successions linking with the trace fossil sequence and/or chemostratigraphy, magnetostratigraphy, or sequence–event stratigraphy; and (iii) tracing of the level into deeper sedimentary basins could be achieved through chemostratigraphy, magnetostratigraphy, and sequence–event stratigraphy.

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5.10.3 Ordovician–Silurian

C. R. BARNES & S. H. WILLIAMS

Historical background

The Ordovician System was introduced by C. Lapworth in 1879, in a successful attempt to solve the mid-nineteenth century acrimonious debate begun by A. Sedgwick and R. Murchison. Lapworth established a stratigraphy both in southern Scotland and in Wales, primarily by employing graptolites to develop biostratigraphic subdivision and correlation (Fig. 1).

It was soon recognized that both upper and lower boundaries of the system were marked by widespread breaks in sedimentation. The global regression during the Late Ordovician is now thought to be related to a glaciation in the Southern Hemisphere; evidence was first documented in Northern Africa, but periglacial deposits have since been found in South Africa, South America, Spain, and possibly northwest France (Rong *in* Bruton 1984). Brenchley and Newall (*in* Bruton 1984) estimated that the glaciation extended northwards to 40°S, with a high sea-level stand during the Rawtheyan Stage, global regression in the Early Hirnantian Stage (*Paraorthograptus pacificus*/*Climacograptus? extraordinarius* Zone), then dramatic eustatic rise during the *Glyptograptus persculptus* Zone.

Evidence for such eustatic change is seen in many areas, where late Ordovician regressive sequences are commonly followed by a hiatus equivalent to the *C? extraordinarius* Zone or longer, then by sudden onset of black shale sedimentation during the *G. persculptus* Zone or *Parakidograptus acuminatus* Zone. A distinctive shelly fossil assemblage termed the *Hirnantia* fauna is found within many of these late Ordovician marine deposits. It is diachronous, probably ranging in age from the *Dicellograptus anceps* Zone (*D. complexus* Subzone) to the *G. persculptus* Zone, and has been considered to represent a cold water fauna related to the late Ordovician glaciation. Such conclusions have, however, been questioned (Rong *in* Bruton 1984). In addition to the eustatic changes, a major palaeobiological event occurred during the Late Ordovician; this is one of the four largest mass extinctions during the Phanerozoic (Section 2.13.2).

Ordovician–Silurian Boundary Working Group

In 1976, the Ordovician–Silurian Boundary Working Group of the IUGS Commission on Stratigraphy (Section 5.8) was created to formally define the stratigraphic level and boundary stratotype location for the base of the Silurian System. Over the subsequent eight years it received over 50 reports from geologists around the world and organized major field excursions. The criteria which ideally should

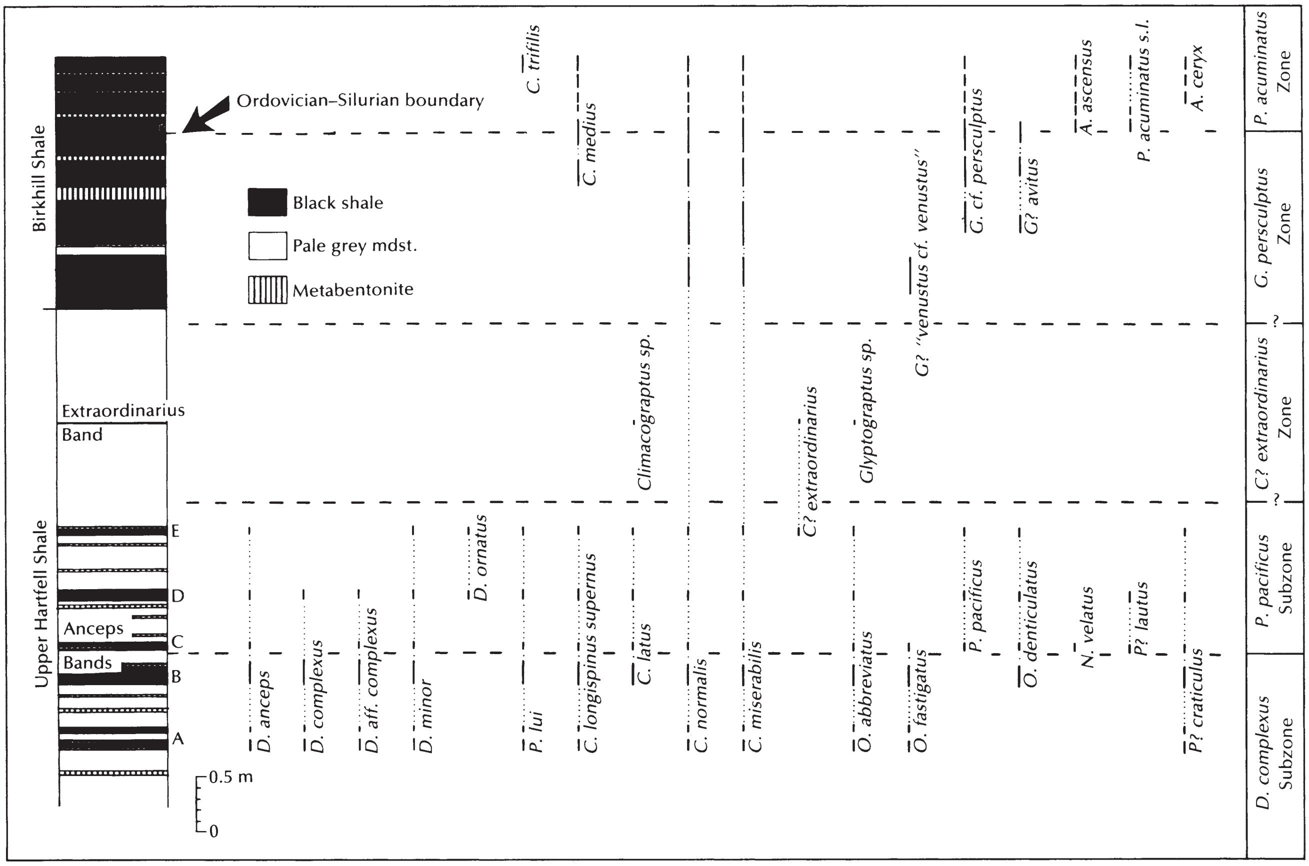

Fig. 1 Stratigraphy and graptolite ranges of the Late Ordovician and Early Silurian in the Linn Branch, Dob's Linn, near Moffat, Southern Uplands, Scotland.

be met by boundary stratotypes are set out in Section 5.10.1. The task of the Working Group proved unexpectedly difficult as sections became subjected to intense research. In most localities thought to approach the ideal criteria, one or more stratigraphic breaks occurred (e.g. disconformity, barren interval, or regional regression) and they were therefore deemed inadequate for stratotype status. The recognition that a low sea-level stand near the boundary exposed many regions of earlier deposition forced the Working Group to focus on sections representing marginal basins (e.g. Anticosti Island, eastern Canada) or deep oceanic settings (e.g. Dob's Linn, southern Scotland). These were contrasting sections in many of their attributes, and neither provided a perfect candidate for the boundary stratotype.

Anticosti Island in the Gulf of St. Lawrence, Quebec, preserves a 1500 m stratigraphic section of late Ordovician–early Silurian age. Limestones and minor shales predominate and represent deposition within a low latitude marginal basin. The strata are accessible, well exposed, scarcely deformed or thermally altered, and yield prolific, well preserved fossils (Barnes 1988). Graptolites are rare, but biostratigraphic control is possible with several other fossil groups, of which conodonts are the best studied. McCracken & Barnes (1981) proposed a system boundary 0.9 m above the base of member 7 of the Ellis Bay Formation at Baie Ellis, based on the first appearance of *Ozarkodina oldhamensis*. The section possesses most of the characteristics required for a stratotype, but lacks sufficient graptolites to provide good correlation into oceanic facies.

Dob's Linn lies within the Southern Uplands of Scotland, northeast of Moffat. The Moffat Shale Group comprises over 100 m of black, grey and siliceous shale and is divided into four formations ranging from the *Nemagraptus gracilis* Zone (Llandeilo) to the *Rastrites maximus* Zone (Llandovery). With the exception of the Upper Hartfell Shale Formation, most of the Moffat Shale is continuously graptolitic and has been renowned for its rich, diverse fauna since Lapworth published his landmark study in 1878. Other fossil groups are, however, mainly absent, with the exception of rare deep-water trilobites, brachiopods, and conodonts.

The late Ordovician and early Silurian succession at Dob's Linn has recently been subjected to critical, systematic study (see Williams 1988). Although most of the Upper Hartfell Shale is composed of grey, non-graptolitic mudstones, occasional graptolitic black shale bands occur. Of particular importance to the Ordovician–Silurian boundary are the Anceps Bands and Extraordinarius Band (Fig. 1). The Anceps Bands yield a rich, diverse fauna; in contrast, the following Extraordinarius Band contains only three graptolite taxa, as does the lowest part of the Birkhill Shale belonging to the *G. persculptus* Zone. During this and the succeeding *P. acuminatus* Zone, new taxa appear to give a more diverse, typically Silurian assemblage. The Ordovician–Silurian boundary was historically considered to lie at the boundary between the Upper Hartfell and Birkhill Shale; the Working Group, however, considered this to be an unsuitable horizon at which to place the boundary, owing to unfossiliferous strata and the lack of major faunal change. The boundary was consequently defined at the base of the *P. acuminatus* Zone, 1.6 m above the base of the Birkhill Shale. It is recognized by the first occurrence of *Akidograptus ascensus* and *P. acuminatus*, an event which may be accurately correlated in many sections throughout the world.

The final recommendation of the Working Group, with Dob's Linn as stratotype, was approved by the IUGS in 1984. Some concerns about the decision were expressed by Lesperance *et al.* (1987).

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5.10.4 Silurian–Devonian

C. H. HOLLAND

The standardization of the Silurian–Devonian boundary can be taken as a case history in international stratigraphic procedure. As the first such boundary to be agreed in modern fashion, some have regarded it as a kind of model. Others see the period of more than 12 years involved in settling the matter as being something of a warning. The main problem, causing this long gestation, was that of the 'lost series' (now referred to as the Přídolí) — a series lost in previous erroneous correlations.

Historical background

In 1834 R. Murchison showed the Tilestones of south Wales to be the basal part of the Old Red Sandstone. Later he moved the basal boundary to the top of the Tilestones, perhaps because by then he regarded their lower part as corresponding to the Downton Castle Sandstone of Shropshire, which he had previously taken as the top of his Upper Ludlow Rock. There is no available section crossing from the marine Devonian rocks in their type area of Devon into the Silurian System in its type area in the Welsh borderland. The different positions of the boundary accepted by various subsequent authors through the years have been documented by White (1950).

White chose the base of the Ludlow Bone Bed as the base of the Old Red Sandstone, making for the sake of practicality the 'slight adjustment' necessary beyond the boundary originally designated by Murchison. Later workers in the Welsh borderland were grateful for the stability thus achieved. In their revision of the Ludlow Series in its type area, Holland *et al.* (1963) designated a standard section for the base of the Ludlow Bone Bed at 'Ludford corner' in the town of Ludlow, Shropshire. In the meantime, Martinsson was achieving success in the use of ostracodes to correlate the Welsh borderland succession into the Baltic region and beyond, and Boucot was beginning to recognize the presence in such areas as Podolia (Ukraine, U.S.S.R.) of a brachiopod fauna which appeared to fall between that of the Ludlow Series and that of the Gedinnian in Belgium.

Committee on the Silurian-Devonian Boundary

In Central Europe, however, research workers, building upon the monumental work of Barrande, were becoming increasingly disillusioned with a Silurian–Devonian boundary that they found consirably difficult to use in correlation. They needed a succession in fully marine facies. At a meeting in Prague in 1958 Czech stages were formalized, but much more was achieved at the epic Bonn–Brussels meeting of 1960 organized by H.K. Erben. There was one particular discussion (at the back of a coach) during this meeting when everything became clear. Suddenly there was the realization that the graptolites did not disappear in some mystical way at the end of Silurian time but continued into the Devonian. After the meeting, correlation tables were rapidly changed, much new work was initiated, and the Committee on the Silurian–Devonian Boundary began its 12 years of work. Because of the previously erroneous correlation, the choice of a horizon for the boundary had to come first and it was inevitable that this would involve a measure of compromise (Fig. 1A). A level at the base of the *Monograptus uniformis* Biozone was first suggested by Holland (1965) and received early support in a paper by Czech colleagues. This horizon was eventually accepted by the Committee. At this time, the Committee also developed a set of criteria which it judged to be important in the subsequent selection of a location for the boundary stratotype. These included level of faunal and floral development, stratigraphic considerations, structural situation, facies diversity, geographical accessibility, and the possibility of conservation of the section. After many submissions had been received and members of the Committee had undertaken a variety of field visits, a short-list of four candidates emerged for the boundary stratotype: Morocco; Nevada, U.S.A.; Podolia, Ukraine, U.S.S.R.; and Bohemia, Czechoslovakia.

In the desert country on the edge of the Sahara in southwest Morocco, the Silurian–Devonian Boundary can be located near the small oasis of Ain Deliouine. It is difficult of access, but the factor most weighing against this section was the serious effect of desert weathering upon the graptolites

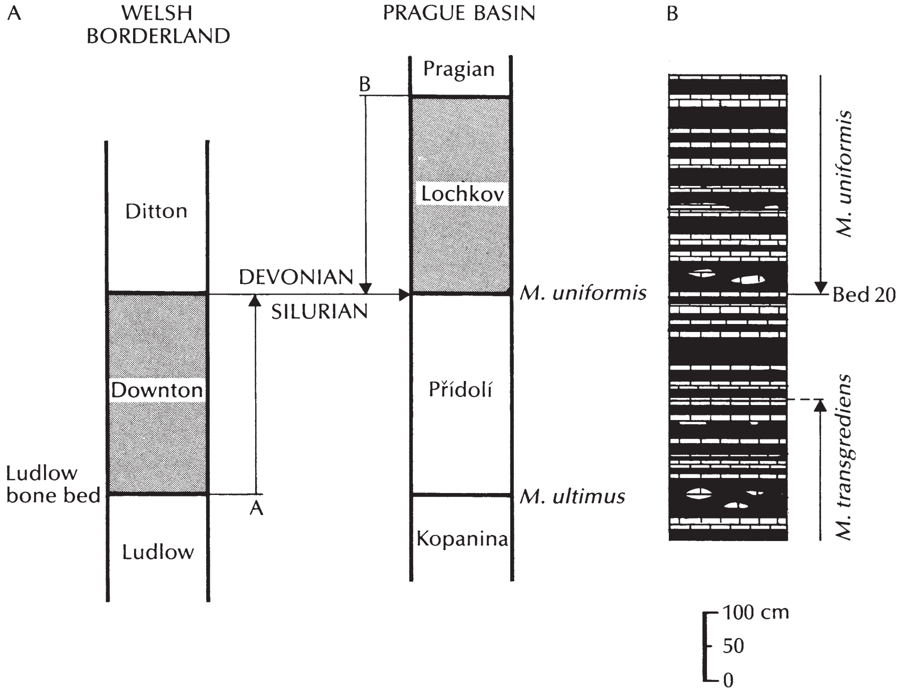

Fig. 1 A, The compromise involved in establishing international agreement on the placing of the Silurian–Devonian Boundary. (After Holland 1986.) B, Boundary stratotype for the base of the Devonian System at Klonk, Prague Basin, Czechoslovakia. (After Chlupáč *et al.* 1972.)

close to the boundary. In Nevada, the basin and range country provides good Silurian–Devonian sections. In spite of the tectonic isolation of the ranges, individual sections (such as those in the Roberts Mountains) are clear. It is important, however, that decisions on stratigraphic standardization should be achieved with reasonable expedition, and work in Nevada was insufficiently advanced. Podolia in the Ukraine is a magnificent area for Silurian–Devonian geology, with highly fossiliferous strata exposed in structurally simple sections along kilometre after kilometre of the Dnestr River and its tributaries. Unfortunately, no graptolites had been found in the beds immediately below the chosen horizon and there were also some problems of access. So Barrande's classic area in the Prague basin (Barrandian area) was chosen for the stratotype (Chlupáč *et al.* 1972), backed by extensive collections in the National Museum, Prague. The section at Klonk (Fig. 1B) was preferred to the structurally more complex alternative at Karlstejn; the 'golden spike' was placed at the point where *Monograptus uniformis* first appears within 'Bed 20'.

This final decision was ratified at the International Geological Congress in Montreal in 1972, when the Committee on the Silurian–Devonian Boundary reported through the Chairman, D. J. McLaren, to its parent body, the International Commission on Stratigraphy (Section 5.8), and thence to the International Union of Geological Sciences (Martinsson 1977). Since then the choice of horizon has proved significant, allowing for sensible correlation tables in which the Přídolí Series plays its part as the fourth series of the Silurian System.

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5.11 Fossils and Tectonics

R. A. FORTEY & L. R. M. COCKS

Introduction

The history of palaeontology has been closely connected with contemporary developments in other branches of the earth sciences. Until 30 years ago the subdisciplines of geology were less clearly separated than they are now, and the all-round geologist might routinely use fossils as part of his armoury of field data in unscrambling the problems of a structurally complex area. Fossils had an immediate part to play in resolving tectonic problems, and the structural geologist would use them at an early stage in the generation of his hypotheses; conversely, many invertebrate palaeontologists would not feel abashed at concocting structural hypotheses of their own. In the U.K. this was particularly true of Lower Palaeozoic studies, and it would not be overstating the case to say that palaeontology made as much of a contribution to working out the structure of Wales as any other geological discipline. In the nineteenth century the great works of Murchison and Sedgwick carried their palaeontological notes and appendices (e.g. Murchison 1839), and it is obvious that these authors used the fossils as guides and friends to find their way through these 'interminable greywackes'.

Nowadays there are few great generalists of this kind — the sheer proliferation of techniques and knowledge has made it impossible. As a consequence, tectonics, geochemistry, and sedimentology have separated as independent disciplines, and theories of structural intent may come from any one of them. Palaeontology is too often neglected entirely — but this is to miss evidence of practical usefulness. Conversely, the number of palaeontologists with an eye for structural problems has also diminished, partly because of the growth in the palaeobiological side of the subject, and partly because of the increasing specialization which is characteristic of all science.

Fossils do, however, still have an important part to play in the testing of tectonic theories in parts of the world where metamorphism has not destroyed the evidence entirely — and even in global problems. Perhaps the best way to regard fossils in a tectonic context, and the role of palaeontology as a separate discipline, is as a critical test of theories generated from any of the other geological subdisciplines; conversely, theories derived from palaeontological evidence must themselves pass muster with the tectonicist, the geochemist, or the sedimentologist. No matter how a theory is originally derived, it becomes plausible only when supported by different lines of evidence from several disciplines. The unique contribution of palaeontological evidence is that it does not depend directly or covertly on other sources of evidence; circular arguments are always hard to avoid in geology, and fossils can cast a hard factual light on tectonic speculation.

Classical uses of fossils in tectonic problems

The most basic use of fossils, especially invertebrates, is in the dating of rocks. In spite of the tremendous advances in radiometric geochronology there is no substitute for a reliable palaeontological age, because, unlike radiometric 'clocks', fossils cannot be 'reset' by later events (see also Section 5.10.1). Limitations are only set by the recognition of the fossils themselves — but occasionally these can be powerful limitations if the rocks that contain them have been heavily cleaved, distorted, or metamorphosed. Even so, it is surprising how much punishment fossils can endure before they are completely obliterated. For example, in the Appalachians Silurian brachiopods have survived sillimanite grade metamorphism to date a huge tract of otherwise barren metamorphics (Boucot & Thompson 1963); in the Alps belemnites are still recognizable after enduring extreme tectonization. Generally, fossils in shales are severely affected before those in limestones or sandstones. Even such distortions have their uses, if the original dimensions of the fossil are known, because they can provide a measure of extension or compression and thereby permit the calculation of the strain ellipsoid affecting the enclosing rocks.

The classical uses of palaeontological dates in tectonics can be summarized in three categories:

1 *The dating of phases of movement or igneous/metamorphic activity from unconformities.* An unconformity between two sedimentary formations can provide a close control on the age of movement, which is after the youngest fauna or flora found below the unconformity and prior to the oldest fauna found above it. This can provide a very precise control, as in the famous Bala unconformity in the Ordovician of north Wales where there is a gap between the Middle Caradoc and the Middle Ashgill. Dates for phases of intrusion or metamorphism are only 'older than' the age of the earliest overlying sediment and need supplementary evidence from radiometric dating.

2 *The determination of facing direction or 'way up' in folded areas.* In geologically complex country the younging direction of beds is frequently obscure, especially where the rocks are monotonous in lithology. Fossils often provide the only means of unscrambling such successions. The classic example is C. Lapworth's interpretation of the Southern Uplands of Scotland, which ran in tandem with the same author's identification of the sequence of graptolite faunas. Lapworth made sense of a hitherto uninterpretable stretch of country, comprising apparently endless shales. It is only recently that Lapworth's structural interpretation has been revised; even now, his palaeontological evidence stands almost intact.

3 *Dating volcanic activity.* Submarine or subaerial volcanics are often interbedded with fossiliferous rocks, and have long been dated thereby. Volcanics play an important part in the history of active continental margins. More recent work on the geochemistry of such rocks is able to identify the palaeogeographical setting precisely (such as whether they are island arc or back arc volcanics). With fossils to provide the chronology, the tectonic and volcanic history can now be detailed more informatively than in the days before plate tectonic modelling. Such an approach has profoundly altered our understanding of marginal basins, such as the Caledonian Welsh basin (Kokelaar & Howells 1984). A few kinds of fossils — graptolites and radiolaria especially — can even be found in the sediments

associated with ocean-floor basalts. These provide the only non-radiometric evidence for the date of eruption of ocean-floor magma, and for the subsequent obduction of volcanics.

Such applications rely on fossils as tools for dating rocks, without necessary regard to the palaeobiology, palaeoecology, or distribution of the organisms concerned. Although such uses have a long tradition, they are as appropriate today as they ever were. For those with the patience to search tectonized areas new faunas still turn up; and when they do, the implications can be important. For example, unpromising-looking limestones in the Highland Border Complex of Scotland have recently yielded Ordovician silicified faunas (Curry *et al.* 1984) which not only rule out at least one previous tectonic interpretation, but also suggest the presence of former Ordovician basins in the area now occupied by the Midland Valley. Other recent applications of fossils in tectonics draw on the whole range of properties of fossil assemblages as well as their capacity to date rocks. These are considered next.

Nappe tectonics

Nappes are the characteristic feature of the Alpine style of deformation, in which great, dislocated folds are translated horizontally — in some cases many kilometres from their original 'root zone'. Nappe may pile on nappe, often with the highest nappe being the one that has travelled furthest. Such scrambled geology often resists interpretation. Fossils can contribute in several ways to unravelling these complexities: (1) they can date each nappe 'package', which often has a discrete stratigraphy when compared with its neighbours; and (2) the kind of facies and faunal assemblages can often contribute to locating the site from which the nappe has travelled, or help towards the reconstruction of the original palaeogeography. It is only unfortunate that nappe country is often also metamorphosed, removing fossil evidence. Even so interpretation can proceed on occasion by extrapolation from adjacent, less metamorphosed areas.

The interpretation of the Swedish Caledonides in terms of nappe tectonics is a relatively recent innovation; faunal evidence is sporadic, but has made a vital contribution to unravelling the complex tectonics in the upper allochthon of the Trondheim region (Gee & Roberts 1983). In a generally analogous way the somewhat monotonous tract of dominantly clastic Upper Palaeozoic rocks of southwest England is now being reinterpreted as a nappe complex. Fossils (especially conodonts and goniatites where these occur) supply valuable fixed points in this shifting stratigraphy. In the continuation of the Alpine belt eastwards into the complex regions of Timor, where arcs have appeared, disappeared, and collided, the microfossil stratigraphy (especially using foraminifera) has proved the key to unlocking the late Tertiary structural history (e.g. Audley-Charles 1986). In such areas the structural geologist and the palaeontologist work closely together, to their mutual benefit.

Palaeobiogeography and tectonics

Fossil taxa, unless they are unique examples, have a spatial distribution which can be used to construct palaeobiogeographical maps. For post-Palaeozoic distributions these maps can be tested against continental reconstructions derived from geophysical data, but nowadays the fossils themselves are not often used as the basis of reconstructing past geography, although they were very much part of the argument about Pangaea in the twenties and thirties (see also Section 6.5.2). In the earlier Palaeozoic, however, geophysical data are sparse and ambiguous, and the continental configurations were different both from Pangaea and from the present; here fossil distributions can still contribute to hypotheses about the disposition of ancient continents. Such continents were, of course, separated by oceans as they are today — but oceans that have long since vanished. The proof of their former existence is tectonic, in that the disappearance of an ocean by subduction leaves a unmistakable tectonic imprint. But former oceans also influenced palaeobiogeography. Oceanic separation tends to induce endemicity in the seas surrounding separated continents — especially among shallow-water organisms — and particularly if oceanic separation is accompanied by latitudinal separation and hence a climatic barrier. The former existence of such an ocean can then be recognized by the close apposition today of two large areas with their own endemic shallow-water faunas. Between such areas there should be a 'mobile belt' with its own faunal peculiarities, as we describe below. These palaeobiogeographical differences should not be attributable to some other physical factors, such as salinity or substrate.

Once the possibility of the existence of a former ocean is identified using fossils, the tectonicist and geochemist may search for the other signatures that a vanished ocean leaves in the folded rocks. One example concerns the Ordovician history of the British Isles. It has long been recognized that the early Ordovician rocks of northwest Scotland were very different from those of Wales and the Lake District, and contained different faunas. Recent plate tectonic interpretations explained such differences by postulating the existence of a former ocean — a 'proto-Atlantic' or Iapetus. The destruction of this ocean at the end of the Lower Palaeozoic resulted in the Caledonian mountain belt, which extends both soutwards into the Appalachians and northwards all along the western coast of Scandinavia. Northwest Scotland (indeed Scotland as far south as the Southern Uplands) belonged to the North American side of Iapetus, which explained both the faunal differences and the tectonics. The continent at the other side of the ocean was regarded as comprising the Anglo-Welsh area (together with the rest of Southern Europe) as well as Baltica. However, faunal studies showed great differences between the shallow-water trilobite and brachiopod faunas of Southern Europe, including England and Wales, and those of the Baltic platform. These areas approach one another closely today, and it is not possible to explain away these differences simply as a geographical cline. Cocks & Fortey (1982) showed that the differences in the Early Ordovician were consistent with climatic separation: Laurentia (and Scotland) was tropical; Baltica was probably at temperate latitudes; while the Anglo-Welsh area was likely to have been at high palaeolatitudes as part of an Ordovician Gondwana (Fig. 1). An oceanic tract, called Tornquist's Sea, was considered to have separated Baltica from the Anglo-Welsh area. Since this ocean subsequently closed, the region of closure should have the appropriate tectonic style.

Geological investigations being carried out at the moment seem to confirm the idea of a vanished Tornquist's Sea. This is a case where a knowledge of fossils has led directly to new tectonic interpretations. Such methods do depend on the actualistic assumption that climatic zones controlled the distribution of fossil taxa in the same way as they control the distribution of the living biota. The fact that other, independent geological evidence seems to confirm the conclusions drawn from fossils vindicates these methodological assumptions.

Biofacies and tectonics

Recent marine environments are diverse and provide different habitats for animals and plants according to such factors as substrate type, water depth, temperature, oxygen saturation, and so on. Communities of benthic organisms tend to 'club together' in appropriate environments, even though many such communities intergrade in complex ways. There is no reason to suppose that fossil faunas were any different, although identification of fossil 'communities' is hampered by the partiality of the fossil record. None the less it is common to find constant associations of fossil taxa (usually genera) associated with particular palaeoenvironments. Sometimes these generic associations persist for tens of millions of years. Many different terms have been applied to describe such associations — communities, community types, constant generic associations (CGAs), for example — but the one in commonest currency is *biofacies*, the palaeobiological equivalent of the sedimentary lithofacies (Sections 4.17, 4.18).

Biofacies can be important aids in tectonic problems. Some of the more important biofacies are related to the depth–temperature profile running from shallow-water epicontinental to deep-water oceanic. As we have seen, the shallow-water faunas may lead us to conclusions about palaeoclimatic distribution of faunas — and hence to conclusions about the presence of ancient oceans. In a complementary way, the more exterior, ocean-facing biofacies may afford a method of charting the edges of former oceans, or at least deep marginal basins. Such marginal biofacies should be found along putative sites of former subduction. However, the deeper biofacies do *not* provide a ready method of saying which side of an ocean a fauna occurred, because one of the properties of exterior biofacies is that they are less tied to one particular continent — some genera may, indeed, be pandemic. An example from the Ordovician, contemporaneous with Iapetus (above), is the distribution of the graptolite *isograptid biofacies*. Even at the same time as the epicontinental faunas were divided into separate endemic faunas, corresponding with the distribution of continents and climatic belts, the isograptid biofacies is found worldwide, but its distribution corresponds very closely with the margins of the proposed continents (Fig. 2). This means that the discovery and mapping of sites containing the isograptid faunas can contribute to the understanding of global tectonics: since such a biofacies can be readily identified, even from small fragments (Fortey & Cocks 1986), it can afford valuable clues to the former existence of deep basins in advance of detailed geological mapping.

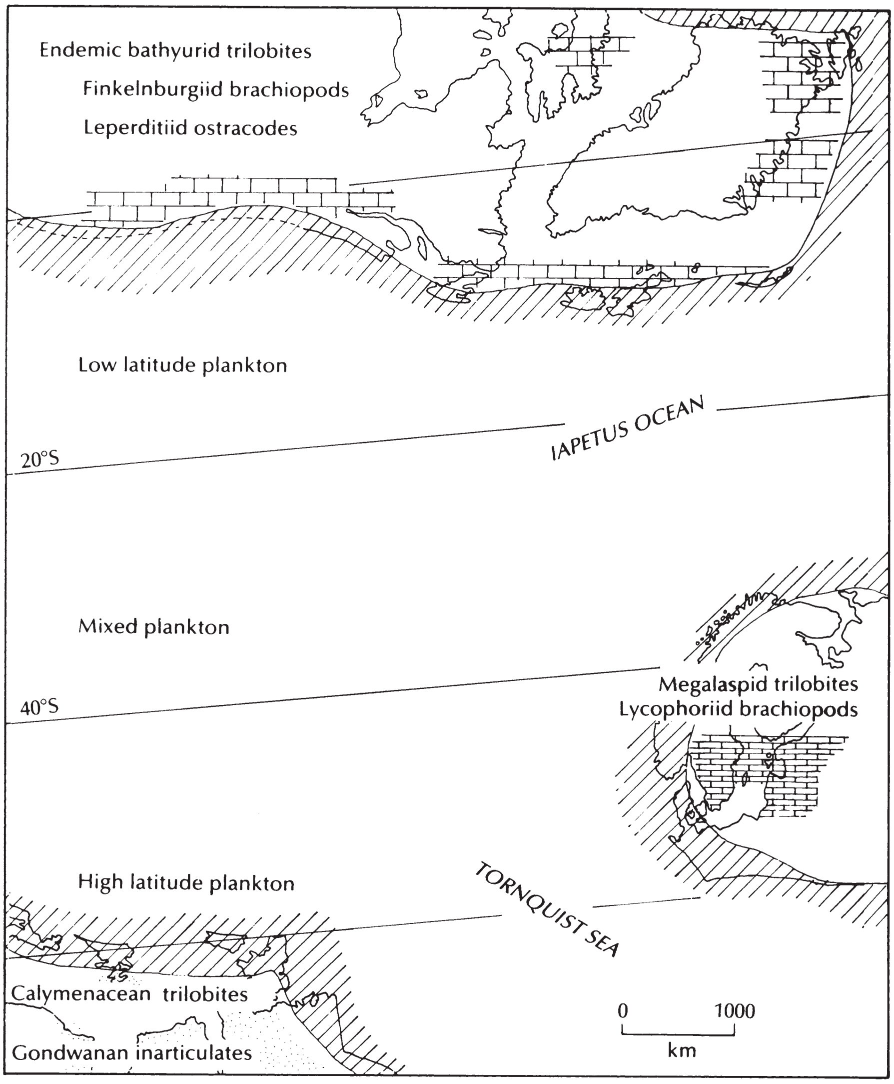


Fig. 1 Lower Ordovician (Arenig–Llanvirn) reconstruction of the North Atlantic area showing the use of endemic shallow-water faunas, temperature-dependent plankton, and lithological facies to infer the presence of former oceanic areas. Large blocks = tropical limestones; small blocks = temperate limestones; stippling = Grès armoricain and associated lithofacies; cross-hatching = marginal bio- and lithofacies belts at the edge of the former continents. Some of the characteristic endemic faunas are listed. (From Fortey & Cocks 1988.)

Where continents converge during phases of subduction, the normal sequence of biofacies may become tectonically reshuffled. This may allow some estimate of the horizontal and vertical displacement involved during earth movements. In the Cambrian–Ordovician Cow Head Group of western Newfoundland (James & Stevens 1986), autochthonous shales accumulated off the edge of the North American shelf, and were augmented by gravity slides of boulders derived from shallower biofacies. Fossils from these boulders show that the gravity slides included samples from deep shelf environments, originally at several hundred metres water depth, as well as typical shelf limestones. Subsequently, the whole Cow Head Group has been thrust onto the platform — moving deep-water biofacies onto shallow-water biofacies in the process.

Independent proof for suspect terranes

Suspect terranes are pieces of crust of less than continental size, the original position of which is in dispute; some have become detached and displaced, even for many hundreds of kilometres. It is obvious, from such major tectonic movements as the San Andreas Fault in western North America today, that relative displacement of terranes can occur quite quickly. However, in analysing fossil distributions which can indicate such terrane movement in the past, it is essential to be sure that the correct comparisons are made between relevant fossils of the same age and biofacies. It is much easier to differentiate movements north–south across latitudes by palaeontological methods, since temperature plays such an important role in controlling the distribution of many fossils, than east–west across

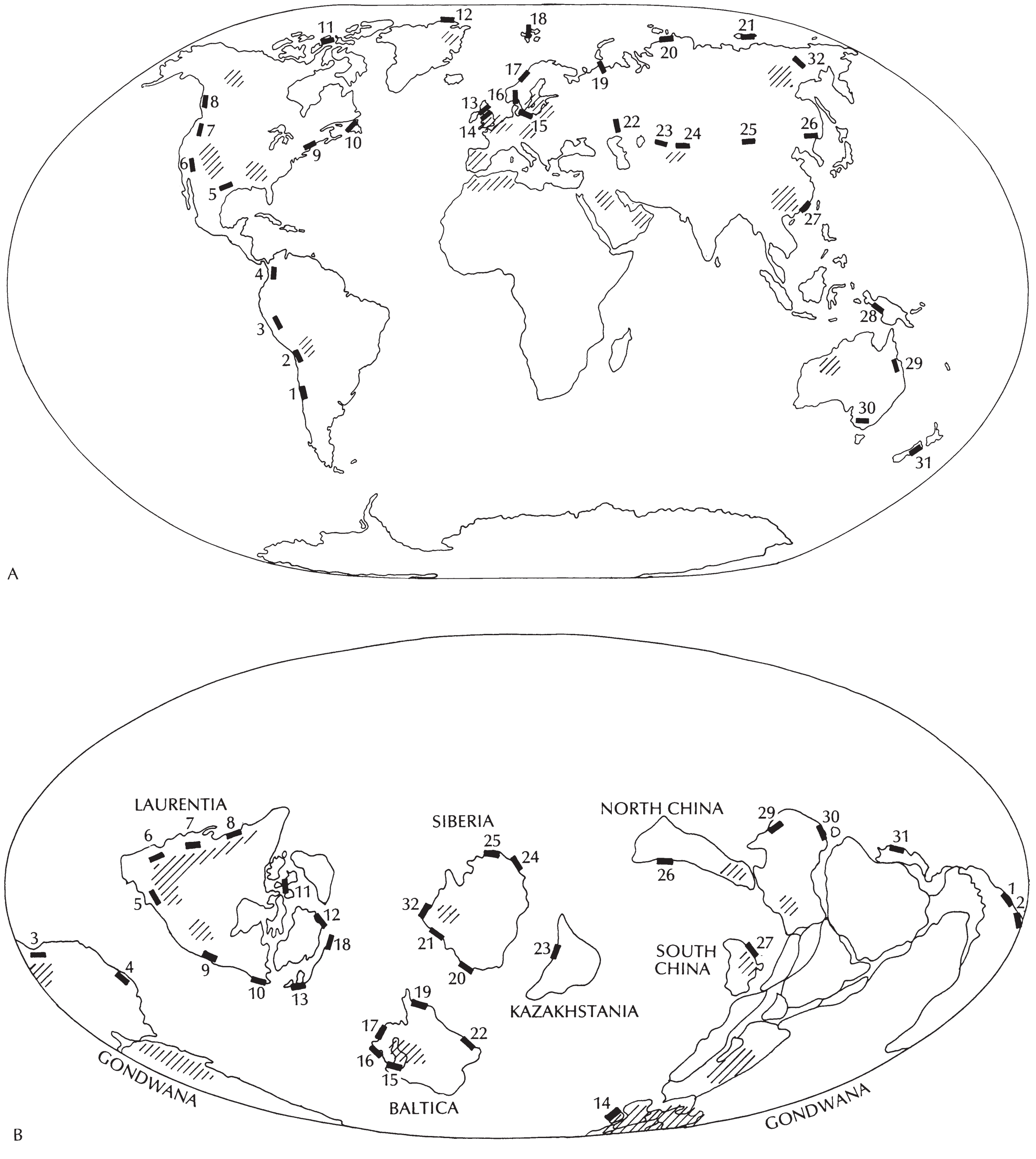
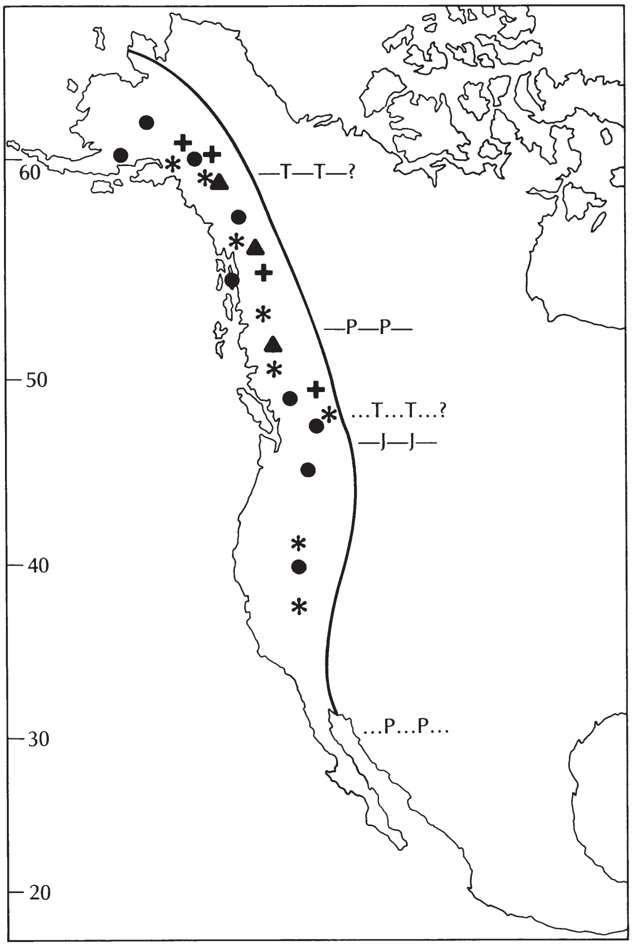


Fig. 2 A, Distribution of Arenig–Llanvirn isograptid graptolite faunas (black rectangles) and shallow-water non-isograptid faunas (cross-hatching) on a modern geographical map. B, The same data plotted on a palaeogeographical reconstruction (originally compiled from palaeomagnetic data but modified by biostratigraphic information) to show how the isograptid biofacies plots out at former continent edges. (From Fortey & Cocks 1986.)

longitudes, where significant terrane movement can occur without appreciable change in the faunas. For example, an analysis of fusuline foraminifera of Permian age along the western North America belt reveals that verbeekinid fusulines, which are characteristic of the Eurasian Tethys, are confined to a fault-bounded area, the Cache Creek Terrane of British Columbia; in contrast, the surrounding areas have fusulines of non-Tethyan, North American cratonic aspect (Monger & Ross 1971). Such work has led to the recognition of nine separate allochthonous terranes along the Pacific seaboard, some of which appear to have been as far away as Japan in Permian times (Fig. 3). Some longitudinal displacements may be detected when discrete faunal provinces that were originally separated, perhaps by a major oceanic barrier, subsequently become juxtaposed after terrane movement; but this can be recognized only when differing faunas are displaced towards one another, as opposed to tracking the east–west path of a terrane diverging away from its parent palaeocontinent.

Tectonic uses of sea-level curves

By assessing the distribution of benthic fossils in a basin at a single geological period, shallow- to deep-water assemblages may be recognized, with diversity (number of different species) increasing away from the shore. From these distributions a qualitative assessment of water depth (at least from shoreface, shallow shelf, mid-shelf, deep shelf, to oceanic assemblages) may be made (see also Section 4.19.5). By plotting and comparing these relative palaeodepths from one area over a succession of geological ages, a graph may be drawn up of changing depths with time, known as a *sea-level curve*. Whilst such curves are relatively objective, their interpretation requires more thought, since the change of sea-level at one place can be caused either by the rise and fall of the sea itself (eustatic changes), or by the rise and fall of the ocean floor (tectonic changes), or by a combination of the two. However, if the migration of biofacies indicating a transgression or regression is paralleled at exactly the same time in several tectonically independent palaeocontinents, then it is fairly certain that the sea-level changes were eustatic (Fig. 4). For example, sea-level changes appear to have been at their highest during the Cretaceous (Cenomanian) and Ordovician (Caradoc), which explains the wide-spread transgressive sequences recorded from those times, and at their lowest during such events as the late Ordovician and late Permian glacial intervals, when substantial amounts of water must have been locked up as polar ice.



KEY

—J—J—	Boundary of Tethyan and Boreal Provinces in Jurassic
—T—T— —P—P—	Boundary of High and Middle Palaeolatitude faunas in Triassic and Permian
...T...T... ...P...P...	Boundary of Middle and Low Palaeolatitude faunas in Triassic and Permian

Tethyan faunas:

▲ Permian
● Triassic
✚ Jurassic (Pliensbachian)

Boreal faunas:

✱ Jurassic (Pliensbachian)

Fig. 3 Displaced terranes of the North American Cordillera with latitudinally displaced Permian, Triassic, and Jurassic faunas, showing how displacement of faunas reveals the sense of movement. (From Hallam 1986.)

When sea-level curves are anomalous and move in different ways in different places, then tectonic control is indicated. Fig. 5 shows an analysis of sea-level curves for Wales during an extended interval of nearly 70 Ma in the Ordovician and Early Silurian, as compared with the global eustatic sea-level curve (Fortey & Cocks 1986). The separate curves for north Wales and south Wales parallel the global curve for much of the period, but in the Late Arenig, Llandeilo, and Late Caradoc the north Welsh curve is much displaced from the global curve and displacement occurs in the south Wales curve at the

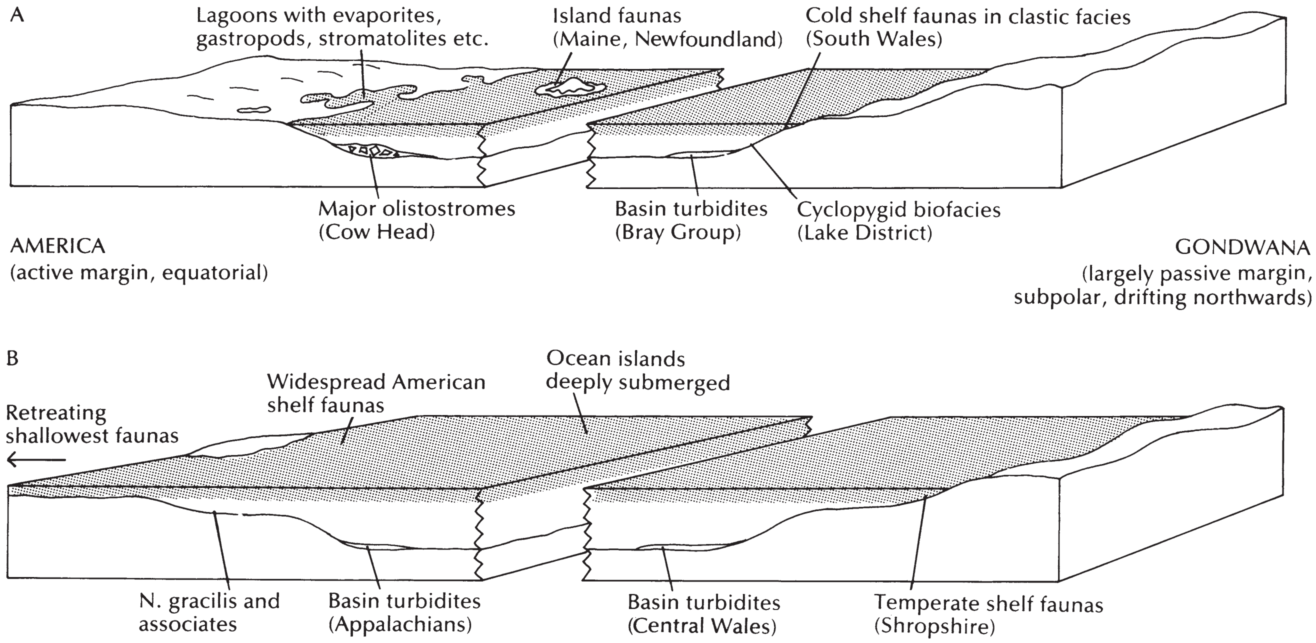


Fig. 4 Contemporary facies on opposites sides of the Iapetus Ocean. A, in regressive early Ordovician (Llanvirn) times. B, in transgressive middle Ordovician (Caradoc) times. (From Fortey & Cocks 1988.)

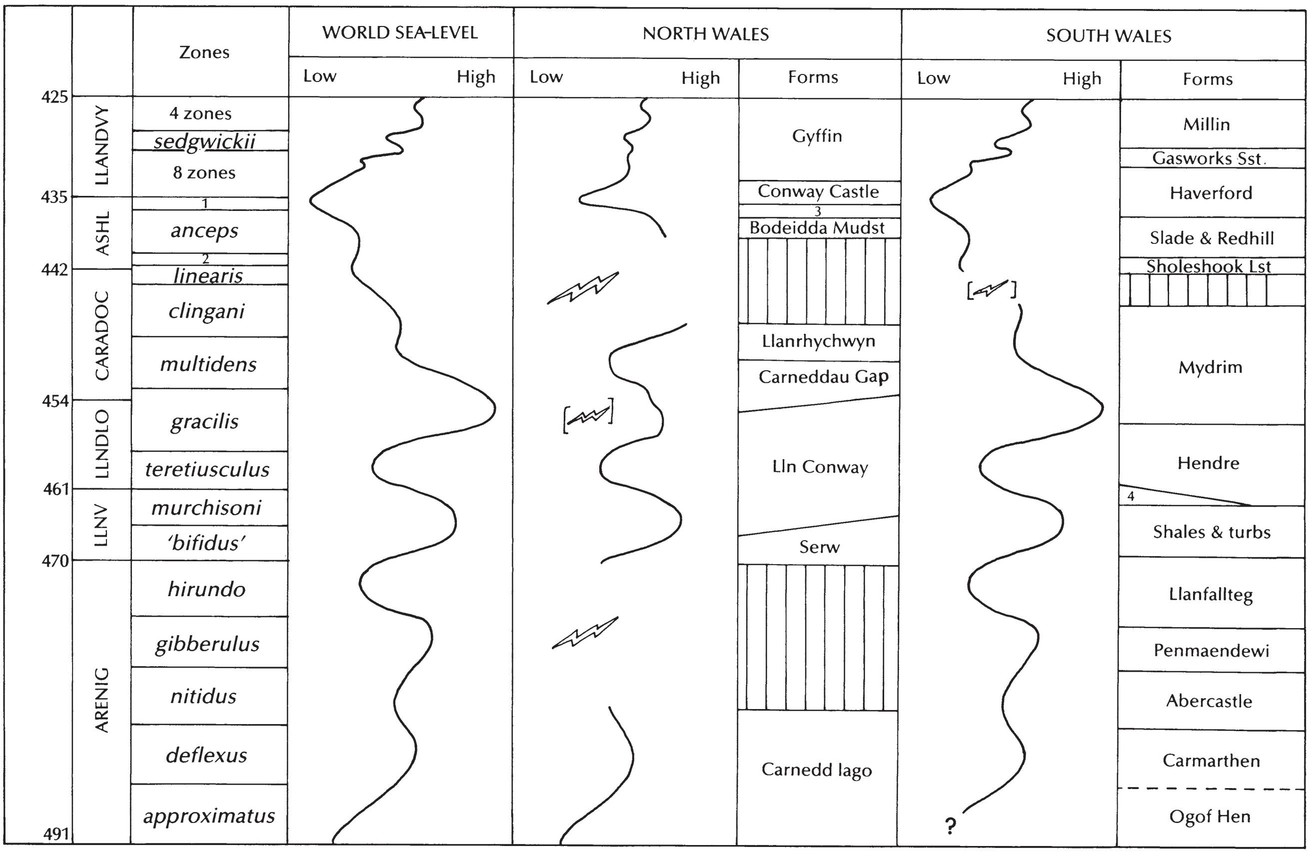


Fig. 5 Sea-level curves recording onlap and offlap of sediments for the Ordovician and Lower Silurian, comparing the global eustatic curve (left) with two local curves from north and south Wales (including the stratigraphical sequences from which they were derived). Note how the local eustatic curves follow the global curve except when they are modified by nearby tectonic activity. (From Fortey & Cocks 1986.)

same (late Caradoc) time. These discrepancies reveal not only periods of contemporary tectonic unrest, but how far-reaching any particular tectonic disturbance was. It is interesting to note, for example, that the sea-level curve is affected by the late Llandeilo vulcanicity in north Wales, which includes the volcanic outpourings of what are today Snowdon and other mountains, whilst the contemporary curve for south Wales, only 120 km to the southwest, appears to have been closer to the global curve. This indicates that, assuming an Ordovician geographical separation of the two areas similar to that seen today (which seems likely), the volcanic tectonicity in north Wales was relatively restricted in area.

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