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THE ORDOVICIAN SYSTEM, PROGRESS AND PROBLEMS

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INTRODUCTION

A Superlative System and Period

The Ordovician Period was approximately 80 m.y. in duration, the longest of any Paleozoic period and equivalent in span to the Cretaceous. The period probably began 510–515 m.y. ago and ended close to 435 m.y. ago.

The period witnessed great volcanicity (notably in active belts bordering tectonic plates), widespread inundations of continents, and explosive organic evolution. Despite the extinction of many taxa at the end of the Cambrian, trilobites remained abundant and increasingly diverse. There was a great increase in numbers of diverse nautiloid, conodont, and bivalve taxa. The appearance and expansion of graptolites among the protochordates was paralleled by that of clitambonitid, triplesiid, strophomenid, pentamerid, rhynchonellid, and spiriferid brachiopods. The Ordovician witnessed not only the beginnings of rugose and tabulate corals, but also the flourishing of bryozoans and three major types of stromatoporoids. As noted by James (1982), with these frame builders came structures that could be called reefs.

Global Correlation Charts

Any review of the Ordovician must take advantage of the extensive references and summaries now available with correlation charts published by the International Union of Geological Sciences (IUGS) and sponsored by the Subcommission on Ordovician Stratigraphy. One of the prime purposes of the charts is to lay a foundation for recognizing possible global events during the period. Already published by the IUGS are charts for *China* (Sheng 1980); the *Middle East* (Dean 1980); *Australia, New Zealand,*

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and Antarctica (Webby et al 1981); *Canada* (Barnes et al 1981), *southwestern Europe* (France, Spain, and Portugal) (Hammann et al 1982); and the *United States of America* (Ross et al 1982b). Extensive correlation charts for component tectonic elements within the Soviet Union are cited in what follows. Here I attempt no synthesizing or comparative chart; that will be fitting only after the remaining Ordovician charts are published.

Born in Conflict

It is well known that the Ordovician System was born in conflict and nurtured in compromise. C. H. Holland (1974) has given us a sympathetic account of the unfortunate and bitter disagreement that marred the later lives of two good friends: Professor Adam Sedgwick of Cambridge University, founder of the Cambrian System, and Sir Roderick I. Murchison of the Geological Survey of Great Britain, founder of the Silurian System. The upper part of Sedgwick's Cambrian and the lower part of Murchison's Silurian overlapped stratigraphically. The overlapping parts, the subject of heated feuding for more than 35 years, became the basis for the compromise proposed by Professor Charles Lapworth in 1879—the Ordovician System.

The Ordovician was accepted in Scandinavia almost immediately. The US Geological Survey (USGS), under the directorship of Charles D. Walcott, became the first national survey to recognize the system in its 24th Annual Report (p. 25), published in 1903.

The Highest is Ordovician

Yin & Kuo (1978) reported on the successful geologic and mountaineering exploration of the high Himalayas in the vicinity of Mount Jolmo Lungma (Mount Everest) in May 1975. Geologic mapping was undertaken, and a cross section through the peak was constructed. Following earlier workers, they recognized an upper Jolmo Lungma Formation and a lower Yellow Band, both of Ordovician age, resting on gneisses and schists of Cambrian and Precambrian age and capping both Jolmo Lungma and Mount Changtse. These same units have been mapped at localities to the north of the peak and at lower elevations. At Chaya, and along the Chiuhala and Chienchin Rivers, all less than 35 km north of Everest, brachiopods and other fossils have been collected and are clearly of Whiterock age. Farther to the west around Nyalam, this same fauna is present in the Lower Chiatsun Group (Sheng 1980, chart column II). We infer that the highest place on Earth is not only Ordovician, but also Whiterockian, essentially equivalent to the upper Arenig and Llanvirn of the British standard series and to the upper Antelope Valley Limestone of the Toquima Range, Nevada.

Oldest Articulated Fish Are Ordovician

Disarticulated elements attributed to fish have been reported from Cambrian strata, but the oldest fossils of nearly complete fish are found in the Darriwilian Stairway Sandstone of the Amadeus Basin of Australia (Ritchie & Gilbert-Tomlinson 1977; see Webby et al 1981, column 8). These remarkable fossils occur as imprints in shallow-water marine sandstones and show exceptionally fine details of armor plating and ornament. They antedate the ostracoderms of the Harding Sandstone of Colorado, which are usually found as separated bony plates. But both occurrences are in very similar sediments (Fischer 1978), reinforcing the belief that the earliest fish were marine.

First Antarctic Ordovician

T. O. Wright early in 1983 collected trilobites from an outcrop in north Victoria Land, Antarctica, while participating in West Germany's project GANOVEX. Genera include *Harpides* (?), *Pseudokainella*, a saukiid resembling *Andersonnella* and *Sinosaukia* but differing from both, and *Tsinania*. Similar assemblages have been reported from the Middle East, Kazakhstan, North China, and western Queensland; some of these have been listed as early Ordovician in age, others as very late Cambrian. From the same collection, John Repetski has identified the first true conodonts of early Ordovician age from the South Polar continent. More complete discussions will appear in *Geology* (Wright et al 1984) and in the *Geologische Jahrbuch, GANOVEX III* special issue.[1]

SERIES

The Original Series

The Ordovician System is British in origin. Its pieces were assembled by British stratigraphers and paleontologists, who established the succession of stratigraphic units that they had found and studied in Wales, Shropshire, the Lake District, and southern Scotland (Williams et al 1972). The pieces were fossiliferous rocks and were called series. Originally, the series were constructional units, with which the system was built. Later, they became time-rock units.

There are six series in the British succession. They are utilized around the world as a standard. Almost always their international use is based on graptolites, which is a paradox because the dating of five of the six series was

[1] C. F. Burrett and R. H. Findley have recently informed me that they have found Tremadocian conodonts from another sample collected at the same time as Wright's. Their report is to be published in *Nature* (Burrett & Findley 1984).

originally based on shelly fossils (Table 1). Only the Llanvirn Series was based on graptolites. Murchison's type Llandeilo (Bassett 1972, pp. 29–30, 32, Figure 5, column W9) was based entirely on shelly fossils, but the section near Builth also contained graptolites and became the basis for equating the zone of *Glyptograptus teretiusculus* with the bottom of the Llandeilo.

Nonetheless, the British series are almost always cited with corresponding graptolite zones. This practice seems to be derived from Table B of Elles & Wood (1914, p. 526).

In discussing classification of the Ordovician System based on the British standard series, Skevington (1969) deplored the fact that most of the fossils of the series are shelly forms and that it is impossible (with the exception of the Llanvirn) to define the series on the basis of graptolites, "which, in the majority of cases, they do not contain. Rather, the units of Series category are better retained for the shelly facies only. . . ." Too few scholars outside the British Isles are aware of this deficiency.

Table 1 British Ordovician series, their principal fossil faunas, and selected references

British Series	Principle fauna	Selected references
Ashgill	Trilobites and brachiopods.	Ingham 1966, 1970, 1977, Ingham & Wright 1970, 1972, Temple 1968 (part)
Caradoc	Trilobites and brachiopods. Graptolites very rare. Conodonts disappointing.	Bancroft 1945, Dean 1958, 1960a,b, 1961, 1962a,b, 1963, 1972, Savage & Bassett, in preparation
Llandeilo	Brachiopods, trilobites, and graptolites. *Glyptograptus teretiusculus*	R. Addison, in Bassett 1972, pp. 35–36, Bassett 1972, Elles 1940, Hughes 1969, 1971, Toghill 1970, Williams 1948, 1949, 1953
Llanvirn	Graptolites. *Didymograptus murchisoni* ?"*D. bifidus*"?, not Hall	Bassett 1972, pp. 30, 38, Elles 1904, 1940, p. 397, Hicks 1875, Hopkinson & Lapworth 1875, C. J. Jenkins, in preparation
Arenig	Trilobites, brachiopods?, graptolites. *D. hirundo* *D. deflexus*	Whittington 1966b, Bates 1969, Skevington 1969, p. 169, Bassett 1972, p. 23
Tremadoc	Trilobites, but graptolites limited to lowest part. At base, *Dictyonema flabelliforme*.	Whitworth 1969, Skevington 1969, p. 163, Cowie et al 1972, p. 11

Australian Practice

In Australia (Webby et al 1981), Ordovician time is divided into 10 stages based on graptolites. Because the graptolites are more closely related to those of North America (Berry, in Ross & Berry 1963, pp. 69–71), these stages can be correlated with the British series with difficulty. They differ from the British series because they are based on Australian stratigraphic rock successions, not because the graptolites differ. VandenBerg (1981), in reviewing the basis for each of the stages, indicated the type section or area for each of the graptolite zones. Each of the Australian stages is properly based on a time-rock unit, so that the original series designations of T. S. Hall could still be applied to them. Comparison of the British series and the Australian stages (series?) is made by Webby et al (1981).

These graptolitic stages are readily applicable in Victoria, New South Wales, and New Zealand, but conodonts, trilobites, brachiopods, corals, and stromatoporoids must be used for correlations in the vast areas of Western Australia, Northern Territory, and Queensland. Furthermore, the shelly faunas are more readily correlated with those of North America, Kazakhstan, or the Russian platform than with those of the British series.

Webby (1978) has presented a meaty, well-illustrated account of the Ordovician history of the Australian platform and its margins. In our search for worldwide events we may note that there is no unconformity in the lower or middle Ordovician not attributed to local orogeny, and only a suggestion that the late Ordovician unconformity may have been related to a lowering of sea level.

Series in the USSR

Although stratigraphic practice in the Soviet Union has been undergoing revision, it is important for Westerners to understand some differences in the use and meaning of words. The Russian *svita*, or suite, is close in meaning to a formation, but not to a purely lithogenetic formation; the meaning is closer to one of the biostratigraphic formations of the Cincinnati area of 50 years ago.

The word *otdel* is translated by the Anglo-American as *series*, and to him a series is a building block of which one constructs a system. But the literal meaning betrays the Russian concept of a series as quite the reverse. The Russian and many of his European colleagues start with a complete system and then divide it into parts, preferably lower, middle, and upper series.

Gorizont (= horizon) is used as a regional stage. It is always a time unit, but inasmuch as it is usually named for a specific *seriya* or *svita*, it may be equivalent to a time-rock unit.

A comparison of correlation charts for widely separated structural mountain belts, such as those of northeastern USSR (Chugaeva 1976, Oradovskaya 1970), the Urals (Breivel et al 1980), and eastern Kazakhstan (Nikitin 1972, Shligin & Bandaletov 1976), shows under the column *YARUS* (= stage) the British series, adjoined by the inevitable graptolite zones. Under *gorizont* are regional stages that I would consider provincial series. Each "horizon" may, but in some cases does not, correlate precisely with some other horizon in one of the major regions. Each horizon seems to have been established on a combined lithogenetic and biostratigraphic unit, much as were the British series, and each therefore reflects some aspect of provincial geologic history.

Soviet stratigraphers have separated subparallel facies zones within each structural belt, so that the graptolite-bearing strata tend to be segregated from those enclosing shelly fossils. The latter are more likely to compare with North American, Australian, or Balto-Scandinavian faunas than with those of the British series.

Ordovician Series in China

The Ordovician of China is divided into three series: lower Ichangian Series, middle Neichiashanian Series, and upper Chientangkiangian Series. According to Sheng (1980), the boundary between the middle and upper series falls between the zones of *Climacograptus peltifer* and of *Climacograptus wilsoni* (a level within the Balto-Scandian zone of *D. multidens* in Figure 2), equivalent to the base of the Pagoda Limestone. This boundary was placed above the Pagoda Limestone by Lu (1959), presumably mid-Caradocian and above the zone of *Dicranograptus clingani.* Mu (1974) has presented a third scheme, based entirely on graptolite zones and seemingly without regard to lithologic units, that divides the system into Lower, Middle, and Upper parts. These do not agree with the divisions of either of the other authors.

Another stratigraphic chart, constructed by Lu et al (1976), reconciles the stratigraphic occurrences of a variety of fossil taxa. It appears to have marked differences with the chart of Sheng (1980). The differences not only involve the relatively unimportant question of the exact boundaries of a middle Ordovician series, but more importantly the stratigraphic level of the major unconformity accounting for the absence of middle and upper Ordovician rocks across the whole North China platform. Sheng (1980, Table 1) has demonstrated that three schemes of ages (= stages) portray stratigraphy in South China, in western Hubei and Ichang Gorges, and in North China, reflecting the differing geologic histories of these regions.

Ordovician Series in Southwestern Europe

In southwestern Europe the mainly siliciclastic and volcanic Ordovician is classified according to both British and Bohemian series (Hammann et al 1982). There are no natural divisions of stratigraphic units that coincide with series boundaries. The abundance of limestone in the late Ordovician throughout the Iberian Peninsula is unexpected for a time correlative with and a place believed to have been adjacent to a supposed center of glaciation in Morocco and Algeria. Chamositic iron ore in sandstone and quartzite of Arenig age has its counterpart in the Wabana deposits beneath Conception Bay, Newfoundland (Barnes et al 1981, column 83). These ores have been discussed by Van Houten & Bhattacharyya (1982).

Near and Middle Eastern Ordovician Deposits

The Ordovician of the Near and Middle East (Dean 1980) is devoid of carbonate rocks and is dated by graptolites, trilobites, and trace fossils, relative to the British series. The best record is found in the Arenig and Caradoc, with other series only sporadically represented. Late Caradoc diamictites in Saudi Arabia have been interpreted as tillites, but if they are of glacial origin they may have been dropstone deposits.

North American Series and Stages

The Ordovician stratigraphy of Canada and of the United States has been summarized by Barnes et al (1981) and by Ross et al (1982b), respectively. Of the two, the Canadian summary, with accompanying correlation chart, is the more conservative, considering the system to be composed of a lower Canadian Series, a middle Champlainian Series, and an upper Cincinnatian Series. The US chart breaks with some recent usage and with much tradition to update the series.

IBEX SERIES, FORMERLY CANADIAN Ross and Hintze (Ross et al 1982b, pp. 4–12, sheet 1) have noted that the modern concept of the Canadian is very different from J. D. Dana's original, that it has been stripped of its original type section, and that there have been a succession of substitute patchwork type and reference sections. The stratigraphic section in the Ibex Hills, Millard County, west-central Utah, is without peer for continuous exposure, abundance and variety of fossils, and accessibility. The Ibex succession not only equals the range of the Canadian, but it is also so complete at the base as to be a serious candidate for stratotype of the Cambrian-Ordovician boundary. The section is continuous into the overlying beds of Whiterock age. Traditionalists may wish to continue the use of the term Canadian, but the Ibex section is already well established as the standard for the Lower Ordovician in the United States. To emphasize its importance, it is urged that the lower series henceforth be called the *Ibex Series.*

WHITEROCK SERIES Based on sections in and faunas from Nevada, Cooper (1956, pp. 7–8, chart 1) erected the Whiterock Stage as the oldest in the middle Ordovician Mohawk Series. Recognizing that the old Chazy Stage was unsatisfactory, he also proposed the Marmor to take its place. Eventually it became evident that much of the Whiterock was of the same age as both the Chazy Group and the Marmor (Ross et al 1982b, pp. 10–12, column 50). Because the Chazy Group is bounded above and below by unconformities and is unsatisfactory as a type for a stage, the Whiterock has been extended to include all the Chazy. The *extended* Whiterock is now considered a series and represents approximately 15 m.y.

The Whiterock Series has particular tectonic significance because it was deposited peripheral to the North American continent when the interior was being eroded and deeply weathered (Ross 1976). The Chazy Group is best considered a shallow-water, partly reef facies of the Whiterock. Equivalents of the Whiterock are recognized widely on the basis of brachiopods and trilobites (Ross & Ingham 1970), including the Himalayan exposures.

MOHAWK SERIES The Black River and Trenton stages have traditionally composed the Mohawk Series in New York. Unfortunately, the Black River beds rest on Precambrian crystalline rocks (Fisher, in Ross et al 1982b, pp. 44, 46). Therefore, a new type locality for this series has been designated at the base of the conodont zone of *Prioniodus gerdae* near the base of the Elway Formation at the Lay School, Hogskin Valley, Tennessee (Bergstrom, in Ross et al 1982b, p. 12). The Mohawk Series is the result of renewed marine invasion of the North American continent.

The stages of the Mohawk Series have suffered added confusion because of the discovery that the upper Trenton and the Eden Stage of the Cincinnati Series are correlative. Despite obvious regional preferences, i.e. New York vs Ohio, for purposes of the latest correlation chart the Eden has been maintained intact (Bergstrom, in Ross et al 1982b, pp. 12–13, sheet 1).

CINCINNATI SERIES Rocks of Cincinnatian age provide evidence of the greatest marine submergence of the North American continent in Paleozoic times. Furthermore, in Nevada, Oklahoma, Missouri, Arkansas, Illinois, and the Williston Basin in North Dakota and Montana (Ross et al 1982b), there is evidence that the submergence continued into the Silurian.

Summary of Series

In the United Kingdom and in the United States, Ordovician series are based on lithogenetic units that have assumed temporal significance. In the Soviet Union, comparable units are called "horizons." The "horizons" differ from one major tectonic belt to another, are not coincidently correlative from area to area, and are based as much on shelly faunas as on graptolites. In all three countries, such units not only provide a means of measuring relative time, but also an insight into provincial depositional and tectonic history. Similarly, Sheng (1980, Table 1) demonstrated that three differing schemes portray stratigraphy in South China, in western Hubei and Yichang Gorges, and in North China, reflecting differing tectonic behaviors.

When the British series are used abroad, they seldom have any lithogenetic significance and are, in fact, time units. With few exceptions, they are correlated on the basis of graptolites into a black shale and chert facies, from which correlations into the carbonate facies may be impossible or very difficult. This misfortune will be rectified by improved biostratigraphic discipline, probably starting with the use of conodonts. There is no reason why dating should not be done with brachiopods or trilobites.

Jaanusson (1960) reviewed the confusion occasioned by the attempt to use the British standard series in continental Europe. Reasonably, Jaanusson attributed our inability to find suitable worldwide series to "extensive paleozoogeographical differentiation," to which I would add the basic differences in tectonic behavior and resulting patterns of sedimentation. Series are time-rock units and by their fundamental nature reflect geologic history, particularly in their type areas. By the same fundamental nature, they cannot reflect geologic history in areas far distant from the type areas. We must take stock of Jaanusson's (1960, p. 79) recommendation that series be provincial. But to do away with the international use of the British series (as stages) would be unthinkable.

Lower, Middle, and Upper

Jaanusson (1960) also called attention to the misunderstanding inherent in the use of the terms "Lower," "Middle," and "Upper," which have conflicting meanings in different continents, regions, and countries of the world. These three terms can be used informally (not capitalized) to convey the uncertainty or ignorance intrinsic in their use. There is no reason to formalize ignorance. We are in danger of having the use of these three terms dictated internationally for the sake of consistency, concerning which Emerson commented, "Consistency is the hobgoblin of little minds."

SYSTEM BOUNDARIES

Cambrian-Ordovician Boundary

The founding of the Ordovician System was not without its problems. At the outset there was ambiguity about the lower boundary (Williams 1972a, pp. 2–3), caused by some unfortunate stratigraphy not of Lapworth's doing. This led Lapworth to alter his original suggestion that the base of the system should coincide with the base of the Arenig Series; instead, he included part of the Tremadoc Series (Table 1). Henningsmoen (1973) has presented a superb review of the history, the stratigraphic alternatives, and the biostratigraphic principles concerned with the lower boundary. The Cambrian-Ordovician Boundary Working Group (IUGS) has voted formally to include the entire Tremadoc Series in the Ordovician System (J. Miller, written communication, May 1983), agreeing with virtually universal practice. But the working group has yet to choose formally the precise zone on which or the stratotype section in which the boundary is to be pegged. Bassett & Dean (1982) have edited a fine collection of 15 papers dealing with fossil faunas and potential stratotype sections from widely separated parts of the world. The only major area not represented is China, but representatives of the working group examined candidate sections in China in October and November 1983.

Ordovician-Silurian Boundary

Over the past 10 years the Ordovician-Silurian Boundary Working Group, chaired until autumn of 1981 by R. B. Rickards, produced over 50 reports on potential sites for a boundary stratotype—a remarkable accomplishment. In these reports, objective biostratigraphic data from around the world were presented. By 1979 the number of candidate sections had been narrowed considerably.

In August of 1979 an international field meeting was arranged by Dr. B. S. Sokolov (Koren et al 1979) to examine the exposures of the boundary along Mirny Creek, a tributary of the Kolyma River, in northeastern USSR. In the summer of that year, a meeting of the working group inspected the field relationships of the base of the type section of the Llandovery Series in Wales and the base of the Birkhill Shale at Dob's Linn, east of Moffat, Southern Uplands, Scotland. Both of these stratigraphic units immediately overlie the Ordovician-Silurian boundary. By tradition these were the original sections of Murchison (for shelly fossils) and of Lapworth (for graptolites). During the meeting in the United Kingdom, it was decided that the Dob's Linn section should take precedence over all those that had been examined already, but that a section on Anticosti

Island, Quebec, should be examined at a field conference in 1981. Regrettably, although Chinese representatives were present, no effort was made to nominate a Chinese section.

The Anticosti Island section, in the carbonate facies, produced almost unanimous enthusiasm among those attending the 1981 field conference. Exposure and accessibility were found to be excellent. The fauna is abundant, and the proposed level of the boundary can be pegged precisely. Although the formal proposal of McCracken & Barnes (1981) defines the boundary on conodonts, it was obvious that brachiopods and trilobites could support the choice of horizon. Unfortunately, only two specialists on graptolites attended the field meeting, and only three members represented areas outside North America.

Despite the excellence of the Anticosti section, the voting members of the Boundary Working Group have chosen the Dob's Linn section as the stratotype section. This section has two advantages. (*a*) It is the original boundary section on which Lapworth based his upper Ordovician and lower Silurian graptolite zones. (*b*) Fission tracks in zircon crystals from bentonite beds in the zone of *Monograptus cyphus*, a very short distance above the base of the Birkhill Shale, provide an isotopic date of approximately 437 m.y. (Ross et al 1982a, Ross & Naeser 1984). Few intersystem boundaries can be dated this closely. Whether the base of the zone of *Glyptograptus persculptus* or of the zone of *Akidograptus acuminatus* will mark the boundary remains to be decided.

The graptolitophilic choice must not be permitted to deny the use of the section in the upper Ellis Bay Formation, on the west side of Ellis Bay (McCracken & Barnes 1981) on Anticosti Island, as a parastratotype for students of almost every other kind of fossil. Nor should the graptolitic section in the Wufeng Shale at Huanghuachang, north of Yichang, be overlooked (Wang et al 1982). That and a more westerly section in the Yangtze Gorges were visited by representatives of the Ordovician Subcommission in 1978 and found to be rich in graptolites and structurally little disturbed.

ISOTOPIC DATING

The Ordovician and Silurian systems are isotopically dated more thoroughly than any other Paleozoic systems. Fission-track dating (Ross et al 1982a, Ross & Naeser 1984) gives a good indication of the relative lengths of the British standard series of both systems. The early Silurian zone of *Monograptus cyphus* has yielded a date of 437 ± 10 m.y. using fission tracks (Ross et al 1982a, p. 144) and 433 ± 3 m.y. based on the K/Ar method

(Lanphere et al 1977). Another sample, from the late Ordovician zone of *Dicellograptus anceps*, gave a fission-track date of 434 ± 12 m.y. Compston et al (1983), using an ion microprobe, have analyzed zircons from the same sample of bentonite from the Birkhill Shale that produced the fission-track date on the zone of *M. cyphus*. They conclude that the age may be closer to 431 m.y. Despite large analytical errors, it would seem that the Ordovician-Silurian boundary is close to 435 m.y. ago.

The oldest Ordovician fission-track date is from a tuff in the Llyfnant Flags of early Arenig age and is 493 ± 11 m.y. From the late Tremadocian Rhobell volcanics a date of 508 ± 11 m.y. has been obtained, using the K/Ar method, by Kokelar et al (1982). Two fission-track dates on Middle Cambrian bentonites from the Grand Canyon (Ross & Naeser 1984)—535 ± 12 m.y. for the *Bathyuriscus-Bolaspidella* zone and 563 ± 12 m.y. for the *Glossopleura* zone—give support to placing the Cambrian-Ordovician boundary at 510–515 m.y. (Figure 1).

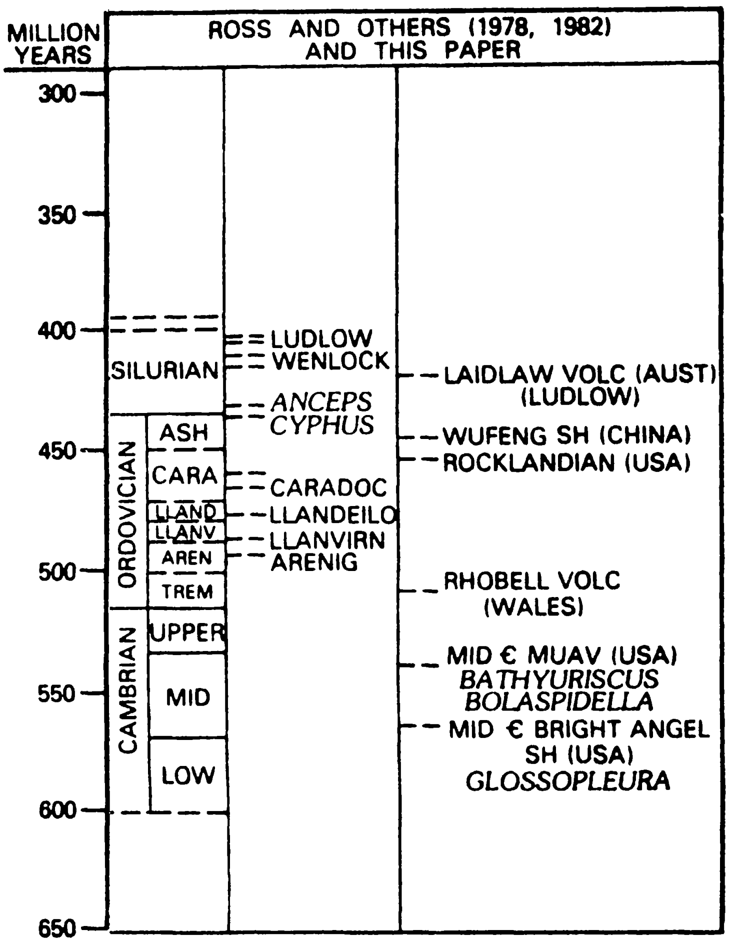

Figure 1 Isotopic dates significant in gauging the age and duration of the Ordovician Period (modified from Ross & Naeser 1984).

WIDESPREAD VOLCANISM

An incomplete review of the Ordovician provincial series of the world indicates that volcanism was widespread. It is evident in tectonically complex linear belts, especially those bordering the stable platforms in the Soviet Union. One may speculate that much of the volcanism took place along subduction zones and that the Iapetus Ocean was only one of several that closed or were closing in Ordovician time.

Europe

Tuffs, ashes, bentonitic ashes, and related intrusive and extrusive rocks abound in Wales from the Lleyn Peninsula to the Berwyn Hills and from St. David's to Builth (Bassett 1972). The Ordovician volcanic rocks along the Welsh Borders from South Shropshire to the Breidden Hills range in age from the lower Llanvirn Stapeley volcanic group to the Caradoc Acton Scott beds (Dean 1972, Ross et al 1982a). In Yorkshire and the Lake District of northern England (Ingham & Wright 1972), the thick rhyolites, andesites, and tuffs of the Borrowdale volcanic complex are considered to be of Caradocian age, while the Cautley volcanic beds are late Ashgillian. In Scotland (Whittington 1972) and in Ireland (Williams 1972b), volcanic rocks are Arenigian to Silurian in age, if one includes the bentonites interbedded in the highest Ordovician Hartfell Shale and the lowest Silurian Birkhill Shale at Dob's Linn, east of Moffat.

In southern France (Hammann et al 1982, p. 18, columns 11–14), rhyolitic and andesitic tuffs and flows are exposed from the Montagne Noire to the eastern Pyrenees. Far to the north in Sweden, bentonite in the Caradocian Dalby Limestone is evidence of a distant volcanic source. Similarly, bentonite in the middle Ordovician of Latvia (Ulst et al 1982, Figure 48) probably originated in volcanic areas bordering the Russian platform.

Examples in the Soviet Union

In the folded and thrust belt of the Urals (Breivel et al 1980), the elongate Sakmaro-Lemvinskaya zone is characterized by great thicknesses of middle Ordovician tuff, basalt, porphyry, spillite, and diabase. In the upper Ordovician, volcanic rocks are mixed with carbonates. In the upper Kuyagach Suite of Arenig age, tuffs and other effusive rocks are intertongued with limestone.

To the east in the drainage basin of the Rassokha River, northwest of the Omulev Mountains, of northeastern USSR, Oradovskaya (1970) and Chugaeva (1976) report volcanic rocks from the upper Arenig to the top of the system. In this complex north-south belt, along the Serechen River, middle and upper Ordovician basalt, andesite, dacite, trachytic lavas, and volcanogenic sandstone aggregates 1560 m in thickness.

Nikitin (1972) described five north-south zones in southeastern Kazakhstan, of which the Stepnyak-Betpakdala zone and the Chirghiz-Tarbagati zone are characterized by volcanic rocks throughout the Ordovician section. Only upper Ordovician rocks are known in the Dzungaro-Balkhash zone, and most of them are volcanic.

Mongolia

There are no complete Ordovician sections in Mongolia. In the Agach-ula section in the Kobdinskaya district of southwestern Mongolia, Arenigian, Llanvirnian, and lower Llandeilian rocks are composed mainly of siltstone, sandstone, shales, and tuffs (Rozman et al 1981).

Thick Volcanics in China

A cursory examination of the Ordovician correlation chart for China (Sheng 1980, column IV) reveals that the thickest Ordovician section is in the north slope of the Chilien Shan (Qilian Shan). Over 2000 m of interbedded limestone, shale, chert, and a variety of volcanic rocks range in age from bottom to top of the system. Graptolites and certain trilobites suggest that this was an outer-shelf environment, possibly a continental margin.

The discovery of a datable bentonite layer in the Wufeng Shale of Ashgill age (Ross & Naeser 1984) in the Yangtze Gorges suggests that more volcanics will eventually be found.

Australian Volcanics

The Ordovician sections in New South Wales and east-central Queensland include great thicknesses of andesite and tuffs along the north-south fold and thrust belt of eastern Australia (Webby et al 1981, columns 34–53, 58). The oldest are the Mount Windsor volcanics of Queensland (column 58), but ages range throughout the Ordovician.

Arenig Volcanics in Argentina

In the Famatina and Puna regions of northwestern Argentina, Ordovician volcanics range in composition from rhyolitic to andesitic, occurring as tuffs, flows, breccias, ignimbrites, and a few spillites (Acenolaza & Toselli 1981, 1982). Graptolites indicate that these are of Arenig age. Ordovician volcanics are also known in southern Bolivia and southern Peru.

North America

Bentonitic ashes are widespread in the middle Ordovician of the Mississippi Valley, Kentucky, Tennessee, New York, Maine, Ontario, Quebec, and Newfoundland. Their sources may now be in the British Isles or in easternmost Canada, but they probably were related to subduction along the former eastern margin of the continent. Williams & Hatcher (1982) preview a more explicit portrayal of the volcanic and tectonic history of the Appalachian orogen, an intriguing story of suspect terrains. Volcanic rocks are widespread in eastern Canada (Barnes et al 1981, columns 64, 65, 69, 76, 79, 80, 82). The composition of the tholeiitic amphibolites and greenstones of the middle Ordovician Ammonoosuc volcanics of New Hampshire and Vermont led Aleinikoff (1977) to conclude that they were partly of abyssal oceanic and partly of island-arc affinity.

In the western United States, greenstones and pillow basalts of the middle Ordovician Valmy Formation in Nevada were erupted along the supposed trailing border of the continent. Similarly, in British Columbia and Yukon (Douglas et al 1969, Figure VIII-9), volcanics are interbedded with shales west of the carbonate belt. Ophiolitic suites are present in the Klamath Mountains of northern California, indicating that volcanism was active wherever that terrane was in the Ordovician (Ross et al 1982b, column 8, pp. 30–33).

SEA-LEVEL CHANGES

In much of the cratonic part of North America, an unconformity exists above units of Ibex (= Canadian) age (Ross et al 1982b, sheets 1–3). This would be approximately equivalent to the conodont zone of *Oepikodus evae* and to the Arenig graptolite zone of *Didymograptus hirundo*. An upper limit on the unconformity is placed in the southern Appalachians in the Lenoir Limestone of late Whiterock age at the base of the zone of *Pygodus serra*. That conodont zone is approximately equal to the Llanvirn graptolite zone of *Didymograptus murchisoni*. In the northern midcontinent region, the St. Peter Sandstone of approximate Llandeilo age rests above the unconformity. This unconformity of late Arenig through Llanvirn age is the basis for the sea-level drop postulated by Vail et al (1977, p. 84, Figure 1), supposedly the most prominent of the Ordovician sea-level changes.

Examination of the Chinese sections (Sheng 1980) indicates that in the North China platform there is a post-Llandeilo unconformity, lasting throughout the period. In northeastern USSR (Chugaeva 1976), Tremadoc and most of the lower Arenig sediments are missing in the terrigenous, volcanic, and transitional zones, but a complete Ordovician section is present in the carbonate facies. This suggests that the unconformity resulted from local, very early Ordovician tectonic activity, not from a sea-level change.

No unconformities are evident in Kazakhstan except in a volcanic-rich section in the Kazik Range of central-east pre-Balkhash (Shligin & Bandaletov 1976, Table 5, column 32). This unconformity is Llanvirn in age and is probably tectonic in origin.

On the other hand, on the Siberian platform (Chugaeva 1976, p. 287) there is a post-Arenig/pre-Llandeilo break similar to south-central North America. The Latvian sections (Ulst et al 1982, Table 23, p. 170) contain three Tremadoc and Arenig unconformities and one at the Arenig-Llanvirn boundary. There is no reason to associate these minor breaks with local tectonism, nor do they correlate with breaks elsewhere to suggest universal sea-level changes.

In Australia (Webby et al 1981), there is an unconformity above the Darriwillian (post-Llanvirn) and below the Eastonian (lower Caradoc) in New South Wales. But in Western Australia the upper limit is Silurian, and in the Northern Territory it is Devonian to Cretaceous. Dating of the discontinuity in New South Wales does overlap that in the United States, but their coincidence is not impressive.

Locally in Spain and Portugal, the Caradoc section is missing (Hammann et al 1982). The positions of unconformities in the British Isles are erratic. In Wales they are locally present in the Llanvirn, Llandeilo, upper Caradoc, and lower Ashgill (Williams et al 1972, Figure 6). Along the Welsh Borderland and in northern England (Williams et al 1972, Figures 7, 8), it is more a matter of determining how much Ordovician section is present than what is missing locally. In the United Kingdom, tectonism must have been far more important than sea level in determining the position of unconformities during Ordovician time.

Evidence for a late Arenig to late Llanvirn drop in sea level, as proposed by Vail et al (1977, p. 84), is shaky at best. There is ample indication of local tectonic unrest during the Ordovician if one couples the evidence of local unconformities with that of volcanism. Only an infinitesimal percentage of that evidence has been assembled here, but it is enough to suggest that preoccupation with the behavior of the Atlantic Ocean and its predecessor(s?) may blind us to the existence of other oceans and subduction zones active during the Ordovician.

ORDOVICIAN CLIMATES

North African Evidence

Ordovician climates, particularly the supposedly late Ordovician glaciation in Gondwana, have received much attention of late. Spjeldnaes (1981) has written a very thorough review of early Paleozoic climates, with special reference to glaciations. The beautifully illustrated work of Beuf et al (1971), following their work (1966) on the extent of Silurian glaciation in the Sahara, leaves no doubt that there are glacial features and deposits of early Paleozoic age in North Africa. However, there is no mention of an Ordovician fossil in the 1971 report. In fact, there is very little biostratigraphy to support claims of Ordovician, rather than Silurian, glaciation. If one checks the references cited by Spjeldnaes (1981, pp. 230–35), one will understand why Spjeldnaes himself (p. 234) has written, "The dating of the Ordovician glaciation is still somewhat doubtful." Legrand (1974, 1981a,b) commented on the tectonic instability of the great area of Algeria and Morocco in the Ordovician and Silurian, and noted that the youngest Ordovician fossils beneath glacial deposits are Caradocian in age and that the oldest Silurian fossils above the deposits are late Llandoverian, a span of 30 m.y. Destombes (1976, p. 413) has recorded Hirnantian (latest Ordovician) brachiopods associated with glacial deposits, but only in the Anti-Atlas Mountains of southern Morocco. Dean (1980, p. 8) cites glacially derived, probably dropstone, deposits in Saudi Arabia of Caradocian age.

A variety of stratigraphic and biostratigraphic phenomena have been attributed to this late Ordovician or early Silurian glaciation. The supposed drop in sea level that resulted in deposition of middle Silurian sediments on late Ordovician or older strata in cratonic North America is one of these phenomena, but whether there is a worldwide unconformity at this stratigraphic level remains to be documented. The question of how much of any such change in sea level might be related to spreading rates of continental plates, rather than to accumulations of ice, must be considered. But Thompson & Diecchio (1982) have already shown that in the eastern United States alone there was no such unconformity because of the rapid accumulation of the Queenston Delta, which spread westward onto the craton from the crumpled eastern continental margin.

Drastic changes in the composition of brachiopod faunas are supposed to have been caused by the glaciation (Sheehan 1973), particularly in North America. However, Amsden (1974, 1980, 1982, 1983) has found no marked differences between latest Ordovician and earliest Silurian faunas in Oklahoma, despite an interruption of the stratigraphic sequence by beds inhospitable to brachiopods and one lower Silurian unconformity. It is possible that faunas found closer to the cratonal center might seem to demonstrate a greater change because the entire lower Silurian is missing (see also Ross et al 1982b, column 40). Future studies in other lands are needed to assess faunal changes, their magnitude, and the reasons for the changes.

Earliest Land Plants from Libya

According to Gray et al (1982), the discovery of spores from Caradocian subsurface rocks of Libya provides the oldest evidence of land plants. They speculate that land plants may have radiated from a North African center. When in the future more is known about these primitive plants, they may provide improved information regarding the rigors of a polar climate approximately 460 m.y. ago. In the same paper (Figures 2–6), they show similar spores from the late Ordovician Elkhorn Formation of Kentucky and the early Silurian of New York and Libya, suggesting a biostratigraphic succession in which increased size may be important.

Strother & Traverse (1983) are critical of this report and its lack of proper taxonomy. They claim that similar evidence of Ordovician land plants is far more plentiful and widespread than realized by Gray et al, who (1983) reply to the charge. These published discussions and accompanying references are informative sources for students of land-plant origins.

The Empty Arctic

As noted by Ziegler et al (1979), Ross (1975), Ormiston & Ross (1979), and Spjeldnaes (1981), there is no record of any land area around the North Pole during the Ordovician. Presumably the northern ocean was open. Without obstruction to oceanic circulation or to mixing with equatorial waters, the climate of the northern hemisphere may have been mild all the way to the pole. Surely there was a very different weather pattern from what we experience today. Warm-water life should have been able to flourish far north of present latitudinal limits.

BIOSTRATIGRAPHIC CORRELATION

Lapworth's Legacy, Concurrent Ranges

In addition to the Ordovician System, Lapworth's most valuable legacy is exemplified by his use of overlapping stratigraphic ranges of many graptolite taxa to define zones. It is the overlapping ranges based on measured sections—the *concurrent ranges* of several taxa—that define the standard graptolite zones and give to them a stable utility not yet equaled by other kinds of assemblage and range zones.

Facies Faunas

Biostratigraphic correlation within the Ordovician seems to be good so long as measured sections have been the basis for determining ranges of various taxa and all the components of the fauna are taken into account. The greatest problems are met when the contemporaneity of coeval faunal facies is not recognized, and the facies are concluded to be sequential. Jaanusson (1976) studied the changes in faunal distribution around the Baltic within the Viruan Series (middle Ordovician), noting that some were related to lithologic changes, while the reason for others was obscure. He also found that no single factor, such as water depth, could explain the distributions of all elements of a fauna. In a far more complex tectonic setting, Jaanusson & Bergstrom (1980) were able to delineate three faunal facies belts in the Appalachian Mountains of essentially the same age as those in the Baltic study. Brachiopods fell into three belts parallel to and bounded by the major thrust faults. Conodont distributions paralleled those of the brachiopods, as did some of the trilobites. But inasmuch as correlative lithologies do not precisely parallel the thrusts, the control on faunal distributions is not evident. Yet, so different are faunas of the more widely separated belts that one might easily conclude that they are of different ages.

Faunal developments and worldwide distributions of fossil taxa throughout the Ordovician have been reviewed by Jaanusson (1979). It has become customary to think of early and middle Ordovician faunas as having been provincial, while late Ordovician faunas were cosmopolitan. Graptolite faunas supposedly exemplify such distributions, although trilobites (Whittington & Hughes 1972, Ross 1975) have been similarly cited. Jaanusson (1979), however, noted that there were several geographically distinct shelly faunal assemblages in the late Ordovician. Among these is an assemblage characterized by *Monorakos* (Ormiston & Ross 1979) and found only in the Siberian platform, northeastern USSR (Kolyma Platform), and the Seward Peninsula of Alaska.

Another assemblage, characterized by *Dicoelosia* and other brachiopods, has been reported (Ross & Dutro 1966) from Jones Ridge, close to the border between Alaska and Yukon; from Percé, Quebec (Schuchert & Cooper 1930); from the Drummuck Group near Girvan, Scotland; and from the Klamath Mountains, northern California (A. W. Potter, personal communication, and Ross et al 1982b, column 8). This brachiopod assemblage may be depth controlled and may border the former North American continent, as well as other continents, since several of its elements have been reported by Amsden (1974) from Oklahoma and by Roomusoks (1968) from Estonia. It has little in common with correlative(?) Cincinnati faunas of Ohio and Kentucky.

Ludvigsen (1975, 1978a) and Chatterton & Ludvigsen (1976), working in the southern MacKenzie Mountains (District of MacKenzie), have documented superbly preserved, silicified trilobite faunas of late Whiterock to late Mohawk age in alternating transgressive-regressive sequences. The trilobites of a late Cincinnati age trilobite and conodont assemblage from the Hanson Creek Formation of central Nevada (Ross et al 1980) are so similar to those of Ludvigsen's shelf-edge Biofacies III that they might have been considered correlative had not the associated conodonts confirmed the younger age of the Nevada occurrence. In their next more westerly exposure, the Hanson Creek beds are composed of very thinly laminated limestone-bearing graptolites and radiolarians, but no shelly fossils.

Obviously, Ludvigsen's (1978a) paleoecologic analysis is applicable to this younger fauna about 3000 km distant from the MacKenzie Mountains.

Dating Facies Faunas, and Graptolite Depth Zones

How are fossil assemblages as strongly influenced by environment as these to be correlated? Traditionally, biostratigraphers might have appealed to graptolites, but Jaanusson (1979) has noted the provincialism of these fossils.

Despite Skevington's cautioning (1969, p. 161), it is often assumed that graptolites, unlike other animals, were not affected by environmental conditions. Unfortunate disputes concerning the stratigraphic value of graptolite zonation are related in large part to the failure to recognize the possibility of facies control. In an important ongoing study of middle Ordovician stratigraphy in western New York state, Cisné & Chandlee (1982) have used numerous bentonite layers to establish time planes along which they traced graptolite populations from shallow- to deeper-water paleoenvironments. They documented the lateral change of faunas dominated by *Orthograptus* (including *O. ruedemanni* and *O. amplexicaulus*) to contemporaneous assemblages dominated by *Corynoides* (including *C. americanus* and *C. calicularis*). This discovery bears on the graptolite correlation problem discussed in the correlation chart for the United States (Ross et al 1982b, pp. 2–3, chart sheet 1 of 3). Clearly the same kind of documentation is needed for the whole stratigraphic range of graptolite zones, although bentonites are not ordinarily available to provide the necessary temporal control.

Need for Unbiased Stratigraphic Data

Concurrent range zones are applicable to any fossil group studied in the context of measured sections. The increased interest in using conodonts for purposes of correlation is a matter of discipline, addressed recently by Sweet (1982). The biostratigraphic use of microfossils, which cannot be seen by the collector, requires disciplined measurement of sections and recording of lithologies. The unbiased end result produces detailed information on stratigraphic ranges of genera and species. All too often in the past, macrofossils have been collected and lumped as the "fauna of formation X" with little regard to stratigraphic detail. Macropaleontologists who put more emphasis on biostratigraphy (for example, see Stitt 1971, 1977) will remedy this deficiency.

Pelagic Fossils—Trilobites and Conodonts(?)

The biostratigraphically useful trilobites were surely pelagic; some, like the olenids, were widespread in their distribution, while others, such as the bathyurids, preferred shallower, platform environments (Whittington

1966a, Ross 1975, Fortey 1974, 1975a,b, 1980). In these habits, conodonts may have resembled trilobites, on whom they may have preyed.

Briggs et al (1983) have discovered the first fossil conodont animal and have discussed the possible relationship of conodonts with and their similarity to Chaetognathids, or "arrow worms." If Briggs et al are correct, the conodonts may have been the carnivorous scourge of the planktonic realm in Paleozoic time. The distribution of conodonts indicates that they were as cosmopolitan as graptolites. It is known that they occur in shallow-water populations over carbonate platforms, as well as in distinct deeper(?) water assemblages, and that they can be used for accurate worldwide correlation. Conodont taxa that characterize the presumably warm, shallow-water facies [North American Midcontinent fauna (Sweet et al 1971, Barnes & Fahraeus 1975, Barnes et al 1973)] are recognized as the same fauna in Australia (Palmieri 1978; see Webby et al 1981, column 56). Although the shallow-water forms might be thought to be endemic to a continent, their distribution on continential platforms that seem to have been widely separated all through the Phanerozoic indicates that these forms were widespread.

Conodont-Graptolite Correlations

In a comprehensive review of the evidence mainly from Balto-Scandia, from the British Isles, and from North America, Bergstrom (1984) has attempted to show the equivalence of conodont and graptolite zones. This herculean effort has produced close to 80 ties between the two schemes, despite the rarity of conodonts in graptolitic shales. More ties are available in Arenig through Llandeilo time than later in the period. Furthermore, the graptolite zones of Balto-Scandia are not precisely the same as those of Britain, just as the zones of eastern North America (Riva 1969) differ from those of western North America [Berry 1960, Jackson 1964–1979 (see Barnes et al 1981, p. 19)]. The North Atlantic conodont zones, preferred by Bergstrom, are difficult to mesh with the North American cratonic zones. Despite these and other difficulties, Bergstrom's review is a tribute to his persistence (Figure 2).

Sweet (1979a, 1982) has been revising and updating the North American conodont zonal scheme using Shaw's (1964) graphic solution of concurrent ranges, as modified by Miller (1977). This is a very different method from the evolutionary lineage zones employed by Bergstrom.

Trilobites, Brachiopods, and Other Taxa

One of the most complete recent efforts to coordinate the concurrent ranges of trilobites, brachiopods, ostracodes, graptolites, and conodonts is found in a book on the Ordovician of Latvia (Ulst et al 1982). There is nothing like it for North America. To be sure, trilobite zones have been erected for the lower and lower middle Ordovician by Ross (1951) and Hintze (1952), but these are assemblage zones rather than concurrent range zones. Ross (1964, 1967, 1970) and Hintze (1979) showed the ranges of Ibexian (= Canadian of authors) and Whiterockian trilobites, brachiopods, and other macrofossils relative to stratigraphic sections in Nevada and Utah, as Harris et al (1979) and Ethington & Clark (1981) have done for conodonts. It is important to

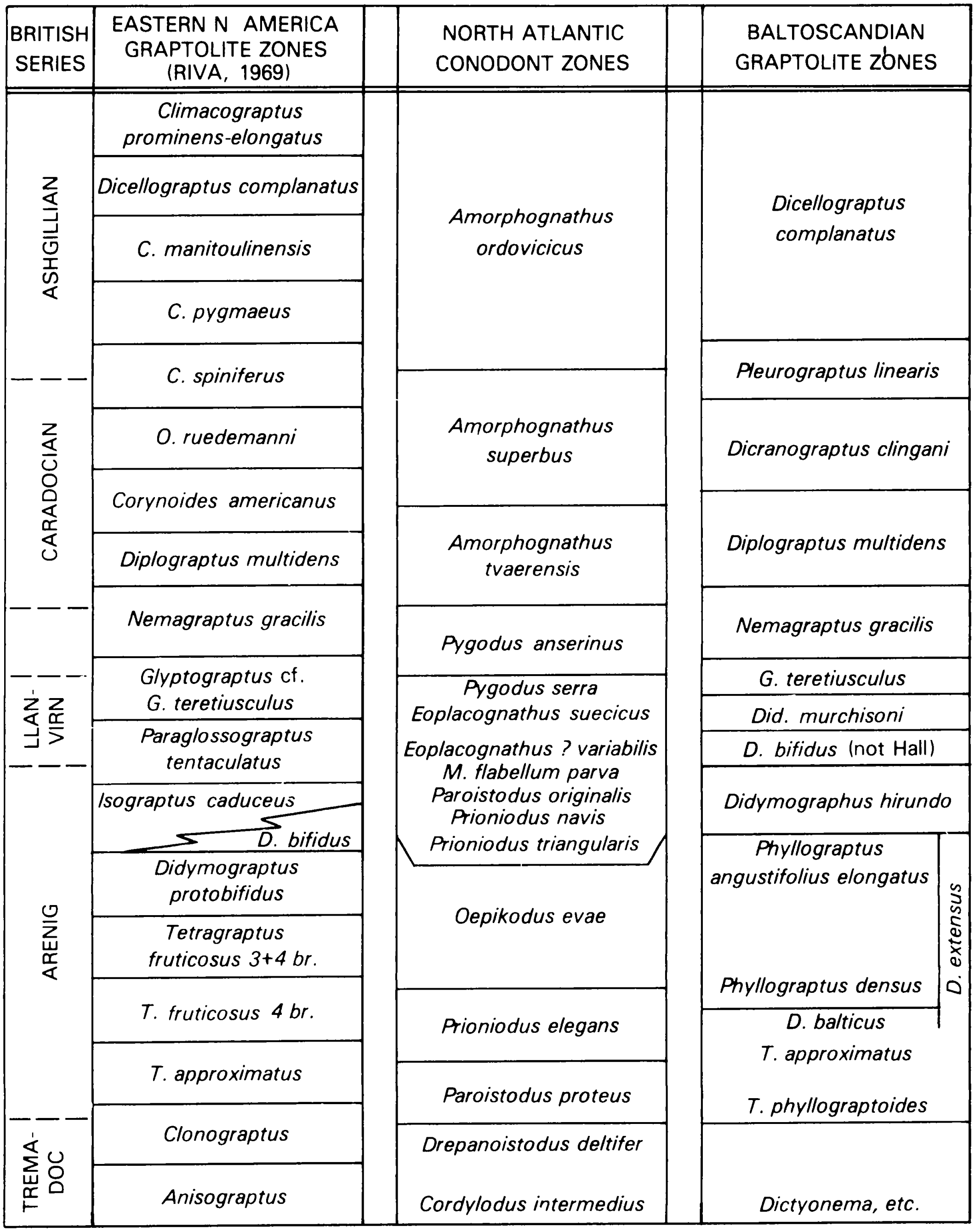

Figure 2 Comparison of conodont and graptolite zones (modified from Bergstrom 1984). Note that the graptolite zones of Balto-Scandia and those of northeastern North America are not precisely correlative.

note that Cooper's (1956) brachiopod assemblage zones are fundamental to the Whiterock with only minor changes.

Ludvigsen (1978b) has produced a brief, well-illustrated trilobite biostratigraphy, in which he has tabulated concurrent range zones for southern Ontario. This plus Ludvigsen's (1978a) work in the MacKenzie Mountains should form a firm base for continent-wide trilobite zones in the Mohawk and Cincinnati series.

Despite excellent reconstruction of the complex facies relationships of upper Mohawkian strata of the Cincinnati Arch (Cressman 1973), there is no study of the faunas integrated with the stratigraphy. Similarly, in spite of a complete updating of the mapping of most of the classical Eden, Maysville, and Cincinnati areas, only a few stratigraphic and faunal reports have been written (Pojeta 1979, Alberstadt 1979, Howe 1979, Ross 1979, Bell 1979, Branstrator 1979, Sweet 1979b). These cover only a few taxa and are not integrated into a stratigraphic summation. The USGS effort to map lithologies provided an important break from the earlier practice of mapping faunas, but the biostratigraphic fruits have yet to be reaped to produce a concurrent range chart for the macrofossils of the type Cincinnati Series.

Faunas Away from Home

A single trilobite, *Colpocoryphe* (a Tethyian genus), was reported from the subsurface Ordovician of Florida (Whittington 1953). It and two graptolite species are considered evidence that Florida is a remnant of western Africa left attached to North America after a late Paleozoic collision. And the asaphid fauna at Oaxaca, Mexico (Robison & Pantoja-Alor 1968), may have a like significance with reference to South America.

Similarly, the brachiopod assemblage of the Klamath Mountains, noted above, might be cited in support of the currently popular theory that calls for accretion of Ordovician ophiolitic terrain of northern California to North America long after Ordovician time. The distribution of the trilobite *Monorakos*, cited above, provides evidence of post-Ordovician joining of the Seward Peninsula to Alaska. On the other hand, probably Ordovician sediments in roof pendants of the Sierra Nevada Batholith near Convict Lake (Rinehart & Ross 1964, Ross et al 1982b, column 19) are so similar to sequences eastward in Nevada as to suggest that they were part of Ordovician North America and thus not accreted later.

SUMMARY

Before indulging in further speculation about faunal migrations, sea-level changes, or sudden extinctions due to climatic changes, it would seem wise to seek the participation of specialists outside the field of biostratigraphy. The various massifs of Soviet Asia, China, and South America have individual histories about which paleomagnetists can surely add to our enlightenment. The positions of Ordovician island arcs and the timing of volcanism allied with subductions should provide evidence of the closing or altering of several seas, accompanied by changes in oceanic currents, sea levels, and faunal distributions.

In North America, the Ordovician histories of the Reelfoot Basln and Michigan Basin (Ross et al 1982b, pp. 36–40), as well as the en echelon eastern Great Lakes and St. Lawrence estuary, need to be studied as possible sites of rift valleys and early extensional phases.

Completion of the correlation charts for South America, northern Europe, Mexico, and Africa will surely produce surprises. Extensive charts for the major tectonic terrains of the Soviet Union have been available, and several were cited in the above discussions of series and volcanism. But we must either translate them into English or learn our Russian better to fully appreciate the information therein. A similar comment is in order concerning China.

The Ordovician is only beginning to release its secrets to us and remains a fertile field for all kinds of geologic endeavor.

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