

CARBON-ISOTOPE STRATIGRAPHIC CORRELATIONS IN THE LATE PERMIAN

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ABSTRACT. A uniquely high level of ^{13}C in marine limestones of Late Permian time from the western USA, East Greenland, north-western Europe, southern China, and the Bellerophon Basin of the Carnic and Dolomite Alps was described previously. This paper tests the thesis that its onset and termination are sharp worldwide events that provide stratigraphic markers of high precision in the Permian. The onset marker, close to the end of the Capitanian Stage, correlates the Bell Canyon-Castile contact of the Delaware Basin of West Texas, the Kupferschiefer-Zechsteinkalk contact of the Zechstein Series in Germany and the North Sea, and the Gröden-Bellerophon contact in the marine Tethyan of the Alps. The termination marker correlates the top of the Changxing Limestone in southern China with the upper part of the Bellerophon Formation in the Alps but may correspond to para-conformities elsewhere.

INTRODUCTION

Several distinctive isotope shifts such as those of $\delta^{18}\text{O}$ in carbonate of the Pleistocene (Shackelton and Opdyke, 1976), $\delta^{13}\text{C}$ in carbonate of the Cretaceous (Scholle and Arthur, 1980), and $\delta^{34}\text{S}$ in sulfate of the Early Triassic (Holser, 1977) have been described previously from marine rocks (Holser, 1984). Such "isotopic events" are now beginning to be applied as time lines in stratigraphic correlations. In this paper we discuss stratigraphic correlations of a shift in $\delta^{13}\text{C}$ in carbonates during part of Late Permian time, to high positive values unapproached at any other time in the known carbon isotope record of the marine Phanerozoic. The anomalous high has now been observed in half a dozen basins around the world, mainly through our own analytical program. The purpose of this paper is to test the thesis that the carbon isotope anomaly is contemporaneous worldwide, and that its onset and termination represent time lines useful for stratigraphic correlation. A definitive worldwide biostratigraphic correlation scheme has not yet been established for the Permian. We use the available correlations of various faunal groups, within the limits set by slightly differing paleontologic opinion, to constrain our isotope correlations. As a further step we suggest some sharper correlations assuming that the isotope shifts are true time lines. In this paper we are concerned solely with the stratigraphic implications of the geochemical results; the details of the isotope profiles and their geochemical interpretations are given in papers on each area, which are referenced in the discussion.

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LATE PERMIAN STRATIGRAPHY

Correlations of Late Permian sections have been of special interest because the biotic crisis associated with the Permian-Triassic interval is the most dramatic in the Phanerozoic record (Raup and Sepkoski, 1982). However, the precise intercontinental correlations required for quantitative evaluation of extinctions in the Late Permian have been frustrated by both procedural and substantive controversies owing to limitations of the paleontology on which such correlations have previously depended. These controversies have been extensively debated in symposia (Logan and Hills, 1973; Pakulska, 1981) and intensively reviewed by Ruzhentsev and Sarycheva (1965), Smith and others (1974), Waterhouse (1976; 1978), Kozur (1977, 1978), and Anderson (1981). A few of the bases of controversy are:

1. Lack of suitable stratotypes for defined stages of the Permian, in part because the classic type sections of the Permian in Russia were mainly non-marine, and few marine sections subsequently proposed are complete for more than one stage.
2. Disagreement as to which taxa — ammonoids, brachiopods, fusulinids, conodonts, or palynomorphs — are the most definitive for correlation by virtue of their cosmopolitan, isochronous, and finely divisible biostratigraphic zonation.
3. A prevalence in many important sections of endemic, restricted, or impoverished taxa — or no fossils at all.
4. Difficulties of recognizing paraconformities in which one or more stages are apparently missing from certain marine sections, without deformation, weathering, erosion, or other evidence of the hiatus.

NATURE OF CARBON ISOTOPE ANOMALIES IN MARINE CARBONATE ROCKS

The $^{13}\text{C}/^{12}\text{C}$ ratio in a marine carbonate rock is conventionally described in terms of its deviation in parts per thousand from the PDB standard, defined as “ δ ” units. The $^{13}\text{C}/^{12}\text{C}$ ratio in a marine carbonate sediment is closely related to that of the marine bicarbonate from which it was deposited by organic or inorganic processes, subject to deviations dependent on mineralogical, kinetic, and “vital” (specific biological) effects. Alteration of $\delta^{13}\text{C}$ from that of the primary carbonate may (but not necessarily does) occur during diagenetic mineral transformations or later equilibration with meteoric waters. We have sought to minimize both primary and secondary deviations of $^{13}\text{C}_{\text{carb}}$ from that of the original marine bicarbonate by basing selection on the following criteria: (A) micritic carbonate free of obvious fossils and vein carbonates, (B) shelf facies, (C) dolomite (Magaritz, 1985), and (D) core rather than outcrop samples. The ultimate verification, that original $\delta^{13}\text{C}$ values were preserved, rests on their match with other sections in the same or distant basins.

Positive shifts in marine $\delta^{13}\text{C}_{\text{carb}}$ are in general caused by an increase in net storage rate of organic carbon, which has $\delta^{13}\text{C}_{\text{org}}$ about -25 per mil. One might expect the resulting positive anomaly in $\delta^{13}\text{C}_{\text{carb}}$ to be evident most immediately and dramatically in the bicarbonate (hence deposited carbonate) of the surface waters of the basin in which the increase

of C_{org} deposition occurred. However, equilibration with atmospheric CO_2 and mixing of marine surface waters are so fast that the $\delta^{13}C$ anomaly will be spread worldwide in a few years, at the same time that it is diluted by this larger surface-water reservoir. Further mixing with the even larger reservoir of the deep sea below the pycnocline will take about 10^3 yrs in the present regime of vertical circulation that is driven by cold polar waters and perhaps several times longer during geological intervals when thermohaline circulation was dominant. Consequently, isotopic shifts of $\delta^{13}C_{carb}$ due to excess storage of C_{org} , when detected, are expected to be found in all marine waters, at approximately the same intensity. These shifts should be synchronous within a few hundred or thousands of years. On the other hand, the mixing with large reservoirs so greatly dilutes an isotope shift (due to a given transfer of C_{org}) that only a very unusual event will be detectable. The $\delta^{13}C_{carb}$ anomaly in the Late Permian is such an unusual event and has been detected worldwide in carbonate sections on marine shelves (not deep sea).

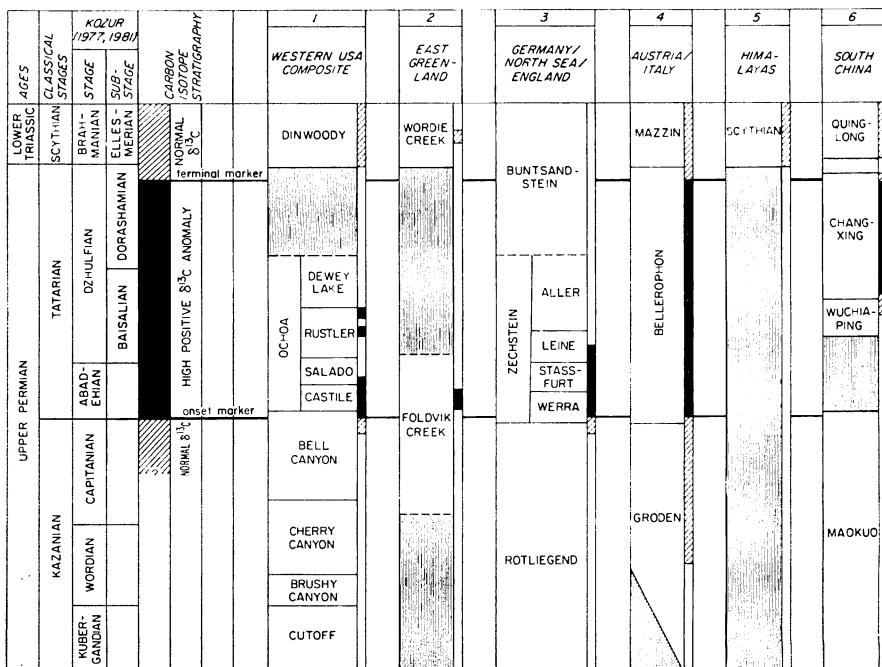


Fig. 1. World-wide correlations in Late Permian time. Correlations from carbon isotope stratigraphy are shown as heavy lines; other correlations interpolated from Kozur (1977) and other authors (see text). Each stratigraphic section is bordered on its right by a space in which solid black indicates a measured positive anomaly of ^{13}C ($> +3$ per mil), a diagonal pattern indicates normal ^{13}C ($= 0 \pm 1$ per mil), white indicates no measurements. Sources of isotope data are mainly as follows (also see text): western United States of America, Magaritz and others (1983) and Wilgus (ms); east Greenland, Clemmensen, Holser, and Winter (1985); Germany and North Sea, Magaritz and Schulze (1980), Magaritz, Turner, and Kading (1981), Magaritz and Turner (1982); Austria and Italy, Holser and Magaritz (1985); Himalayas, Magaritz (unpub.); South China, Chen and others (1984).

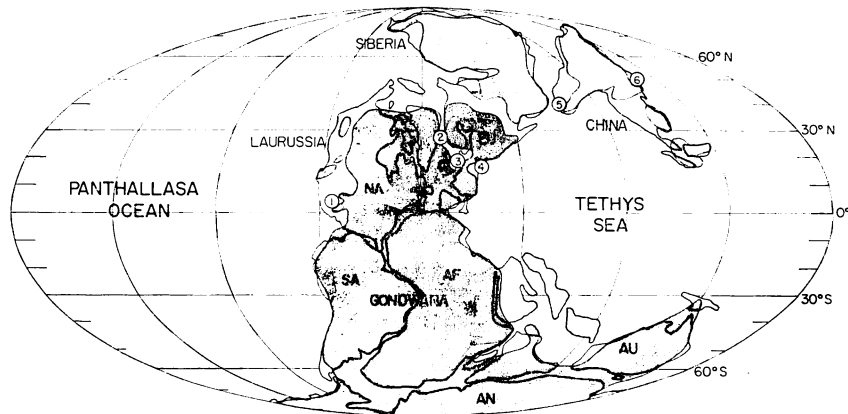


Fig. 2. Paleogeography of Late Permian time (adapted from Bambach, Scotese, and Ziegler, 1980), indicating the worldwide distribution of the measured sections of Late Permian marine rocks. The numbers correspond to those heading the columns in figure 1.

THE LATE PERMIAN CARBON ISOTOPE ANOMALY

General characteristics.—At a time very close to the end of the Capitanian Stage of the Late Permian time $\delta^{13}\text{C}$ rose sharply by 5 to 7 per mil. Values of ^{13}C above +4 continued with only minor variations until very near the end of the Dorashamian Stage, that is, near the Permian-Triassic boundary. Lowermost Triassic rocks return to $\delta^{13}\text{C}$ near zero.

This carbon isotope anomaly has been described from widely separated regions. The sections in which the anomaly has been detected are summarized in figure 1, and their locations with respect to Permian paleogeography are shown in figure 2. Figure 1 also indicates the intercontinental correlations of Late Permian stratigraphy that have been deduced from an evaluation of the new isotope stratigraphy combined with the previous biostratigraphic determinations.

This Late Permian high of $\delta^{13}\text{C}$ is apparently a final phase of a general high level of $\delta^{13}\text{C}$ in Late Carboniferous and Permian time previously documented only in statistical fashion (Veizer, Holser, and Wilgus, 1980; Saltzman, Lindh, and Holser, 1982; Lindh, ms) or in particular times and places (Given and Lohman, 1985; Lohman, 1986). Thus the value near $\delta^{13}\text{C} = 0$, which characterizes the initial part of each profile in the detailed sections reviewed below, may actually be a short excursion back to low $\delta^{13}\text{C}$. The complete delineation of these earlier variations will be resolved only by further detailed isotopic analyses of key stratigraphic sections of early Permian and Carboniferous age.

Although the anomaly is clear and widespread, we do not yet have independent evidence of the massive storage of C_{org} that would account for the highly positive $\delta^{13}\text{C}$. Holser and Magaritz (1984) point out that if this major deposition of C_{org} had taken place in marine muds, it should have been accompanied by an equally massive deposition of pyrite sul-

fide (Goldhaber and Kaplan, 1974), with a consequent positive shift of $\delta^{34}\text{S}_{\text{sulfate}}$. The residence time in the world ocean for sulfur ($\sim 10^7$ yr) is much longer than that of carbon ($\sim 10^5$ yr), and consequently the *full* rise of $\delta^{34}\text{S}$ might be delayed for several million years after the corresponding rise of $\delta^{13}\text{C}$. But *no* positive shift of $^{34}\text{S}_{\text{sulfate}}$ is evident in the Late Permian either in general (Claypool and others, 1980) or specifically in the sections showing a positive shift of $\delta^{13}\text{C}_{\text{carb}}$ (Magaritz and others, 1983; Holser and Magaritz, 1985; Clemmensen, Holser, and Winter, 1985). Consequently Holser and Magaritz (1984) conclude that the carbon storage was probably on land, where sulfate is deficient (Berner and Raiswell, 1983). Perhaps large amounts of (low-sulfide) organic carbon were deposited by forests flourishing at the close of the late Paleozoic glaciation (Holser and Magaritz, 1984) that continued into Kazanian time (Ham-brey and Harland, 1981).

Although we do not yet have a very specific model for the origin of the Late Permian high of $\delta^{13}\text{C}$, we have considered and eliminated several models that would have been independent for each basin and therefore not a basis for intercontinental correlations. Specifically, many of our colleagues have suggested that the rise in $\delta^{13}\text{C}$ may have been connected somehow with the incidence of evaporitic conditions in many basins of Late Permian time. Recently Stiller, Rounick, and Shasha (1985) have reached very high $\delta^{13}\text{C}$ by experimental evaporation of brines in the potash facies, owing to kinetic fractionation during effusion of CO_2 . We have argued (Magaritz and others, 1983, p. 119) that such evaporitic degassing cannot explain the rise of $\delta^{13}\text{C}$ in Late Permian basins; to summarize: (A) high $\delta^{13}\text{C}$ is not found in Cenozoic evaporites; and (B) in Permian basins that include evaporite (Zechstein and Delaware Basins) the rise of $\delta^{13}\text{C}$ occurs in marine sediments preceding the initial CaSO_4 evaporite deposition, and the high continues through all subsequent facies and cycles. Recently, the Late Permian high of ^{13}C has been confirmed in the marine part of the Bellerophon Basin and in the completely marine South China Basin (see detailed discussion below). Arthur (1984) suggests that the low $\delta^{13}\text{C}$ at the base of our Delaware Basin sections (Magaritz and others, 1983) represents an overprint on a generally high $\delta^{13}\text{C}$ in the Late Permian by diagenesis in formations rich in organic carbon ($\text{C}_{\text{org}} = 5\text{-}9$ percent). But our detailed analyses for organic carbon in those profiles (Magaritz and others, 1983, p. 115) and qualitative observations in other basins show no such anticorrelation, for example, $\delta^{13}\text{C}_{\text{carb}}$ is not low in proportion to C_{org} being high.

Review of described occurrences.—Although ^{13}C enrichment in the second cycle of the Zechstein Series (Z2Ca) had been implicit in earlier published data (Muller and others, 1968; Marowsky, 1969), the rapid onset of the high in the first cycle (Z1) was first delineated by Magaritz and Schulze (1980), who called attention to its anomalous nature. The anomaly was subsequently confirmed across the Zechstein Basin by Magaritz and others (Magaritz, Turner, and Kading, 1981; Magaritz and Turner, 1982), supplemented by additional data that became available incidental to other isotopic studies of Zechstein rocks (Clark, 1980; Botz and Muller,

1981). We then searched for and found an analogous anomaly all the way across Pangaea in the Delaware Basin of Texas (fig. 2). This anomaly occurs in a well-documented varve sequence that timed the onset to have taken less than 5000 yrs (Magaritz and others, 1983). Chen and others (1984) sampled and analyzed one of the classic Permian-Triassic sections in southern China and found the same anomaly.

What may be a rather complete representation of the anomaly in the Bellerophon Basin of Austria and Italy (Holser and Magaritz, 1985) is shown in figure 3, where it lies entirely within the Bellerophon Formation of latest Permian age. High values of $\delta^{13}\text{C}$ from +2.5 to over 4 per mil extend (with one interruption) through about 80 m of section. The steep rise to these high values takes place in the Bellerophon Formation, within a few meters of its base. The end of the anomalous high lies within a 50-m covered interval, near the Permian-Triassic boundary.

We have also surveyed some samples from seven sections in the Himalayas furnished by A. Nicora of the University of Milan (Baud and others, 1984) and Eric Hatleberg of the University of Wisconsin, Madison.

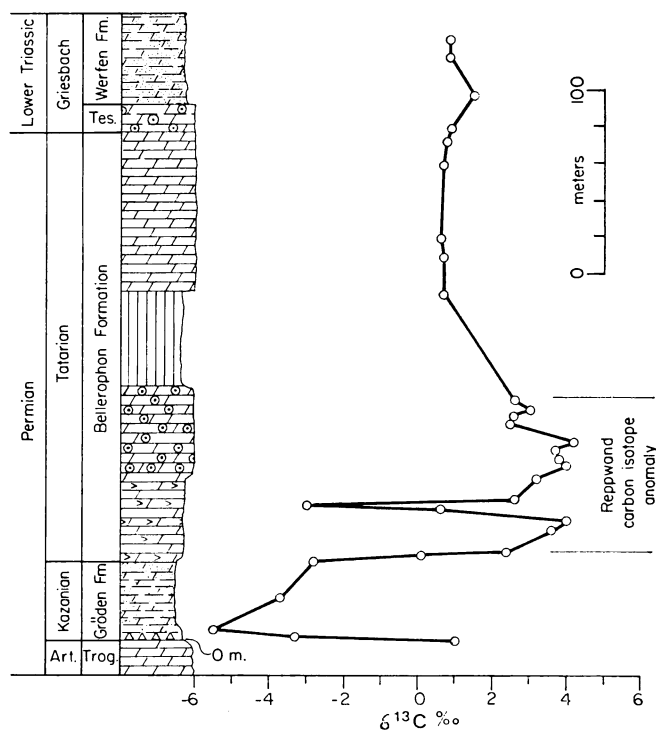


Fig. 3. Carbon isotope profile at the Reppwand, Carnic Alps, Austria (Holser and Magaritz, 1985). Symbols (from top downward): Werfen siltstone and dolostone; Tesoro, oolitic dolomite; Bellerophon, dolostone, covered, oolitic dolostone, dolostone with Rahwacke beds (evaporitic breccia); Groden, dolomitic siltstone, dolostone breccia; Trogkofel, dolostone.

In these sections limestones of earliest Triassic age overlie sandstones of of Late Permian age, and $\delta^{13}\text{C}$ in the Triassic limestones is universally normal.

ISOTOPE-STRATIGRAPHIC CORRELATIONS IN THE PERMIAN

Stipulations and assumptions.—On the basis of the above and previous (Magaritz and others, 1983) discussions, we are convinced that high positive levels of $\delta^{13}\text{C}$ detected in Late Permian rocks are a reflection of a worldwide excursion of this isotope ratio in marine bicarbonate (and the atmosphere), that is so far unique in its magnitude. The anomalously high level of $\delta^{13}\text{C}$ lasted for a substantial part of Late Permian time. Recent evaluations of the stratigraphic time scale arbitrarily assign about 5 Ma to the whole Tatarian stage (for example, Harland and others, 1982) — consequently the duration of the anomaly may be about that long. The onset has been observed to have taken only a few thousand years (Magaritz and Turner, 1982; Magaritz and others, 1983), and the termination may be equally abrupt (Chen and others, 1984). On theoretical grounds, as discussed above (see also Magaritz and others, 1983), marine levels of $\delta^{13}\text{C}$ would be expected to be established worldwide within at most a few thousand years. Therefore, the onset and termination events each should be synchronous worldwide on a time scale much finer than biostratigraphic zonation. The sharpness and wide geographic distribution of these markers are comparable to those of magnetic reversal stratigraphy.

The Late Capitanian onset marker.—Figure 1 displays suggested intercontinental correlations in Late Permian time, tied to the onset and termination markers of the carbon-isotope anomaly, that are still within the range of biostratigraphic fact and opinion. The left side of figure 1 shows the classical stages of the Late Permian and the stages and substages of Kozur (1977, 1978). The choice of stratigraphic subdivisions, and the Permian-Triassic boundary itself, is not at issue here — our objective is to establish some time lines and limits among the actual sections from widely separated basins.

In the Delaware Basin of Texas, the studied sections (Magaritz and others, 1983) of the Bell Canyon Formation are near the top of the Delaware Mountain Series and of the Capitanian Stage (Furnish, 1973). $\delta^{13}\text{C}$ begins to rise within the Bell Canyon Formation only about 35,000 yrs after deposition of the Lamar Limestone Member (near the top of the Bell Canyon Formation) and is completed 4500 yrs later within the lowermost Castile Formation (Anhydrite I Member) (Magaritz and others, 1983). The Castile Formation is without fossils, and we assign it to the Abadehian Stage on the basis that it overlies, apparently conformably, the Delaware Mountain Series. Furnish (1973) and Waterhouse (1976, p. 166) have placed the Lamar Limestone Member in the Abadehian (= Amarasian = Urushtenian) Stage, which would make the Castile at least later Abadehian, but Kozur (1977, p. 101) leaves the Lamar with the rest of the Delaware Mountain Series in the Capitanian on the basis of both fusulinid and conodont faunas.

The carbon isotope onset marker is clearly seen in both the Delaware Basin of Texas and the Zechstein Basin of northwestern Europe, and in both basins the subsequent high of $\delta^{13}\text{C}$ continues without known interruption through the last Permian marine deposition (fig. 1). The isotope data consequently indicate a time line between the Bell Canyon Formation just before the beginning of evaporite deposition in the Castile Formation, in Texas, and the Kupferschiefer just before its smooth transition to the Zechsteinkalk in the first cycle (Z1 = Werra) of the Zechstein Series. This isotope correlation agrees with some paleontological interpretations but disagrees with others. A sequence of development within the palynological genus *Luekispores* equates the base of the Zechstein with the base of the Abadehian (= base of the Tatarian) (Visscher, 1973; Kozur, 1978, p. 112; Warrington in Smith and others, 1974, p. 36). Kahler (1974b) correlates the Zechstein (and the Bellerophon) in the *Conodofusiella* fusulinid zone of Abadehian age. This assignment is also accepted in Anderson's (1981) world-wide correlation table for the Permian-Triassic. However, based on brachiopod (and possibly other invertebrate fauna) the Zechstein Series has been assigned alternatively to the Kazanian or even the Kungurian (Waterhouse, 1976, p. 113; Waterhouse in Smith and others, 1974, p. 34). Conodont zonation should have the biostratigraphic precision to resolve this question, but again one finds differing interpretations of morphological evolutionary series. One of us (D.L.C.) has recognized a late stage of the *Neogondolella serrata postserrata* Assembly Zone in both the Lamar Limestone of Texas and the uppermost Gerster Formation of Nevada-Utah, where in the latter case it overlies the *Neogondolella rosenkrantzi-Neospathodus divergens* Assembly Zone (Clark and others, 1977, and unpublished; Behnken, 1975). *N. divergens* has long been known as a prominent guide fossil of the Zechstein 1 in both Germany and England (Swift and Aldridge, 1982). However, Kozur (1978, p. 107) has asserted that the Nevada conodont material is *not* the same as the Zechstein material and has reassigned the former to a Kazanian *Gondolella bitteri-Stepanovites meyeri-Merrillina* [= *Neogondolella*] *praedivergens* Assembly Zone, followed by a *Gondolella bitteri-Stepanovites inflatus-Merrillina divergens* Assembly Zone, which includes the Zechstein and is assigned an Abadehian age. The paleontological correlations are clouded by differing "communities" (Behnken, 1975) of conodonts (facies dependent?) and by judgments of developmental lineages. Thus while the most authoritative paleontological opinion would have the Zechstein 1 of Europe somewhat older than the uppermost Bell Canyon Formation of Texas, sufficient uncertainty may remain to accommodate the time equivalence of these formations indicated by the carbon isotope data. An alternative is that the onsets detected in the two basins represent the ends of two independent excursions that occurred at two different times in the Late Permian, but no later event has yet been found in the isotope record of either basin.

A few samples have been analyzed for $\delta^{13}\text{C}$ from the Foldvik Creek Formation of East Greenland (fig. 1, column 2; Clemmensen, Holser, and

Winter, 1985); they all have high $\delta^{13}\text{C}$. The Foldvik Creek Formation has traditionally been correlated with the Zechstein Series of northeastern Europe (for example, Birkelund and Perch-Nielsen, 1976) but without specification as to which cycle(s) of the Zechstein is represented in Greenland. Such a correlation is indirectly supported by conodonts found in the Foldvik Creek Formation at Cape Stosch by Sweet (1973, p. 640), which Kozur (1978, p. 102) places in a developmental series that confines the Greenland occurrence to the Abadehian. A study of the brachiopod fauna places the Foldvik Creek Formation in the Kazanian stage by correlation with those of Spitzbergen (Grant and Cooper, 1973), but only on a statistical basis. Corals also suggest a pre-Dzhulfian age (Flügel, 1973). Critical Cyclolobid ammonoids are controversial in identification, phylogeny, and range (Dunbar, 1955; Furnish, 1973; Grant and Cooper, 1973; Waterhouse, 1976, p. 116).

The Bellerophon Formation of the Italian Dolomites and the Austrian Carnic Alps is generally assigned to the last stage of the Permian (Kozur, 1981, p. 419; Anderson, 1981; Waterhouse, 1976, p. 83), mainly on the basis of brachiopods (Assereto and others, 1973, p. 187), fusulinids (Kahler, 1974b, p. 127), and palynomorphs (Kozur, 1977, p. 112), although the biostratigraphy has never been studied in systematic detail (Flügel, 1981). This general relation is sharpened by isotope correlation of the onset marker that matches the Kupferschiefer-Zechsteinkalk transition of the Zechstein Basin with a level just above the Gröden-Bellerophon boundary at the Reppwand (fig. 1, column 4; fig. 3). Where the underlying Gröden Formation is marine it is generally correlated as Wordian to Capitanian on the basis of fusulinids (Kahler, 1974a; 1974b).

In the South China section (fig. 1, column 6) Chen and others (1984) found low $\delta^{13}\text{C}$ values in their two stratigraphically lowest samples, which span the boundary of the Wuchiaping and the overlying Changxing Formations. These formations are both assigned to the Dzhulfian on the basis of typical ammonoids (Chao, 1965); conodont and fusulinid zonation (Zhao and others, 1981) place the Changxing in the Dorashamian (upper Dzhulfian) and the Wuchiaping in the Baisalian (Lower Dzhulfian) (Kozur, 1978, p. 108). A detailed carbon isotope study is needed of the whole Wuchiaping (and Maokuo) formations to determine whether the low value of $\delta^{13}\text{C}$ is only a brief excursion at the top of the Wuchiaping or extends throughout the section. In the first instance the low $\delta^{13}\text{C}$ may represent a brief return to low values that have not yet been detected in other sections. If the low $\delta^{13}\text{C}$ turns out to be continuous through the Wuchiaping, the isotope and paleontological correlations would be in conflict.

The Late Dzhulfian termination marker.—Column 1 of figure 1 arbitrarily juxtaposes the Lower Triassic Dinwoody Formation of Idaho and Utah above the Ochoa Series of Texas and New Mexico, because no marine lowermost Triassic is found any closer to the Upper Permian formations of West Texas. The youngest Permian rocks in Texas analyzed for carbon isotope composition are from the Rustler Formation (Wilgus, ms), which is correlated as Dzhulfian on the basis of gastropod fauna

(Batten, 1973). A few determinations of $\delta^{13}\text{C}$ in the Dinwoody (lowest Triassic; Clark and others, 1977) are normal (Wilgus, ms), but the latest Permian Gerster Formation, which underlies the Dinwoody in western Utah, has not yet been studied isotopically.

In East Greenland (fig. 1, column 2) a few analyses for $\delta^{13}\text{C}$ from the Wordie Creek Formation of Griesbachian (lowermost Triassic) age are normal (Clemmensen, Holser, and Winter, 1985), and the termination marker apparently lies within the paraconformity that is generally considered to separate the Wordie Creek from the Permian Foldvik Creek Formation (for example, Teichert and Kummel, 1973). In the probably correlative main basin of the Zechstein (fig. 1, column 3) the youngest anomalous $\delta^{13}\text{C}$ is in the third cycle (Z3 = Leine) of the Zechstein Series (Magaritz, unpub. data) — the overlying formations (through the Lower Triassic) are thought to be non-marine.

In the Bellerophon Basin the termination marker lies within the Bellerophon Formation (fig. 3; fig. 1, column 4) — most clearly in the Reppwand (Austria) section; the overlying Mazzin Member of lowermost Triassic age is everywhere normal (70 samples from throughout the Dolomite Alps analyzed by C. Nelson, personal commun., 1983). The termination marker thus lies below the Permian-Triassic boundary as defined somewhat arbitrarily (Assereto and others, 1973, p. 182) in the Dolomite Alps. As discussed above, correlations of the Bellerophon Formation with critical sections of Late Permian age are somewhat indefinite. Assereto and others (1973, p. 188) conclude that the Bellerophon is older than the *Paratirolites* zone, the final ammonoid zone of the Dorashamian stage (fig. 1), but the isotope correlation with south China suggests that the Bellerophon of the Reppwand includes the *Paratirolites* zone. Most of the paleontology on which Assereto based his conclusions was from the western part of the basin in the Italian Dolomites, and the top beds of the Bellerophon may not be of the same age everywhere (Assereto et al., 1973, p. 180).

The sections in southern China studied isotopically by Chen and others (1984; see fig. 1, column 6) pinned down the termination marker (in two related sections) within the Changxing Limestone just one bed below its contact with the Triassic Quinglong Formation. Although this area is generally considered to have one of the best representations in the world of the Permian-Triassic transition (for example, Furnish, 1973, p. 545), the contact is nevertheless locally disconformable (Yang and Yang, 1981 — category III; Rostovtsev and Azaryan, 1973). Kozur (1977, p. 105) reviews evidence that the type Dorashamian (latest Permian) of the Transcaucases is *in part* younger than the Changxing Limestone. Consequently, the termination marker of the carbon isotope anomaly may lie within the Permian, slightly below the Permian-Triassic boundary.

CONCLUSIONS

A uniquely high level of $\delta^{13}\text{C}$ values occurs in marine limestones, worldwide, in the Late Permian. Its sharp onset near the top of the Capitanian Stage and termination near the top of the Dzhulfian Stage each

provide stratigraphic markers of potentially high precision. The onset marker correlates the Bell Canyon-Castile contact of West Texas, the Kupferschiefer-Zechsteinkalk contact of northwestern Europe, and the Gröden-Bellerophon contact of the Alps. The termination marker correlates the top of the Changxing Limestone in south China with a level high in the Bellerophon Formation of the Alps; this level lies within paraconformities of the latest Permian in the western United States of America and east Greenland. These correlations may help to resolve a number of uncertainties and conflicts that have previously confused the stratigraphy and paleontology of Late Permian time.

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REFERENCES

- Anderson, J. M., 1981, World Permo-Triassic correlations: Their biostratigraphic basis, in Cresswell, M. M., and Vella, P., Gondwana five: Rotterdam, Balkema, p. 3-10.
- Arthur, M. A., 1984, Carbon isotope anomalies?: *Nature*, v. 310, p. 450-451.
- Assereto, R., Bosellini, A., Fantini Sestini, N., and Sweet, W. C., 1973, The Permian-Triassic boundary in the southern Alps (Italy): *Canadian Soc. Petroleum Geologists Mem.* 2, p. 176-199.
- Bambach, R. K., Scotese, C. R., and Ziegler, A. M., 1980, Before Pangea: The geographies of the Paleozoic world: *Am. Scientist*, v. 68, p. 26-38.
- Batten, R. E., 1973, The vicissitudes of the gastropods during the interval of Guadalupian-Ladinian time: *Canadian Soc. Petroleum Geologists Mem.* 2, p. 596-607.
- Baud, A., Gaetani, M., Garzanti, E., Fois, E., Nicora, A., and Tintori, A., 1984, Geological observations in southeastern Zaskar and adjacent Lahul area (northwestern Himalaya): *Eclogae Geol. Helvetiae*, v. 77, p. 171-197.
- Behnken, F. H., 1975, Leonardian and Guadalupian (Permian) conodont biostratigraphy in western and southwestern United States: *Jour. Paleontology*, v. 49, p. 284-315.
- Berner, R. A., and Raiswell, R., 1983, Burial of organic carbon and pyrite sulfur in sediments over Phanerozoic time: A new theory: *Geochim. et Cosmochim. Acta*, v. 47, p. 855-862.
- Birkelund, T., and Perch-Nielsen, K., 1976, Late Paleozoic-Mesozoic evolution of central East Greenland, in Escher, A., and Watt, W. S., eds., *Geology of Greenland: Copenhagen, Grønlands Geol. Undersøg.*, p. 305-339.
- Botz, R., and Muller, G., 1981, Mineralogie, Petrographie, anorganische Geochemie und Isotopen-Geochemie der Karbonatgesteine des Zechstein 2: *Geol. Jahrb.*, v. D47, p. 3-112.
- Chao K.-K., 1965, The Permian ammonoid-bearing formations of South China: *Sci. Sinica*, v. 14, p. 1813-1825.
- Chen J., Shao M., Huo W., and Yao Y., 1984, Carbon isotopes of carbonate strata at Permian-Triassic boundary in Changxing, Zhejiang: *Sci. Geol. Sinica*, 1984, no. 1, p. 88-93 (in Chinese; summary in English).
- Clark, D. L., Carr, T. R., Behnken, F. H., Wardlaw, B. R., and Collinson, J. W., 1979, Permian conodont biostratigraphy in the Great Basin: *Brigham Young Univ., Geol. Studies*, v. 26, p. 143-149.

- Clark, D. L., Peterson, D., Stokes, W. L., Wardlaw, B. R., and Wilcox, J. D., 1977, Permian-Triassic sequence in northwest Utah: *Geology*, v. 5, p. 655-658.
- Clark, D. N., 1980, The diagenesis of Zechstein carbonate sediments: *Contr. Sedimentology*, v. 9, p. 167-203.
- Claypool, G. E., Holser, W. T., Kaplan, I. R., Sakai, H., and Zak, I., 1980, The age curves of sulfur and oxygen isotopes in marine sulfate and their mutual interpretation: *Chem. Geology*, v. 28, p. 199-260.
- Clemmensen, L. B., Holser, W. T., and Winter, D., 1985, Stable isotope study through the Permian-Triassic boundary in East Greenland: *Geol. Soc. Denmark Bull.*, v. 33, p. 253-260.
- Dunbar, C. O., 1955, Permian brachiopod faunas of central east Greenland: *Meddel. Grønland*, v. 110, no. 3, 169 p.
- Flügel, E., 1981, The Permian of the Carnic Alps — depositional environments and microfacies, in Pakulska, Z., ed., *Internat. symposium central European Permian*: Warsaw, Geol. Inst., p. 84-94.
- Flügel, H. W., 1973, Rugose Korallen aus dem oberen Perm Ost-Grönlands: *Geol. Bundesanstalt Verh.*, 1973, p. 1-57.
- Furnish, W. M., 1973, Permian stage names: *Canadian Soc. Petroleum Geologists Mem.* 2, p. 522-548.
- Given, R. K., and Lohman, K. C., 1985, Derivation of the original isotopic composition of Permian marine cements: *Jour. Sed. Pet.*, v. 55, p. 430-439.
- Goldhaber, M. B., and Kaplan, I. R., 1974, The sulfur cycle, in Goldberg, E. D., ed., *The Sea*, v. 5: New York, John Wiley & Sons, Inc., p. 569-655.
- Grant, R. E., and Cooper, G. A., 1973, Brachiopods and Permian correlations: *Canadian Soc. Petroleum Geologists Mem.* 2, p. 572-595.
- Hambrey, M. J., and Harland, W. D., 1981, *Earth's Pre-Pleistocene glacial record*: Cambridge, Cambridge Univ. Press, 1004 p.
- Harland, W. B., Cox, A. V., Llewellyn, P. G., Pickton, C. A. G., Smith, A. G., and Walters, R., 1982, *A geologic time scale*: Cambridge, Cambridge Univ. Press, 128 p.
- Holser, W. T., 1977, Catastrophic chemical events in the history of the ocean: *Nature*, v. 267, p. 403-408.
- 1984, Gradual and abrupt shifts in ocean chemistry during Phanerozoic time, in Holland, H. D., and Trendall, A. G., 1984, *Patterns of change in Earth evolution*. Dahlem Konferenzen: Berlin, Springer-Verlag, p. 123-143.
- Holser, W. T., and Magaritz, M., 1984, Chemical events near the Permian-Triassic boundary: *EOS*, v. 65, p. 297.
- 1985, Late Permian carbon isotope anomaly in the Bellerophon Basin, Carnic and Dolomite Alps: *Geol. Bundesanstalt Wien Jahrb.*, v. 128, p. 75-82.
- Kahler, F., 1974a, Einige Gedanken zur Gliederung der Permzeit: *Carinthia II*, v. 164/84, p. 73-78.
- 1974b, Fusuliniden aus T'ien-schan und Tibet mit Gedanken zur Geschichte der Fusuliniden-Mere im Perm: *Rept. Sci. Exped. N. W. Province China Under Leadership Dr. Sven Hedin*, Pub. 52, v. 4, 148 p.
- Kozur, H., 1977, Beiträge zur Stratigraphie des Perms: Teil I. Probleme der Abgrenzung und Gliederung des Perms: *Freiberger Forsch.*, v. C319, p. 79-121.
- 1978, Beiträge zur Stratigraphie des Perms Teil II: Die Conodonten-chronologie des Perms: *Freiberger Forsch.*, v. C344, p. 85-161.
- 1981, The boundaries and subdivisions of the Permian System, in Pakulska, Z., ed., *International symposium central European Permian*: Warsaw, Geol. Inst., p. 401-425.
- Lindh, T. B., ms, 1983, Temporal variations in ^{32}S , ^{34}S and global sedimentation during the Phanerozoic: M.S. thesis, Univ. Miami, 98 p.
- Logan, A., and Hills, L. V., 1973, The Permian and Triassic systems and their mutual boundary: *Canadian Soc. Petroleum Geologists Mem.* 2, 766 p.
- Lohman, K. C., 1986, Covariant carbon and oxygen isotopic trends in calcitized marine cement: estimation of marine isotopic signatures: *Jour. Sed. Pet.*, in press.
- Magaritz, M., 1985, The carbon isotope record of dolostone as a stratigraphic tool: A case study from the Upper Cretaceous shelf sequence, Israel: *Sed. Geology*, v. 45, p. 115-124.
- Magaritz, M., Anderson, R. Y., Holser, W. T., Saltzman, E. S., and Garber, J., 1983, Isotope shifts in the Late Permian of the Delaware Basin, Texas, precisely timed by varved sediments: *Earth Planetary Sci. Letters*, v. 66, p. 111-124.
- Magaritz, M., and Schulze, K.-H., 1980, Carbon isotope anomaly of the Permian Period: *Contr. Sedimentology*, v. 9, p. 269-277.
- Magaritz, M., and Turner, P., 1982, Changes in the carbon cycle of the Zechstein Sea: Isotopic transition zone in the Marl Slate: *Nature*, v. 297, p. 389-390.

- Magaritz, M., Turner, P., and Kading, K.-C., 1981, Carbon isotopic change at the base of the Upper Permian Zechstein sequence: *Geol. Jour.*, v. 16, p. 243-254.
- Marowsky, G., 1969, Schwefel-, Kohlenstoff- und Sauerstoff-Isotopenuntersuchungen am Kupferschiefer als Beitrag zur genetischen Deutung: *Contr. Mineralogy Petrology*, v. 22, p. 290-334.
- Muller, E. P., Theilig, F., Maass, I., Geissler, C., and Dostal, P., 1968, Die isotypen Zusammensetzung des Kohlenstoffs in Sedimenten des Perms und ihre Bedeutung für die Fazies: *Zeitsch. Angew. Geologie*, v. 18, p. 250-257.
- Pakulska, Z., ed., 1981, International symposium central European Permian: Warsaw, Geol. Inst., 656 p.
- Raup, D. M., and Sepkoski, J. J., Jr., 1982, Mass extinctions in the marine fossil record: *Science*, v. 215, p. 1501-1503.
- Rostovtsev, K. O., and Azaryan, N. R., 1973, The Permian-Triassic boundary in Transcaucasia: *Canadian Soc. Petroleum Geologists Mem.* 2, p. 89-99.
- Ruzhentsev, V. E., and Sarycheva, T. G., 1965, The development and change of marine organisms at the Palaeozoic-Mesozoic boundary. I. General Part: *Akad. Nauk SSSR, Trudi Paleontol. Inst.*, v. 108 [translation: Pub. no. 117, Geology Dept., Australian Natl. Univ., Canberra, A.C.T., 1968, 137 p.]
- Saltzman, E. S., Lindh, T. B., and Holser, W. T., 1982, Secular changes in ^{13}C and ^{34}S , global sedimentation, pO_2 and pCO_2 during the Phanerozoic: *Geol. Soc. America Abs. with Programs*, v. 14, p. 553.
- Scholle, P. A., and Arthur, M. A., 1980, Carbon isotope fluctuations in Cretaceous pelagic limestones: Potential stratigraphic and petroleum exploration tool: *Am. Assoc. Petroleum Geologists Bull.*, v. 64, p. 67-87.
- Shackleton, N. J., and Opdyke, N. D., 1967, Oxygen isotope and paleomagnetic stratigraphy of Pacific core V-28-239; Late Pliocene to latest Pleistocene: *in* Cline, R. M., and Hays, J. S., eds., *Investigations of late Quaternary Paleocyanography and Paleoclimatology*: *Geol. Soc. America Mem.* 145, p. 449-464.
- Smith, D. B., Brunstrom, R. G. W., Mannin, P. I., Simpson, S., and Shotton, F. W., 1974, A correlation of Permian rocks in the British Isles: *Geol. Soc. London Jour.*, v. 130, p. 1-45.
- Stiller, M., Rounick, J. S., and Shasha, S., 1985, Extreme carbon-isotope enrichments in evaporating brines: *Nature*, v. 316, p. 434-435.
- Sweet, W. C., 1973, Late Permian and early Triassic conodont faunas: *Canadian Soc. Petroleum Geologists Mem.*, v. 2, p. 630-646.
- Swift, A., and Aldridge, R. J., 1982, Conodonts from the Upper Permian strata of Nottinghamshire and North Yorkshire: *Palaeontology*, v. 25, p. 845-856.
- Teichert, C., and Kummel, B., 1973, Permian-Triassic boundary in the Kap Stosch area, East Greenland: *Canadian Soc. Petroleum Geologists Mem.* 2, p. 269-293.
- Veizer, J., Holser, W. T., and Wilgus, C. K., 1980, Correlation of $^{13}\text{C}/^{12}\text{C}$ and $^{34}\text{S}/^{32}\text{S}$ secular variations: *Geochim. et Cosmochim. Acta*, v. 44, p. 579-587.
- Visscher, H., 1973, The Upper Permian of western Europe — A palynological approach to chronostratigraphy: *Canadian Soc. Petroleum Geologists Mem.* 2, p. 200-219.
- Wardlaw, B. R., and Collinson, J. W., 1978, Stratigraphic relations of Park City Group (Permian) in eastern Nevada and western Utah: *Am. Assoc. Petroleum Geologists Bull.*, v. 62, p. 1171-1184.
- Waterhouse, J. B., 1976, World correlations for Permian marine faunas: *Univ. Queensland Papers Dept. Geology*, v. 7, no. 2, 232 p.
- , 1978, Chronostratigraphy for the world Permian: *Am. Assoc. Petroleum Geologists Studies Geology*, v. 6, p. 299-322.
- Wilgus, C. K., ms, 1981, A stable isotope study of Permian and Triassic marine evaporite and carbonate rocks, Western Interior, USA: Ph.D. dissert., Univ. Oregon, 100 p.
- Yang Z., Wu S., and Yang F., 1981, Permian-Triassic boundary in the marine regime of South China, *in* Cresswell, M. M., and Vella, P., eds., *Gondwana five*: Rotterdam, Balkema, p. 71-77.
- Zhao Jin-ke, Sheng Jin-zhang, Yao Zhao-qi, Liang Xi-luo, Chen Chu-zhen, Rui Lin, and Liao Zhuo-ting, 1981, The Changsingian and Permian-Triassic boundary of south China: *Nanjing Inst. Geology Palaeontology Acad. Sinica Bull.*, 1981, no. 2, p. 58-72.