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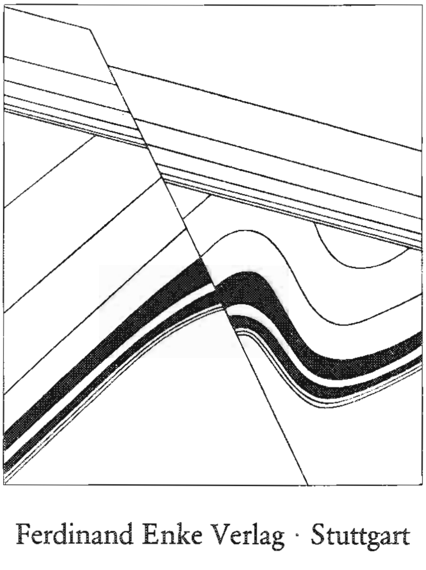

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Permian-Triassic of the Tethys: Carbon isotope studies

By Aymon Baud, Lausanne, Mordeckai Magaritz, Rehovot, and William T. Holser, Eugene*)

With 18 figures

Zusammenfassung

Untersucht wurden Profile von Kohlenstoff-Isotopen mariner Karbonate aus dem Oberperm und der Untertrias der Tethys-Region aus 20 Lokalitäten in Jugoslawien, Griechenland, der Türkei, der Sowjet-Republik Armenien, dem Iran, Pakistan, Indien, Nepal und China. Die oberpermischen Proben zeigen dieselben hohen positiven $\delta\ ^{13}C$ Werte, wie sie vorher auch aus den oberpermischen Becken NW-Europas und dem Westen der USA berichtet wurden. Anhand von vollständigeren Abschnitten der Tethys kann dargelegt werden, daß die $\delta\ ^{13}C$ Werte von der Murgabium- bis zur Dzhulfium-Phase des Oberperms abnehmen und dann innerhalb der letzten zwei Biozonen des Dorashamiums abrupt gegen Null verlaufen. Diese $\delta\ ^{13}C$ Niveaus sind repräsentativ für die Tethys und den Weltozean. Sie gelten außerdem für alle Wassertiefen, wie durch ähnliche Werte aus Tiefsee-Sedimenten von Salamis (Griechenland) bestätigt wird. Unsere Annahme ist, daß die hohen $\delta\ ^{13}C$ Werte auf spätpaläozoische Speicherung organischen Kohlenstoffs zurückzuführen ist. Die Abnahme stellt episodische Sedimentationsschwankungen des organischen Materials dar, während der die organischen Substanzen über einen Zeitraum von mehreren Millionen Jahren zum Teil aufoxidiert wurden. Das Kohlenstoff-Isotop Profil entspricht parallelisiert in etwa dem Muster des Massen-Aussterbens während des Oberperms.

Abstract

Profiles of carbon isotopes were studied in marine limestones of Late Permian and Early Triassic age of the Tethyan region from 20 sections in Yugoslavia, Greece, Turkey, Armenian SSR, Iran, Pakistan, India, Nepal, and China. The Upper Permian sections continue the high positive values of $\delta\ ^{13}C$ previously found in Upper Permian basins in NW Europe and western USA. In the more complete sections of Tethys it can now be demonstrated that the values of $\delta\ ^{13}C$ drop from the Murgabian to the Dzhulfian Stages of the Upper Permian, then sharply to values near zero during the last two biozones of the Dorashamian. These levels of $\delta\ ^{13}C$ sample the Tethys Sea and the world ocean, and equal values from deep-water sediments at Salamis Greece indicate that they apply to the whole water column. We hypothesize that the high values of $\delta\ ^{13}C$ are a consequence of Late Paleozoic storage of organic carbon, and that the declines represent an episodic cessation of this organic deposition, and partial oxidation of the organic reservoir, extending over a period of several million years. The carbon isotope profile may reflect parallel complexity in the pattern of mass extinction in Late Permian time.

Résumé

Des profils isotopiques du carbone ont été établis dans des calcaires marins d'âge tardi-permien à éo-triasique répartis dans 20 endroits du domaine téthysien: Yougoslavie, Grèce, Turquie, République Socialiste d'Arménie, Iran, Pakistan, Inde, Népal et Chine. Les profils établis dans le Permien supérieur montrent les mêmes valeurs positives de $\delta\ ^{13}C$ observées antérieurement dans des bassins de même âge en Europe occidentale et dans l'ouest des USA. Dans les profils les plus complets de la Téthys, il est maintenant établi que les valeurs de $\delta\ ^{13}C$ décroissent depuis le Murgabien jusqu'au Dzhulfien (Permien supérieur) pour devenir proches de zéro dans les deux dernières biozones du Dorashamien. Ces valeurs de $\delta\ ^{13}C$ sont caractéristiques de la Téthys et de l'Océan mondial; elles s'appliquent à toutes les profondeurs d'eau, comme en témoignent les valeurs fournies par des sédiments de mer profonde à Salamis (Grèce). Nous formulons l'hypothèse que les hautes valeurs de $\delta\ ^{13}C$ sont la conséquence du stockage du carbone organique au Paléozoïque supérieur et que leur décroissance traduit un arrêt épisodique de cette sédimentation organique, accompagné d'une oxydation partielle de la matière organique s'étendant sur une période de plusieurs Ma. L'influence parallèle des phénomènes d'extinction massive à le fin du Permien se reflèterait également dans les profils isotopiques du carbone.

Краткое содержание

Краткое содержание

С помощью изотопного анализа углерода исследовани пробы, взятые из 20 местностей /Югославия, Греция, Турция, Армения, Иран, Пакистан, Непал и Китай/ в профилях морских карбонатов верхней

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перми и нижнего триаса региона Тетиса. Верхнепермские известняки характеризуются высокими значениями $\delta^{13}C$, как это известно из верхнепермских проб бассейнов северо-западной Европы и запада США. На основании более полно исследованных профилей Тетиса можно сказать, что значения $\delta^{13}C$ в период от Murgabium'а до Dzhulfium'а резко понижаются до О. Это значение $\delta^{13}C$ является характерным для Тетиса и мирового океана. Кроме того, они справедливы для всех глубин океана, что подтверждается данными по осадочным породам из глубин озера Саламис / Греция /. Считают, что более высокие значения $\delta^{13}C$ могут отображать накопление органического С в позднепалеозойское время. Уменьшение же его представляет собой эпизодические явления колебания процесса осадконакопления органического материала в то время, когда органические субстанции в отрезках времени в несколько миллионов лет частично самоокислялись. На основании распределения изотопов С по профилю в перми / триасе названных выше районов предполагают, что оно, по всей вероятности, связано с вымиранием организмов в этот период.

Introduction

During Permian-Triassic (P-Tr) time one of the important transformations in Earth history took place. A major tectonic cycle ended with the creation of Pangaea (SMITH et al., 1981), a major period of glaciation ended (in mid-Permian – HAMBREY & HARLAND, 1981; CAPUTO & CROWELL, 1985) and fauna changed from a Paleozoic Fauna to a Modern Fauna (SEPKOSKI, 1981). This change in faunal composition is marked by the most dramatic extinction event during Phanerozoic time (RAUP & SEPKOSKI, 1982; 1986). The extinction near the end of the Permian was of long duration, perhaps several million years, but accelerating greatly at the end of the final stage of the Permian (LI et al., 1986; NAKAZAWA, 1985; XU et al., 1986; YIN, 1985). In this respect it differs from some other extinctions that may have occurred within a single biozone. During the P-Tr large changes in ocean chemistry also took place: salt content in the ocean dropped by 4‰ (HOLSER et al., 1980), and carbon, sulfur and strontium isotope compositions underwent large shifts (HOLSER & MAGARITZ, 1987). This paper describes the details of carbon isotope composition of the ocean through this period for the Tethys Sea, the major locus of marine sedimentation in Late Permian time.

The carbon isotope composition of marine carbonate rocks shows large variations through the geological record (VEIZER et al., 1980). Of these vari-

nate rocks shows large variations through the geological record (VEIZER et al., 1980). Of these vari-

ations the enrichment of $\delta^{13}C$ during Late Paleozoic time (HOLSER et al., 1986; POPP et al., 1986) stands out as an unusual event matched only in the Late Precambrian (KNOLL et al., 1986; MAGARITZ et al., 1986). Detailed studies show that the carbon isotope composition of marine carbonates during the Pennsylvanian and Permian fluctuated between low and high values of $\delta^{13}C$, possibly related to low and high stands of sea level (HOLSER & MAGARITZ, unpublished). The last of these highs was detected in the western USA, northwestern Europe and the Alps (HOLSER et al., 1986). The termination of this high was obviously a major geochemical event, involving a drop of more than −6‰, much greater than the −3‰ observed at the Cretaceous-Tertiary boundary (PERCH-NIELSEN et al., 1982; ZACHOS & ARTHUR, 1986). It was associated at first tentatively with the P/Tr boundary itself (HOLSER & MAGARITZ, 1985; HOLSER et al., 1986). More recently we demonstrated in two sections that the final drop was gradual across the stratigraphic P/Tr boundary, reaching a minimum in earliest Triassic (MAGARITZ et al., 1988). The main objective of the present study was to chart in detail the time duration, and form of this drop, in sections having the best possible stratigraphic control.

These variations, and others more recent, reflect shifts of carbon fluxes among its principal reservoirs (KUMP & GARRELS, 1986; BERNER, 1987). An increase in the rate of deposition of organic carbon in either the oceanic or land environment will enrich $\delta^{13}C$ in the reservoir of inorganic carbon in the ocean, while a rate of oxidation of organic matter above the norm will deplete $\delta^{13}C$. Such changes may have been caused by changes of sea level (BROECKER, 1982), by extension of an oxygen-minimum zone accompanying changes in oceanic circulation (SCHOLLE & ARTHUR, 1980; ARTHUR et al., 1987), or by changes in productivity either in the ocean or on land (BERGER & VINCENT, 1986). On land, extensive deposition of coal in the Late Paleozoic is a possible site of C_{org} accumulation (HOLSER et al., 1986). However, the question remains open as to just where the deposition of C_{org} occurred that accounts for the Late Paleozoic high of $\delta^{13}C$.

Several difficulties arise in the study of carbon isotope variation during the transition period from uppermost Permian through lowermost Triassic: (a) Marine sediments representing this period are missing in most regions of the world, especially at the boundary itself (NEWELL, 1973; SHENG et al., 1984); (b) The decrease in faunal population and the prevalence of endemic faunas make correlation between sections difficult.

The record of marine Late Permian and Early
sections difficult.

The record of marine Late Permian and Early Triassic time is best preserved on the shores of the Tethys. During that interval the Tethys was a wide western embayment of the Panthallasa Ocean, in which pieces of Gondwanaland (»Cimmerian Continent« of SENGOR, 1984) were beginning to rift and move northward (Fig. 1), eventually to collide with Asia in Late Triassic to mid-Jurassic time (MCELHINNY et al., 1981; LIN et al., 1985; SENGOR, 1984; SENGOR & HSU, 1984; LIVERMORE et al., 1986; BAUD & STAMPFLI, 1989). Consequently this region of the Tethys comprised both the old »Paleo-Tethys« to the northeast and an incipient newly opening »New-Tethys« to the southwest. We have analyzed many of the best studied sections of the Permian-Triassic across the Tethyan belt, from both the microplates of Cimmeria and the northern edge of Gondwanaland. Their carbon isotope profiles are compared to extract a common denominator of carbon isotopic variation in the Tethys Sea. This is the basis for our discussion of the geological and paleontological changes that marked this time interval. The data are charted according to the stratigraphic stages and biozones of Figure 2.

Sampling and Analysis

Whole rock samples were selected to minimize extraneous vein calcite. Thin section examination eliminated samples that had suffered coarse or extensive recrystallization. Isotope ratios for C and O in the carbonate were determined by the method of MAGARITZ & KAFRI (1981). The results were normalized against a laboratory standard calibrated against NBS 19, and presented using the conventional »δ« notation, relative to PDB. Reproducibility on replicated samples is better than 0.10‰ for $\delta^{13}C$.

The results are presented as carbon isotope profiles. No attempt will be made here to interpret the corresponding data for ^{18}O, which is much more susceptible to diagenetic alteration than is ^{13}C. This is because the oxygen system is dominated by the oxygen of the altering water, while the carbon system is dominated by the carbon of the carbonate rock, as has been shown in numerous case studies (e.g.

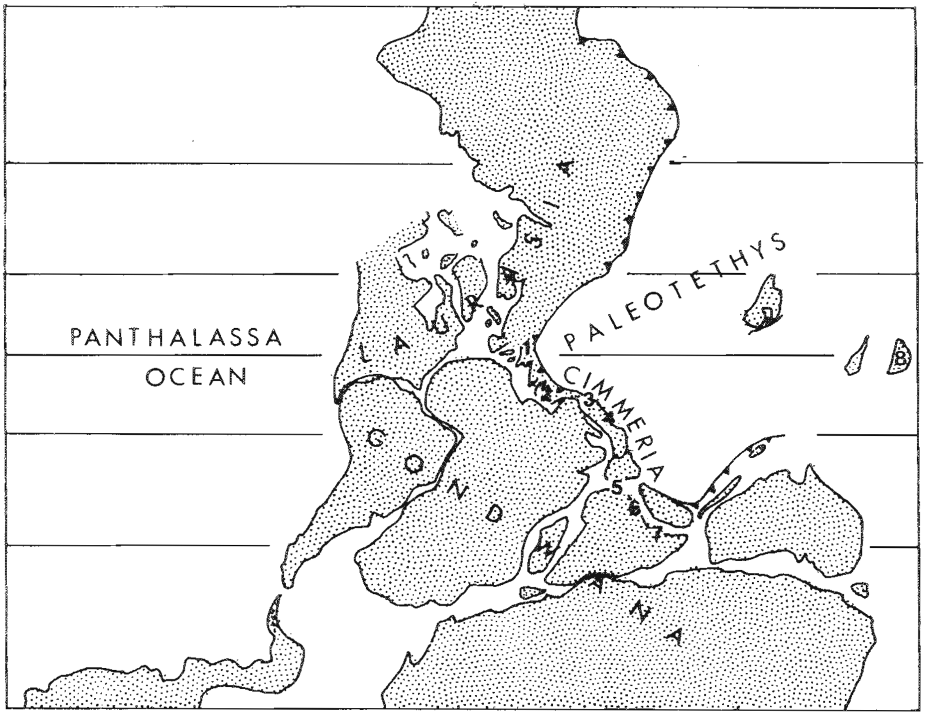


Fig. 1. Paleogeography of the Tethys at the P/Tr boundary, adapted from SENGOR (1985). Segments of the Cimmerian continent are beginning to rift away from the northern border of the main Gondwana continent; during Triassic time they will be crossing the Tethys Sea, then collide with Laurasia as Paleo-Tethys is consumed. The locations of sections analyzed or discussed in this paper are indicated by numbers as follows: 1. Southern Alps – Idrijca River, Yugoslavia; 2. Salamis, Greece, and Antalya – Çürük Dağ and Kemer Gorge, Turkey; 3. Transcaucasus – Kuh-e-Ali Bashi, Iran, and Vedi and

or discussed in this paper are indicated by numbers as follows: 1. Southern Alps – Idrijca River, Yugoslavia; 2. Salamis, Greece, and Antalya – Çürük Dağ and Kemer Gorge, Turkey; 3. Transcaucasus – Kuh-e-Ali Bashi, Iran, and Vedi and

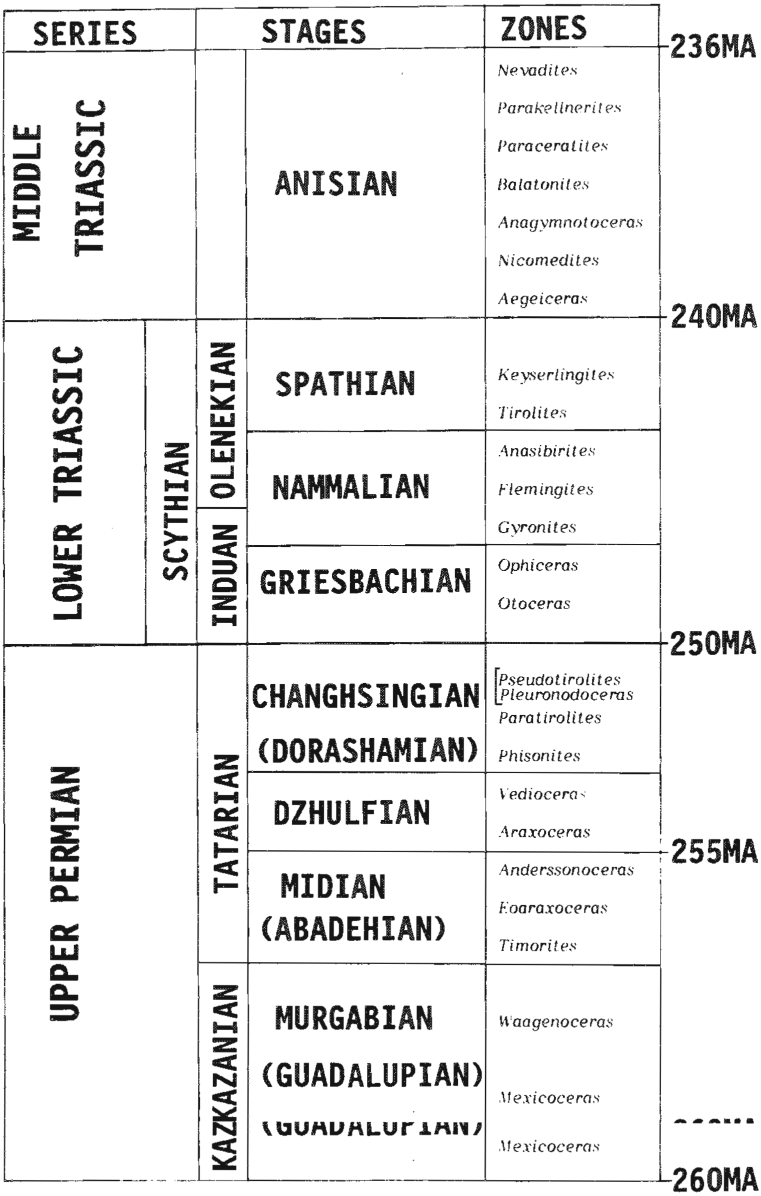
Sovetashen, Armenian SSR (see Fig. 3); 4. Elburz Mts. – Emarat, Iran; 5. Salt Range – Nammal Gorge, Pakistan; 6. Zanskar Himalayas – Thongde, India; 7. Nepal Himalayas – Thakkhola; 8. South China Block – Shangsi, Guangyuan, and Meishan, Changhsing, China. The South China Block may have been much farther west in Tethys (LIN et al., 1985).

Magaritz, 1975). In a model calculation assuming typical isotope parameters, Magaritz (1983) found that although oxygen isotope ratios were affected at even very low water/rock ratios, carbon isotope ratios were not appreciably changed (decreased) until the water/rock ratio was raised to 1000 or more. Overall correlative shifts of $\delta^{13}C$ with $\delta^{18}O$ were not found in our sections, indicating that even if $\delta^{18}O$ was altered by diagenesis, $\delta^{13}C$ was not similarly effected.

Sections in the Tethyan Cimmerides

Overview

The Cimmerides occupy a key central position in the geology of the western part of the Tethys belt (Fig. 1). The Transcaucasus area was on the western edge, and the Elburz Mts. area was on the northern edge, of the Iranian plate – a principal unit of Cimmeria – facing the southwestern margin of Paleotethys. The Permian-Triassic of the Trans-



SERIES		STAGES		ZONES	
MIDDLE TRIASSIC			ANISIAN	*Nevadites* *Parakellnerites* *Paraceratites* *Balatonites* *Anagymnotoceras* *Nicomedites* *Aegeiceras*	236MA 240MA
LOWER TRIASSIC	SCYTHIAN	OLENEKIAN	SPATHIAN	*Keyserlingites* *Tirolites*	
			NAMMALIAN	*Anasibirites* *Flemingites* *Gyronites*	
		INDUAN	GRIESBACHIAN	*Ophiceras* *Otoceras*	250MA
UPPER PERMIAN		TATARIAN	CHANGHSINGIAN (DORASHAMIAN)	[*Pseudotirolites* [*Pleuronodoceras* *Paratirolites* *Phisonites*	
			DZHULFIAN	*Vedioceras* *Araxoceras*	255MA
			MIDIAN (ABADEHIAN)	*Anderssonoceras* *Eoaraxoceras* *Timorites*	
		KAZKAZANIAN	MURGABIAN (GUADALUPIAN)	*Waagenoceras* *Mexicoceras* *Mexicoceras*	260MA

Fig. 2. Stratigraphic time scale for Late Permian and Triassic time; ages of boundaries (not to any linear scale) adapted from Haq et al. (1987).

caucasus includes several important sections, some in Soviet Armenia of which we studied Sovetashen, Vedi-1 and Vedi-2, and others in northwestern Iran of which we studied Kuh-e-Ali Bashi-1, -2 and -4 (Fig. 3). The stratigraphic correlations among these and other sections in this region are illustrated by Kotlyar et al. (1984) and in detail show considerable variation in their representation of the biostratigraphic zones of the latest Permian. The corresponding stratigraphy in the Elburz Mountains is described by Altiner et al. (1979) and Jenny-Deshusses (1983).

Transcaucasus: Kuh-e-Ali Bashi (Julfa, Iran)

This locality (KAB) is in northwestern Iran near the classical sections of Dzhulfa and Dorasham in Nakhichevan ASSR (Fig. 3). Here, strata with a typical Dzhulfian ammonoidae fauna are overlain by a sequence of red nodular limestone and marl – the Ali Bashi Formation (Teichert et al., 1973), its top part a red ammonoidae rosso limestone containing *Paratirolites* (Fig. 4). These limestones are capped by a red marly boundary bed, 0.5 to 1 m in thickness. The age of the Ali Bashi Formation had been discussed by Teichert et al. (1973) and Rostovtsev & Azaryan (1973); the latter proposed these beds as representing a final Dorashamian Stage of Permian time with stratotype at Dorasham, corresponding exactly to the Ali Bashi Formation. Later Zakharov (1985) worked on the red boundary marls at Dorasham, and identified *Pseudotirolites sp.*, an ammonoid that belongs to the youngest Permian biozone in the Changxing Formation in southern China. Thus the KAB section includes the final stage of the Permian, and the youngest biozone of that stage. This is overlain by the Elika Formation described by Baud et al. (1974), which has been dated with *Ophiceras* fauna as Late Griesbachian (Rostovtsev & Azaryan, 1973). Evidently even in this section the lowermost part of the Triassic – the Lower Griesbachian – is absent.

For our geochemical studies we were fortunate to be able to use the actual samples collected by B. Kummel for the Permian part (Teichert et al., 1973) and by Baud, Brönnimann & Zaninetti (1974) for the Triassic part; both were described by Baud (Altiner et al., 1979). Stable isotope results (Fig. 4) show $\delta^{13}C$ enrichment of about +3.5 ‰ in the lower part of the Ali Bashi Formation – the lower three biozones. Values of $\delta^{13}C$ gradually decreased in the upper part of the formation to about +2.5 ‰. At the P/Tr boundary $\delta^{13}C$ drops by 2.5 ‰ in the boundary red marls, and the low values of $\delta^{13}C$ continue through the lower 40 m of the limestone unit of the Elika Formation (= Unit 1 in Baud et al. 1974 – Late Griesbachian), after which an increase of 1.5 ‰ occurs. Two other

Fig. 3. Localities sampled in the Transcaucasus region.

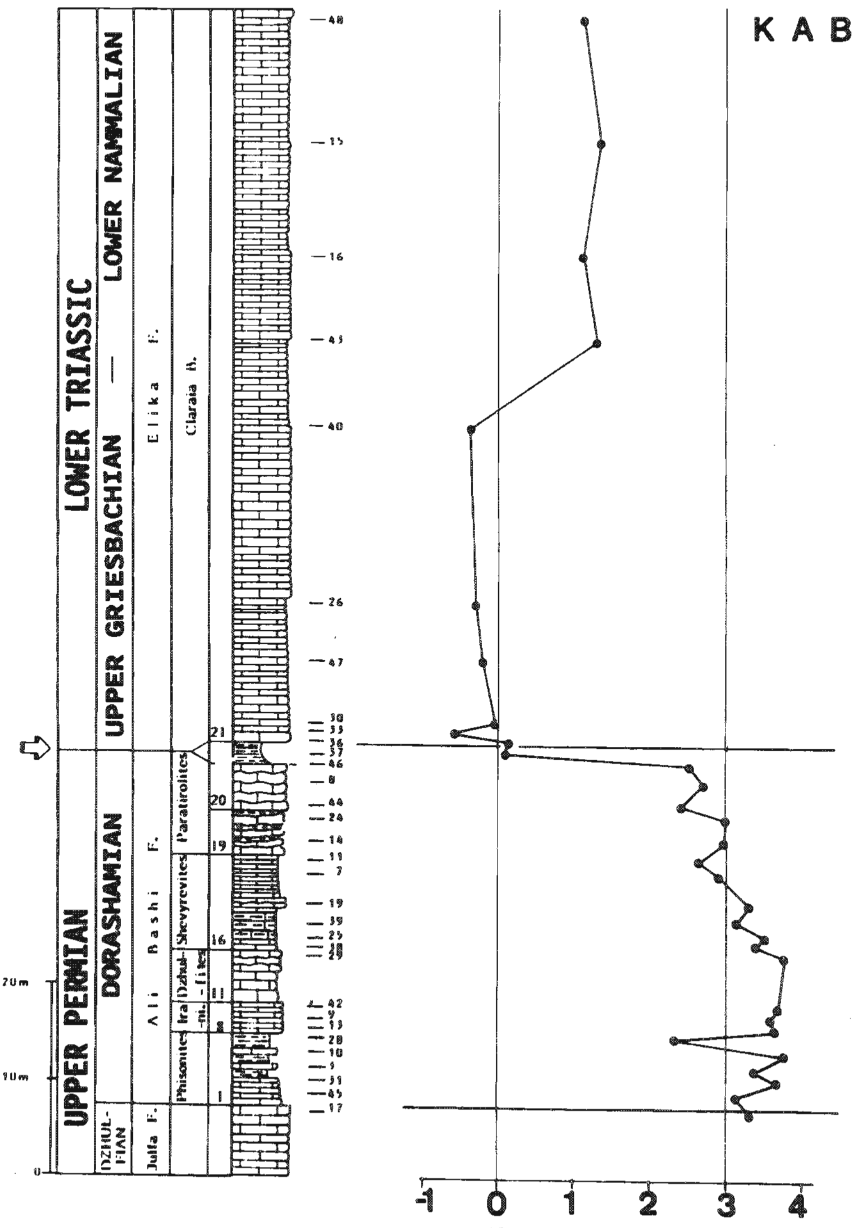


Fig. 4. Carbon isotope profile at Kuh-e-Ali Bashi-1, north-western Iran. The arrow indicates a hiatus in the Lower Griesbachian; the underlying top part of the Dorashamian is highly condensed.

sections (KAB-2 and -4) only sampled the top of the
Transcaucasus: Vedi (Armenian SSR)

sections (KAB-2 and -4) only sampled the top of the Ali Bashi Formation, and they show high values of δ ^{13}C (about +3‰) similar to the section (KAB-1) illustrated in Figure 4.

Transcaucasus: Vedi (Armenian SSR)

Section Vedi-2 lies in the Armenian SSR 80 km northwest of KAB (Fig. 3). The section (KOTLYAR et al., 1984; ASLANIAN, 1984) begins in black cherty limestone of the Khachik Formation of Midian age, overlain by 17 m of gray nodular limestones of Dzhulfian age. After a hiatus, the upper Dorashamian Stage is represented by 6 m of gray nodular limestones of the *Shevyrevites* and *Paratirolites* Zones. A few cm of red marl marks the Permian-Triassic boundary, and may represent the final *Pleuronodoceras-Pseudotirolites* Zone of the Permian, as described at Dorasham. The lowermost bed of Triassic age consists of a cryptalgal buildup of domal stromatolite type. This is in turn overlain by thin-bedded gray limestones of the Kara Baglyar Formation (equivalent to the Elika Formation), containing *Ophiceras* and *Claraia* which indicate a Late Griesbachian age.

As displayed in Figure 5, the values of $\delta\,^{13}$C are +4‰ or more at the base of the sampled Midian. Two drops occurred in the Upper Midian, and values between +2‰ and +3‰ are maintained through the Dzhulfian. Sample 913 at $\delta\,^{13}C = -0.8$‰ is an exception, for reasons that are not apparent. In the top Dorashamian *Paratirolites* beds $\delta\,^{13}$C drops to +0.9‰ at the P/Tr boundary and to +0.5‰ a meter above the boundary, rising thereafter to +1.4‰.

Transcaucasus: Sovetashen (Armenian SSR)

This section is also in Armenian SSR, 15 km southwest of Vedi. The sedimentation and stratigraphy are similar to those at Vedi, except that here the *Paratirolites* Zone of the Dorashamian is thicker (KOTLYAR et al., 1984; ASLANIAN, 1984).

The carbon isotope profile at Sovetashen (Fig. 6) is more irregular than those at KAB (Fig. 4) and Vedi (Fig. 5). Study of the thin sections reveals that in the Dzhulfian part of the section all of the sampled rocks that showed low values of $\delta\,^{13}$C were dedolomitized. This later mineralogical alteration may have been accompanied by an isotopic exchange with water depleted in $\delta\,^{13}$C, as has been described in other cases of dedolomitization (MAGARITZ & KAFRI, 1981); these are charted as isolated points in Figure 6 and are disregarded in further discussions of the results. Below in the Midian part of the section we did not find any clear indications of alteration, although it may be present. Consequently the excursions seen in the Midian at Sovetashen remain ambiguous.

The isotope curve shows values near $\delta\,^{13}C = 3$‰ through the Dzhulfian and part of the Dorashamian, then a drop that begins in the *Paratirolites* Zone and continues into the lower part of the Triassic section, thereafter rising to over +1‰.

then a drop that begins in the *Paratirolites* Zone and continues into the lower part of the Triassic section,

Sample 80, with $\delta\,^{13}$C about −1‰, is from a 10-cm red marl at the very top of the Permian section. By its stratigraphic position this may represent a condensed equivalent to the *Pleuronodoceras* Zone as described above from Dorasham. But G. J. RETALLACK (pers. comm., 1984) described it as clearly a paleosol, so its low value of $\delta\,^{13}$C cannot confidently be assigned as a marine value for that zone.

Elburz Mountains, Iran: Emarat

Stratigraphy and sedimentation of the Permian-Triassic rocks of the Elburz Mountains, which lie 550 km southeast of KAB, were described by STAMPFLI (ALTINER et al., 1979). The section at Emarat was described by JENNY-DESHUSSES (1983), who collected and described the samples that we analyzed. The Emarat section exposes 300 m of the Dorud Formation of Early Permian (Middle Asselian) age (Emarat-1), 470 m of the Ruteh Formation of Middle to Upper Murgabian age (Emarat-2), and 120 m in a section (Emarat-3) that crosses the P/Tr boundary from the Nesen Formation of Midian to Dzhulfian age to the Elika Formation of Late Griesbachian age. OKIMURA et al. (1985) confirmed Lower Dzhulfian foraminifers in the Nesen Formation at this locality.

As shown in Figure 7, the Nesen Formation comprises nodular and cherty limestones interbedded with shales, capped by a bed of ferruginous breccia cemented by calcite. The Elika Formation begins with thick-bedded non-fossiliferous limestones with stylolitic partings, followed by thin-bedded ferruginous limestones containing *Claraia*.

Values of $\delta\,^{13}$C in the Asselian to Murgabian limestones of Emarat-1 (not shown) and −2 (Fig. 7) lie mostly in the range +3 to +5‰. Beginning 13 m below the top of the Nesen Formation, as exposed at the base of Emarat-3 (Fig. 7), $\delta\,^{13}$C drops from +3 across the P/Tr contact to −0.2 in the base of the Elika Formation. Values of $\delta\,^{13}$C stay between 0 and −1‰ through the first 60 m of the Elika Formation, after which they rise irregularly to near +1‰.

Sections on the Gondwana Margin

Southern Alps

The Permian-Triassic marine rocks exposed in classic sections of the southern Alps (Dolomites of Italy, Carnic Alps of Austria and Julian Alps of Yugoslavia) represent the westernmost extension of the Tethys Ocean, and were deposited along its southwestern shore (ASSERETO et al., 1973; Italian IGCP 203 Group, 1986). Some carbon isotope data from this area were presented in preliminary form by HOLSER & MAGARITZ (1985) and detailed studies are

are deposited along its south-
western shore (ASSERETO et al., 1973; Italian IGCP

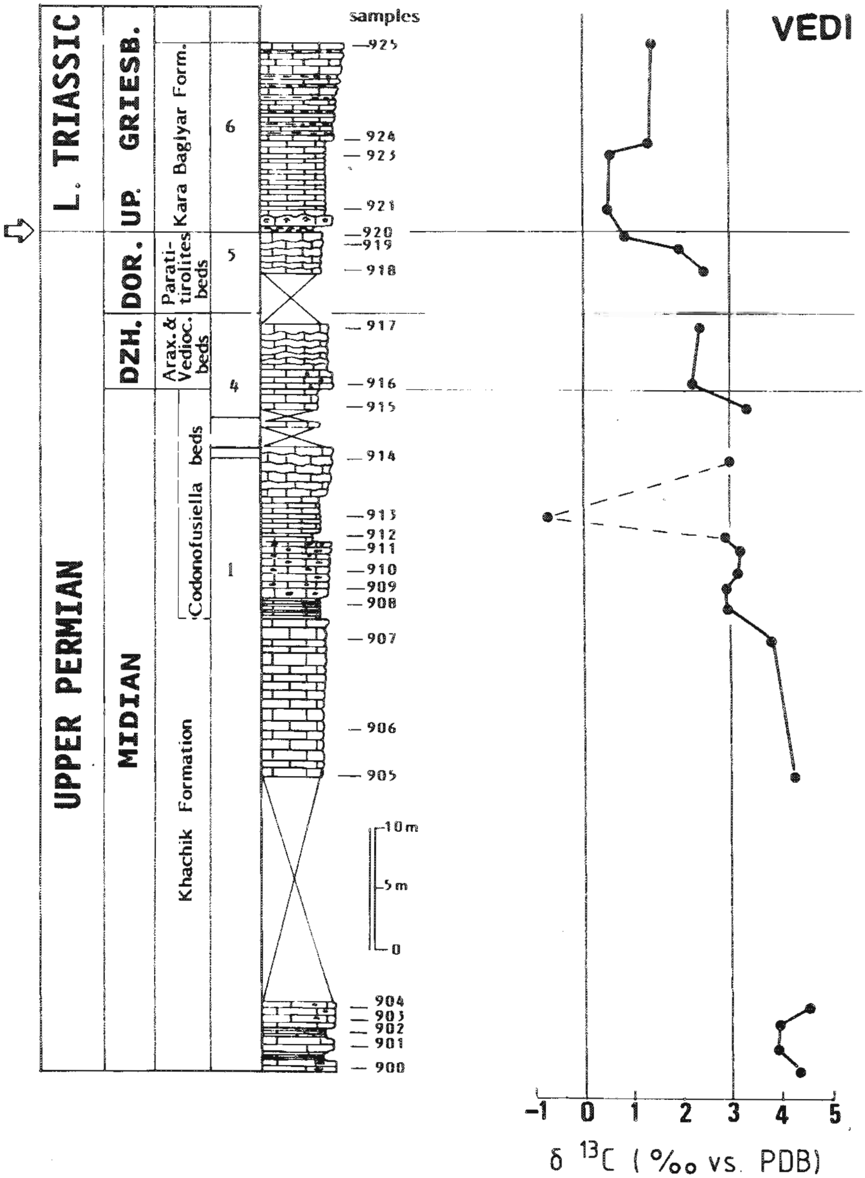


Fig. 5. Carbon isotope profile at Vedi-2, Armenian SSR. The arrow indicates a hiatus in the Lower Griesbachian.

published elsewhere (Magaritz et al., 1988; Holser et al., 1989). For comparison with other Tethyan sections, we include here a single section from the more marine part of the Alpine area, from Idrijca River, Yugoslavia (Fig. 8). In the section described by Ramovs (1986), we have sampled 15 m of black

Yugoslavia (Fig. 8). In the section described by Ramovs (1986), we have sampled 15 m of black

biomicritic limestone of the Upper Permian Zazar Beds, and 10 m of gray dedolomitized limestones of the Lower Triassic Scythian beds. The Zazar Beds correspond to the Bellerophon Formation in other parts of the southern Alps, which is definitely Upper Permian and in its upper part Dorashamian (Neri et al., 1986). The overlying Scythian in the southern Alps is of Griesbachian age (Broglio-Loriga, 1986), but whether it includes the lowermost zone of

Alps is of Griesbachian age (Broglio-Loriga, 1986), but whether it includes the lowermost zone of

the Griesbachian is not determined.

In the Idrijca River section δ ^{13}C remains high (+3 to +4‰) through most of the Permian Zazar Beds.

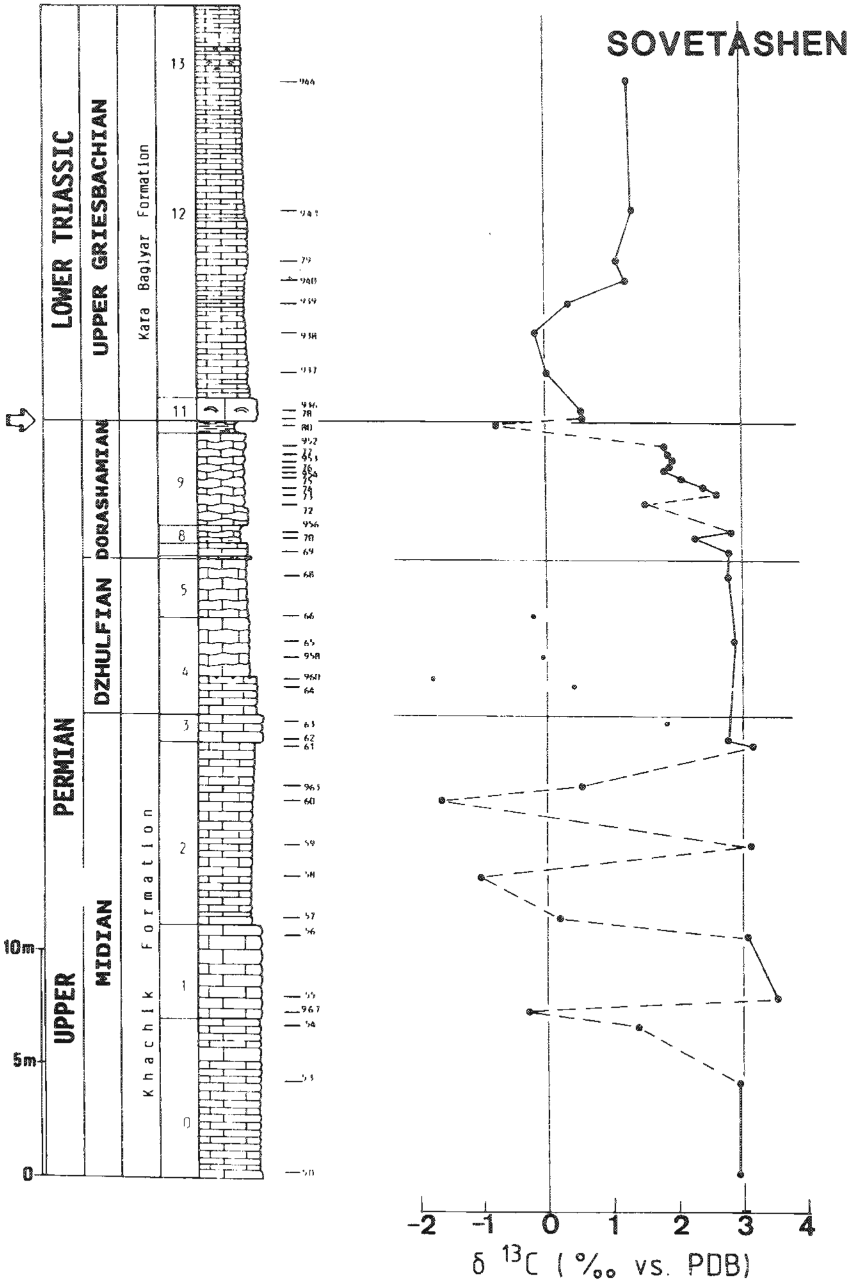


Fig. 6. Carbon isotope profile at Sovetashen, Armenian SSR. The arrow indicates a hiatus in the Lower Griesbachian. Small filled circles are analyses on dedolomitized samples. Dashed lines are questionable – see text.

Starting in the Permian and continuing in the Triassic,

Starting in the Permian and continuing in the Triassic, δ ^{13}C drops – to −1‰ in the last sample analyzed, through 10 m across the P/Tr boundary, in this case apparently unaffected by dedolomitization.

Antalya, Western Turkey

Antalya, Western Turkey

The analyzed profiles are in the Antalya nappes, at Çürük Dağ 15 km northwest of Kemer, and the

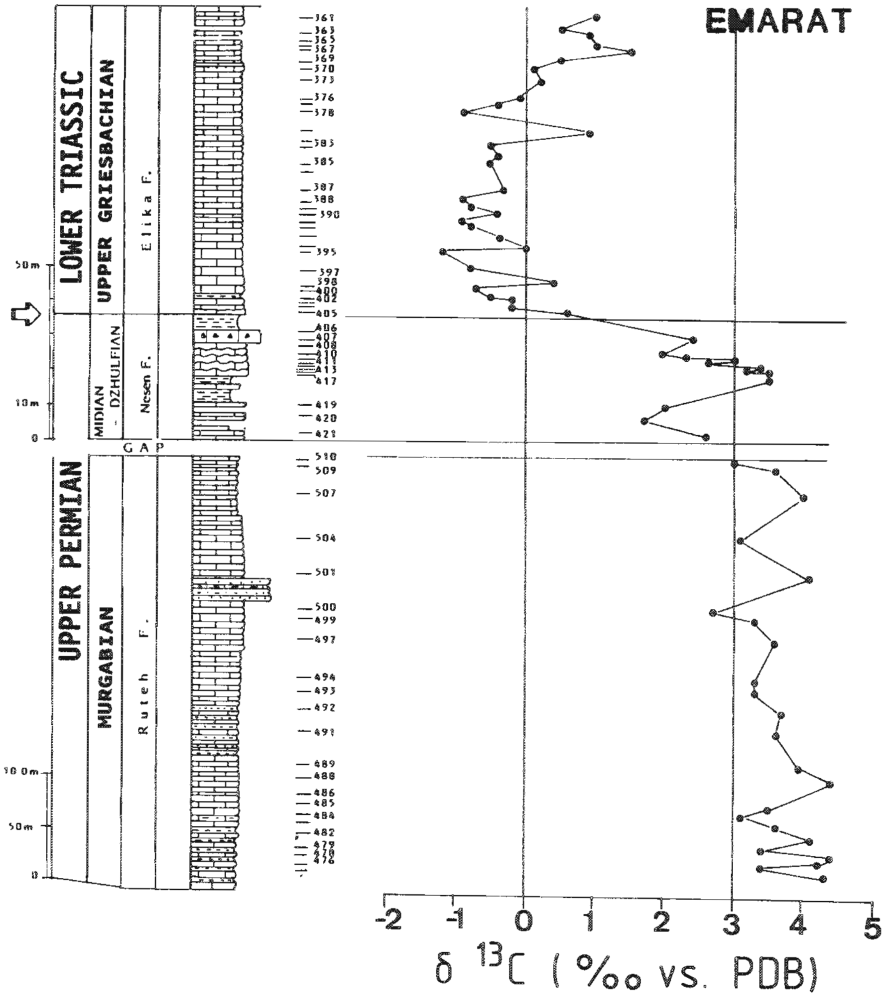


Fig. 7. Carbon isotope profiles at Emarat-2 (below the gap) and -3 (above the gap – note larger scale) on the northern slope of the Elburz Mountains, northern Iran; stratigraphy and sampling by JENNY-DESHUSSES (1983): The arrow indicates a hiatus in the Lower Griesbachian.

Kemer Gorge, 6 km west of Kemer. The general stratigraphy was described by LYS & MARCOUX (1978), and the Çürük Dağ section will be described by MARCOUX & BAUD (1988; see also MARCOUX et al., 1986). Micropaleontology has been studied by M. Lys, and the details of paleontology for the section at Çürük Dağ were worked out by C. Jenny-Deshusses. Additional stratigraphical information based on brachiopod determinations was communicated by K. NAKAMURA (pers. commun., 1986).

The Dzhulfian Pamucak Formation is a bedded
cated by K. NAKAMURA (pers. commun., 1986).

The Dzhulfian Pamucak Formation is a bedded wackestone with foraminifers and calcareous algae, topped at Çürük Dağ by a few cm of oolitic packstone, and by a pedogenic calcrete at the P/Tr boundary. The overlying Late Griesbachian to Spathian Katarasi Formation comprises light, well-bedded limestones and domal stromatolites, and higher up oolitic grainstone followed by variegated limestone and marl (Fig. 9). Although the bedding is parallel in these outcrops, a disconformity is apparently present: the Dzhulfian Pamucak Formation is incomplete, the Dorashamian and Early Griesbachian are missing, and the calcrete at the P/Tr boundary indicates subaerial exposure.

At Çürük Dağ the general section was sampled by
cates subaerial exposure.

At Çürük Dağ the general section was sampled by J. Marcoux, and a detailed boundary section was sampled by Baud & Holser. The sections and their isotope results are shown in Figures 9A and 9B,

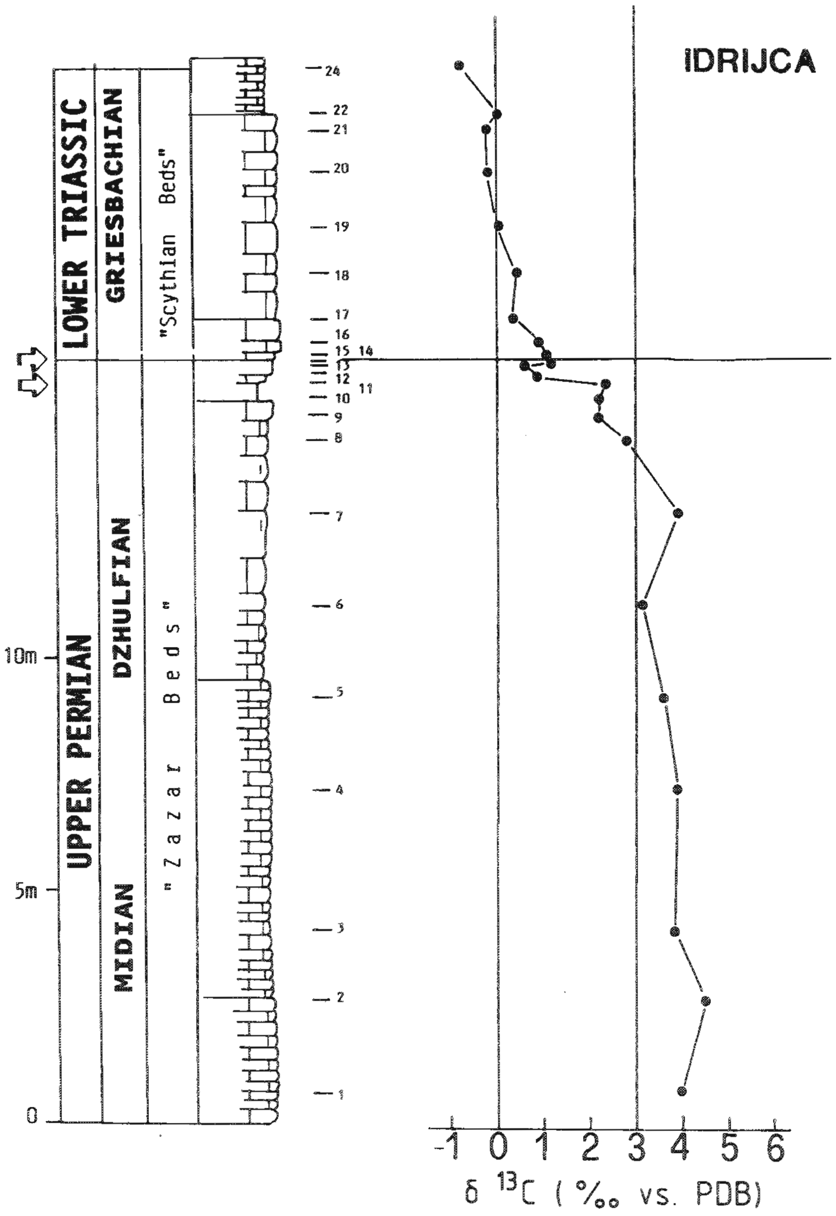


Fig. 8. Carbon isotope profile at Idrijca River, western Yugoslavia. The lower arrow indicates a hiatus in the Lower Dzhulfian; the upper arrow indicates a possible hiatus in the Lower Dorashamian.

respectively. In general the Dzhulfian limestones are enriched in δ ^{13}C (δ ^{13}C > +4‰), and the Lower Triassic rocks are relatively depleted with δ ^{13}C of about +1‰. In detail (Fig. 9B) δ ^{13}C declines gradually from +4.5‰ at the base of the sampled section to about +3.5‰ near the boundary. The transition across the P/Tr boundary is rather abrupt, dropping sharply through about 1 m across the disconformity. However, intermediate values during the drop (six analyses – Fig. 9B) suggest that this one-meter section may include condensed deposition during part of the disconformity interval.

Triassic rocks are relatively depleted with δ ^{13}C of about +1‰. In detail (Fig. 9B) δ ^{13}C declines gradu-

analyses – Fig. 9B) suggest that this one-meter section may include condensed deposition during part

The Kemer Gorge sections on both sides of the gorge were sampled by J. Marcoux (Figs. 10A, 10B).

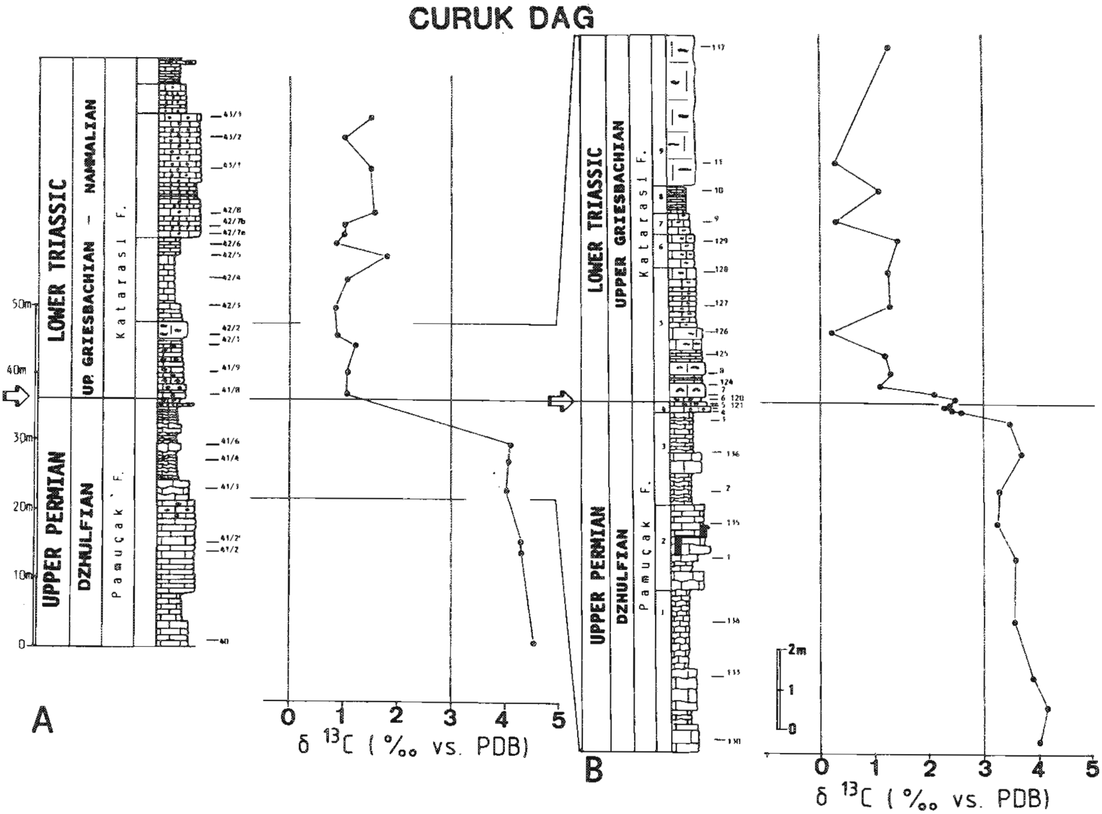


Fig. 9. Carbon isotope profile at Çürük Dağ, Antalya, south-western Turkey: (A) Overall section; (B) P/Tr boundary interval sampled in greater detail. The arrow indicates a hiatus in the Dorashamian and possibly in the Lower Griesbachian.

The Pamucak Formation is very similar to that at Çürük Dağ. The Katarasi Formation shows some differences: The basal 10 m is oolitic wackestone to packstone-grainstone followed by 6 m of yellow to reddish marls. The carbon isotope data are generally similar to those at Çürük Dağ. The drop in δ ^{13}C again occurs in not much more than a meter across the stratigraphic P/Tr boundary, and there is one intermediate value in this more coarsely sampled section.

Salt Range, Pakistan: Nammal Gorge

In Permian time the present area of the Salt Range of northern Pakistan lay along the northern border of the Gondwana continent (Fig. 1). Our samples are from one of the classic sections, at Nammal Gorge. In the Upper Permian the Chhidru Formation overlies the Wargal Formation conformably, and is in turn

In the Upper Permian the Chhidru Formation overlies the Wargal Formation conformably, and is in turn

overlain by the (mainly Lower Triassic) Kathwai and Mittiwali Members of the Mianwali Formation (KUMMEL & TEICHERT, 1970; PAKISTANI-JAPANESE RESEARCH GROUP, 1985) (Fig. 11). The uppermost Wargal Formation – the Kalabagh Member – is composed mostly of limestone with chert nodules. The Chhidru Formation is divided into four sub-units, increasing in quartzitic sand upwards. The main components of the lower part of this formation are mudstones, with limestone horizons (Fig. 11). The Kathwai Member is a dolostone and calcareous sandstone at its base, and bedded limestone at the top. The Mittiwali Member comprises alternating limestone and mudstone. Detailed stratigraphy and paleontology are given by the PAKISTANI-JAPANESE RESEARCH GROUP (1985).

The age of the Kalabagh Member of the Wargal Formation is Lower Dzhulfian, based on its foraminifer and conodont assemblage (PAKISTANI-JAPANESE RESEARCH GROUP, 1985). A Dzhulfian age (probably Late Dzhulfian) was suggested for the

JAPANESE RESEARCH GROUP, 1985). A Dzhulfian age (probably Late Dzhulfian) was suggested for the

Chhidru Formation; there is no paleontological evidence for Dorashamian rocks in this formation (PAKISTANI-JAPANESE RESEARCH GROUP, 1985). The

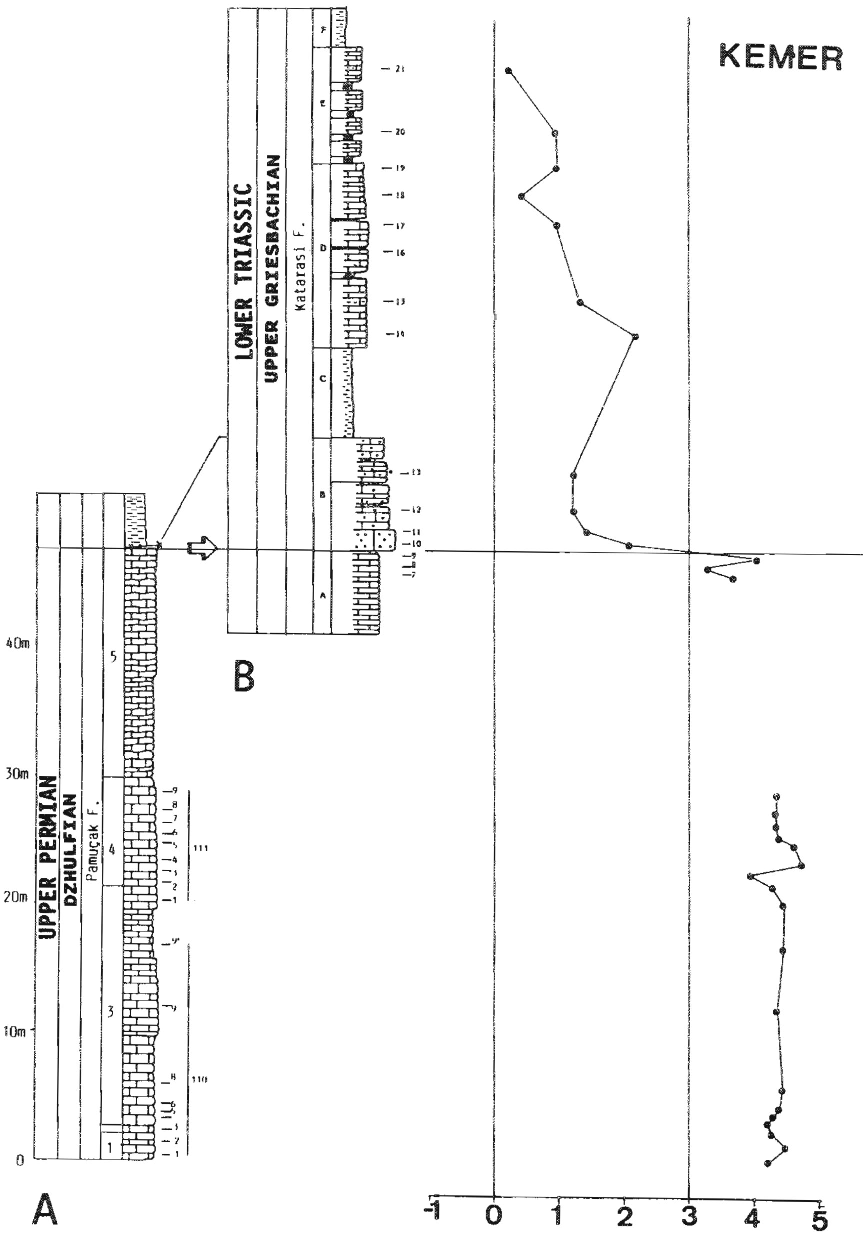
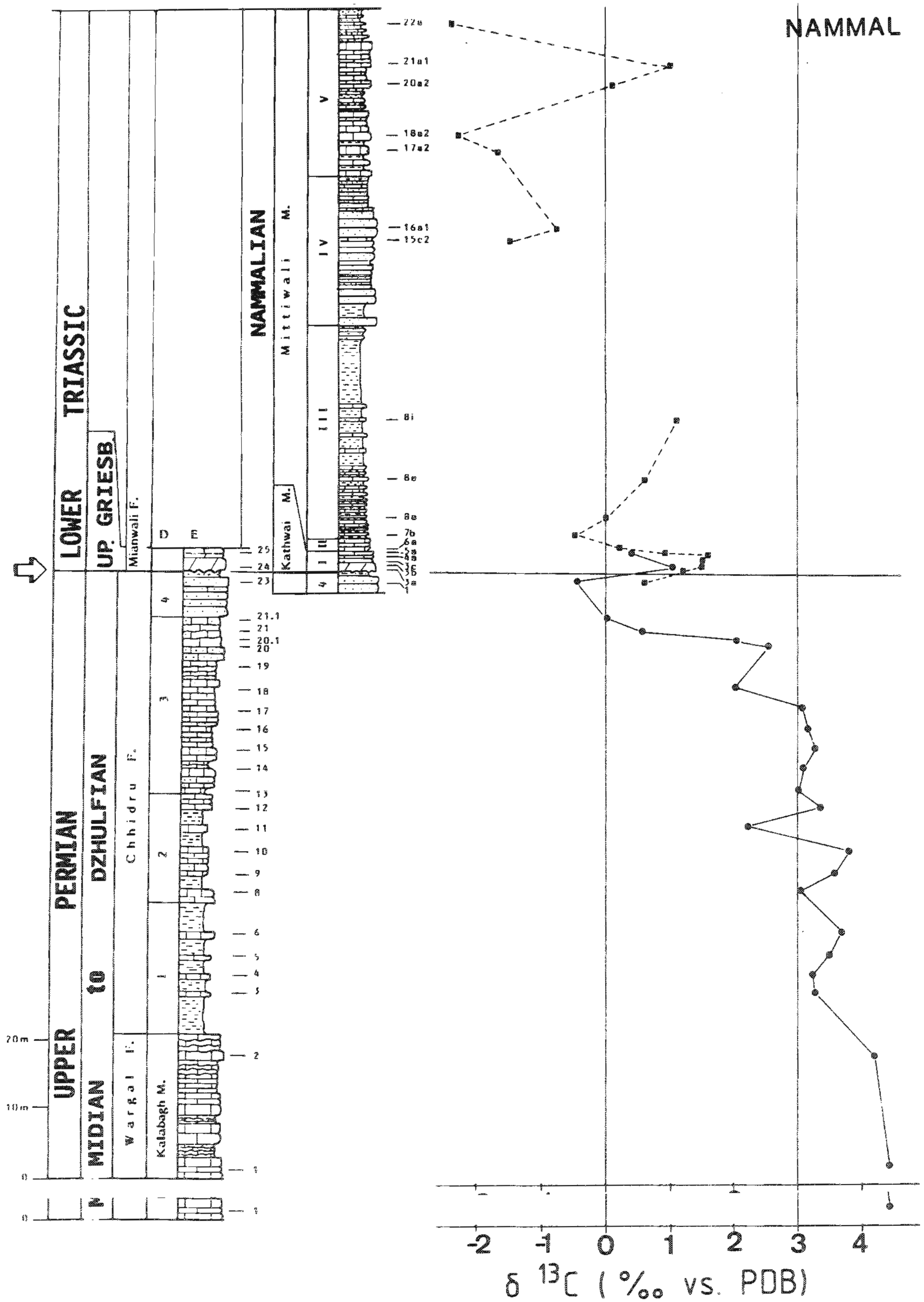


Fig. 10. Carbon isotope profiles at Kemer Gorge, Antalya: (A) western side and (B) eastern side. The arrow indicates a hiatus in the Dorashamian and the Lower Griesbachian.

»Lower Unit« of the Kathwai Member may be latest Dorashamian, according to the Pakistani-Japanese Research Group. This Permian part of the Kathwai Member, which is only about 10 cm thick at Nammal Gorge (Pakistani-Japanese Research Group, 1985, Fig. 14) is too thin to be distinguished on our Figure 11. The upper part of the Kathwai Member is Late Griesbachian in age, so at least a part of the Lower Griesbachian rocks is missing. The overlying Mittiwali Member is Nammalian in age (Guex, 1978). We

»Lower Unit« of the Kathwai Member may be latest Dorashamian, according to the Pakistani-Japanese

Fig. 14) is too thin to be distinguished on our Figure 11. The upper part of the Kathwai Member is Late Gries-


NAMMAL
LOWER TRIASSIC
UPPER PERMIAN
UP. GRIESB
NAMMALIAN
DZHULFIAN
MIDIAN
10
Mianwali F.
Chhidru F.
Wargal F.
Kathwai M.
Mittiwali M.
Kalabagh M.
D
E
I
II
III
IV
V
1
2
3
4
20m
10m
0
22a
21a1
20a2
18a2
17a2
16a1
15c2
8i
8e
8a
7b
6a
5a
4a
3c
3b
3a
25
24
23
21.1
21
20.1
20
19
18
17
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14
13
12
11
10
9
8
6
5
4
3
2
1
-2
-1
0
1
2
3
4
δ 13C (‰ vs. PDB)

suggest that this sequence represents at least two large regression-transgression cycles: from the base of the Wargal to the top of the Chhidru Formations and from the base to top of the Mianwali Formation.

We analyzed two sets of samples (Fig. 11): one mainly of the Permian Chhidru Formation collected by J. B. Maynard, and one of the Triassic Mianwali Formation collected by Baud. The carbon isotope profile (Fig. 11) shows a gradual decline from $\delta^{13}C = +4.5$ ‰ in the Upper Wargal Formation to +2 ‰ near the top of Unit 3 of the Chhidru Formation. Carbon isotope levels in the Mittiwali Member are variable in the range −2 to +2‰. The drop, through the upper part of the Chhidru Formation and the Kathwai Member, is complex. An initial drop to −0.5‰ occurs in calcareous sandstones of Units 3 and 4 of the Chhidru Formation, and may represent only diagenetic cement; low boron content at this horizon suggests a fresh-water inflow to the basin (Pakistani-Japanese Research Group, 1985). In the Kathwai Member of the Mittiwali Formation the two sample sets agree that $\delta^{13}C$ is near +1 ‰ in the lowest level sampled (Dorashamian ?), dropping to about zero near the boundary with the Mittiwali Member. The Pakistani-Japanese Research Group (1985) found the P/Tr boundary between the Lower and Middle Units of the Kathwai Member. If we discount as non-marine the low values in the top part of the Chhidru Formation, then the P/Tr boundary is crossed during a sharp drop in $\delta^{13}C$, at a value of about +1.2‰. Results of a resampling in greater detail will be presented in a future publication.

Zanskar, Western Himalayas, India

The Zanskar area of the western Himalayas was situated during Permian time on the distal northern margin of India (at that time part of the Gondwana continent), 400 km east of the Salt Range area (Fig. 1). The P-Tr sequence comprises the Kuling Formation of Dzhulfian to Dorashamian age and the Tamba Kurkur and Hanse Formations of Early to Middle Triassic age (Fig. 12). The base of the Tamba Kurkur Formation is composed of limestones alternating with sandy sericitic shales; limestones increase upwards. The age ranges from Lower Griesbachian at the base, through Nammalian and Spathian to all of the Anisian in the upper part of the formation. The overlying Hanse Formation is composed of gray marls and black platey thin-bedded limestones of Late Ladinian age (Baud et al., 1984; Nicora et al., 1984).

Samples for analysis were taken from two sections of the Tamba Kurkur limestones. Carbon isotope results for the most complete section (Fig. 12) show values about 0 ‰, with a general trend of $\delta^{13}C$ enrichment up to +1 ‰ between the lower, shaly part of the Tamba Kurkur Formation and its upper part. Only one Permian sample was analyzed, of a carbonate-rich layer in the quartz arenite of the Kuling Formation.

Nepal Himalayas: Thakkhola

The Thakkhola area lies in north-central Nepal north of the Main Central Thrust and south of the Neo-Tethys suture zone, on what was the northern margin of Gondwana, 700 km east of Zanskar. The stratigraphy of the poorly exposed Permian-Triassic interval has been described by Bassoullet & Mouterde (1977), Waterhouse (1979), Kapoor & Takuoka (1985), and others. The sections and samples that we analyzed were described by Hatleberg (1982; Hatleberg & Clark, 1984), who determined the conodont fauna in the same samples.

The section begins with the red sandstone of the Nisal Member (of the Senja Formation) of Dorashamian age (Waterhouse, 1978), but this formation was not analyzed. It is overlain by about a meter of red microdolomite of the Panjang Formation, which is dated as Early Griesbachian on evidence of both ammonoids (Waterhouse, 1977) and conodonts (Hatleberg & Clark, 1984), although brachiopods concentrated in the base of the bed are of Permian aspect (Waterhouse, 1979). The Panjang Formation is overlain by a meter of basal limestones of the Thinigaon Formation, which is also of Griesbachian age, probably Early Griesbachian. Together the Panjang Formation and the basal Thinigaon Formation have a very close resemblance to the Kathwai Formation of the Salt Range (Hatleberg & Clark, 1984). In both areas the sequences from sandstones through red dolomites to thin wavy-bedded limestones with their associated changes of fauna are ascribed to a rapid transgression (Kapoor & Tokuoka, 1985).

Six samples from four outcrops of the Panjang Formation gave $\delta^{13}C = -0.8 \pm 0.7$‰, and four samples from three of these outcrops of the basal Thinigaon Formation gave -1.4 ± 0.6‰, with no significant trends.

Hanse Formation is composed of gray marls and trends.

◀ Fig. 11. Carbon isotope profile at Nammal Gorge, Salt Range, Pakistan. Sections independently sampled by J. B. Maynard (solid line) and A. Baud (dashed line). The arrow indicates a hiatus in the Dorashamian and in the Lower Griesbachian.

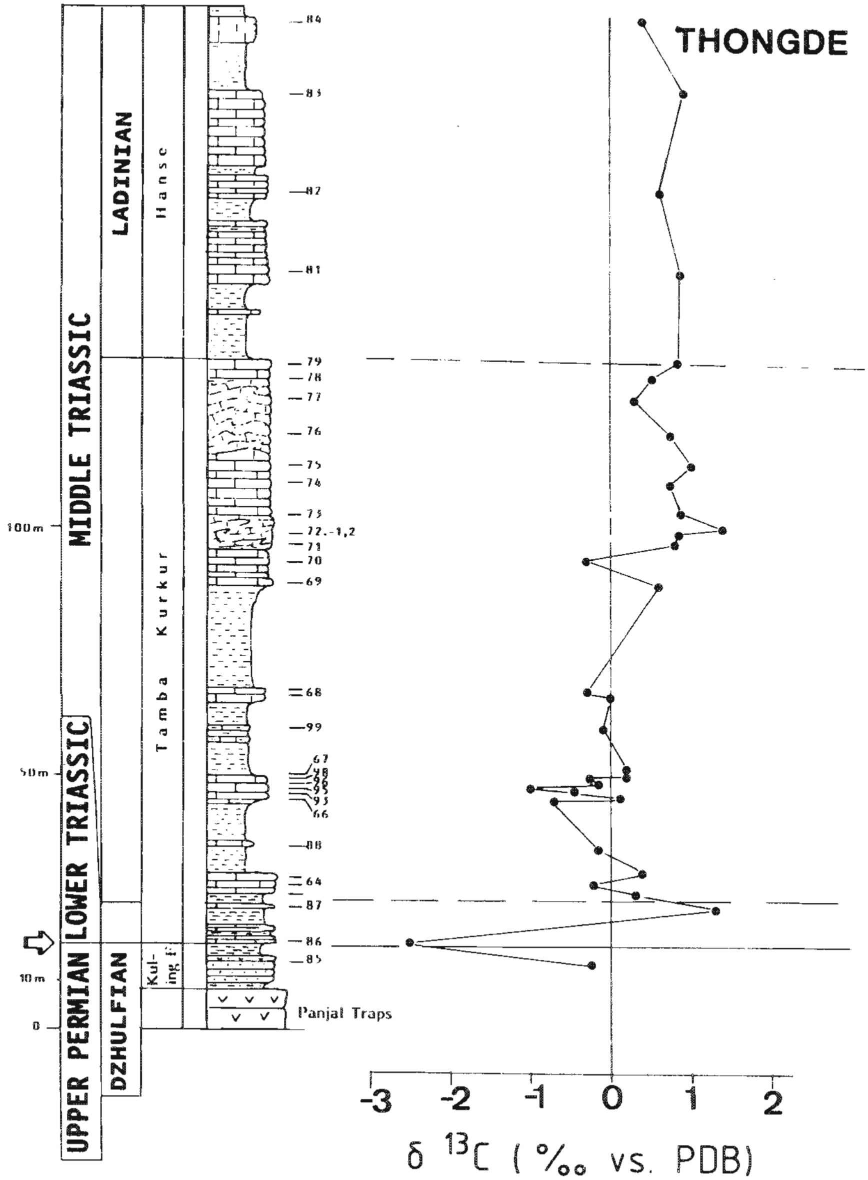

Fig. 12. Carbon isotope profile at Thongde, Zanskar Himalayas, India. Lithology and stratigraphy after NICORA et al. (1984); sampling by Baud, Gaetani and Nicora. The arrow indicates a hiatus in the Dorashamian.

Sections in Other Paleogeographical Situations

China: Shangsi (Guangyuan, Sichuan Province)

Sections were sampled for isotope analysis in two

Sections were sampled for isotope analysis in two areas of China: Shangsi on the northwestern edge of the South China (Yangtze) Block, and Meishan near the northeastern corner of the same tectonic unit. In Late Permian time this block lay near the equator in the midst of the Paleo-Tethys Sea (LIN et al., 1985; OPDYKE et al., 1986); much of its area was the site of P-Tr marine deposition (SHENG et al., 1985).

The Upper Permian section at Shangsi (LI et al.,
P-Tr marine deposition (SHENG et al., 1985).

The Upper Permian section at Shangsi (LI et al., 1984, 1986; XU et al., 1985) is composed of basinal facies carbonates with abundant chert concretions (Fig. 13). For 4 m around the stratigraphic P/Tr boundary the dark siliceous limestones are interbedded with light-colored claystones that may be of volcanic origin (Li et al., 1986; Zhou, 1987). The boundary is also marked by a shallowing of sedimentation to gray medium-bedded micrites of a tidal-flat facies. The sections seem to be complete and conformable,

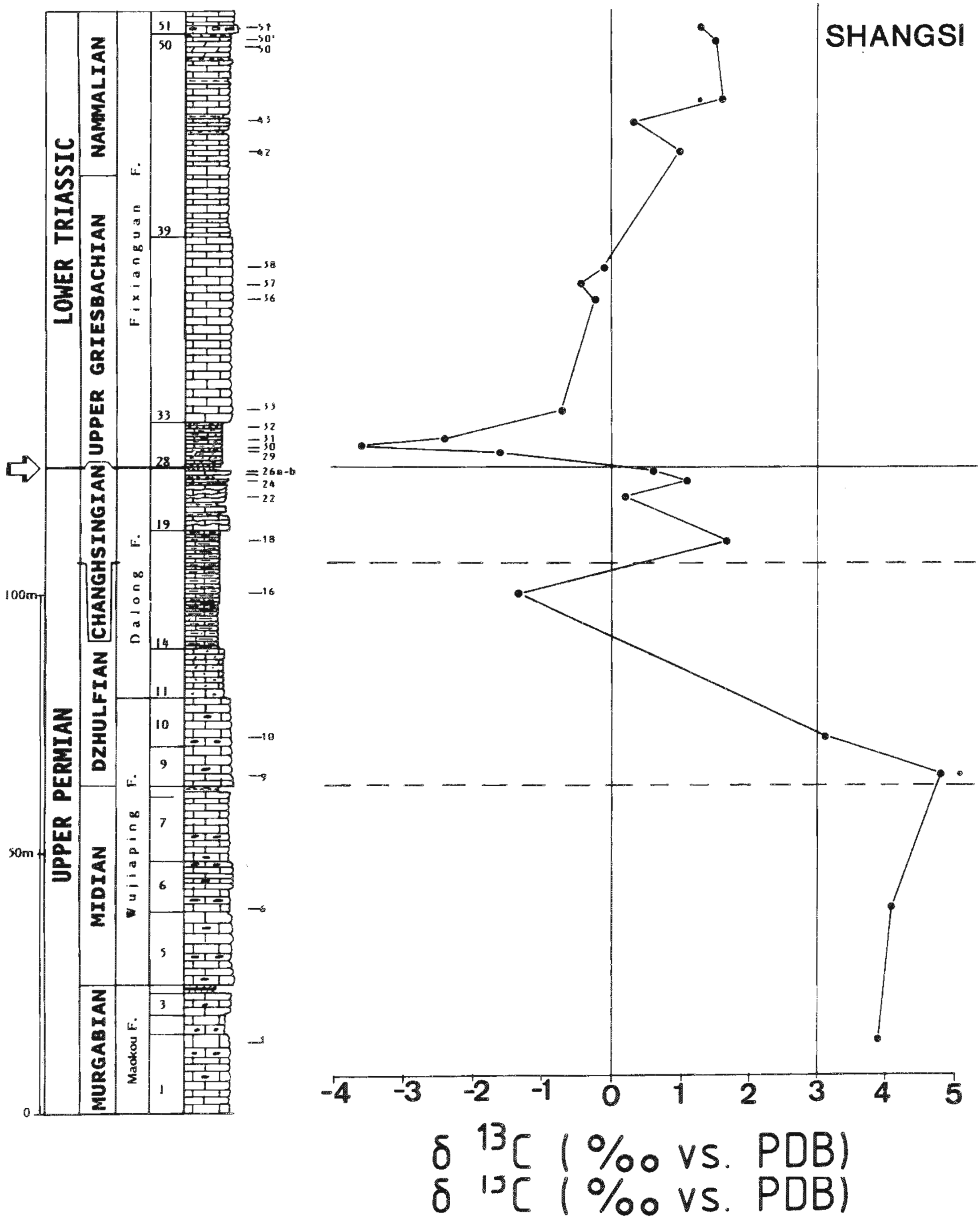

Fig. 13. Carbon isotope profile at Shangsi, China. Small dots are additional samples from the same horizon. See also a more detailed profile of the same section published by Li et al. (1986). The arrow indicates a hiatus in the Lower Griesbachian.

although only two biozones (*Tapanashites*, and *Pseudotirolites-Pleuronodoceras*) can be distinguished in the Changhsingian (= Dorashamian) (Fig. 2), and the Lower Griesbachian is less than half a meter thick. The Permian of the Shangsi section is highly fossiliferous (e.g. ammonoids, conodonts), but both diversity and abundance decline rapidly in the highest beds for the Changhsingian; one Permian ammonoid and four conodont species survive into a 16-cm mixed zone at the very base of the Triassic (LI et al., 1986).

LI et al. (1986) published a detailed carbon isotope profile from about 70 samples ranging from Midian to Dienerian in age; our profile of 20 samples (Fig. 13) complements and confirms those data. The drop in δ ^{13}C begins in the Dzhulfian, and continues through the Changhsingian and the lowermost Triassic, reaching a minimum of −4 ‰ in the Upper Griesbachian and rising again to over +1 ‰ in the Dienerian (Fig. 13; LI et al., 1986). Some of the low values in the Dhzulfian, shown in both samplings, may be due to a partial oxidation of the very high content of organic carbon

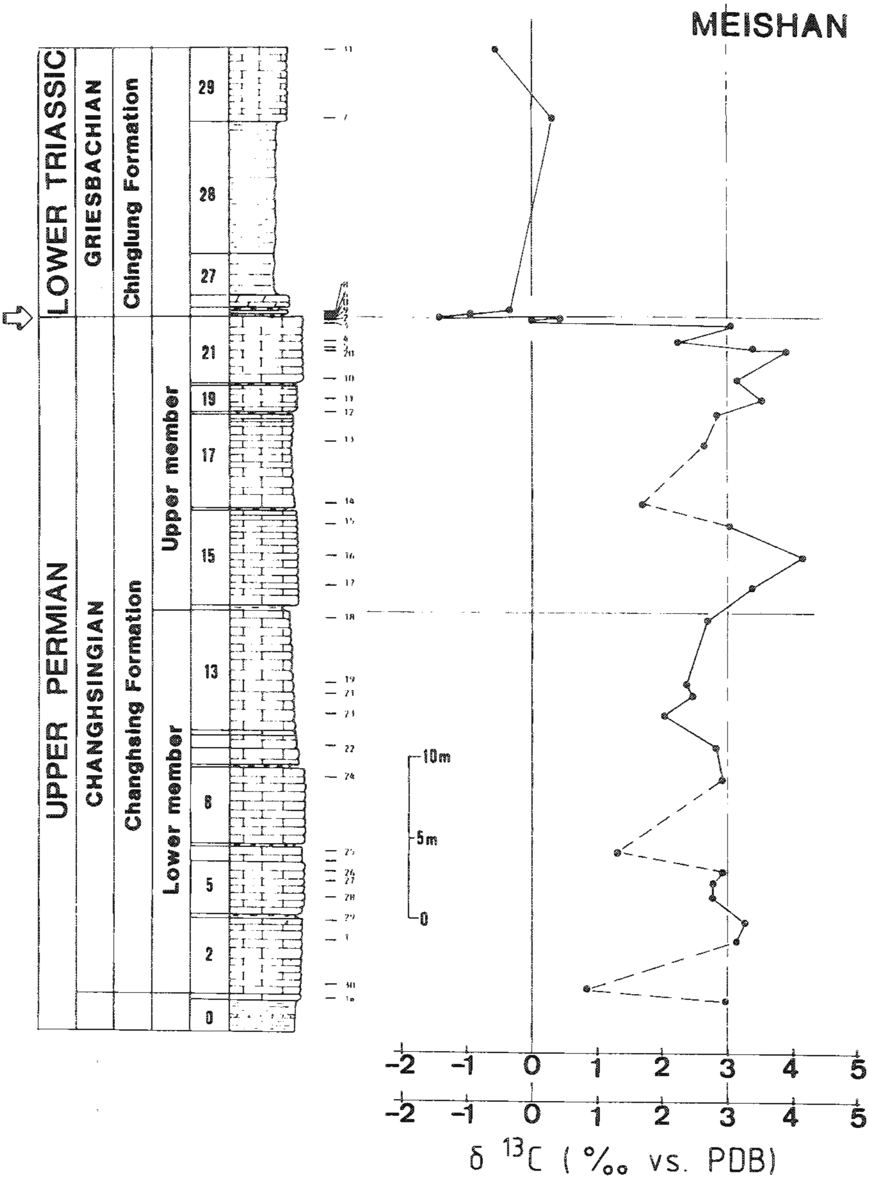

Fig. 14. Carbon isotope profile at Meishan, Section D, China. The arrow indicates a hiatus in the Lower Griesbachian.

(recorded by Li et al., 1986), in black shales and radiolarian cherty limestones (observed by A. Baud).

China: Meishan (Changhsing, Zhejiang Province)

Meishan lies 1250 km east of Shangsi. As at Shangsi, two biozones are recognized in the uppermost Permian Changhsingian (Sheng et al., 1984). The stratotype section, labelled »D« (Baoquing Quarry) by Sheng et al. (1984), is the one sampled for this study (Fig. 14). The lithology and stratigraphy are similar to those at Shangsi.

The carbon isotope profile (Figs. 14 and 15) shows generally high δ ^{13}C up to nearly the top of the Changhsingian (Fig. 14), whence it drops within half a meter to a level of -1.5 ‰ (Fig. 15). Carbon-isotope profiles previously published from Meishan area by Chen et al. (1984) & Xu et al. (1986) are different, but

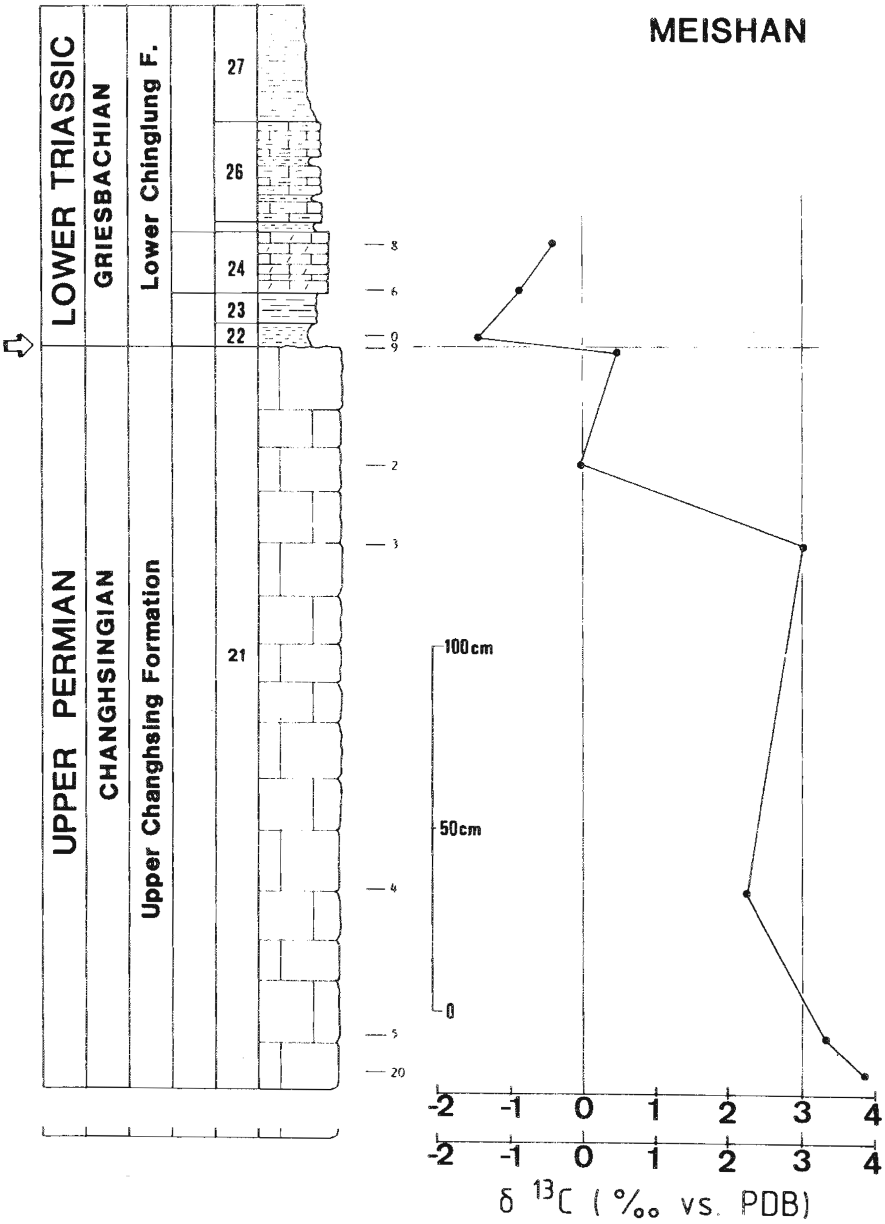

Fig. 15. Detailed carbon isotope profile across the P/Tr boundary at Meishan, Section D, China.

are not tied to specific described sections or stratigraphy. Trace elements (including iridium) across the P/Tr boundary at Meishan have been repeatedly studied in detail by Asaro et al. (1982), Sun et al. (1984), Clark et al. (1986), Zhou (1987) & Boclet et al. (1988).

Salamis, Greece: Kaki Vigla Bay

Permian and Triassic marine sediments occur in isolated sections at several localities in the Aegean region (Jacobshagen, 1972; Kauffmann, 1976). Complexity of structural zones makes reconstruction of the paleogeography at the end of the Permian very difficult. We have studied a section at Kaki Vigla Bay on the island of Salamis, previously described by Nakazawa et al.(1975) and Baud & Papanikolaou (1981). This area is tentatively assigned to the Subpelagonian tectonic zone (Montrakis, 1986) and paleogeographically to the western margin of Cimmeria. In spite of the indefinite tectonic situation of this section, it is of particular interest for the facies developed there. Baud & Papanikolaou (1981) described a breccia of all sizes of blocks of limestones and dolostones, which they interpreted as olistostromes derived from shallow-water limestones (Fig. 16). These are interlayered with black shales, limestones and calcareous sandstones, some of which have graded bedding characteristic of turbidites and slump deposits. Of particular interest are radiolarian calcareous mudstones. All of these types of sedimentation are suggestive of final deposition in moderate to deep water – olistoliths, slump deposits, and turbidites as derivatives from a shallow-water shelf, and the radiolarian mudstones as direct deep-water sedimentation.

The section is faulted into four segments; the field relations imply the stratigraphic order shown in Figure 16, with undetermined thicknesses faulted out. Most of the section is dated as Late Dzhulfian to Dorashamian, based on foraminifers, or as Dorashamian based on brachiopods and corals (Nakazawa et al., 1975). The top segment is a few meters of limestone of Lower Triassic age (Papanikolaou & Baud, 1982).

Two sample sets were collected independently at nearby localities by Baud and Papanikolaou and by Holser; the isotope results are illustrated in Figures 16 A and 16 B, respectively. The lower segment begins with relatively low values of $\delta^{13}C$ in shaly and sandy limestones (Fig. 16 A, units 2 and 3), rising to a level of +3‰ that continues through the breccia unit of the second segment (both sample sets). In the third, and highest Permian segment both samplings show drops in $\delta^{13}C$. These low values are particularly evident in samples 305–309 of Figure 16 B; these samples were highly tectonized and their low values may be due to alteration accompanying the later tectonic event. It is not clear whether the drop in samples 43–45 of Figure 16 A is primary, near the top of the Permian, or whether it is also due to alteration around the overlying fault.

shaly and sandy limestones (Fig. 16 A, units 2 and 3), rising to a level of +3‰ that continues through the

Despite the possible interference of tectonics in the upper part of the Salamis profiles, this does not affect the important result that neighboring autochthonous and allochthonous sediments, both bedded radiolarites-mudstone and olistolithic block-matrix pairs, differ in $\delta^{13}C$ by less the 1‰. This is evidence for a relatively low contrast of $\delta^{13}C$ between surface and deep waters in at least this part of the Paleo-Tethys Sea.

Synthesis of Carbon Isotope Composition in the Upper Permian and Lower Triassic of Tethys

General statement

Our profiles from the shores of Tethys represent the variations of its marine carbon isotope content during Late Permian and Early Triassic time. Our work did not aim to study particular sections in detail, but rather to develop a general isotope curve based on measurements from a wide region. Most of the sections are difficult to reach, and some of our samples were originally collected for stratigraphic and petrographic studies. In some cases coarse sampling resulted in »excursions« of the isotope curve that are only defined by a single sample, but we will disregard these pending verification by more detailed studies. Evidence that particular trends are real is mainly found in the similarity of trends in more than one locality. Also one should not expect that the absolute values of $\delta^{13}C$ in different sections will be equal, because: (a) at present the bicarbonate of surface ocean water has different values of $\delta^{13}C$ at different localities as a result of varying productivity (Kroopnick, 1985; Berger & Vincent, 1986); and (b) differing diagenetic histories may have slightly altered the original record. It may be for similar reasons that the more recent extinction event at the Cretaceous-Tertiary boundary is marked by drops in $\delta^{13}C$ that vary with locality from 0 to 2.5‰ (Zachos & Arthur, 1986).

One other problem with which we are faced is the precise definition of the stratigraphic ages of our rock units. In some cases only a general age assignment has been made; in other cases experts are still debating the stratigraphy. In the following discussion we will assume the stratigraphic scheme that we presented above (Fig. 2).

units. In some cases only a general age assignment has been made; in other cases experts are still debating

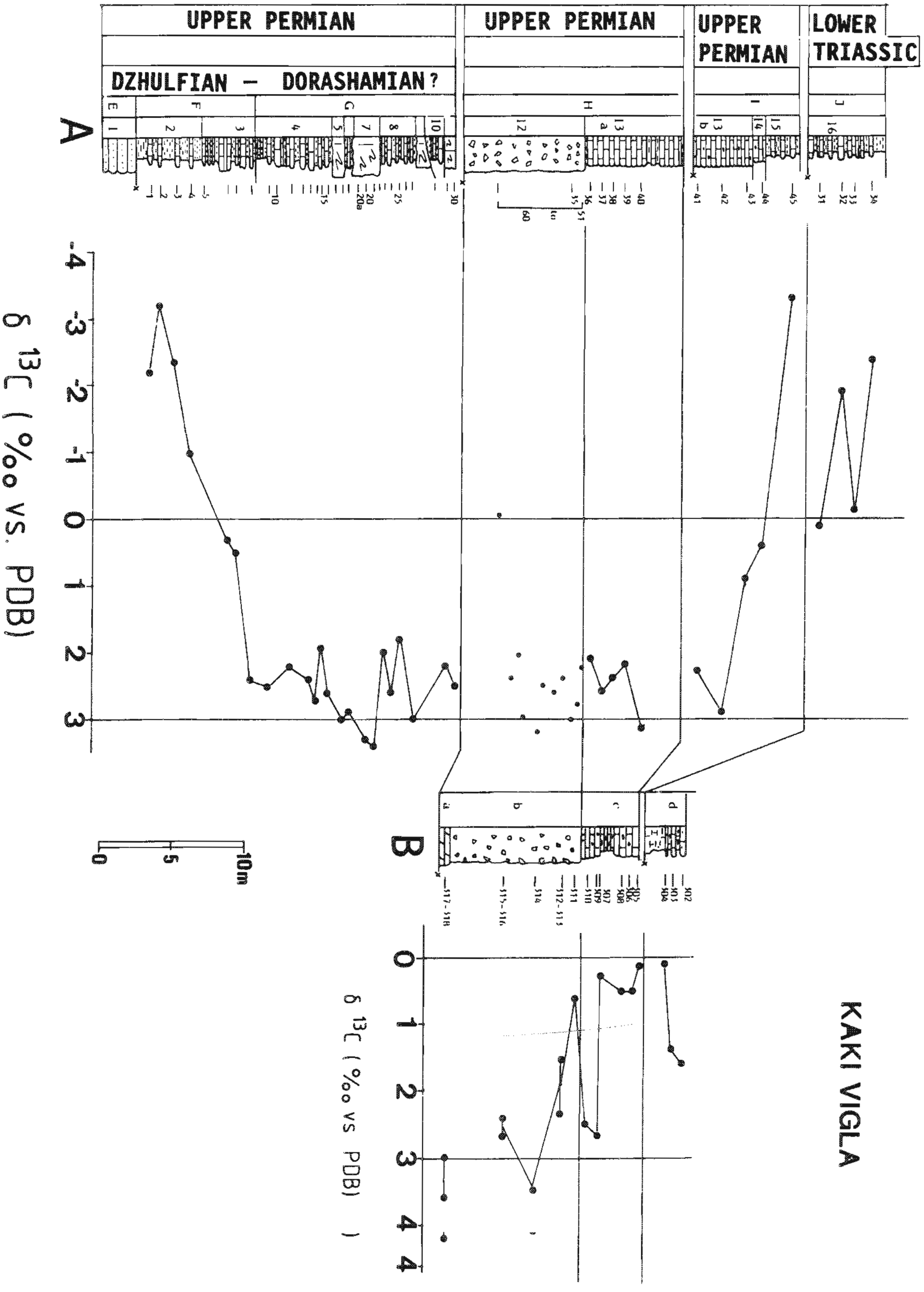

Fig. 16. Carbon isotope profile at Kaki Vigla Bay, Salamis, Greece. Nearby sections were independently collected by (A) A. Baud and D. Papanikolaou, and (B) W. T. Holser.

Some representative sections are collected in Figure 17, all at the same scale for ease of comparison. A synthesis is made in Figure 18, which represents our best estimate of the secular variation of $\delta\,^{13}C$ for the Tethyan Sea during Late Permian and Early Triassic times. In constructing Figure 18, most weight was given to those sections that included one or more stage or biozone boundaries, to tie at least one point of each section provisionally to the stratigraphic time scale. Within each stage (or biozone where known) the sample points for each section were scaled with the arbitrary assumptions of uniform sedimentation rate and no hiatus. This synthesis is of course provisional, and in this approximation one should not expect that either levels or variations of $\delta\,^{13}C$ will be exactly the same among the sections.

The following discussion will consider in turn the details of the Murgabian-Dzhulfian, Dorashamian, P/Tr boundary, and Early Triassic intervals.

Murgabian to Dzhulfian Stages

Figure 18 collects the data in this interval from sections in the Transcaucasus, Iran, Pakistan and China,

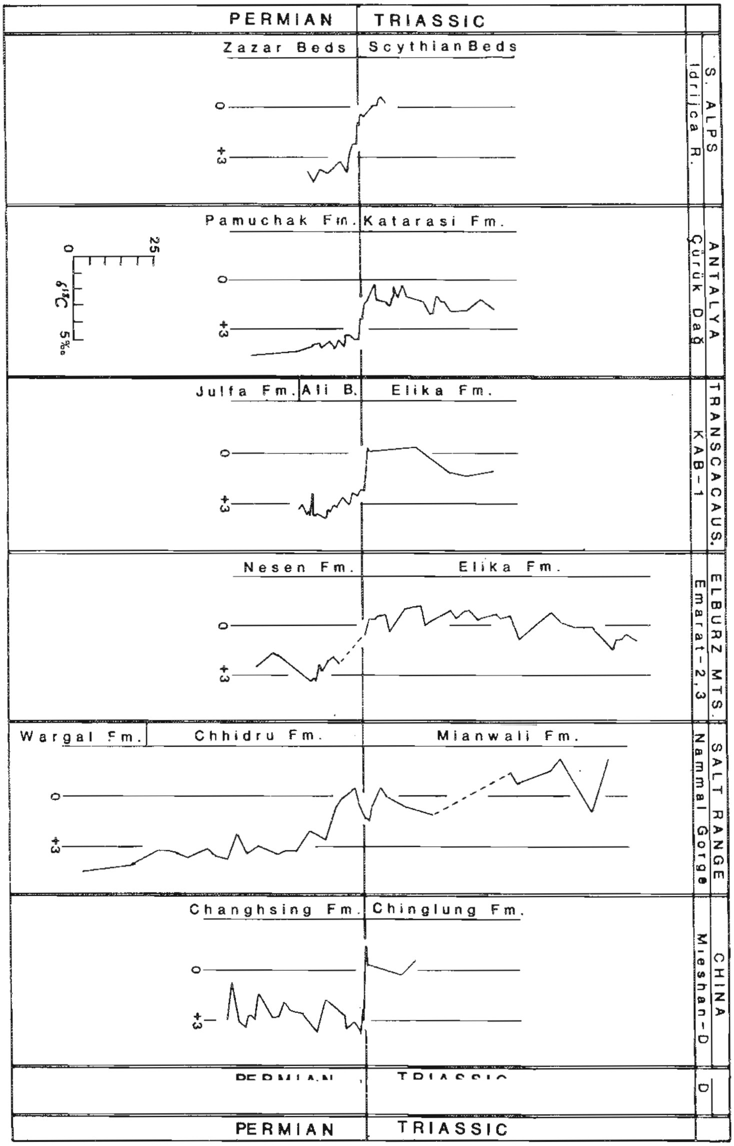

Fig. 17. Comparison of carbon isotope profiles, on equal scales, across the Tethys belt from the Alps on the left to China on the right.

although not all stages are represented in each section. These four definitive sections are supplemented by other analyses from the Southern Alps, Greece, Turkey and Nepal.

The collected data validate a general high of δ ^{13}C for the Late Permian, starting with a value of +4 ‰ at the beginning of the Murgabian (boundary of the Lower and Upper Permian). Most of the data from the Murgabian Stage are from the section at Emarat-2 (Fig. 7), but generally confirmed by a few analyses from the bases of the sections at Vedi-2 (Fig. 5) and Shangsi (Fig. 13). Data for the Midian Stage are scat-

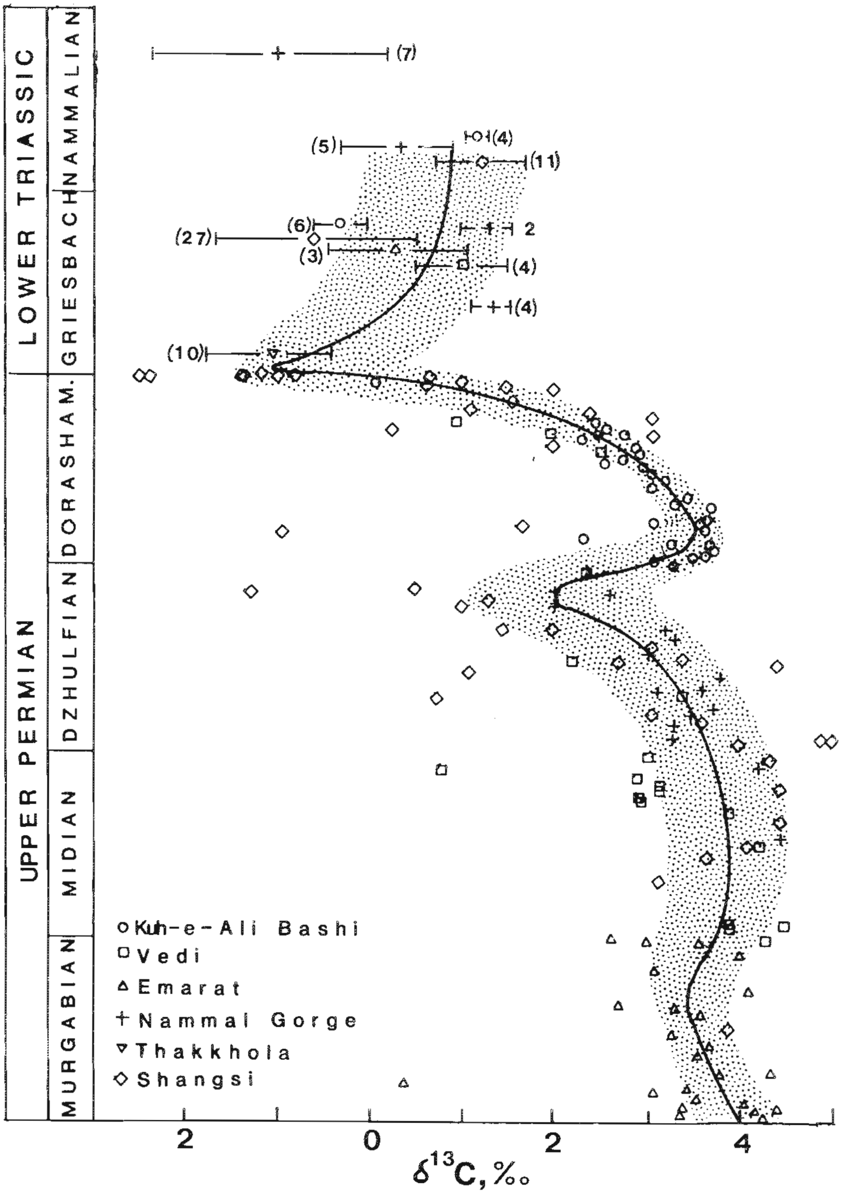

Fig. 18. Synthesis of carbon isotope data in the Tethyan area for Late Permian and Early Triassic time. Data are plotted from six of the best sections, and including data published for the Shangsi section by Li et al. (1986). For the Permian the

Fig. 18. Synthesis of carbon isotope data in the Tethyan area for Late Permian and Early Triassic time. Data are plotted from six of the best sections, and including data published for the Shangsi section by Li et al. (1986). For the Permian the

solid line indicates our best estimate of a carbon isotope age curve for the Tethys Sea, and the shaded zone its region of uncertainty. For the Triassic, data are shown only as means and standard deviations for each stratigraphic interval and locality. For time scale see Figure 2.

tered: many samples from Shangsi as well as the two samples from the Wargal Formation in Nammal Gorge (Fig. 11) are up to 1.5 ‰ higher than those from Vedi-2. Many data from Shangsi and Nammal Gorge indicate that near the top of the Dzhulfian Stage $\delta\ ^{13}C$ drops to +2 ‰ or even lower. Values for the Dzhulfian from Antalya are generally higher – +3.5 to 4.5 ‰ – but also show a decrease toward their tops (Figs. 9, 10); these sections were not included in the compilation of Figure 18 because their stratigraphic positions within the Dzhulfian are uncertain. The variations in $\delta\ ^{13}C$ within the Murgabian-Dzhulfian interval, sketched in Figure 18, need confirmation by detailed studies of selected sections.

Dorashamian Stage

The most definitive data for most of Dorashamian time – the final stage of the Permian – are from the KAB sections (Fig. 4), which are closely correlated with the stratotype section for this stage nearby at Dorasham (Fig. 3). From the low at the end of Dzhulfian time, at the base of the KAB section, $\delta\ ^{13}C$ rises again to about +3.5 ‰, but throughout the remainder of the section it decreases, to a value of +2 ‰ at the top of the *Paratirolites Zone*. The details of this decline are circumscribed by division of the KAB section into six biostratigraphic zones as shown in Figure 4; these zones are taken into account in constructing Figure 18 although not shown there.

The final biozone of the Dorashamian – *Pseudotirolites-Pleuronodoceras* – is best exposed in China (Figs. 13–15). Our data from Shangsi combined with that published by Li et al. (1986) continue the decline already evident in the earlier biozones at KAB, and at an accelerating rate (Fig. 13). In the last half meter of the Permian eight samples (Li et al., 1986, Beds 25 through 27) showed a definite low of $\delta\ ^{13}C = 1.3 \pm 1.0$ ‰, but without any evident trend. The profile at Meishan (Fig. 14, and Chen et al., 1984) drops more sharply from $\delta\ ^{13}C = +4$ to less than −1 ‰ within a thickness of 2 meters. Three samples from the very top of the Dorashamian at KAB and Vedi probably correlate somewhere within this zone, and have $\delta\ ^{13}C = 0$ to +2 ‰. At Nammal Gorge (Fig. 13) the lowest samples of the Kathwai Formation in each of the two sections, with $\delta\ ^{13}C = +1.0$ and 0.6 ‰, are also possibly of latest Dorashamian age (Pakistani-Japanese Research Group, 1985; Sheng et al., 1984). In all of these cases the Late Dorashamian has $\delta\ ^{13}C$ lower than all other intervals of the Late Permian.

$\delta\ ^{13}C$ lower than all other intervals of the Late Permian.

The Permian-Triassic Boundary

The transition of $\delta\ ^{13}C$ through the P/Tr boundary is difficult to assess directly, for the reason that in most sections either the uppermost Permian (Dorashamian – particularly the last, *Pseudotirolites-Pleuronodoceras Zone*) or the lowermost Triassic (Lower Griesbachian: the *Otoceras Zone*) (Fig. 2) is missing (e.g., Nakazawa et al., 1980; Dagis & Dagis, 1987).

As discussed in the previous section of this paper, a major drop in $\delta\ ^{13}C$ occurs within the Dorashamian Stage: in some sections (Shangsi, Vedi) the drop is spread over that stage, but in others (Meishan, KAB) the drop is concentrated in its uppermost meter or two. Although many consider the sections in China to represent continuous deposition across the P/Tr boundary (Li et al., 1986; Sheng et al., 1984), the sharp change in sedimentary facies probably marks an interruption in the sedimentary record (Tozer, 1979; confirmed by microfacies studies by Baud). We propose that sections showing more gradual drops in $\delta\ ^{13}C$ represent more complete records of sedimentation across the P/Tr boundary, even though some such sections may be poorly defined by biostratigraphic zonation. Thus the corresponding decline from $\delta\ ^{13}C = +4$ to less than +1 ‰ in the top 3 meters of the Permian in the Idrijca section (Fig. 8) is consistent with the assignment, elsewhere in the Southern Alps, of the topmost Permian to the Dorashamian Stage. In this section, as elsewhere in the Southern Alps (Magaritz et al., 1988; Holser et al., 1988), $\delta\ ^{13}C$ continues to decline slowly and smoothly through 10 to 20 m of the overlying Lower Triassic beds. This suggests to us that these sections in the Southern Alps represent continuous deposition across the Permian-Triassic boundary, and that the lowermost Triassic beds there are of earliest Griesbachian age.

In other sections a discontinuous drop near the P/Tr boundary implies the absence of at least the last zone of the Permian. Thus the sections in Antalya display this feature.

Early Triassic

In general even the highest $\delta\ ^{13}C$ in Triassic samples is lower than those from all except the last zone of the Permian. We have presented one other set of data for the Lower Griesbachian from the sections at Thakkhola, showing a range of −0.1 to −2.0 ‰, but with no Permian analyzed. However, the data from the various sections analyzed are so disparate, and in some cases so stratigraphically indefinite, that detailed trends of $\delta\ ^{13}C$ through the Early Triassic cannot yet be defined. Consequently in Figure 18 our data for this epoch are represented by their mean values, and the precision indicated for the isotope age curve is correspondingly lowered.

tailed trends of $\delta\ ^{13}C$ through the Early Triassic cannot yet be defined. Consequently in Figure 18 our

In Figure 18 there is some suggestion of an upward trend from Early Griesbachian to Early Nammalian (Dienerian) time, but this remains to be confirmed by further studies with close stratigraphic control. The section at Nammal Gorge (Fig. 11), the stratotype for the Nammalian Stage, seems to trend irregularly downward through that stage, but this is not yet confirmed elsewhere. Our sections in Zanskar (Fig. 12) show values of $\delta^{13}C$ of −1 to +1 ‰ through the overlying Anisian and Ladinian.

Discussion

The results presented in this study indicate that during Late Permian and Early Triassic time several shifts occurred in the marine carbon isotope curve, as generalized in Figure 18. These events are established in sections from the Alps to China. A minimum of $\delta^{13}C$ occurs near the boundary of the Dzhulfian and Dorashamian Stages. The major negative shift occurs near the P/Tr boundary, as already suggested by HOLSER et al. (1986), but the details of the drop are now better resolved. Thus from a second high of +3.5 ‰ in the Lower Dorashamian, $\delta^{13}C$ drops to +2 ‰ at the top of the *Paratirolites* Zone, and then rather sharply to below zero through the *Pseudotirolites-Pleuronodoceras* Zone. The length and smoothness of the drop in $\delta^{13}C$ measures the continuity and completeness of sedimentation across the P/Tr boundary. Where no Dorashamian rocks are present a discontinuity is observed at the P/Tr boundary. In all sections values of $\delta^{13}C$ reach a minimum a little above the boundary. Above that, in the Early Triassic, a gradual upward trend is suggested, for at least 10 to 70 m above the P/Tr boundary.

In the Late Permian Castile Formation in the Delaware Basin, New Mexico (MAGARITZ et al., 1983) and in the Zechstein sequence in northwestern Europe (MAGARITZ et al., 1981), the high values of +5 ‰ to +6 ‰ correspond to levels of $\delta^{13}C$ = +4 to +4.5 ‰ in the Midian where sampled in Tethys. In both New Mexico and northwestern Europe the sedimentation becomes non-marine before reaching the end of the Permian and its drops in $\delta^{13}C$. Another important feature of the Late Permian sections in the USA and northwestern Europe is a sharp rise of $\delta^{13}C$ near the Kazanian/Tatarian (= Murgabian/Midian) boundary (HOLSER et al., 1986). This marker was well characterized in many sections in those regions, and seemed to represent the end of a final negative excursion of $\delta^{13}C$ from the generally high levels found elsewhere during Pennsylvanian and Early Permian time (e.g., VEIZER et al., 1980, 1986; POPP et al., 1986). Most of our data for this time interval in the present survey of the Tethyan region are from Emarat-2 (Figs. 7, 17), which does not show this sharp rise. Sampling of other sections that are well represented in this time interval will be required to resolve this issue.

seemed to represent the end of a final negative excursion of $\delta^{13}C$ from the generally high levels found

The carbon isotope profiles that we have presented are primarily a record of carbon isotope ratios in the surface waters of the Tethys Sea. But the equivalence of values in deep- and shallow water carbonates in the data from Salamis indicates that the contrast of $\delta^{13}C$ between surface and deep ocean waters of Tethys may have been even less than in today's ocean. Consequently we can have some confidence that the carbon isotope profiles record mean values for the entire Tethys Sea and likely for the world ocean as a whole.

Based on a mass balance model (KUMP & GARRELS, 1986) one expects the carbon isotope composition of oceanic dissolved carbonate to shift in a short time ($2-3 \times 10^5$ yr) following a change in the flux to the sediments of organic carbon (C_{org}) relative to total carbon (C_{tot}). So the longer term changes in $\delta^{13}C$, from the Murgabian to the P/Tr boundary – 6 to 7 Ma – do not represent a single flux event of the carbon cycle, but rather an extended series of events that are followed closely by the marine $\delta^{13}C$ curve. Even the final drop of $\delta^{13}C$ was spread through two of about ten biozones of Late Permian time (Fig. 2), corresponding to 1 or 2 Ma.

There is a similarity between the patterns of $\delta^{13}C$ and faunal diversity in the P-Tr interval. RAUP & SEPKOSKI (1982) show that the extinction event at the end of the Paleozoic began with a decline in total diversity at the beginning of Late Permian time. HOLSER & MAGARITZ (1987) replotted the data of RAUP & SEPKOSKI for the Permian-Triassic interval, from which it is apparent that the decline in diversity begins in the Murgabian and continues to the P/Tr boundary. Extinction toward the end of Permian time may have been in part stepwise, as has been proposed for the end-Cretaceous (HUT et al., 1987; KAUFFMAN, 1986), although neither our generalized carbon isotope age curve (Fig. 18), nor the diversity statistics of RAUP & SEPKOSKI are capable of such fine resolution. Recovery of diversity was slow, delayed through Early Triassic time.

The similarity of these trends (faunal diversity and the fraction of C_{org}) may reflect a common cause: Perhaps these two phenomena had in common a change in the environment and extent of the shallow shelves in which both diversity and biomass is concentrated. The last stages of the Permian witnessed a dramatic drop in sea level (BAUD, 1985; HOLSER & MAGARITZ, 1987), also evident in the rarity of marine sequences for the transitional sections. As one ap-

centrated. The last stages of the Permian witnessed a

proaches the boundary the number of sections representing the time interval decreases. Note that the shores of the Tethys oceans were a major locale of what marine sedimentation there was at that time, while in other areas of the world (e. g., western North America and northwestern Europe) marine sections of Early Carboniferous to Early Permian age are succeeded by non-marine deposits of Late Permian to Early Triassic age. Even in Tethys many of the existing marine sections show indications of lower sea level by increases of terrigenous material (e. g., Nammal Gorge, Pakistan). Decreased sea level not only reduces the venues for the proliferation of marine life, but also exposes to oxidation the C_{org} that was deposited in the preceeding interval.

Conclusions

In this paper we present carbon isotope data from many of the classical sections of the P-Tr of the Tethys Sea. The isotopic results show a pattern of depletion of ^{13}C from the Murgabian to Dzhulfian and Dorashamian. The decline in $\delta\,^{13}C$ is thus spread over at least 5 Ma of Late Permian time, accelerating to a steeper drop in the last two or three biozones of the Permian, but continuing smoothly across the stratigraphic P/Tr boundary. The lowest values of $\delta\,^{13}C$ occur just above the P/Tr boundary. Low values persist in the lowermost Triassic, but at some time during the Late Griesbachian $\delta\,^{13}C$ may have returned to only slightly positive values. The pattern of change of $\delta\,^{13}C$ is similar to that of faunal diversity, and both changes may have been related to changes of sea level.

In the course of our detailed study we have also shown that carbon isotopes in marine limestones have considerable potential as a stratigraphic tool, in fine-scale correlations and in the detection of hiatuses of sedimentation.

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