ELSEVIER

Palaeogeography, Palaeoclimatology, Palaeoecology 136 (1997) 79–95

PALAEO

Palaeoenvironmental interpretation of a Triassic–Jurassic boundary section from Western Austria based on palaeoecological and geochemical data

Christopher A. McRoberts [a,*], Heinz Furrer [b], Douglas S. Jones [c]

[a] *Institut für Paläontologie der Universität Würzburg, Pleicherwall 1, D-97070 Würzburg, Germany*
[b] *Paläontologisches Institut und Museum der Universität Zürich, Karl Schmid-Strasse 4, CH-8006 Zürich, Switzerland*
[c] *Florida Museum of Natural History, University of Florida, Gainesville, FL 32611, USA*

Received 17 December 1996; received in revised form 25 March 1997; accepted 4 April 1997

Abstract

A section spanning the Triassic–Jurassic boundary is described from near the village of Lorüns in the Vorarlberg region of western Austria. At Lorüns, the uppermost Triassic is characterised by bedded carbonates of the Kössen Formation supporting a stenotopic fauna indicative of a shallow sub-tidal environment of normal marine salinity. The Triassic–Jurassic boundary may be represented as a sequence boundary developed on top of a 1.1 m thick red mudstone of the lower Schattwald Shale, which is interpreted to have been deposited in a marginal marine environment, possibly a mud flat. Above the boundary beds, the upper Schattwald Shale is characterised by thin-bedded marl and dark limestone beds with an earliest Hettangian macrofauna dominated by epifaunal filter-feeding bivalves, including ostreids, mytilids and oxytomids, which suggest a shallow, subtidal, salinity-controlled environment typical of an interplatform lagoon. Carbonate production rejuvenated in the later Early Hettangian with development of the Lorüns oolite, a shallow subtidal oolitic and oncolitic unit bearing echinoderms indicative of normal marine conditions.

Low Th/U ratios from the remainder of the section are a result of reduced thorium in carbonate-rich sediments and not from authigenic uranium in anoxic sediments. In the boundary beds evidence for marine anoxia (or dysoxia) is absent where Th/U values, determined by gamma-ray spectrometry, are above 5. The negative excursion in $\delta^{13}C$ and positive excursion in $\delta^{18}O$ in the boundary beds may be due to secondary geochemical effects, due to organic diagenesis or the precipitation of caliche during paleosol development. Alternatively, the excursions may reflect a primary geochemical signal recording short-term decline in primary productivity. Comparison in $\delta^{18}O$ and $\delta^{13}C$ values between the Kössen Formation and Lorfüs oolite indicate no significant long-term geochemical changes are evident in the section and suggest that any environmental perturbations were restricted to the boundary beds and possible sequence boundary. © 1997 Elsevier Science B.V.

Keywords: extinction; Triassic; Jurassic; Austria; palaeoecology; geochemistry

* Present address: Department of Geology, SUNY Cortland, P.O. Box 2000, Cortland, NY 13045 USA. Fax: +1 607 753 2927. E-mail: mcroberts@cortland.edu

0031-0182/97/$17.00
PII S0031-0182(97)00074-6

1. Introduction

The close of the Triassic period is marked by one of the five largest mass extinctions of the Phanerozoic affecting both marine and non-marine biotas. A recent generic compilation (Sepkoski, 1996) indicates about 53% of marine genera and 23% of marine families went extinct at the end of the Triassic, an event which exceeds in magnitude the extinction at the close of the Cretaceous. Of marine invertebrates, ammonoids, bivalves, corals, and ostracodes were among the most severely affected; the conodonts and several brachiopod and gastropod clades were completely eliminated. Although the non-marine record of the extinction is less clear, some groups of vertebrate tetrapods suffered heavy losses (Benton, 1986; Olsen et al., 1987; although see Cuny, 1995) as did many of the palynomorph taxa (Fowell and Olsen, 1993).

Like most other mass extinctions, the various explanations for the cause of the end-Triassic event are controversial. Recent discussions have led to two different hypotheses to account for the end-Triassic crisis: (1) a reduction in habitable marine environments due to sea-level fall and the spread of anoxic water during subsequent sea-level rise (e.g., Hallam, 1981, 1990a) or (2) a decrease in primary productivity leading to the collapse of both marine and terrestrial food webs (e.g., McRoberts and Newton, 1995; McRoberts et al., 1995). Although the second hypothesis is consistent with an extraterrestrial impact, for which some evidence exists in the form of shocked quartz (e.g., Badjukov et al., 1987; Bice et al., 1992), many Earth-bound mechanisms are available that could alter both marine and non-marine productivity levels. Both hypotheses, however, are still in need of further substantiation with additional sedimentologic, geochemical, and palaeontologic data and must be consistent with the magnitude, timing, and mode of extinctions in both the marine and non-marine realms.

One of the largest problems in delimiting the causes of the end-Triassic extinction is the paucity of continuous marine sections spanning the Triassic–Jurassic boundary. Of the several sections potentially spanning the boundary, only four are known to contain the earliest Jurassic ammonoids in conformable succession above uppermost Triassic sediments: (1) New York Canyon in western Nevada (Muller and Ferguson, 1939; Laws, 1982); (2) Utcubamba Valley, Peru (Von Hillebrandt, 1994); (3) St. Audries Bay in Somerset, England (Whittaker and Green, 1983; Warrington et al., 1994); and (4) Kendelbachgraben in the Osterhorn Mountains of Austria (Suess and Von Mojsisovics, 1868; Golebiowski and Braunstein, 1988). A fifth section at El Antimonio in Sonora, Mexico (González-León et al., 1996) is now known to represent an erosional unconformity in which most, if not all, of the Hettangian is missing (González-León, 1997). All of the sections advocated as 'complete' not only have a biostratigraphic gap of no less than 5 m between a demonstrably Rhaetian fauna and overlying Hettangian ammonoids (e.g., Hodges, 1994), but exhibit evidence of a stratigraphic hiatus and, in some cases, erosion at or near the boundary. This can be seen in the limestone pebbles at the base of Grenzmergel from Kendelbachgraben and the limestone and phosphatic nodules at the base of the pre-*planorbis* beds at St. Audries Bay (Hallam, 1990b). Although sedimentary gaps across the systemic boundary naturally limit the possible interpretations derived from such sections, the bounding sediments themselves do provide a wealth of information which can be applied towards corroborating or excluding causal hypotheses for the extinctions.

To better understand the environmental constraints that may have induced diversity changes, we describe in this paper the lithology, biostratigraphy, palaeoecology, and geochemistry from one of the least known but best exposed sections spanning the Triassic–Jurassic boundary in the Northern Calcareous Alps. The section is situated in Vorarlberger Zementwerks limestone quarry near Lorüns Austria (Fig. 1). Although the section was mentioned in field guides (e.g., Bertle et al., 1979) and as part of a regional stratigraphic and sedimentological study (Furrer, 1993), it is described here in detail with specific reference to Triassic–Jurassic boundary problem and the end-Triassic extinction.

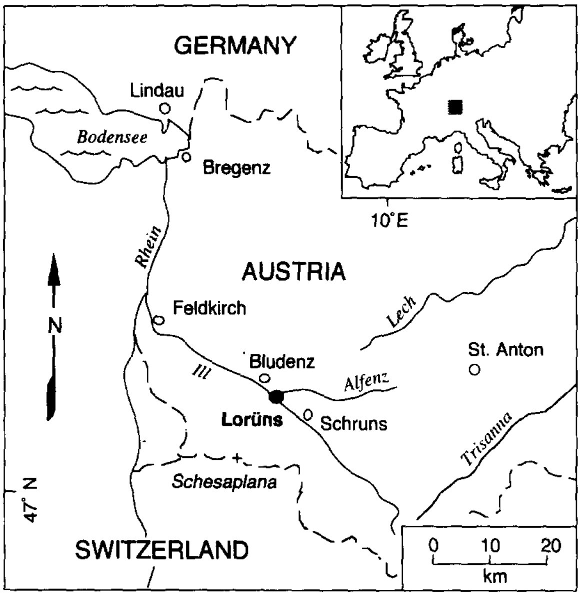


Fig. 1. Map of Vorarlberg region of western Austria showing the Lorüns quarry locality about 5 km southeast of Bludenz at the confluence of the Alfenz and Ill Rivers.

2. Geologic and paleogeographic setting

During the Late Triassic through Early Jurassic, the sedimentary rocks of the Northern Calcareous Alps were deposited on an extensive carbonate platform developed on the western margin of the Tethys seaway. Rhaetian sediments, generally referred to as the Kössen Formation in the northern Alps, record a regressive carbonate succession with diverse and abundant fossil assemblages, recording normal marine conditions in a muddy interplatform basin, separated from the open ocean to the east by extensive carbonate platforms (e.g., Dachstein Limestone). Although large-scale reef complexes, such as the Steinplatte, are known from this time (e.g., Piller, 1981; but see Stanton and Flügel, 1989), many coral–sponge–algal build-ups are small and/or lack constructive frameworks and are best described as patch reefs or mounds. At different places and times within the middle and upper Rhaetian carbonates, relative sea-level fell, exposing parts of the carbonate platforms and creating interplatform peritidal environments supporting restricted marine faunas characterised by megalodontid bivalves and shallowing-upwards Lofer cycles, or the so-called 'Rhaetoliasriffkalk' (Tollmann, 1976) or Zirmenkopf Limestone (Furrer, 1993). By the earliest Jurassic, a regional transgression onlaps the carbonates bringing with it supposed deeper water mudstones and dirty carbonates (generally referred to as the Kendelbach Formation or Schattwald Shale) which still developed on the subsiding platforms (Tollmann, 1976). By the later Early Jurassic the platforms were dismembered by active rifting and in places quickly subsided to greater depths, causing the cessation of shallow-water carbonate production and the onset of deposition of nodular, ammonoid-bearing, pelagic limestone of the Adnet Formation in the Sinemurian.

This stratigraphic overview is borne out with minor variations in the Vorarlberg Region on the western end of the Lechtal Nappe of the Northern Calcareous Alps (Fig. 2). Like elsewhere in the Northern Alps, the Rhaetian is characterised by the bedded carbonates attributable to the Kössen Formation. The Triassic–Jurassic boundary is

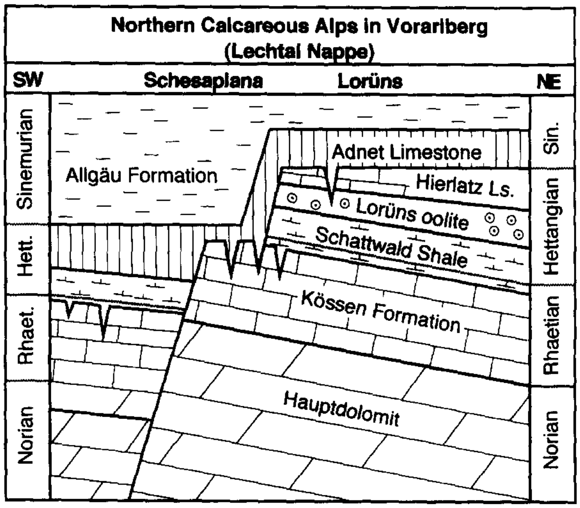
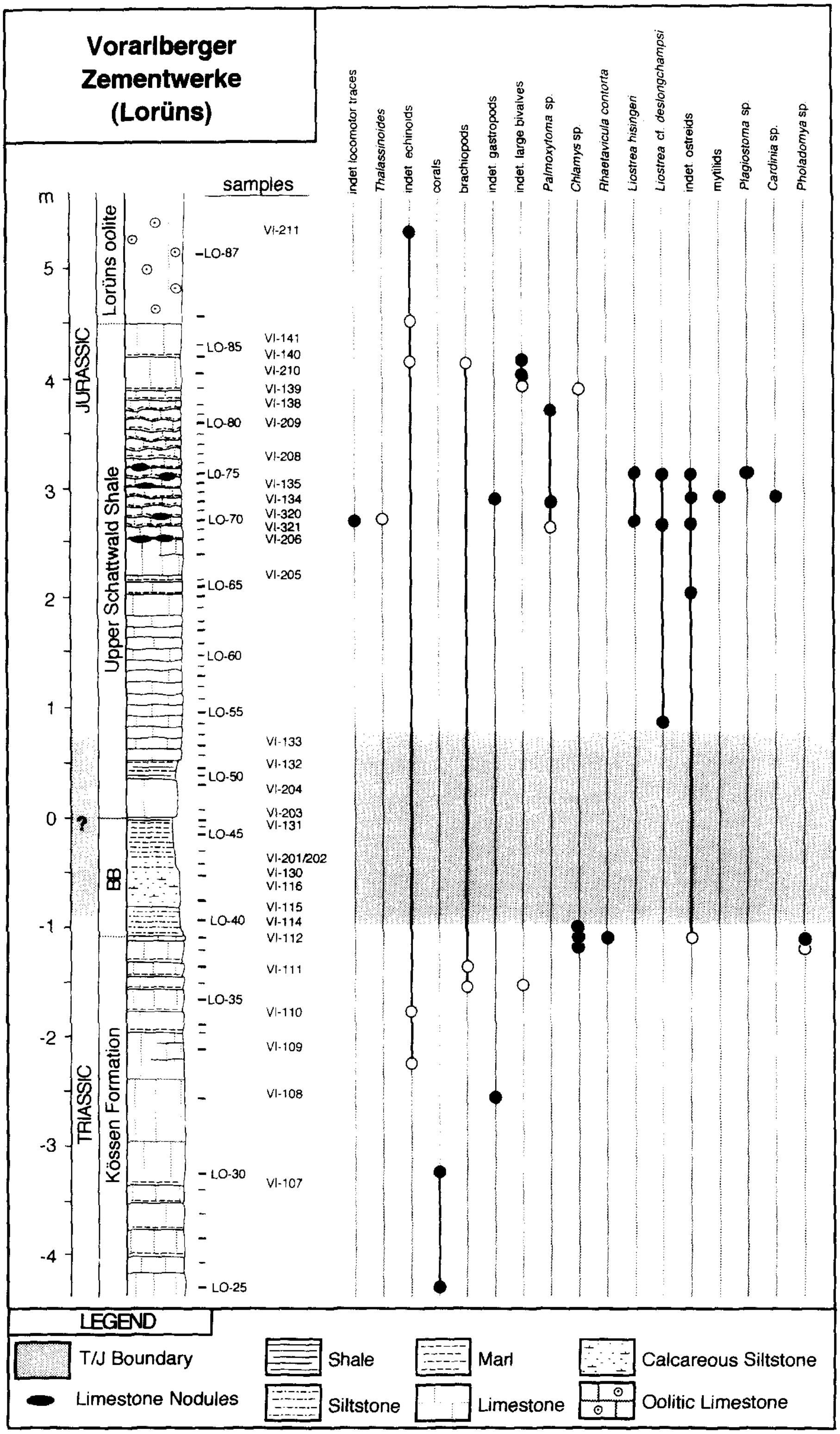


Fig. 2. Simplified regional Upper Triassic–Lower Jurassic stratigraphy of the Vorarlberg region of the Northern Calcareous Alps. The Lorüns area represents an isolated platform high and shows an expanded shallow-water platform sequence which contains fissure fillings within Lorüns oolite, containing clasts of Hierlatz Limestone. Near Schesaplana, about 12 km to the southwest of Lorüns, the Schattwald Shales and younger Jurassic deep-water sediments rest on top of or are contained within, fissure fills within the Rhaetian Kössen Formation. Modified from Furrer (1993).


Vorarlberger Zementwerke (Lorüns)
m
samples
JURASSIC
TRIASSIC
Lorüns oolite
Upper Schattwald Shale
BB
Kössen Formation
indet locomotor traces
Thalassinoides
indet echinoids
corals
brachiopods
indet gastropods
indet. large bivalves
Palmoxytoma sp.
Chlamys sp.
Rhaetavicula contorta
Liostrea hisingeri
Liostrea cf. deslongchampsi
indet ostreids
mytilids
Plagiostoma sp
Cardinia sp.
Pholadomya sp
LEGEND
T/J Boundary
Limestone Nodules
Shale
Siltstone
Marl
Limestone
Calcareous Siltstone
Oolitic Limestone

marked by the development of the Schattwald Shale, a lithologically variable marl–shale–limestone unit strikingly similar to the Kendelbach Formation (including the Grenzmergel) as known from the Salzkammergut. Using a variety of lithostratigraphic and biostratigraphic criteria, different authors suggest that the Schattwald Shale either spans the Rhaetian–Hettangian boundary or occurs entirely within the Hettangian, where it rests unconformably upon the eroded Kössen Formation (Reiser, 1920; Tollmann, 1976; Furrer, 1993). Above the Schattwald Shale are ooid-bearing carbonate rocks of the Hettangian Lorüns oolite, which indicate a return of carbonate production on topographic highs. This apparently did not occur in interplatform troughs such as at Schesaplana, situated on the Swiss–Austrian border southwest of Lorüns, where siliciclastic sedimentation predominated (Furrer, 1993). These platform carbonates are, in turn, overlain by red crinoidal limestones of the Upper Hettangian Hierlatz Limestone and magniferous pelagic micrites of the Sinemurian Adnet Formation noted for its ammonite fauna but conspicuously barren of macrobenthos, with the exception of the trace fossil *Chondrites*.

This generalised stratigraphy is further complicated in some localities where the top of the Kössen Formation, limestone beds in the Schattwald Shale, and the Lorüns oolite are dissected by large-scale fissures and smaller cavities, filled by an early fibrous calcitic cement and a secondary, green to red, micritic limestone lacking any fossils. The same cement–sediment infilling is often observed in cavities of dissolved, originally aragonitic thick shells of megalodontid bivalves in the uppermost Kössen Formation. Fissures and cavities are interpreted as the effects of faulting in the lithified carbonates during the initial rifting of the Tethys in Late Hettangian time, combined or followed by dissolution of aragonite under influence of freshwater, then by cementation and infilling of fine-grained sediment (Furrer, 1993).

3. Triassic–Jurassic boundary ecostratigraphy

The measured parts of the Lorüns section include sediments from the Upper Triassic Kössen Formation through the Upper Triassic–Lower Jurassic Schattwald Shale to the Lower Jurassic informally named 'Lorüns oolite'. Although the beds spanning the boundary are observable from several different levels in the Lorüns quarry, most of the data (and the section shown in Fig. 3) were collected in 1995 and 1996 from the most intact and accessible beds on the third level of active quarrying (samples with LO prefix). Additional exposures spanning the boundary were studied on the second and fourth level of the quarry during 1976 and 1978 (Furrer, 1993) and yielded some of the fauna as well as aiding in our interpretation (samples with VI prefix).

3.1. Kössen Formation

Although the Kössen Formation at Lorüns quarry is estimated to be more than 60 m thick, we discuss only the upper 4 m because it relates to the question of the extinction. The lower part of the Kössen Formation occurs in a structurally disrupted section 300 m to the south of the main section along the quarry access road. The upper contact of the Kössen Formation is here taken as the upper surface of a 1 cm thick reddish carbonate shell bed (sample LO-39 in Fig. 3). This contact is abrupt and may represent a period of minor non-deposition or an event horizon.

The measured part of the section begins in bedded carbonates where individual beds range from 1 cm to 1 m thick and are intercalated with very thin marly interbeds. Total organic carbon (TOC) values for the Kössen samples are all low, averaging much less than 1% by weight. Microfacies analysis of the carbonate sediments indicates a predominance of peloidal mudstones, molluscan wackestones, and molluscan–echinoderm packstones. The bioclasts are generally small

Fig. 3. Lithostratigraphy and biostratigraphy of the Lorüns section. Dots = in situ samples; circles = approximate stratigraphic position taken from float blocks and/or other sections in the quarry. Based on lithological grounds, the Boundary Beds (*BB*) are separated from the upper Schattwald Shales. The stippled region indicates the absence of biostratigraphically useful fossils, and thus the region in which the Triassic–Jurassic boundary could be contained.

in size (1–10 mm) yet are quite angular, suggesting little post-mortem transport. Although originally calcitic, bioclasts (derived from brachiopods, echinoderms and some molluscs) appear not to have been significantly diagenetically altered, most aragonitic clasts (derived from scleractinian corals and some molluscs) have undergone some alteration and have mostly been replaced by sparry calcite. The upper 0.5 m of the Kössen Formation in the Lorüns quarry is characterised by reddish limestones with marly intercalations, atypical for the relatively clean carbonates of the uppermost Kössen Formation in the Schesaplana area or other interplatform regions such as near Kössen or Kendelbachgraben.

The upper 4 m of the Kössen Formation produces a moderately diverse macrofauna consisting of bivalves, brachiopods, corals, echinoderms, and few other invertebrate groups. Accurate quantitative measures of abundance and diversity are unobtainable due to the nature of outcrop exposure and the relatively low number of individuals recovered from the section. Although it is unfortunate that latest Triassic ammonoids are unknown from the Lorüns quarry, the uppermost bed of the Kössen yielded the biostratigraphically useful bivalve *Rhaetavicula contorta* (Portlock) and the foraminifer *Triasina hantkeni* Majzon, which are only known from uppermost Triassic and are characteristic of the Rhaetian (sensu Dagys and Dagys, 1994). This same shell bed also yielded numerous individuals of the bivalve *Chlamys valoniensis* (DeFrance) and rare *Pholadomya* sp., which are consistent with a Rhaetian age, even though they also occur in younger sediments.

The relatively pure carbonates of the upper Kössen Formation were probably deposited in shallow waters of normal marine salinity. This environmental interpretation is further supported by the presence of stenotopic invertebrates such as echinoderms and corals which are present at several scattered levels within the measured parts of the Kössen Formation. This shallow subtidal environment of the uppermost Kössen Formation can be contrasted to more thickly bedded carbonates bearing megalodontid bivalves characteristic of restricted lagoonal environments which occur within 5 m below the measured interval.

3.2. Boundary beds (of the lower Schattwald Shale)

The 1.1 m of red, green, white, and black mudrocks and siltstones above the top of the Kössen Formation are here informally termed the boundary beds of the lower Schattwald Shale. Based on a facies change, the lower contact of the boundary beds with the underlying carbonates of Kössen Formation is taken as the upper bedding surface immediately above the *Chlamys* shell bed mentioned above. The lower part of the boundary beds is characterised by a 0.25 m thick, carbonate-rich, red siltstone with discontinuous 1–2 cm thick lenses of coarser-grained siltstone and marlstone. This carbonate siltstone is sharply overlain by a single, fining upwards, 0.73 m thick bed of red, pale green and white siltstone to silty mudstones with a mottled appearance. In 1978 a large bedding plane with mud cracks was exposed within this part of the boundary beds (Furrer, 1993). The top of the boundary beds is marked by a 1 cm thick black shale with TOC values of over 3% by weight (Fig. 4B). This shale bed exhibits well developed oblique partings, presumably due to compaction and not due to primary lamination.

A few fossils suggest a Rhaetian age for at least the lower part of the boundary beds of the lower Schattwald Shale. Although a Rhaetian age is consistent by a horizon bearing rare *Chlamys valoniensis* [and perhaps *C. pollux* (d'Orbigny)] in the lowermost boundary beds and by the poorly preserved isolated foraminifer *Triasina hantkeni*, possibly reworked from the underlying Kössen Formation. No additional fossils of any sort have been found in the uppermost part of the boundary beds.

Given the lithologic and palaeontologic attributes, including oxidised sediments and paucity of fossils above the basal boundary beds, we interpret the environment as being marginal marine, perhaps best characterised as a mud flat. The high percentage of quartz grains suggests a nearby terrestrial source and the absence of an abundant macro or microfauna attests to rather harsh conditions.

It is further suggested that a period of emergence, with possible paleosol development, may have succeeded deposition of the marginal marine

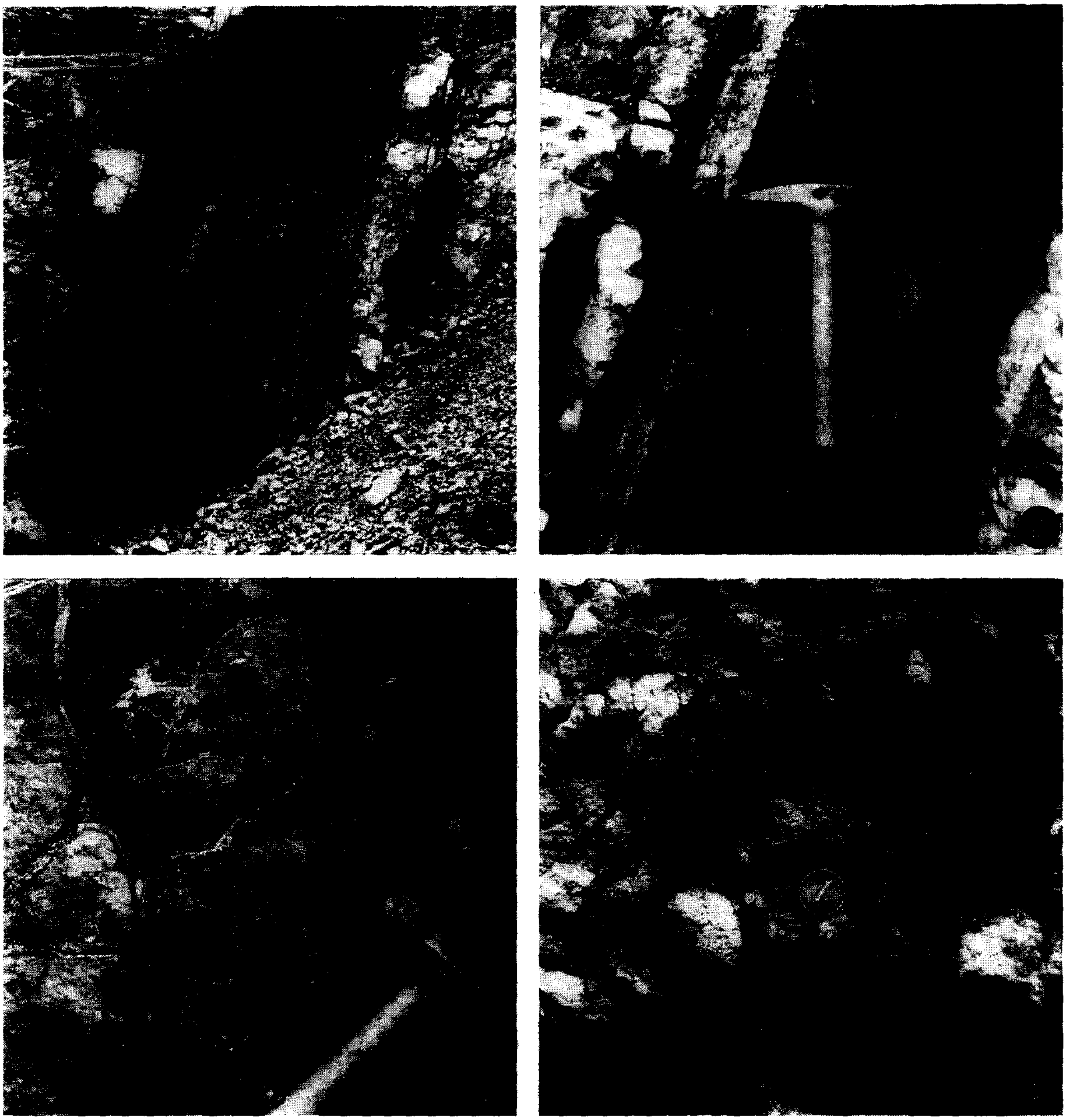


Fig. 4. Outcrop photos. (A) Outcrop photo showing entire sequence spanning the Triassic–Jurassic boundary, stratigraphic up is to the upper left. (B) Detailed section of boundary interval showing lighter coloured interval in the boundary beds and lowermost limestone of the Schattwald Shale, stratigraphic up is to the left and point of hammer is 3 cm below top of boundary beds. (C) Desiccation cracks from float block derived from the middle part of the Schattwald Beds. (D) Limestone nodules with small borings from lowermost nodular layer 2.5 m above the top of boundary beds.

sediments of the boundary beds. The primary evidence for paleosol development resides in abrupt colour changes in the boundary beds. These changes include about 1 m of mostly oxidised sediments overlain by 5 cm of greenish–white mudstone, which is, in turn, overlain by 1 cm of black organic-rich mudstone (see Figs. 4B, 5 and 7). The thin organic-rich layer at the top of the boundary beds may have been derived from terrestrial plants and deposited in quite shallow water, or perhaps in an aerially exposed environment. Although additional direct or indirect evidence for paleosol development, such as root casts or vadose cements, is lacking, an exposure interval is corroborated elsewhere in the region (for example nearby Schesaplana) where the upper Schattwald Shale

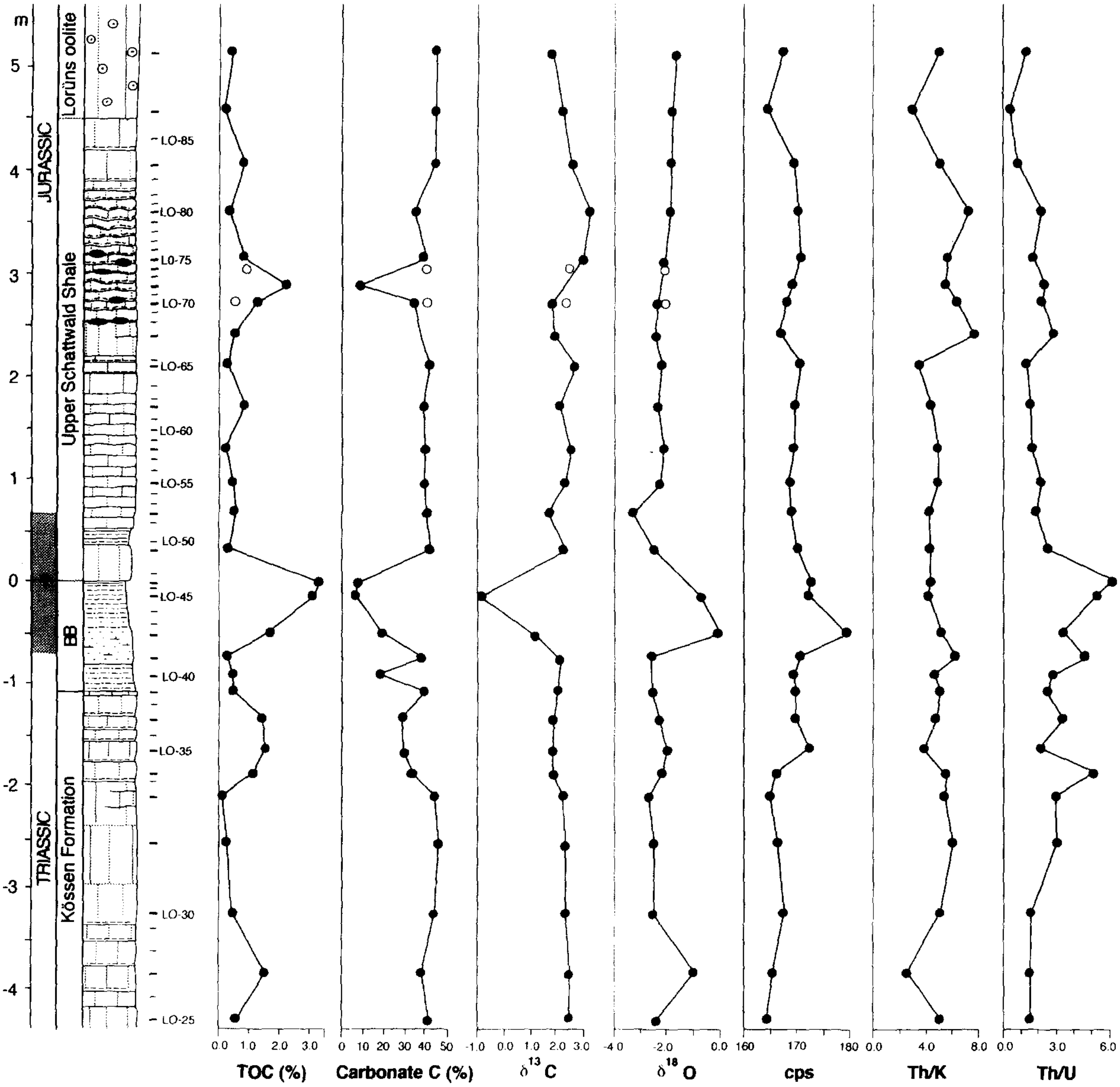


Fig. 5. Geochemical data from the Lorüns section. Note: circles represent measurements taken from the nodules presumed to be reworked from the underlying Kössen Formation. Cps = counts per second. See Fig. 3 for lithologic key.

rests unconformably on an erosional surface of the Kössen Formation.

3.3. *Upper Schattwald Shale*

We assign the 4.5 m of mixed carbonate–siliciclastic sediments resting above the boundary beds to the upper Schattwald Shale. This is dominated by dark grey and black alternations of marl and thin-bedded limestone. The marl layers are typically 1 cm thick and coarsen upwards into the thicker limestone beds, which average about 10 cm in thickness. Organic carbon values for the upper Schattwald Shale are quite variable, ranging from 0.09 to 2.25 wt%. The excursion in TOC which occurs in sample LO-72 corresponds to a laminated marly interbed and is not characteristic of the adjacent limestones. Thin sections reveal a diverse suite of microfacies, including barren, laminated, lime mudstones, which in places bear evidence for limited replacement by pyrite. Also common, especially in the upper part of the individual beds, are molluscan wackestones and concentrated layers of molluscan packstones.

About 2.5 m above the top of the boundary beds, several horizons contain rounded limestone pebbles, wood fragments and bivalves. The pebbles (Fig. 4D) are between 2 and 10 cm in diameter and sometimes encrusted by ostreids. They contain many circular borings 3–5 mm in diameter, believed to be made by small lithophagid bivalves, together with irregular borings of smaller diameter (1–2 mm). The limestone pebbles contain microfossils, including the foraminifer *Triasina hantkeni*, suggesting that most are derived from the underlying Rhaetian Kössen Formation, exposed and eroded in an intertidal or supratidal environment.

These pebbly beds in the upper Schattwald Shale support a moderately diverse macrofauna dominated by bivalves and trace fossils such as *Thalassinoides*. The bivalve fauna includes *Plagiostoma, Mytilus, Liostrea, Cardinia, Palmoxytoma*, indeterminate lophids and gryphaeid ostreids, typical of earliest Hettangian faunas from elsewhere in the Alps (Golebiowski and Braunstein, 1988; Golebiowski, 1990). Although no ammonoids have been found in the Schattwald Shale at Lorüns, an early Hettangian age for the upper Schattwald Shale is indicated by two late early Hettangian ammonites found in the overlying Lorüns oolite of the quarry and a rich psiloceratid ammonite fauna of the late early Hettangian (e.g., *Psiloceras* sp. and *Waehneroceras* sp.) found in a section in the Schesaplana region at the base of overlying condensed red limestones of Adnet type (Furrer, 1993). Another poorly preserved psiloceratid ammonite was found in the Schesaplana region just above the Schattwald Shale, in a reddish limestone with a bivalve fauna, noted as a typical Adnet Limestone by Furrer (1993).

The upper Schattwald Shale is characterised by a number of different environments. The return of marine invertebrates in various horizons points to shallow subtidal marine conditions, whilst the lack of any true stenohaline elements in the fauna and the presence of bivalves typical of brackish conditions (e.g., mytilids and ostreids) suggests a salinity-controlled environment. Conversely, conditions must have been intertidal or supratidal at other times, as evidenced by the desiccation cracks and reworked Rhaetian pebbles (Fig. 4C,D).

3.4. *Lorüns oolite*

In the Lorüns quarry, the informally named Lorüns oolite is 20–25 m thick. The lower boundary of the Lorüns oolite is arbitrarily taken as the first ooid-bearing carbonate above the Schattwald Shale. This contact appears to be gradational and is marked by a sharp increase in carbonate content. The Lorüns oolite is characterised by massively bedded, dark to light grey oolitic to oncolitic packstone and grainstone. The ooids of up to 1 mm in diameter and oncoids 1–10 mm in diameter show an irregular outline controlled by the nucleus, consisting of echinoderm, brachiopod and mollusc bioclasts. The lower part of the Lorüns oolite is clearly bedded and dominated by packstones with many bioclasts and intraclasts within a lime mud matrix. Massively bedded oolitic grainstones with cross bedding occur only in the upper part. Samples from this unit contained very little organic carbon (<0.5% TOC).

In agreement with earlier interpretations (Furrer, 1993), we believe the Lorüns oolite to represent a broad barrier or bar in a shallow subtidal setting. The presence of stenotopic invertebrates, including echinoderms, attests to normal marine salinities of the shallow-water lagoon or platform edge barrier. Very rare ammonites in the lower part (*Discamphiceras* sp.) suggest a late early Hettangian age for this locality.

4. Geochemistry

To better document environmental changes and constrain the Triassic–Jurassic boundary, we performed a variety of geochemical analyses from sediment samples and outcrop field measurements. We discuss below the results of an analysis of carbon and oxygen stable isotopes and gamma-ray spectrometry.

4.1. Stable isotope geochemistry

Thirty one samples from Lorüns were analysed for their carbon and oxygen isotopic composition (Figs. 5 and 6). The results were obtained from whole-rock analysis of the bulk carbonate and marl samples. The ratios of carbon and oxygen isotopes were determined on a fully automatic VG Isogas PRISM Series I mass spectrometer and are reported in standard $\delta^{13}C$ and $\delta^{18}O$ format in parts per thousand (‰) relative to the PDB standard (Pee Dee Formation Belemnite). Average reproducibility was $< \pm 0.1$‰ for both oxygen and carbon.

The carbon isotopic values recorded in the section vary across the boundary interval (Figs. 5 and 6, Table 1). The Kössen beds at Lorüns are characterised by relatively constant $\delta^{13}C$ values, ranging from 2.0 to 2.5‰. These values can be contrasted to those in the boundary beds of the lower Schattwald Shale, which record a pronounced negative excursion in $\delta^{13}C$ with a value of -0.8‰ at sample LO-45. Above the excursion in the boundary beds, the $\delta^{13}C$ values return to levels similar to the underlying Kössen carbonates and average between 1.7 and 3.2‰.

In general, we interpret little or no diagenetic influence on carbon isotope values across most of the section sampled. The excursion in both carbon and oxygen isotopes within the boundary beds, however, require special explanation in that they may reflect a primary signal or a diagenetic artefact. If the isotope values of the boundary beds were a result of diagenetic alteration due to meteoric (or vadose) secondary recrystallization, one would expect a negative shift in the $\delta^{18}O$, which is not evident in our data. Furthermore, we discount the possibility that the excursion in $\delta^{13}C$ in sample LO-45 of the boundary beds may be a result of oxidised organic matter and subsequent enrichment of the lighter isotope because there was no corresponding negative excursion in $\delta^{18}O$.

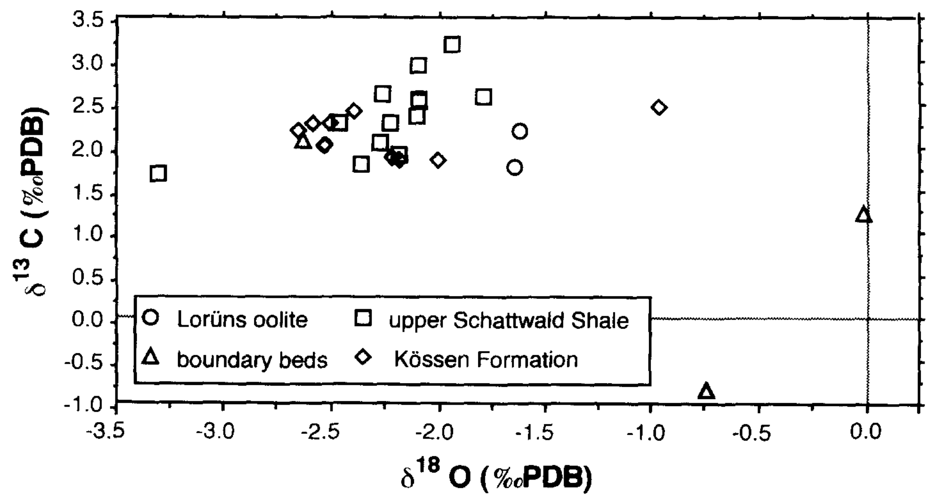


Fig. 6. Scatter plot of $\delta^{13}C$ and $\delta^{18}O$ values for samples across the Triassic–Jurassic boundary.

Table 1
Geochemical data

Sample	Organic C (wt%)	Carbonate C (wt%)	$\delta^{13}C$ (‰PDB)	$\delta^{18}O$ (‰PDB)	cps	Th (ppm)	U (ppm)	K (%)	Th/U	Th/K
Lorüns oolite										
LO-87	0.47	43.13	1.78	−1.65	167.5	1.5	1.2	0.3	1.3	5.0
LO-86	0.19	43.15	2.18	−1.62	164.4	1.2	2.7	0.4	0.4	3.0
Upper Schattwald Shale										
LO-84	0.09	42.66	2.57	−1.79	169.5	4.1	4.5	0.8	0.9	5.1
LO-80	0.36	33.08	3.20	−1.94	170.3	9.5	4.3	1.3	2.2	7.3
LO-75	0.86	38.12	2.93	−2.09	170.8	8.5	4.9	1.5	1.7	5.7
LO-74N	0.89	36.70	2.56	−2.10				1.9		
LO-72	2.25	7.45			169.1	7.7	3.4	1.4	2.3	5.5
LO-70N	0.50	40.85	2.36	−2.11						
LO-70	1.21	32.90	1.80	−2.37	168.1	7.5	3.5	1.2	2.1	6.3
LO-67	0.31	35.78	1.90	−2.18	166.9	7.7	2.7	1.0	2.9	7.7
LO-65	0.30	41.02	2.61	−2.26	171.0	3.7	2.9	1.1	1.3	3.4
LO-62	0.87	38.44	2.04	−2.28	169.7	8.2	5.0	1.9	1.6	4.3
LO-58	0.23	39.20	2.53	−2.09	169.4	7.6	4.8	1.6	1.6	4.8
LO-55	0.46	38.59	2.28	−2.23	168.5	7.2	3.5	1.5	2.1	4.8
LO-52	0.54	39.07	1.67	−3.31	169.0	7.2	3.9	1.7	1.8	4.2
LO-49	0.37	40.92	2.26	−2.47	170.0	8.1	3.1	1.9	2.6	4.3
Boundary Beds (Lower Schattwald Shale)										
LO-47	3.35	7.47			172.6	14.3	2.3	3.3	6.2	4.3
LO-45	3.17	6.93	−0.82	−0.75	172.1	13.8	2.6	3.3	5.3	4.2
LO-42	1.66	21.07	1.24	−0.02	179.4	14.1	4.1	2.7	3.4	5.2
LO-41	0.29	36.79	2.07	−2.64	170.8	13.6	2.9	2.2	4.7	6.2
LO-40	0.47	19.38			169.5	9.3	3.5	2.0	2.7	4.7
Kössen Formation										
LO-39	0.62	37.29	2.03	−2.53	169.7	8.3	3.2	1.6	2.6	5.2
LO-37	1.48	28.39	1.88	−2.22	169.8	6.3	1.9	1.3	3.3	4.8
LO-35	1.50	28.64	1.85	−2.01	172.6	4.9	2.3	1.3	2.1	3.8
LO-34	1.16	31.64	1.84	−2.18	166.0	7.1	1.4	1.3	5.1	5.5
LO-32	0.11	42.07	2.20	−2.66	165.0	4.3	1.4	0.8	3.1	5.4
LO-31	0.29	43.39	2.26	−2.51	166.4	5.4	1.8	0.9	3.0	6.0
LO-30	0.43	42.82	2.26	−2.59	167.7	2.5	1.6	0.5	1.6	5.0
LO-27	1.50	38.15	2.47	−0.97	165.3	2.3	1.5	0.9	1.5	2.6
LO-25	0.53	41.28	2.41	−2.40	164.2	2.5	1.8	0.5	1.4	5.0

Alternatively, there may be some diagenesis due to organic processes, giving rise to isotopically light carbonate carbon. A breakdown in organic matter could shift the $\delta^{13}C$ values negatively and may also be responsible for the corresponding positive shift in $\delta^{18}O$. These isotopic data can be contrasted with results from the Kendelbach section (Hallam and Goodfellow, 1990; Hallam, 1994; Morante and Hallam, 1996), which show a diagenetic overprint characterised by co-varying negative excursions in $\delta^{13}C_{carb}$ and $\delta^{18}O$ values and a positive excursion in $\delta^{13}C_{org}$ within the Grenzmergel.

The negative excursion in $\delta^{13}C$ can be interpreted as resulting from primary precipitation of caliche developed about 20 cm below the inferred paleosol horizon. This interpretation is corroborated by colour changes from the same interval in which the sediments are light green. Furthermore, formation of caliche would be predicted, given soil development within arid environments such as has been suggested for the margins of the western Tethys at low palaeolatitudes (e.g., Parrish, 1993). Given that both carbon and oxygen isotopic values in pedogenic carbonates can be influenced by a number of factors, including the presence of vegetation, depth and temperature of carbonate formation, and soil respiration rate (Cerling, 1991), it is difficult to attribute a specific pedogenic mechanism for the excursion.

Alternatively, the boundary excursion in carbon isotopes may represent a short-lived decrease in primary productivity during deposition of the boundary beds. The observed fall in $\delta^{13}C$ values can be compared to those known from other mass extinctions such as the Permian–Triassic and Cretaceous–Tertiary (e.g., Magaritz, 1989), which have been interpreted as resulting from a decrease in primary productivity (e.g., Arthur et al., 1987; Zachos et al., 1989; Holser et al., 1995). Although the temporal duration of any productivity decline cannot be ascertained, the nearly 0.5 m of the upper boundary beds (including an overlying sequence boundary) would allow sufficient time for the collapse and subsequent rapid recovery of marine and non-marine ecosystems after such a short-lived perturbation.

In spite of short-term changes within the boundary beds and occluded record within any hiatus, the $\delta^{18}O$ for the sequence remains relatively constant, suggesting that palaeotemperatures (or other controls on oxygen isotopic composition) were not altogether dissimilar between the Rhaetian Kössen Formation and Lorüns oolite. Notwithstanding possible diagenetic differences in the Kendelbachgraben discussed above, these results are in agreement with those reported by Hallam and Goodfellow (1990) and Morante and Hallam (1996) and differ from those reported by Fabricius et al. (1970), who noted a long-term negative shift in $\delta^{18}O$, and thus palaeotemperature, between uppermost Triassic and lowermost Jurassic sediments.

4.2. *Gamma-ray spectrometry*

Abundances of uranium, thorium, and potassium were measured from the section with a portable multi-channel scintillation spectrometer and detector (an Exploranium GR 320 and GPS 21 respectively). Such data collected from outcrop gamma-ray spectrometers are increasingly becoming an important tool in interpreting depositional environments. For example, low Th/U ratios, usually values below 3.0, are generally considered to reflect abundant authigenic U formed under anoxic conditions in marine mudstones (Myers and Wignall, 1987) and higher values, usually above 7.0, are characteristic of continental deposits (Adams and Weaver, 1958). Caution must be exercised in interpreting ancient oxygen levels from Th/U ratios because both thorium and uranium concentrations are highly dependent upon a host of other sedimentary constituents, such as carbonate content, which may provide extremely low Th/U values in rocks deposited in fully oxygenated environments (e.g., Adams and Weaver, 1958).

The gamma-ray data (Table 1, Fig. 5) show several significant excursions across the measured section. The signal strength, measured as number of counts per second (cps), is relatively high, thus permitting short count times (2 min) and a precision better than 5%. The Th/K ratios are rather constant, at about 4, across the section. A noted departure occurs high in the Schattwald Shale where the Th/K ratios are highly variable, showing increases to nearly 8 in sample LO-67. The reason for this variability and general increase may be due to decreased K-bearing clay minerals in the marly interbeds or post-depositional removal of potassium. A smaller peak in the Th/K ratio occurs about 0.4 m below the top of the boundary beds. This small peak in the Th/K ratio is smaller than would be expected during removal of water-soluble potassium by aqueous medium.

The Th/U ratios are all very low; in only six measurements are the ratios above 3.0. The higher Th/U ratios that occur within the boundary interval could be due to their higher oxidised state and approach levels of some deltaic and continental deposits. The highest Th/U ratios are recorded at the top of the boundary beds (samples LO-45 and LO-47) indicating a lack of authigenic uranium, as would be expected in a paleosol and exactly opposite of what would be expected in an anoxic, sulphate-reducing environment. The low Th/U ratios for most of the remaining samples are due more to a depletion in thorium (see Table 1) typical of many marine carbonates (e.g., Adams and Weaver, 1958) rather than an increase in authigenic uranium, as would be expected due to anoxia. This explanation is further corroborated by palaeoecologic evidence derived from the diverse and abundant fossil assemblages recovered from the same levels.

5. Causes for extinction and biotic recovery

Lithologic, palaeontologic and geochemical analysis of the Lorüns section leads us to interpret the Lorüns section as being composed of several major palaeoenvironments which may have, at least locally, controlled diversity (Fig. 7). In sequence stratigraphic terms, a highstand system tract is delimited by the Kössen Formation shallowing upwards into the boundary beds of the lower Schattwald Shale. A sequence boundary, possibly corresponding with the systemic boundary, is developed on top of the boundary bed and, in turn, is overlain by the deepening-upwards upper Schattwald Shale–Lorüns oolite which represents a transgressive system tract. The relatively simple regression–transgression scenario is repeated elsewhere in the Northern Calcareous Alps and elsewhere in the western Tethys and northwest Europe (Tollmann, 1976; Hallam, 1981; McRoberts, 1994).

If the systemic boundary is represented by the sequence boundary, the cause of extinction can only be determined indirectly from the Lorüns section. In spite of this apparent drawback, the effects of extinction and the subsequent biotic recovery can be recorded in the faunal and palaeoecologic characteristics of the upper Schattwald Shale, especially when compared with those of the older Kössen Formation. It should be noted that at Lorüns none of the upper Kössen taxa reappear in Jurassic sediments. Thus, at least locally, the extinction was complete; a biotic response expected, given different palaeoenvironments on either side of the boundary. The post-extinction recovery as seen in the Lorüns section was apparently quite rapid, achieving fully habitable marine conditions less than 2 m above the top of the boundary beds. These fossiliferous beds are more diverse than any within the measured parts of the Kössen Formation and the lower part of the Schattwald Shale.

Our palaeoenvironmental interpretation of the Lorüns section supports a decrease in water depths in the latest Rhaetian, culminating in the sequence boundary and paleosol development. A fall in sea-level would naturally affect local populations and may well be responsible for the disappearance of the Kössen fauna at Lorüns. The regional and

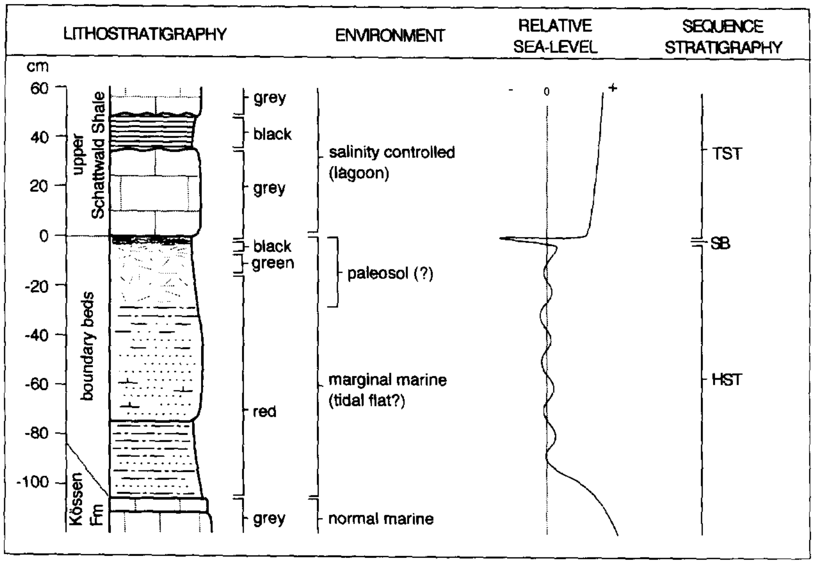


Fig. 7. Expanded view of boundary beds and local paleoenvironmental interpretation. See Fig. 3 for lithologic key. *HST* = highstands system tract; *SB* = sequence boundary; *TST* = transgressive systems tract.

global effect of sea level are difficult to assess and cannot be determined at Lorüns alone. As has been discussed elsewhere (McRoberts, 1994), habitable area reduction due to a fall in sea-level does not appear to have been sufficient to account for the magnitude or mode of extinction at the end of the Triassic. In addition, a sharp increase in water depth and the role of a pronounced period of anoxia can be ruled out as a factor in the extinction: the earliest Jurassic sediments at Lorüns are not only shallow and probably well within the zone of wave-induced surface mixing but they also contain a moderately diverse fauna lacking any forms specifically adapted to low-oxygen environments (e.g., flat clams). Furthermore, given the theoretical and empirical problems associated with inducing a mass extinction based solely on species–area effects [both regression and anoxia models are based on this premise (McRoberts and Aberhan, 1997)], alternative factors which may have contributed to the extinction should be explored.

Clues to the cause of extinction may be obtained from the surviving fauna in the Schattwald Shale. The observed bivalve fauna from the Schattwald Shale at Lorüns is qualitatively identical to nearly all earliest Jurassic faunas from the Northern Alps as well as northwest Europe, suggesting a common response to regional, if not global, phenomena. That the earliest Jurassic fauna of Lorüns (and elsewhere in Alpine Europe) is dominated by epifaunal, filter-feeding bivalves may be due to several reasons. As has been shown elsewhere, epifaunal bivalves selectively survived the extinction in Alpine and northwest Europe when compared to infaunal bivalves (McRoberts and Newton, 1995; McRoberts et al., 1995). Based on ecological and physiological constraints, this selective survival is interpreted to have been caused by a decrease in primary productivity rather than the spread of anoxic waters (McRoberts and Newton, 1995; McRoberts et al., 1995). It is important to note the absence of protobranch bivalves and low-oxygen tolerant opportunists in the Schattwald Shale, which would be expected in reduced-oxygen environments with increased organic detritus. Instead, the dominance of epifaunal taxa may reflect an ecological response to environmental parameters, such as reduced salinity, in which epifaunal eurytopic faunas are able to tolerate brackish conditions.

Because of the poor biostratigraphic resolution of the boundary beds and the presence of a possible sequence boundary, it is impossible to determine the temporal duration of the extinction from the Lorüns section. Regardless of this shortcoming, the nearly 1 m thick boundary bed (in addition to the sequence boundary) should have provided ample time for a variety of oceanographic phenomena, including a productivity decline, to have an effect. It is important to note that any ocean chemistry changes, such as might be expected from a productivity decline, must be of sufficient duration (10^5 yr) to be discernible in isotopic data derived from most sedimentary rocks (Kump, 1991). It is therefore entirely plausible that whatever perturbation occurred may have been both ecologically prolonged enough to have had a deleterious effect on the marine biota and geologically short enough to be preserved in the Lorüns sediments.

6. Conclusions

(1) Geochemical analyses support the above interpretation of palaeoenvironments and sea-level changes. The Rhaetian–Hettangian sediments at Lorüns record a regional regression–transgression couplet. The generally regressive upper Kössen Formation is dominated by shallow-water stenotopic taxa representing normal marine conditions. This, in turn, is overlain by the predominantly siliciclastic boundary beds of the lower Schattwald Shale upon which a paleosol possibly developed. The Triassic–Jurassic boundary is interpreted as a sequence boundary at the top of the paleosol, below the upper part of the Schattwald Shale. Above the boundary beds, the upper Schattwald Shale is characterised by thin-bedded marl and dark limestone beds with a Hettangian macrofauna dominated by epifaunal filter-feeding bivalves, including ostreids and mytilids, which suggest a shallow, subtidal, salinity-controlled environment typi-

cal of a interplatform lagoon. Anoxic or dysoxic conditions were not prevalent in the lowermost Jurassic Schattwald Shale. Carbonate production began again in the later Early Hettangian with the development of the Lorüns oolite, a shallow, subtidal, oolitic and oncolitic unit bearing echinoderms, indicative of normal marine conditions.

(2) Geochemical analyses support the above interpretation of palaeoenvironments and sea-level changes. The negative excursion in $\delta^{13}C$ and positive excursion in $\delta^{18}O$ at the boundary beds is entirely consistent with the interpretation that there was a short-term decrease in primary productivity across the Triassic–Jurassic boundary. It may, however, reflect the effects of organic diagenesis or the development of caliche during paleosol formation. The spectral gamma-ray analysis of potassium, uranium, and thorium suggest that there was no protracted period of marine anoxia within the Triassic–Jurassic boundary beds. Very high Th/U ratios from within the boundary beds may reflect higher oxidation states of terrestrial deposits. Low Th/U ratios from the remainder of the section are a result of reduced thorium in carbonate-rich sediments and not of authigenic uranium in anoxic sediments.

(3) Like other known mass extinction boundaries, the post-extinction biotic recovery was apparently rapid, as demonstrated in the moderately diverse molluscan assemblage about 2 m above the interpreted boundary and probably within the lower Hettangian *Psiloceras* ammonoid zone. The post-extinction fauna from Lorüns is dominated by filter-feeding bivalves including epifaunal *Mytilus, Plagiostoma, Palmoxytoma*, and ostreids, and infaunal *Cardinia*. While this assemblage may be viewed as the recovery fauna, it consists of an unremarkable assemblage typical of salinity-controlled shallow-water environments and is qualitatively similar to the earliest Jurassic faunas elsewhere in the Northern Calcareous Alps and northwest Europe.

(4) The ultimate cause of the ecologic factors leading to extinction cannot be determined directly from the section at Lorüns nor can it be determined from the other sections which are advocated as being 'complete', yet show evidence of a hiatus. Thus, clues obtainable from the Lorüns section can only be derived from the sediments, geochemistry, and faunas from beds adjacent to the sequence boundary. While these ecostratigraphic and geochemical data cannot rule out a loss of habitable ecospace due either to regression or anoxia, they are entirely consistent with a reduction in primary productivity leading to the mass extinction at the end of the Triassic.

Acknowledgements

C.A.M. acknowledges financial support provided by the Alexander von Humboldt Foundation and the research facilities provided by Würzburg University. D.S.J. acknowledges financial support provided by NSF Grant EAR-9316295. Thoughtful reviews by M. Gaetani, P. Wignall, and F. Surlyk led to a much improved manuscript. Thanks to A.L.A. Johnson for identifying some of the bivalves, J. Scallan for assisting in the field work and reading an earlier draft of the manuscript, A. Hallam, and L. Derry for comments, R. Schlatter for determination of the ammonites, H. Stollhofen for use of the gamma-ray spectrometer, and Vorarlberger Zementwerk Lorüns AG for allowing access to the locality.

References

Adams, J.A.S., Weaver, C.E., 1958. Thorium-to-uranium ratios as indicators of sedimentary processes: example of concept of geochemical facies. AAPG Bull. 42 (2), 387–430.

Arthur, M.A., Zachos, J.C., Jones, D.S., 1987. Primary productivity and the Cretaceous/Tertiary boundary event in the oceans. Cretaceous Res. 8, 43–54.

Badjukov, D.D., Lobitzer, H., Nazarov, M.A., 1987. Quartz grains in the Triassic–Jurassic boundary sediments from Northern Limestone Alps, Austria. Lunar Planet. Sci. Lett. 28, 38–39.

Benton, M.J., 1986. More than one event in the late Triassic mass extinction. Nature 321, 857–861.

Bertle, H., Furrer, H., Loacker, H., 1979. Geologie des Walgaues und des Montafons mit Berücksichtigung der Hydro-

geologie (Exkursion G am 20. April 1979). Jahresber. Mitt. Oberrheinischen Geol. Ver. 61, 101–115.
Bice, D.M., Newton, C.R., McCauley, S., Reiners, P.W., McRoberts, C.A., 1992. Shocked quartz at the Triassic–Jurassic boundary in Italy. Science 255, 443–446.
Cerling, T.E., 1991. Carbon dioxide in the atmosphere: Evidence from Cenozoic and Mesozoic paleosols. Am. J. Sci. 291, 339–376.
Cuny, G., 1995. French vertebrate faunas and the Triassic–Jurassic boundary. Palaeogeogr. Palaeoclimatol. Palaeoecol. 119, 343–358.
Dagys, A.S., Dagys, A.A., 1994. Global correlation of the terminal Triassic. Mém. Géol. (Lausanne) 22, 25–34.
Fabricius, F.H., Fiedrichsen, V., Jacobshagen, V., 1970. Paläotemperaturen und Paläoklima in Obertrias und Lias der Alpen. Geol. Rundsch. 59, 805–826.
Fowell, S.J., Olsen, P.E., 1993. Time calibration of Triassic–Jurassic microfloral turnover, eastern North America. Tectonophysics 222, 361–369.
Furrer, H., 1993. Stratigraphie und facies der Trias–Jura-Grenzschichten in den Oberostalpinen Decken Graubündens. Ph.D. Thesis, Univ. Zurich.
Golebiowski, R., 1990. The Alpine Kössen Formation: a key for European topmost Triassic correlations. Albertiana 8, 25–35.
Golebiowski, R., Braunstein, R.E., 1988. A Triassic–Jurassic boundary section in the Northern Calcareous Alps (Austria). IGCP Project 199, Rare Events in Geology, Abstracts of Lectures and Excursions Guide, vol. 15, pp. 39–46.
González-León, C.M., 1997. The Triassic–Jurassic boundary in the Antimonio Formation from new evidences. In: González-León, C.M., Stanley, G.D. (Eds.), Abstracts of the International Workshop on the Geology of Sonora. Instituto de Geología, UNAM, Hermosillo, pp. 41–44.
González-León, C.M., Taylor, D.G., Stanley, G.D., 1996. The Antimonio Formation in Sonora, Mexico, and the Triassic–Jurassic boundary. Can. J. Earth Sci. 33, 418–428.
Hallam, A., 1981. The end-Triassic bivalve extinction event. Palaeogeogr. Palaeoclimatol. Palaeoecol. 35, 1–44.
Hallam, A., 1990. The end-Triassic extinction event. Geol. Soc. Am. Spec. Pap. 247, 577–583.
Hallam, A., 1990. Correlation of the Triassic–Jurassic boundary in England and Austria. J. Geol. Soc. London 147, 421–424.
Hallam, A., 1994. Strontium isotope profiles of Triassic–Jurassic boundary sections in England and Austria. Geology 22, 1079–1082.
Hallam, A., Goodfellow, W.D., 1990. Facies and geochemical evidence bearing on the end-Triassic disappearance of the Alpine reef system. Historical Biol. 4, 131–138.
Hodges, P., 1994. The base of the Jurassic System: new data on the first appearance of *Psiloceras planorbis* in southwest Britain. Geol. Mag. 131 (6), 841–844.
Holser, W.T., Magaritz, M., Ripperdan, R.L., 1995. Global isotopic events. In: Walliser, O.H. (Ed.), Global Events and Event Stratigraphy in the Phanerozoic. Springer, Berlin, pp. 63–88.
Kump, L.R., 1991. Interpreting carbon-isotope excursions: Strangelove oceans. Geology 19, 299–302.
Laws, R.A., 1982. Late Triassic depositional environments and molluscan associations from west-central Nevada. Palaeogeogr. Palaeoclimatol. Palaeoecol. 37, 131–148.
Magaritz, M., 1989. ^{13}C minima follow extinction events: a clue to faunal radiation. Geology 17, 337–340.
McRoberts, C.A., 1994. The Triassic–Jurassic ecostratigraphic transition in the Lombardian Alps, Italy. Palaeogeogr. Palaeoclimatol. Palaeoecol. 110, 145–166.
McRoberts, C.A., Aberhan, M., 1997. Marine diversity and sea-level changes: numerical tests for association using Early Jurassic bivalves. Geol. Rundsch. 86, 160–167.
McRoberts, C.A., Newton, C.R., 1995. Selective extinction among end-Triassic European bivalves. Geology 23 (2), 102–104.
McRoberts, C.A., Newton, C.R., Allasinaz, A., 1995. End-Triassic bivalve extinction: Lombardian Alps, Italy. Historical Biol. 9, 297–317.
Morante, R., Hallam, A., 1996. Organic carbon isotopic record across the Triassic–Jurassic boundary in Austria and its bearing on the cause of the mass extinction. Geology 24, 391–394.
Muller, S.W., Ferguson, H.G., 1939. Mesozoic stratigraphy of the Hawthorne and Tonopah quadrangles, Nevada. Geol. Soc. Am. Bull. 50, 1573–1624.
Myers, K.J., Wignall, P.B. 1987. Understanding Jurassic organic-rich mudrocks — new concepts using gamma-ray spectrometry and Palaeoecology: examples from the Kimmeridge Clay of Dorset and the Jet rock of Yorkshire. In: Leggett, J.K., Zuffa, G.G. (Eds.), Marine Clastic Sedimentology. Grahm and Trotman, London, pp. 172–189.
Olsen, P.E., Shubin, N.H., Anders, M.H., 1987. New Early Jurassic tetrapod assembledges constrain the Triassic–Jurassic tetrapod extinction event. Science 237, 1025–1029.
Parrish, J.T., 1993. Climate of the supercontinent Pangea. J. Geol. 101, 215–233.
Piller, W.E., 1981. The Steinplatte reef complex, part of an Upper Triassic carbonate platform near Salzburg, Austria. In: Toomey, D.F. (Ed.), European Fossil Reef Models. SEPM Spec. Publ. 30, 261–290.
Reiser, K.A., 1920. Geologie der Hindelanger und Pfrontener Berge im Allgäu. Geognostische Jahresh. 33, 57–198.
Sepkoski, J.J.J., 1996. Patterns of Phanerozoic extinction: a perspective from global data bases. In: Walliser, O.H. (Ed.), Global Events and Event Stratigraphy in the Phanerozoic. Springer, Berlin, pp. 35–51.
Stanton, R.J., Flügel, E., 1989. Problems with reef models: the Late Triassic Steinplatte "reef" (Northern Alps Salzburg/Tyrol, Austria). Facies 20, 1–138.
Suess, E., Von Mojsisovics, E., 1868. Studien über die Gliederung der Trias und Jurabildungen in den östlichen Alpen 2. Die Gebirgsgruppe des Osterhornes. Jahrb. K.K. Geol. Reichsanstalt 18, 167–200.
Tollmann, A., 1976. Analyse des Klassischen Nordalpinen Mesozoikums. Monographie der Nördlichen Kalkalpen. Franz Deuticke, Wien, 580 pp.
Von Hillebrandt, A., 1994. The Triassic/Jurassic boundary and

Hettangian biostratigraphy in the area of the Utcubamba Valley (Northern Peru). Geobios 17, 297–307.

Warrington, G., Cope, J.C.W., Ivimey-Cook, H.C., 1994. St. Audrie's Bay, Somerset, England: a candidate global stratotype section and point for the base of the Jurassic system. Geol. Mag. 131 (2), 191–200.

Whittaker, A., Green, G.W., 1983. Geology of the Country around Weston-super-Mare. Mem. Br. Geol. Surv., 147. H.M.S.O., London.

Zachos, J.C., Arthur, M.A., Dean, W.E., 1989. Geochemical evidence for the suppression of pelagic marine productivity at the Cretaceous/Tertiary boundary. Nature 337, 61–64.