Upper Triassic (Carnian) mud mounds from northern Sichuan (China)

JOBST WENDT

Geologisch-Paläontologisches Institut der Universität, Sigwartstrasse 10, D-72076 Tübingen, Germany.
E-mail: jobst.wendt@uni-tuebingen.de

ABSTRACT:

WENDT, J. 2001. Upper Triassic (Carnian) mud mounds from N-Sichuan (China). *Acta Geologica Polonica*, **51** (1), 1-13, Warszawa.

During the late Carnian a great number of carbonate mud mounds were constructed along the submerged north-western margin of the Yangzi Platform in Sichuan, in the transition zone between the Songpan Garze Trough in the west and the Chuan Dian Shelf in the east. Individual mounds are up to 80 m thick and have base diameters of up to several hundred metres. Thickness ratios between mound and intermound deposits are about 5 : 1 with mound slopes not exceeding 15°. The bulk of the rock volume consists of a microsparitic matrix which due to its peloidal structure and common laminated crusts is probably a cyanobacterial precipitate. Siliceous sponges contributed to mound stabilization but did not form a rigid framework. Several other invertebrate groups (mainly crinoids) inhabitated the mound surfaces and were transported into adjacent depressions. Stromatactoid cavities, which are so characteristic for Palaeozoic mud mounds, are extremely rare. Generally they are completely occluded with late diagenetic blocky spar; only a few cavities are lined with an early marine RFC cement. The latter is distinguished by relatively heavy $\delta^{18}O$ signatures of -3,4‰ PDB which contrast with the isotopic composition of the burial cements displaying mean values of -9,7 ‰ $\delta^{18}O$ PDB. $^{87}Sr/^{86}Sr$ ratios of early cements, matrix and non-luminescent brachiopod shells fit well into the curve of the isotopic evolution of the Phanerozoic seawater.

Key words: Triassic, Carnian, Mud mounds, China, Diagenesis, Stable isotopes.

INTRODUCTION

Mud mounds are a common type of carbonate buildup which are widely distributed in marginal and deeper ramp settings. In contrast to reefs, mud mounds lack a rigid framework and consist predominantly of carbonate mud, often with many interspersed stromatactoid cavities which were occluded by calcite cements and/or internal sediment. Spectacular examples of mud mounds have been described from all over the world from Palaeozoic environments (summary in PRATT 1995). It is evident that with the demise of Palaeozoic reef-builders at the end of the Permian, mud mounds were also subject to a considerable decline. In spite of their rapid re-establishment in the early Triassic (LEHRMANN 1999), they never again attained their former importance, and examples of typical mud mounds of Mesozoic and Cenozoic age are extremely rare. They are distinguished from Palaeozoic counterparts by different associations of organisms, a more gentle relief and the scarceness or absence of stromatactoid cavities. The few well-known post-Palaeozoic mud mounds are either of uncertain extent and geometry (MATHUR 1975) or belong to the mudbank type which developed into a reefal facies (CALVET & TUCKER 1995). In contrast, the Upper Triassic mud mounds in Sichuan resemble the spectacular Palaeozoic ones in terms of geometry and spatial concentration. It is the aim of this

study to present the organic, sedimentologic and diage-
netic inventory of this rare type of carbonate buildup. A
compilation of the observations gathered during a visit
to the Longmenshan in northern Sichuan in 1997
appears imminent because extensive quarrying in
recent years will sooner or later lead to a total disap-
pearance of the majority of these unique mounds.

PREVIOUS WORK

The study of the Sichuan mud mounds was initiated
by their wealth of siliceous sponges among which are
the earliest representatives of the order Lychniscosa.
They were discovered in the mid-seventies by WU who
gave a first account of them in 1977 (WU & al. 1977).
Due to the predominance of sponges as presumed
frame builders, these buildups were first considered as
reefs or patchreefs (FAN 1979; WU & al. 1979; WU &

ZHANG, 1982, 1983; WU 1984). The observation that
these organisms do not constitute a rigid framework
and hence the mud mound nature of these massive
limestones was first made by WENDT & al. (1989).
Because of the inaccessibility of the major part of the
mound area at that time, the mound-intermound rela-
tionships and the diagenetic history of the mound car-
bonates had to be largely ignored in that study. Later,
the highly diverse sponge fauna has been systematically
described by WU (1989a, 1990).

GEOGRAPHIC AND GEOLOGIC SETTING

The mound tract is situated on the eastern margin
of the Longmenshan (shan = mountains) close to the
boundary with the Sichuan Basin farther east. Due to
the latitudinal and climatic position of this area, a dense
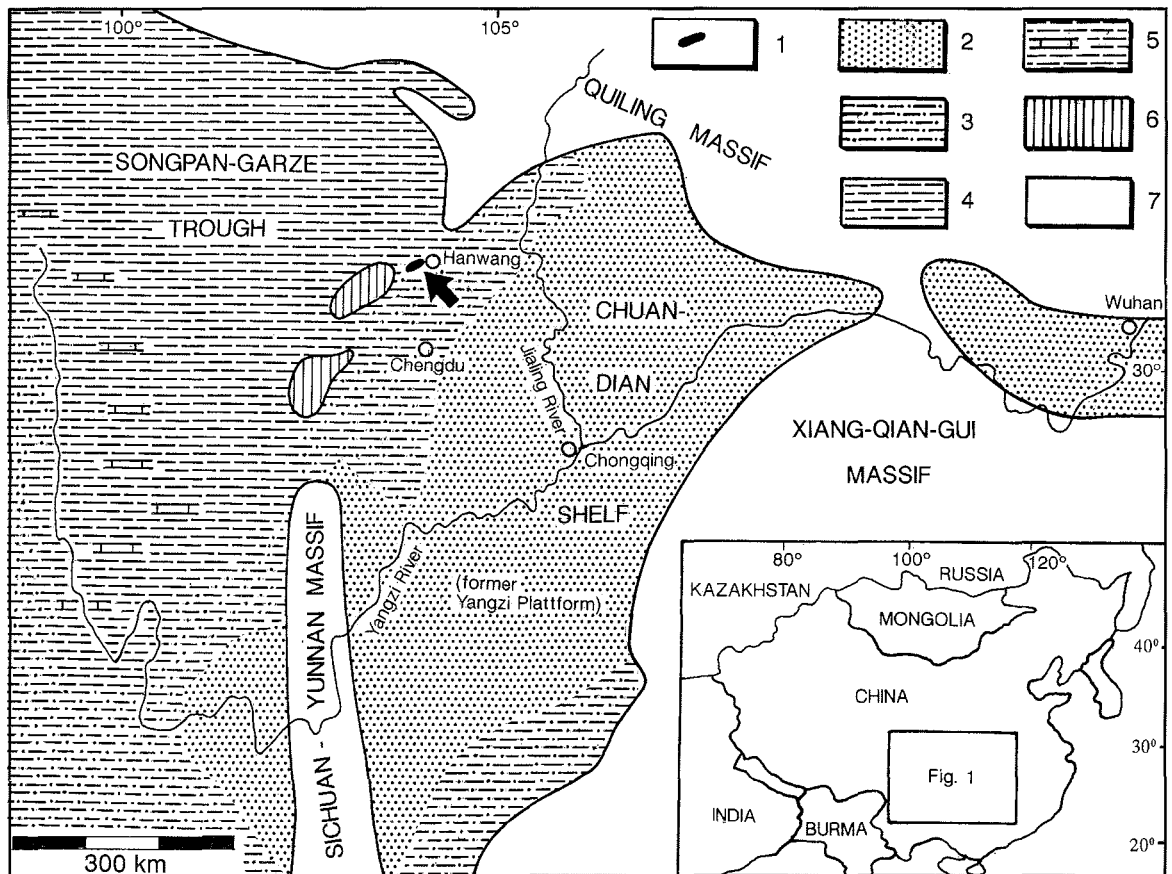vegetation covers the deeply eroded mountains and

Fig. 1. Palaeogeography and facies patterns of the Upper Triassic in south China with location of the study area (modified from WENDT & al. 1989); 1
= mud mound belt (arrowed, area of inset in Text-fig. 2), 2 = onshore basinal and paralic clastics, 3 = clastic shelf deposits, 4 = fine-grained clastics
and flysch (marginal sea), 5 = clastics, carbonates and volcanics (island arc), 6 = shelf marginal barrier (submarine shoals), 7 = land areas (including
inland basins)

natural outcrops can only be studied in limited roadcuts and along the few rivers that cut the NE-SW running tectonic units. Much more detailed observations can be made on fresh rock surfaces in the numerous quarries in which these pure limestones are exploited for cement production in the newly established factory near the township of Hanwang. Intense quarrying, however, will sooner or later result in the total destruction of the mounds examined in this study. The entire area is still subject to considerable uplift causing numerous cracks and brittle zones even in freshly exposed quarry walls which are therefore almost unaccessible (Pl. 1, Fig. 1).

Palaeogeographically the mound area is situated at the northwestern margin of the Yangzi Platform, a vast carbonate platform which existed from the late Precambrian into the Middle Triassic (ENOS & al. 1998). At the Middle/Late Triassic transition almost the entire Yangzi Platform situated in the provinces of Yunnan, Guizhou, Guangxi and southern Sichuan became emerged. Only the northwestern margin in northern Sichuan was drowned and covered with dark mudstones (LIU & XU 1994). A shallow marine gulf extended from the deep marine Songpan-Garze Trough in the west onto the former platform margin farther east (FAN 1979). This Upper Triassic embayment was limited by the Quiling Massif in the north and the Sichuan-Yunnan Massif in the south (Text-fig. 1). The mud mounds were constructed on the gently sloping seafloor in a transitional zone between the Chuan-Dian Shelf in the east and the Songpan-Garze Trough in the west.

STRATIGRAPHY

WU (1989b) subdivided the Middle and Upper Triassic deposits of the study area into the following formations (Text-fig. 2):

Tianjingshan Formation (Ladinian)

This formation consists of thick-bedded white carbonates (generally dolomite, rarely limestone) in which birdseye structures, cyanobacterial lamination, stromatolites and storm layers indicate deposition in intertidal to shallow subtidal environments. In some places intensely brecciated zones of very limited extent occur which cross-cut the normal bedding. The clasts of the breccias often show a good fitting and sedimentary contacts towards the adjacent undisturbed rocks (Pl. 1, Fig. 2). These features suggest an *in-situ* brecciation of narrow zones within the normal sequence and hence a synsedimentary tectonic origin of the breccias which may be interpreted as an early stage of the fragmentation of the Yangzi Platform. Rare findings of pelecypods and brachiopods point to a Ladinian age of the Tianjingshan Formation (WU 1989b).

Lower Hanwang Formation (lower Carnian?)

The carbonates of the Tianjangshan Formation are overlain, locally with a sharp boundary, by white, thick-bedded oolitic grainstones. The ooids are poorly to medium-sorted and grew around peloids and skeletal fragments as nuclei. The latter generally show micritic envelopes. The ooids are cemented by blocky spar which represents one generation only. Apart from some undeterminable mollusc remains, a few crinoids, brachiopods and ostracodes, this unit is poorly fossiliferous and has not yet been precisely dated. Due to the age of the under- and overlying rock units, an early Carnian age is most feasable. The lower Hanwang Formation is 25-60 m thick and represents an oolite shoal along the northwestern margin of the Yangzi carbonate platform.

Upper Hanwang Formation (upper Carnian)

The largely persistent facies pattern of the Ladinian/?lower Carnian becomes more diversified during the late Carnian. In various places mud mounds were established on top of the underlying carbonates. They interfinger with clays and marls with intercalated mud- to wackestones. Locally these mounds overlie the oolites of the lower Hanwang Formation directly with a sharp contact suggesting a minor break in sedimentation (Text-fig. 3). In other sites a several metres thick transitional zone of bituminous wackestones with abundant crinoids, brachiopods and mollusc remains constitutes the lower part of the upper Hanwang Formation (Text-fig. 2; Pl. 1, Fig. 1). The basal portion of this sequence contains still some (probably reworked) ooids while the upper part shows numerous hexactinellid sponges and thus is transient into the mound lithology proper. The poor outcrops of mound and intermound rocks do not allow reliable estimates of their total thickness. Moreover, numerous faults and overthrusts complicate the reconstruction of a complete stratigraphic column. In outcrop, individual mounds are up to 80 m thick; the equivalent intervening off-mound lithologies attain only about one fifth of this thickness (Text-fig. 2). In relation to the distance from the adjacent mound, lithology and fauna of the intermound sequence are highly variable. Close to the mounds, transported sponge skeletons are common (Pl. 1, Fig. 3). Their decrease in number and
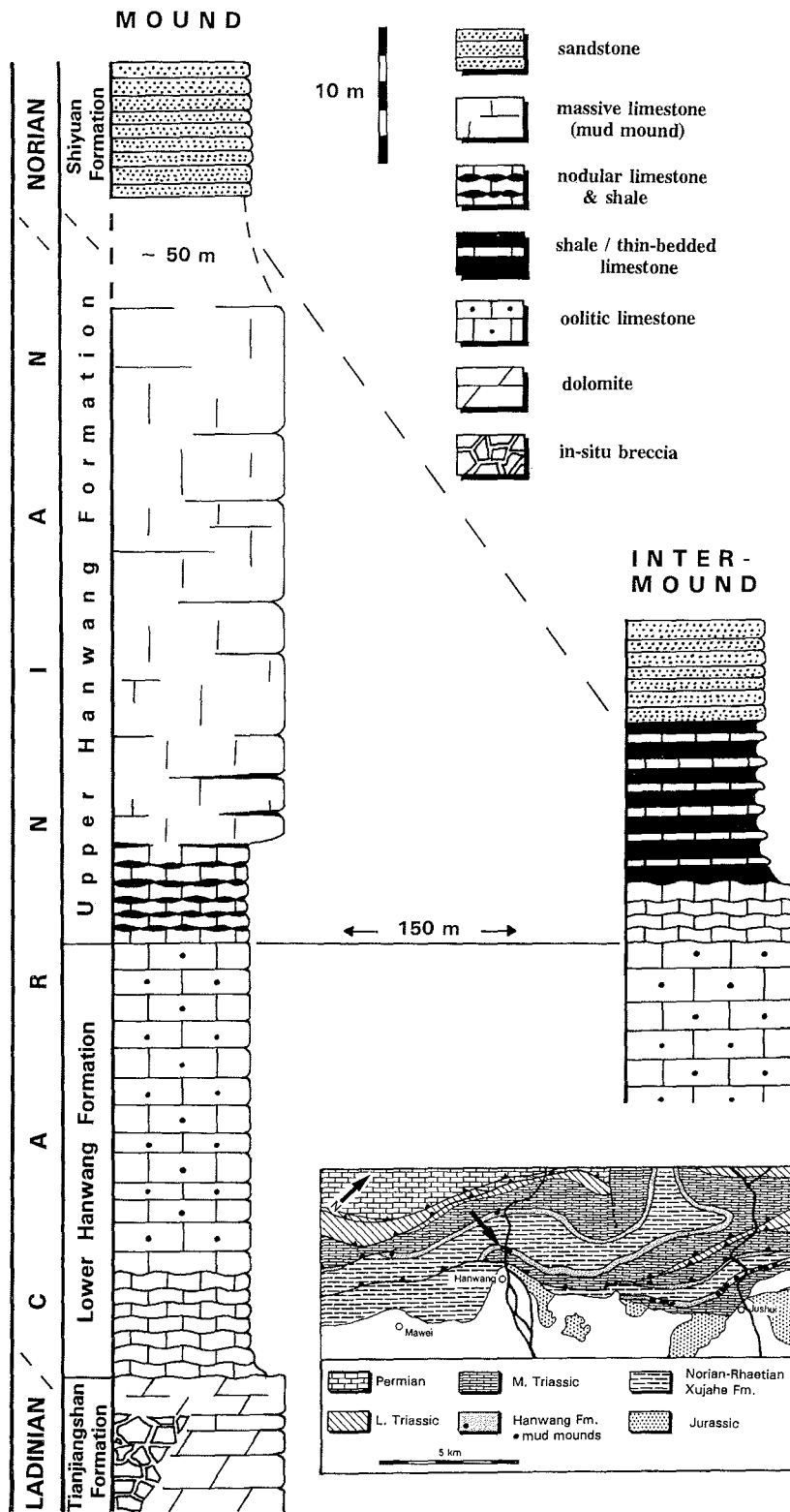
Fig. 2. Lithostratigraphy of the upper Ladinian to lower Norian formations in northern Sichuan with correlation of mound and intermound section; right side of Hanwang River (C 36, C 37); note approximate 5 : 1 thickness ratio of mound to intermound sequence. Inset: Location of section (modified from WENDT & *al.* 1989)
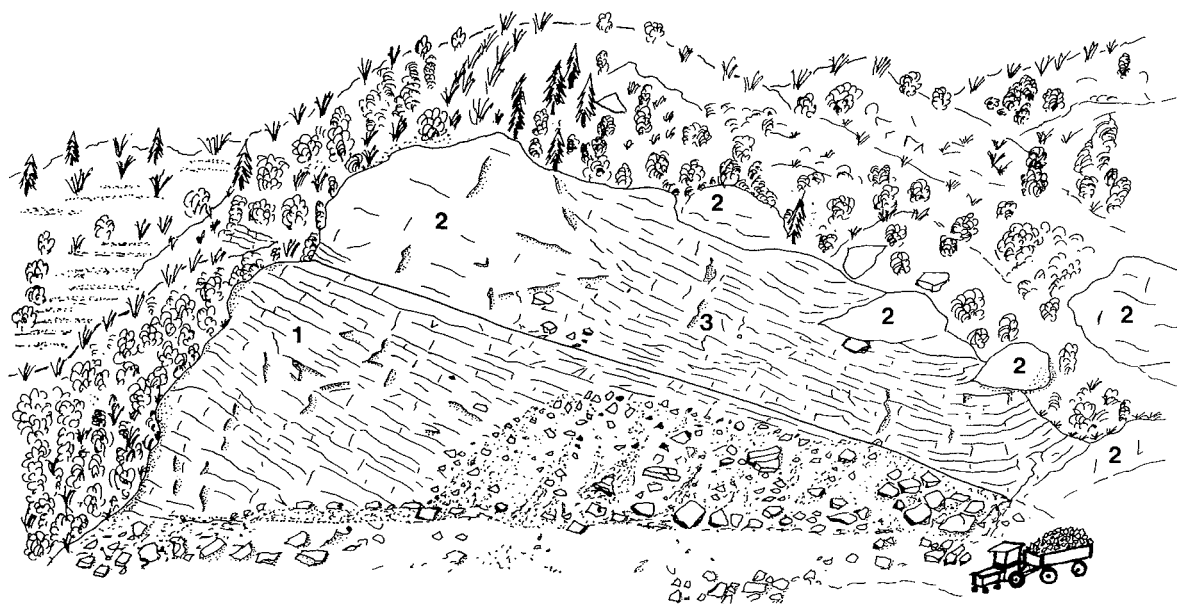
Fig. 3. Field sketch of Shilongshan quarry (C 34); 1 = well-bedded oolites of lower Hanwang Formation, 2 = mud mounds, 3 = well-bedded inter-mound facies; note that the largest mound was established directly upon the oolites, while smaller ones are intercalated in higher levels

size appears to correlate with an increasing clay content of the intermound deposits. The latter contain numerous crinoids (isolated columnals, larger stem fragments, tiny cups), brachiopods (mostly terebratulids), bryozoans, small (dwarfed?) ammonoids and other mollusc remains which have locally preserved their original fabric and aragonitic mineralogy (WENDT & al. 1989). The ammonoid fauna indicates a late Carnian age of the upper Hanwang Formation (WU 1989b). Residues of dark mudstones dissolved in acetic acid yielded triactine and tetractine sponge spicules, echinoderm debris, fish teeth and questionable cephalopod jaw fragments, but no conodonts.

Shiyuan Formation (Norian)

Wherever the top of major mounds is exposed, it shows a sharp contact toward the overlying fossiliferous shales showing that these exposed surfaces were modelled by local non-deposition. Within the depressions between the mounds, however, this boundary appears continuous. In both areas within a few metres a transition into dark claystones with an increasing quartz content and an intercalation of fine-grained sandstones is observed. The claystones and intercalated sandstones show evidence of sedimentary deformation, principally through the development of slump folds. WU (1989b) has mentioned numerous pelecypods and some

ammonoids from this formation which indicate a late Norian age.

The facies evolution from the Ladinian into the Norian reflects a continuous deepening of the depositional area: The intertidal carbonates of the Ladinian Tianjangshan Formation and the oolitic limestones of the overlying lower Hanwang Formation represent the inner to middle ramp of the eastern Yangzi Platform. The mound and intermound deposits of the upper Hanwang Formation indicate a transitional zone from the middle to the outer ramp (in the sense of BURCHETTE & WRIGHT 1992). The more monotonous siliciclastics of the Shiyuan Formation were deposited in a marginal basin in which intercalated turbidites and local slumping phenomena document the presence of gentle slopes.

MUD MOUNDS

Geometry

Morphologically some mounds stand out in relief as isolated hills with steep (up to 45°) flanks (figures in WENDT & al. 1989 and WU 1989b). Such remnants of mounds are, however, largely modelled by erosion and do not allow conclusions about their original shape. WU (1989b) has mentioned primary slopes of 25-30° and elliptical outlines of the mounds in which the long axis

(80-100 m) are aligned in a NW-SE-direction. In the 15 mounds, which have personally been examined, similar observations could not be made. Exposed or estimated base diameters of larger mounds range from several tens to about 200 m; their thickness is in the order of 10 to about 80 m, but additional amounts removed by erosion are unknown. Mapping of mounds is made impossible by the dense vegetation. Observations on the mound-intermound transitions, which are well exposed in several quarries, were only possible from a certain distance (Text-fig. 3). A more detailed inspection of

these zones on the steep and brittle quarry walls has not been tried for safety reasons.

In one mound exposed on the right bank of the Hanwang river (C 36, see appendix), the obviously undisturbed juxtaposition of a massive calcareous mound and the adjacent limestone-marl intermound sequence could be examined (Text-fig. 2). From the spatial distance of the two sections and their thickness ratio (about 5 : 1), a mound slope of about 20° has been calculated. The predominantly shaly intermound rocks, however, have been much more compacted than the

		Substrate		Mud mound	Intermound	Capping beds
		Tianjingshan Formation	lower Hanwang Formation	upper Hanwang Formation		Shiyuan Formation
LITHOLOGY	Mudstone	■	●		■	
	Wackestone		●	■	■	
	Grainstone		■			
	Boundstone	●		■		
	Sandstone/Siltstone					■
	Shale				■	■
	Ooids		■ - □	□		
	Peloids	●	●	● - □		
	Intraclasts	●	□	●	□	
	Lithoclasts	□				
	Microbial crusts	■		●		
	Stromatactis			O		
	Micritic envelopes	O	O	O		
	Slumping					□
	RFC cements			O		
	Blocky calcite	□	■	●	O	
	Thickness (m)	100	25 - 60	up to 80	10 - 20	90
BIOTA	Calcareous algae		●			
	Foraminifera	O	□ - O		□	
	Siliceous sponges		□	■	●	
	Sponge spicules		□	■		
	Coralline sponges			◇		
	Scleractinia		◇		O	
	Brachiopoda	O	O	O	●	O
	Bryozoa			□	□	
	Ostracoda		O		□	
	Worm tubes			●		
	Pelecypoda	O	O	O	□	O
	Gastropoda	O	◇	O	O	
	Ammonoidea		◇		O	◇
	Crinoidea	O	O	●	■	
	Echinoidea	◇	O	O	□	
	Conodonta			◇		
	Plant remains					●
Environment		carbonate platform		outer ramp		marine gulf
		tidal flat	oolite shoal			

Tab. 1. Relative abundance of lithologies and biota of substrate, mud mound, intermound and capping beds (compiled from data of WENDT & al. 1989, WU 1989b and own observations) ■ = very common, ● = common, □ = rare, O = very rare or faint, ◆ = isolated specimens

early lithified mound proper causing an assumed thickness reduction of about 50-70%. Therefore the original slope was probably only in the order of 10-15°. A similar value (11°) has been calculated from the dip of the beds onlapping the mound flank after rotation to the horizontal. The presence of a noticeable relief on the ancient seafloor is also evident from numerous slumping phenomena in the intermound sequence close to adjacent mounds (Pl. 1, Fig. 6). In one quarry the transition of mound into intermound lithologies could be observed (Text-fig. 3) showing, however, that the relief of the mounds above the surrounding bedded facies was not very prominent. In this locality several small mounds (a few metres across) are intercalated like patch reefs into the intermound sequence.

With their gentle slopes of about 10°, the Upper Triassic mud mounds from Sichuan are similar to counterparts from the SW-German Jurassic (GWINNER 1976) in which siliceous sponges (Hexactinellida and Lithistida) are also the major skeletal constituent. Palaeozoic mounds, however, often have much steeper flanks of up to 45° (WENDT & al. 1997; KAUFMANN 1998), but lens-shaped mounds with gentle slopes are also known from these settings (WENDT & KAUFMANN 1998).

Lithofacies, biota (Tab. 1)

WU (1989b) has examined several mounds in the surroundings of Hanwang, some of which have been revisited with him in 1997. In these, WU had previously distinguished the following lithofacies types: (1) crinoid-algal bank, (2) oolitic bank, (3) bioclastic bank,
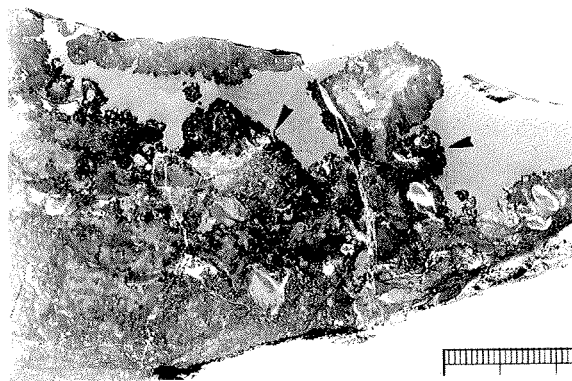

Fig. 4. Polished slab of typical mound lithology; note clotted structure of micritic matrix and dark (probably microbial) crust on internal surfaces (arrowed); the light-grey internal sediment shows a faint lamination downwarping into the depressions of the crust (visible only at high magnifications); scale in mm; Shilongshan quarry (C 34)

(4) core, (5) inner flank, (6) outer flank and (7) intermound. In many places ooid banks form the foundation of the mounds, whereas crinoid-algal banks (1) and bioclastic banks (3) have only locally been observed and pass gradually into the mound facies proper (4). Inner (5) and outer flank facies (6) could not be separated during our field work. Therefore WU 's (1989b, Fig. 6) model of a facies zonation within the mounds appears too idealistic because even on exposed quarry walls (which in 1989 were not available) equivalent lithofacies patterns were not recognised.

The abundance of hexactinellid sponges within the mounds is highly variable but shows no obvious trends. Only on the mound flanks where they may have acted as bafflers of fine sediment, and in the marginal intermound lithologies, sponges may locally be more abundant than in the core (Pl. 1, Fig. 5). The high percentage of micrite (> 90%) with respect to the predominantly shaly intermound sediments indicates its autochthonous origin. The cloudy, clotted and often peloidal structure of the matrix (Text-fig. 4) suggests a microbial origin of the micrite (cf. PICKARD 1992, REITNER 1993). This interpretation is emphasized by the fact that carbonate mudstones are much rarer or absent in the intermound sequence. Fine-grained, totally unfossiliferous internal sediment is patchily dispersed throughout the autochthonous mound rock (Text-fig. 4) and at high magnification exhibits a fine lamination downwarping into the depressions of internal surfaces.

Stromatactoid structures are very common and characteristic in Palaeozoic mud mounds. These bedding-parallel, originally open voids of cm- to dm-scale, generally display a flat base and a digitated roof (cf. DUPONT 1881; BATHURST 1982; PRATT 1982) and are filled with one or several generations of cement, sometimes with internal sediment at the base. The organic vs. sedimentary or diagenetic origin of these structures has comprehensively been discussed by FLAJS & HÜSSNER (1993), HÜSSNER (1994), PRATT (1995) and others. In the Sichuan mounds, however, stromatactoid cavities are extremely rare. The few samples which were used for diagenetic studies (see below) could only be collected from loose blocks in the quarries in which their primary orientation with respect to the mound surfaces could not be reconstructed. The major part shows irregular outlines (Pl. 2, Fig. 1); only a few display the typical flat base and a digitated roof. If present, such a flat base is either a primary outline (Pl. 1, Fig. 4) parallel to the mound surface or due to the levelling of an irregular floor by internal sediment. In thin sections it becomes evident that these cavities are primary because they are partly lined by dark crusts which may be of cyanobacterial origin (Pl. 3, Figs 1-2). No evi-

dence was found for their origin as solution cavities resulting from meteoric dissolution.

The predominant skeletal components in the mounds are hexactinellid sponges which comprise a great variety of genera and species (WU 1990). The majority of the specimens within the mounds appears in original growth position while in the argillaceous inter-mound facies they are clearly transported and general-ly flattened by compaction (Pl. 1, Fig. 3). Many sponge skeletons are encrusted by *Terebella* worm tubes (WENDT & *al*. 1989, Fig. 7). Coralline sponges which are among the most common frame-builders in Middle and Upper Triassic buildups, are extremely rare or absent. Some hexactinellid sponges, however, show reg-ular constrictions and thus mimic Sphinctozoa. Scleractinian corals have not been found. Among the mound-dwelling fauna, pelecypods and brachiopods (mostly terebratulids) are most common, followed by other molluscs (small gastropods and ammonoids). In marginal mound areas and in the shaly intermound facies crinoid remains predominate. They include a very rich fauna of holocrinids, isocrinids and some pen-tacrinids which is presently being examined by H. HAGDORN (Ingelfingen, Germany). In thin sections, rare bryozoans, sponge spicules (generally monactines, rarely triactines), miliolid foraminifera and ostracodes were observed.

Diagenesis

A disgenetic sequence for the buildups was pro-posed in an earlier study (WENDT & *al*. 1989). This sequence was based solely on petrographic evidence; no geochemical data was available at that time. The prin-cipal diagenetic processes to affect the buildups inclu-ded recrystallization of the micritic matrix, neomorphic transformation of metastable biogenic mineral phases, cementation, and compaction of the bedded inter-mound deposits.

Cementation stages in mud mounds can be best studied in the stromatactoid cavities which are occlud-ed by calcite cement (WENDT & *al*. 1997; KAUFMANN & WENDT 2000). As mentioned above, these cavities which are so typical for Palaeozoic mud mounds, are extremely rare in post-Palaeozoic mud mounds (e. g. MATHUR 1975; MATYSZKIEWICZ 1993). In the Upper Triassic mounds from Sichuan they have been discov-ered only by thorough examination of freshly blasted blocks in the quarries. A total of 50 samples were col-lected and prepared for light optic, cathodolumines-cence and stable-isotope analysis. The majority of these void fillings consists of only one cement generation of

blocky spar (Pl. 1, Fig. 4). Only in 8 samples could two cementation phases be distinguished, a yellowish rim cement and a clear sparry calcite which fills the centre of the cavities (Pl. 2, Fig. 1). Analyses of stable C- and O-isotopes revealed that three samples of the early cements were obviously contaminated by the sampling procedure so that the following discussion is based on data from 5 samples only. Nevertheless, the results from the isotope analysis display a very distinctive dia-genetic trend.

A 0.3 to 3 mm thick rim of fibrous calcite covers the internal surface of the cavities and has also been observed as the first cement generation within a dou-ble-valved brachiopod shell. Crystals and subcrystals of these cements display an undulose extinction and a divergent (from the nucleation surface) pattern of the fast fibration directions of the crystals and subcrystals composing this type of cement (Pl. 2, Fig. 2). The lat-tices of the crystals are curved, with the concave side facing the cavity wall. Because of this crystallographic property these cements can be classified as radiaxal fibrous calcite (RFC) in the sense of KENDALL (1985). Under normal light the crystals have a cloudy appear-ance which is probably due to inclusions of microdolomite. This assumption (which has not been tested with microprobe) would point to a Mg-calcitic precursor of these cements. Under cathodolumines-cence, but not under plane-polarized light, they dis-play a distinct layering due to oscillating amounts of incorporated Mn (Pl. 3, Fig. 1, 2). The isotopic com-position of these early cements is between 3.2 and 3.7‰ δ^{13}C PDB (mean: 3.3‰ δ^{13}C PDB) and -2.4 to -4.3‰ δ^{18}O PDB (mean: -3.4‰ δ^{18}O PDB) (Text-fig. 5). These values are similar to the isotopic composi-tion of two samples of the micritic host rock which are between 3.5 and 3.8 ‰ δ^{13}C PDB (mean: 3.7 ‰ δ^{13}C PDB) and -2.0 to -2.7‰ δ^{18}O PDB (mean: -2.3‰ δ^{18}O PDB). The isotopic composition of four non-luminescent brachiopod shells is positioned in the same field (Text-fig. 5). Because of their low-Mg cal-cite composition brachiopods have always been con-sidered as the most reliable indicator of the isotopic composition of ancient seawater (VEIZER & *al*. 1997; BRUCKSCHEN & VEIZER 1997). The isotopic composi-tion of the Sichuan brachiopods is between 2.5 and 3.6‰ δ^{13}C (mean: 3.0 ‰ δ^{13}C PDB) and -1.3 to -3.5‰ δ^{18}O PDB (mean: -2.4‰ δ^{18}O PDB). The good coincidence of these data suggest that the early cements have been precipitated in equilibrium with the ambient seawater. Similar results have been obtained by MAUL (1991) and ZEEH & *al*. (1995) from equivalent diagenetic stages in the upper Wetterstein Limestone (Carnian, Northern Calcareous Alps) and
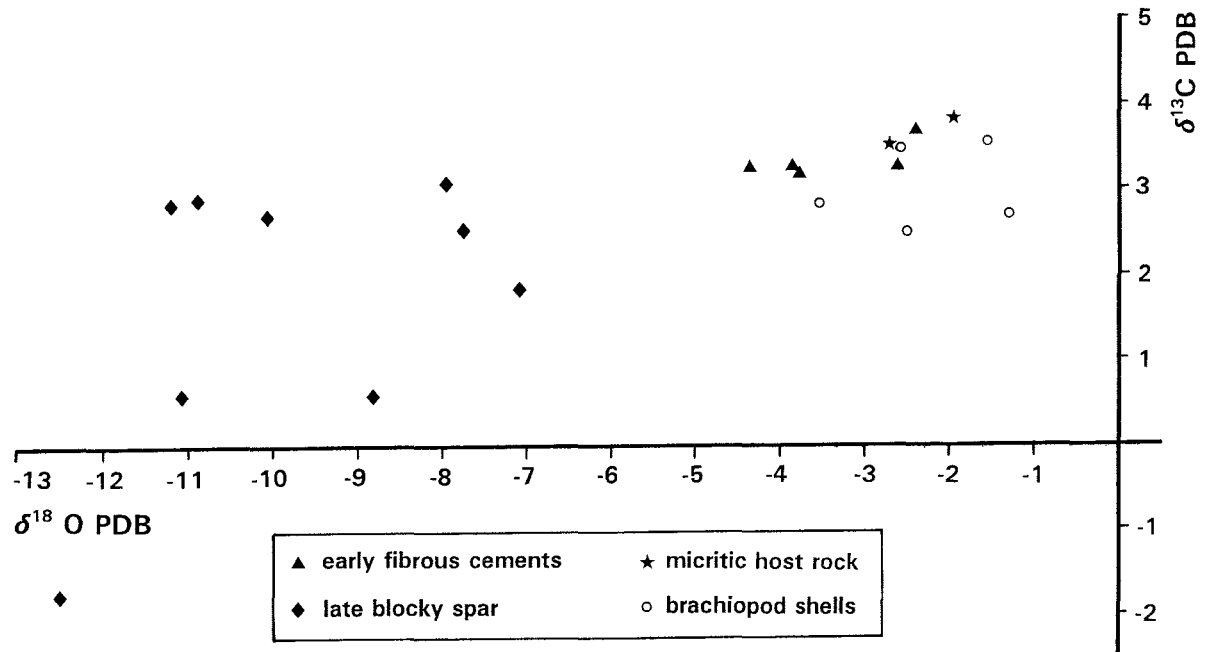
Fig. 5. Isotopic compositions of early fibrous cements, late blocky spar and micritic host rock of mound, as well as of brachiopod shells of intermound lithologies

by numerous diagenetic studies of Palaeozoic mud mounds. The results of MAUL (1991) and ZEEH & al. (1995), however, are based only on one isotope analysis from a single brachiopod shell.

The second generation of cement consists of clear blocky calcite (Pl. 2, Figs 1, 2) which, in the majority of the examined stromatactoid cavities, represents the only void fill. The isotope data cover a large field in the diagram of Text-fig. 5 without any obvious correlation to particular sampling spots. In the centre of the cavities the luminescence is slightly weaker than in the marginal zones (Pl. 3, Fig. 2), but these zones could not be sampled separately. The isotopic values obtained from the blocky calcites are between -1.7 and +3.1 ‰ δ^{13}C PDB (mean: +2.0‰ δ^{13}C PDB) and -7.1 to -12.5‰ δ^{18}O PDB (mean: -9.7‰ δ^{18}O PDB) (Text-fig. 5). The more negative δ^{18}O signatures for the blocky calcite cements suggest precipitation at elevated temperatures during deep burial. This interpretation is strongly supported by the general deepening-up trend of the facies evolution from the Ladinian into the Norian. This trend makes it unlikely that meteoric waters have flushed through the sediments at an early stage fo burial. The fact that blocky calcite is the only type of cement within the majority of stromatactis cavities can be explained

in two ways. (1) Eventually present primary fibrous cements could have been totally recrystallized and not be detectable any more, even by cathodoluminescence. (2) The stromatactoid cavities represented restricted diagenetic environments with no permeability for high rates of percolating seawater required for early marine cementation. This interpretation is favoured here and is supported by the extreme scarceness of stromatactis and their lack of interconnection between individual cavities.

Determination of the ^{87}Sr/^{86}Sr ratio in three samples has yielded the following results:
 • RFC-cement in stromatactoid cavity: 0.707928
 • micritic host rock of the same sample: 0.707897
 • brachiopod shell of intermound lithology: 0.707813.

The three measurements fit within the narrow band of the ^{87}Sr/^{86}Sr isotopic evolution curve of VEIZER & al. (1997) at the time of the Carnian (Text-fig. 6). Plotting of the data from Sichuan into this curve, however, is somewhat problematic because some boundaries of the absolute time scale used by VEIZER & al. (1997) are not compatible with more recent calculations. The ^{87}Sr/^{86}Sr values of the first two samples are very close together and are slightly increased with respect to the value
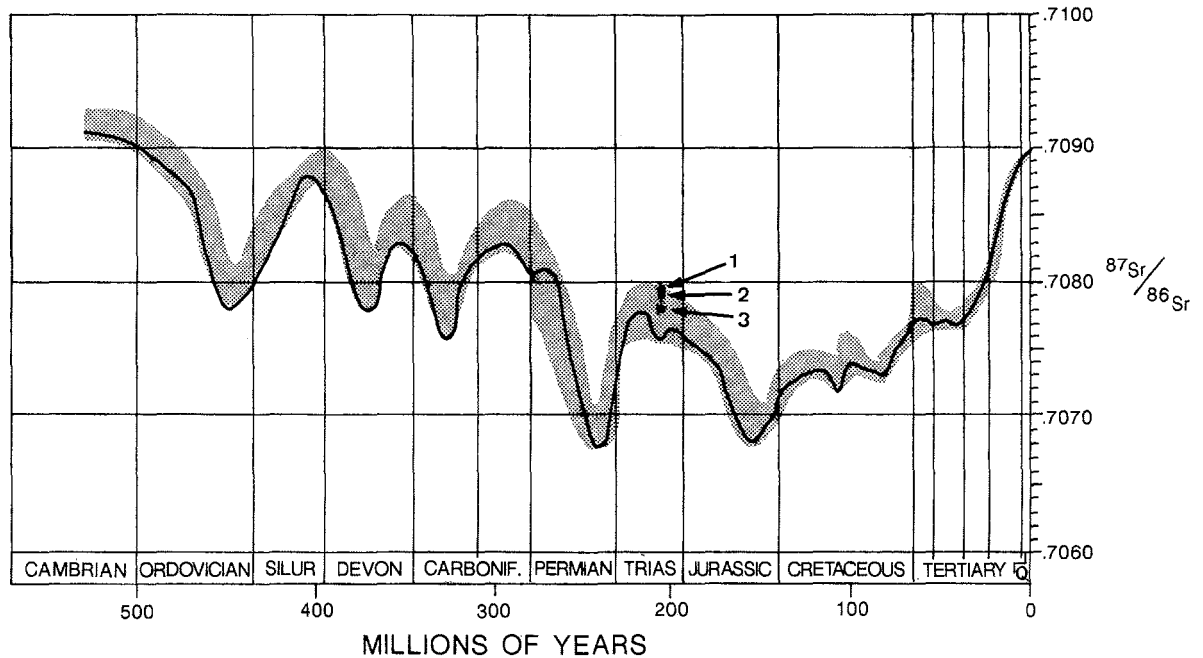
Fig. 6. The $^{87}Sr/^{86}Sr$ isotopic seawater evolution during the Phanerozoic (modified from VEIZER & al. 1997) and the position of the data from the Carnian of northern Sichuan; 1 = RFC-cement, 2 = mound micrite, 3 = brachiopod shell from intermound shales

obtained from the brachiopod shell. The latter coincides best with the VEIZER curve. This sample has yielded the heaviest $\delta^{18}O$ value (-1.3) of the five brachiopod shells which have been analyzed. Its original low-Mg mineralogy is less likely to have been altered during burial, whereas the early marine RFC cements are likely to have stabilized to a low-Mg mineralogy from a probable high-Mg precursor.

DISCUSSION AND CONCLUSIONS

From their biota and lithologic composition, the Carnian buildups of Sichuan are typical mud mounds. Though siliceous sponges (mostly hexactinellids and to a lesser degree demosponges) may constitute relatively high portions of the rock volume, these organisms cannot be considered as true frame-builders. Only locally they may have contributed to the accumulation of mud by baffling. The bulk of the matrix mud is considered to be a product of microbial activity. This interpretation is supported by the enormous quantity of micrite within the mounds proper with respect to the coeval shaly and carbonate-poor intermound deposits. This dispropor-

tion cannot be explained by mechanical accumulation in one place and by removal in an adjacent one. Microbial activity is also suggested by the clotty (peloidal) microstructure of the micritic matrix and by dark, indistinctly laminated crusts lining sponge skeletons and internal surfaces of some stromatactoid voids.

Apart from sponges and probable cyanobacteria, terebellid worms and small bryozoans contributed to mound stabilization. A diverse invertebrate fauna consisting of crinoids, echinoids, pelecypods, gastropods, ammonoids, brachiopods, rare miliolid and other foraminifera and ostracodes lived in niches or at the surface of the mounds and appears most diverse at their base. The absence of scleractinian corals, coralline sponges, calcareous algae and intense micritization suggests a bathymetric position in the lower part of the photic zone at a depth of some tens to about one hundred metres. Palaeogeographically the buildups appear to mark the transition between the inner ramp of the Middle Triassic Yangzi Platform to the east and a deep basin (the Songpan-Garze Trough) to the west.

Because of the intense erosion and poor outcrops, the original size, morphology and spacing of individual mounds can only roughly be assessed. Thicknesses of

major mounds ranges from about ten to eighty metres, but in their vicinity many smaller mounds of only a few metres in size occur which are intercalated into the intermound sequence. Base diameters of the major mounds are in the order of tens to several hundred metres. Mound slopes appear rather gentle and did probably not exceed 15°. From personal inspections and those of others (WU 1984; WU & ZHANG 1982) about 20 major mud mounds are known so far from the surroundings of Hanwang and Jushui; many others are probably hidden under the dense vegetation or are not yet discovered in the higher mountains.

Though, in contrast to Palaeozoic mounds, stromatactoid cavities are extremely scarce in the Carnian sponge mounds of Sichuan, the diagenetic history of these buildups is best documented by the cementation stages of these primary voids. A first generation of RFC-cements displays only slightly negative O-isotopic signatures and was probably precipitated in equilibrium with the ambient sea-water. These values are in good agreement with isotope data from the neighbouring micritic matrix and from non-luminescent brachiopod shells. A second generation of blocky calcites, distinguished by more negative $\delta^{18}O$ values, was precipitated under burial conditions. The fact that in the majority of the cavities, blocky calcite is the only visible cementation stage, is probably due to the absence of interconnection between these voids. The sparse and widely spaced stromatactoid cavity systems inhibited the circulation of marine pore waters, a process that is considered essential to precipitate thick generations of marine cement. Presumably seawater would have been the initial connate fluid in the cavities, but owing to poor circulation little or no marine cements precipitated. Nevertheless, early lithification of autochtonously precipitated micrite must have considerably contributed to the stabilization of the mound surfaces creating an irregular relief at the seafloor. In the intermound areas skeletal debris from the mound flanks and finely-siliciclastic deposits were accumulated in which a high organic content reflect poorly oxygenated conditions. Unfortunately, the dense vegetation and tectonic complications of the area are a serious constraint and a discouragement for a more detailed palaeogeographic reconstruction and the unravelling of the depositional history of the former margin of the Yangzi Platform in northern Sichuan during the late Triassic.

Acknowledgements

REFERENCES

BATHURST, R. G. C. 1982. Genesis of stromatactis cavities between submarine crusts in Palaeozoic carbonate mud buildups. *Journal of the Geological Society of London*, **139**, 165-181. London.

BRUCKSCHEN, P. & VEIZER, J.1997. Oxygen and carbon isotopic composition of Dinantian brachiopods: Paleoenvironmental implications for the Lower Carboniferous of western Europe. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **132**, 243-264. Amsterdam.

BURCHETTE, T. P. & WRIGHT, V. P. 1992. Carbonate ramp depositional systems. *Sedimentary Geology*, **79**, 3-57. Amsterdam.

CALVET, F. & TUCKER, M. E.1995. Mud mounds with reefal caps in the upper Muschelkalk (Triassic), eastern Spain. *In:* C. L. V. MONTY, D.W. J. BOSENCE, P.H. BRIDGES & B. R. PRATT (*Eds*) Carbonate mud-mounds. Their origin and evolution. *Special Publication of the International Association of Sedimentologists*, **23**, 311-333. Oxford.

DUPONT, E. 1881. Sur l'origine des calcaires Dévoniens en Belgique. *Bull. Acad. roy. Belg., Cl. Sci., sér. 3*, **2**, 264-280. Bruxelles.

ENOS, P., WEI, J. & LEHRMANN, D. J. 1998. Death in Guizhou - Late Triassic drowning of the Yangtze carbonate platform. *Sedimentary Geology*, **118**, 55-76. Amsterdam.

FAN, J. 1979. The main features of marine Triassic sedimentary facies in southern China. *Riv. Ital. Paleont. Stratigr.*, **85**, 1125-1146. Milano.

FLAJS, G. & HÜSSNER, H. 1993. A microbial model for the Lower Devonian Stromatactis mud mounds of the Montagne Noire (France). *Facies*, **29**, 179-194. Erlangen.

GWINNER, M. P. 1976. Origin of the Upper Jurassic limestones of the Swabian Alb (southwest Germany). *Contributions to Sedimentology*, **5**, 1-75. Stuttgart.

HÜSSNER, H. 1994. Reefs, an elementary principle with many complex realizations. *Beringeria, Würzburger geowiss. Mitteilungen*, **11**, 3-99. Würzburg.

KAUFMANN, B. 1998. Facies, stratigraphy and diagenesis of Middle Devonian reef- and mud-mounds in the Mader (eastern Anti-Atlas, Morocco). *Acta Geologica Polonica*, **48**, 43-106. Warszawa.

KAUFMANN, B. & WENDT, J. 2000 in press. Calcite cement successions in Middle Devonian (Givetian) carbonate mud buildups of the southern Ahnet Basin (Algerian Sahara), Carbonates and Evaporites, Troy, N.Y.

KENDALL, A. C.1985. Radiaxal fibrous calcite: a reappraisal. - In: SCHNEIDER, N. & HARRIS, P. M. (*Eds*) Carbonate cements. *SEPM Special Publication,* **36**, 59-77, Tulsa, Oklahoma.

LEHRMANN, D. J. 1999. Early Triassic calcimicrobial mounds and biostromes of the Nanpanjiang basin, south China. *Geology*, **27**, 359-362. Boulder, Colorado.

LIU, B. & XU, X. (*Eds*) 1994. Atlas of the lithofacies and palaeogeography of South China (Sinian - Triassic), pp. 1-192, Science Press; Beijing, New York.

MATHUR, A. C. 1975. A deeper water mud mound facies in the Alps. *Journal of Sedimentary Petrology*, **45**, 787-793. Tulsa, Oklahoma.

MATYSZKIEWICZ, J. 1993. Genesis of stromatactis in an Upper Jurassic carbonate buildup (Mlynka, Cracow region, southern Poland): internal reworking and erosion of organic growth cavities. *Facies*, **28**, 87-96. Erlangen.

MAUL, B. 1991. Vom vadosen Bereich zur Anchimetamorphose: Diagenese des Oberen Wettersteinkalks der westlichen Nördlichen Kalkalpen. *Diss. Geowiss. Fak. Albert-Ludwigs-Universität,* 1-247. Freiburg i. Br..

PICKARD, N. A. H. 1992. Depositional controls on Lower Carboniferous microbial buildups, eastern Midland Valley of Scotland. *Sedimentology*, **39**, 1081-1100, Oxford.

PRATT, B. R. 1982. Stromatolitic framework of carbonate mud-mounds. *Journal of Sedimentary Petrology*, **52**, 1203-1227. Tulsa, Oklahoma.

— 1995. The origin, biota and evolution of deep-water mud-mounds. *In:* C. L. V. MONTY, D. W. J. BOSENCE, P. H. BRIDGES & B. R. PRATT (*Eds*) Carbonate mud-mounds. Their origin and evolution. *Special Publication of the International Association of Sedimentologists*, **23**, 49-123. Oxford.

REITNER, J. 1993. Modern cryptic microbialite/metazoan facies from Lizard Island (Great Barrier Reef, Australia) - formation and concepts. *Facies*, **29**, 3-40, Erlangen.

VEIZER, J., BUHL, P., DIENER, A., EBNETH, S., PODLAHA, O. G., BRUCKSCHEN, P., JASPER, T., KORTE, C., SSCHAAF, M., ALA, D. & AZMY, K. 1997. Strontium isotope stratigraphy: potential resolution and event correlation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **132**, 65-77. Amsterdam.

WENDT, J., BELKA, Z., KAUFMANN, B., KOSTREWA, R. &

HAYER, J. 1997. The world's most spectacular carbonate mud mounds (Middle Devonian, Algerian Sahara). *Journal of Sedimtary Research*, **67**, 424-436. Amsterdam.

WENDT, J. & KAUFMANN, B. 1998. Mud buildups on a Middle Devonian carbonate ramp (Algerian Sahara). - *In:* V. P. WRIGHT & T. P. BURCHETTE (*Eds*) Carbonate ramps. *Geological Society of London, Special Publication*, **149**, 397-415. London.

WENDT, J., WU, X. & REINHARD, J. W. 1989. Deep-water hexactinellid sponge mounds from the Upper Triassic of northern Sichuan (China). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **76**, 17-29. Amsterdam.

WU, X. 1984. Paleoecological characteristics of late Triassic sponge patch reefs in north-western Sichuan, China. *Journ. Chengdu Coll. Geol.*, **1984**, 43-54. Chengdu. [*In Chinese with English abstract*]

— 1989a. Late Triassic Carnian strata in western Sichuan Basin and a new sponge family. *Acta Palaeontologica Sinica*, **29**, 766-772. Beijing. [*In Chinese with English abstract*]

— 1989b. Carnian (Upper Triassic) sponge mounds of the northwestern Sichuan Basin, China: Stratigraphy, facies and paleoecology. *Facies*, **21**, 171-188. Erlangen.

— 1990. Late Triassic Lychniscosa fauna in northwestern Sichuan. *Acta Palaeontologica Sinica*, **29**, 349-363. Beijing. [*In Chinese with English abstract*]

WU, X. & ZHANG, L. 1982. Late Triassic (Carnian) sponge patchreefs in northwestern Sichuan Basin. *Scientia Geologica Sinica*, **1982**, 379-385. Chengdu. [*In Chinese with English abstract*]

— & — 1983. Lithological features of late Triassic sponge patch reef complex in north-western Sichuan, China. *Minerals and Rocks*, **4**, 59-67. Chengdu. [*In Chinese with English abstract*]

WU, X., ZHANG, L. & ZHU, Z. 1977. Discovery of upper Triassic organic reefs in front of the Longmen mountains in NW-Sichuan, China. *Sci. Techn. Inform. Petrol. Geol.*, **30**, 62-71. Chengdu. [*In Chinese with English abstract*]

— , — & — 1979. Discovery of upper Triassic reefs in front of the Longmenshan mountains of NW Sichuan, China. *Journ. Petrol. Inst. Minist. Geol. Miner. Res.*, **23**, 82-96. Chengdu. [*In Chinese with English abstract*]

ZEEH, S., BECHSTÄDT, T., McKENZIE, J. & RICHTER, D. K. 1995. Diagenetic evolution of the Carnian Wetterstein platforms of the Eastern Alps. *Sedimentology*, **42**, 199-222. Oxford.

APPENDIX: **List of visited localities**

C 28 Huang-mao-shan near Yushui. New quarry, mud
mound. N: 31° 30,999'; E: 104°, 14,144'.

C 29 Yandoibao near Yushui: Mud mound (WENDT &
al. 1989, Fig. 3). N: 31° 30,798'; E: 104° 14,125'.

C 30 Valley of Jushui River, mud mound. N: 31°
30,718'; E: 104° 30,862'.

C 31 Jian-cao-gou, new quarry, mud mound. N: 31°
28,925'; E: 104° 12,736'.

C 32 Right side of Jushui River near village of Yushui,
mud mound. N: 31° 30,329'; E: 104°13,905'.

C 33 Muoziping, Shichanggou, south of Jushui, new
quarry, mud mound below C 32. N: 31° 29,677'; E:
104° 13,623 .

C 34 Shilongshan, Baixicun, Gongxing community.
Quarry exposing several mud mounds, about 2 km
north of C 31. N: 31° 29,217'; E: 104° 13,024.

C 35 First lateral valley on right side of Hanwang-
River. Abandoned quarry along a foot path to
pagode on top of mountain above Hanwang town.
Natural outcrop near bridge and small temple.
Flank of a mound, which is almost destroyed by
quarrying. N: 31° 27,718'; E: 104° 09,410'.

C 36 Right side of Hanwang-River. Natural section of
mud mound and underlying formations. Section
on Text-fig. 2. N: 31° 28,349'; E: 104° 08,834'.

C 37 About 100 m above C 36. Small lateral valley of
Hanwang River; about 150 m NE (40°) from top
of C 36 section. N: 31° 28,273'; E: 104° 08,804'.

C 38 Left side of Hanwang River, opposite of C 36, natur-
al section of mud mound, probably the same as C 36.

C 40 Hanwang, about 500 m upstream of pedestrian
bridge, left side of Hanwang River. Natural sec-
tion of mud mound and underlying formations.

C 41 Several quarries on northwestern margin of
Hanwang city, end of lateral valley on left side of
Hanwang River. Strongly faulted sections of
Tianjingshan and lower to upper Hanwang
Formations with remnants of mounds.

PLATE 1

1 – Jian-cao-god quarry (C 31); sequence of oolitic grainstones of lower (a) and upper Hanwang Formation (b) with remnant of mud mound on top (c); height of outcrop is approximately 25 metres.

2 – Lateral transition of intertidal dolomites of Tianjangshan Formation (right) into sedimentary *in-situ* breccia with good fitting of clasts. Section C 36; hammer for scale.

3 – Marly intermound facies with numerous transported hexactinellid sponges which are deformed by compaction (arrows); Muoziping (C 33); coin for scale.

4 – Typical stromatactoid cavities with flat base and digitated roof, filled with one generation of blocky spar; C 32.

5 – Surface of mound flank with numerous fragments of hexactinellid sponges; Hanwang River (C 35).

6 – Marly intermound facies onlapping mound flank; note thin limestone layers deformed by slumping (arrows). Hanwang River (C 35); coin for scale.
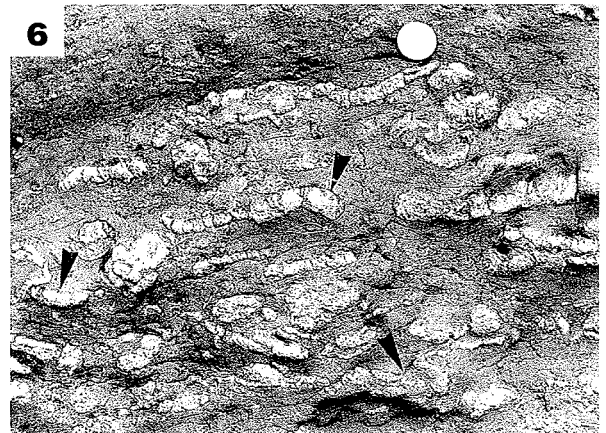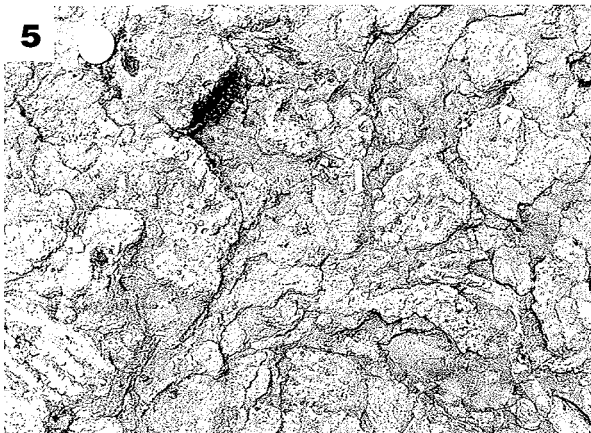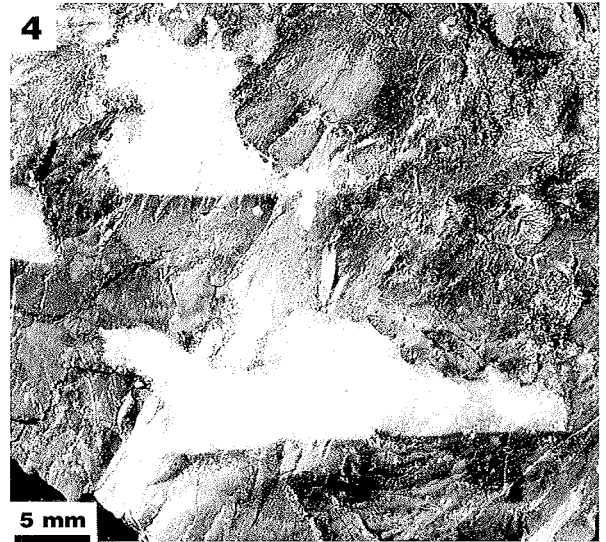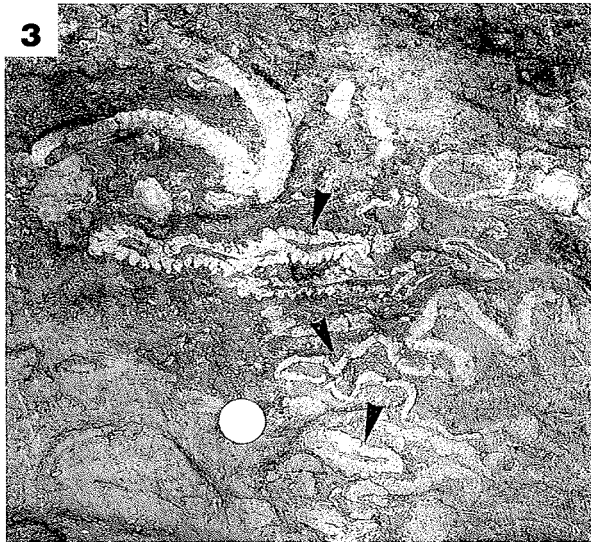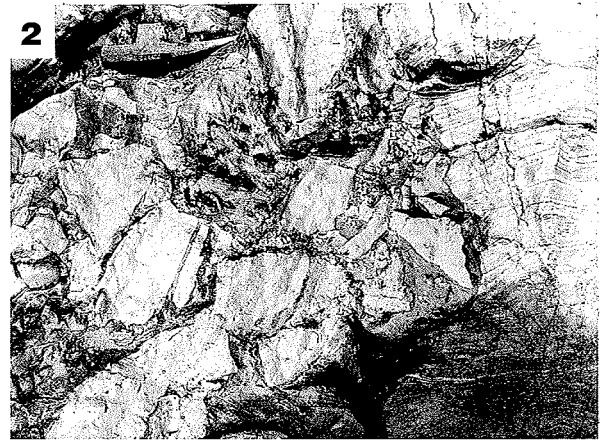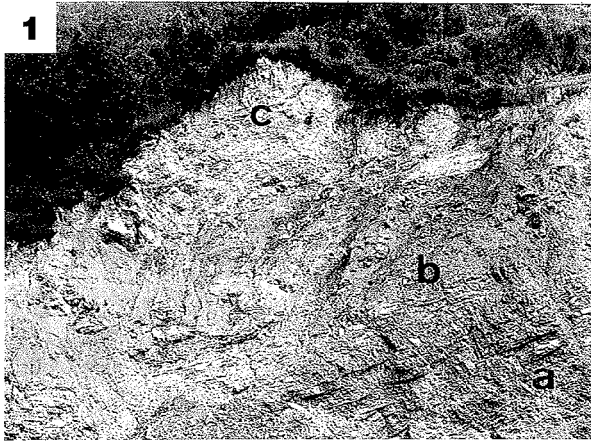
PLATE 2

1 – Irregular stromatactoid cavity with two cementation phases consisting of a yellowish RFC rim cement (arrowed) and blocky calcite (asteriscs); C 32.

2 – Thin section of small stromatactoid cavity; a = host rock, b = RFC-cement rim, c = blocky calcite. Crossed nicols; C 32.

PLATE 3

1 – Boundary between host rock (a) with cyanobacterial crust (b) and stromatactoid cavity, occluded by two cementation phases; c = RFC cement, d = blocky calcite; normal light; C 32.

2 – Same as Fig. 1, but under cathodoluminescence; note banding in weakly luminescent RFC cement; C 32.

1

d

c

b

a

0.25 mm

2

d

c

b

a

0.25 mm