JAHRBUCH DER GEOLOGISCHEN BUNDESANSTALT
Jb. Geol. B.-A. | ISSN 0016-7800 | Band 137 | Heft 2 | S. 297–318 | Wien, November 1994

Sequence Stratigraphy in Late Permian and Lowest Triassic of the Southern Alps (Dolomites; Northern Italy) with Special Regard to the Permian/Triassic Boundary

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7 Text-Figures and 3 Plates

Italien
Dolomiten
Perm
Trias
Sequenzstratigraphie

Contents

Sequenzstratigraphie im Operperm und in der Untertrias der Südalpen (Dolomiten; Norditalien) unter besonderer Berücksichtigung der Perm/Trias-Grenze

Zusammenfassung

Anhand der lateralen und vertikalen Sedimentationsmuster sowie der Foraminiferen-Biostratigraphie werden die oberpermischen (Djulfian und Dorashamian) und basalen triassischen (unteres Skyth; Griesbachian und unteres Nammalian) Ablagerungen im zentralen Teil der Südalpen (Dolomiten) sequenzstratigraphisch interpretiert. Das Gebiet stellte den westlichsten Abschnitt der golfartigen Paläotethys dar, in dem sich die relativen Meeresspiegelschwankungen in coastal onlap-Mustern abbilden.

Die Westgrenze des WNW/ESE-streichenden Paläotethys-Golfs ist durch eine alluviale Ebene aus siliziklastischen Rotsedimenten sowie einen randmarinen Bereich mit stark klastischem Einfluß markiert. Diese Serie geht seewärts (nach E) in einen eingeschränkten Innenschelf-Bereich über, der im E von einem strukturellen Hoch begrenzt wird.

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Die sedimentäre Entwicklung im Oberperm und unteren Skyth spiegelt relative Meeresspiegelschwankungen wieder, die von Subsidenz, Eustasie und Sedimentation gesteuert wurden. Die Subsidenzrate blieb auf dem eingeschränkten Innenschelf-Bereich nahezu im gesamten Oberperm konstant und wurde durch die Sedimentationsrate ausgeglichen, so daß ein Accommodationspotential von wenigen Metern vorherrschte. Die Wassertiefe wurde von kleinmaßstäblichen eustatischen Meeresspiegelschwankungen nur leicht modifiziert. Nach den vertikalen Sedimentationsmustern im Oberperm der Dolomiten liegen vier Sequenzen dritter Ordnung vor, die von Sequenzgrenzen des Typs 2 begrenzt werden.

Im obersten Perm führte eine generelle Abnahme der Subsidenzrate zusammen mit einer erhöhten Sedimentationsrate zu einer relativen Meeresspiegelabsenkung und Verringerung des Accommodationspotentials, so daß der flachmarine Schelfbereich in ein tiefliegendes Watt verwandelt wurde. Der Kulmination dieser relativen Meeresspiegelabsenkung an der Perm/Trias-Grenze ging ein geringer eustatischer Anstieg voraus, der durch coastal onlap-Muster belegt ist. Messungen stabiler Kohlenstoff-Isotope über die Perm/Trias-Grenze geben keine Hinweise auf anoxische Bedingungen, die für das Massensterben verantwortlich gewesen sein könnten. Die Sedimentabfolgen des unteren Skyth weisen zwei Sequenzen vom Typ 2 auf, die bei konstanter Subsidenzrate von relativen Meeresspiegelschwankungen dritter Ordnung gesteuert sind.

Abstract

On the basis of lateral and vertical sedimentary patterns and foraminiferal biostratigraphy, marine Upper Permian (Djulfian and Dorashamian) and lowest Triassic (Early Scythian; Griesbachian and Nammalian) deposits of the Southern Alps are interpreted on the basis of sequence stratigraphy. Relative sea level fluctuations here are well documented by coastal onlap patterns in the central part of the Southern Alps (Dolomites) which represents the westernmost part of the gulf-like Paleotethys at that time.

The westernmost border of the WNW/ESE trending Paleotethys gulf consists of an alluvial plain with siliciclastic red beds, and of a narrow marginal-marine area with strong clastic influx. This series grades seaward (eastward) into an extended restricted inner-shelf area. A fault-bounded structural high borders the restricted inner-shelf area in the east.

Late Permian and Early Scythian sedimentary evolution reflects sea level history which was controlled by subsidence, eustasy and sedimentation. Subsidence remained constant during most of the Late Permian and was easily compensated by sedimentation. It provided an accommodation space of a few meters on the restricted inner-shelf which was slightly modified by small-scale eustatic fluctuations. According to vertical stratal patterns, marine Upper Permian rocks in outcrop sections constitute four third-order sequences bounded by type 2 sequence boundaries.

During latest Permian, a general decrease in subsidence rates and increased sedimentation rates caused a relative sea level fall and diminished the accommodation potential, changing the extended shallow-shelf area into a low-lying peritidal flat. A minor eustatic rise, documented by coastal onlap, preceded the culmination of the relative sea level drop which is observed at the Permian/Triassic boundary. Stable carbon isotope data measured across the Permian/Triassic boundary do not support anoxic conditions as a possible cause of mass extinction. Early Scythian sediments record two type 2 sequences which are controlled by third-order relative sea level fluctuations with a constant rate of subsidence.

1. Introduction

Marine Upper Permian and lowest Triassic strata of the Southern Alps between Val Adige (South Tyrol, northern Italy) in the west and the Karawanken Mountains (Slovenia) in the east have been studied with respect to carbonate sedimentology, paleogeography, biostratigraphy and paleoecology (Noé, 1987, 1988). This area, located at the northern margin of Gondwana, composes the westernmost shelf area of the WNW/ESE trending, gulf-like Paleotethys and its transition to a siliciclastic hinterland. In the present paper, vertical and lateral sedimentary patterns and depositional systems of the Dolomites (South Tyrol or "Alto Adige") are interpreted in terms of sequence stratigraphy.

2. Setting

During Late Carboniferous and Early Permian, the metamorphic Hercynian basement of the Dolomites was deformed by extensional tectonism, and thereby differentiated subsidence which produced a block-fault mosaic of intermontane basins of rhomboidal geometry (Italian IGCP 203 Group, 1986). An Early Permian caldera of volcano-tectonic origin was filled by rhyolitic ignimbrites, lavas and tuffs with some intercalated fluvial and lacustrine sediments ("Piattaforma porfirica atesina" or "Bozener Quarzporphyr"). Ensuing tectonic deformation and erosion at the Early/Middle Permian boundary ("Saalian orogenetic phase" according to Kahler, 1980 or "Palatinian phase" according to Kozur, 1980) produced a major unconformity with associated breccias. In the course of the Late Permian, the block-faulted topography was leveled.

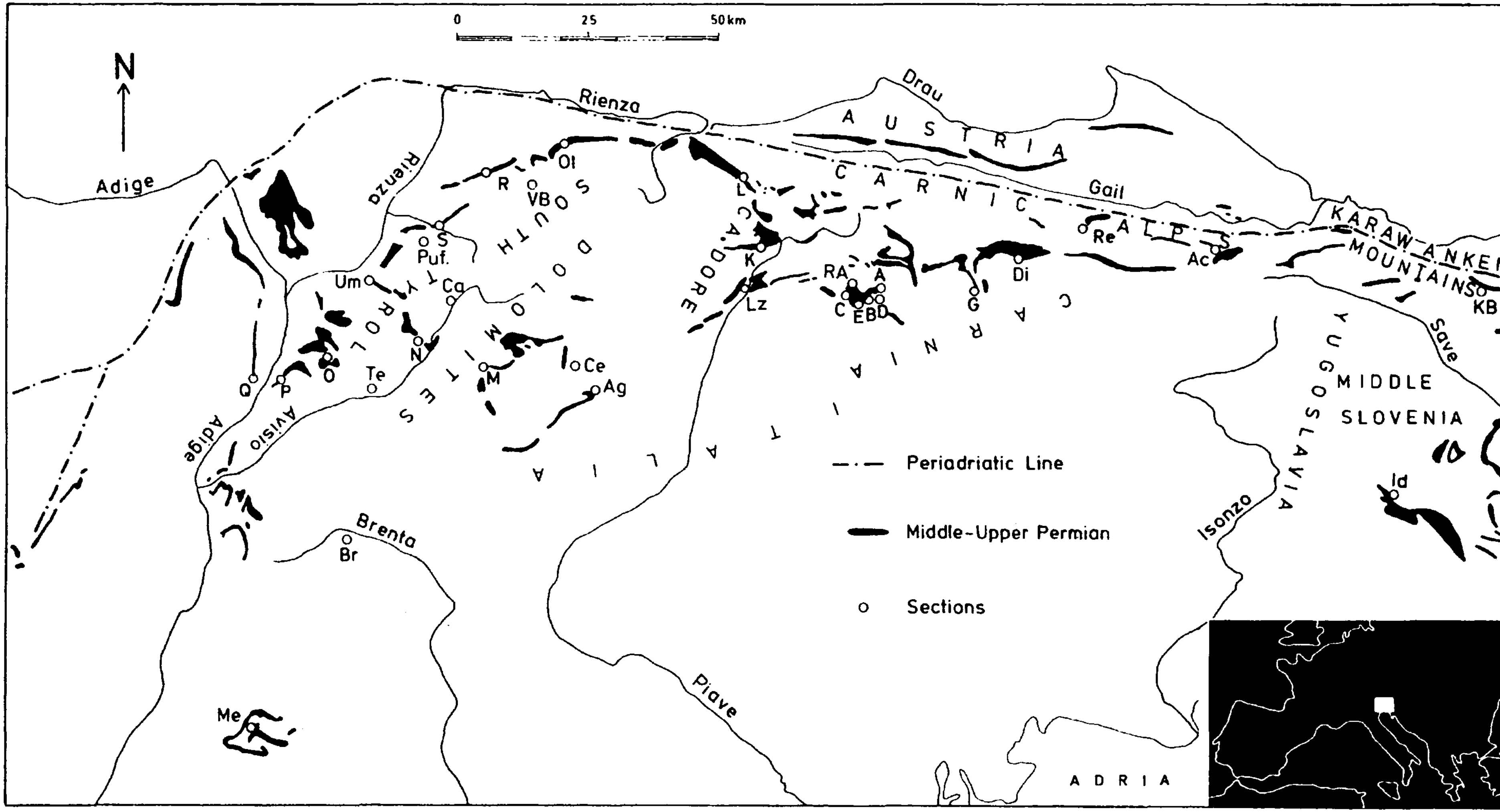
The succession investigated in the Dolomites refers to the upper Late Permian only. It comprises the uppermost part of the Val Gardena Sandstone Formation (lower Late Permian), the Bellerophon Formation (upper Late Permian; Djulfian and Dorashamian age) with a thickness up to 380 m, and the lower part of the conformably overlying 4–6 m thick Tesero Horizon (topmost Permian and lowest Triassic strata; latest Dorashamian and earliest Griesbachian age). The Bellerophon Formation, mainly deposited in a shallow-marine realm, interfingers in the Val Adige area with terrigenous red beds. Stepwise transgression across a very low-gradient hinterland was responsible for repeated interfingering of continental red beds, peritidal, and shallow lagoonal sediments, causing a diachronism of continental and marine facies.

The Bellerophon Formation was sampled in several sections between Val Adige and Karawanken Mountains (Text-Fig. 1). Based on microfacies analysis and biostratigraphic investigations, Late Permian paleogeography was reconstructed (Noé, 1987). The Bellerophon Formation was subdivided into four paleogeographic units. These are, from W (landward) to E (seaward):

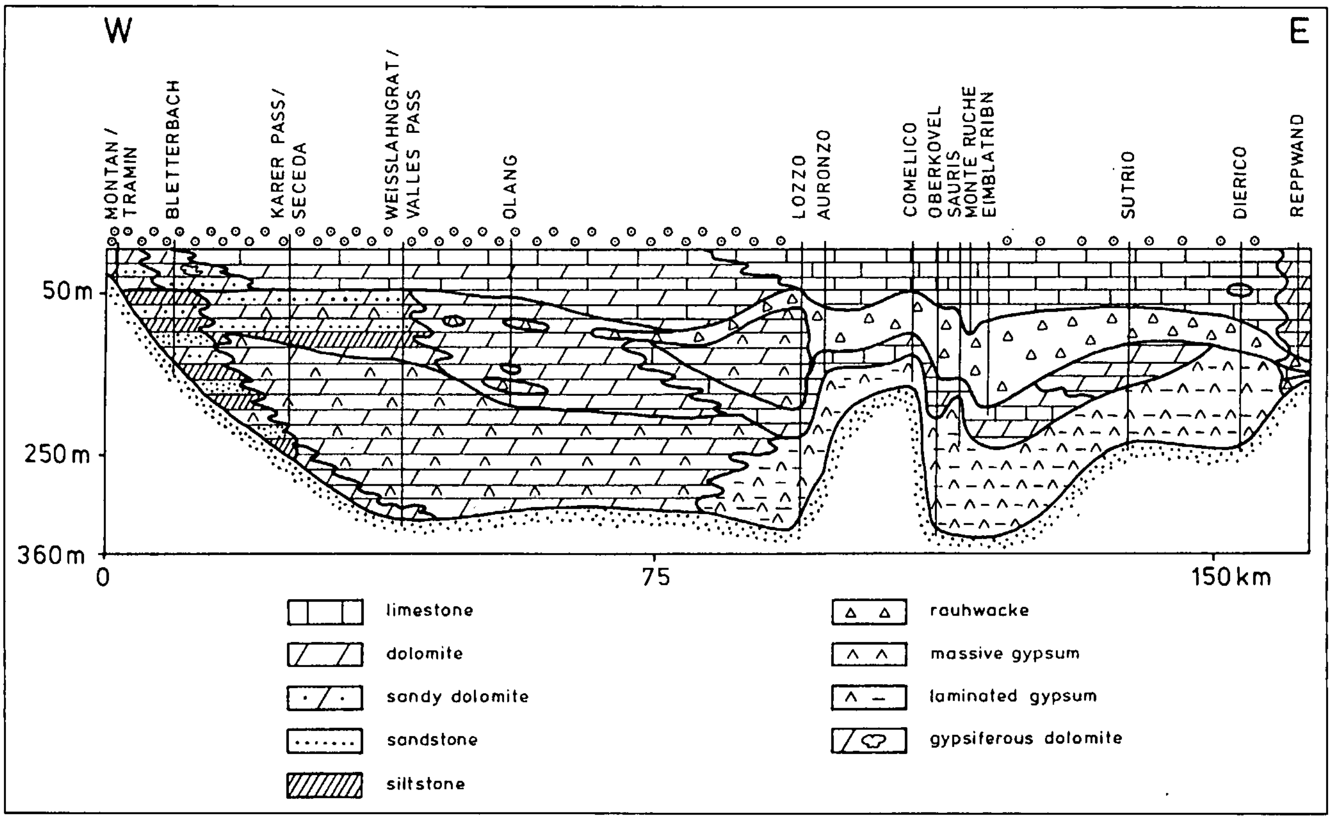
① The hinterland, a non-marine alluvial plain consisting of fine-grained siliciclastic red beds, grades into a narrow marginal-marine area characterized by a non-cyclic alternating gypsum/dolomite section with strong clastic influx.

② A restricted inner-shelf area dominated by small-scale, peritidal cycles, which consists of the following facies units, from base to top: shallowing-upward gypsum/dolomite (sabkha) cycles in the lower part, a non-cyclic dolomite/marlstone alternation with a silt-/sandstone "tongue" in the middle part, and regressive limestone/dolomite cycles in the upper part.

③ A less restricted inner-shelf area consisting of subaqueous, laminated gypsum in the lower part, complex limestone/dolomite cycles and overlying cellular dolomites in the middle part, and limestones at the top.



Text-Fig. 1.
Sections studied in the Southern Alps.
From W to E: Q = Tramin; P = Montan; O = Bletterbach; Me = Merendaore; Br = Val Sugana; Um = Umes; Te = Tesero; N = Karer Paß: Puf = Pufels; S = Seceda; Ca = Campestrin; R = Weißlahngrat; VB = Val Badia; Ol = Olang; M = Passo di Valles; Ce = Cencenighe; Ag = Agordo; L = Kreuzberg; K = Auronzo; Lz = Lozzo; RA = Rio Ampiade; C = Comelico; E = Oberkovel; B = Sauris; D = Monte Ruche; A = Eimblatribn; M = Mione; G = Sutrio; Di = Dierico; Re = Reppwand; Ac = Monte Acomizza; KB = Kosutnik River; Id = Idrija.



Text-Fig. 2.
Cross section of the depositional area of the Bellerophon Formation (according to NOÉ, 1987).
The Comelico High is located between Auronzo and Comelico Section.

④ An off shore part of the inner-shelf area with a thin evaporitic succession (cellular dolomite) at the base and dolomitized limestones in the middle and upper part.

The Bellerophon Formation was deposited on a homoclinal ramp slightly dipping eastward (NOÉ, 1987). Strong turbidity and elevated salinity of water prevented reef growth during this time.

A fault-bounded structural high (Comelico High) separates the nearshore restricted inner shelf area, characterized by low rates of subsidence (Units 1 and 2; Dolomites), from the deeper, less restricted part of the inner-shelf with an increased rate of subsidence (Units 3 and 4; Carnic Alps). Shallowing-upward cycles therefore appear solely in the shallower, restricted inner-shelf area. The Comelico High, probably responsible for the restricted environment in the landward area to the west, consists of the same facies units of a subtidal environment as accumulated on the seaward part of the inner-shelf (Text-Fig. 2). The thickness of Comelico facies units, however, is reduced due to slight tectonic uplift along synsedimentary faults, which were active up to the Tesero Horizon (BUGGISCH & NOÉ, 1986). In spite of this fault-bounded high, which did not form a major topographic feature in the Late Permian, lateral and vertical facies patterns of the Bellerophon Formation indicate that the topography of the sea floor became nearly featureless during the Late Permian. At the same time, open-marine influence shifted towards the coast, which culminated in an open shallow-marine area covering the entire depositional area of the uppermost Bellerophon Formation.

During latest Permian, a slightly eastward dipping homoclinal carbonate ramp (upper Bellerophon Formation) developed upon siliciclastic red beds (Val Gardena Sandstone Formation), evaporites (coastal sabkha and lagoonal gypsum of the lower Bellerophon Formation), and evaporite/carbonate alternations deposited in a hypersaline lagoon (middle Bellerophon Formation).

Low to moderate water energy and nearly normal oceanic salinity controlled the accumulation of carbonate muds and sands on the shallow ramp in latest Permian time.

3. Sequence Stratigraphy in the Upper Permian of the Dolomites

3.1. General Features of Sequence Stratigraphy in the Upper Permian of the Dolomites

The sequence boundaries (SB in Text-Figs. 3–5) which form during a relative sea level fall are characterized by subaerial exposure and minor concurrent subaerial erosion of the preceding peritidal and shallow-marine areas. Angular unconformities were not found in the field. Time of non-deposition comprises a short interval within one biostratigraphic zone. These type 2 sequence boundaries (VAN WAGONER et al., 1988) may be followed by a lowstand systems tract (LST) which forms during the late relative sea level fall and early rise. Due to the shallow-water inner ramp setting of the Upper Permian succession of the Dolomites, the sequence boundaries usually coincide with the onset of the following transgression and thus represent erosional unconformities (mainly ravinement surfaces) which are directly overlain by transgressive sediments. Only one lowstand systems tract is recognized in the study area, located at the base of the third sequence. It consists of terrigenous siliciclastic sediments which constitute a progradational wedge covering the landward part of the inner-shelf area (Dolomites). It laps out on the ramp landward of the underlying offlap break (Text-Fig. 4). The offlap break marks the position of the fair-weather wave-base of the previous highstand systems tract (VAIL et al., 1991). The lowstand surface at the top of a lowstand systems tract indicating the change from progradation to retrogradation is characterized by the transgressive surface (TS) which represents the first flooding surface above maximum progradation (VAIL et al., 1991).

Overlying transgressive systems tracts (TST) form during a rapid relative sea level rise. They consist of carbonates which are thinning in landward direction by coastal onlap, producing a vertical and lateral interfingering of continental and marine facies. Condensed sections, indicators of sediment starvation caused by very low sedimentation rates, winnowing, erosion or dissolution, characterize the upper part of the transgressive systems tract and the lower part of the overlying highstand systems tract of many settings. In the study area, however, condensed sections have not developed, due to slow relative sea level rises which were compensated by sedimentation. The top of the transgressive systems tract is the maximum flooding surface (mfs). This downlap surface marks the change from retrogradation to aggradation. By analogy to the transgressive systems tracts, the Upper Permian maximum flooding surfaces in the Dolomites area were not produced by sediment starvation, but are indicated by thin carbonate sand sheets which were deposited in a shallow-marine, partially high-energy environment. Fossil assemblages found in these strata show a maximum diversity and abundance, due to optimum life conditions.

Highstand systems tracts (HST) are bounded by a maximum flooding surface at the base and by a sequence boundary at the top. They form during the late part of a relative sea level rise, stillstand, and early part of sea level fall. Generally, a highstand systems tract is made up of three parts: early highstand, late highstand prograding complex, and late highstand subaerial complex (VAIL et al., 1991). The early highstand which is formed during the late part of relative sea level rise differs from the underlying transgressive systems tract in that the retrograding parasequences of the transgressive systems tract aggrade and succeedingly prograde during the highstand systems tract. The late highstand prograding complex and the late highstand subaerial complex are deposited contemporaneously during a relative sea level stillstand and the early part of a sea level fall. Both are characterized by prograding parasequences. The highstand systems tracts of two sequences in the Late Permian of the Dolomites are composed of small-scale shallowing-upward cycles (parasequences *sensu* VAN WAGONER et al., 1988).

According to the vertical sedimentary patterns, four third-order sequences are recognized in the Late Permian of the Dolomites. They comprise the uppermost strata of the Val Gardena Sandstone Formation, the total Bellerophon Formation, and the lower part of the Tesero Horizon reaching up to the Permian/Triassic boundary (Text-Fig. 3). Except for the third sequence, the sequences are composed of transgressive and highstand systems tracts only, lacking any lowstand systems tracts. The first and third sequence are rather thick and reveal similar cyclic patterns. However, these genetically related parasequences are composed of different lithologies which accumulated in different environments. On the other hand, thicknesses of the second and fourth sequence are strongly reduced due to erosion; the fourth sequence even consists of a thin transgressive systems tract solely.

3.2. Detailed Sequence Stratigraphy in the Upper Permian of the Dolomites

Text-Fig. 3 shows lithologies, transgressive-regressive curves, and systems tracts as developed in restricted inner-shelf area (Weißlahngrat and Passo di Valles Section). Text-Fig. 4 illustrates lithofacies and geometry of the lithostratigraphic units as developed in the area between the hinterland and restricted inner-shelf. Two sections in "key position" will be described in detail: Section Weißlahngrat which represents the characteristic succession as developed in the central part of the restricted inner-shelf area, and Section Bletterbach which exhibits the transgressive-regressive patterns in the marginal-marine area (see Text-Figs. 1 and 2 for location).

3.2.1. First Sequence

The base of the first sequence is located within the uppermost Val Gardena Sandstone Formation (lower Late Permian) at the top of a conspicuous gypsum layer of supratidal origin (coastal sabkha gypsum), intercalated in the terrigenous red beds. Paleogeographic reconstructions of the upper Val Gardena Sandstone Formation of the Dolomites show that this area was covered by an extended alluvial plain with meandering streams as indicated by point bar sequences in a semiarid setting (BOSELLINI & HARDIE, 1973). A gradual transgression of a shallow sea from E to W across a low-relief hinterland with a slightly fluctuating sediment supply in course of the lower Late Permian resulted in a multiple interfingering of terrigenous siliciclastic red beds, coastal sabkha evaporites and lagoonal carbonates along the shoreline (Text-Fig. 4). Such marginal-marine conditions continued during the deposition of the lower Bellerophon Formation and thus of most of the first sequence.

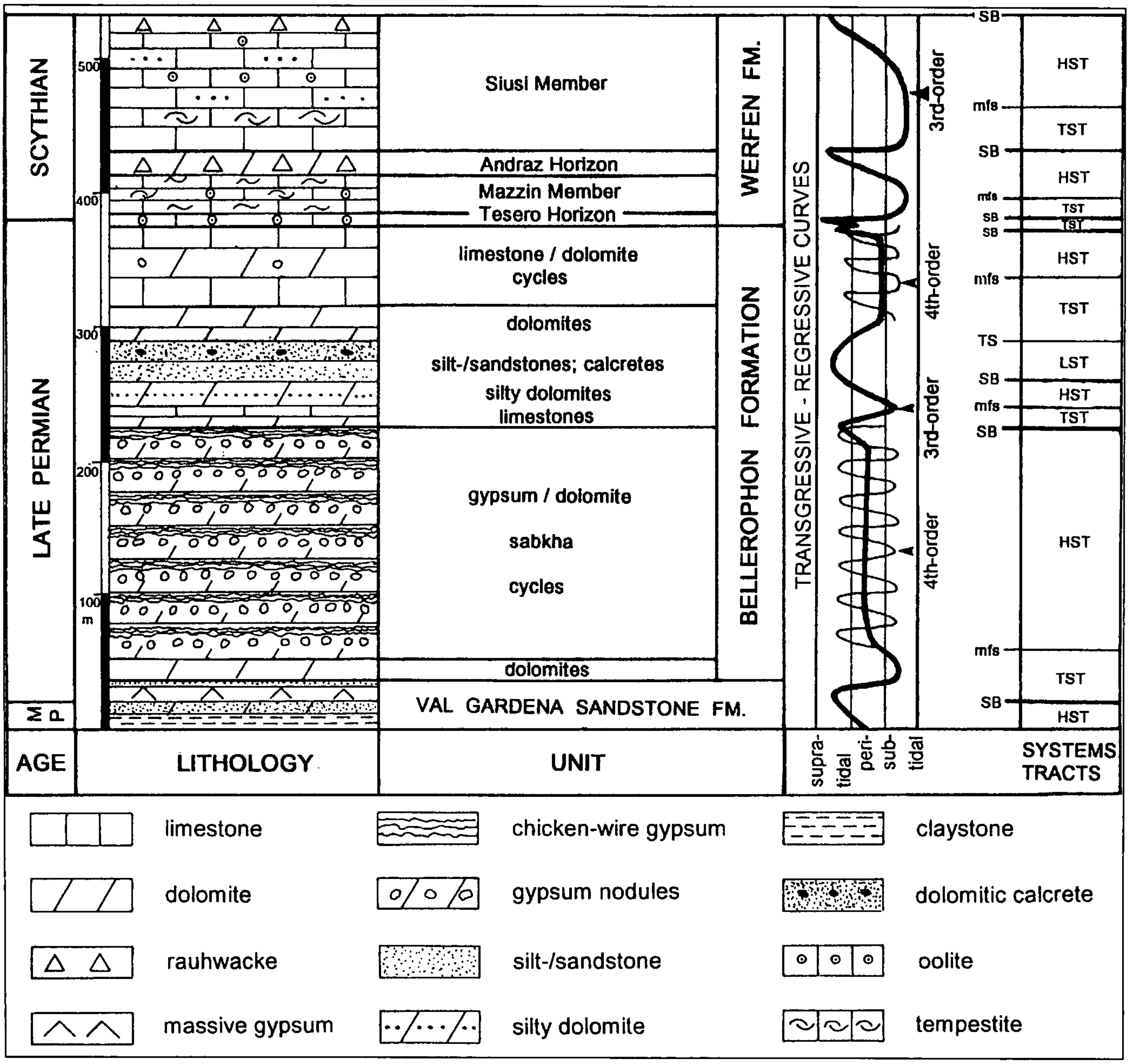
3.2.1.1. Transgressive Systems Tract

Generally, the topmost layers of the Val Gardena Sandstone Formation and the basal strata of the Bellerophon Formation reflect the transition from continental siliciclastic accumulations to chemically precipitated coastal evaporites and lagoonal carbonates (BUGGISCH, 1978).

Within the uppermost 10 m of the Val Gardena Sandstone Formation in the restricted inner-shelf area (Weißlahngrat Section), the transition from continental to peritidal deposits is indicated by an alternation of red terrigenous mudstones and sandstones, intercalated with some gypsum, dolomicrites and thin oolite beds.

According to the Italian IGCP 203 Group (1986), these facies patterns represent distal alluvial fans and overbank deposits which grade into a coastal mud flat. Occasional storms carried oolites onto the flat. In contrast, the marginal-marine area (Bletterbach Section) is totally composed of terrigenous red beds of the Val Gardena Sandstone Formation; this area was located within the alluvial plain area during lower Late Permian.

In terms of sequence stratigraphic interpretation, continental strata underlying the supratidal gypsum layer, which represent a slightly prograding alluvial fan and meandering stream facies, constitute the upper part of the highstand systems tract. The base of the gypsum horizon corresponds with a sequence boundary and thus with the base of the first sequence studied in the present paper. The highest section of the Val Gardena Sandstone Formation, reflecting the transition from an alluvial plain to a coastal mud flat facies, constitutes the lower part of a



Text-Fig. 3.
Late Permian and earliest Triassic lithology of the restricted inner-shelf area as measured in Weißlahngrat Section showing the transgressive-regressive curves and sytems tracts (see chapter 3.1 for abbreviations of systems tracts).

transgressive systems tract which formed during initial sea level rise.

The boundary between the Val Gardena Sandstone Formation and the Bellerophon Formation in the restricted inner-shelf area is fixed lithologically with the uppermost red silty layer. It is located within the transgressive systems tract of the first sequence. Thus, the basal strata of the Bellerophon Formation accumulated during a continuous transgression covering the eastern Dolomites area. In the restricted inner-shelf area (Weißlahngrat Section), the basal Bellerophon Formation consists of a 20 m thick alternation of dolomites, dolomitic marlstones, and some rare gypsum layers, which provide evidence of a restricted lagoonal environment. Thin, oolitic and intraclastic layers here were derived from storms. This unit interfingers landward with siliciclastic red beds of an alluvial fan setting which are exposed in the Seceda and Bletterbach Section. The dolomitic strata form the upper part of the transgressive systems tract.

3.2.1.2. Highstand systems tract

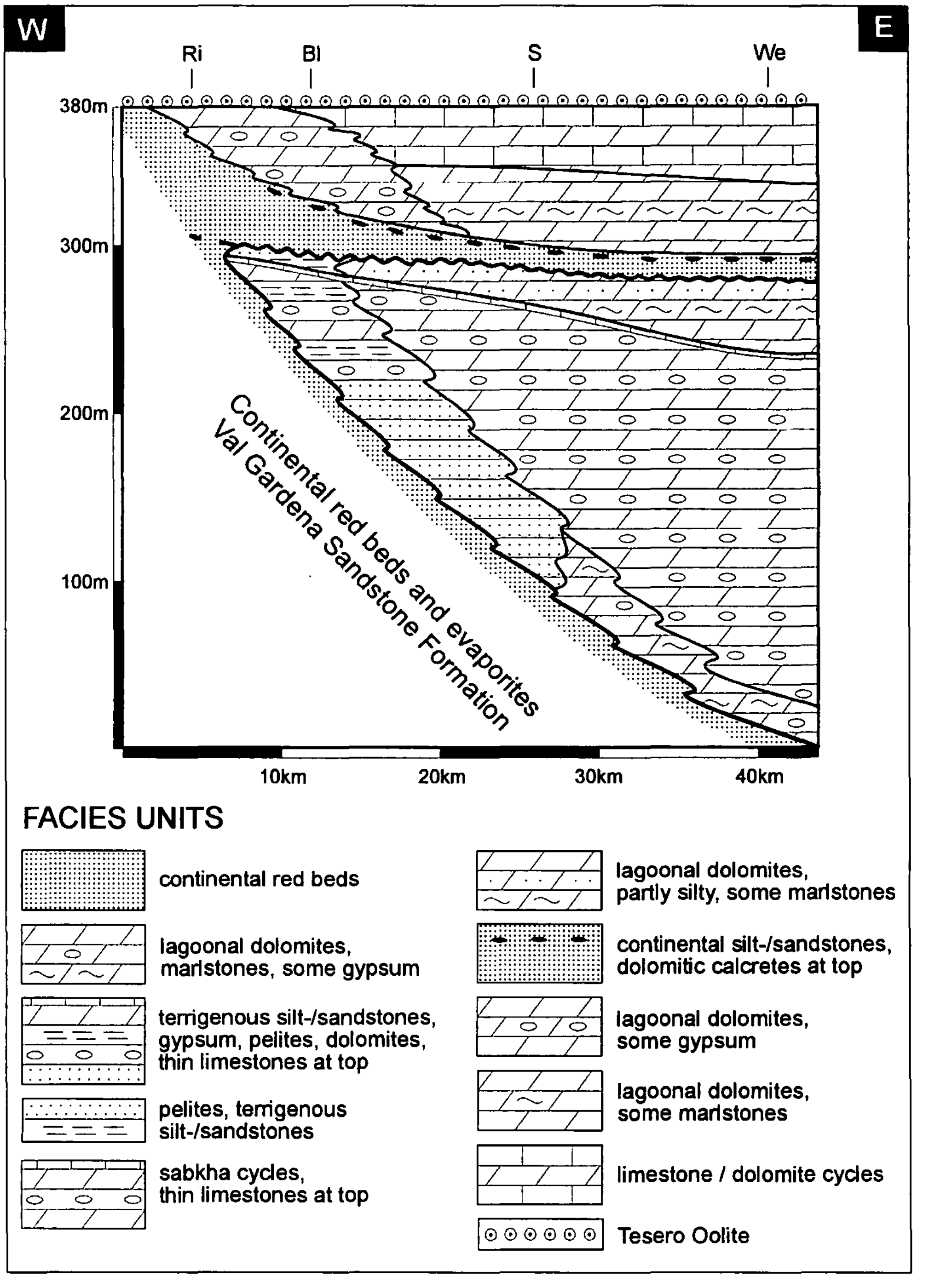
Restricted inner-shelf area

The basal dolomites of the Bellerophon Formation are overlain in the restricted inner-shelf area by a thick unit of gypsum/dolomite cycles, thinning out in landward direction, where they superimpose continental red beds.

An "ideal cycle" with a thickness of 2–5 m consists of four members, from base to top: lagoonal silty dolomicrites, peritidal dolomitic algal laminites penetrated by gypsum nodules, layered nodular gypsum, and supratidal nodular-mosaic gypsum. These fourth-order regressive cycles formed in a marginal-marine environment (coastal sabkha) under arid to semiarid conditions (Bosellini & Hardie, 1973).

According to the "standard model" of Bosellini & Hardie (1973), repetitive deposition of the shallowing-upward cycles is controlled by fluctuations of the sedimentation rate under a constant rate of subsidence (autocyclic con-

Text-Fig. 4.
Cross section of the restricted inner-shelf area and marginal-marine area during the upper Late Permian.
Sections studied: RI = Rio Inferno; BI = Bletterbach; S = Seceda; We = Weißlahngrat.



trol). Cycle formation starts when the water depth of the lagoon amounts to a few meters, enough to allow a circulation system to produce carbonate sediment. Strong evaporation of pore fluids enriched with sulfate enhances penecontemporaneous precipitation of gypsum within the non-lithified carbonate mud. During that period, sediment supply exceeds subsidence, and the shoreline progrades seaward. Gypsum growth ceases when the lagoon is filled by evaporites which then form a supratidal sabkha plain. Continuous subsidence is responsible for the following gradual inundation of the gypsum plain, generating the next cycle.

In Valles Paß Section, where the most complete succession of the gypsum/dolomite cycles is exposed – BOSELLINI & HARDIE (1973) counted 46 cycles – two phenomena provide evidence for an autocyclic control:

a) many cycles are symmetric in that they show peritidal members developed during the shallowing interval as well as during the deepening stage; other cycles, in contrast, lack a subtidal member. This evident symmetry is caused by the strong evaporation of saturated pore fluids responsible for evaporite precipitation in a vast peritidal to supratidal area;
b) lateral interfingering of the different members composing a cycle is commonly observed in the outcrop over a few tens of meters, indicating a different sedimentation rate (i.e., precipitation of gypsum which changes from place to place, dependent on evaporation and topography).

The unit of sabkha cycles is regarded as regressive cycles characterized by progradation of the supratidal members. The base of each cycle is controlled by a minor relative sea level rise across the coastal sabkha flat and the low-gradient hinterland. The lack of a conspicuous relief enables the sea to flood several kilometers of the underlying supratidal sabkha plain and of the bordering siliciclastic red beds during a sea level rise of a few meters only. Thus, the strata which are regressive during a relative sea level rise and which follow the transgressive strata of the basal Bellerophon Formation constitute a highstand systems tract. The maximum flooding surface at the base of the highstand systems tract is located at the top of the lowest dolomite layer of the sabkha cycles. The top of the last supratidal gypsum layer represents a sequence boundary which terminates the first sequence.

Marginal-marine area

Time-equivalent continental red beds of the narrow marginal-marine area interfingering with the sabkha cycles in the west were investigated by the Italian IGCP 203 Group (1986) in the Bletterbach Section. A vertical section through the Bellerophon Formation in a continental setting gives evidence of a fining-upward trend as shown by the following units: a fanglomerate/pelite alternation of a semiarid alluvial fan setting superimposed by an interval representing braided streams. This unit is followed by a series of stacked point-bar sequences and intercalated overbank mudstones, deposited in a meandering stream setting. Gypsum nodules occurring in some of the red mudstones are interpreted as pedogenic features (Italian IGCP 203 Group, 1986). Rare dolomicritic layers are intercalated in the upper part.

The lower portion of this section reflects a transgressive trend in continental facies evolution: fine-grained, mature sediments produced by meandering streams onlap onto a braided stream facies which in turn overlaps immature, coarse-grained sediments that accumulated at the rise of the Hercynian volcanic massifs. Because of the lateral interfingering with the sabkha unit, this section is regarded to comprise the most landward strata of the lower Bellerophon Formation; it is therefore included into the transgressive and highstand systems tracts of the first sequence.

The lateral boundary between the siliciclastic red beds of the Bellerophon Formation and the continental red beds of the Val Gardena Sandstone Formation is not clearly fixed. Continental strata in the Val Adige area do not reveal a clear transgressive trend, and are generally regarded as belonging to the Val Gardena Sandstone Formation.

3.2.2. Second Sequence

3.2.2.1. Transgressive Systems Tract

The sabkha cycles of the restricted inner-shelf are overlain by 5 m thick dolomicrites which are followed by 1–2 m thick dolomitized biosparitic layers bearing microfossils which exhibit increasing abundances and diversities towards the top. In the Weißlahngrat Section, a highly diverse mollusc fauna (NERI & POSENATO, 1985) is associated with abundant fusulinids, smaller foraminifera and calcareous algae. A corresponding calcareous sandstone horizon in the Bletterbach Section, occurring at the top of the meandering stream deposits, bears a cephalopod fauna originally described by MUTSCHLECHNER (1933), which correlates with the mollusc fauna of the Weißlahngrat Section. Palynological data also support time-equivalence of the horizon in both areas (Italian IGCP 203 Group). These conspicuous strata onlapping onto the restricted inner-shelf and marginal-marine area (Text-Fig. 4) accumulated during a marine incursion which covered the subaerially exposed sabkha and alluvial plain with a shallow, well agitated sea of nearly normal salinity. They constitute a thin transgressive systems tract with the top of the carbonate horizon representing a maximum flooding surface. The retrogradational stacking patterns change into aggradation with the overlying strata.

3.2.2.2. Highstand Systems Tract

In the restricted inner-shelf area, a non-cyclic alternation of silty to sandy dolomicrites and marlstones, gradually thinning landward, overlies the carbonate horizon. A poor euryhaline fauna and flora indicate deposition in a shallow restricted lagoonal environment of low water energy. The siliciclastic influx rapidly increases from the middle part towards the top. The terrigenous supply was responsible for a gradual shallowing and filling of the shallow lagoon, ending with subaerial exposure. The corresponding unit in the marginal-marine area (Bletterbach Section) consists of only 3 m of cross-bedded sandy-pelitic alternations, capped by a channel fill. Facies are interpreted by the Italian IGCP 203 Group (1986) as a transitional environment: a coastal mud flat, temporarily flooded by a very shallow sea, covered by continental deposits of encroaching meandering rivers.

The lower part of these units was deposited during a relative sea-level stillstand, responsible for the formation of aggradational stacking patterns at the shoreline. Higher in the section, aggradation changed into progradation, due to an increasing terrigenous influx with a constant rate of subsidence. The regressive trend was probably enhanced by a eustatic sea level fall, because the eastern part of the restricted inner-shelf area (not illustrated in Text-Fig. 4), which is not influenced by terrigenous siliciclastic sediments, shows pedogenetically-altered dolomite horizons and some nodular-mosaic gypsum indicating emersion. Thus, the lower, carbonate-dominated part of the unit is interpreted as early highstand, while the upper part showing stronger siliciclastic influx corresponds to a late highstand prograding complex with transition to a late highstand subaerial complex (*sensu* VAIL et al., 1991).

The regressive trend culminates with subaerial exposure of the total marginal-marine and restricted inner shelf area, producing a sequence boundary. The exposure surface, recognized in the field by the first massive sandstone horizon cutting sandy dolomites (Text-Fig. 3), mostly runs approximately parallel to bedding; a distinct subaerial erosional relief is found, however, in some places.

3.2.3. Third Sequence

3.2.3.1. Lowstand Systems Tract and Lower Part of the Transgressive Systems Tract

Restricted Inner-Shelf Area

Continental red beds following the subaerial unconformity are characterized in the restricted inner-shelf area by red and green silt-/sandstones and silty marlstones with plant remains, regarded as a "Val Gardena Sandstone tongue interfingering with the Bellerophon sequence" (Italian IGCP 203 Group, 1986). This prograding terrigenous tongue is thinning in seaward direction and finally pinches out approx. 10 km east of Weißlahngrat Section. Some channel-fill deposits pointing to fluviatile transport are recorded in the lower part only. Overlying fine-grained and well-sorted sediments, in contrast, do not show any distinct sedimentary structures; they are believed to represent eolian sheet sand deposits. The upper part of the unit is characterized by conspicuous dolomite nodules which are conformably intercalated within the siltstones. They are interpreted as pedogenic calcretes, precipitated from ascending hypersaline pore fluids in a semiarid setting. The calcretes are intercalated in time-equivalent silt-/sandstones across the restricted inner-shelf and marginal-marine area, and thus, represent important lithostratigraphic markers. By analogy to related lowstand siltstone/sandstone horizons of the Yates Formation in the Permian Reef Complex, USA (BORER & HARRIS, 1989, 1991), this terrigenous unit is interpreted as lowstand systems tract.

Strata following the lowstand systems tract are distinguished by decreasing clastic influx and an increase of carbonate accumulation; this is evidenced by an irregular dolomite/marlstone alternation bearing a low-diverse euryhaline fauna and flora. In Weißlahngrat Section, a few dolomite layers interspersed with gypsum nodules are restricted to the lowermost part of the unit. The sediments accumulated in a shallow lagoon of low water energy and more or less increased salinity. This unit gives evidence of a strongly decreasing terrigenous input, linked with a slight relative sea level rise, covering the exposed area with a very shallow sea. It represents the lower part of the transgressive systems tract of the third sequence in the restricted inner-shelf area. The transgressive surface occurs at the base of the first dolomicritic layer devoid of any siliciclastic detritus, which shows a distinct onlap in landward direction onto the marginal sabkha and the Val Gardena Sandstone tongue.

Marginal-marine area

The siliciclastic "tongue" thickens in a landward direction as measured in sections located in the marginal-marine area (Text-Fig. 4). The record exposed in the Bletterbach Valley and in Rio Inferno displays an overall transgressive trend: channel-fill sandstones and mudstones alternating with sheet-like lenticular sandstone layers constitute the lower part. It is overlain by the characteristic pedogenic calcrete interval. The following unit consists of wave-rippled sand-/siltstones with some mud drapes and mud-cracked mudstones with gypsum nodules, and bears tetrapod footprints (determination of the ichnofauna by the Italian IGCP 203 Group, 1986). This conspicuous horizon is finally superimposed by laminated silty dolomicrites. According to the IGCP 203 Group (1986), facies evolution characteristic of a transitional setting starts with a fluviatile system and ends with a temporarily flooded coastal sabkha: gypsum-bearing muddy flats of the marginal sabkha giving evidence of storm events onlap onto flood-generated sheet sands and eventually onto ephemeral "wadi" distributaries, accompanied by pedogenetically altered interchannel muds.

The prograding siliciclastic tongue in Val Gardena Sandstone facies constitutes the lowstand systems tract, which developed during late relative sea level fall. High terrigenous input may be invoked by a minor uplift of the hinterland. Succeedingly, sedimentation was controlled by an initial sea level rise and decreasing sediment supply, indicated by a change from siliciclastic to carbonate sediments. It marks the base of the transgressive systems tract of the third sequence. The section starts with a lagoonal dolomicritic layer at the top of a thick greenish siltstone/pelite alternation. The greenish-gray fine-grained siliciclastics yielding dolomitic calcretes accumulated upon the last siliciclastic red beds of the Val Gardena Sandstone tongue. These sediments are overlain by transgressive coastal sabkha deposits.

3.2.3.2. Upper Part of the Transgressive Systems Tract and Highstand Systems Tract

Restricted Inner-Shelf Area

In the restricted inner-shelf area, the upper part of the transgressive systems tract and the highstand systems tract of the third sequence is composed of limestone/dolomite cycles which interfinger in the marginal-marine area with an inhomogenous carbonate/evaporite alternation. This unit, in turn, grades landward into terrigenous red beds of the Val Gardena Sandstone tongue.

The 4–6 m thick limestone/dolomite cycles were deposited in a lagoonal and muddy tidal flat environment. They consist of the following members:

1) Slightly winnowed calcareous biosparites (packstones) with a high diversity of foraminifera including fusulinids and calcareous algae form the subtidal part of a cycle. The degree of winnowing of the packstones reflects a decreasing water circulation towards the top of the member. Thin, calcareous marlstones are intercalated in regular intervals; in addition, they always form the base of the member, and thus, the base of a cycle.
2) This member is overlain by peritidal calcareous and/or dolomitic wackestones with some gypsum nodules and *Skolithos*-like burrows. Some algal fragments were transported onto the mud flat during stormy periods.
3) Dolomitic mud-/wackestones bearing strongly fragmented algal thalli form the top of a cycle; abundant gypsum nodules which precipitated in the vadose zone indicate a supratidal origin of the sediment. High-resolution investigations of microfacies and geochemistry have shown fourth-order and fifth-order shallowing-upward cycles (BUGGISCH et al., 1994).

Three factors count for a eustatic control of the cycles:

a) The grain-dominated shallowing-upward cycles are traced in two orders of magnitude.
b) In contrast to the nearly symmetrical sabkha cycles of the lower sequence, the regressive limestone/dolomite cycles are asymmetric in that a gradual shallowing phase from a shallow subtidal to supratidal environment is followed by a rapid deepening into the subtidal realm again where a new cycle formation starts. No peritidal sediments are recorded from the deepening stage. The evident asymmetry of sea level fluctuations is reflected by the thickness of the members: the subtidal member exhibits greater thickness than the peritidal and supratidal member together. Because of their distinct asymmetry, cycles are believed to represent punctuated aggradational cycles (BUGGISCH et al., 1994).
c) The single members of a cycle do not interfinger with each other on the outcrop scale and probably may be traced over several kilometers, due to the limited extension of the outcrops.

The lower interval of the limestone/dolomite cycles reflects a distinct transgressive trend, followed by a minor regressive oscillation in the upper part. Such directed sea level fluctuations – probably of eustatic origin – immediately controlled water depth, water circulation, and thus had strong influence on the marine benthic fauna and flora. Abundances, diversities, and distributional patterns of the micro- and macroorganisms therefore clearly display the transgressive-regressive trends (NOÉ, 1988).

The lower part of the limestone/dolomite cycles is composed of cycles as described above, yielding a diverse mollusc fauna (identification of species by the Italian IGCP 203 Group, 1986). This interval as a whole displays a transgressive trend as manifested by an increase of water circulation and thus constitutes the upper part of the transgressive systems tract of the third sequence. The transgression culminates in a layer revealing maximum diversity and abundance of micro- and macrofossils (Italian IGCP 203 Group, 1986). This layer may be interpreted to represent a minor maximum flooding surface. The limestone/dolomite cycles overlying the maximum flooding surface reflect a minor regressive trend as evidenced by an impoverished fauna and flora – e.g., fusulinids and other stenohaline organisms are absent. Rock fabrics of the members constituting a cycle, however, are the same as observed in the underlying transgressive part.

The limestone/dolomite cycles end with a 2 m thick pile of calcareous biosparites and intrabiosparites, bearing a highly diverse stenohaline fauna and flora which indicates open shallow-marine conditions. According to these paleoenvironmental conditions, the highest diversity of the Bellerophon Formation is recorded from its topmost interval (NOÉ, 1987 and 1988). The limestones show a shallowing-upward trend as indicated by a decrease in clay content, an increasing abundance of packstones to grainstones, and an increase of grain size and bed thickness, probably pointing to an increased sedimentation rate. The limestones accumulated on an open shallow-marine area with moderate to high water-energy and normal oceanic salinity. The preexisting shallow shoal topography of the sea floor was leveled at that time.

The shallowing was probably induced by an increase of the sedimentation rate and a decrease in rate of subsidence. The limestone/dolomite cycles following the maximum flooding surface form the highstand systems tract of the third sequence. The shoaling in the uppermost Bellerophon beds indicates the late highstand. It culminates in subaerial exposure at the topmost dolomite layer of the cycles as indicated by mud cracks. The top of this dolomite layer represents a sequence boundary.

The Bellerophon Formation ends in the restricted inner-shelf area with 30 cm thick limestones of an open shallow-marine environment: slightly to well winnowed algal-foraminiferal biosparites (Plate 1/2), superimposed by intrabiosparites (grapestone facies: Plate 1/7). They grade into the basal oolites of the overlying Tesero Horizon (Plate 2/1-2). These strata form the lower part of the transgressive systems tract of the fourth sequence.

Marginal-marine area

The upper part of the transgressive systems tract and the highstand systems tract mainly consist of a non-cyclic alternation of carbonates and evaporites which display an overall transgressive trend towards the top, interrupted by a minor regressive event in the middle/upper part. The transgressive/regressive intervals may be correlated with those recorded from the restricted inner-shelf area (Text-Fig. 4). The upper part of the transgressive systems tract starts with unfossiliferous lagoonal dolomicrites and thin intercalations of nodular and laminated gypsum which formed on a coastal sabkha plain. This interval is overlain by lagoonal dolomicrites yielding euryhaline organisms. These fossils are concentrated in the topmost dolomite layer which represents a maximum flooding surface, analogous to the restricted inner-shelf area. The succeeding regressive interval which constitutes the highstand systems tract is initiated by a terrigenous silt-/sandstone alternation occurring in the marginal-marine area only. The overlying carbonate/evaporite alternation contains a few dolomite horizons with conspicuous thick gypsum nodules, and was deposited in a strongly hypersaline lagoon that graded into an evaporative mud flat during shallowing periods. The regressive trend culminates in a thick layer of massive laminated gypsum of supratidal origin.

By analogy to the restricted inner-shelf area, this gypsum layer indicates subaerial exposure and thus a sequence boundary. The following transgression is manifested by 10 cm thick calcareous marlstones at the base, followed by 30 cm thick limestones. These grainstones are, from base to top:

1) slightly winnowed algal biosparites (Plate 1/1);
2) biosparites rich in foraminifera (Plate 1/5-6) as well as in calcareous algae and echinoderms, alternating with silty diagenetic packstones rich in echinoderms (Plate 1/3-4);
3) intrabiosparites (grapestone facies) which constitute the topmost 30 cm of the Bellerophon Formation, grading into the oolitic facies of the basal Tesero Horizon (Plate 1/8). The grapestone facies is distinguished by the highest abundance and diversity of micro- and macrofossils found in the Bellerophon Formation of the marginal-marine area. It represents the base of the transgressive systems tract of the fourth sequence.

3.2.4. Fourth Sequence

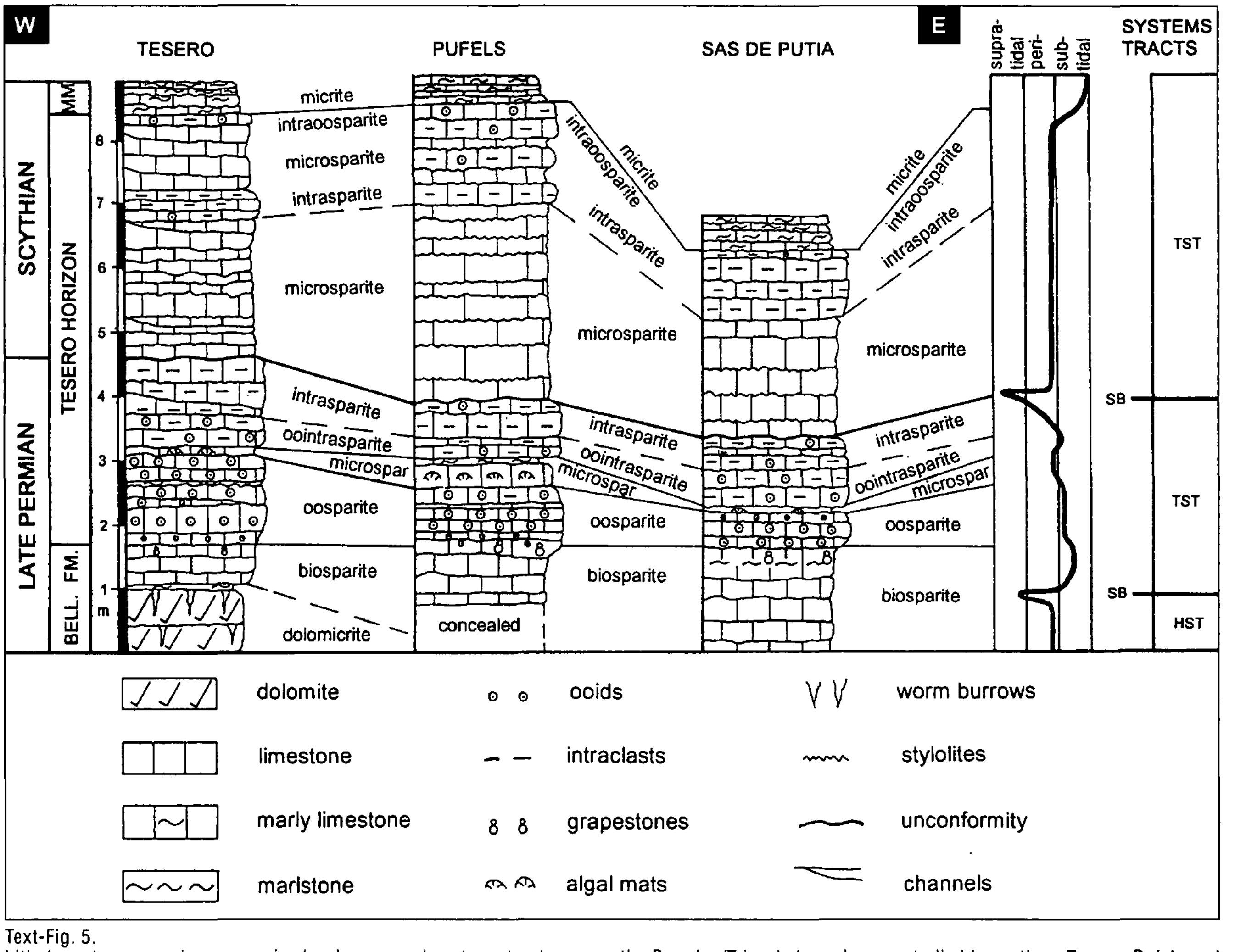
The fourth sequence reaches a thickness of 3–4 m only. It solely consists of a transgressive systems tract; numerous ravinement surfaces give evidence that the highstand systems tract became removed by erosion.

3.2.4.1. Transgressive Systems Tract: Lower and Middle Part of Tesero Horizon

The Bellerophon Formation is conformably overlain by the Tesero Oolite which represents the lower part of the Tesero Horizon (Text-Fig. 5). The grapestone facies of the topmost Bellerophon Formation, which was deposited in an open shallow-marine environment with a low relief, extended from the marginal-marine area across the total inner-shelf of the homoclinal ramp (Text-Fig. 2). The transition from the grapestone facies to the oolitic facies of the basal Tesero Horizon is observed within one layer. Facies evolution from the topmost Bellerophon Formation to the top of the 1–2 m thick Tesero Oolite reflects an increase of water energy, an increase of the sedimentation rate, and a shallowing of the sea from a very shallow subtidal to peritidal realm: the basal mixed oolite facies (oobiosparite) characterized by superficial ooids (Plate 2/1), is followed by a thick oosparitic unit (grainstones) consisting of normal-size ooids with increasing grain size (Plate 2/2–4), eventually grading into multiple ooids. Hummocky cross stratification, further evidence of high-energy conditions, commonly occurs in the higher part of the Tesero Oolite. On the other hand, a decrease in abundance and diversity of the Permian microfossils is observed upward in this section (NOÉ, 1987).

The Tesero Oolite accumulated during a transgression of a very shallow sea from southeastern direction towards the west, onlapping on to continental sediments. High water energy was responsible for the formation of tongue-like oolitic sheets covering the open shallow-marine area of the topmost Bellerophon Formation on a regional scale. The oolite transgression solely bypassed the western part of the Comelico High which was subaerially exposed due to slight tilting of a block along synsedimentary faults. In the surroundings of Val Adige, coastal onlap is manifested by oolites unconformably overlying dolomites of a muddy tidal flat facies and, further to the west, terrigenous red beds (Text-Fig. 4).

Consequently, paleogeography of the lower Tesero Horizon (Tesero Oolite) was controlled by a simultaneous shallowing of the sea and by a directed transgression across the open shallow-marine area and bordering continental area with a senile topography. A relative sea level fall and a coastal onlap occurring at the same time may be caused by the following factors: a simultaneous gradual decrease in rate of subsidence and increase of the sedimentation rate reduced the accommodation space and thus caused the shallowing. This long-term trend is modified by a short-term eustatic sea level rise which induced the directed flooding and coastal onlap.



Text-Fig. 5.
Lithology, transgressive-regressive level curve and systems tracts across the Permian/Triassic boundary as studied in sections Tesero, Pufels and Weißlahngrat (Sas de Putia). See chapter 3.1 for abbreviations of systems tracts.

Overlying approx. 120 m thick strata of the middle Tesero Horizon which show many ravinement (erosional) surfaces seem to be controlled by a general relative sea level fall, due to a continuous decrease in rate of subsidence. This trend was slightly modified by small-scale eustatic sea level fluctuations of low amplitude as indicated by vertical changes of very shallow subtidal, peritidal and supratidal environments. The distinct decrease of subsidence largely balanced eustasy, preventing major changes in water depth. Field studies and microfacies analyses contrast the investigations of WIGNALL & HALLAM (1992) in that definite indices of a deeper-marine environment during deposition of the Tesero Horizon were not found in the stratigraphic record. Numerous intraoosparitic layers contain small ooids and show mud-cracked intraclasts pointing to temporary subaerial exposure. According to our results, facies patterns therefore do not reflect regressive punctuated aggradational cycles (*sensu* GOODWIN & ANDERSON, 1985) as interpreted by WIGNALL & HALLAM (1992). The low-amplitude sea level fluctuations solely modified the course of the shoreline, due to the leveled topography of the extended shelf and of the hinterland.

The lithologic record of the middle part of the Tesero Horizon is subdivided into three units:

1) A layer of light-gray microsparite (mudstone) of 1–3 cm thickness superposes the Tesero Oolite. Desiccation cracks at the top indicate a short-term emersion. Cyanobacterial laminations and/or fenestral fabrics are very rare. In contrast, features of storm reworking (Plate 2/5) and of burrowing activity are commonly observed. Syngenetic pyrite occurs throughout the unit. The sedimentary structures provide evidence for a low-lying peritidal flat with a local siliciclastic influx. The unit indicates a short-term shallowing after the oolite sedimentation into a low-lying peritidal flat.
2) The ensuing sea level rise submerges the muddy tidal flat into a very shallow subtidal environment. High-energy conditions are responsible for the formation of oolites and oolitic grapestones and for the reworking of the lithified mud forming mud-cracked flat pebbles. The oointrasparites (grainstones) show a continuous decrease of microfossil abundance, while the diversity is the same as observed in the upper part of the Tesero Oolite. Abundance of ooids decreases in the same direction. Thickness of the oointrasparitic unit amounts to 30–40 cm.
3) The overlying 30–80 cm thick alternation of intrasparites (grainstones) and microsparites of cyanobacterial origin (mudstones: Plate 3/5 to bindstones: Plate 3/6) develops gradually from the intraoosparitic unit after a slight eustatic sea level fall, responsible for the formation of a low-lying muddy tidal flat and the cessation of oolite production. The peritidal conditions triggered an intensive growth of algal mats and stromatolites (Plate 3/6). By analogy to the underlying Unit 2, the

intrasparites consist of irregularly oriented flat pebbles showing tiny borings (Plate 3/3-4) and desiccation cracks (Plate 3/1-2) which represent the reworking products of the algal mat sediments. They also contain irregularly-shaped lumps composed of peloids and micritic ooids (Plate 2/7). Both components were produced during storms. Intact microsparitic layers are rarely preserved. The sedimentologic features indicate alternating low-energy / high-energy conditions as well as fluctuations of emersion and submersion. A low-diverse, parautochthonous association of calcareous algae (*Gymnocodium bellerophontis* ROTHPLETZ: Plate 2/8), smaller foraminifera, molluscs, and brachiopods occurs up to the top of the intrasparitic unit (Text-Fig. 6).

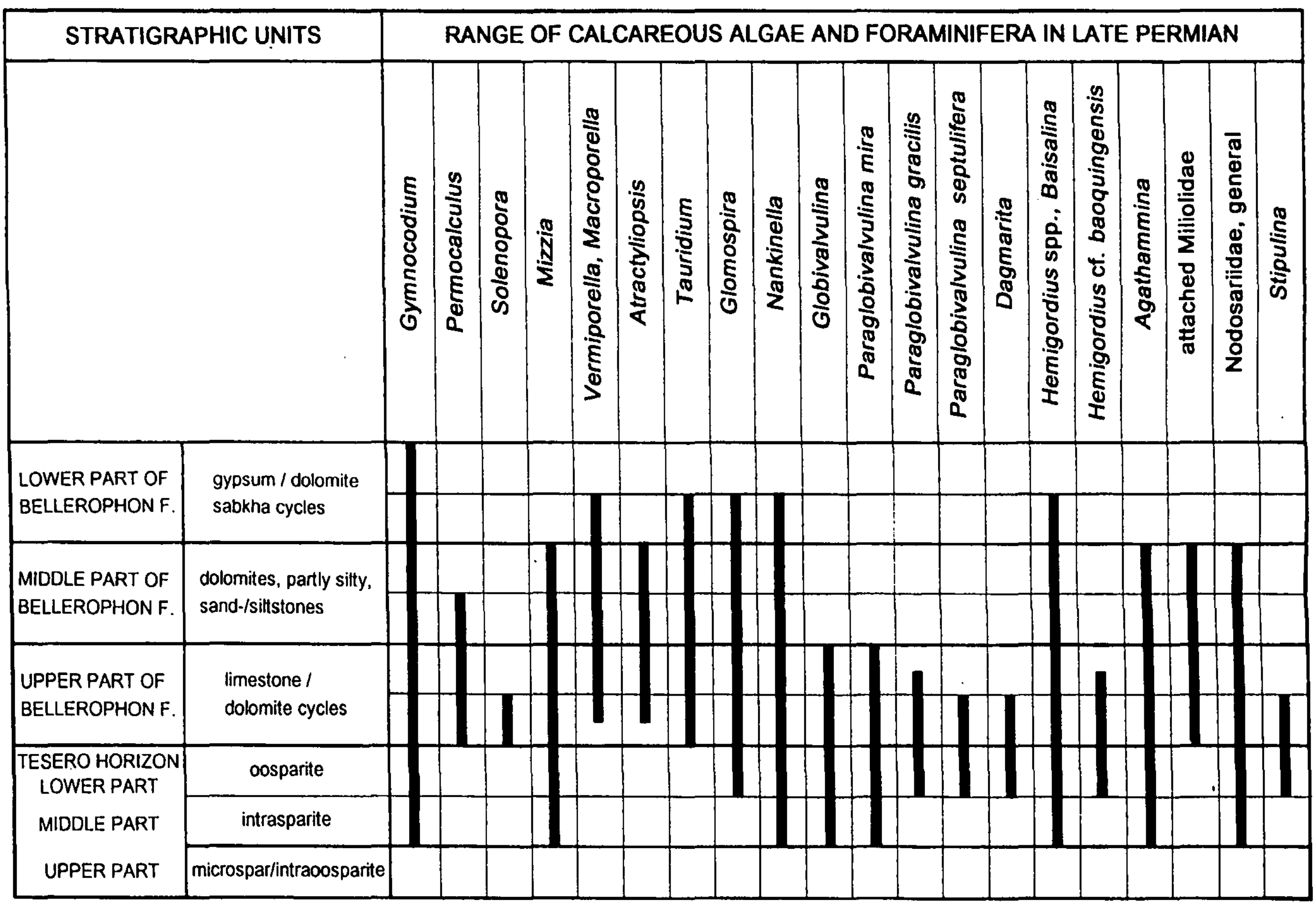
3.2.4.2. Sequence Boundary: The Permian/Triassic Boundary

Culmination of the relative sea level drop during latest Permian is manifested by emersion of the shelf at the Permian/Triassic boundary. Subaerial exposure responsible for a stratigraphic gap in the marine sedimentary record indicates a type 2 sequence boundary which terminates the fourth sequence of the Late Permian. The sequence boundary coincides with the Permian/Triassic boundary as defined by biostratigraphy. The youngest Permian microfossils indicating a Dorashamian age are found up to the last layer of Unit 3 (intrasparites; Text-Fig. 6). The conformably overlying microsparitic unit constituting the upper Tesero Horizon (Chapter 4.1.) bears a mixed fauna of Permian-type brachiopods and Triassic-type bivalves (NERI & PASINI, 1985), while Permian-type microfossils are missing (Text-Fig. 6). A corresponding mixed fauna occurring in South China is associated with *Otoceras woodwardi*, the index ammonite of the earliest Triassic (SHENG et al., 1984). Using the correlation with South Chinese sections, which are regarded to be the most complete Permian/Triassic boundary sections of the Tethys, the microsparitic unit of the upper Tesero Horizon is of earliest Triassic age (NOÉ, 1987, 1988). The stratigraphic gap between latest Permian and earliest Triassic was probably short in the westernmost part of the Paleotethys – the amount is at least less than the duration of a biostratigraphic zone since the sections studied in the Dolomites and Carnic areas do not reveal any angular unconformity or major subaerial erosion along the sequence boundary. However, the time interval of subaerial exposure was sufficient to allow meteoric pore fluids to flush through the underlying sediments, occluding open pore space.

The coincidence of the Permian/Triassic mass extinction event with a third-order sequence boundary during a time interval of low subsidence in the westernmost Paleotethys supports the results of EMBRY & BEAUCHAMP (1993).

3.2.4.3. Studies on Stable Carbon Isotope Ratios Across the Permian/Triassic Boundary

In order to reconstruct the paleoenvironmental conditions across the Permian/Triassic boundary, stable carbon isotopes were analyzed from two closely sampled sections in the Dolomites (Tesero and Valles, Text-Fig. 7). Ad-



Text-Fig. 6.
Stratigraphic range of calcareous algae and foraminifera in Late Permian of the Southern Alps.
The Permian/Triassic boundary is intercalated between the intrasparite unit of the middle part of Tesero Horizon and the microsparite/intraoosparite unit of the upper Tesero Horizon.

ditional data were taken from MAGARITZ et al. (1988) and MAGARITZ & HOLSER (1991). Groundmass (micrite, sparite) and components were analysed separately with a Finnigan MAT 252 mass spectrometer.

All sections show a uniform trend (Text-Fig. 7): high $\delta^{13}C$ values (+3 ‰ to 4 ‰ PDB) are found in the uppermost Bellerophon Formation. They rapidly drop to zero at the base and/or within the Tesero Horizon and reach negative values (–2 ‰ PDB) in the lowermost Mazzin Member (earliest Scythian). In the Reppward section, the decrease starts in the topmost Bellerophon Formation, indicating a succession of greater thickness (MAGARITZ & HOLSER, 1991). Our data reflecting a rapid drop of $\delta^{13}C$ values at the Permian/Triassic boundary coincide with the $\delta^{13}C$ curves measured by BAUD et al. (1989) from 20 sections across the Paleotethys in shelf and basin sediments and with observations evidenced from British Columbian sections (WANG et al., 1994). According to these authors, the change from generally high values of $\delta^{13}C$ in Late Permian (Murgabian to Early Dorashamian) to the succeeding drop of $\delta^{13}C$ values are regarded to have been controlled by:

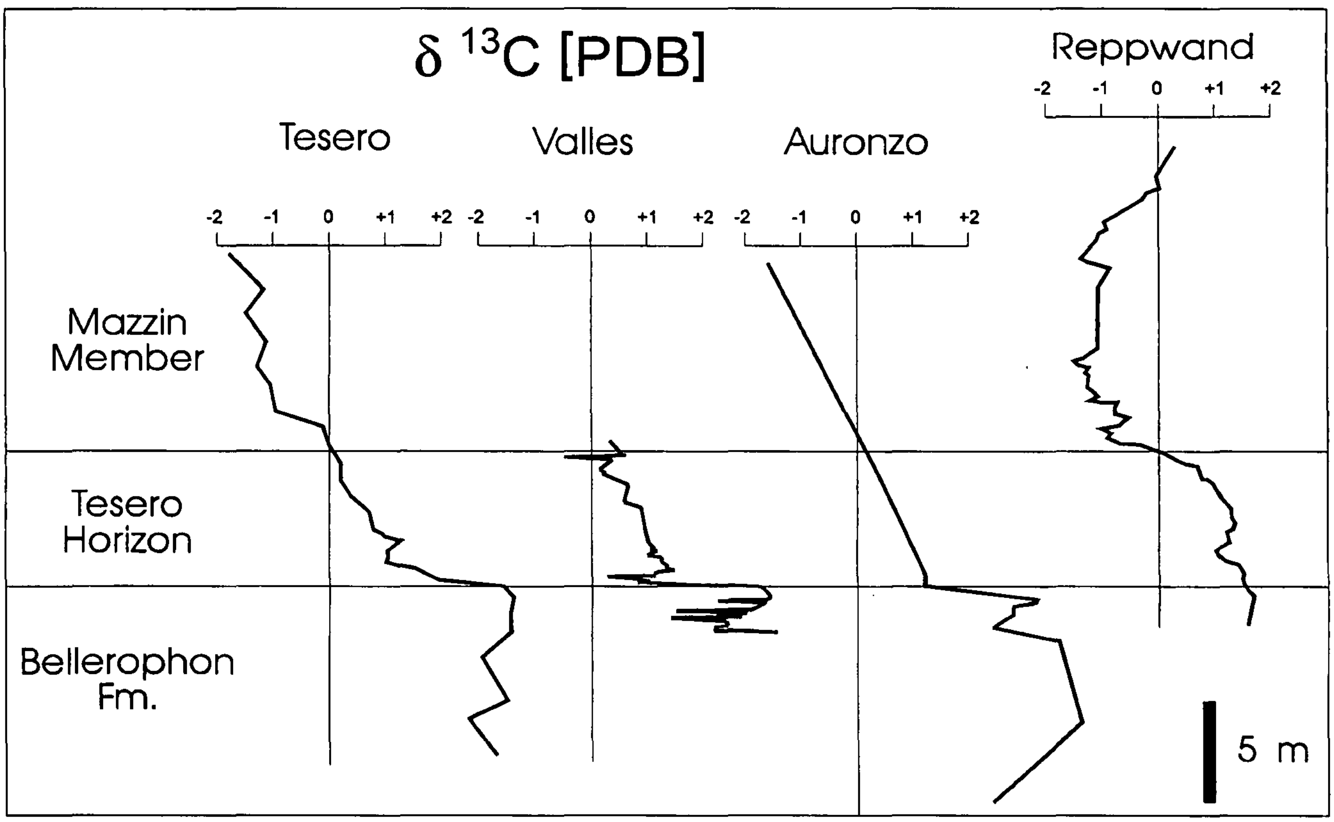
1) Decrease of surface water primary productivity;
2) Factors supporting a recycling of the stored organic matter: erosion and/or partial oxidation of C_{org}, freshwater influx, increase of water circulation, and climatic change.

According to the $\delta^{13}C$ curve of BAUD et al. (1989) and to our data, oxic conditions therefore prevailed in the Paleotethys during latest Permian and across the Permian/Triassic boundary. A unique geochemical record observed in the uppermost Tesero Horizon and lowermost Mazzin Member, however, provides evidence for an onset of an oxia after the Permo-Triassic extinction event: increasing Ce/La ratios, increasing abundances of syngenetic pyrite, high S/C ratios, positive $\delta^{34}S$ values, and high Ir concentrations (HOLSER et al., 1989). Instead, microfacies of the limestones as well as the low $\delta^{13}C$ values across the Permian/Triassic boundary do not support a contention of anoxia as a cause of the Permian/Triassic mass extinction (*sensu* WIGNALL & HALLAM, 1992). A positive $\delta^{13}C$ excursion, like observed at the major anoxic events in earth history – e.g., Frasnian/Fammenian boundary (JOACHIMSKI & BUGGISCH, 1993), Cenomanian/Turonian boundary (ARTHUR et al., 1987) - should characterize the Permian/Triassic boundary in the Dolomites to support the hypothesis of WIGNALL & HALLAM (1992); see also discussions by ERWIN (1993, 1994).

4. Sequence Stratigraphy in the Lowest Triassic of the Dolomites

In this paper, the sequence stratigraphy of the lower Werfen Formation (Early Scythian) comprising the upper part of the Tesero Horizon, Mazzin Member, Andraz Horizon (all of Griesbachian age), and Siusi Member (Late Griesbachian and Early Nammalian age) is described. The Werfen Formation was deposited on a very low-gradient southern shelf of the Paleotethys gulf, which was bordered in the south and west by oolitic shoals and subaerially exposed mud flats (NERI, 1991). Facies associations mainly comprise three types:

1) Micritic deposits with some distal storm layers, which accumulated in a low-energy subtidal environment beneath the fair-weather wave base;



Text-Fig. 7.
Stable carbon isotope curves across the Permian/Triassic boundary from four sections of the Southern Alps.
Section Tesero according to BAUD et al. (1989) and to own analyses; Section Valles according to own analyses; Section Auronzo according to MAGARITZ et al. (1988); Section Reppwand according to MAGARITZ & HOLSER (1991).
The scale relates to the Bellerophon Formation and Mazzin Member solely showing their true thickness. The true thicknesses of the Tesero Horizon which differ from one section to another are adjusted to a mean value.

2) Oolitic/bioclastic sand bodies found in a wave- to tide-controlled shallow-shelf environment;
3) Fine-grained intrasparitic sediments of a peritidal environment and mud-cracked supratidal dolomitic laminites.

The Werfen Formation, deposited after the Permian/Triassic mass extinction, is generally poor in fossils. The Scythian is especially distinguished by a complete lack of calcareous algae in the shelves surrounding the Tethys. The faunal recovery was initiated by a mollusc association revealing a slowly increasing diversity.

The rocks of the lower Werfen Formation constitute two third-order sequences (Text-Fig. 3). Due to a constant rate of thermal subsidence, a tectonic inactivity, a mostly constant sedimentation rate, and a featureless topography of the sea floor, the uniform sedimentation was modified by third-order eustatic sea level fluctuations (NERI, 1991). Eustasy is evidenced by the asymmetry of the sea level curve showing gradual regressions and rapid transgressions (Text-Fig. 3). The lower sequence consists of the upper part of the Tesero Horizon, the Mazzin Member, and the Andraz Horizon. The upper sequence comprises most of the Siusi Member, excluding the topmost strata only.

In general, lowstand systems tracts are missing in the lower Werfen Formation. The transgressive systems tracts, characterized by extended coastal onlap patterns, consist of mudstones and a few intercalations of tempestites and oolites. The maximum flooding surface, deposited in a high-energy environment (compare Chapter 3.1.), is characterized by a grainstone layer rich in fossils revealing an increased diversity. The early highstands consist of aggrading off shore mudstones which reflect a gradual shallowing in section upward as evidenced by oolitic intercalations. The late highstands are composed of peritidal and supratidal mud flat deposits, locally interspersed with gypsum nodules. The type 2 sequence boundaries, located at the top of these horizons, are accompanied by minor erosion, while angular unconformities are missing. In the following, the formations are described under the aspect of facies evolution and sequence stratigraphy.

4.1. Upper Part of Tesero Horizon

The Permian/Triassic boundary at the top of the intrasparitic unit of the middle Tesero Horizon is overlain by a 150–370 cm thick light-gray homogenous microsparitic unit (Plate 3/5) showing varying thickness in different sections across the study area (Text-Fig. 5). The facies indicates a low-lying muddy tidal flat environment which formed after a slight, but rapid eustatic sea level rise following the Permian/Triassic boundary. In spite of a dominance of carbonate mud, cyanobacterial laminations with birdseye structures and some stromatolitic horizons occur (comparable to those of Plate 3/6). The upper part of the unit was affected by storms which eroded the flat producing intrasparites and some superficial ooids. These intrasparitic layers pinch out laterally. Microspar is due to early diagenetic recrystallization of a former micrite in the stagnant freshwater phreatic zone. This unit bears the mentioned mixed fauna of Permian-type brachiopods and Triassic-type bivalves; it lacks, in contrast, any microfossils except for some rare gastropods and ostracods. Syngenetic pyrite characterizes some levels within the unit. The peritidal facies resembles to that of late highstand sediments of the overlying Werfen Formation. It differs, however, by a lack of evaporites and tepee structures, due to more humid conditions as indicated by the intense freshwater influx.

The Tesero Horizon ends with a thin intraoosparitic layer with a facies similar to that of the unit beneath the Permian/Triassic boundary. It consists of flat pebbles, superficial ooids, and oolitic grapestones (Plate 3/7-8), produced in a moderate to high-energy environment. A poor fauna of ostracods and gastropods occurs. This horizon terminates the sedimentation of a very shallow subtidal to peritidal environment which characterizes the Tesero Horizon, since the overlying homogenous marly-micritic sedimentation of the lower Mazzin Member gives evidence for a distinct deepening of the shelf.

In terms of sequence stratigraphy, the upper part of the Tesero Horizon is interpreted to represent the basal part of the transgressive systems tract of the first Scythian sequence.

4.2. Mazzin Member

Most of the 30–40 m thick Mazzin Member consists of marly micrites and calcareous marlstones, pointing to low water energy. The oligotopic low-diverse faunal association is composed of bivalves, gastropods, brachiopods and ostracods. Thin ripple-marked layers of oosparites, intrasparites and tempestites, which are concentrated in the middle part of the section, give evidence of low- to moderate-energy storm events which produced and transported the components.

The micritic sediment, distinguished from the algal micrites of the Tesero Horizon by dark-gray to brownish colors, consists of very fine-grained carbonate muds which accumulated in the quiet-water realm. Algal structures (e.g., laminae) are not present. The limestones are overprinted by late diagenetic pressure dissolution which produced a stylolaminated to stylonodular fabric.

The Mazzin Member was deposited in a deeper subtidal realm of a low-gradient open shelf with predominantly low-energy conditions as found below the fair-weather wave base, but above storm wave base. No evidence of a "Mazzin lagoon" limited by a barrier island has been found on a regional scale (BROGLIO LORIGA et al., 1983).

The lower micritic part of the Mazzin Member, characterized by retrogradational patterns which grade into terrigenous red beds in the west (ASSERETO et al., 1973), constitutes the major part of the transgressive systems tract of the lowermost Scythian sequence (Text-Fig. 3). The maximum flooding surface, located in the middle part of the Mazzin Member, is represented by a high-energy tempestite layer revealing a diverse mollusc fauna (e.g., *Claraia griesbachi*, *Gervillia* sp., *Nucula* sp.). Overlying mudstones forming aggradational stacking patterns represent an early highstand. A thin oolite horizon at the top of the Mazzin Member indicates a distinct shallowing.

4.3. Andraz Horizon

The 20 m thick Andraz Horizon, a yellowish dolomitic algal laminite with fenestral fabrics, bioturbation, small tepee structures, dissolved gypsum nodules, and thin alternating reddish marlstone and silty dolomicrite layers, provides evidence of a mostly subaerially exposed mud flat. It represents a late highstand subaerial complex within an arid setting. Its top showing numerous desiccation cracks is marked by subaerial exposure corresponding to a sequence boundary which terminates the lowermost sequence of the Werfen Formation.

4.4. Siusi Member

The base of the 90-100 m thick Siusi Member is characterized by a rapid transgression across the exposed mud flat of the Andraz Horizon. The sediments accumulated in a subtidal environment with predominantly low-energy conditions as indicated by marly, locally silty micrites and thin marlstones, poor in fossils. From the middle part upward in section, some oolites, biosparites with coated grains and tempestites composed of *Claraia* shells are intercalated at different intervals, pointing to high-energy, shallow subtidal conditions. These sediments form a transgressive systems tract which is manifested by considerable coastal onlap extending to the Bergamasc Alps in the west (ASSERETO et al., 1973). The early highstand consists of mudstones rich in terrigenous quartz silt. Gradual shallowing is evidenced by grainstones exhibiting hummocky cross stratification. Sea level fall culminates at the top of a dolomitic algal laminite horizon. This approx. 10 m thick yellowish horizon consists of peritidal to supratidal dolomitic mudstones resembling to the Andraz Horizon. The top of this late highstand subaerial complex represents a subaerial unconformity which is interpreted as a sequence boundary terminating the second Scythian sequence.

5. Conclusions

Marine Upper Permian rocks of the Dolomites consist of the uppermost Val Gardena Sandstone Formation, the entire Bellerophon Formation, and the lower/middle part of the Tesero Horizon. The lowest Triassic (Early Scythian) described in this paper consists of the upper Tesero Horizon and of the lower Werfen Formation (Mazzin Member, Andraz Horizon, Siusi Member). While the Late Permian paleogeography of the Dolomites area was differentiated into a restricted inner-shelf area and a marginal-marine area, Triassic sediments accumulated on an open shelf with a leveled topography, characterized by extended facies belts with uniform depositional conditions. Sedimentary patterns of Late Permian and earliest Triassic are strongly controlled by the sea level history which in turn is controlled by subsidence, eustasy and sedimentation. According to the paleoenvironmental evolution and to the geometries of the stratal patterns, the depositional systems were interpreted under the aspect of sequence stratigraphy.

Upper Permian strata include four third-order sequences bounded by type 2 sequence boundaries. The stratal patterns of both sequences are mainly controlled by eustasy and sedimentation with a constant rate of subsidence. At the end of the Late Permian, however, the combination of a distinct decrease in rate of subsidence and an increase of the sedimentation rate caused a relative fall in sea level. A simultaneous short-term eustatic sea level rise modified the general shallowing trend by producing a coastal onlap pattern during maximum flooding. Due to the decreased subsidence which strongly reduced the accommodation potential, the overlying thin transgressive systems tract of the fourth Upper Permian sequence as well as the following transgressive systems tract of the basal Scythian sequence overlying the Permian/Triassic boundary accumulated in a peritidal environment.

The Permian/Triassic boundary, a prominent sequence boundary located within the Tesero Horizon, separates an oolitic to mixed oolite/algal laminite facies from a muddy tidal flat facies unit. These shallow-subtidal to partly emerged facies units clearly differ from the biograinstone complex of the underlying Bellerophon Formation which was deposited in a high-energy shallow subtidal environment, and from the overlying unfossiliferous mudstones of the basal Mazzin Member, which accumulated in a deeper subtidal realm.

The lower Werfen Formation consists of two third-order sequences which are controlled by third-order relative sea level fluctuations with a constant rate of subsidence. These controlling factors were responsible for the uniform composition of the sequences. Major parts of them consist predominantly of mudstones and some grainstones which accumulated in a low-energy subtidal realm of an open shelf, affected by local storm events. Both sequences are terminated by a peritidal/supratidal evaporitic dolomite horizon.

Acknowledgements

We dedicate this paper to our academic teacher and colleague, Prof. Dr. ERIK FLÜGEL, to his 60th birthday. We are indebted to him and his wife for numerous stimulating discussions which helped to improve this work.

Our thanks go to Dr. M. JOACHIMSKI, Erlangen, who provided the stable isotope data, and to Dipl.-Geol. P. ZÜGEL, Bremen, who kindly helped with the drafts. Dr. A. EMBRY, Calgary, Alberta (Canada), and Dr. S.J. MAZZULLO, Wichita, Kansas (USA), kindly reviewed the manuscript. Critical remarks of an anonymous reviewer helped to improve this work.

Plate 1

Uppermost limestones of the Bellerophon Formation and transition to the Tesero Horizon

Fig. 1: **Slightly winnowed algal/foraminiferal biosparite (packstone)**
with *Gymnocodium bellerophontis* ROTHPLETZ, *Hemigordius* sp., shell debris, and fecal pellets.
Uppermost Bellerophon Formation, marginal-marine area (Section Tesero).
×83.

Fig. 2: **Slightly winnowed algal/foraminiferal biosparite (packstone)**
with fecal pellets enriched in nests.
Uppermost Bellerophon Formation, restricted inner-shelf area (Section Weißlahngrat)
×83.

Fig. 3: **Calcareous marlstone: diagenetic packstone**
rich in echinoderms (crinoids and echinoids). The individual elements acting optically as single calcite crystals mostly resisted to pressure solution.
Uppermost Bellerophon Formation (Section Tesero).
×83.

Fig. 4: **Same facies as in Fig. 3**
showing solution coronas (syntaxial rim cements) surrounding the crinoid fragments.
Section Tesero.
×258.

Figs. 5-6: **Biosparites (grainstones)**
rich in calcareous algae (*Gymnocodium bellerophontis* ROTHPLETZ), micritized miliolids (*Hemigordius* spp.), crinoid fragments, and echinoid spines.
Uppermost Bellerophon Formation (Section Tesero).
×83.

Fig. 7: **Intrabiosparites (grainstones; grapestone facies)**
showing grapestones, lumps, small micritic intraclasts, gymnocodiacean fragments, fusulinids (*Nankinella* sp; left margin of photograph), and some shell debris.
Topmost layer of the Bellerophon Formation (Section Weißlahngrat).
×83.

Fig. 8: **Mixed oolite facies (oobiosparite, grainstone)**
of the basal Tesero Horizon, consisting of small superficial ooids, *Gymnocodium bellerophontis*, micritized miliolids, and brachiopods. Micritic matrix is locally preserved. This facies gradually evolves from the underlying grapestone facies of the topmost Bellerophon Formation. The transition is found within one 10–20 cm thick layer.
Section Tesero.
×83.

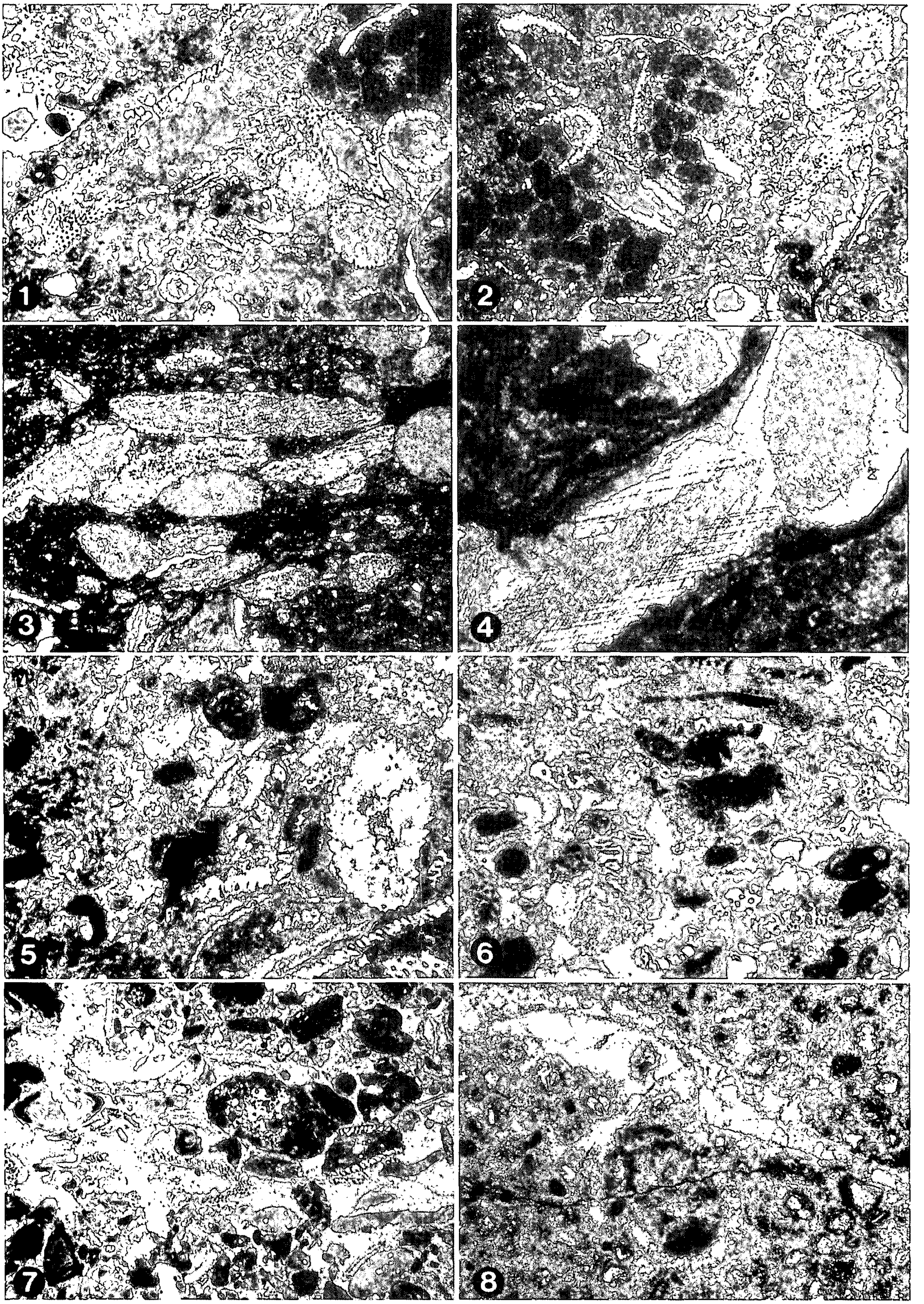

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Plate 2

Lower and middle part of the Tesero Horizon, Section Tesero

Fig. 1: **Mixed oolite facies (oobiosparite, grainstone)**
at the base of the Tesero Horizon with superficial ooids, micritized fusulinids and miliolids, calcareous algae, and coated shell fragments. Many ooid nuclei are micritized; some of them are dissolved with the oomoldic porosity being filled by granular calcite cement.
×83.

Fig. 2: **Lower part of the Tesero Oolite.**
Oobiosparite (grainstone), consisting of normal-size ooids and fragments of *Gymnocodium bellerophontis* ROTHPLETZ. Some ooids are micritized.
×83.

Fig. 3: **Middle part of the Tesero Oolite.**
Oosparite (grainstone).
Normal-size ooids show well-preserved cortices with a tangential internal fabric. Nuclei are either micritized or dissolved. Some smaller ooids are totally micritized. Note pressure solution of ooids along a stylolite (center).
×83.

Fig. 4: **Upper part of the Tesero Oolite.**
Oosparite (grainstone) with a 0.5 cm thick micritic layer (microsparite, mudstone) in the upper part.
Ooids are entirely micritized. The mudstone layer grades into the overlying 1–3 cm thick microsparite which superposes the Tesero Oolite (Unit 1 of the middle part of the Tesero Horizon).
×83.

Fig. 5: **Unit 1 of the middle part of the Tesero Horizon.**
Slightly reworked microsparite representing a low-lying muddy tidal flat.
×83.

Fig. 6: **Unit 2 of the middle part of the Tesero Horizon.**
Intraoosparite (grainstone) showing poorly sorted, irregularly oriented micritic intraclasts and some superficial ooids with dissolved nuclei. Intraclasts are reworked from the underlying peritidal flat.
×41.

Fig. 7: **Unit 3 of the middle part of the Tesero Horizon.**
Intrasparite (grainstone) showing micritic intraclasts and irregularly shaped lumps composed of micritized ooids and peloids.
×83.

Fig. 8: **Top of Unit 3 of the middle part of the Tesero Horizon.**
Packstone area intercalated into the intrasparitic unit. The last occurrence of the Permian index fossil *Gymnocodium bellerophontis* ROTHPLETZ was observed in this layer.
×83.

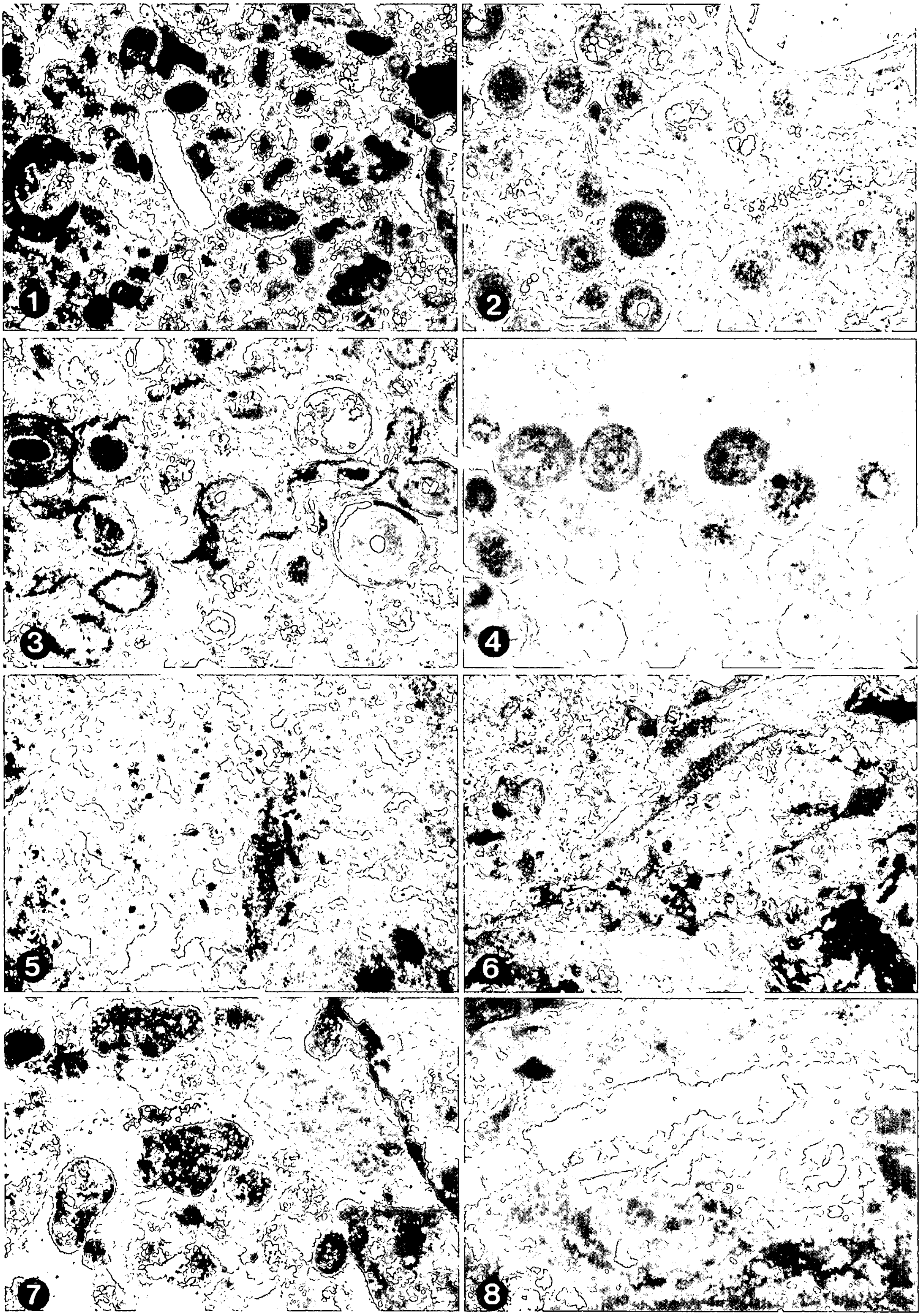
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Plate 3

Middle and upper part of the Tesero Horizon, Section Tesero

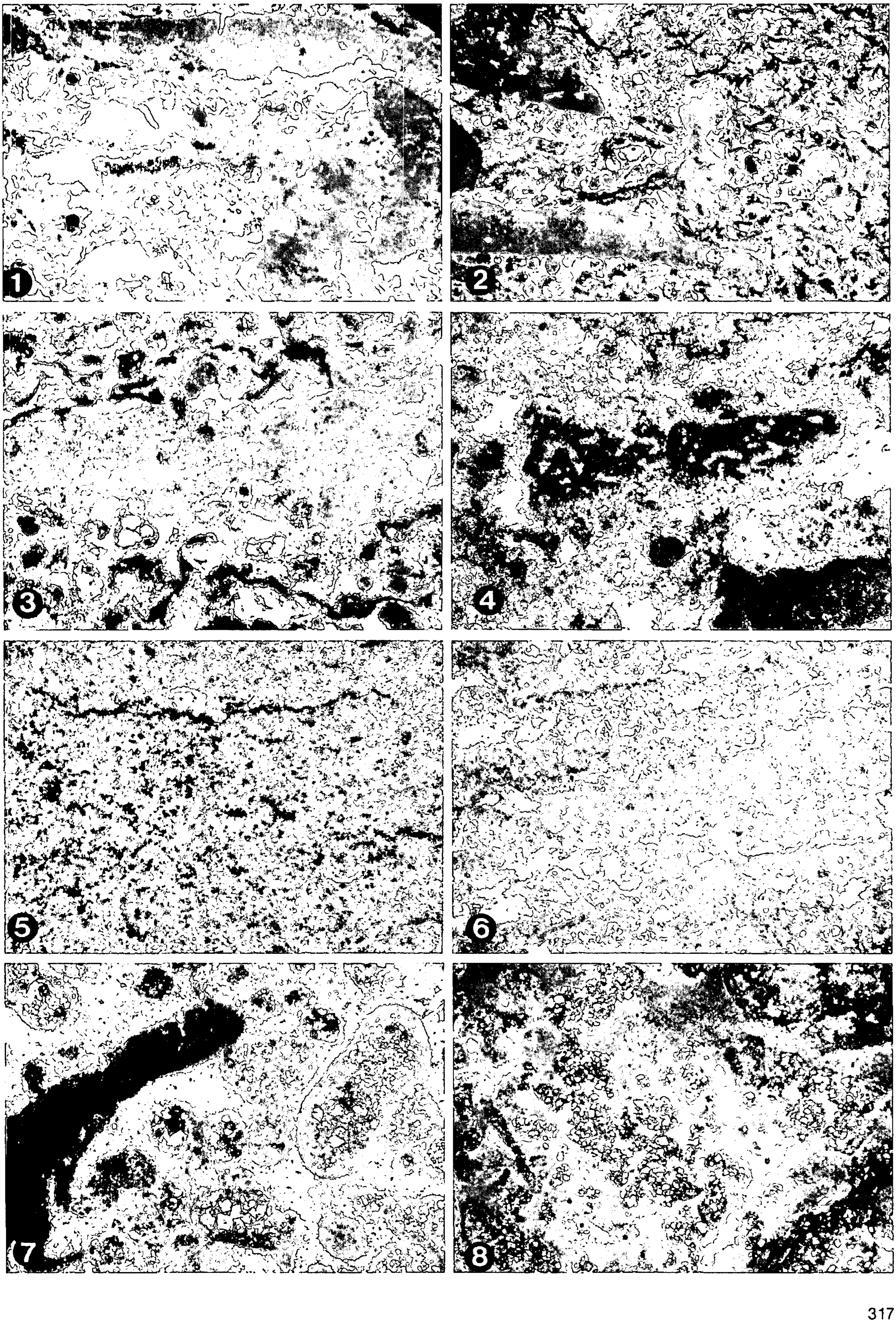
Figs. 1–2: **Unit 3 of the middle part of the Tesero Horizon.**
Intrasparite (grainstone) showing flat pebbles with desiccation cracks and smaller, partially recrystallized micritic intraclasts, which represent reworking products of the underlying peritidal flat. Mud cracks of the flat pebbles indicate a temporary subaerial exposure of the muddy tidal flat.
×83.

Figs. 3–4: **Same facies as in Figs. 1-2,**
showing intraclasts with tiny borings.
×83.

Fig. 5: **Homogenous microsparitic unit of the upper Tesero Horizon.**
The mudstones represent a low-lying peritidal flat. Microfossils are missing, except some thin-shelled ostracods. This basal Triassic unit bears a characteristic mixed fauna of Permian-type brachiopods and Triassic-type bivalves, corresponding to the fauna of the lower *Otoceras* beds in the eastern Paleotethys.
×83.

Fig. 6: **Stromatolite with fenestral fabric occurring in the upper part of the microsparitic unit.**
×41.

Figs. 7–8: **Topmost layer of the Tesero Horizon.**
Intraoosparite (grainstone) with some smaller micritic areas. The layer consists of superficial ooids, oolitic grapestones, and flat pebbles reworked from the underlying muddy tidal flat. Common desiccation cracks observed in these micritic intraclasts point to a short-term subaerial exposure of the muddy tidal flat. Facies indicates moderate- to high-energy conditions. The oolitic grapestones are interspersed by dolomite rhomboedra of a late-diagenetic stage.
×83.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Manuskript bei der Schriftleitung eingelangt am 9. Dezember 1994

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