Sedimentology, palaeoecology, and high-resolution sequence stratigraphy of a carbonate-siliciclastic shelf (Oxfordian, Swiss Jura Mountains)

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(based on work by Robin Allenbach[3], Christophe Dupraz[4], Wolfgang Hug[2], and Bernard Pittet[5])

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Introduction

On this field trip, the lateral and vertical variability of depositional environments on a strongly structured, carbonate-siliciclastic shelf will be illustrated. The first outcrops show the sedimentary record of epicontinental basins, then platform sections will be examined. Within a relatively well-established biostratigraphic frame, the detailed analyses of facies and stacking pattern allow to correlate the visited outcrops and to interpret them in terms of sequence stratigraphy and cyclostratigraphy. Furthermore, the evolution of the depositional environments during the Oxfordian will be discussed in terms of high- and low-frequency changes of relative sea level, palaeoclimate and palaeoecology.

Palaeogeographic setting and stratigraphy

The area of the Swiss Jura belonged to an epicontinental, shallow-marine sea during the Jurassic (e.g., Ziegler, 1990). In such settings, sediment accumulation clearly responds to sea-level changes, because environmental factors such as waves, currents, light penetration, input of clastics and nutrients, etc., are strongly affected by water depth or distance to coast. The use of sequence stratigraphy emphasizes the role of eustatic sea-level changes on stratal organisation, and it shows the correlatability of lithologic units. However, it neglects the question of which factors influence the spatial distribution of facies. In the study area, sediment thickness, lithology and/or facies distribution were affected by differential subsidence (e.g., Wetzel *et al.*, 1993). The subsidence pattern in the study area was found to be related to pre-existing tectonic structures in the basement (e.g., Wetzel *et al.*, 1993; Gonzalez, 1996; Burkhalter, 1996; Wetzel & Allia, 2000). These structures initially formed when a mega-shear zone developed between the Ural and the Appalachians towards the end of the Palaeozoic (Arthaud & Matte, 1977). Strike-slip movements led to the formation of numerous basins, grabens, or half-grabens (e.g., von Raumer, 1998). Within the study area and its surroundings, a system of basins is known from seismic records, including the socalled "North-Swiss Permocarboniferous Trough" (e.g., Diebold, 1988; Thury *et al.*, 1994; see below). This trough system started to form during the Late Carboniferous (e.g., Matter, 1987). Then, during the Permian, the basin was inverted (e.g., Laubscher, 1987). In addition to the basin system, a roughly N-S-trending fault system formed at the position of the future Rhine Graben, the so-called „Rhenish Lineament" or „Rhine Graben Lineament", including a fault zone in the southern Black Forest. After the Permian tectonic phase, subsidence continued and peneplanation took place. During the Triassic, continental and restricted marine deposits accumulated in central Europe. Following an initial transgression during the Lias, an epicontinental sea covered wide parts of Europe during the Jurassic.

In middle to late Oxfordian times, a wide, carbonate-dominated shelf covered the realm of today's Jura Mountains (Fig. 1). It was structured by differential subsidence along faults inherited from older lineaments. None of these, however, cut through the Mesozoic sedimentary cover. To the north, very shallow depositional environments predominated, whereas to the south deeper epicontinental basins developed. Siliciclastic material was furnished episodically by the erosion of crystalline massifs in the hinterland (Fig. 1). The study area was situated at a palaeolatitude estimated between 33° and 38°N (Barron *et al.*, 1981; Dercourt *et al.*, 1993; Smith *et al.*, 1994).

Lithostratigraphy and facies of the middle to upper Oxfordian in the Swiss Jura Mountains have been studied extensively by, e.g., Ziegler (1956), Ziegler (1962), Gygi (1969, 1992) and Bolliger & Burri (1970). The biostratigraphy based on ammonites was established mainly by Gygi (1995: including summary of earlier work). Gygi & Persoz (1986) used bio- and mineralostratigraphy to reconstruct the widely used scheme of platform-to-basin transition (simplified in Fig. 2). A correlation with the Oxfordian of the French Jura was offered by, e.g., Enay *et al.* (1988). More recently, a sequence-stratigraphic interpretation has been proposed by Gygi *et al.* (1998). Selected intervals calibrated by high-resolution sequence stratigraphy and cyclostratigraphy have been analysed by Pittet (1996) who concentrated on facies and palaeoclimate, Plunkett(1997) who studied the diagenetic history, Dupraz (1999) who worked out the reef ecology, and Hug (2001)

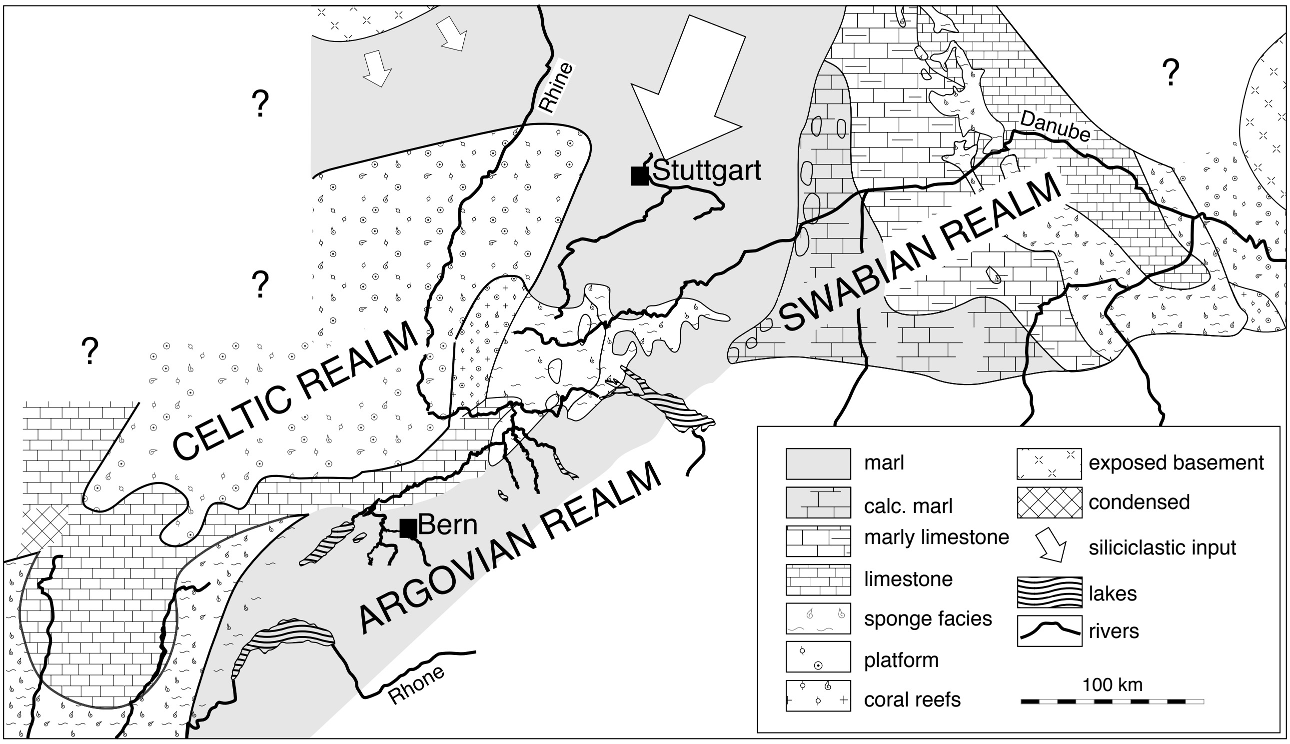

Fig.1. Palaeogeographic map of the Swiss Jura Mountains and adjoining areas during the middle Oxfordian (from Allenbach, 2001c).

who focussed on oncoid formation. The formation of platform and basin facies in space and time and their relationship to pre-existing structures was analysed in detail by Allenbach (2001a, b, c; Fig. 3).

The terminology of formations and members used in this field guide and their biostratigraphic attribution follow Gygi (1995; Fig. 2). The major sequence boundaries are labelled according to Hardenbol *et al.* (1998), and the chronology is based on Gradstein *et al.* (1995).

Itinerary

Zurich (main station) – Baden – Zurzach – Rekingen (Stop 1: basinal facies, slumps) – Baldingen – Endingen – Villingen (Stop 2: basinal facies, advancing platform) – Brugg – Auenstein (Stop 3: basinal facies, channels) – Aarau – Olten – Burgbuel (Stop 4: basin-platform transition) – Solothurn (overnight) – Oensingen – Moutier – Delémont – Liesberg (Stop 5: basin-platform transition) – Delémont – Chapelle de Vorbourg (Stop 6: platform-interior facies) – Hautes Roches (Stop 7: tidal, lagoonal and coral-reef facies) – Rainfo (Stop 8: coral build-ups) – Moutier (overnight) – Gorges de Moutier (Stop 9: dinosaur footprints) – Gorges de Court (Stop 10: sequence- and cyclostratigraphic correlations) – Péry-Reuchenette (Stop 11: platform-basin transition) – Bienne – Aarau – Zurich (main station).

Stop 1: Effingen Beds (Wildegg Formation) with multiple slides near Rekingen.

In an abandoned quarry in the Tabular Jura (Fig. 4; coordinates 665.600/268.710), Effingen and Geissberg Beds (Middle Oxfordian, Fig. 2) crop out. The base of the Effingen Beds is not exposed. The boundary between Effingen Beds and the overlying Geissberg Beds is gradational; within a 15 m thick interval the carbonate content increases significantly. The Geissberg Beds have been partially eroded before the Miocene. At the onset of the Upper Marine Molasse, the top of the Jurassic deposits was encrusted by oysters and bored. This unconformity is overlain by about 1-2 m green sands belonging to the Upper Marine Molasse (Middle Miocene). The shallow-marine sands are overlain by the Upper Freshwater Molasse, consisting of reddish, fine-grained mudstones with incised channels. These are filled by conglomerates (Nagelfluh) delivered from the rising Black Forest.

The Effingen Beds in the Rekingen outcrop display several angular unconformities overlain by conformable packages of marl-limestone alternations. After restoration for tectonic tilt, the unconformities dip at up to 5-10° to the south. The lowermost unconfomity (1) is overlain by material identical to the underlying marl-limestone alternations. The following unconformities (2 and 3) are overlain by mudflow material enriched in blackened macrofossils. These unconformities are interpreted as slide scars which later were filled by continuing background sedimentation (1) or by material that has been displaced downward (2 and 3) .

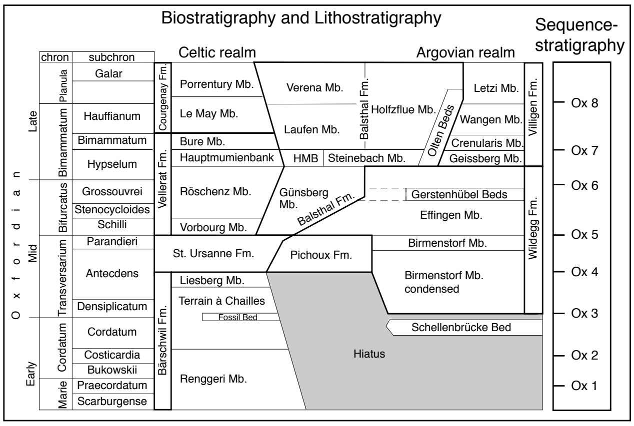

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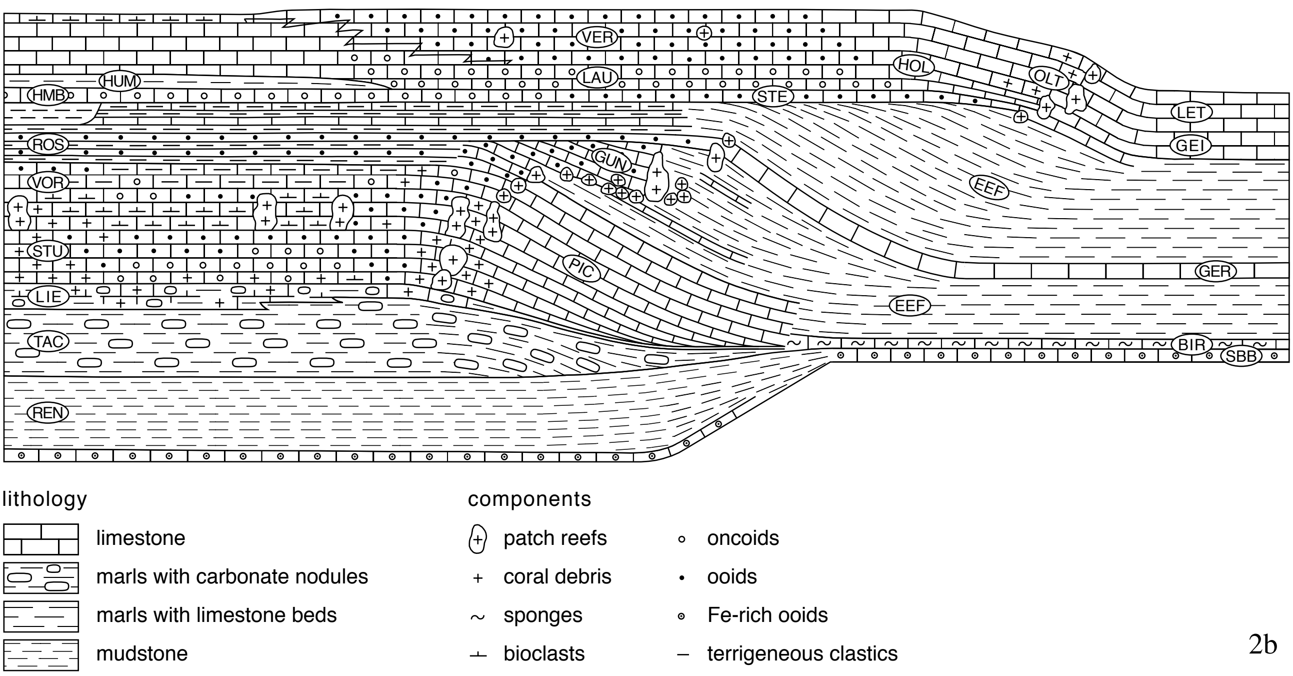
Fig. 2. (a) Bio- and lithostratigraphy used in this paper (based on Gygi, 1995); sequence boundaries after Hardenbol *et al.* (1998).

(b) Geometry and correlation of Oxfordian sediments in northern Switzerland (after Gygi & Persoz, 1986; modified). Tags refer to stratigraphic units (in alphabetical order): BIR Birmenstorf Mb., EFF Effingen Mb., GEI Geissberg Mb., GER Gerstenhübel Beds, GUN Günsberg Fm., HMB Hauptmumienbank Mb., HOL Holzflue Mb., HUM Humeralis Mb., LAU Laufen Mb., LET Letzi Mb., LIE Liesberg Mb., OLT Olten Beds, PIC Pichoux Fm., REN Renggeri Mb., ROS Röschenz Mb., SBB Schellenbrücke Bed, STE Steinebach Mb., STU St. Ursanne Fm., TAC Terrain à Chailles Mb., VER Verena Mb., VOR Vorbourg Mb.



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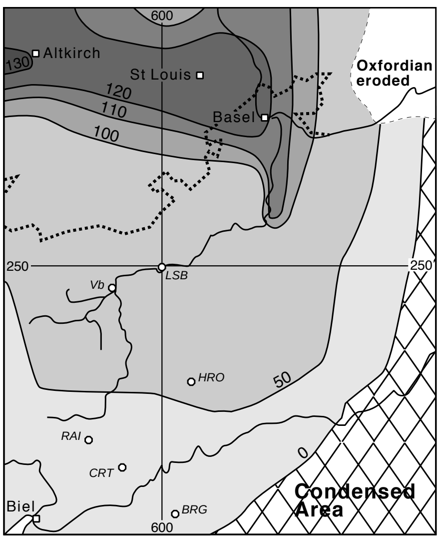

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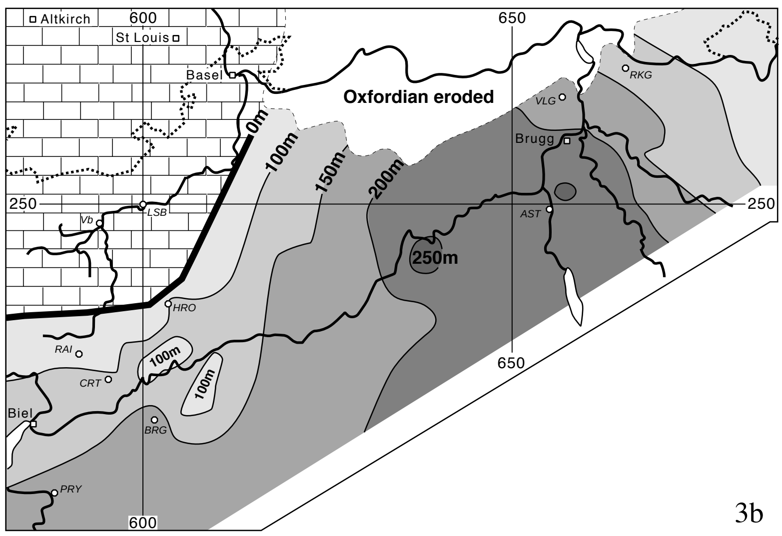

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Fig. 3. Palinspastic reconstruction of both the Bärschwil Formation (a) and the Effingen Member (b). Note that the basin depocentres switched from the north (Bärschwil Fm.) to the south (Effingen Mb.) with time, followed by the coeval shallower environments (from Allenbach 2001c). White circles mark localities visited during this field trip; AST (Auenstein, Stop 3), BRG (Burgbuel, Stop 4), CRT (Gorges de Court, Stop 10), HRO (Hautes Roches, Stop 7), LSB (Liesberg, Stop 5), PRY (Péry, Stop 11), RAI (Rainfo, Stop 8), RKG (Rekingen, Stop 1), VIL (Villingen, Stop 2), Vb (Chapelle de Vorbourg, Stop 6). The localities visited were palinspastically restored to illustrate their position within the basins, the river network and the cities, however, are shown at their present position.

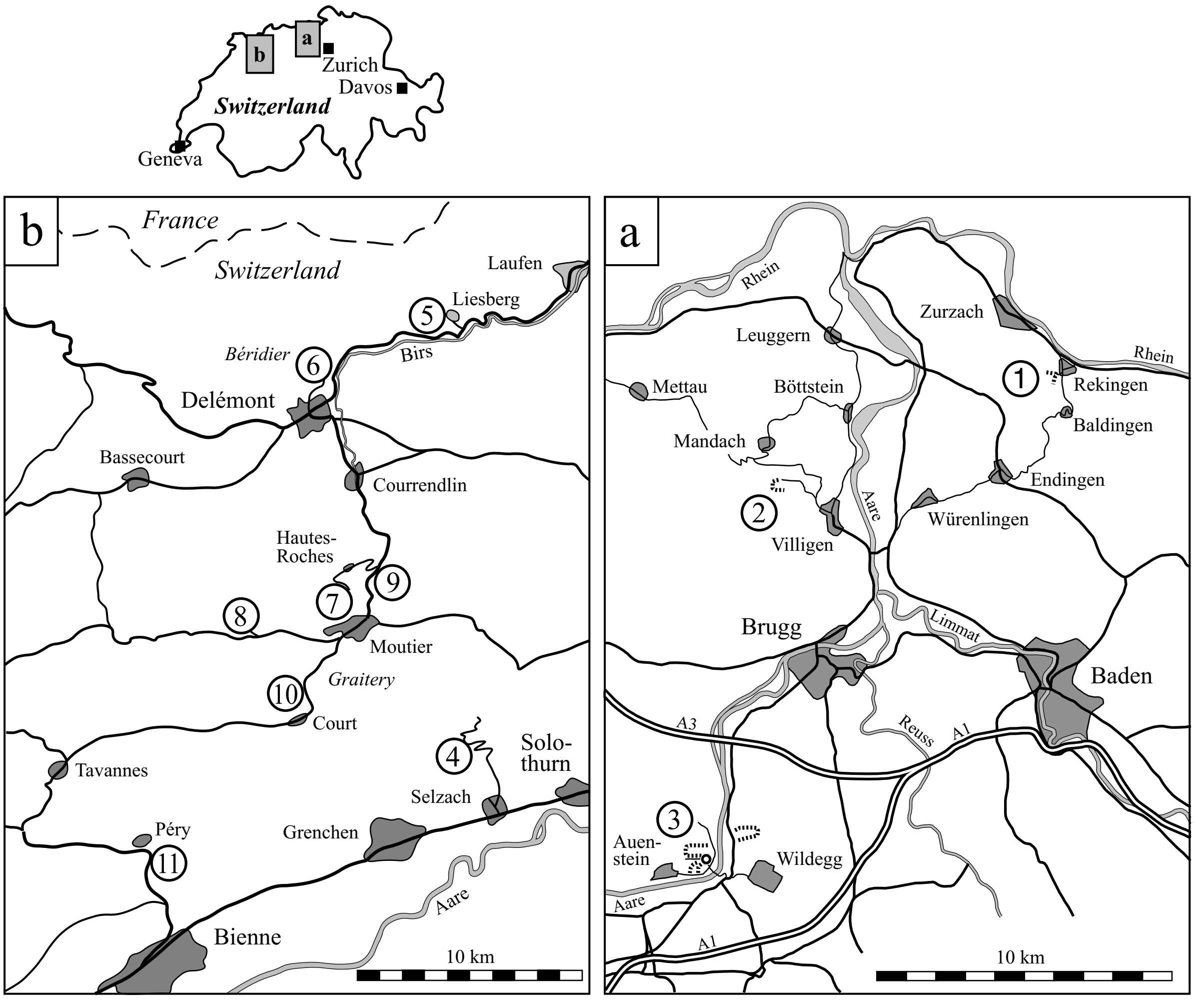


Fig. 4. Maps with localities visited during this field trip.

The Rekingen outcrop is located above the fairly well documented northern boundary fault of the North-Swiss Permocarboniferous Trough. Supposedly, differential subsidence has led to steepening of the relief during deposition and to initiation of the slumps. In fact, all the slumps known from the Effingen beds are located above faults in the basement (Allenbach, 2001a; Fig. 5). The accumulation of the Effingen Beds corresponds to a time of enhanced subsidence (e.g., Wildi *et al*., 1989), and basement structures had a high potential to become re-activated. Besides the slides, several tempestitic/turbiditic layers display palaeoflow in southern directions (Fig. 5). In spite of the frequent mass movements, synsedimentary (Jurassic) normal faults have not been observed, neither in the outcrops nor on seismic records (e.g., Thury *et al*., 1994). Therefore, we assume that the differential movements along the faults in the basement were too small to induce faulting within the sedimentary cover; the sedimentary cover was only affected by flexure-like deformations (Wetzel & Allia, 2000), which triggered the observed mass movements.

Due to the frequently occurring slumps and the limited biostratigraphic control, the sequence-stratigraphic interpretation is restricted; only the base of the Geissberg Beds is seen as a transgressive surface between sequence boundaries Ox6 and Ox7 (Hardenbol *et al.,* 1998), both not being exposed in this outcrop.

Stop 2: Middle Oxfordian basinal deposits near Villingen

In a cement raw-material quarry near Villingen (Fig. 4; coordinates 656.800/265.080) about 130 m of middle Oxfordian sediments exhibit the transition from basinal sediments (Effingen Beds) to the marginal platform carbonates (Geissberg Beds). The beds dip 15-20° to the south. The lower part of the quarry is occupied by about 58 m of marl-limestone alternations (Effingen Beds). Tempestitic beds therein indicate a palaeoflow in NW to NE directions (Fig. 5). The transition to the Geissberg Beds, which represent the marginal part of the carbonate platform (Fig. 2), is gradational and about 15 m thick. Carbonate content as well as bed thicknesses increase upward. Most of the beds are carbonate-rich tempestites which contain some shallow-water material. Further up, several packages of limestone beds can be distinguished; 42 m of micrite contain shallow-water biodetritus, commonly enriched in nests which are of biogenic or physical origin. The content in bioclasts steadily increases upward, pointing to a progradation of the platform. Then, in the interval from 108-114 m, the bioclast content is low. Further up, the bioclast content increases again up to section-metre 120. There, the bedding surface is encrusted by oysters; below it, solution cavities along *Thalassinoides* burrows indicate freshwater diagenesis. This horizon is in-

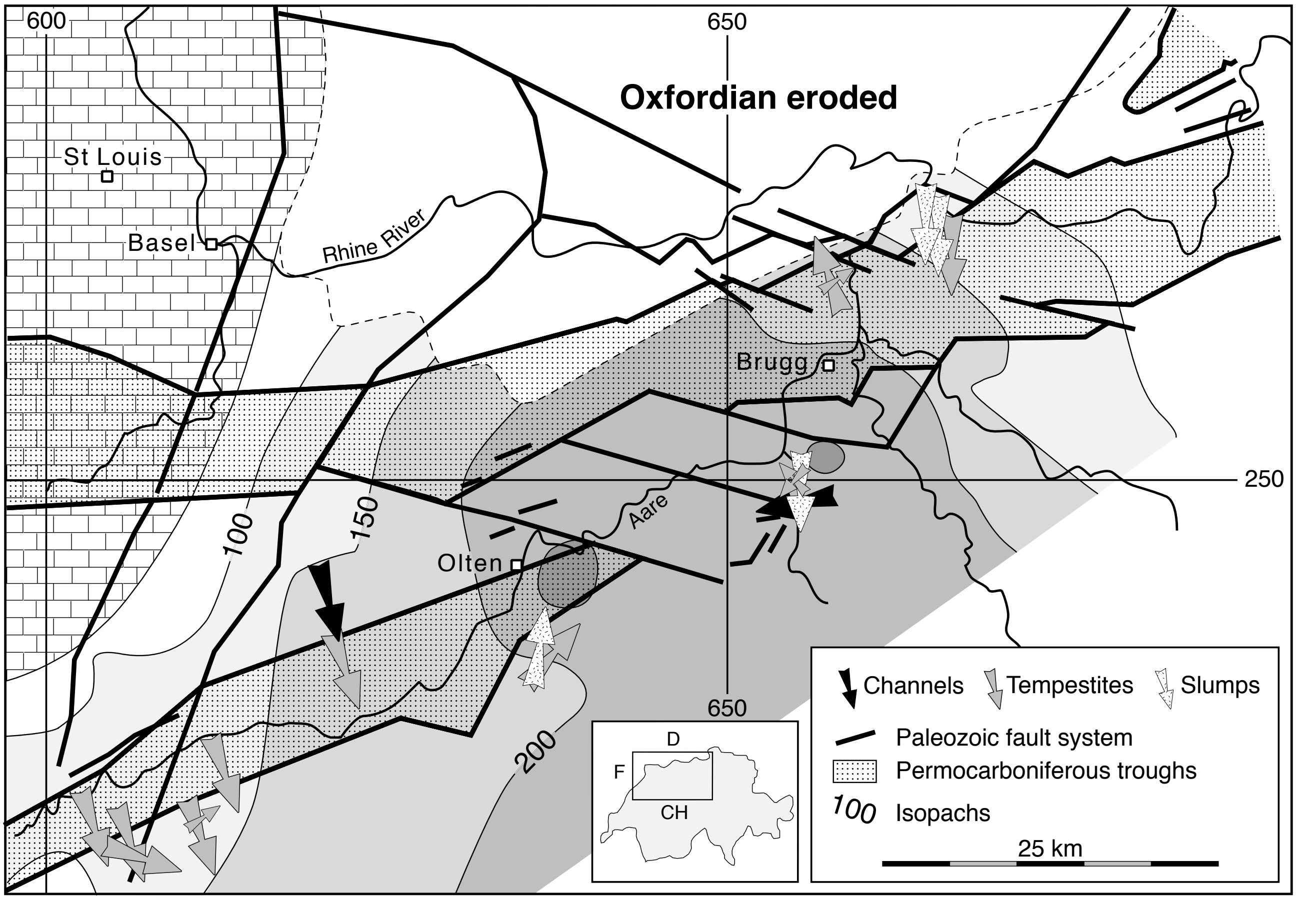


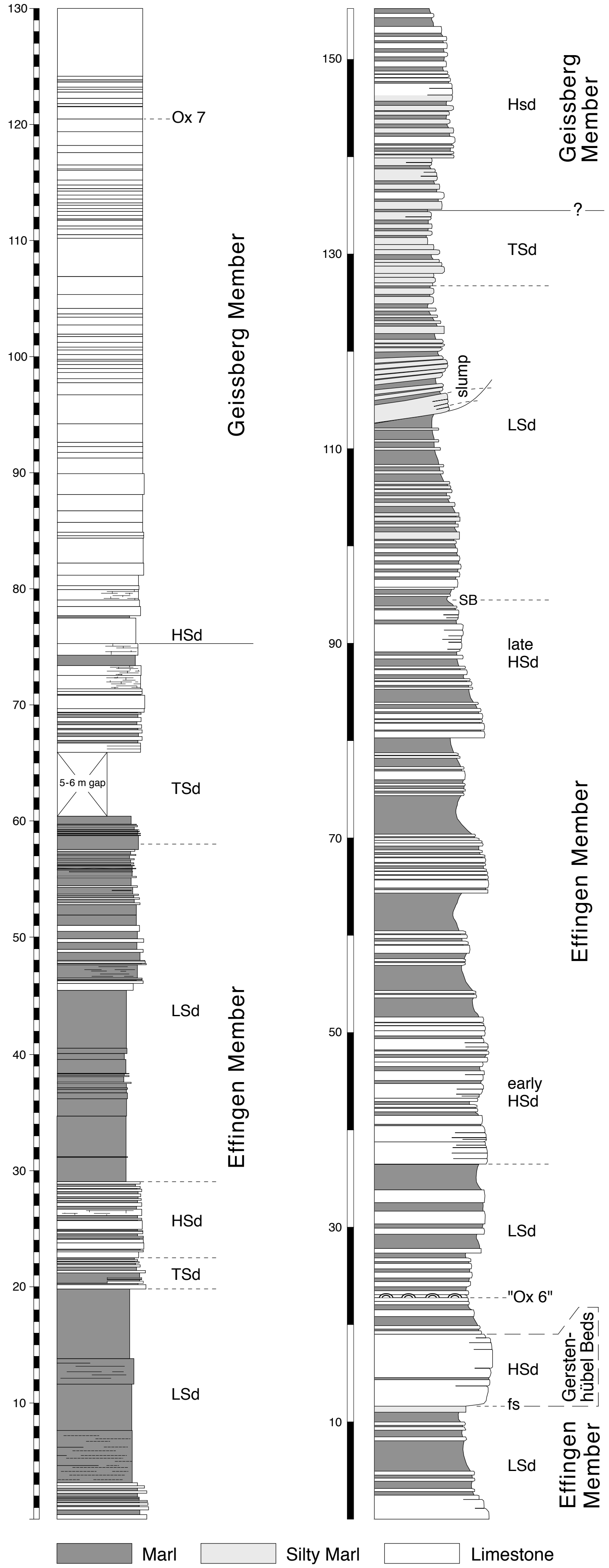
Fig. 5. Palaeogeographic map for the middle Oxfordian. For the Effingen Member isopachs and dominant palaeoflow directions (slumps/slides, tempestites, channels) are shown. Note the spatial coincidence of depocentres and facies boundaries with Palaeozoic faults within the basement (compiled from different data of Allenbach 2001b, c).

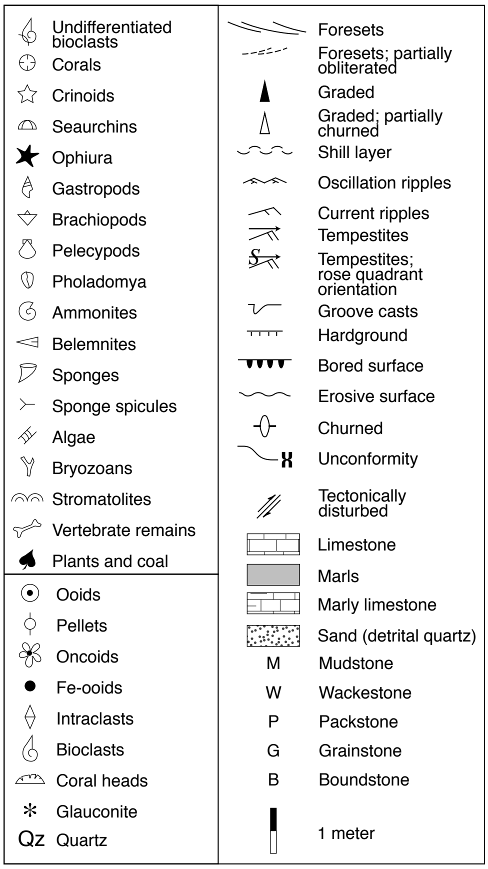
terpreted to represent sequence boundary Ox7 of Hardenbol *et al.* (1998). It is overlain by a reddish colored limestone. The following beds display high amounts of bioclasts, but further up the bioclast content decreases dramatically. These carbonate-rich packages are interpreted as TST and HST deposits (Fig. 6, left).

Stop 3: Lower to middle Oxfordian basinal deposits near Auenstein

The oldest deposits visited in this outcrop (Fig. 4; coordinates 653.830/252.700) are Callovian sandbars mainly composed of crinoid debris, overlain by the condensed Schellenbrücke Bed and Limonitic Crust of the uppermost lower Oxfordian (Figs. 2, 6 (right), 7). The upper Callovian deposits at this location formed on a swell (Bitterli, 1977), and the reduced sedimentation during the early Oxfordian is attributed to a persistence of this swell (c.f. Gygi & Persoz, 1986). Similarly, the sponge communities of the overlying Birmenstorf Member formed on a submarine swell. The facies typically consist of marls and micrites rich in sponges and ammonites. Within the overlying lower Effingen Member a series of channels crops out. Internal structuring is virtually absent within the channels, apart from some lag deposits. They are interpreted as the lowstand deposits following SB Ox5 (Gygi *et al.*, 1998). Due to a low sea level, gravity flows from shallower environments were able to incise the sea floor. Based on the channel structures, palaeocurrent direction was from east to west (Fig. 5)

The following about 70 m consist of marl-limestone alternations and display an upward-increasing carbonate content. They are seen as transgressive deposits leading up to the sponge crust which is interpreted as a period of non-deposition (maximum-flooding surface), while the limestones are regarded as highstand carbonates washed in from the platform. With the continued marl deposition up to the Gerstenhübel Beds, a further lowstand is documented in the Effingen Basin. The onset of the 16 m thick limestone deposits of the Gerstenhübel Beds represents a flooding followed by highstand sedimentation with increased carbonate production. A few metres above the top of the Gerstenhübel Beds, a 5-10 cm thick mudstone bed is capped by a limonite/pyrite crust up to 3 mm thick. Burrows and borings in this hardground suggest a multiphase formation. The sequence-stratigraphic significance of this horizon is debatable; Pittet (1996) interepreted it as maximum-flooding surface, whereas Allenbach (2001c) suggested a type II sequence boundary (SB Ox6) and sediment by-passing. The relief inherited from the Callovian might still have existed. The upper Effingen Member consists again of marl-limestone alternations with a number of carbonate-rich intervals. Towards the top of the section, thin tempestites (less than 10 cm thick) composed mainly of detrital quartz become fairly abundant.





Legend to sedimentological logs

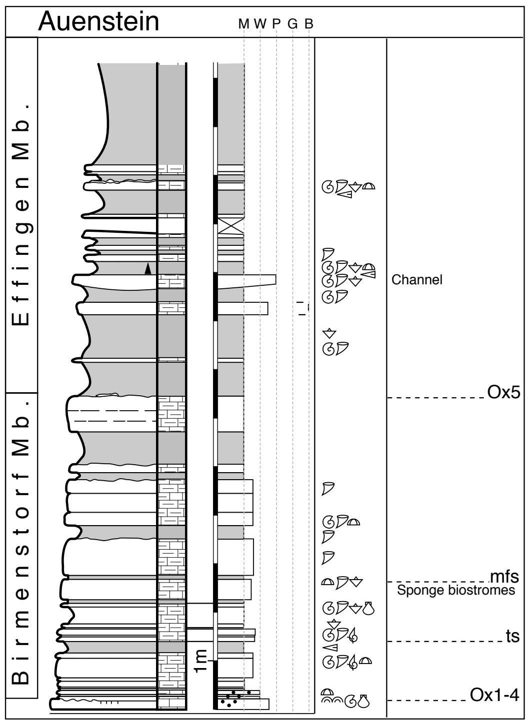


Fig. 7. Sedimentological log and interpretation of the basal part of the Auenstein section (Stop 3); based on Allenbach (2001c).

Fig. 6. Sedimentological log and interpretation of the sections at Villingen (left; Stop 2) and at Auenstein (right, Stop 3). The Villingen section is drawn after data of Allenbach (unpublished); the Auenstein section after Pittet (1996, slightly changed).

Stop 4: Late Oxfordian patch reefs and sandbars near Burgbuel

The Burgbuel section crops out along a small forest road (Fig. 4; coordinates 599.800/231.275). The section begins with coral patch reefs emerging from the uppermost part of the Effingen Member, announcing the advance of the carbonate platform as is typical for the change from the Effingen to the Günsberg Member (Fig. 8). A stretch of tunnel with concrete walls obscures the following 14 m. Judging by the exterior cliffs, the covered rocks are calcareous, yet unstable possibly due to a higher clay content. Peloid and ooid grainstones represent the carbonate sand bars of the platform margin and display dominantly south-vergent foresets. Towards the top of the Günsberg Member, the amount of bioclasts and quartz increases. The increase of bioclasts and oncoids in the upper Günsberg Member, along with the change to somewhat thinner beds, indicates a shift to less exposed environments as well as a decrease in the rate of carbonate production and deposition. The top of the Günsberg Member is placed at a horizon containing oscillation ripples on top of a carbonate sand bar. With the oscillation ripples and mud drapes overlying a sandbar, the shallowest interval so far is attained (SB Ox6).

The Röschenz Member continues with grainstones assembled in graded event beds. While grainstone deposition continues, the increased presence of oncoids and gastropods suggest the incursion of lagoonal components into these sediments. Within the upper Röschenz Member, a 1m thick interval containing three mudstone beds is separated by ferroan pack- and grainstones with worn and abraded allochems. They have micrite envelopes and are embedded in a dolomite matrix. This interval represents a period of minor deposition in a shallow environment, with the mudstones being interpreted as carbonate mudflats. The converging palaeocurrent orientations deduced from the foresets may be of tidal origin. Above, carbonate production and deposition increased rapidly in response to a renewed transgression. This is documented by the re-appearance of peloidal and oolitic sand bodies with dominantly south-vergent foresets and even small patch reefs, as marginal platform conditions are again established. The top of the Röschenz Member is placed just below the first patch-reefs of the Steinebach Member, embedded in pack- and grainstones.

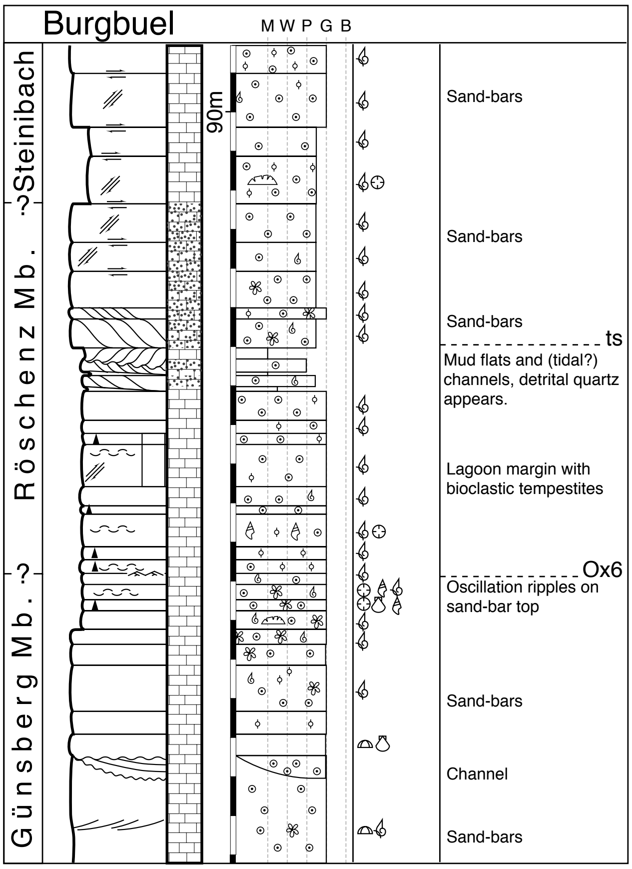


Fig. 8. Sedimentological log and interpretation of the Burgbuel section (Stop 4). For legend see Figure 7; based on Allenbach (2001c).

Stop 5: Middle Oxfordian carbonate-platform progradation across lower Oxfordian basinal deposits near Liesberg

A section from the top of the Callovian to the middle Oxfordian (Fig. 9) is exposed in an abandoned quarry (Fig. 4; coordinates 598.640/250.140). The Callovian calcarenites crop out at the southern wall of the pit. There, 20-30 cm wide, up to several m long furrows are interpreted as feeding traces of swimming vertebrates (Geister, 1998). The Callovian sediments are overlain by a series of mudstones belonging to the Bärschwil Formation (lower Oxfordian; Fig.2). The Renggeri Beds are 29.5 m thick homogeneous, carbonate-poor mudstones; their thickness was reduced by tectonic translations - nearby a thickness of 57m was measured. Above, the Terrain à Chailles consist of 37.5 m mudstones which contain layered carbonate concretions and some thin carbonate beds; the thickness of this member was also affected by tectonic translations. Within this interval, the content in fossil debris slightly increases up to the so-called "fossil-rich bed", which is located roughly in the middle of the Terrain à Chailles. The boundary to the overlying Liesberg Member is fairly sharp. The Liesberg Member is 25 m thick. These deposits contain a varying amount of platy corals which are embedded in a muddy matrix (Insalaco, 1996). Furthermore, root parts of crinoids are fairly frequent. The top of the Liesberg Member is formed by platy carbonates being rich in corals and crinoids. Above, oncolites of the St. Ursanne Formation are exposed.

Renggeri Beds, Terrain à Chailles and Liesberg Beds are time-equivalent to the hiatus and the condensed Schellenbrücke Bed seen at Stop 3 (Fig. 2). Although the section displays a general shallowing-upward trend, sequence boundaries, transgressive and maximum-flooding surfaces can be identified from palaeontological and sedimentological data (Lauer, 1985; Gygi *et al.*, 1998). In the mud-dominated Terrain à Chailles, maximum quartz content as well as abundant serpulids appear to characterize SB Ox3. Levels rich in ferroan calcite cement and glauconite indicating slow sedimentation are interpreted as flooding or maximum-flooding surfaces. Further up, the Liesberg Member displays three sedimentary cycles; they are marl-dominated at the base and then show an upward-increasing amount of platy corals and serpulids. Sequence boundary Ox4 is placed at the transition from coral limestones to lagoonal oncolites.

Stop 6: Middle to upper Oxfordian platform-interior cyclical sedimentation at the Chapelle de Vorburg

The Chapelle-de-Vorbourg section (Fig. 10) crops out along the small road that cuts through the Béridier anticline north of Delémont (Fig. 4; coordinates 593.850/247.625). The thick beds of the Saint-Ursanne Formation form the crest on which, below the road, a chapel has been constructed. The following beds thin stratigraphically upwards (southwards in the outcrop); they belong to the Vorbourg Member that has been defined in this section by Ziegler (1962). The outcrop then is partly covered by a parking lot where the relatively marly lithologies of the Röschenz Member predominate. The thicker limestone beds of the Steinebach and Hauptmumienbank Members then define the southern end of the parking lot.

This section demonstrates well the gradual loss of accommodation space and the increasing confinement of the depositional environments: open lagoons with small coral reefs gradually pass into restricted lagoons and tidal flats. Detrital quartz and clays are present in the Röschenz Member, suggesting that climate changed from more arid to more humid conditions. Root traces point to vegetation. A transgression then leads back to the carbonate-dominated tidal bars and oncoid-rich lagoons of the Steinebach and Hauptmumienbank Members.

The sequence-stratigraphic interpretation based on detailed facies analysis and lateral correlation with other sections (Pittet, 1996), as well as the general stratigraphic framework (Gygi & Persoz, 1896; Gygi, 1995), allow the identification of two major sequence boundaries: Ox5 and Ox6 (Hardenbol *et al.*, 1998). Ox5 is indicated by the first important tidal-flat interval terminating a generally subtidal facies evolution. Ox6 is placed where a thick level of desiccation polygons occurs. The cyclostratigraphic analysis of this section and the comparison with the other studied sections suggests that three medium-scale sequences occur between Ox5 and Ox6. Each of these is composed of four small-scale sequences (see Discussion chapter for definitions). The time interval between Ox5 (dated at 157 Ma by Hardenbol *et al.*, 1998) and Ox6 (155.8 Ma) is 1.2 million years. This suggests that the medium-scale sequences may have formed in tune with the 400-ka eccentricity cycle of the Earth's orbit, and that the small-scale sequences were controlled by the 100-ka eccentricity cycle.

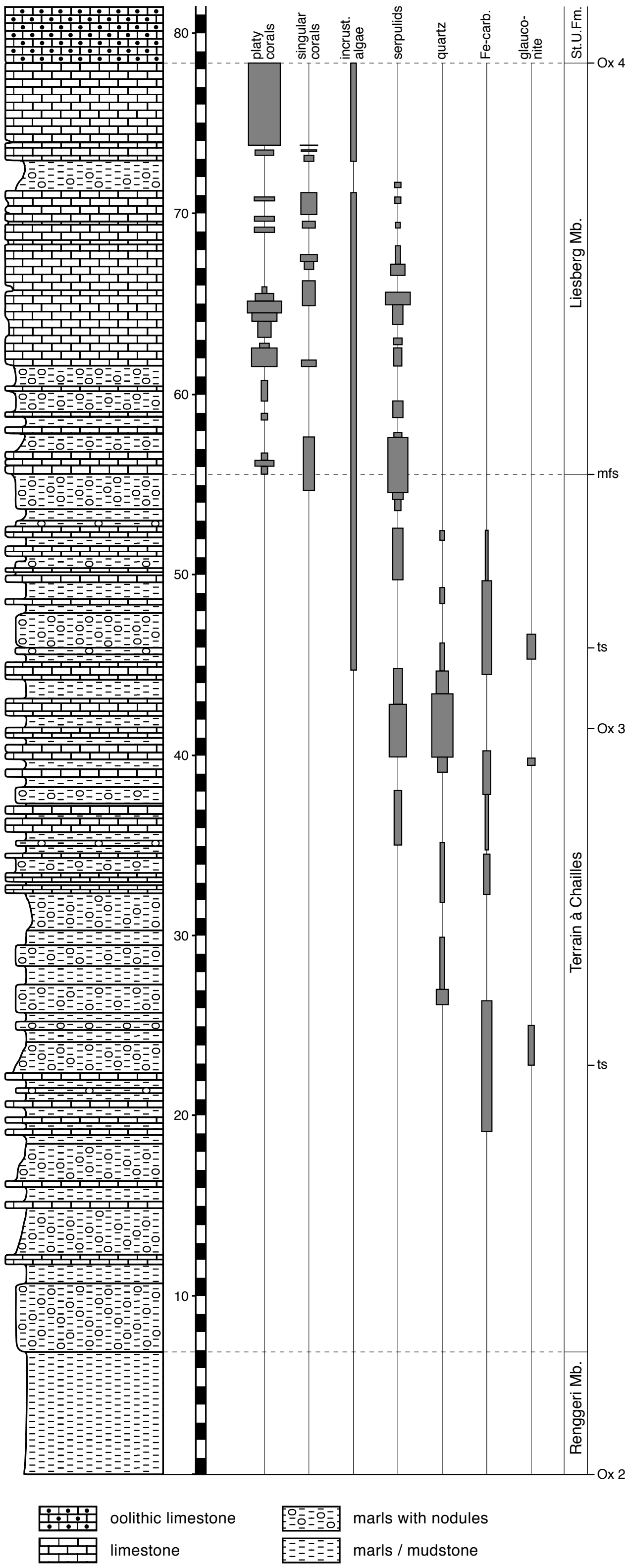


Fig. 9. Sedimentological log and interpretation of the Liesberg section (Stop 5). Lithologic data based on Lauer (1985), sequence stratigraphy after Gygi *et al.* (1998).

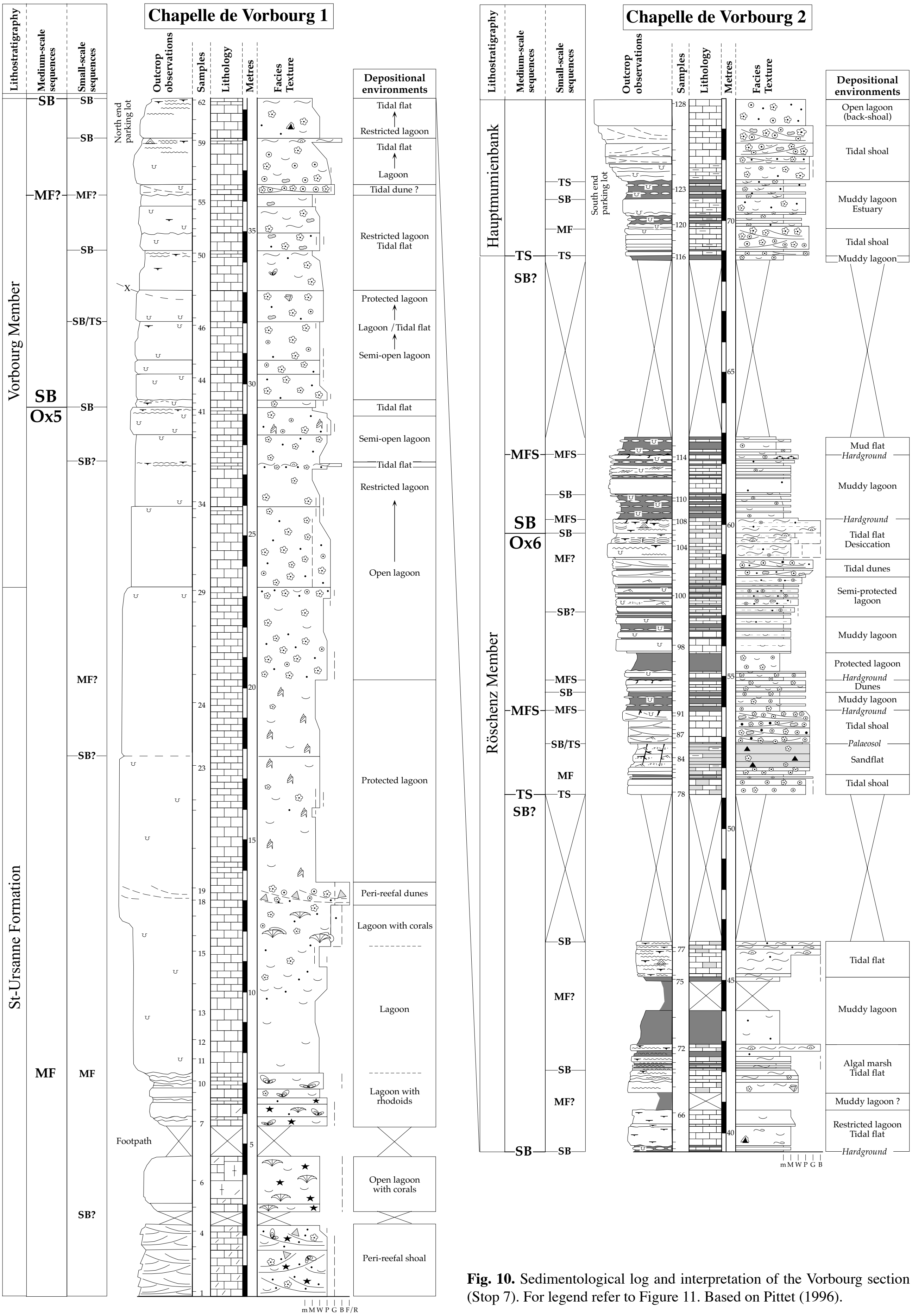


Fig. 10. Sedimentological log and interpretation of the Vorbourg section (Stop 7). For legend refer to Figure 11. Based on Pittet (1996).

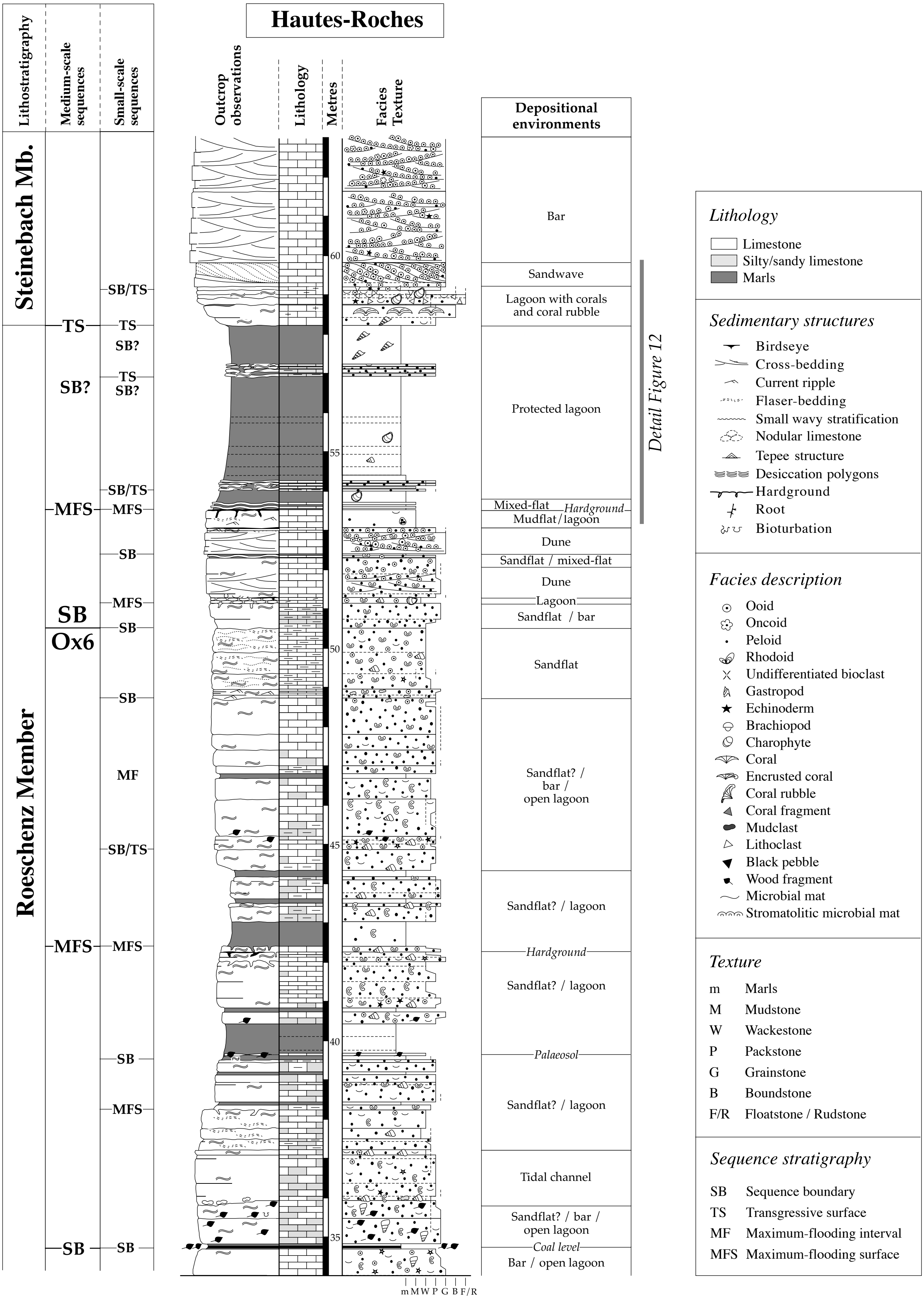


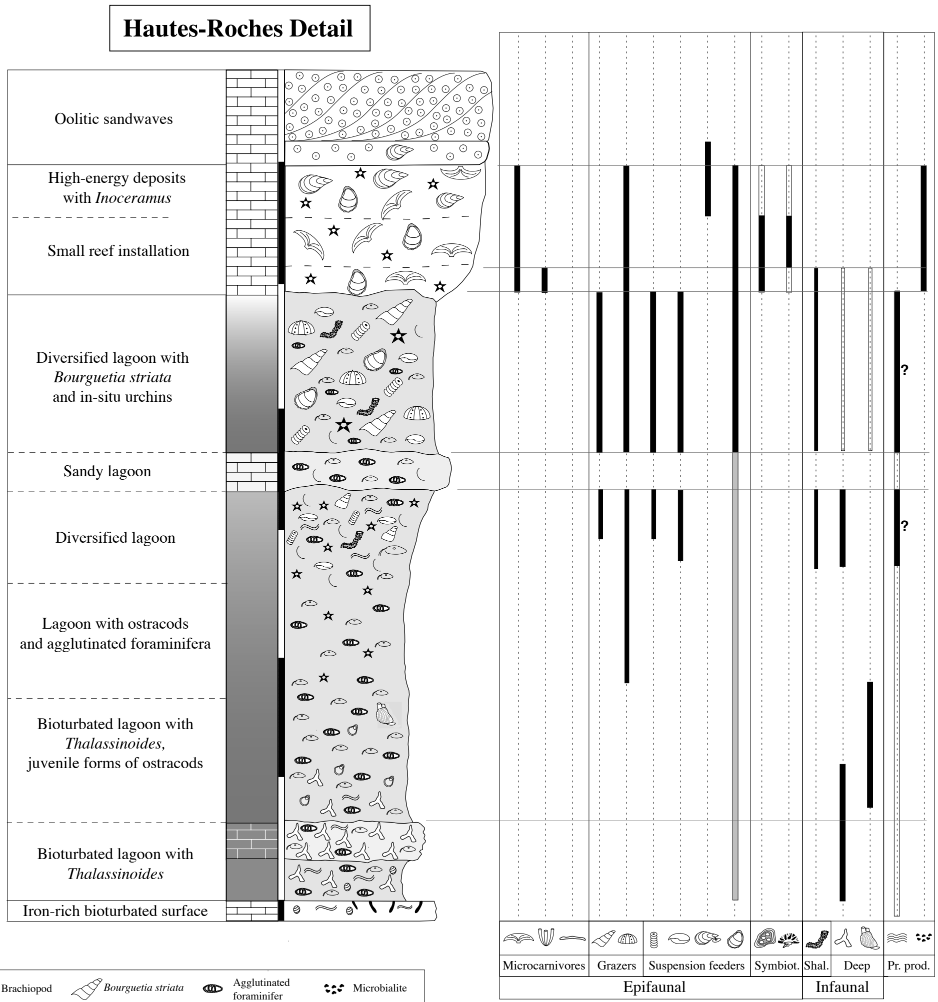
Fig. 11. Sedimentological log and interpretation of the Hautes-Roches section (Stop 8). Based on Pittet (1996) and Dupraz (1999).

Stop 7: Upper Oxfordian tidal, lagoonal, and coral-reef facies near Hautes-Roches

The section along a forest path south of the hamlet of Hautes Roches (Fig. 4; 594.950/238.250) has been studied in detail by Pittet (1996) and Dupraz (1999). For the purpose of this field trip, only the upper part is illustrated (Fig. 11).

As in Vorbourg, the Röschenz Member is rich in siliciclastics. A coal level points to emersion and is interpreted as having formed around a sequence boundary of a medium-scale (400-ka) sequence. The prominent hardground (42.3 m, Fig. 11) suggests sediment starvation related to maximum flooding of this medium-scale sequence. This surface can be correlated with the hardground at 53.8 m in Vorbourg (Fig. 10). Sequence boundary Ox6 is placed above a sandflat and below peloidal grainstones that represent the beginning transgression of the following medium-scale sequence. An iron-rich hardground is interpreted as a maximum-flooding surface, above which marls predominate. The rapid change to coral rudstones and cross-bedded ooid grainstones indicates the important transgression that defines the base of the Steinebach Member.

Dupraz (1999) and Dupraz & Strasser (1999) have analysed the various coral reefs of the Hautes-Roches section in detail. Figure 12 shows the facies and ecological evolution from the marls of the upper Röschenz Member to the coral level at the base of the Steinebach Member. Reworked charophyte oogons point to nearby lacustrine environments. The fact that they occur around the hardground interpreted as a maximum-flooding surface implies that high-frequency sea-level fluctuations, superimposed on a long-term early-transgressive trend, still caused local emersion (Strasser *et al.*, 1999). The marls contain mainly infaunal organisms in their lower part, pointing to abundant and rapid clay input. In the upper part of the marls, clay input decreases but nutrients are still high, and the grazing gastropods *Bourguetia*, echinoderms and brachiopods become predominant. When oligotrophic conditions without siliciclastics are restored, corals install themselves. However, high energy causes toppling of many of the corals. An oolitic sand wave then covers the reef.



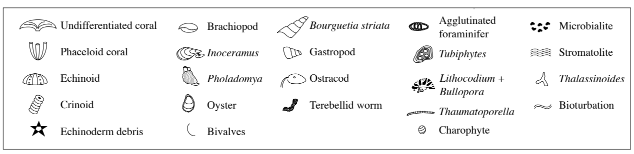


Fig. 12. Distribution of palaeoecologically significant organisms in the upper part of the Hautes-Roches section (Stop 7). Modified from Dupraz (1999).

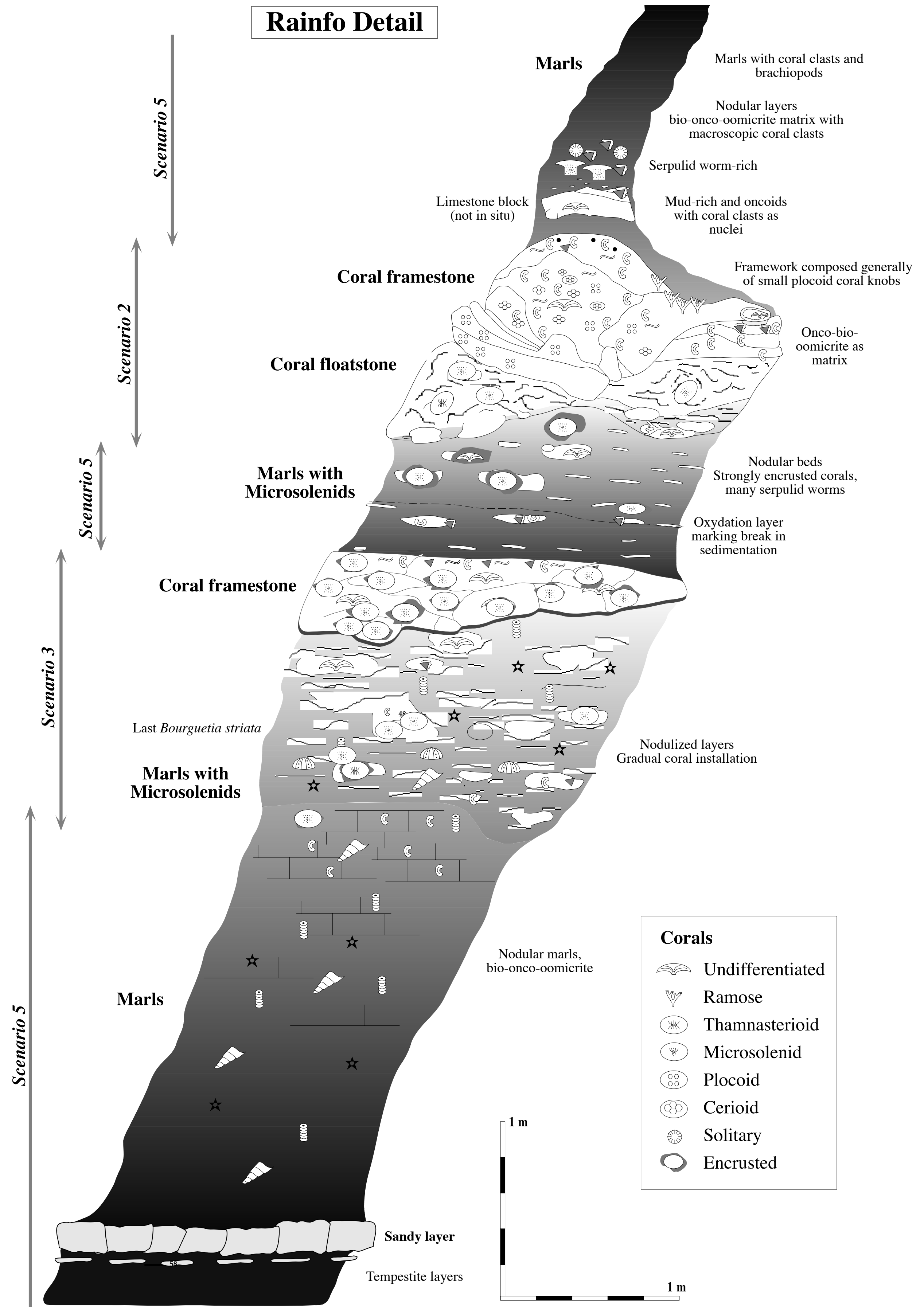


Fig. 13. Detail of the upper part of the Rainfo section (Stop 8). For legend refer to Figure 11. Modified from Dupraz (1999).

Stop 8: Middle to upper Oxfordian coral build-ups at Rainfo

In a section west of Moutier, which is exposed along the small road leading to Le Coulou farm (Fig. 4; coordinates 590.450/326.350) sediments of the Röschenz Member crop out. They have been studied in detail by Dupraz (1999). On Figure 13, only the two coral levels are shown. As in the example of Hautes-Roches, each of these levels evolves from marls, suggesting that the change from input of siliciclastics and associated eutrophication to less siliciclastic influence and rather oligotrophic conditions controlled the ecology of these sedimentary systems.

Based on the Rainfo outcrop and on coral levels studied in other Oxfordian sections, six ecological scenarios can be proposed (Fig. 14; Dupraz, 1999; Dupraz & Strasser, 1999). Coral growth and especially the distribution and importance of micro-encrusters and microbialite strongly depend on terrigenous input that influences sedimentation rate and waterturbidity through clay suspension. Nutrients are washed into the system together with the siliciclastics and lead to mesotrophic or eutrophic conditions. Phytoplankton blooms cause water turbidity, and bacterial decomposition of abundant organic matter induces oxygen deficiency. A delicate ecological balance is established between corals, encrusting organisms and microbialites, which shifts according to the environmental conditions. Since terrigenous input is directly related to rainfall in the hinterland, the evolution of these ecosystems through time thus is a record of climate change. Sea-level fluctuations were of relatively low amplitude and did not directly control the coral reefs. However, they indirectly influenced these systems through accommodation changes and/or through opening or closing of lagoons.

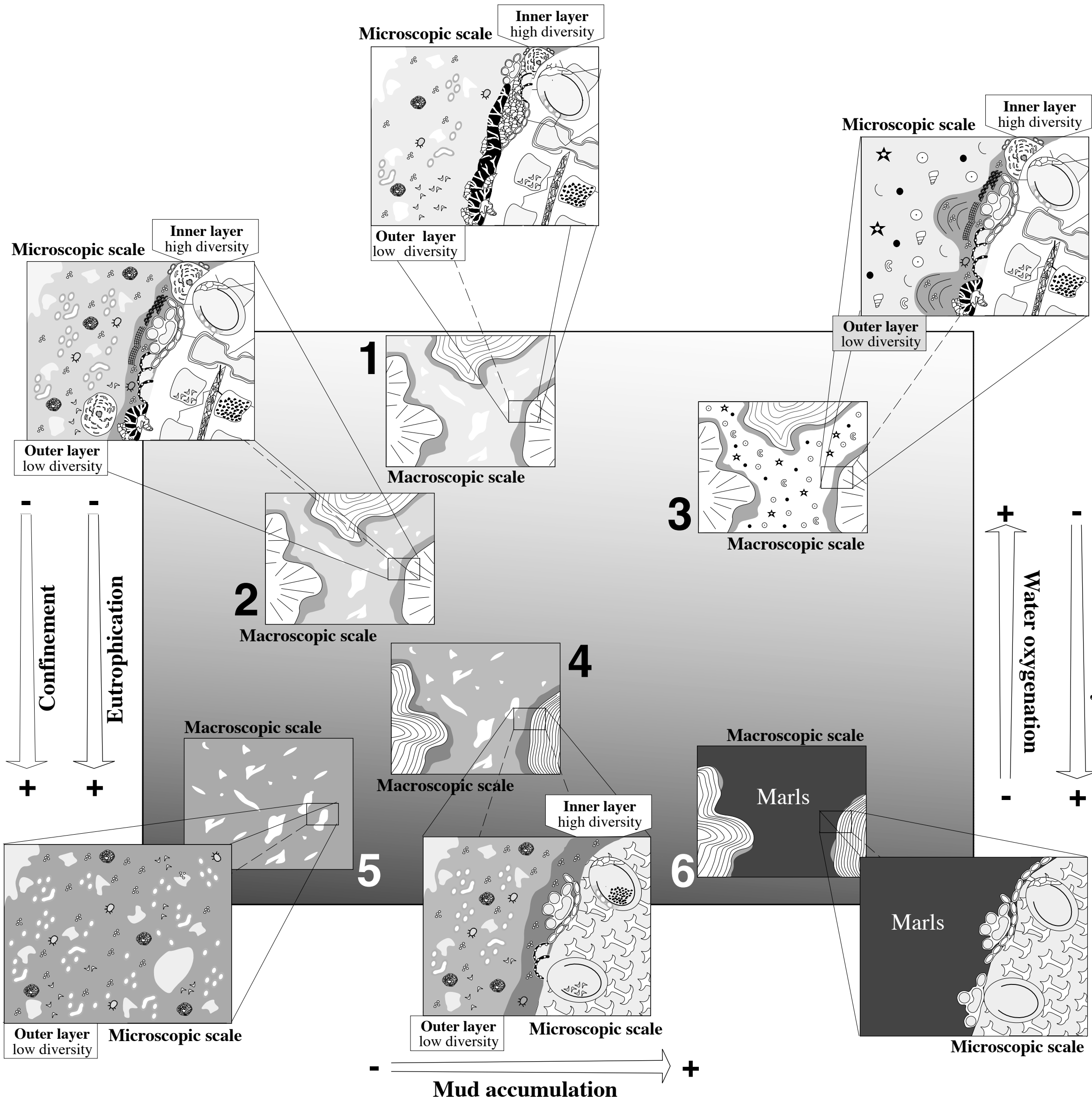


Fig. 14. Six scenarios of coral – microencruster – microbialite relationships depending on nutrients and siliciclastic input. For discussion refer to text. Modified from Dupraz (1999).

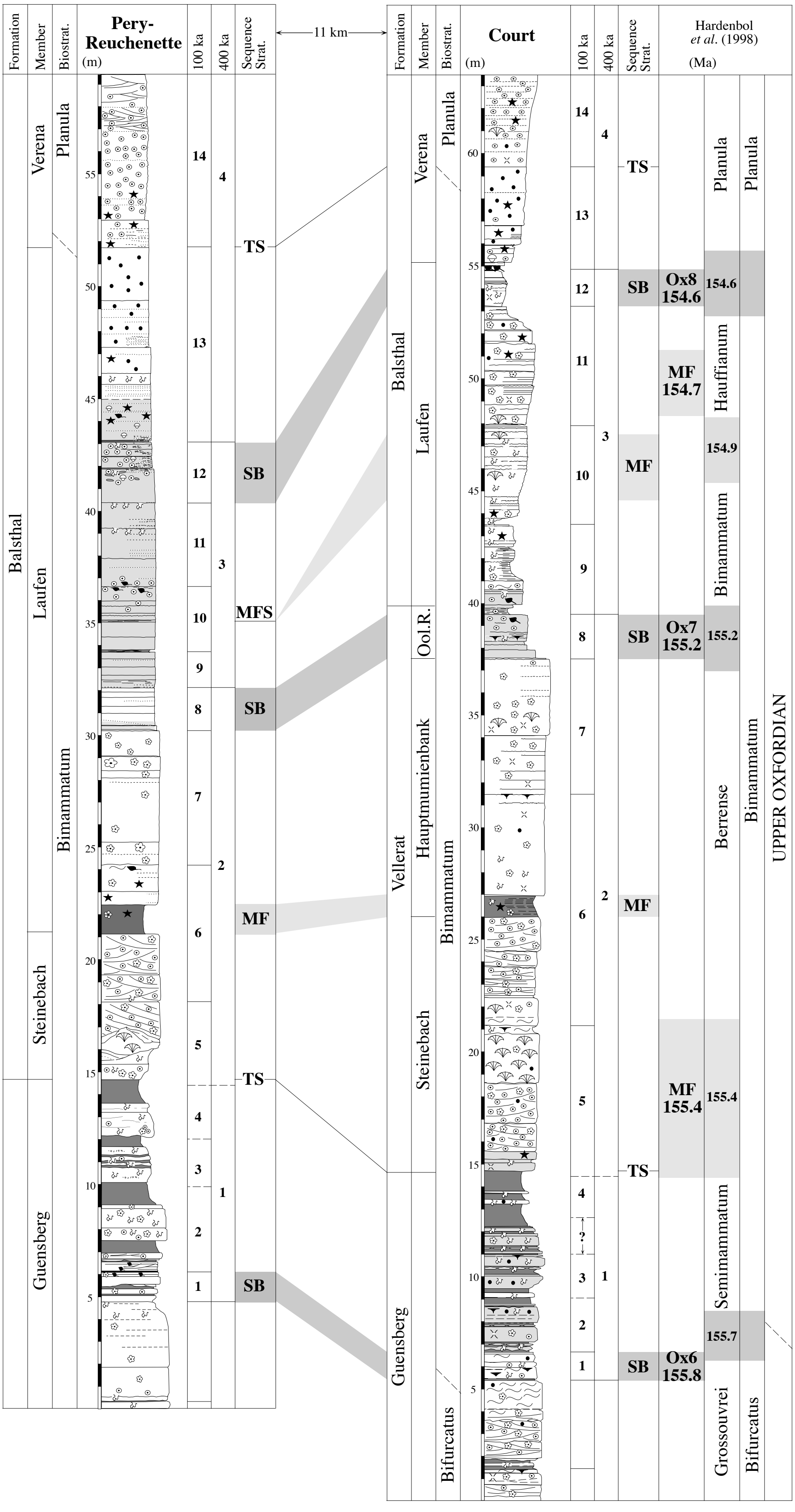


Fig. 15. Sequence-stratigraphic and cyclostratigraphic interpretations of the Court and Péry-Reuchenette sections (Stops 10 and 11), and correlation with the sequences of Hardenbol *et al.* (1998). For legend refer to Figure 11. Ool.R. = Oolithe rousse. Court section based on Hug (2001), Péry-Reuchenette section on Pittet (1996) and Hug (2001).

Stop 9: Dinosaur Disco – an ancient stomping ground in the Gorges de Moutier

In the Gorges de Moutier, above the road Choindez – Moutier (Fig. 4; coordinates; 594.580/238.050), the second largest dinosaur tracksite in Switzerland, in terms of surface area and number of footprints, is exposed in deposits of the Reuchenette Formation (lower Kimmeridgian *sensu gallico*). As one of the Swiss national pastimes is rock climbing, it is through this activity that this dinosaur tracksite has been found. About 2000 footprints are distributed more or less randomly across a steeply inclined surface of 6000 square metres. Only a few tracks are sufficiently clear, and only a few allow to distinguish large hind footprints (pes tracks) from small front footprints (manus tracks) of sauropod dinosaurs. The substrate is a micrite with birdseyes overlain by stromatolitic layers indicating deposition in the intertidal zone of a large mudflat.

Stop 10: Upper Oxfordian sequence- and cyclo-stratigraphy in the Gorges de Court

On the southern flank of the Graitery anticline, northeast of the village of Court, the upper Oxfordian and the Kimmeridgian are well exposed (Fig. 4; coordinates 592.920/ 232.970). Along a footpath running along the Birs river, the Günsberg, Vellerat and Balsthal Formations can be observed. This section has been analysed in detail by Hug (2001).

Based on the lithostratigraphic and biostratigraphic frame furnished by Gygi & Persoz (1986) and Gygi (1995), and on the detailed analyses of stacking pattern and facies evolution, a sequence-stratigraphic and cyclostratigraphic interpretation is proposed (Fig. 15). This interpretation is consistent with the other sections studied (e.g., Péry-Reuchenette; Fig. 15). However, superposition of higher-frequency sea-level fluctuations on a long-term trend of sea-level change led to repetition of diagnostic surfaces, defining sequence-boundary zones (Montañez & Osleger, 1993; Strasser *et al.*, 1999). Relatively fastest rise of sea level either caused distinct maximum-flooding surfaces (which again may be repeated defining a maximum-flooding zone), or is recorded by the relatively deepest or most open-marine facies. Major transgressive surfaces generally correlate well from one section to another.

Comparing the interpretation of the studied sections with the sequence stratigraphy of Hardenbol *et al.* (1998) established in European basins, sequence boundaries Ox6, Ox7 and Ox8 can easily be identified. On the other hand, maximum-flooding surfaces or intervals appear to be shifted by one or two small-scale sequences. This again may be due to superposition of several frequencies of sea-level fluctuations. Depending on the morphology of the platform and the basin, the relatively deepest, most marine, or condensed facies will thus not appear at exactly the same time in all locations, but within an interval related to the relatively fastest rise of long-term sea level.

The radiometric ages attributed by Hardenbol *et al.* (1998) to Ox6, Ox7 and Ox8 allow to estimate the duration of the small- and medium-scale sequences identified in the studied outcrops, assuming that each sequence of a given order had the same duration: about 100 ka for the small-scale sequences, and about 400 ka for the medium-scale ones.

Stop 11: Upper Oxfordian and Kimmeridgian platform progradation across middle Oxfordian basinal deposits at Péry-Reuchenette

The Oxfordian and Kimmeridgian deposits exposed in the large quarry of Péry-Reuchenette (Fig. 4; coordinates 585.800/226.000) have been studied in detail by Pittet (1996), Allenbach (2001c), Hug (2001) and Colombié (in prep.). During this fieldtrip, only a general overwiew will be given (Fig. 16).

At the base of the quarry, ca. 5 m of dark grey clays of the Bärschwil Formation are overlain by about 35 m of grey micrites with marly partings belonging to the Pichoux Formation; they are capped by a hardground (SB Ox5). The overlying Effingen Member displays a general shallowing-upward trend. The advancing platform is represented by patch reefs of the Günsberg Formation. Up-section the reefs become denser and are finally overrun by oolites of the upper Günsberg Formation. The major transgression at the base of the Hauptmumienbank and Steinebach Members then allowed for enhanced carbonate production on the platform. It is marked by a distinct lithological change to lagoonal

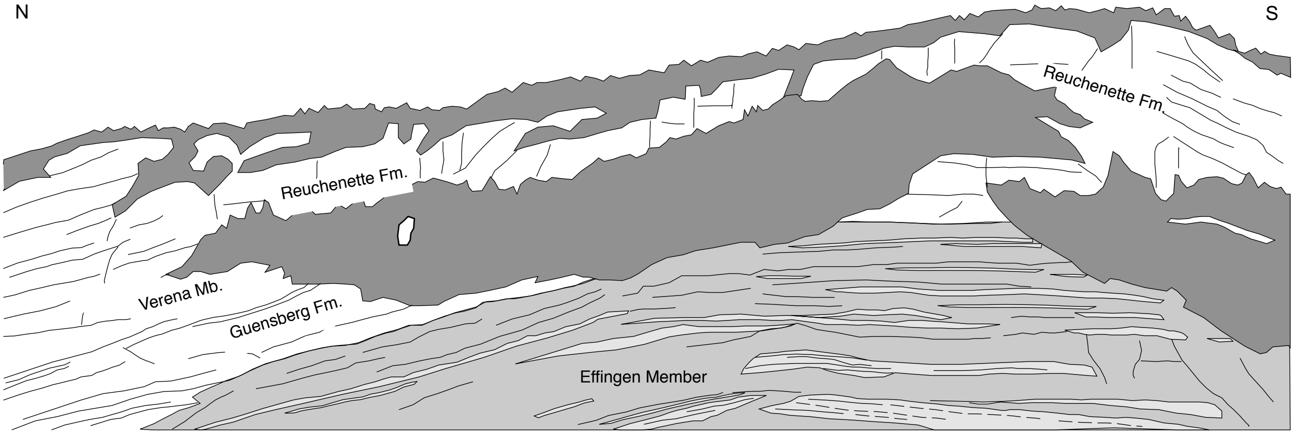


Fig. 16. Simplified sketch of the Péry-Reuchenette quarry, looking east.

deposits. Abundant carbonate production on the platform resulted in a rapid progradation and a southward shift of the reef belt on the platform margin (Gygi & Persoz, 1986). Despite of periodic sea-level falls causing sequence boundaries Ox7 and Ox8, the general transgressive trend continued, and massive oolite dunes dominated on the platform margin in the uppermost Oxfordian (Verena Member). During the Kimmeridgian, the platform margin still prograded towards the south, and thick-bedded, mainly lagoonal facies with peritidal caps developed in the platform interior.

Discussion

Differential subsidence

Thickness and facies patterns of the Oxfordian sediments in northern Switzerland can be interpreted as markedly affected by differential subsidence (Allenbach 2001a, b, c). Obviously, the differentiation into platforms and basins switched with time (Figs. 2, 5, 17). During the early Oxfordian, a depocentre filled with mudstones formed in the NW part of the study area (Bärschwil Fm.), whereas an area of non-deposition or condensation was identified to the SW. The latter probably belonged to a submarine swell which has been described by, for instance, Debrand-Passard & Courbouleix (1984). To the end of the early Oxfordian, a carbonate platform prograded from northwest southeastward. Its south-eastern boundary, however, did not significantly prograde across a fault zone which forms part of the Rhenisch Lineament (*sensu* Ziegler, 1990; Figs. 3, 5). During the late middle Oxfordian, subsidence accelerated in the southwestern part of the study area and, once again, depocentres developed in the vicinity of faults within the basement (Fig. 5). Mass movements and tempestitic currents were directed to these depocentres and, hence, classify them as synsedimentary depressions. In spite of the ample evidence for synsedimentary differential subsidence in Jurassic sediments (see Introduction) no faults cutting through the Jurassic sedimentary cover have been observed so far. We assume that the Triassic salt deposits below deformed plastically; in this way vertical movements within the basement resulted in flexures of the overlying sediments. The locally opposing palaeoflow directions encountered in the Effingen Member, in addition, indicate that the subsidence of the whole area was not continuous but that individual blocks had their own subsidence history (e.g., Bolliger & Burri, 1970; Wetzel & Allia, 2000).

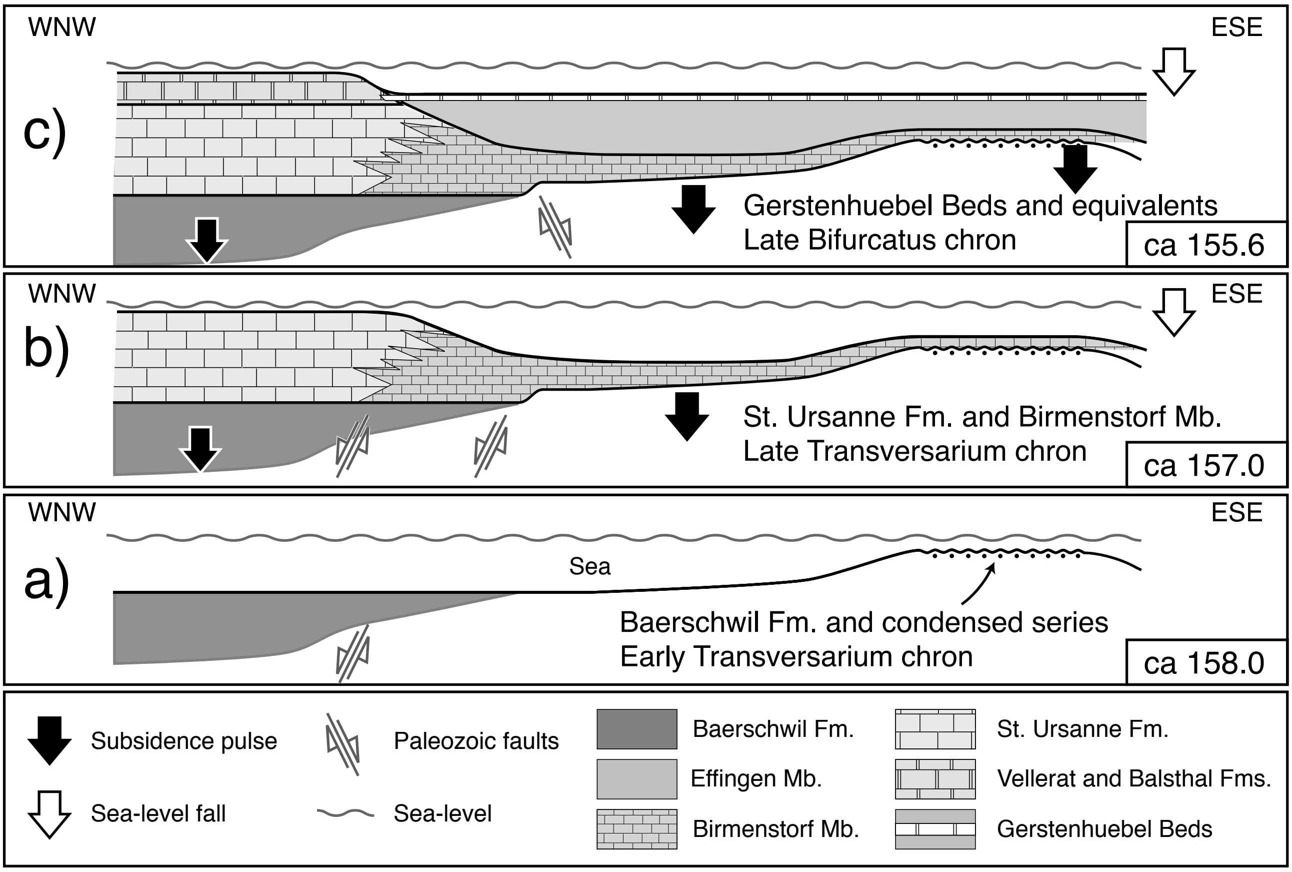


Fig. 17. Schematic representation how differential subsidence affected the facies development in northern Switzerland. (a) During the early Oxfordian, subsidence in the NW provided accommodation space for the Bärschwil Formation whereas non-deposition or condensation occurred on a swell further to the SE. (b) As clastic input ceased in the early middle Oxfordian, platform carbonates prograded south(east)ward. (c) During the late Oxfordian, enhanced subsidence in the SE provided accommodation space for the sediments of the Effingen Member, to the NW platform carbonate accumulation continued. All sketches from Allenbach (2001b).

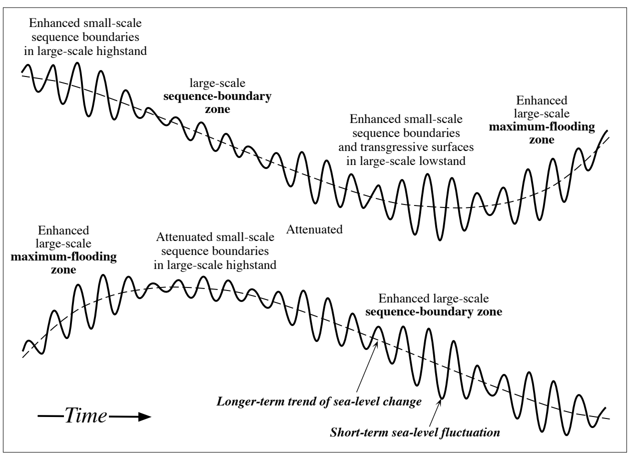
Low- and high-frequency sea-level fluctuations

Despite the important lateral variability of facies, which was controlled by platform morphology and probably also by current regimes, it is possible to recognize the major elements of depositional sequences such as sequence boundaries, transgressive surfaces and maximum-flooding surfaces or intervals. In the studied sections, four orders of sequences (or sedimentary cycles) have been recognized (Strasser *et al.,* 1999):

- Elementary sequences consisting of one or several beds but showing one cycle of facies evolution.
- Small-scale sequences commonly consisting of 3 to 6 elementary sequences.
- Medium-scale sequences consisting in many cases of 4 small-scale sequences.
- Large-scale sequences that consist of two or more medium-scale sequences.

Most small- and medium-scale sequences can be correlated over the entire study area, although in some cases a best-fit solution has to be looked for (Pittet, 1996; Hug, 2001). This suggests that changes of relative sea level occurred and controlled, at least partly, facies distribution on the platform. Elementary sequences are difficult to correlate from one section to the other and, in some outcrops, even difficult to identify. Local migration of sedimentary bodies or high-energy events such as washovers apparently masked the sea-level signal. In some intervals, the sea-level amplitudes were too small to create facies contrasts and, consequently, the record of elementary sequences is lost.

Within the basinal sediments, hard or firm grounds, channels and tempestitic beds reflect to some degree platform dynamics and sea-level changes, respectively. Channel incision was related to sea-level lowstand. Hardgrounds could result either from reworking by currents during low sea-level or by starvation during flooding, both displaying different characteristics. Thicknesses and carbonate contents of tempestitic beds in the Effingen Member increased when carbonate production on the platform was enhanced. This normally occurred during periods of rising or high sea level. Therefore, sea-level changes on the platform are reflected by carbonate cycles in the basin.



The observed hierarchical stacking of depositional sequences is interpreted as being a consequence of a superposition of high-frequency sea-level fluctuations on a lower-frequency trend of sea-level change (Fig. 18). This may result in the repetition of diagnostic surfaces defining sequence-boundary or maximum-flooding zones (see example at Stop 10).

As already mentioned at Stops 6 and 10, the chronologic timing available from Gradstein *et al.* (1995) and applied by Hardenbol *et al.* (1998) to date the sequence boundaries recognized in various European basins allows to estimate the duration of the intervals between Ox5, Ox6, Ox7 and Ox8 (Fig. 2). Dividing these time spans by the number of small-scale and medium-scale sequences identified between the respective sequence boundaries gives values that correspond to the Milankovitch frequency band. This suggests that the observed hierarchical stacking pattern is related to sea-level changes that were in tune with the Earth's orbital cycles. Thus, elementary sequences would correspond to the 20-ka cycle of precession of the equinoxes, and the small- and medium-scale sequences to the two cycles of eccentricity of 100 and 400 ka, respectively. The evidence for the 40-ka obliquity cycle is difficult to demonstrate in the studied sections (Pittet, 1996). It is interesting to note that the several 400-ka sequences identified on the Oxfordian of the Swiss Jura appear to correspond to "third-order" sequences recognized also in other basins (Strasser *et al.,* 2001). This suggests that these sequences were, at least indirectly and partly, controlled by climatic changes that translated into sea-level changes.

In the Late Jurassic, ice in high latitudes and altitudes probably was present (Fairbridge, 1976; Frakes *et al.*, 1992; Eyles, 1993) but ice volumes were small and glacio-eustatic fluctuations of low amplitude. However, orbitally induced climate changes also caused thermal expansion and retraction of the uppermost layer of ocean water (Gornitz *et al.*, 1982), thermally-induced volume changes in deep-water circulation (Schulz & Schäfer-Neth, 1998), and/or water retention and release in lakes and aquifers (Jacobs & Sahagian, 1993). These processes potentially contributed to low-amplitude sea-level changes (Plint *et al.*, 1992). Concerning the orbital parameters, Laskar *et al.* (1993) presented a quasiperiodic approximation for the last 20 Ma. Berger *et al.* (1989) showed that the 100-ka and 400-ka periodicities were relatively stable in the geologic past, and that the precession cycle had a periodicity of about 20 ka in the Late Jurassic to Early Cretaceous. The duration of the cycles implied by our study can thus be considered a good approximation of the duration of hypothetical sea-level cycles, but amplitudes and shapes of the latter may have varied considerably.

Fig. 18. Hypothetical sketch showing how varying amplitudes of high-frequency sea-level changes superimposed on a long-term trend of sea-level evolution may enhance or attenuate the expression of sequence-stratigraphic surfaces, and how sequence-boundary and maximum-flooding zones are defined. The high-frequency sea-level signal is approximated from the variations of the caloric equator due to orbital cyclicity calculated by Berger (1978) for the Quaternary, assuming that insolation changes translate directly into sea-level changes. Modified from Strasser *et al.* (1999).

Climatic and ecological changes

Orbitally induced climate changes not only influenced sea level but also water temperature and salinity, wind and current patterns, as well as rainfall in the hinterland that in turn affected siliciclastic and nutrient input into the studied depositional environments. The coral-microbialite reefs as seen at Stops 7 and 8 are particularly sensitive to such environmental changes (Dupraz, 1999; Dupraz & Strasser, 1999). Temperature and salinity changes through one depositional sequence certainly were of importance but are difficult to evaluate. On the other hand, the reef evolution clearly recorded changes in terrigenous input and trophic levels (Fig. 14).

In the upper Oxfordian, evaporite pseudomorphs are locally found to be contemporaneous with increased siliciclastic input. This implies that either the siliciclastics were furnished during a humid phase and then redistributedduring more arid conditions, or else that rainfall occurred above the crystalline massifs to the north (Fig. 1) whereas the carbonate platform further to the south was situated in a more arid climatic belt (Hug, 2001). A palaeolatitudinal control on the distribution of siliciclastics was demonstrated by Pittet (1996) and Pittet & Strasser (1998) with high-resolution correlations between the Swiss Jura and Spain. While siliciclastics in the Jura concentrate rather around the boundaries of small- and medium-scale sequences (e.g., Fig. 10b, 15), they occur in the transgressive or maximum-floodingintervals in the time-equivalent sequences of the Spanish sections.

Conclusions

During the Oxfordian, northern Switzerland belonged to a shallow epicontinental sea. A differentiation into platforms and basins resulted from differential subsidence. Major facies boundaries follow pre-existing structures in the basement. The depocentre of the lower Oxfordian sediments appears to be spatially related to elements of the roughly NW-SE striking Permocarboniferous trough system and its northwestern prolongation. During the middle and late Oxfordian, the platform-basin transition seems to coincide spatially with faults belonging to the NNE-SSW striking Rhenish Lineament.

Clays were imported from the NW during the early Oxfordian and from the NE (Bohemian massif) later on. This was intensified during periods of falling or low relative sea level, but also during more humid climatic phases. Carbonate was produced on the platforms, especially during times of rising and high relative sea level.

Million-year-scale progradational, aggradational, and retrogradational patterns on the platform and in the basin allow to establish a sequence-stratigraphic framework. Especially the basinal sections are biostratigraphically well dated and thus allow for correlation of these sequences with the sequences recognized in other European basins. Cyclostratigraphical analyses of the studied sections suggest that orbitally induced climatic changes translated into high-frequency, low-amplitude sea-level changes that are recorded in the depositional sequences. Within this narrow time-frame (100-ka scale), sedimentological, ecological, and climatic changes can be monitored in detail. Lateral and vertical facies distributions point to a complex carbonate-siliciclastic sedimentary system that was influenced by a morphologically highly structured substrate as well as by changes of sea level, climate, and ecology.

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