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ORIGINAL ARTICLE

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Late Jurassic sea-level fluctuations in NW Switzerland (Late Oxfordian to Late Kimmeridgian): closing the gap between the Boreal and Tethyan realm in Western Europe

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Abstract In Late Jurassic times, the Swiss Jura carbonate platform occupied the transition between the Paris Basin and the Tethys and thus connects the Boreal and Tethyan realm. Up to now, the lack of index fossils in the Reuchenette Formation prevented a reliable correlation between both areas (its sediments are characterised by a prominent sparseness of index fossils). Now, seven recently in situ collected species of ammonites helped to establish a new sequence-stratigraphical frame for the platform sediments of the Reuchenette Formation in NW Switzerland. Based on biostratigraphical data, five third-order sedimentary sequences were assigned to the Late Oxfordian to Late Kimmeridgian. The upper three third-order sequences correspond to the Boreal sequences Kim3–5 of Hardenbol et al. (1998). The deduced large-scale sea-level fluctuations match those from other European regions (Spain, Russia). This biostratigraphically based sequence-stratigraphical frame is a prerequisite to refine correlations within a wider area covering the Swiss Jura and parts of adjacent France and Germany.

Keywords Sequence stratigraphy · Biostratigraphy · Kimmeridgian · Jurassic · NW Switzerland · Reuchenette Formation

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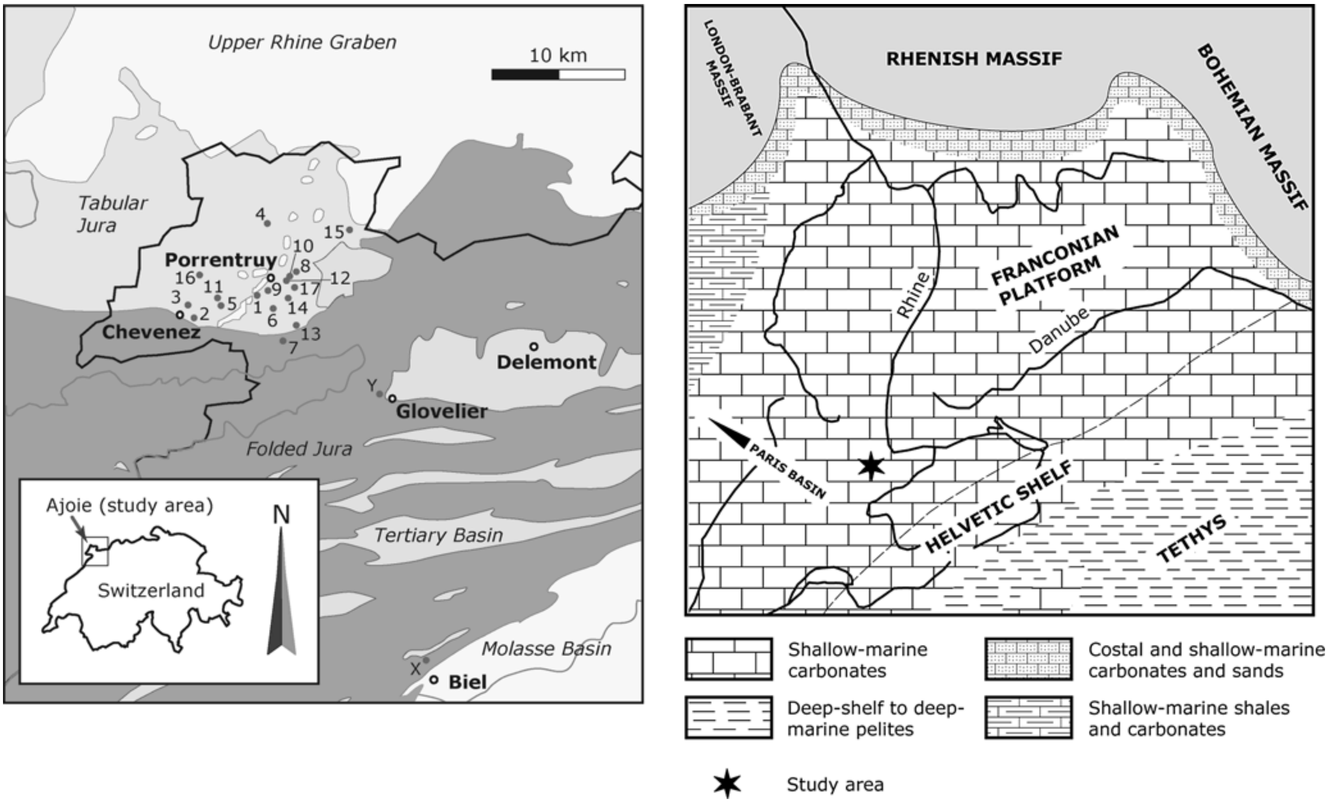
Introduction

Depocentres of Mesozoic sediments in the Swiss Jura Mountains appear to be related to the synsedimentary reactivation of Permo-Carboniferous basement structures (Gonzalez 1993; Wetzel et al. 1993, 2003; Allia 1996; Burkhalter 1996; Pittet 1996; Allenbach 2002). This is also the case for the Late Jurassic Reuchenette Formation exhibiting thickness variations of up to 100 m within a maximum thickness of approximately 160 m (Gygi and Persoz 1986; Meyer 1993). These thickness variations and the sparseness of index fossils within the Reuchenette Formation—including the type section in the quarry La Reuchenette near Péry BE (see "X" in Fig. 1)—led to numerous different approaches on how to correlate the strata and estimate their age (e.g., Thurmann 1832; Greppin 1870; Thalmann 1966; Chevallier 1989; Meyer 1989; Gygi 2000). Even more recent studies based on sequence, cyclo and mineralo stratigraphy (Gygi and Persoz 1986; Gygi 1995; Mouchet 1995, 1998; Gygi et al. 1998; Meyer 2000; Colombie 2002) rely on only a few high-resolution biostratigraphical markers (i.e., ammonites). Unfortunately, most of those markers occur in different, widely spaced or very small outcrops restricting their biostratigraphical use. Consequently, the biostratigraphical data for Kimmeridgian shallow-water platform sediments were too sparse to establish a reliable (biostratigraphically dated) sequence-stratigraphical link between the Paris Basin and the Tethys (Boreal and Tethyan realm). Recently, the construction work of the Transjurane motorway in the Ajoie-Region provided new outcrops of the Reuchenette Formation. The exposures are closely spaced and well suited to study these sediments and, in addition, a considerable number of index fossils (ammonites) were found.

It is the purpose of this paper (1) to describe the depositional environments and (2) to provide an improved sequence-stratigraphical frame for the Reuchenette Formation in NW Switzerland based on a refined biostratigraphy and additional sedimentological, lithostratigraphical and



	Code	Sections	Coordinates		Interval(s)
1	BAN	Tunnel Le Banné (Westportal), base	571,833	250,504	top Thalassinoides Limestones, base "Nautilidenschichten"
2	CHV	La Combe (Carrière Combe de Varu), base	567,753	248,930	Nerinean Limestones... Oyster Limestones
3	CHVs	Chevenez (La Scierie), base	567,175	249,675	Lower Grey and White Limestones, base Banné Marls
4	COE	Coeuve (Carrière), base	574,725	256,075	top Thalassinoides Limestones, "Nautilidenschichten"
5	CRE	Creugenat, base	569,173	249,748	top Thalassinoides Limestones, base "Nautilidenschichten"
6	FON	Fontenais (Carrière communale), base	573,050	249,575	top Thalassinoides Limestones, base "Nautilidenschichten"
7	PAU	Chemin Paulin	573,790	247,100	Porrentruy Member… Banné Marls
8	PMS	Pré Monsieur (Carrière), base	574,887	252,262	Coral Limestones
9	RAS	La Rasse (Carrière)	572,560	250,840	Porrentruy Member… Lower Grey and White Limestones
10	RDM	Roches de Mars, base	574,372	252,021	Nerinean Limestones, (Virgula Marls)
11	SCR	Sur Combe Ronde, base Virgula Marls	568,869	250,082	top Nerinean Limestones, VirgulaMarls
12	TUP	Cras d'Hermont (base little road)	573,958	251,694	"Nautilidenschichten", Lower Grey and White Limestones
12	TUP	Cras d'Hermont (end little road)	574,108	251,750	base Banné Marls
12	TUP	Cras d'Hermont (betw. motorway and car shop)	574,058	251,797	top Banné Marls, base Nerinean Limestones
12	RDMa	Cras d'Hermont (car shop)	573,970	251,844	base Nerinean Limestones
13	VAB	L'Alombre aux Vaches (Carrière Vabenau)	574,800	248,200	top Thalassinoides Limestones... Banné Marls
14	VAT	Vatelin (Carrière)	574,300	250,500	top Thalassinoides Limestones... Lower Grey and White Lst.
15	VEN	Vendlincourt (Carrière), base	578,950	255,475	top "Nautilidenschichten"... Banné Marls
16	VTT	Vâ tche Tchâ (Combe de Vâ tche Tchâ)	568,720	252,155	Banné Marls
17	BDH	Bas d'Hermont (Carrière)	574,600	251,000	top Thalassinoides Limestones, base "Nautilidenschichten"
X	REU	La Reuchenette (Carrière)	585,890	226,240	type-section
Y	GLO	Contournement de Glovelier	581,521	242,515	

Fig. 1 Geological and palaeogeographical (Kimmeridgian) overview maps, Swiss coordinates of locations and lithological intervals. Slightly modified palaeogeographical map after Ziegler (1990)

microfacial data. These data are essential to define and date already established and newly determined sequence boundaries, to establish an integrated sequence-stratigraphical overview and to re-evaluate existing interpretations.

Geological setting

The study area (Ajoie-Region) is located at the transition from the Folded Jura Mountains to the Tabular Jura of

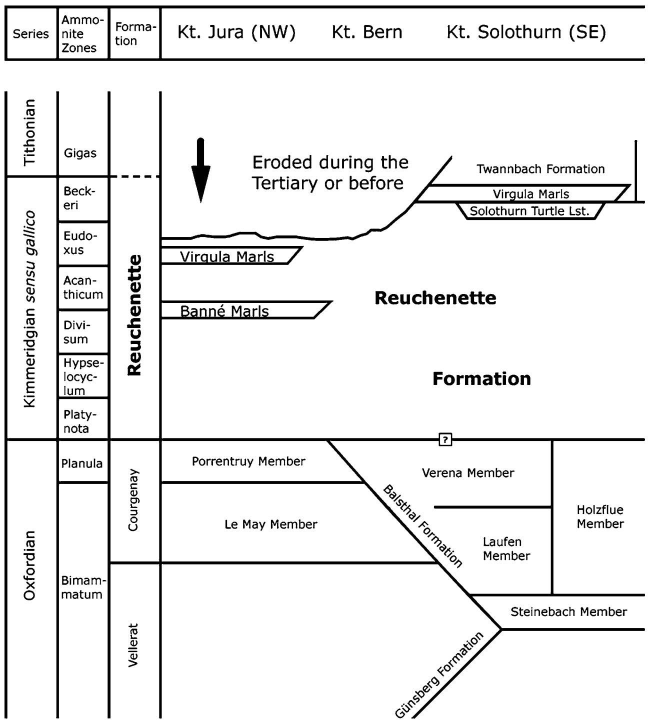


Fig. 2 Litho- and biostratigraphical scheme for the Reuchenette Formation (NW Switzerland), based on data from Meyer (1990, 1993), Gygi (2000), Jank (2004) and this study. Arrow indicates position of the measured sections. The biostratigraphical position of the boundary between the Reuchenette Formation and the Courgenay/Balsthal Formation is still a matter of debate (Thalmann 1966; Gygi 1995, 2000; Colombie 2002)

NW Switzerland (Fig. 1). During the Late Jurassic, the study area was covered by a shallow epicontinental sea (carbonate platform) between the Tethys in the south and the Paris Basin in the north and northwest (Fig. 1). Sea-level fluctuations affected the platform on which mainly shallow-water limestones and some marls accumulated. The climate was subtropical at this time (e.g., Frakes et al. 1992). During the Early Tertiary or even earlier, the study area became exposed and a considerable part of the uppermost Jurassic was removed by erosion, including the Twannbach Formation, which is absent in the study area but rests on the Reuchenette Formation further to the south; it is unknown how much sediment has been eroded. A general stratigraphical overview is given in Fig. 2.

Methods, material and terminology

Detailed sedimentological, palaeontological and microfacial analyses were performed on 17 sections throughout the Ajoie-Region (Fig. 1). The evaluation of the microfacies type of approximately 500 thin sections and of the facies is based on the classifications of Dunham (1962), Embry and Klovan (1972) and Flügel (1982, 2004).

The facies and their bounding surfaces form the base for defining sedimentary cycles and sequences based on the concepts of Van Wagoner et al. (1988), Vail et al. (1991) and Strasser et al. (1999). Short-term cycles and systems tracts are numbered in relation to the number of the sequence boundary underneath, for instance, TST3: transgressive systems tract following sequence boundary 3. Long-term sea-level fluctuations are numbered with letters (e.g., TST-A). The lowstand systems tract (LST) and transgressive systems tract (TST) are illustrated as one half-cycle. The term “bedding” is used for the internal characteristics/composition of a bed, e.g., flaser bedding, nodular bedding, cross bedding, laminated, etc.

The term “layering” is used to characterise the thickness of a bed or bed set, e.g., massive layered (>1 m), thick layered (0.3–1 m), thin layered (1–3 dm), very thin layered (<1 dm), etc.

Thin sections of oriented samples were studied by light microscopy and by cold cathodoluminescence microscopy (CITL Mark II) to evaluate diagenetic effects. To estimate the influence of meteoric diagenesis for some of these samples, the isotopic composition of oxygen was measured at the isotope laboratory of the ETH Zürich. Samples for oxygen and carbon isotope measurements were taken with a dental drill from the same pieces as the thin sections, so isotope samples can be easily related to the microscopically defined limestone domains. The isotopes were measured by a VG Isogas PRISM mass spectrometer. Isotope compositions are expressed in notation as per mil deviations from the international PDB carbonate standard. Analytical precision based on routine analysis of the internal standard (Carrara Marble) was ±0.10‰ for $\delta^{18}O$ and ±0.05‰ for $\delta^{13}C$.

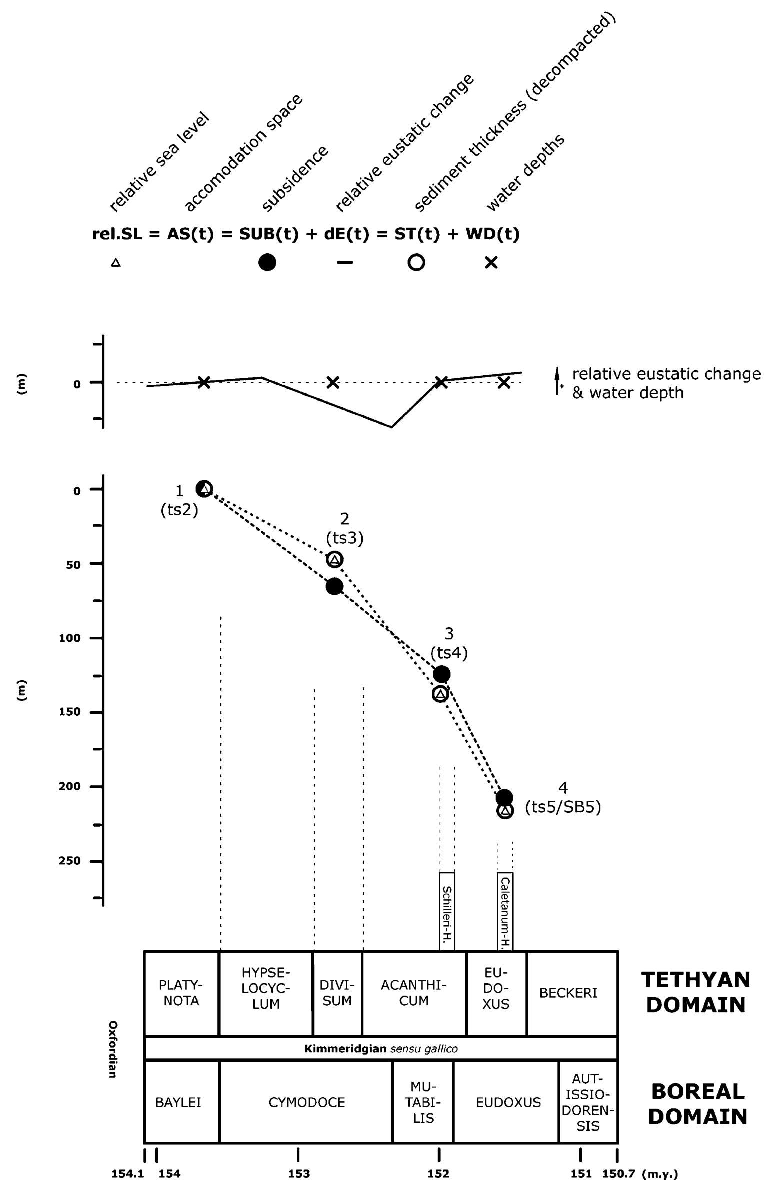
To illustrate the thickness development and the subsidence history, the decompaction factors of Moore (1989), Goldhammer (1997) and Matyszkiewicz (1999) were used (decompaction factor * thickness = initial thickness, when deposited; for details see Fig. 3). The available accommodation space was estimated as suggested by Strasser et al. (1999).

Due to the limited space in publications, five long and (if possible) ammonite-bearing sections (La Combe, La Rasse, Cras d’Hermont, L’Alombre aux Vaches, Vendlincourt; no. 2, 9, 12, 13 and 15 in Fig. 1) have been selected to illustrate the results. The sections La Rasse (no. 9 in Fig. 1), Chemin Paulin (no. 7 in Fig. 1) and parts of L’Alombre aux Vaches (no. 13 in Fig. 1) are already measured and described by Mouchet (1995, 1998) and Gygi (2000). They were reinvestigated and partly extended.

Biostratigraphy

The evaluation of sea-level changes in terms of relative time is based on eight in situ collected species of ammonites (see biostratigraphical frame, Fig. 4). A detailed discussion of the ammonites would be beyond the scope of this paper; biostratigraphical details of the ammonites of the studied sections are discussed in Jank (2004) and Schweigert et al. (in prep.). Gygi and Persoz (1986) and Gygi (1995, 2000, 2003) give further information about index fossils found in the Reuchenette Formation.

	"position"	thickness difference (m)	thickness difference, decompacted (m)	thickness development, decompacted (m)	water depth (m)	relative eustatic change (m)
1	4 m below ts2 in Coeuve (stromatolite)	0	0	0	0	0
2	4 m below ts3 in Vendlincourt (stromatolite with birds eyes and mudcracks)	24	48	48	0	-17
3	ts4 in La Combe (crumbly and platy mudstone with mudcracks)	8 (marl) & 33	90	138	0	15
4	ts5/SB5 in La Combe (stromatolite with birds eyes)	1 (marl) & 37	76	214	0	3



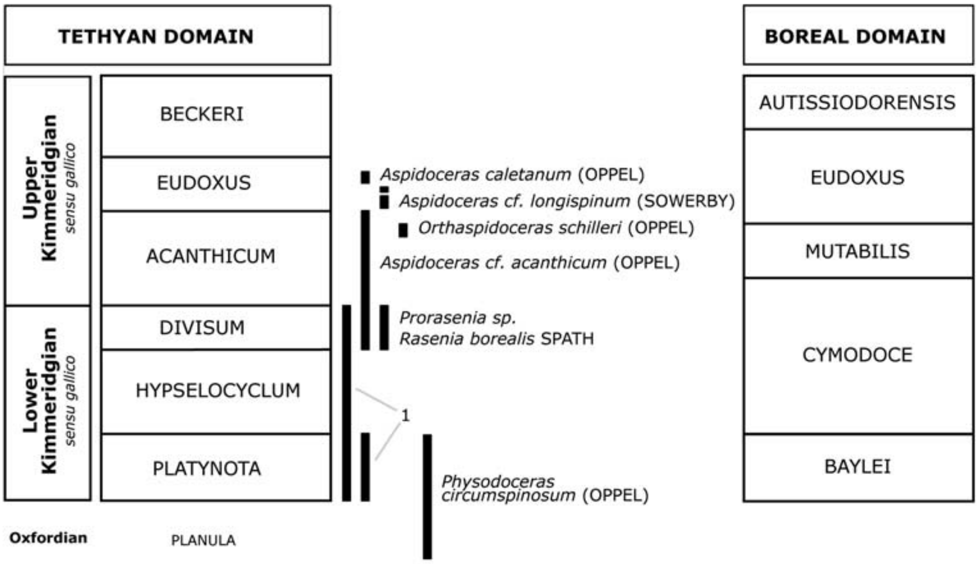


Fig. 4 Biostratigraphical frame based on ammonites. Zonation of the Kimmeridgian sensu gallico (Hantzpergue et al. 1997). Tethyan Domain is used *sensu* Domaine Téthysien, Province subméditerraneénne; Boreal Domain is used *sensu* Domaine Boréal, Province subboréale. All ammonites were collected in situ, except *Aspidoceras* cf. *acanthicum* (Oppel) (Gygi 1995). Biostratigraphical reach and localities: 1: *Lithacosphinctes* cf. *janus* (Choffat); Platynota-Zone (according to Schweigert) or Perisphinctidae indet.; ≈ Early Kimmeridgian (according to Gygi, personal communication); L'Alombre aux Vaches. *Physodoceras circumspinosum* (Oppel); Late Oxfordian to Early Kimmeridgian (Planula- and Platynota-Zone; according to Hantzpergue, personal communication); excavation pit near Fontenais. *Rasenia borealis* Spath; Divisum-Zone; Coeuve. *Prorasenia* sp.; Divisum-Zone; Vâ tche Tchâ. *Aspidoceras* cf. *acanthicum* (Oppel); Divisum- to Acanthicum-Zone; L'Alombre aux Vaches. *Orthaspidoceras schilleri* (Oppel); Acanthicum-Zone, Lallierianum-Sub-Zone, Schilleri-Horizon; La Combe, Roches de Mars and Sur Combe Ronde. *Aspidoceras* cf. *longispinum* (Sowerby); lowermost Eudoxus-Zone; La Combe. *Aspidoceras caletanum* (Oppel); Eudoxus-Zone, Caletanum-Sub-Zone, Caletanum-Horizon; La Combe and Sur Combe Ronde

Lithology

In the study area, the preserved part of the Reuchenette Formation is subdivided into nine intervals. Characteristic lithological features including colour, fossils and composition are used for naming them.

In the Ajoie-Region, the Porrentruy Member (top member of the Courgenay Formation *sensu*, Gygi 1995) is overlain by the Reuchenette Formation (Fig. 2). The Porrentruy Member is composed of massive layered, white, calcarenitic to micritic, chalky limestones with nerinean gastropods, small oncoids and coated intraclasts. The latter two occasionally display brownish rims.

The *Thalassinoides Limestones* form the base of the Reuchenette Formation. They consist of monotonous, thick- to massive-layered, well-bedded, bioturbated, grey, micritic limestones that contain some bioclasts and reddish-brown or greyish, coarse-grained pseudo-oolites (mainly rounded intraclasts and peloids) within pockets, patches or strings within a micritic matrix. Thin- to thick-bedded layers commonly show abundant *Thalassinoides* and iron-stained bed surfaces, and fracture conchoidally. The burrows are in many cases filled with coarse-grained rounded intraclasts and peloids (pseudo-oolites). Some massive-layered white chalky limestones are intercalated.

The overlying "*Nautilidenschichten*" has a conspicuous 10–15 cm thick reddish-brown storm-lag deposit at its base that has a strongly varying fossil content with occasional ammonites and/or large nautilids, e.g., ?*Paracenoceras ingens* n. sp. (holotype; Tintant et al. 2002). The "Nautilidenschichten" consist of thick- to massive-layered, strongly bioturbated, marly limestones and limestones with a weak internal nodular bedding. The lower part tends to exhibit marl-limestone alternations when weathered; calcarenitic, storm-influenced marly limestones alternate with bioturbated marly micritic background sediment. Locally, some bored and biogenically encrusted hardgrounds occur.

The "Nautilidenschichten" grade upward into the *Lower Grey and White Limestones*. They are composed of thin- to thick-layered, grey and white, micritic and calcarenitic limestones. The interval is capped by a regionally bored and biogenically encrusted hardground.

The overlying *Banné Marls* form a prominent marl intercalation. They comprise grey, thin- to thick-layered, slightly nodular marlstones, calcarenitic marls and marly limestones with a rich fauna of bivalves associated with some brachiopods, nautilids, echinoids, vertebrate remains, *Thalassinoides* and very rare ammonites. Interca-

◀ **Fig. 3** Accommodation space, subsidence and sediment thickness between ts2 and ts5. Note the point where relative sea-level rise gets ahead of subsidence coincides with point of maximum regression in the curve of eustatic change, i.e., the following accommodation space is additionally provided by eustic sea-level rise (besides the subsidence). Approximated decompaction factors: marl x3, limestone x2 (based on Moore 1989; Goldhammer 1997; Matyszkiewiez 1999). Chronometric time scale according to Hardenbol et al. (1998). Relative eustatic changes according to Sahagian et al. (1996; Russian Craton)

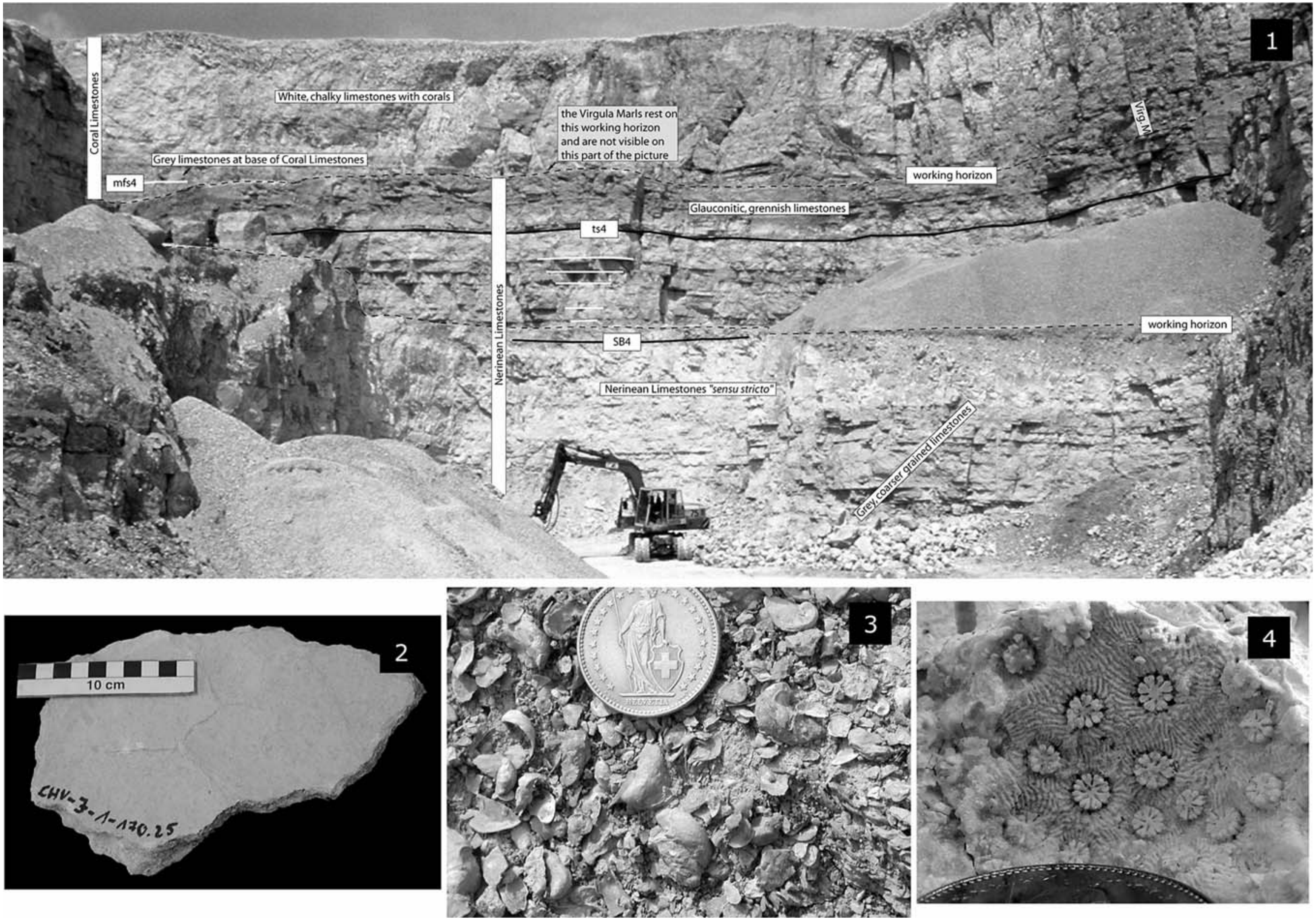


Fig. 5 Position of discontinuities SB4 to mfz4 (1) and typical sedimentological and lithological features (2–4). (**1**) Lower part of the quarry La Combe—Sequence boundary/turnaround 4 can be observed at the base of several biolaminitic limestones with birds eyes in the upper part of the outcropping Nerinean Limestones. A very thin bed of crumbly and platy mudstone (2) at the boundary to the glauconitic top part of the Nerinean Limestones marks ts4. Maximum flooding zone 4 is located at the transition between the Virgula Marls and the ferruginous lower few metres (grey coloured) of the Coral Limestones. A close-up of the conspicuous Virgula Marls is shown in 3. (**2**) Crumbly and platy mudstone with mudcracks and mud polygons with curling-up edges. (Bed CHV-170, La Combe). (**3**) Virgula Marls. (scale: Ø≈2,5 cm; Sur Combe Ronde). (**4**) Cast of ?*Stylina* sp. (scale: Ø≈2,5 cm; Coral Limestones, La Combe)

lated shelly and calcarenitic horizons, that in many cases separate the beds, probably result from reworking and winnowing by storms.

The overlying interval, the *Nerinean Limestones*, starts with thin- to thick-layered, grey, calcarenitic limestones followed by white, thick- to massive-layered, chalky limestones with nerinean gastropods, bioloaminite-layers and dinosaur foot prints. At the top it grades into greenish weathering, glauconitic, coarse-grained calcarenitic limestones. These greenish sediments show characteristic, strongly bored and biogenically encrusted, regional hardgrounds that contain cephalopods.

On top, the dark-grey, thin-layered *Virgula Marls* interval contains a rich fauna of bivalves and cephalopods, but small oysters dominate. Vertebrate remains, such as plesiochelid turtles and marine crocodiles, and coaly plant remains were often found.

Overlying the Virgula Marls, the *Coral Limestones* form an interval with some metres of thin-layered, grey, micritic limestones at their base that are overlain by the Coral Limestones sensu stricto. These are a massive unit composed of thin- to thick-layered, white, chalky, micritic limestones with re-crystallised corals and conspicuous red-brown-coloured rhynchonellid brachiopods; (see Fig. 5(4)) separated by thin marl seams.

This interval grades into the *Upper Grey and White Limestones*. This thick- to massive-layered, monotonous, micritic interval is separated by a slightly coarse-grained, marly intercalation. The limestones break blocky with conchoidal fractures. Body fossils and *Thalassinoides* are sparse.

The *Oyster Limestones* form the uppermost interval. The base consists of calcarenitic limestone and a layer with *Cladocoroposis mirabilis* that is overlain by thin layers of occasionally platy, marly, fine-grained (micritic) limestones, dominated by oysters.

Facies and depositional environments

Facies 1: cast and filled *Thalassinoides* tubes

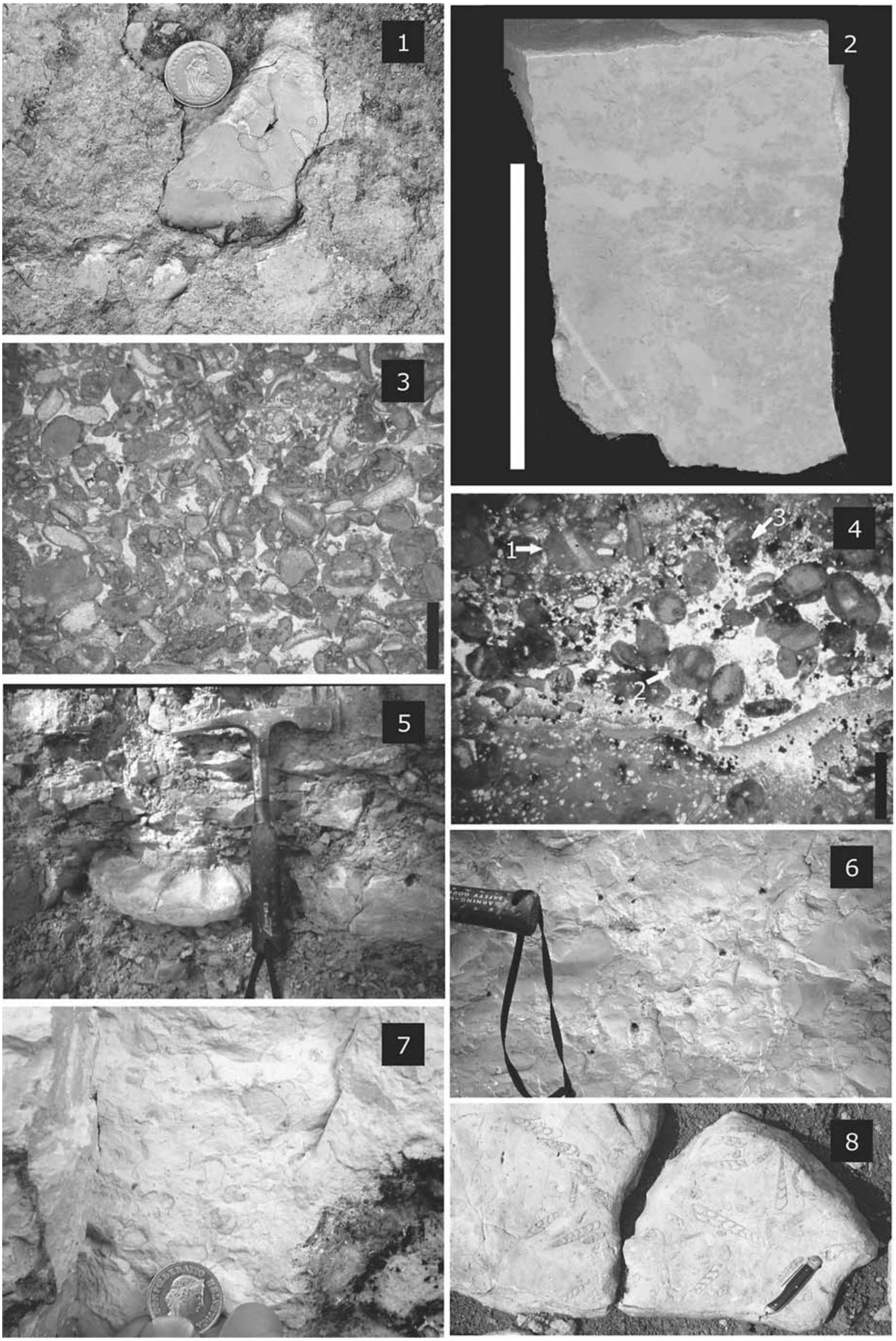
In the sediments studied, *Thalassinoides* generally comprises unwalled tubes, but their sharp outlines and their passive fill suggest a lining. The burrows are mainly horizontal, rather than vertical to subvertical. The fill differs in composition from the host sediment and in many cases records the preceding sedimentological development. There are a few layers wherein *Thalassinoides* tubes contain coarse block cement (Fig. 6(6)) that is indicative of an incomplete fill of at least some tubes' segments.

Interpretation: the observed *Thalassinoides* are comparable to burrows of recent *Alpheus crassimanus* that lives in intertidal to shallow-subtidal lime mud in shallow lagoons in tropical areas (e.g., Farrow 1971). *Thalassinoides* is regarded a part of the environmentally wide-ranging *Glossifungites* ichnofacies and is common in firmgrounds such as dewatered compacted mud, colonised under relatively low-energy conditions (Bromley 1975; Frey and Seilacher 1980; Pemberton and MacEachern 1995; MacEachern and Burton 2000). Dewatering may result from burial of offshore mud. When the overlying sediments are stripped off by submarine erosion during a lowering of the wave base, the firm substrate is exposed on the seafloor and available for colonisation by the trace makers. Sediment indurations may also be a result of retarded sedimentation and oxidation of organic matter leading to cementation (Wilson and Palmer 1992). Both real soft sediment infauna and many epifaunal organisms avoid such cohesive substrates. Burrowers excavate open tunnels in the firm sediment and leave behind traces such as *Thalassinoides*. The burrows commonly remain open and are subsequently filled with coarser grained shallow-water sediments (Fig. 6(1)), which can be related to the downward shift in sea level (Handford and Loucks 1993). Furthermore, *Thalassinoides* are known to potentially demarcate sequence boundaries, transgressive surfaces and transgressively modified sequence boundaries (MacEachern and Burton 2000); according to Burns and Hooper (2001), abundant *Thalassinoides* filled with coarse material (in this study commonly intraclastic pack- to grainstones) represent periods of omission associated with both transgressive ravinement surfaces and downshift surfaces. The coarse-grained components are derived from both storm-generated lag deposits and more laterally extensive shore face erosion associated with fluctuations in relative sea level (Burns and Hooper 2001). *Thalassinoides* producers could have excavated their burrows through a thicker coarse-grained lag as outlined by Seilacher (1967), Frey and Seilacher (1980) and Pemberton and Frey (1985).

Additionally, washed out and cast trace fossils can be used to identify and quantify storm erosion (Fig. 7(3); e.g., Wetzel and Aigner 1986), because trace fossils show a characteristic depth-zonation within the sediment. Storm-transported material occurring within *Thalassinoides* tubes suggests their passive fill by wave pumping during waning storms (Tedesco and Wanless 1991).

Facies 2: intraclastic pack- to grainstones and lumachelle (shell beds)

Reddish and grey intraclastic pack- to grainstones form thin-bedded bioturbated sand sheets (Fig. 7(3)), pseudo-oolitic fill in *Thalassinoides* tubes (Fig. 6(1)) or amalgamated and mixed relicts (reworked Facies 2) in micritic background sediment (Fig. 6(2)). In the latter case components occur in patches dispersed throughout the sediment producing a floating grain texture (rounded intraclastic material having a pseudo-oolitic appearance); argillaceous parts are heavily affected by stylolites. Moderately to well sorted, abraded (rounded) and coated, reworked material (intraclasts) dominates the composition. Coatings and boundaries of grains in some cases exhibit brownish colours. Shell debris is also generally worn and rounded, and coarse-grained calcarenites are commonly much more abundant than medium-grained calcarenites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(Fig. 6(3)). Regular (e.g., *Hemicidaris mitra*) and irregular sea urchins (e.g., *Pygurus blumenbachi*), coral clasts, large gastropods and some large nautilids also occur in such layers. Locally the pack- to grainstones are selectively dolomitised (now preserved as dedolomite), and stained by Tertiary clays (carstification) and are, therefore, clearly visible. Cast *Thalassinoides* are common on lower surfaces of calcarenitic pack- to grainstone sheets filling an erosional relief (Fig. 7(3)). Thickness variations in such layers are common. Commonly intraclastic pack- to grainstone sheets are also accompanied by conspicuous surfaces that show evidence for colonisation. These surfaces form firmgrounds below calcarenitic sheets (burrowed by *Thalassinoides*). The top of the sheets were colonised by byssally attached (e.g., *Mytilus* sp., *Camptonectes* sp.) and semi-infaunal bivalves (e.g., *Trichites* sp.) or bored and encrusted (Fig. 6(1)).

The lumachelle layers consist of generally well-bedded, thin-layered bioturbated float- and rudstones containing bioclasts (bivalves, corals, echinoderms, etc). Lumachelles form separate layers, amalgamations or indistinct horizons (mixed into the background sediment). The large bioclasts are commonly well preserved, unabraded and disarticulated. Bioturbation usually churns the original bedding and led to the formation of pseudointraclasts. Underneath such layers high-relief bored and biogenically encrusted hardgrounds and reworked pebbles occur.

Interpretation: Lumachelle and intraclastic pack- to grainstones are interpreted as storm deposits. According to Wilson (1975) and Flügel (1982, 2004), intraclastic pack- to grainstone sheets may represent lags in washout zones and represent distal, shallow deposits. They indicate slow average sedimentation rates (condensation, winnowing) and are represented as single- or multi-event layers. This is supported by brownish colouring, corrosion and abrasion of some coatings of the intraclasts (Fig. 6(4)) and reflects transport and their exposure at the sediment–water interface for some time (Bathurst 1966; Millimann 1974). Observations in the Recent support this interpretation (e.g., Ball 1967; Hine 1977; Aigner 1985). Accordingly, the intraclastic pack- to grainstone beds are interpreted to have been deposited by storms and moved as traction bedload. The floating grain texture characterised by coarse grains concentrated in patches dispersed throughout micritic (background) sediment is attributed to soft-ground burrowing communities (Burns and Hooper 2001), suggesting input by storm and bioturbation (biofacies mixing; Tedesco and Wanless 1991). Often storm-influenced bed surfaces either show evidence for post-event colonisation by boring endofauna and/or epi- and infauna (Aigner 1985). Genetically intraclastic pack- to grainstones and shell beds are closely related to each other; shell beds are also genetically related to bioclastic wacke- and packstone (see below).

◀ **Fig. 6** Late Oxfordian to Late Kimmeridgian platform carbonates of NW Switzerland: *Thalassinoides* and storm sediment association (1–4, 6), macrofossils (5, 8) and indicator for reduced sedimentation (7). (**1**) Intraclastic storm-lag deposit (reddish), developed as incipient hardground, covering a grey micritic limestone-firmground and filled into *Thalassinoides* burrows (arrow). (Scale: Ø≈2.5 cm; Bas d'Hermont). (**2**) Storm sediment (brown) biomottled with bioclastic soft-sediment-mudstone—Storm material is composed of ferruginous reworked material, peloids and rounded and micritised bioclasts. The bioclastic mudstone partly forms pseudointraclasts. (Scale bar: 5 cm; bed VAT-180, Vatelin). (**3**) Intrabioclastic pack-to grainstone—Components are composed of intraclasts (from reworked peloidal limestones) and worn and rounded bioclasts. (Scale bar: 1 mm; bed COE-270, Coeuve). (**4**) Intraclastic pack- to grainstone deposited as tempestite indicating lag deposition: (1) bioclastic mudstone intraclast, (2) peloidal mudstone intraclast, (3) abraded intraclast. (Scale bar: 1 mm; bed COE-260, Coeuve). (**5**) *Rasenia borealis* Spath in a bioclastic mudstone. (Bed COE-340, Coeuve). (**6**) Conspicuous horizon composed of *Thalassinoides* filled with coarse-grained spary cement. (Bed VAT-150, Vatelin). (**7**) Porrentruy Member— Brown rimmed oncoids and intraclasts in a white chalky limestone. According to Flügel (1982) ferruginous rims on oncoids occur when sedimentation begins to lag or is interrupted. (Scale: Ø≈2 cm; bed RAS-88, La Rasse). (**8**) Large gastropods (nerineans) in coarser grained peloidal limestone; found a few metres below the Virgula Marls in Sur Combe Ronde

Facies 3: bioclastic mud- and wackestones (± in situ macrofauna)

Typical are thin-bedded, carbonaceous or argillaceous, bioclastic mudstones and wackestones that exhibit slightly nodular bedding and fine wispy laminae. Skeletal material is present in all states of preservation from complete shells to intensely micritised grains. The microfacies is mainly composed of randomly orientated, angular bioclasts and sponge spicules in a lime-mud matrix (Fig. 8(1)). Thin sections further show thin-shelled bivalves, echinoderm fragments, foraminifers (e.g., *Alveosepta jaccardi*, *Lenticulina* sp., *Nautiloculina* sp.), rare algae (e.g., *Solenoporacea* sp.) and peloids. Macrofaunal elements are epi- and infaunal bivalves (e.g., oysters, *Trichites* sp., *Mytilus* sp., *Camptonectes* sp., *Pholadomya* sp.), brachiopods (*Sellithyris subsella*, "*Terebratula* sp.", "*Rhynchonella* sp."; Sulser and Meyer 1998), echinoderm fragments, small gastropods and rare cephalopods. Locally, randomly orientated components and pseudo-intraclasts occur.

Interpretation: the fine-grained texture of bioclastic mud- and wackestones is interpreted as an indication of subtidal deposits accumulated under episodic turbulence below the fair-weather wave base in an open platform area. Randomly distributed bioclasts and pseudo-intraclasts imply bioturbation. Large nautilids point to an open marine influence. Background sediments were deposited from suspension. Owing to its strong micritisation and moderate to good rounding, imported storm-transported material from shallow environments is clearly distinguished from background sediments that are dominated by sponge spicules. The nodular texture is a result of a combination of bioturbation and compaction, although bioturbation seems to be the dominant factor for the development of nodularity (e.g., Kennedy 1975; Werner 1986). Thick packages (as in Vendlincourt, Vatelin and L'Alombre aux Vaches) of this facies type probably accumulated in open lagoonal platform environments. Limestones with normally articulated *Nanogyra* specimens in low density, which probably inhab-

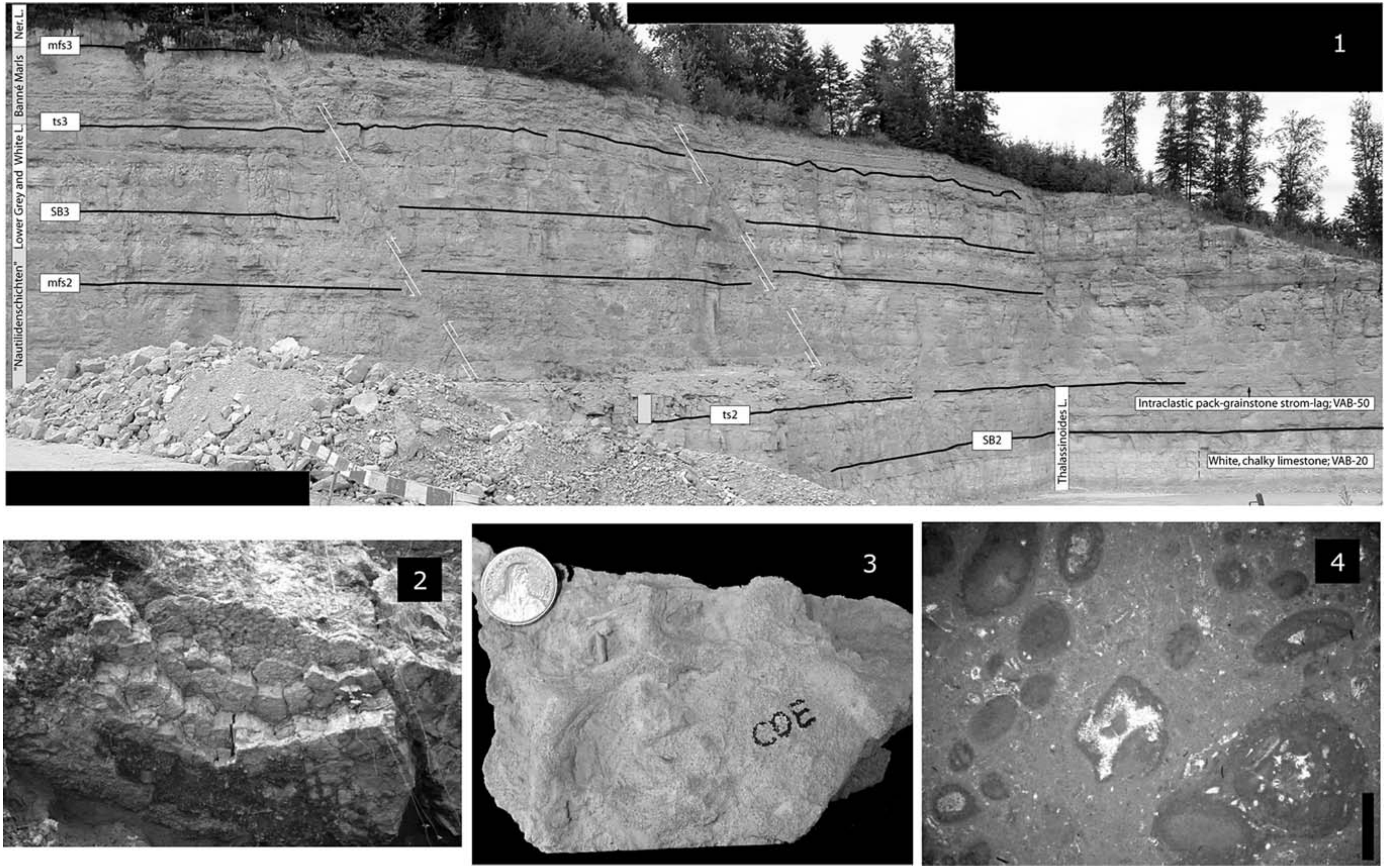


Fig. 7 Position of discontinuities SB2 to mfs3 (1) and typical sedimentological and lithological features (2–4). (**1**) Quarry L'Alombre aux Vaches—SB2 is placed on top of the white, chalky limestones in the top part of the Thalassinoides Limestones (bed VAB-20). The transgressive surface ts2, on top of bed VAB-50, and maximum flooding surface mfs2 have been recorded in the Nautilidenschichten; sequence boundary SB3, ts3 and mfs3 in the Lower Grey and White Limestones and on top of the Banné Marls. (**2**) Mudcracks in laminated and wavy stromatolites—The level of bed VEN- 31 in Vendlincourt corresponds to the third bed below ts3 on 1 and Fig. 13(4), respectively. (**3**) Bottom side of intraclastic pack- to grainstone sheet with cast *Thalassinoides* deposited as tempestite indicating erosion and lag deposition—This sheet correlates with bed VAB-50 in 1. (scale: Ø≈3 cm; bed COE-260, Coeuve). (**4**) Oncoidal wackestone—Oncoid in the right bottom corner shows attached or encrusted bioclasts. Bioclasts act as nuclei. Sample was taken from the white, chalky limestone below SB2 (compare 1). (Scale bar: 1 mm; bed VAB-20, L'Alombre aux Vaches)

ited the soft sea floor, are interpreted to represent the more or less undisturbed habitat of the oysters below the storm wave base (e.g., Fürsich and Oschmann 1986a, b).

Facies 4: chalky bioclastic mudstones with coral meadows

Chalky bioclastic mudstones (locally with floatstone texture) are white and thin- to thick-layered. Wispy marl seams separate beds. Generally, this facies is poor in species but rich in specimens. Macro-components are patch reefs (coral meadows), solitary corals, *Sellithyris subsella, Terebratula* sp., *Rhynchonella* sp. (red-brown-coloured) and some bivalves. The corals (e.g., ?*Calamophilliopsis* sp., ?*Cyathophora* sp., ?*Stylina* sp., ?*Ovalastrea* sp.) are of tuberoid and small dendroid shape, recrystallised and therefore difficult to determine (Fig. 5(4)). The corals dominate the faunal assemblage; some of them show borings by *Lithophaga* bivalves. Brachiopods are also very abundant and often show geopetal fills. Sea urchin spines, bivalves and gastropods (e.g., *Harpagodes oceani*) are less common. Bioclastic aprons are developed around coral meadows. Angular bivalve shells, echinoderm fragments, serpulids, algae clasts (*Marinella* sp., *Cayeuxia* sp.), sponge spicules, oncoids, ?stromatoporids (*Cladocoroposis mirabilis*) and foraminifera (*Pseudocyclamina* sp., *Alveosepta jaccardi*, *Lenticulina* sp.) in a lime-mud matrix can be seen under the microscope. In La Combe, a 10 m high complex composed of stacked coral meadows interfingering with the surrounding micritic beds is visible.

Interpretation: the chalky mud- and wackestones with coral meadows are interpreted as shallow and quiet, stenohaline facies (Flügel 1982, 2004; Leinfelder et al. 1994) deposited under episodic turbulence (fine-grained matrix, poorly sorted and large angular bioclasts). The brachiopods might have lived on the corals (Werner 1986). Beauvais (1973) named these beds biostromes, as they display a lower diversity in genera and species than bioherms. The corals probably settled on a muddy bottom where they could only survive if sedimentation was less rapid (Leinfelder et al. 1994); otherwise they would have been buried. According to Werner (1986), plocoid (e.g., *Stylina* sp., *Ovalastrea* sp.) and ceroid (e.g., *Cyathophora* sp.) corals lived on soft sediment, as well as *Harpagodes oceani*. The deposition of this facies is inferred to have occurred in a normal marine, quiet, shallow lagoon below fair-weather wave base.

Facies 5: marly bioclastic wacke- to packstones and float- to rudstones with in situ macrofauna

This facies solely comprises the Banné Marls and the Virgula Marls. The marly bioclastic wacke- to packstones are dark grey and thin layered with internal nodular bedding. A rich macrofauna occurs in a marly lime-mud matrix. Individual and distinct trace fossils are rare in the thoroughly bioturbated parts. Nevertheless, remnants of sedimentary layering (especially in the Banné Marls) occur as alternations of fossil-/shell-rich marls with less fossiliferous beds or bioturbated marls. Dominant macrofossils are in situ epi- and infaunal bivalves such as *Anchura* sp., *Aporrhais* sp. and *Pholadomya* sp. (in the Banné Marls) and/or monospecific oysters (i.e., *Nanogyra* sp. in the Virgula Marls). Furthermore, gastropods, sea urchins, brachiopods, vertebrate remains, and cephalopods, and scarce lithoclasts, pseudo-intraclasts and coaly plant-fragments occur (B. Hostettler and D. Marty Personal communication). Thin-sections show angular components composed of thin-shelled bivalves, echinoderm fragments and bioclasts (Fig. 8(6)).

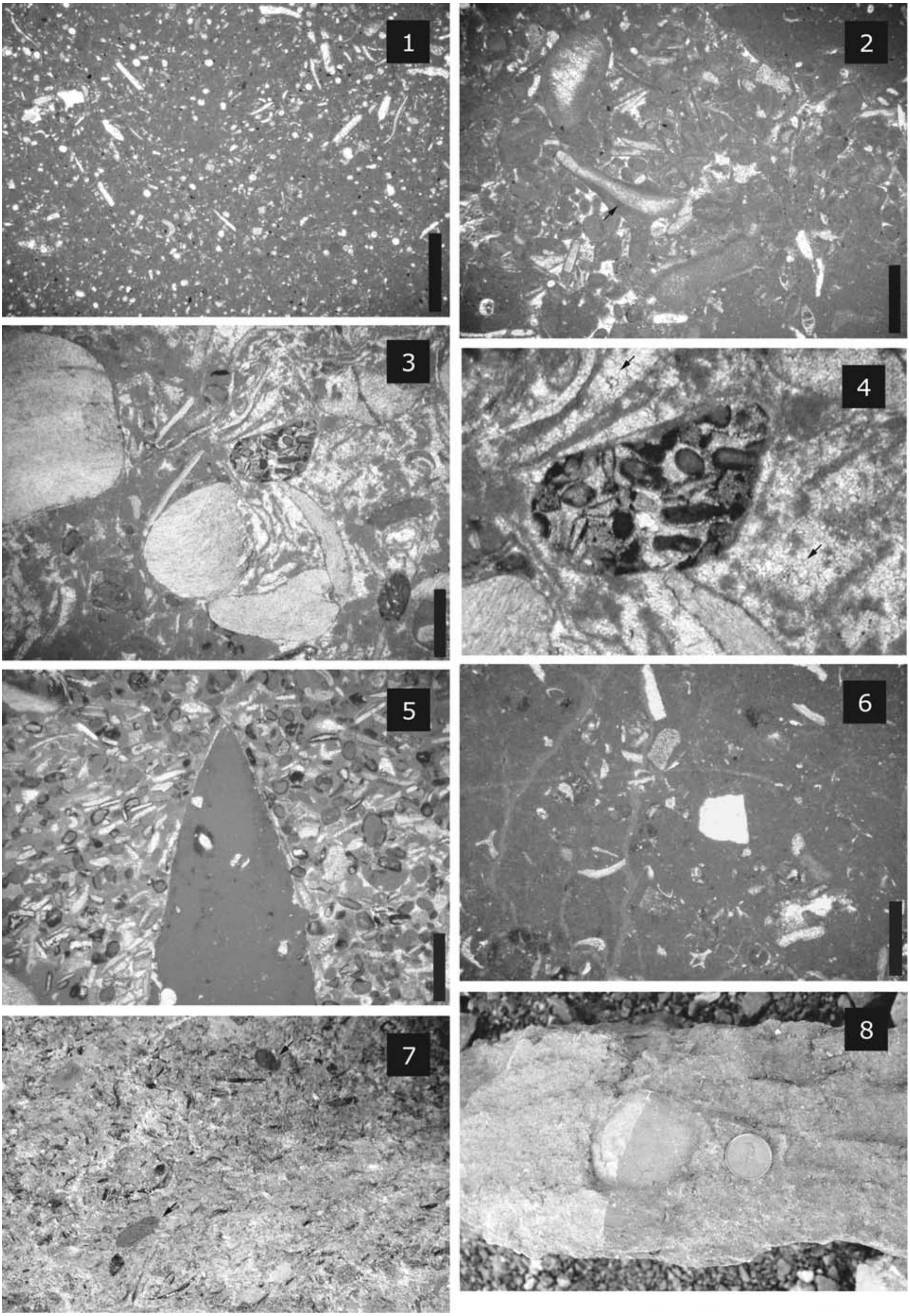
Interpretation: the marly bioclastic wacke- to packstones and float- to rudstones formed under intermittent, moderate turbulence (Folk 1959, 1962); in quiet marine lagoon or bight below fair-weather wave base is inferred. Cephalopods point to a connection to open marine areas. The mass occurrence of oyster shells, bivalves and shell layers, a high amount of marl (clay content), coaly plant fragments and common vertebrate remains imply protected, land-near conditions, occasionally affected by storm deposition or winnowing. The Banné Marls and the Virgula Marls were episodically reworked by storms or affected by runoff from land. Alternatively either open marine and terrigenous material was deposited.

Storm reworking may have led to episodically low rates of sedimentation as documented by composite shell beds in more offshore deeper waters (Fürsich and Oschmann 1986a).

Facies 6: bioclastic wacke- and packstones with in situ macrofauna (±argillaceous, slightly nodular)

These thin- to thick-layered wacke- and packstones show internal, slightly nodular bedding and contain a rich macrofauna. Marly parts display an increased amount of coarse components (fauna and clasts). In some instances faint bedding is observed. The boundaries of nodules are gradational and consist of indistinct clay seams. Large, angular and rounded bioclasts, coated grains, peloids and macrobiota within a lime-mud matrix dominate. The matrix contains sponge spicules. Sorting and rounding is moderate to good. Micritisation of components comprises coating to complete destruction of original structures (e.g., Fig. 8(2)). Calcarenitic grains are dispersed throughout, producing a floatstone texture. *Thalassinoides* occurs as well, but individual and distinct burrows are extremely rare in thoroughly bioturbated parts. The macrofauna comprises brachiopods, sea urchins, bysally attached and infaunal bivalves (e.g., *Pholadomya* sp.), locally oyster shells and gastropods. Locally semi-infaunal and epifaunal biota (*Trichites* sp., *Rhynchonella* sp.) are concentrated in coarse, marly horizons. Thin-sections further show foraminifera (*Alveosepta jaccardi*, *Lenticulina* sp., *Nautiloculina* sp.) and ostracodes.

Interpretation: the bioclastic wacke- and packstones are interpreted to have formed in a normal marine inner shelf setting near skeletal shoals. This facies documents the inter-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action between storm- and background accumulation next to shell shoals. Sea urchins imply normal marine conditions.

Nodular wacke- and packstones interbedded with indistinct marl layers indicate deposition under intermittent to calm conditions. Biogenic sedimentary structures and randomly distributed components and pseudointraclasts point to bioturbation and thus sufficient oxygenation. Storm-imported clasts are rounded and worn (Figs. 8(3,4)) and markedly differ from in situ clasts (Fig. 8(5)). Storm influence is indicated by large angular parautochthonous bivalve clasts, as well. The argillaceous and carbonaceous zones are differentially compacted and probably were enhanced during further burial. The varying nodular texture appears to have formed during diagenesis in response to the bioturbate texture (e.g., Kennedy 1975; Werner 1986). Beds of pervasively burrowed and bioturbated wackestones with a considerable proportion of lime mud probably accumulated under quiet conditions below fair-weather wave base. Extensive bioturbation and storm-imported material usually obliterated the original in situ facies, which is represented by rare nodular limestones with sponge spicules.

Bioclastic pack- to grainstones with rounded intraclasts and micritised bioclasts (Figs. 8(3,4)) imply wash-over sedimentation from sand shoals under strong wave agitation. The wash-over material in more quiet areas of the lagoon indicates mixing of biofacies and input by storms (Tedesco and Wanless 1991). The coarse-grained components represent storm-generated lag deposits, in situ storm-generated reworking (short transport) or are derived from extensive shore face erosion. According to Aigner (1985), shelly pack- to grainstones are interpreted as near-shore shallow skeletal banks and shell shoals interfingering with mud- and wackestones. Therefore, bioturbated, massive skeletal packstones indicate a relatively unprotected environment next to shell shoals, which were episodically affected by storms.

◀ **Fig. 8** Late Oxfordian to Late Kimmeridgian platform carbonates of NW Switzerland: facies types (1–6) and storm sediments (7, 8). (**1**) Bioclastic mudstone composed of angular bioclasts and spongerhaxen. (Scale bar: 1 mm; bed TUP-110, Cras d'Hermont). (**2**) Bioclastic packstone with rounded micritised components and peloids mixed with bioclastic mudstone (top right corner) due to storm input and bioturbation. Elongated big clast in the centre (arrow) probably shows microbial coating. (Scale bar: 1 mm; bed COE-350, Coeuve). (**3–4**) Bioclastic packstone with large rounded bivalve clasts and rounded reworked material (intraclast, see close up in 4). Some micritised bioclasts show no trace of the original shell structure. Casts (arrows) formed by complete solution of probably aragonite shell, followed by precipitation of cement into the void at a later date. The intraclast shows dedolomite rhombs (orange) in a fecal-pellets-packstone texture. Note abrasion of intra particles. This means the grain must have been lithified at the time of reworking and might also be interpreted as an extraclast. (Scale bar: 1 mm; bed CHV-200, La Combe). (**5**) Bioclastic wacke- to packstone with small angular bioclasts and reworked material (brown rimed). Original background sediment (bioclastic mudstone) can be seen in bivalve. (Scale bar: 1 mm; bed CHV-210, La Combe). (**6**) Bioclastic mud- to wackestone composed of angular and some micritised bioclasts. (Scale bar: 1 mm; bed VEN-46, Vendlincourt). (**7**) Black pebbles (arrows) in schill layer—Black bivalve shells are oysters. (Length of large black pebble is about 2 cm; bed CHV-200, La Combe). (**8**) Large intraclast (reworked and rounded) from the base of bed CHV-190 deposited on the top of the same layer above a hardground in a glauconitic storm schill bed. (Scale: Ø≈3 cm; top of bed CHV-190, La Combe)

Facies 7: oncoidal (chalky) wacke- to packstones and float- to rudstones

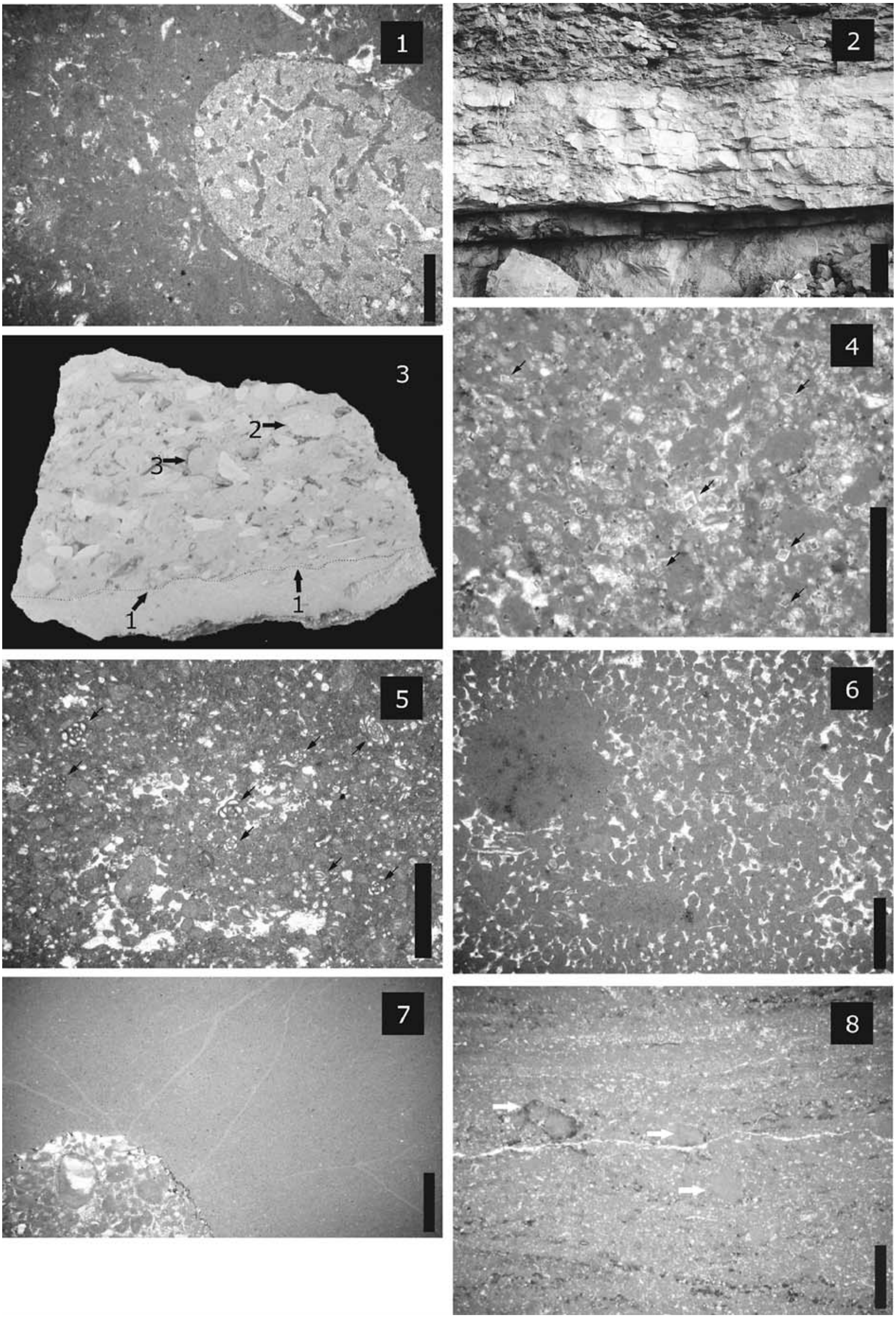
White, thin to thick layers contain mainly oncoids (Fig. 7(4)), pseudo-intraclasts and large nerinean gastropods either floating or in grain-to-grain contact within a lime mud or fine-grained "clastic" matrix. Other large bioclasts are corals and bivalves. The components are randomly distributed throughout the beds. The large components range in size from millimetres to centimetres. Sorting and rounding is moderate to good. Micritised rims on bioclasts are common. *Thalassinoides* filled with coarse block cements are occasionally present. Furthermore peloids and echinoderm fragments occur. Centimetre-sized *Cladocoropsis mirabilis* fragments were found in La Combe (Fig. 9(1)).

Interpretation: frequently occurring oncoids imply restricted conditions. According to Flügel (1982) and Wilson (1975), oncolitic wacke- or floatstones are typical of shallow, relatively quiet backbank environments where they form on edges of ponds and channels in protected lagoons; coarse-grained oncoidal limestones point to moderately high energy in very shallow water. Centimetre-sized *Cladocoropsis mirabilis* also suggests a clear and warm shallow marine environment (Champetier and Fourcade 1967).

Facies 8: peloidal mud- to grainstones

Thin- to thick-layers of intensely bioturbated, peloidal mud- to grainstones contain some macrofauna (e.g., *Camptonectes* sp., *Trigonia* sp., nerineans; Fig. 6(8)), bioclasts and occasionally ooids (Figs. 9(4), 9(6)). Internally they are fairly homogeneous or faintly parallel bedded; bed-parallel stylolite seams enhanced bedding. Some beds show an enrichment of miliolids (Fig. 9(5)) or nerineans. Peloids often merge to a micritic matrix (clotted texture). Thin sections further show thin-shelled bivalves, echinoderm fragments, foraminifera (e.g., *Alveosepta jaccardi*, *Lenticulina* sp., *Nautiloculina* sp.), occasionally algae (*Solenoporacea* sp.), sponge spicules and coated grains. Locally the beds became indurated; firmgrounds, burrowed by *Thalassinoides*, or hardgrounds, bored or encrusted by shells. Cast *Thalassinoides* are common. Bioturbation led to a wide range of textures (wacke- to grainstone) and then indicates sufficient oxygenation. Rounded intraclasts may occur in small pockets or in zones of coarser packstone within a fine matrix.

Interpretation: small peloids are interpreted as fecal pellets (Flügel 1982, 2004), the large ones either as algae clasts or micritised ooids (Koch et al. 1994). Pelsparites are deposited in warm and shallow water with slight circulation. The fecal-pellet rich pack- to grainstones would represent warm, shallow water with only moderate water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circulation (Flügel 1982, 2004; Volk et al. 2001). The mud- to wackestone texture indicates more restricted circulation and deeper water, comparable to the pellet-mud-facies on the Great Bahama Banks west of Andros Island, which is formed under minimal water energy, increased salinity in 2–6 m water depth (e.g., Flügel 1982). According to Sellwood (1986), peloidal mud- to grainstones represent a stable and muddy lime-sand habitat shoreward of an active sand shoal. The enriched miliolids imply fluctuating salinity (e.g., Flügel 1982). According to Werner (1986), nerinean layers are generally associated with a pronounced sedimentological facies change, commonly from lower to higher water energy (e.g., from stromatolitic mudstones to peloidal pack-to grainstones between layers CHV-70 and 80 in La Combe; Fig. 10). In this study (mass-occurring) nerineans probably acted as opportunists occupying a new developed habitat rather than a certain biotope (Wieczorek 1979).

Facies 9: non-laminated homogeneous micrite

Very thin-bedded, non-laminated and homogeneous, occasionally marly, thin-layered mudstones contain few well-preserved, unabraded and disarticulated angular bioclasts and some macrofauna. Clasts commonly show no micritisation. *Thalassinoides* are filled with coarse block cement or coarse-grained sediment (Fig. 9(7)).

Interpretation: homogeneous mudstones are ascribed to (hyper-saline) tidal ponds (Wilson 1975) as they are always developed within a succession of inter- to supratidal sediments. The homogeneous composition and texture, and the few clasts probably point to tidal ponds or protected shallow bights and lagoons with a normal marine influence (compare Werner 1986). Skeletal material has been exposed to transport and abrasion only briefly. *Thalassinoides* were filled with coarse material during storms or by wave pumping (Tedesco and Wanless 1991).

◀ **Fig. 9** Late Oxfordian to Late Kimmeridgian platform carbonates of NW Switzerland: facies types. (**1**) *Cladocoropsis mirabilis* in peloidal packstone matrix. Note peloids merge to micrite. (Scale bar: 1 mm; bed CHV-1900, La Combe). (**2–3**) Channel intercalated into well-bedded limestones. Unit is composed of several amalgamated non-continuous lensoidal sheets. Sample from channel infill (4) shows a crude fining-up sequence following an erosion surface (1). Note reworked and rounded channel-background-sediment (2) mixed with different clasts (e.g., *Marinella* sp. (3)). (Scale bar in 3: 20 cm, length of sample in 4 is about 10 cm; bed BAN-140, Tunnel Le Banné). (**4**) Peloidal wacke- to packstone with large matrix-dedolomite-rhombs (arrows)—Individual peloids are for the most part indistinct. The dedolomite crystals have cloudy centres and clear rims, some are multi-zoned—a commonly observed feature. (Scale bar: 1 mm; bed CHV-140, La Combe). (**5**) Peloidal packstone with miliolids (arrows)—Peloids (fecal pellets and larger peloids) build a grain-supported texture with some fenestrae. (Scale bar: 1 mm; bed VEN-27, Vendlincourt). (**6**) Peloidal grainstone with large peloids/intraclasts and small fecal pellets. (Scale bar: 1 mm; bed CHV-80, La Combe). (**7**) *Thalassinoides* in homogeneous mudstone filled with coarser grained material. (Scale bar: 1 mm; bed COE-240, Coeuve). (**8**) Crumbly and platy mudstone—Irregular laminated alternation of fine peloidal (probably fecal pellets) sediment and carbonate mud separated by sheet parallel fenestrae. They probably correspond to decay of organic matter. Note larger peloids in centre of photograph (arrows). (Scale bar: 1 mm; bed CHV-170, La Combe)

Facies 10: lensoidal pack-/rudstones

A lens-shaped channel-like body (Fig. 9(2)) of peloidal, bioclastic or intraclastic pack-/rudstones, about 1 m thick and tens of metres wide was found intercalated into well-bedded limestones in Tunnel Le Banné. This body is composed of several amalgamated thin, discontinuous layers. Many of these amalgamated layers consist of coarse-grained peloidal packstones; others show crude fining-up packages of skeletal packstones. Some rounded limestone clasts occur (Fig. 9(3)), some of them are clearly derived from the underlying sediment indicating erosion while others seem to be imported (e.g., *Cayeuxia* clasts).

Interpretation: the geometrical and lithological relationship to the sediments below and above and the material of the lensoidal body suggest a channel in a tidal flat or shallow-subtidal environment. Similar channels have been described by Seilacher (1982) and Aigner (1985) and were interpreted as storm surge or rip channels.

Facies 11: laminated mudstones

Laminated mudstones display wavy to parallel, submillimetre thick micritic laminae. Some laminae are fenestral, others are slightly domed or pinch-and-swell like. Components are sparse and macrofauna is nearly absent. Occasionally dedolomite and locally bioclasts and fecal pellets occur within the laminated texture. Some horizons display mud cracks (Fig. 7(2)), birds eyes, key stone vugs, sheet cracks, small ripples or dinosaur foot prints. *Thalassinoides* filled with coarse block cement occur locally. This facies type is closely associated with facies type 12, crumbly and platy limestones (see below).

Interpretation: laminated mudstones are interpreted as biolaminites/stromatolites because of their sedimentological structures. Abundant fenestral pores like birds eyes and sheetcracks are characteristic for the intertidal zone, as reported from the recent by Shinn (1983a, b). Mudcracks and tracks indicate emersion/supratidal conditions.

Facies 12: crumbly and platy mud- and wackestones

Crumbly and platy mudstones and wackestones are reddish-grey or greenish-grey. They consist of a lime-mud matrix with some clay, microspar, occasionally dedolomite and quartz; slight flaser bedding in very thin- to thin-bedded layers may occur (Fig. 5(2)). Macro- (shells) and microfaunal (foraminifera, ostracodes) remains are very rare. Some horizons exhibit mud cracks and sheet cracks. Some thin sections display a clotted or pelsparitic microtexture composed of fecal pellets and peloids (Fig. 9(8)). Vertebrate remains occur occasionally. This facies only forms very

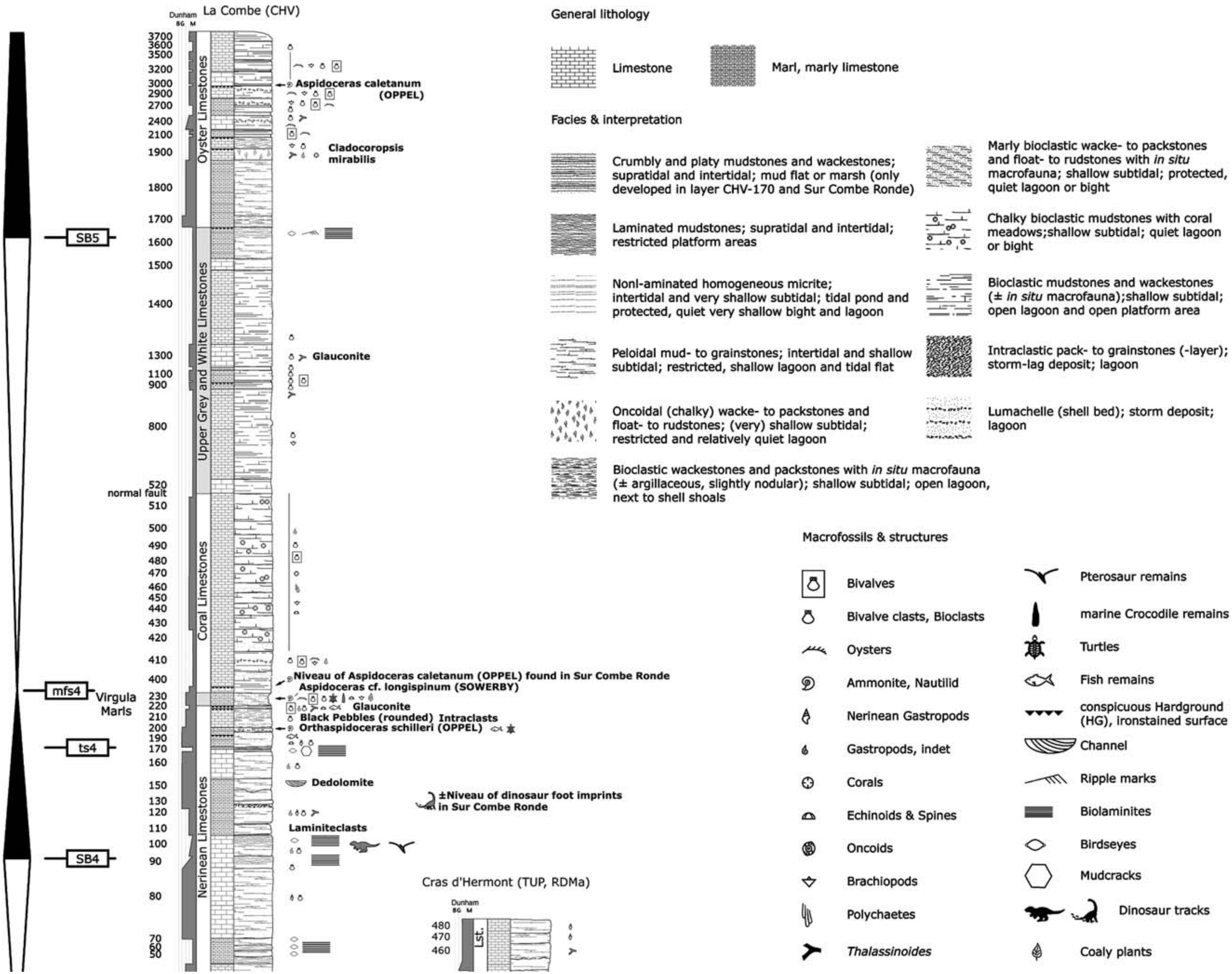

La Combe (CHV)
Dunham BG M
Oyster Limestones
Upper Grey and White Limestones
Coral Limestones
Nerinean Limestones
SB5
mfs4
Virgula Marls
ts4
SB4
normal fault
Aspidoceras caletanum (OPPEL)
Cladocoropsis mirabilis
Glauconite
Niveau of Aspidoceras caletanum (OPPEL) found in Sur Combe Ronde
Aspidoceras cf. longispinum (SOWERBY)
Black Pebbles (rounded) Intraclasts
Orthaspidoceras schilleri (OPPEL)
Dedolomite
±Niveau of dinosaur foot imprints in Sur Combe Ronde
Laminiteclasts
Cras d'Hermont (TUP, RDMa)
Lst.
General lithology
Limestone
Marl, marly limestone
Facies & interpretation
Crumbly and platy mudstones and wackestones; supratidal and intertidal; mud flat or marsh (only developed in layer CHV-170 and Sur Combe Ronde)
Laminated mudstones; supratidal and intertidal; restricted platform areas
Nonl-aminated homogeneous micrite; intertidal and very shallow subtidal; tidal pond and protected, quiet very shallow bight and lagoon
Peloidal mud- to grainstones; intertidal and shallow subtidal; restricted, shallow lagoon and tidal flat
Oncoidal (chalky) wacke- to packstones and float- to rudstones; (very) shallow subtidal; restricted and relatively quiet lagoon
Bioclastic wackestones and packstones with in situ macrofauna (± argillaceous, slightly nodular); shallow subtidal; open lagoon, next to shell shoals
Marly bioclastic wacke- to packstones and float- to rudstones with in situ macrofauna; shallow subtidal; protected, quiet lagoon or bight
Chalky bioclastic mudstones with coral meadows;shallow subtidal; quiet lagoon or bight
Bioclastic mudstones and wackestones (± in situ macrofauna);shallow subtidal; open lagoon and open platform area
Intraclastic pack- to grainstones (-layer); storm-lag deposit; lagoon
Lumachelle (shell bed); storm deposit; lagoon
Macrofossils & structures
Bivalves
Bivalve clasts, Bioclasts
Oysters
Ammonite, Nautilid
Nerinean Gastropods
Gastropods, indet
Corals
Echinoids & Spines
Oncoids
Brachiopods
Polychaetes
Thalassinoides
Pterosaur remains
marine Crocodile remains
Turtles
Fish remains
conspicuous Hardground (HG), ironstained surface
Channel
Ripple marks
Biolaminites
Birdseyes
Mudcracks
Dinosaur tracks
Coaly plants

Fig. 10 Upper

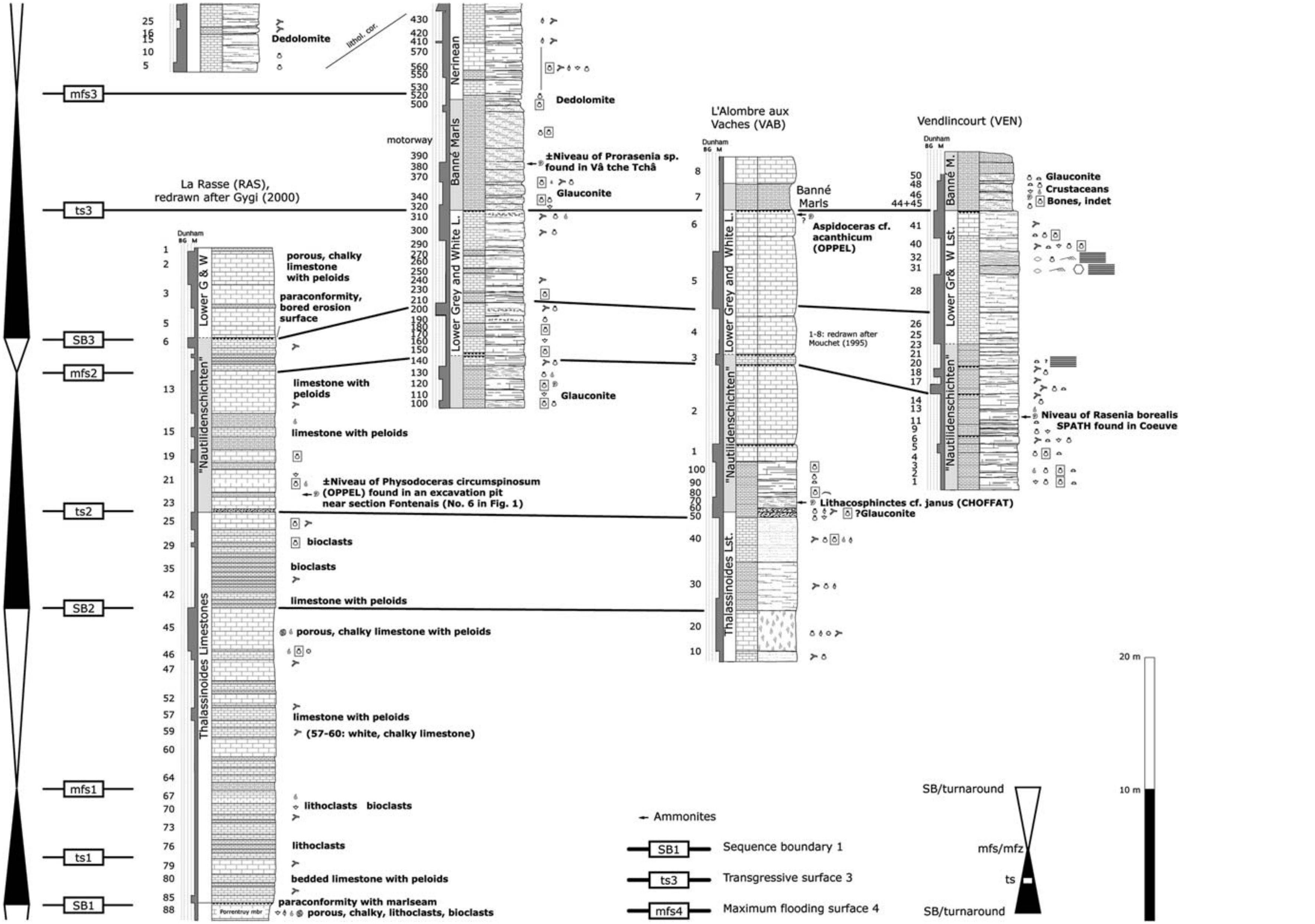


Fig. 10 Lower Sequence-stratigra-phical interpretation—third-order sea-level cycles. Stratigraphical position/arrangement of sections is based on lithological correlations (Jank 2004). The numbers on the left side of the litho logs display bed numbers. Due to the limited space some marine benthos, components and structures are not illustrated (for details see: Jank 2004)

thin sheets on the top part of the Nerinean Limestone interval.

Interpretation: crumbly and platy mudstones and wackestones accumulated on supra- to intertidal mud flats or marshes as evidenced by their stratigraphical relationship to cyanobacterial laminites, mud cracks and fenestral facies. Mud flats were episodically flooded. Mud cracks and other indicators of emersion and the paucity of marine fauna point to a supra- to intertidal origin. Pelsparitic microtextures within crumbly and platy laminated limestones are interpreted as being intertidal and having formed under episodic water agitation.

Facies associations

The shallow-water, inner-platform setting of the investigated sediments exhibits 12 facies types, which are grouped into four major facies associations (Table 1).

Facies 1 and 2 are not considered as facies sensu stricto, which indicate a certain depositional environment, because they occur in almost every other facies association (see above). Nonetheless they are outlined as own facies association (*Thalassinoides* and storm sediment association), because they are genetically closely linked to each other, occasionally they dominate within a bed and then they have sedimentological and (especially) sequence-stratigraphical importance.

The abundance and high diversity of skeletal fauna in facies 3–6 implies normal marine conditions and distinguishes them from the facies in supratidal, intertidal and restricted platform areas. Therefore, these facies are grouped into the open lagoon and bight association.

The low diversity and the high abundance of some skeletal fauna and bioturbation in facies 7–10 imply restricted marine conditions. These facies were deposited under moderately turbulent water at depths of a few metres and less. They take part in the shallow-subtidal to intertidal, restricted platform facies association.

The quasi-absence of fauna and frequent emersion features in facies 11 and 12 indicate very restricted conditions in a supra- to intertidal environment in which cyanobacterial activity is important. They are outlined as supra- and intertidal platform area association.

Sequence stratigraphiy

Facies, bed thickness and grain size were used to define trends; systems tracts are often expressed as several metres to a few tens of metres thick packages (e.g., Pittet and Strasser 1998; Table 1, Fig. 11), which are limited by laterally persistent bounding surfaces (bounding discontinuities). In epicontinental settings often bounding surfaces are replaced by intervals, the so-called turn-arounds (e.g., Strasser et al. 1999; Pawellek and Aigner 2003). The stacking of such packages in combination with the hierarchy of the bounding discontinuities and facies changes were used to separate third-order sea-level cycles, which (presumably) are superimposed on second-order cycles.

In terms of the above outlined characteristics in response to sea-level fluctuations the following third-order cycles are defined:

Sea-level cycle SC 1 (≈20 m; Fig. 12)

Sequence boundary SB1 is indicated by a marked lithological change, which is excellently visible at the base of the La Rasse section. This change separates massive-layered, white, chalky, shallow-subtidal, oncoidal limestones (facies 7, Porrentruy Member; Fig. 6(7)) from grey, micritic, slightly marly, intertidal and shallow-subtidal, peloidal limestones (facies 8). This change can also be seen in the section Contournement de Glovelier (see "Y" in Fig. 1; Jank 2004). Unfortunately, the lack of further easily accessible beds in Chemin Paulin and La Rasse does not allow a more precise description of the first cycle. Nevertheless, the bed-thickness trend at La Rasse (Fig. 12) displays two thickening-upward packages (bed RAS-87–79 and 66–45) and a thinning-upward package (bed RAS-78–67). The same trend in thickness and even in colouring occurs at the contemporaneous Contournement de Glovelier section (Jank 2004), where these trends clearly cover a lowstand, transgressive and highstand systems tract (LST1, TST1 and HST1; Jank 2004). Additionally, the lowstand corresponding to sequence boundary K1 and the associated lowstand sediments of Gygi et al. (1998) lie within LST1 of this study.

Sea-level cycle SC 2 (≈30 m; Fig. 7(1))

Sequence boundary SB2 is marked by a clear break and change in sedimentation from white chalky limestones (facies 7) to grey micritic limestones (facies 8) in the upper part of the Thalassinoides Limestones. The grey, micritic deposits, which are mainly composed of homogeneous and peloidal limestones compose LST2. They show mass occurrence of "sand-filled" *Thalassinoides*, numerous minor iron-stained surfaces and ferruginous reworked material, which forms millimetre to centimetre thick blankets on bed surfaces (Fig. 6(1)) or is concentrated in patches (floating grain texture) in the background sediment. Beds thicken upwards (e.g., Fig. 13(1–3) below the "Nautilidenschichten"). Their composition indicates erosion and condensation in a storm-influenced, inter- to shallow-subtidal setting. These sediments themselves were repeatedly reworked (regressive erosion surfaces). Stromatolitic limestones in Coeuve (no. 4 in Fig. 1) and a channel in Le Banné (no. 1 in Fig. 1) indicate this lowstand as well. In most sections a conspicuous horizon (e.g., beds VAB-40, RAS-25) rich in *Thalassinoides*, which contain considerable amounts of coarse spary calcite cement, also points to very shallow conditions (Fig. 6(6)). The cements show $\delta^{18}O$ values between −7.6‰ and −5.1‰ PDB ($\delta^{13}C$

Table 1 Facies, depositional environments and characteristics of systems tracts

No.	Facies	Bathymetry	Depositional environment	Facies association	Developm. of facies	Systems tracts LST	Systems tracts TST	Systems tracts HST
1	Cast and filled *Thalassinoides* -tubes	shallow subtidal (storm wave-base) to intertidal	lagoon	*Thalassinoides* and storm sediment association	–	√	√	
2	Intraclastic pack- to grainstones (-layer)	shallow subtidal (storm wave-base) to intertidal	lagoon	*Thalassinoides* and storm sediment association	–	√	√	
2	Lumachelle (shell bed)	shallow subtidal (storm wave-base) to intertidal	lagoon	*Thalassinoides* and storm sediment association	–		√	√
3	Bioclastic mud- and wackestones (± *in situ* macrofauna)	shallow subtidal	lagoon or platform (with open circulation; quiet water at or just below fair-weather wave-base)	open lagoon and bight association	distal		√	√
4	Chalky bioclastic mudstones with coral meadows	shallow subtidal	lagoon or bight (with open circulation; quiet water below fair-weather wave-base)	open lagoon and bight association				√
5	Marly bioclastic wacke- to packstones and float- to rudstones with *in situ* macrofauna	shallow subtidal	protected lagoon or bight (normal marine; quiet water below fair-weather wave-base)	open lagoon and bight association			√	√
6	Bioclastic wacke- and packstones with *in situ* macrofauna (± argillaceous, slightly nodular)	shallow subtidal	open lagoon, next to shell shoals	open lagoon and bight association			√	√
7	Oncoidal (chalky) wacke- to packstones and float- to rudstones	(very) shallow subtidal	restricted and relatively quiet lagoon	restricted platform association	<== basinward migration of facies (regression) landward migration of facies (transgression) ==>			√
8	Peloidal mud- to grainstones	intertidal and shallow subtidal	restricted, shallow lagoon and tidal flat	restricted platform association		√		√
9	Non-laminated homogeneous micrite	intertidal and very shallow subtidal	tidal pond and protected, quiet, very shallow bight or lagoon	restricted platform association		√		
10	Lensoidal pack-/rudstone	intertidal	storm surge channel or rip channel in a tidal flat environment	restricted platform association		√		
11	Laminated mudstones	supratidal and intertidal	restricted plarform areas	supratidal and intertidal platform area association		√		√
12	Crumbly and platy mudstones and wackestones	supratidal and intertidal	mud flat or marsh	supratidal and intertidal platform area association	proximal	√		

Systems tracts, major bounding surfaces and their sedimentological and palaeontological features

SB, LST	Sequence boundaries (SB) form in response to rapid relative sea level falls (abrupt basinward shift of facies). They are marked by changes in lithology or variation in the facies curve (onset of landward facies). Lowstand systems tracts (LST) overly SBs and form during maximum regression. **Features:** Mud cracks, birds eyes, erosion surfaces, raggioni, tepees, small-scale ripples,dinosaur foot imprints, tidal channels. Coarse components are commonly ferruginous, worn and rounded and often show signs of corrosion and abrasion. Minor iron-stained bed surfaces. Quasi absence of fauna. Grain-size displays a coarsening-upward trend. Facies display a shallowing-upward trend.
ts, TST	A transgressive surface (ts) is the first pronounced sign of marine flooding (onset of landward migration of facies), marks the base of the transgressive systems tract (TST), the onset of (rapid) sea level rise and change to more open marine conditions (deepening-upward trend). **Features:** Coaly plants, black pebbles, (large) intraclasts, chephalopods. Low diversity and high abundance of fauna. Grain-size displays a fining upward trend. Rapid sea level rise may led to reduced sedimentation and condensation, indicated by hardgrounds, accumulation of shells (winnowing), highly bioturbated and nodular sediments and glauconite accumulation (e.g. Loutit et al., 1988; Sarg, 1988; Brett, 1995); lumachelle and worn and rounded material is deposited as storm sheets.
mfs, HST	The maximum flooding surface (mfs) forms in response to the most rapid sea level rise and separates the TST form the highstand systems tract (HST). After an episode of deposition displaying relative deep water increasingly shallower water is recorded (shallowing-upward trend, basinward migration of facies). A sharply defined surface related to maximum flooding may not be identifiable, instead a maximum flooding zone (mfz) is recognised. **Features:** Cephalopods. High abundance and diversity of fauna. Grain-size displays a coarsening-upward trend. Depending on the distance to the shoreline the sediments are composed of bioclastic, oncoidal, coral, and peloidal and laminated limestones.The maximum flooding often leads to condensation similar to those described above; condensation may be indicated by sediments rich in tests of fauna, which are no longer masked by sediment accumulation.

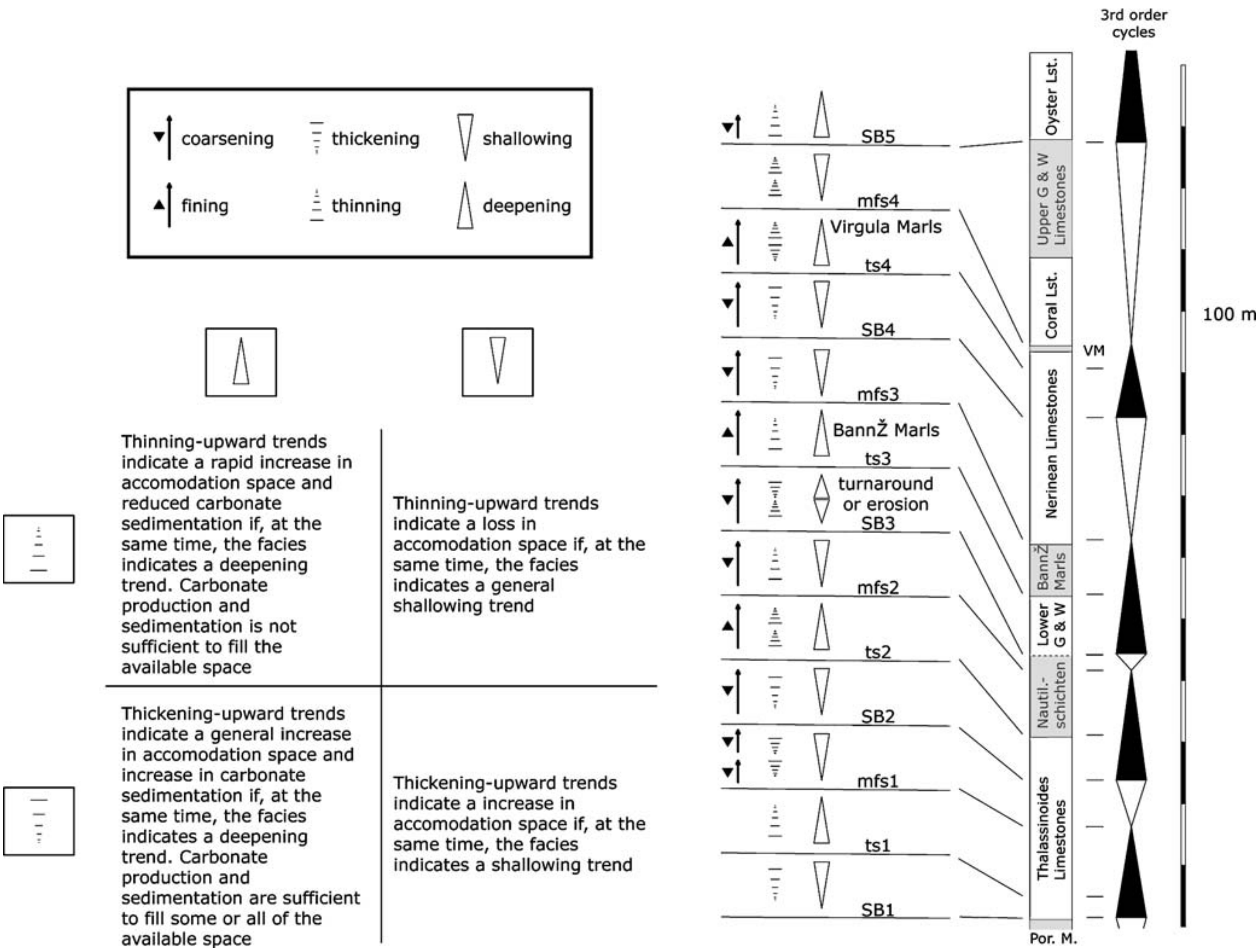


Fig. 11 General development of grain size, thickness and facies. The implied development of the accommodation space is modified after the concept of Strasser et al. (1999)

from −4.5‰ to −0.3‰ PDB). Such an isotopic composition is typical for the interaction between early meteoric and marine diagenesis (e.g., Immenhauser et al. 2003).

Transgressive surface ts2 is marked by a prominent, grey or reddish intraclastic pack- to grainstone sheet (e.g., bed VAB-50; Fig. 7(1)), which separates the preceding reworked limestones (top Thalassinoides Limestones) from the grey, argillaceous and slightly nodular "Nautilidenschichten." This sheet accumulated as a proximal stormlag, as suggested by *Thalassinoides* casts on the lower side of the sheet, which fills an erosion relief (Fig. 7(3)). The reworked grains exhibit brownish, corroded and abraded coatings and boundaries, which imply discontinuous sedimentation, transport and exposure at the sediment–water interface for some time (e.g., Bathurst 1966; Millimann 1974). They formed during transgression when the sea reworked either the previous sequence boundary or the sediments that accumulated during lowstand after the formation of the sequence boundary (ravinement erosion surface). According to Brett (1995) highly corroded, fragmented remains are typical of erosive lowstand or early transgressive conditions and lags consisting of corroded particles typify often highly condensed sections. Transgressive systems tract TST2 is made up by the "Nautilidenschichten," which are composed mainly of slightly glauconitic, open marine, bioclastic wacke- and packstones with minor iron-stained bed surfaces. They clearly show higher abundance and diversity of fauna, compared with the underlying deposits. The lower part is an extremely bioturbated and highly fossiliferous alternation of limestones and marly limestones, in which marly parts contain an increased amount of coarse fossil debris and clasts. Cephalopods indicate a connection to the open sea. A thinning-upward trend in the "Nautilidenschichten" (Figs. 13(1),13 (3,4); between ts2 and mfs2) and lithological change from peloidal and homogeneous to bioclastic limestones indicate a deepening; a fining-upward trend indicates a decrease of hydrodynamic energy.

During the transgression carbonate production could not keep pace with the generated accommodation space as indicated by the decrease in bed thickness and in the amount of storm-influenced and winnowed sediments. Additionally, the preservation of complete fragile regular and irregular sea urchins with spines at the base of the "Nautiliden-

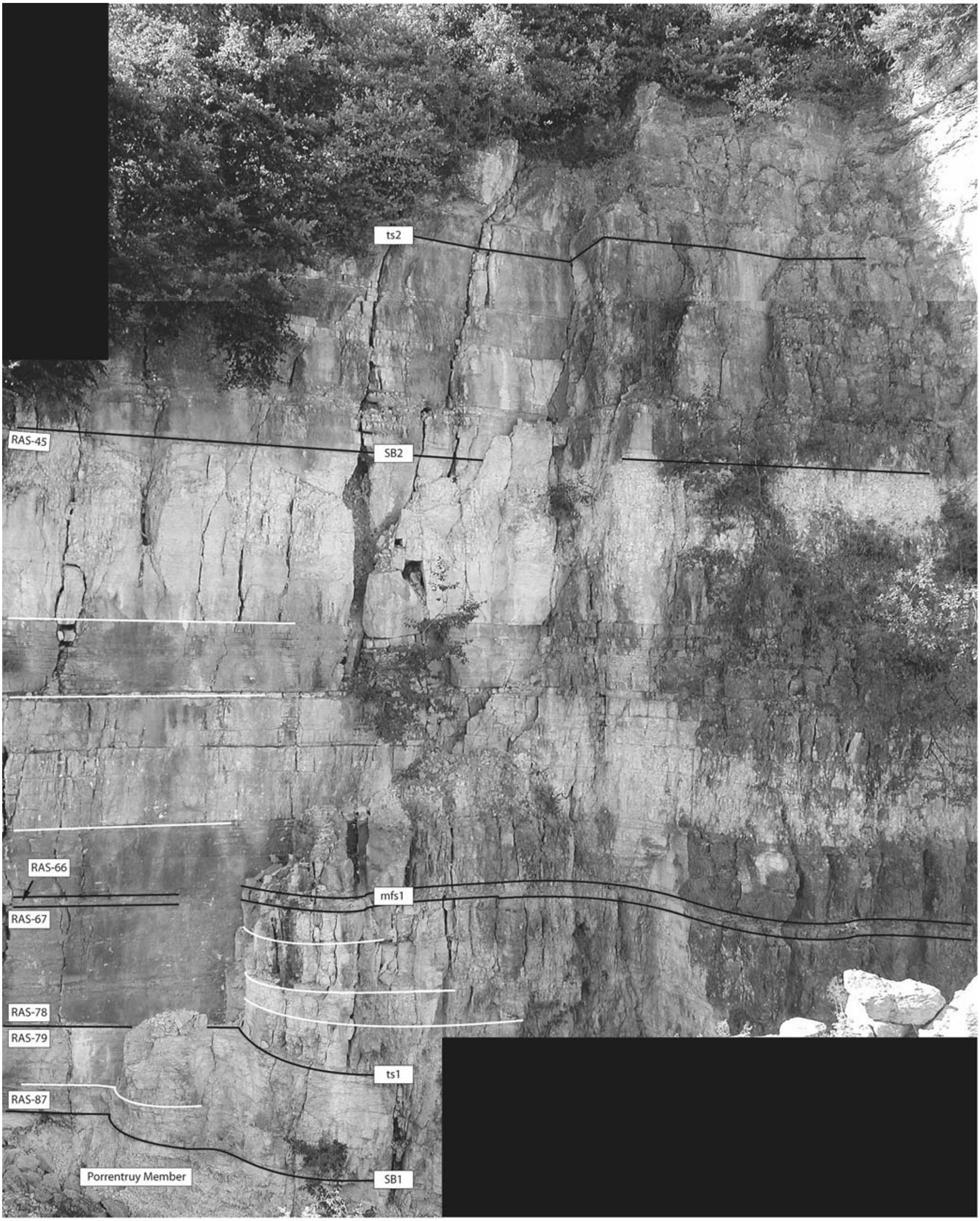


Fig. 12 Overview of the lower part of the quarry La Rasse. Lines mark the thickness and colour trend

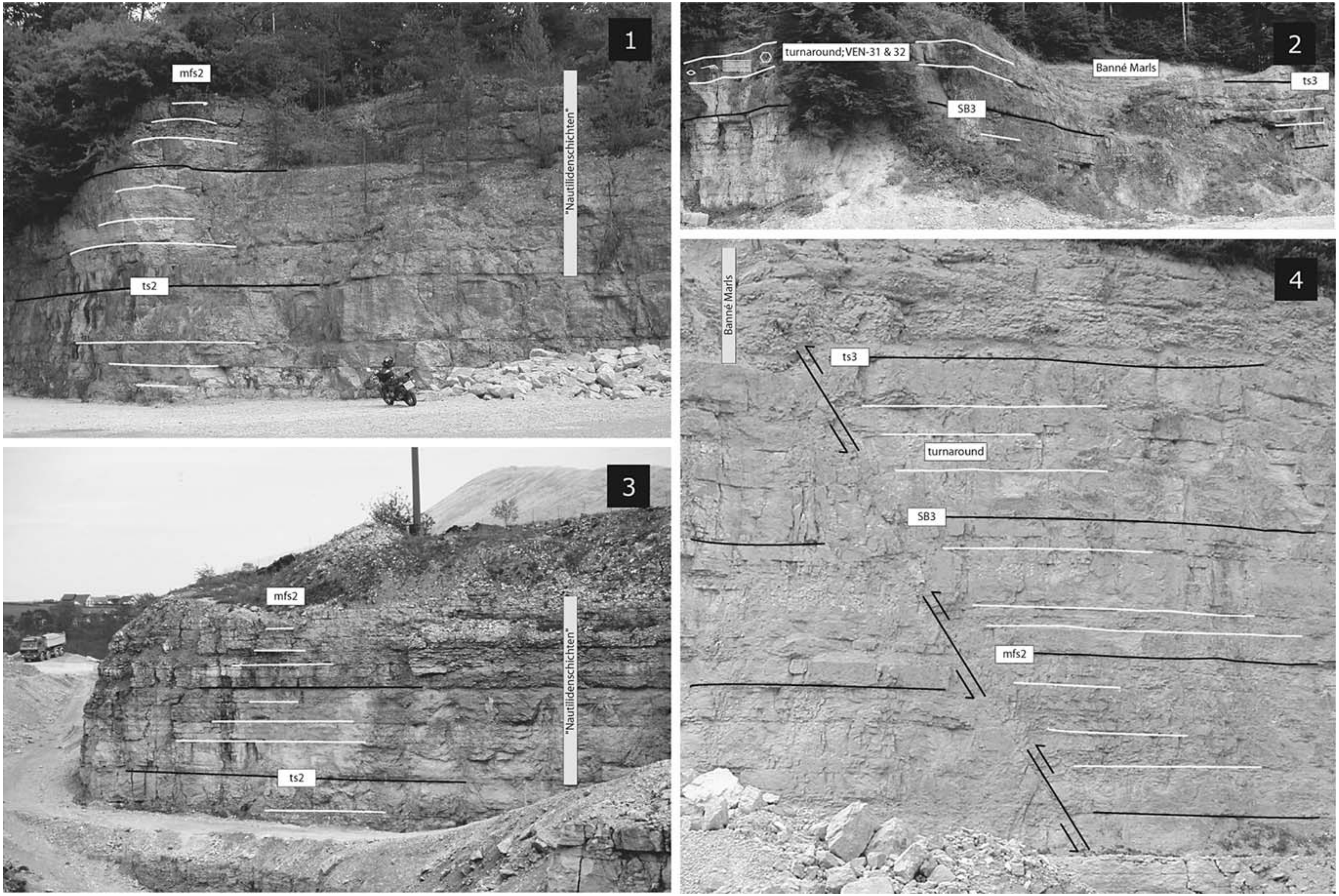
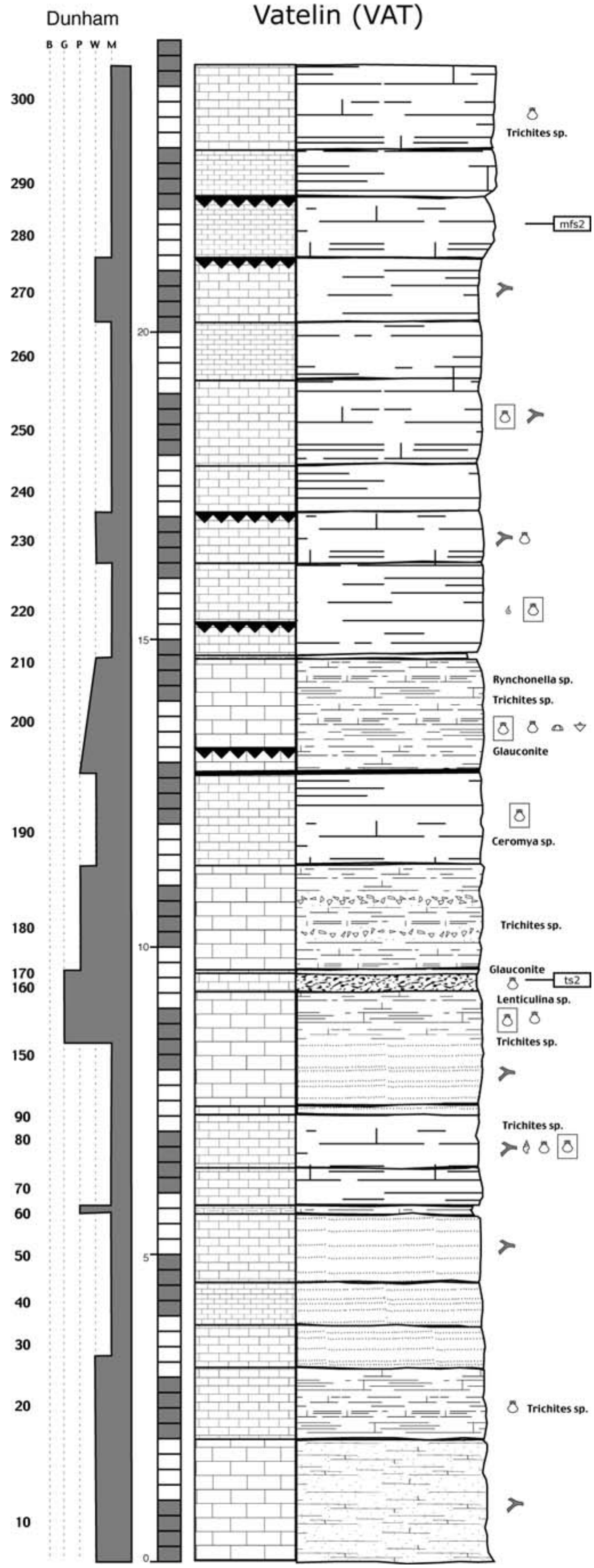


Fig. 13 Thickness trend of the "Nautilidenschichten" and Lower Grey and White Limestones in Bas d'Hermont (**1**), Vendlincourt (**2**), Vatelin (**3**) and L'Alombre aux Vaches (**4**). Below ts2: thickening-upward; between ts2 and mfs2: thinning-upward; between mfs2 and SB3: thinning-upward; between SB3 and ts3: thinning–thickening-upward

Fig. 14 Section Vatelin. The numbers on the left side of the grey-white scale label meters. For legend see Fig. 10



schichten" (found in beds CRE-160 and 170 in Creugenat; no. 5 in Fig. 1) is characteristic of marginal environments, which are too deep to be disturbed by storm waves, but still shallow enough to be occasionally inundated by pulses of rapid storm-generated sediments (Brett 1995).

Maximum flooding surface mfs2 is marked by the transition from the "Nautilidenschichten" into the fine-grained Lower Grey and White Limestones. Highstand systems tract HST2 comprises a thinning-, coarsening- and shallowing-upward trend (Figs. 13(2), 13(4)) and documents a progressive loss of accommodation space (Fig. 11). Maximum flooding and the concomitant loss of carbonate production at the time of largest generation of accommodation space occurred in the vicinity of bed VAB-3 (and corresponding levels) as indicated by a minor facies change (Mouchet 1998), thin layers, condensation (hardground) and intact multi-element skeletons (e.g., Brett 1995). The transition from transgression to highstand marks a maximum flooding zone (mfz2) rather than a maximum flooding surface sensu stricto, as for example indicated by the facies development in Vatelin (Fig. 14) and Vendlincourt. *Lithacosphinctes* cf. *janus* (Choffat) (or Perisphinctidae indet. respectively) has been found at the base of TST2 in bed VAB-70. *Physodoceras circumspinosum* (Oppel) was found within the same level in an excavation pit near Fontenais (B. Hostettler, personal communication; next to no. 6 in Fig. 1). *Rasenia borealis* Spath has been found in Coeuve (bed COE-370; Fig. 6(5)) pointing to the Divisum-Zone.

Sea-level cycle SC 3 (≈30 m; Figs. 7(1), 13(2), 13(4), 5(1))

Two thick stromatolite layers (beds VEN-31 and 32; top Lower Grey and White Limestones) with ripple marks, birds eyes, mud cracks (Figs. 7(2), 13(2)) and iron-stained laminae are considered as sea-level lowstand deposits. Such a composition, which is observed only in Vendlincourt, indicates slow accumulation (emersion subsequently followed by condensation) and the onset of a slightly rising sea level as slightly deeper deposits covered the mud cracks. As the transition from falling to rising sea level is gradual and displays low sedimentation, this interval indicates a turnaround rather than a sequence boundary sensu stricto. A continuous facies-turnaround occurs at the same level in L'Alombre aux Vaches (Mouchet 1995, 1998). At Cras d'Hermont, the corresponding quasi macrofossil-free interval is interpreted as the turnaround but there is no evidence for emersion. At La Rasse, the bored erosion surface (Gygi et al. 1998) overlain by a coarsening-upward trend indicates the pronounced sea-level fall at SB3. Consequently, a kind of lowstand sensu stricto is solely visible in La Rasse.

The onset of transgressive systems tract TST3 is marked by transgressive surface ts3 with an encrusted hardground. On top of it rest the slightly glauconitic Banné Marls. The composition of the Banné Marls varies between slightly nodular marlstones and marly limestones. They contain a rich macrofauna and cephalopods and intercalated shelly and calcarenitic horizons (probably reworked and winnowed by storms). The lithology points to a near-land, quiet marine lagoon or bight below the fair-weather wave base and documents a conspicuous increase of water depth. The Banné Marls represent a time of rapid creation of accommodation space and hence, reduced carbonate accumulation (e.g., Strasser et al. 1999; Fig. 11). They are dated by *Prorasenia* sp. that was found in Vâ tche Tchâ (no. 16 in Fig. 1).

Towards the top of the Banné Marls deposition, carbonate accumulation started to re-establish. The base of the Nerinean Limestones marks the maximum flooding surface mfs3. The highstand systems tract HST3 is represented by the lower part of the overlying Nerinean Limestones and it is composed of fine bioclastic limestones, which change into increasingly coarse peloidal packstones with stromatolites and birds eyes. The lithology of HST3 implies a continuous decrease of water depth accompanied by a continuous increase in grain size (coarsening-upward trend) and finally emersion features. Concomitantly the diversity of the fauna decreases. A slightly progressive increase of accommodation space is reflected by a weak thickening-upward trend (Fig. 11). Locally high-energy deposits such as bioclastic and peloidal winnowed pack- to grainstones with some ooids and oncoids are intercalated.

Sea-level cycle SC 4 (≈50 m; Figs. 5(1), 15(1,2))

A pronounced low sea level and break in sedimentation in lowstand systems tract LST4 is indicated by stromatolitic and peloidal limestones accompanied by tidal channels, birds eyes, mud cracks and dinosaur foot imprints; some of these deposits became reworked and form intraclasts (e.g., top bed CHV-120). Calcite-cement rays, which look like raggioni (Mutti 1994) on a stromatolitic limestone with very small tepees and desiccation cracks in Roches de Mars (bed RDM-140), point to palaeocarst and a very low sea level. LST4 displays a progressive shallowing- and thickening-upward trend finished by a crumbly and platy mudstone with mud cracks (Fig. 5(2)). As there is no significant change in composition at the transition from high to lowstand, this development marks a turnaround rather than a sequence boundary sensu stricto.

Transgressive surface ts4 (bed CHV-190) is marked by the distinct onset of (partially graded) lumachelle or worn and rounded bioclastic and peloidal pack- to rudstones with large intraclasts (Fig. 8(8)), hardground clasts, invertebrate remains and black pebbles (Fig. 8(7)). Such highly corroded, fragmented remains are typical for erosive lowstand or early transgressive conditions and high condensation (e.g., Strasser 1984; Brett 1995). In combination with the onset of glauconite sedimentation and several significant hardgrounds, it is considered as an early part of transgressive systems tract TST4. Further up-section, a fining- and thickening-upward trend implies a deepening but still under strongly storm-influenced, shallow subtidal conditions. The condensed and richly fossiliferous Virgula Marls

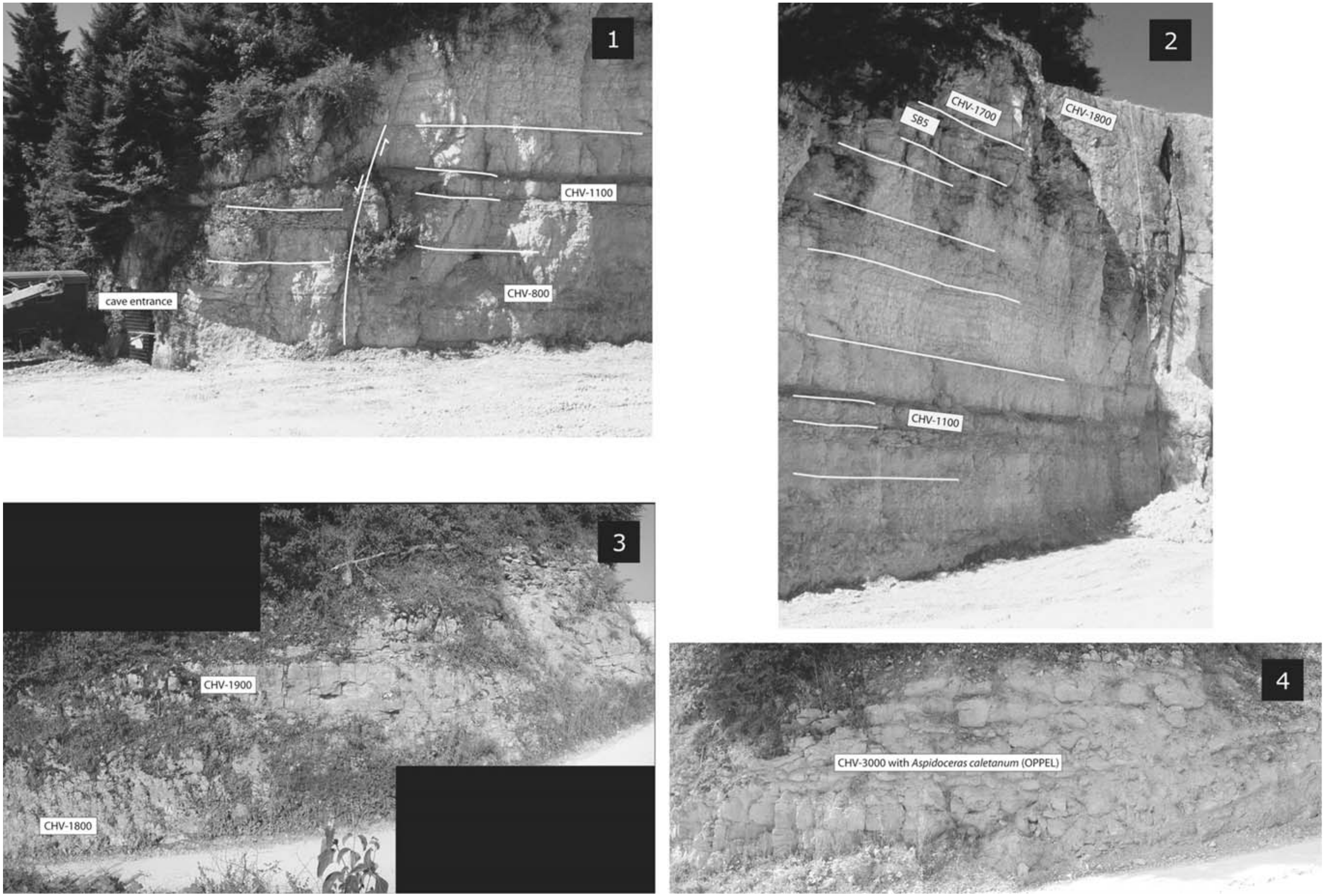
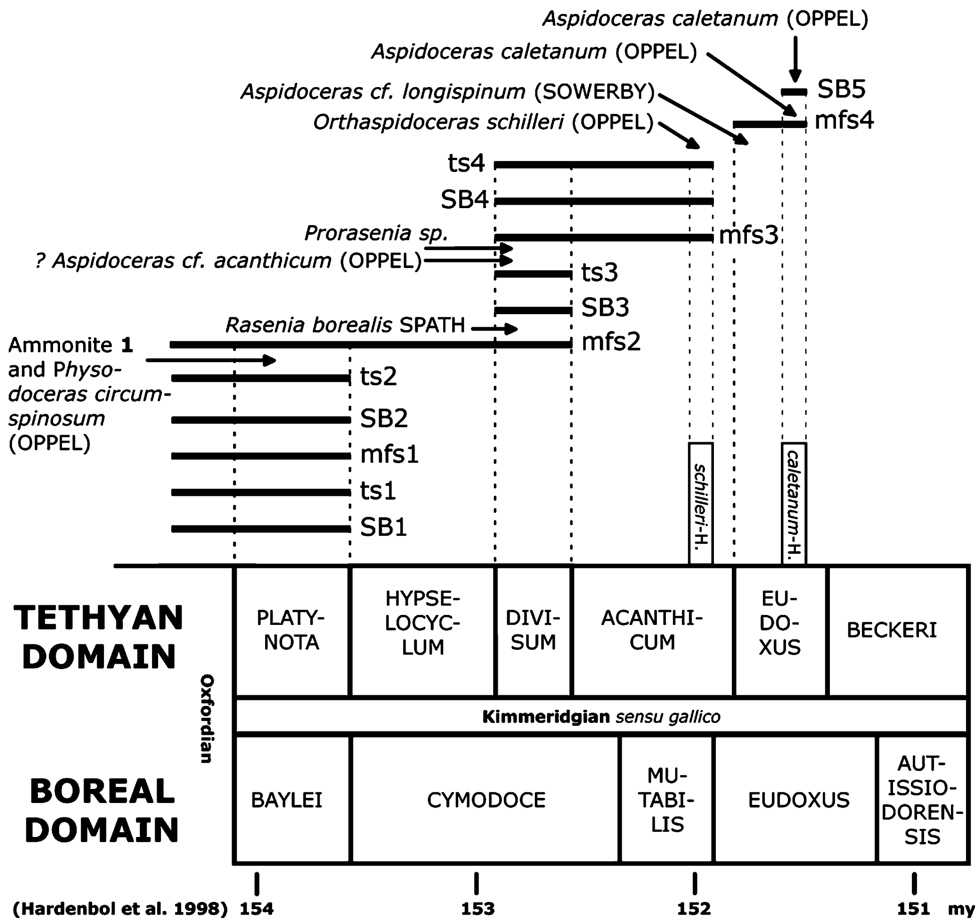


Fig. 15 Upper part of the quarry La Combe. HST4 displays two thinning-upward trends. The upper trend reveals two thinning-upward bed sets (**1–2**). LST5 and TST5 display increasingly marly deposits and thinner beds (**3–4**)

Fig. 16 Possible maximum time ranges of SBs, ts' and mfs' derived from ammonites. Note that SB3, ts3 and SB5 are most precisely dated. The age-assignment of SB1 to ts2 is based on only specimen of *Physodoceras circumspinosum* (Oppel). The two possible ages given by ammonite 1 (see above) are not considered. Nevertheless, the age assignment given by *Lithacosphinctes* cf. *janus* (Choffat) agrees with those given by *Physodoceras circumspinosum* (Oppel)



(Fig. 5(3)), which accumulated in a subtidal, protected, near-land setting, are interpreted as late TST4 that developed during a long lasting transgression of the shoreline and low sediment accumulation. The onset of the early transgression is dated by *Orthaspidoceras schilleri* (Oppel), the intensified creation of accommodation space during deposition of the Virgula Marls by another specimen of *Orthaspidoceras schilleri* (Oppel), and by *Aspidoceras* cf. *longispinum* (Sowerby) and *Aspidoceras caletanum* Spath.

The Virgula Marls are followed by a slightly marly and iron-rich bed (bed CHV-400) incorporated into the base of the Coral Limestones that documents the re-establishment of limestone sedimentation. This is interpreted as maximum flooding surface mfs4. The iron impregnation resulted from condensation attributed to reduced carbonate production around mfs4. Highstand systems tract HST4 is made up by the extremely thick Coral Limestones and the Upper Grey and White Limestones (Figs. 5(1), 15(1,2)), which are mainly composed of a homogeneous very thick subtidal, coral bearing and bioclastic limestones without any significant vertical facies variability. On the top of the Upper Grey and White Limestones, white bioclastic and peloidal mudstones are capped by a stromatolitic mudstone with ripple marks, birds eyes and iron-stained laminae (bed CHV-1600). HST4 comprises a general shallowing-upward trend accentuated by two progressive thinning-upward trends. According to Sarg (1988), a constant bed-thickness within a thick homogeneous succession, like that of the Coral Limestones, characterises the transition from transgression to early highstand. The enormous thickness of HST4 ($\approx$35 m), the constant bed thickness and the low facies variability of the Coral Limestones and the Upper Grey and White Limestones within a wide area are probably a result of enhanced subsidence, which balanced deposition rate and reduction of accommodation space.

Sea-level cycle SC 5 (Figs. 15(2–4))

The stromatolitic mudstone with ripple marks, birds eyes and iron-stained laminae on the top of the Upper Grey and White Limestones are interpreted as sequence boundary SB5. The peloidal and oncoidal pack- and grainstones at the base of the Oyster Limestones then represent the lowstand systems tract LST5 formed in a shallow-subtidal setting with high hydrodynamic energy. Slightly nodular marly limestones with numerous iron-stained minor surfaces and some hardgrounds follow (beds CHV-2000 to 3700). These are composed of intensively bioturbated, oyster-dominated, bioclastic mud- to wackestones alternating with thin marly intercalations. A subtidal, low-energy environment is inferred; cephalopods imply open marine conditions. They are interpreted as a part of the incomplete transgressive systems tract TST5. LST5 and TST5 display an initial thickening-upward followed by a thinning-upward trend with progressive fining and deepening (Figs. 11, 15(2–4)). The numerous iron-stained surfaces indicate condensation. The initial creation of accommodation space was partly compensated by high carbonate production; in a second phase of evolution, carbonate production was probably unable to keep pace with the created accommodation space (TST5). In bed CHV-3000, the Caletanum-Horizon is indicated by *Aspidoceras caletanum* (Oppel).

Interpretation

Vertical rhythmic changes of facies and inferred depositional environment allowed distinguishing five sea-level cycles. Each of them consists of a basal transgressive interval followed by a regressive one.

SB3 and SB5 have been biostratigraphically dated by *Rasenia borealis* Spath, *Prorasenia* sp. and *Aspidoceras caletanum* (Oppel) to the Divisum-Zone and Caletanum-Horizon (Eudoxus-Zone) respectively (Fig. 16). Based on the assumption that these cycles are similar in duration, the time calibration (compare Hardenbol et al. 1998) of the sequence boundaries SB3 and 5 with estimated time duration of about 1.4 my for cycles SC3 and 4 led to an average of about 0.7 my duration for these sea-level cycles. Therefore, the cycles SC1 to 5 are interpreted as third-order sea-level cycles *sensu* Van Wagoner et al. (1988) and Vail et al. (1991). Additionally, 0.7 my cycle duration roughly corroborates the ages of the sequence boundaries SB1, 2 and 4 proposed by the other ammonites (see below).

The persistent vertical rhythm of stacked systems tracts along with the presence of emersion features indicate that periodic change of accommodation played an important role in their formation (compare Strasser 1991). In addition, in some of the systems tracts a number of higher order rhythms were clearly identified as for example visible in L'Alombre aux Vaches, where TST2 is composed of several bed sets, or La Combe where HST4 is composed of two thinning-up bed sets. As in average one cycle is assumed to have lasted for about 0.7 my, the duration of transgressive and regressive successions may fall within the Milankovitch long eccentricity band (400 ky). Furthermore, the third-order rhythms comprise several beds and bed sets, which may indicate the possible influence of the precession (20 ky) and obliquity (40 ky), and short eccentricity (100 ky) Milankovitch cycles (e.g., Figs. 15(1,2)).

SB1 and SB2 can be assigned to the Planula- (Late Oxfordian) and Platynota-Zone (Early Kimmeridgian) because of the find of *Physodoceras circumspinosum* (Oppel). At the same level, however, *Lithacosphinctes* cf. *janus* (Choffat) occurs (compare section Biostratigraphy). Assuming an average cycle length of 0.7 my, SB2 probably lies within the Platynota-Zone. Then mfs2 would lie within the Hypselocyclum-Zone. As mentioned above SB3 is within the Divisum-Zone. *Rasenia borealis* Spath and *Prorasenia* sp. justify placing ts3 (at the base of the Banné Marls) into the Divisum-Zone (see position of ammonites in Fig. 10). Because *Prorasenia* sp. also occurs within the Banné Marls, the sedimentation of the Banné Marls started within the Divisum-Zone; their upper boundary, however, still needs to be biostratigraphically defined. Mfs3 and SB4 fall into the Acanthicum-Zone if the cycles are of roughly similar duration. *Orthaspidoceras schilleri* (Oppel), indicating the Schilleri-Horizon (Upper Acanthicum-Zone), was found 2 m above ts4 and on the hardground directly beneath the Virgula Marls (Marty et al. 2003). Accordingly, ts4 is assumed to be within the Schilleri-Horizon. The base of the Virgula Marls is dated to the Schilleri-Horizon (upper Acanthicum-Zone) by a second specimen of *Orthaspidoceras schilleri* (Oppel) as well; the lowermost Eudoxus-Zone is indicated by *Aspidoceras* cf. *longispinum* (Oppel) (also found in the Virgula Marls); the top of the Virgula Marls is assigned to the Caletanum-Horizon (upper Eudoxus-Zone) by *Aspidoceras Caletanum* (Oppel), which was found in the first limestone layer above the Virgula Marls (D. Marty Personal communication). Mfs4 and SB5 lie also within the Caletanum-Horizon, indicated by another specimen of *Aspidoceras caletanum* (Oppel).

The second-order sea-level fluctuations are believed to be clearly identifiable, only when the development in Oxfordian and Tithonian times is also taken into consideration which would be, however, out of the scope of this paper. Nevertheless the deposits around and between SB3 and SB4 represent a very thick regressive depositional succession as indicated by birds eyes, mud cracks and dinosaur foot imprints. Therefore these deposits are interpreted as lowstand (LST-B) presumably belonging to a second-order sea-level cycle (SC-B; Fig. 17), which begins with SC 3 and 4. The depositional sequences SC 1 and 2 are interpreted as the preceding second-order cycle SC-A from the Planula- to Divisum-Zone; the transgressive peak being in the Hypselocyclum-Zone ("Nautilidenschichten"). The general facies distribution of SC-A shows a fining- followed by a coarsening-upward trend with the inflexion point located around mfs2/mfs-A. The lithology around mfs-A (TST2 and HST2) corresponds to the maximum development of open platform facies and is regarded as the maximum flooding zone of this second-order sequence. LST-A and TST-A show a trend to increasingly open platform facies, up to a maximum around mfs-A. LST-B is recorded by significant hydrodynamical, sedimentological and faunal modifications towards near-land or terrestrial conditions as indicated by for example black pebbles, coaly plants (D. Marty personal communication), crocodile teeth within the Banné Marls (Marty and Diedrich 2002), dinosaur foot imprints and sub-aerial erosion. Therefore, the Banné Marls are considered as third-order, transgressive, probably condensed, intercalation within a second-order, shallowing-upward lowstand (LST-B; Fig. 17). The development following SB4 probably indicates the beginning of the second second-order transgression TST-B.

The thickness of the studied sediments markedly exceeds the depositional water depths and therefore, additional accommodation space must have been provided during deposition (Wetzel et al. 2003). Additionally, subsidence was not synchronous (Fig. 3). For example, the increased thickness between ts4 and ts5 during a moderate eustatic rise (Fig. 3) first led to long lasting condensation

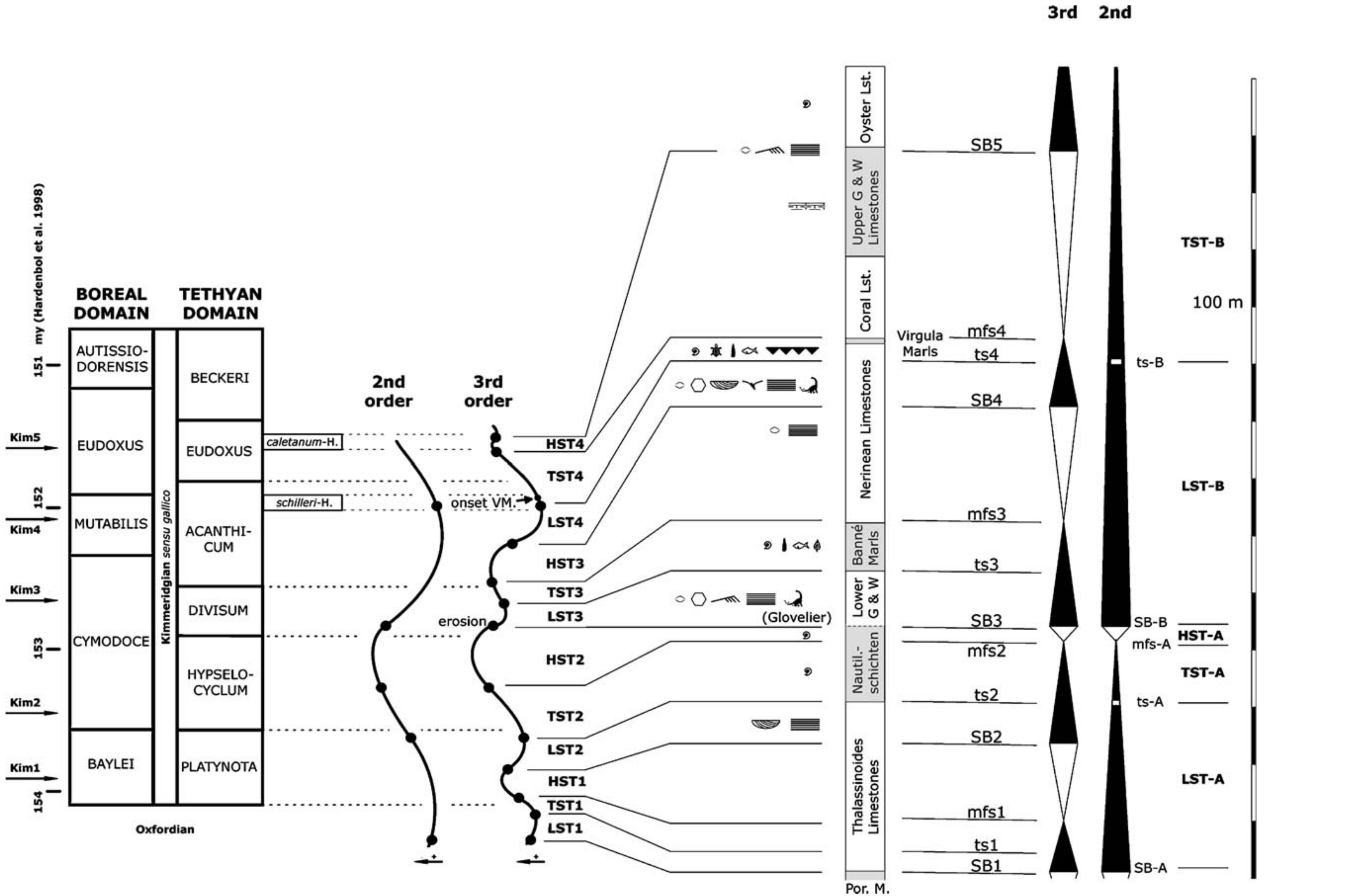


Fig. 17 Systems tracts of the Reuchenette Formation in comparison to absolute time, tentative relative sea-level trend and thickness. Kim1–5 are the Boreal sequence boundaries after Hardenbolet al. (1998). For legend see Fig. 10

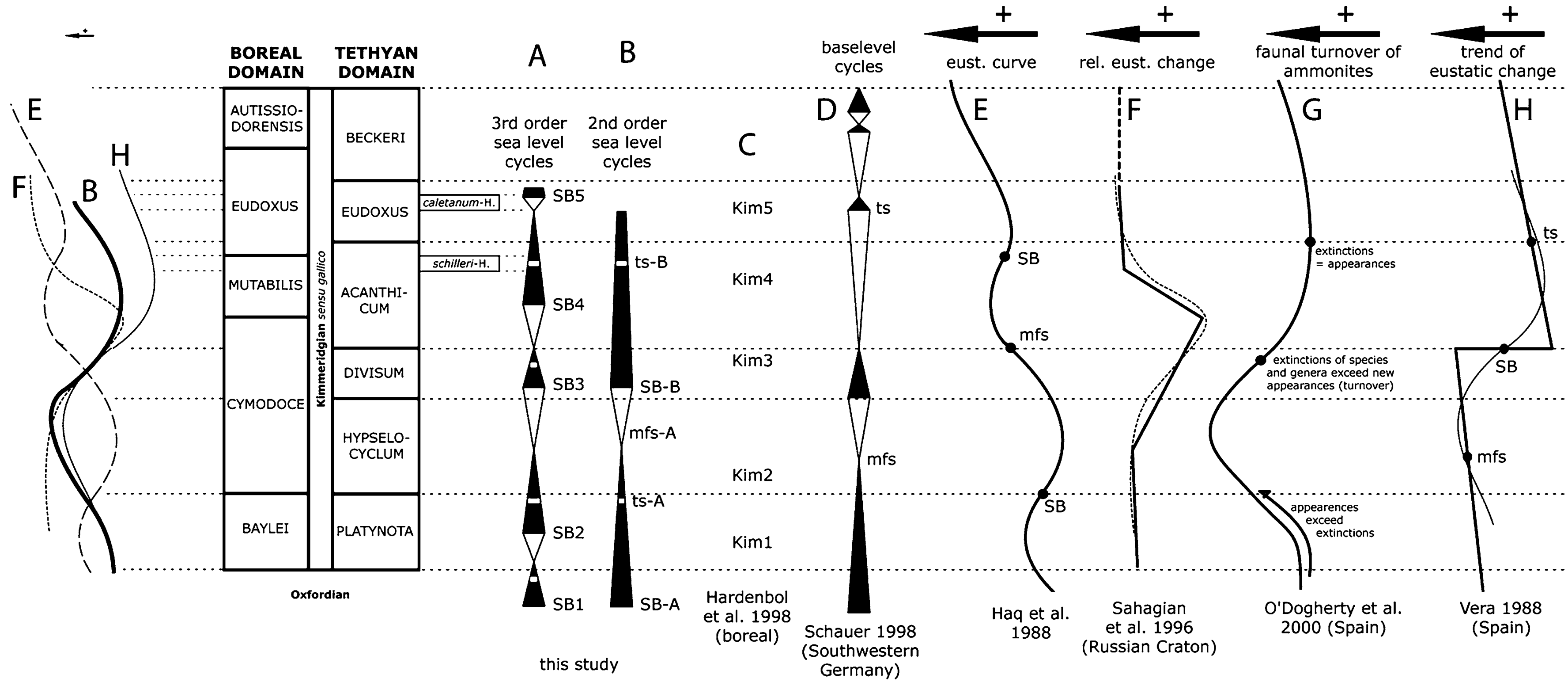


Fig. 18 Right side: comparison of this work (A, B) with other studies (relative changes of E–H are not to scale; thin and small stippled line in F and H: interpreted sinus-curve). The general trend of (F) Sahagian et al. (1996), (G) O'Dogherty et al. (2000) and (H) Vera (1988) fits with the second-order trend of this study. (E) The short term curve of Haq et al. (1988) extremely differs in the lower part (Hypselocyclum-Zone). Number and ages of Boreal sequence boundaries Kim1–5 of (C) Hardenbol et al. (1998) partly match with those of this study (especially Kim3 – 5); discontinuities of (D) Schauer (1998) are occasionally different. As mentioned in the text differences are most probably due to limited biostratigraphical resolution and data and the calibration of the biostratigraphical schemes used in the different studies. Schauer's differences are probably due to the different investigation methods (base level concept). Left side: second-order trend of this study (B) crossed with the curves of Haq et al. (E), Sahagian et al. (F) and Vera (H) in the Divisum-Zone

(represented by the Virgula Marls) and then to very thick deposits that formed within a short time interval (Caletanum-Horizon, compare Fig. 17). Correspondingly, after initial underfill of the created accommodation space, sediment accumulation drastically increased. Such a stacking pattern can be attributed to an aggradational or weakly retrogradational parasequence set in a transgressive systems tract (Van Wagoner et al. 1988). Considering the short time span covered by the Caletanum-Horizon, the enormous thickness of the Coral Limestones and Upper Grey and White Limestones (probably), related to an important gain in accommodation space, resulted from sea-level rise and enhanced subsidence (Wetzel et al. 2003).

Discussion

The sea-level fluctuations deduced in this study are in good agreement with several other investigations (e.g., Vera 1988; Sahagian et al. 1996; Hardenbol et al. 1998; O'Dogherty et al. 2000; Fig. 18) but markedly differ from those of Haq et al. (1988) and Schauer (1998). The sequence boundaries SB3–5 of this study match well the Boreal sequence boundaries Kim3–5 of Hardenbol et al. (1998); see Fig. 18. A significant eustatic minimum, which is enclosed by two prominent eustatic maxima interpreted for the Russian Craton by Sahagian et al. (1996) fits well with the second-order trend of this study; the maxima are within the Hypselocyclum- and Eudoxus-Zones and the minimum within the Acanthicum-Zone. The ammonite-faunal turnover-curve of the Betic Cordillera of Spain of O'Dogherty et al. (2000) also mirrors the second-order sea-level trend of this study. For example, the culmination of the development of new genera and species in the Hypselocyclum-Zone coincides with mfs-A. The following decrease of diversity and the start of recovery are in accordance with this study as well. The age of the turnover coincides with SB-B and recovery approximately with the onset of TST-B. Vera's (1988) trend of eustatic change also represents a significant analogy, which is represented by two eustatic sea-level rises separated by a prominent sequence boundary (at the transition Divisum-Acanthicum-Zone). Pittet and Strasser (1998) have also demonstrated that Spanish and Swiss sea-level fluctuations correlate well in Oxfordian times. Schauer's and Haq's curves only partly match those of this study. The obvious and occasionally rather prominent mismatches between the studies might depend on limited biostratigraphical resolution, limited biostratigraphical data and (especially) the difficult calibration of biostratigraphical schemes used in the different studies (e.g., boreal, tethyan, subboreal, etc.).

Conclusion

New biostratigraphical data, facies and sequence stratigraphical analysis of the Late Jurassic Reuchenette Formation in the Ajoie-Region (NW Switzerland) led to the identification of third-order relative sea-level fluctuations that are superimposed on a presumably second-order sea-level trend. Additionally, considering that high-resolution biostratigraphical data are very rare in the platform carbonates of the Reuchenette Formation, this study provides an improved (more precisely dated) insight into the development of Kimmeridgian sea-level changes in NW Switzerland. The data of this study form a reference frame for a comparison/correlation with adjacent areas.

1. Five sedimentary sequences have been interpreted as result of third-order relative sea-level cycles for the Late Oxfordian to Late Kimmeridgian sensu gallico time interval. The SBs lie in the Planula-, Platynota-, Divisum-, Acanthicum and uppermost Eudoxus-Zone. SB3–5 coincide with the Boreal sequence boundaries Kim3–5 of Hardenbol et al. (1998). The influence of the Boreal realm is partly corroborated by ammonites, which are typical for the Boreal realm sensu stricto (but Tethyan ammonite occur as well; compare Schweigert et al. in preparation.).
2. The sequence boundaries SB1 and SB2 may, but do not have to, be assigned to the Boreal sequence boundaries of Hardenbol et al. (1998) due to the different interpretation of ammonites found in the lower Reuchenette Formation. Therefore, SBs traceable over large distances might provide a reference to rectify biostratigraphy.
3. The first two third-order cycles are superimposed on a second-order transgressive-regressive sea-level cycle, the mfs being in the Hypselocyclum-Zone. Dinosaur foot prints, erosion, birds eyes and mud cracks mark a pronounced second-order lowstand in the Acanthicum-Zone (third-order cycles three and four). A second second-order transgression begins probably with the fourth third-order cycle.
4. Minimum accommodation space resulted in local exposure and very shallow-water to supratidal deposits. The increasing sea-level rise during TSTs led to the most prominent lithological changes on top of condensed suites indicated by marly deposits and winnowing. Maximum floodings resulted in the highest rates of carbonate production (Handford and Loucks 1993) and led to the deposition of thick- and massive-layered relatively deep open shallow-marine carbonates.
5. The preservation of (parts of) fossils appears to be related to the systems tracts; highly corroded, fragmented remains are typical of erosive lowstands or early transgressive conditions. Intact multi-element skeletons characterise rapid background sedimentation during highstands and ferruginous lags of corroded particles and fossils typify condensed sections. Skeletal accumulations develop during intervals of low sediment input. Starved accumulations and winnowed shell beds may indicate transgressions.
6. Synsedimentary differential subsidence modifies the lithological expression of sea-level fluctuations. The sea-level fluctuations are superimposed on differential synsedimentary subsidence; this led to a repeated reorganisation of the depositional environment, favour-

ing shifts of the facies belts and the establishment of specific settings.

Enhanced subsidence within the Caletanum-Horizon (Eudoxus-Zone) led to the formation of extremely thick, homogeneous packages.

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