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Stratigraphy and paleogeography of the Hauptrogenstein and Klingnau Formations (middle Bajocian to late Bathonian), northern Switzerland

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Key words: Oolitic platform, stratigraphy, paleogeography, Middle Jurassic, Switzerland

ABSTRACT

The middle Bajocian to middle Bathonian epicontinental sediments of northern Switzerland consist of shallow-marine oolitic carbonates (Hauptrogenstein Formation, Celtic realm) and marly basinal deposits (Klingnau Formation, Swabian realm). Detailed biostratigraphic data based on ammonites and dinoflagellates provide a time frame for a sedimentologic analysis.

The carbonate series of the Celtic realm is composed of three shallowing-upward successions, each capped by a hardground. In the basinal domain east of the Aare River, marls persist in a monotonous facies throughout the same time period.

The first shallowing-upward succession within the Hauptrogenstein Formation, started during the Blagdeni Subzone with marly beds and intercalated tempestites (Rothenfluh Beds), covered in the western Jura by fine-grained, bioclastic tempestites (Grenchenberg Beds). Simultaneously, the Gislifluh Reef developed in the southeastern Jura, probably on a morphologic high. Oolitic sedimentation started in the central Jura during the Niortense/Subfurcatum Zone (Lower Oolitic Series). The units of 0.5–2 m thick, cross-bedded oolites are attributed to a tidal, shallow-marine, high-energy setting. At the same time, the oolitic beds in the eastern Jura contain up to 35% of mud, and a low-energy setting is inferred (Lower Acuminata Beds). During the Garantiana Zone oolite-belts prograded eastwards reaching the area of the Aare River. An up to 70 m thick oolitic succession was deposited during a period of moderate sea-level rise and a steady subsidence.

The second shallowing-upward succession started in the early Parkinsoni Zone. The production of ooids ceased during a sea-level highstand and marls and bioclastic limestones accumulated in northern Switzerland: the Homomya Marls in the western and the Upper Acuminata Beds in the central and eastern Jura. Later, a drop in relative sea-level during the late Parkinsoni Zone re-established ooid production (Upper Oolitic Series).

The third shallowing-upward succession started during the latest Bajocian and earliest Bathonian (Zigzag Zone). Marly sediments rich in coarse bioclasts (Movelier Beds) are again interpreted as formed during a relative sea-level highstand. They are overlain by micritic oncolites in the western Jura; to the east, sparry bioclastic, locally cross-bedded limestones occur ("Spatkalk"), probably deposited by storms and tides. The deposition of the "Spatkalk" lasted until early Middle Bathonian, prograding eastward and covering the top of the basinal Klingnau Formation.

The facies belts within the Hauptrogenstein and Klingnau Formations suggest the evolution of a middle Jurassic, north-south trending oolitic barrier dominated by tides. Backbarrier facies belts formed to the west and off-barrier assemblages to the east of this barrier. A decrease in the production of sediments, as evidenced by platformwide facies changes and in the thickness of shallowing-upward successions, was probably caused by changes in water circulation and local climate. On the other hand, more or less abrupt lateral changes in thickness and facies within the successions suggest local and regional patterns of differential subsidence.

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ZUSAMMENFASSUNG

In dem epikontinentalen Meer, das während des Mittelbajocian bis Mittelbathonian Mitteleuropa und somit auch die Nordwest-Schweiz bedeckte, wurden einerseits flachmarine, oolithische Karbonate (Hauptrogenstein, Keltischer Faziesbereich) und andererseits vor allem östlich der Aare, in etwas tieferem Wasser mergelige Sedimente (Klingnau Formation, Schwäbischer Faziesbereich) abgelagert. Die oolithische Karbonatserie setzt sich aus drei Abfolgen zusammen, die nach obenhin flachere Ablagerungsverhältnisse widerspiegeln. Die Mergel des tieferen Bereiches sind lithologisch monoton.

Die untere Abfolge der Hauptrogenstein Formation beginnt während der Blagdeni Subzone mit Mergeln und eingeschalteten Sturmlagen (Rothenfluh Schichten). Im südöstlichen Jura entwickelte sich zu der Zeit das Riff der Gislifluh möglicherweise auf einer morphologischen Erhebung. Im zentralen Jura akkumulierten Oolithe ab der Niortense/Subfurcatum Zone (Untere Oolithische Serie). Die vorherrschend auftretenden, 0,5–2 m mächtigen, schräggeschichteten Oolith-Bänke wurden wahrscheinlich in einem gezeitenbeeinflussten, hochenergetischen Milieu gebildet. Demgegenüber enthalten die Oolithe im östlichen Jura mehr als 35% Pelite, und ein niederenergetischer Ablagerungsbereich wird angenommen (Untere Acuminata Schichten). Während der Garantiana Zone verlagerten sich die oolithischen Barrensysteme ostwärts und erreichten die Aare. Ein gemässigter Anstieg des Meeresspiegels und eine stetige Subsidenz bildeten geeignete Rahmenbedingungen für die Ablagerung der etwa 70 m mächtigen Unteren Oolithischen Serie.

Die mittlere Abfolge entwickelte sich ab der frühen Parkinsoni Zone. Zuerst hörte die Bildung von Ooiden aufgrund grösserer Wassertiefe auf, und Mergel wie auch bioklastische Kalke wurden in der nördlichen Schweiz sedimentiert. Im zentralen und östlichen Jura akkumulierten die Oberen Acuminata Schichten, im westlichen die Homomyen Mergel. Nach einem relativen Absinken des Meeresspiegels setzte die Ooid-Bildung während der späten Parkinsoni Zone wieder ein (Obere Oolithische Serie).

Die obere Abfolge begann während des späten Bajocian bis frühen Bathonian (Zigzag Zone). Mergelige Sedimente mit vielen groben Bioklasten (Movelier Schichten) an der Basis werden als Bildungen während eines erneut höheren Meeresspiegels interpretiert. Darüber folgen mikritische Onkolithe im westlichen Jura («Pierre Blanche»); gegen Osten akkumulierten bis ins Mittel-Bathonian bioklastische, lokal schräggeschichtete Kalke («Spatkalk»), die wahrscheinlich stark von Stürmen und Gezeiten beeinflusst wurden. Der «Spatkalk» progradierte bis weit östlich der Aare und überlagert dort teilweise die Klingnau Formation.

Introduction

During the Middle Jurassic, a shallow-marine carbonate platform, the Burgundy Platform or "Plate-Forme Septentrionale" (Mégnien 1980), developed in central Europe, at that time covered by an epicontinental sea (Fig. 1). While the western segments of this carbonate platform were dominated by bioclastic calcarenites, a broad oolitic belt developed in the eastern and central areas, extending southwards to the marginal basins of the opening Tethys (e.g. Ziegler 1990; Fig. 1). The area discussed in this paper lies within the oolitic belt at the southeastern margin of the Burgundy Platform.

The development and evolution of most segments of the Burgundy Platform throughout central Europe are well understood (e.g. Contini 1970, 1979; Mégnien 1980; Ernst 1989). However, not much is known about its eastern border, nowadays exposed in the northern part of the Swiss Jura Mountains and known as "Hauptrogenstein". These sediments represent one of the few preserved portions of the easternmost boundary of the Burgundy Platform.

The "Hauptrogenstein" has been studied several times (e.g. Mühlberg 1900; Rollier 1911; Schmassmann 1945; see Gonzalez 1993 for a complete list of references), but the biostratigraphic resolution remained unclear, and hence, the correlation of lithologic units tentative (Tab. 1). Furthermore, a modern analysis in terms of carbonate sedimentology and depositional processes has not been performed so far. Due to the biostratigraphic uncertainties and the lack of sedimentologic investigations, the lithostratigraphical terms

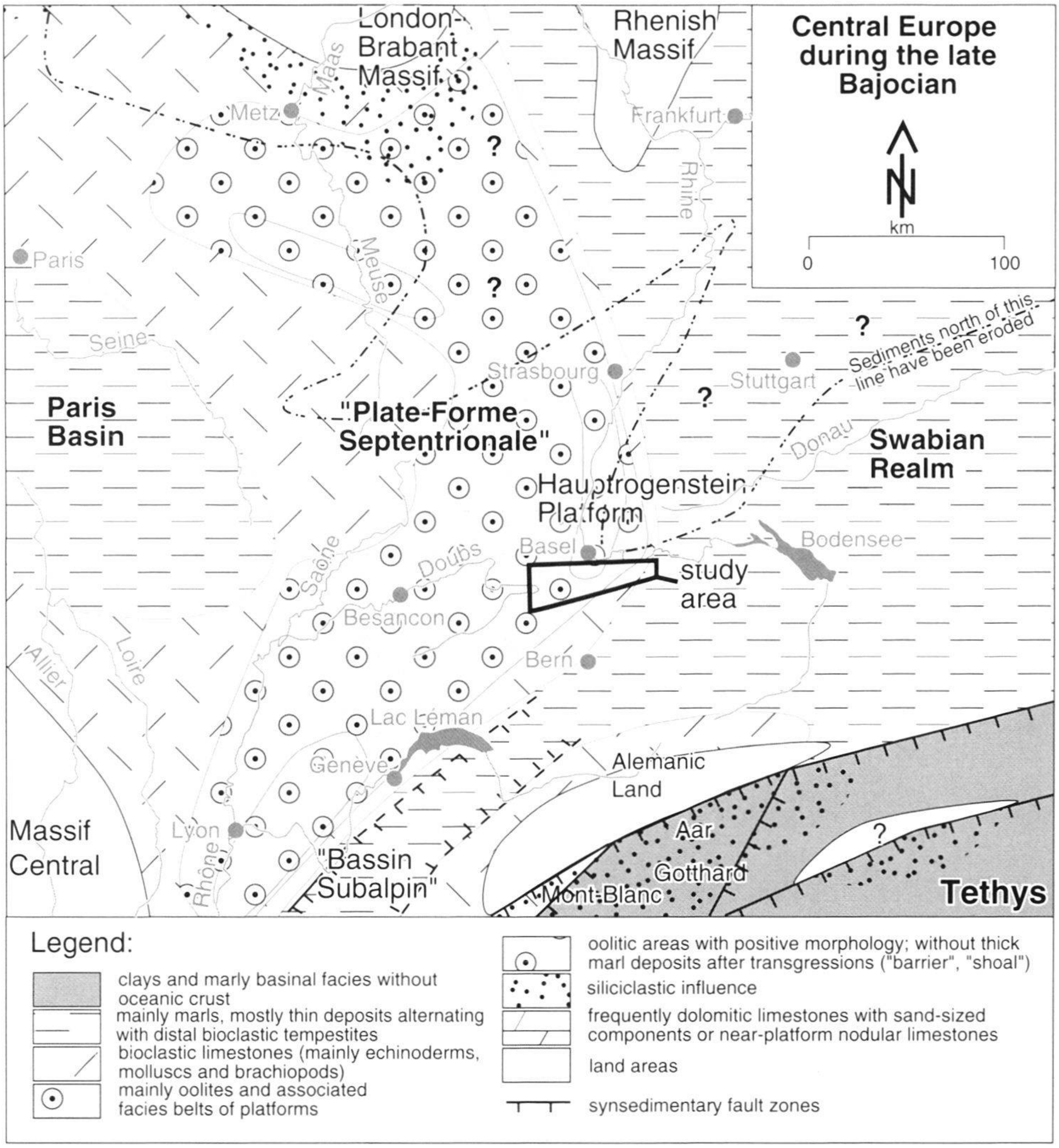


Fig. 1. Paleogeographic, palinspastic reconstruction of Central Europe during the late Bajocian. The interpretation is based on Büchi et al. (1965), Contini (1970, 1979), Gwinner (1978), Fischer (1979), Mégnien (1980), Trümpy (1980), Debrand-Passard (1984), Ziegler (1988, 1990) and Stampfli (1993). East and south of the Alpine realm the paleogeographic/palinspastic reconstruction is uncertain.

in use are not in accordance with modern nomenclature (cf. Arbeitsgruppe für stratigraphische Terminologie 1973).

This paper provides an updated and improved version of the lithostratigraphy of the Hauptrogenstein Formation presented in Gonzalez (1993; Tab. 1), putting it in context with a sedimentologic and paleoenvironmental analysis. Furthermore, a summary of the revised biostratigraphical data is given.

Age \ Author and field area	Thurmann (1832) Ajoie (western Jura Mountains)	Moesch (1867) Kanton Aargau (eastern Jura Mts.)	Greppin (1870) western Jura Mountains	Mühlberg (1900) Northern Switzerland		Rollier (1911) Northern Switzerland		Schmassmann (1945) central and eastern Jura Mountains	This paper Northern Switzerland	
	west	east	west	west	east	west	east	central/ east	west	east
Bathonian	Great-oolite	"Spatkalk"	"assise supérieure de la Grande Oolithe"	Coarse Oolite	"Spätige Kalke + Mergel"	"Pierre blanche", "Oolithe cannabine"	"Calcaires spathiques avec couches ferrugineuses et oolithiques"	Coarse Oolite / "Spatkalk"	Pierre Blanche / Coarse Oncolite	Coarse Oncolite / "Spatkalk"
			"Marnes grises de Movelier"	Movelier Beds		Movelier Beds	"Marnes sableuses à Cid. Mäandrina"	Movelier-Beds	Movelier Beds	
		Upper Hauptrogenstein	"Grande Oolithe"	Oolite	Oolite	"Grande Oolithe"	"Oolithe à Cl. osterwaldi"	Upper Hauptrogenstein	Upper Oolitic Series	
	"Marnes à Ostrea acuminata"	Mäandrina-Beds	"Marnes à Ostrea acuminata"	Upper Acuminata-Beds	Mäandrina-Bed	"Marnes à Homomyes et à O. acuminata"	"Marnes sableuses à Homomyes"	Homomya Marls	Homomya Marls	Upper Acuminata Beds
Bajocian	"Oolite subcompacte"	Sinuatus-Beds	"Oolithe subcompacte"	"Oolithe sub-compacte"	Oolite	"Oolithe bajocienne à Clypeus Ploti"	"Oolithe blanche"	Middle Hauptrogenstein	Lower Oolitic Series	
		Homomya-Marls						Mäandrina-Beds		Mäandrina-Beds
		Unterer Hauptrogenstein						Lower Hauptrogenstein		
	"Oolite ferrugineuse"				Lower Acuminata Beds		"lumachelles oolithiques à O.acuminata"	Lower Acuminata Beds		Lower Acuminata Beds
	"Grés super-liasique"	Blagdeni-Beds	"Marnes sableuses"	Blagdeni-Beds		"Marnes sableuses et bancs coralligènes"	"Marnes sableuses à C. Blagdeni"	Blagdeni-Beds	Grenchenberg Beds; Rothenfluh Beds	

Tab. 1. History of the interpretation of the lithostratigraphic units found within the Hauptrogenstein Formation. The correlation nowadays accepted was proposed by Schmassmann (1945). However, the correct position of the time-limit Bajocian/Bathonian only was recognized by Mühlberg (1900). Schmassmann (1945) was uncertain and proposed three options (dotted lines).

SECTION	COORDINATES (SWISS COOR-DINATE GRID)	LOWEST UNITS IN SECTION	TOP UNITS IN SECTION	THICKNESS		
				first succession	second succession	third succession
La Malcôte	581.050/249.950	Rothenfluh B.	Homomya M.	76	-	-
Les Malettes	582.300/249.200	Grenchenberg B.	Coarse Oncolite	78	35.5	4.5
Pichoux	583.450/237.900	L. Oolitic S.	Pierre Blanche	-	30	15.5
Côte de la Joux	583.450/239.900	Grenchenberg B.	Pierre Blanche	70	20	17.4
Le Coulou	590.700/236.800	Rothenfluh B.	Coarse Oncolite	73	46	-
La Haute Joux	593.250/250.400	Grenchenberg B.	Coarse Oncolite	-	34	5
Les Hautes Roches	594.000/238.350	Grenchenberg B.	U. Oolitic S.	-	-	-
Bellerive	594.000/248.000	Rothenfluh B.	L. Oolitic S.	-	-	-
Choindez	595.350/241.450	L. Oolitic S.	Coarse Oncolite	-	40	8
Soyhières	595.600/249.950	Grenchenberg B.	Coarse Oncolite	-	24	8
Grenchenberg	597.400/231.100	Rothenfluh B.	top L. Oolitic S.	44.5	-	-
Bettlachstock	597.600/230.250	U. Oolitic S.	Coarse Oncolite	-	-	6.3
Liesberg	599.525/249.400	L. Oolitic S.	Coarse Oncolite	-	36.5	6
Cholgraben	600.350/232.400	L. Oolitic S.	Coarse Oncolite	-	44	7.5
Challpass I	601.180/255.650	L. Oolitic S.	Coarse Oncolite	-	-	-
Challpass II	601.400/255.375	L. Oolitic S.	Coarse Oncolite	-	24	7
Fringeli II	602.500/246.900	L. Oolitic S.	Coarse Oncolite	-	-	-
Hinterweissenstein	603.400/232.950	Homomya M.	Coarse Oncolite	-	-	-
La Wustmatte	603.475/240.150	Rothenfluh B.	Coarse Oncolite	58	35	5
Fringeli I	603.500/246.950	U. Oolitic S.	Coarse Oncolite	-	-	4.5
Metzerlenchrüz	603.575/256.250	U. Oolitic S.	Coarse Oncolite	-	-	5.5
Fikigraben	604.450/232.700	Rothenfluh B.	L. Oolitic S.	-	-	-
Sagi	607.350/247.800	L. Oolitic S.	L. Oolitic S.	-	-	-
Lochhus	608.525/242.050	L. Oolitic S.	L. Oolitic S.	-	-	-
Meltingerbrücke	611.775/249.200	L. Oolitic S.	L. Oolitic S.	-	-	-
Eggfluh	611.825/255.450	L. Oolitic S.	L. Oolitic S.	-	-	-
Unt. Chratten	613.225/244.400	Rothenfluh B.	Coarse Oncolite	67	29	-
Neue Welt	615.775/260.150	Rothenfluh B.	Coarse Oncolite	-	-	-
Oensingen	619.100/237.375	L. Oolitic S.	Coarse Oncolite	-	30	5.7
Passwang I (west)	619.275/245.775	Rothenfluh B.	L. Oolitic S.	-	-	-
Passwang II (east)	619.425/246.650	U. Oolitic S.	Coarse Oncolite	-	-	-
Wasserfallen	619.600/247.775	U. Oolitic S.	Coarse Oncolite	-	-	5
Lusenberg	619.700/257.250	L. Oolitic S.	U. Oolitic S.	-	-	-
St.Wolfgang	620.300/241.525	L. Oolitic S.	Coarse Oncolite	-	25	7.4
Schleifenberg	622.750/259.900	Rothenfluh B.	U. Oolitic S.	78	27	-
Waldenburg I	623.400/248.000	Rothenfluh B.	L. Oolitic S.	-	-	-
Waldenburg II	623.500/248.000	Rothenfluh B.	L. Oolitic S.	-	-	-
Oberer Hauenstein	624.350/245.000	L. Oolitic S.	Coarse Oncolite	-	28	-
Bubenried	624.500/254.500	L. Oolitic S.	U. Oolitic S.	55	-	-
Lausen	624.600/257.600	Rothenfluh B.	L. Oolitic S.	-	-	-
Lauchfluh	626.500/247.450	L. Oolitic S.	Coarse Oncolite	57	21.5	3.6
Tenniker Fluh	628.000/254.700	L. Oolitic S.	Coarse Oncolite	-	21.5	-
Sissacher Fluh	628.575/258.600	L. Oolitic S.	L. Oolitic S.	-	-	-
Bohrung Diepflingen	630.500/254.200	Rothenfluh B.	Coarse Oncolite	63.5	19.7	5
Bohrung Rümlingen	632.040/252.590	Rothenluh B.	Spatkalk	67	21	3
Unterer Hauenstein	632.400/247.000	L. Oolitic S.	Spatkalk	46	10	-
Bohrung Häfelfingen	632.780/251.710	Rothenfluh B.	Spatkalk	60	17	5
Rothenfluher Fluh	635.800/257.500	Rothenfluh B.	L. Oolitic S.	46	-	-
Anwil	637.350/255.425	L. Acuminata B.	U. Oolitic S.	58.5	12	-
Bad Lostorf	637.850/249.000	L. Oolitic S.	U. Oolitic S.	55	12	-
Limperg	638.500/257.650	L. Oolitic S.	U. Oolitic S.	-	-	-
Schnäggenberg	639.200/250.800	L. Oolitic S.	U. Oolitic S.	57	-	-
Thiersteinerberg	639.250/260.300	L. Oolitic S.	U. Oolitic S.	-	-	-
Ruine Homberg	640.225/260.150	L. Oolitic S.	U. Oolitic S.	-	-	-
Gugen	641.875/250.500	U. Acuminata B.	Spatkalk	-	25	-
Bohrung Bänkerchlus	645.100/252.850	Rothenfluh B.	Spatkalk	40	28.8	2.5
Asperstrihen	645.275/254.550	Rothenfluh B.	Spatkalk	40	11	-
Bohrung Asperchlus	646.350/253.000	Rothenfluh B.	L. Oolitic S.	-	-	-
Densbüren	646.350/256.125	L. Oolitic S.	Spatkalk	-	-	12
Frickberg	646.400/262.000	Rothenfluh B.	U. Oolitic S.	32	12	-
Hombergeregg	647.350/253.300	L. Oolitic S.	Spatkalk	-	30	15
Thalheim	649.425/254.600	U. Oolitic S.	U. Oolitic S.	-	30	-
Thalheim II	649.525/254.575	U. Acuminata B.	Spatkalk	-	32	-
südlich Grosshalden	650.250/264.000	L. Olitic S.	Spatkalk	-	-	-
Dreierberg	650.500/256.650	Rothenfluh B.	U. Oolitic S.	-	-	-
Gislifluh	650.525/252.950	Rothenfluh B.	L. Oolitic S.	-	-	-
Talhalden	650.600/263.475	Rothenfluh B.	L. Oolitic S.	-	-	-
Auenstein I	653.900/252.700	L. Oolitic S.	L. Oolitic S.	50	-	-
Auenstein II	653.950/252.250	L. Oolitic S.	Spatkalk	-	6	3.5
Holderbank	655.500/252.800	Klingnau Fm.	Spatkalk	-	-	3.5
Bohrung Villigen	659.000/266.250	Klingnau Fm.	Spatkalk	-	-	-

Tab. 2. Studied sections, their location, stratigraphic range and thickness of specific units.

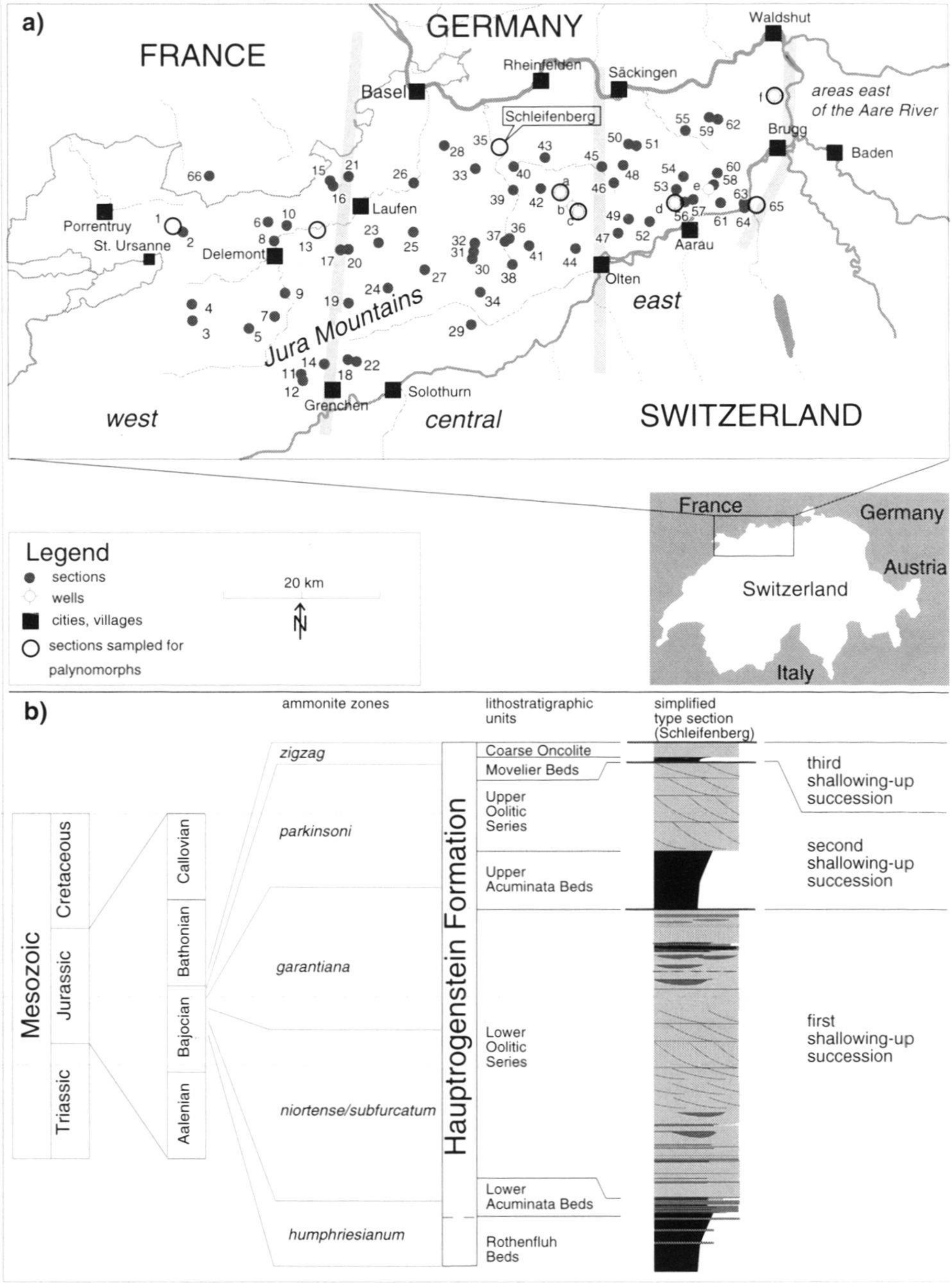


Fig. 2. a) Map of northern Switzerland showing location of the outcrops and wells studied within the Hauptrogenstein Formation. The subdivision into western, central and eastern Jura is related to lithologic changes within the Hauptrogenstein Formation occuring across these lines. The sections shown on this map are discussed in Gonzalez (1993).

b) Idealized type-section of the Hauptrogenstein Formation, including late Bajocian to earliest Bathonian biostratigraphic ammonite zones and their relation to lithostratigraphic units and shallowing-up successions.

Material and methods

The sedimentology of seventy sections in northern Switzerland was studied in detail (Tab. 2; Fig. 2a; Gonzalez 1993). The methods used to interpret paleobathymetry and sea-level fluctuations are discussed in detail elsewhere (Gonzalez 1993, 1996), and are only briefly summarized here. Detailed drawings of the sections and their correlation are made available from the Bibliothek, Geologisches Institut der Universität Basel (address as given above) upon request.

Paleo-environment and -bathymetry

The classification and interpretation of the carbonate rocks are based on the analysis of sedimentary facies and structures in outcrops and microfacies studies in thin sections as described in Wilson (1975), Bathurst (1975), Flügel (1978) and Scoffin (1982).

Paleo-transport directions of sediments were determined from oriented components (Schwarzacher 1963), dip direction of sedimentary structures (Allen 1968, Collinson & Thompson 1982) and the orientation of channels (DeCelles et al. 1983).

The water depth was estimated using the thickness of oblique-stratified oolitic and bioclastic grainstones and comparing sediment composition and faunal evidence to modern sedimentary environments (Gonzalez 1993). The height of sedimentary structures is approximately equal or less than one sixth of the water depth (Allen 1963; Yalin 1964; Jopling 1966). For sand waves with linear crests the average water depth is two times the sand wave height (Rubin & McCulloch 1980). The post-depositional erosion of sedimentary structures of ca. 25% (cf. Saunderson & Jopling 1980) and compaction (see below) were taken into account for the water depth calculations. The water depth of deposits distal to the calcarenitic shoals was estimated to be in the range of 10–20 m for proximal, non bioturbated and 15–25 m and more for distal, bioturbated tempestites, by comparing the sediments to modern counterparts (cf. Howard & Reineck 1981; Nelson 1982; Reineck 1984; Einsele 1992).

Sea-level fluctuations

A curve of third-order relative sea-level change (*sensu* Vail et al. 1977a, b; cf. also Allen & Allen 1990) was calculated (Fig. 3). Only major changes in sedimentation style on the level of members were considered because of the lack of age control at the level of small-scale sedimentary units. The relative sea-level is expressed as:

$$MS(t) = Bat(t) + Sd(t) + Sub(t) \quad (1)$$

Where MS is the relative sea-level at time t; Bat is paleobathymetry; Sd is the decompacted thickness of sediments deposited until time t, and Sub is the relative position of the underlying sedimentary units and hence, a function of the total subsidence. By integrating MS over time, a curve of relative sea-level change during this period is obtained (Fig. 3; Gonzalez 1996).

It is assumed that the total subsidence was constant during the deposition of the Hauptrogenstein Formation because subsidence variations occur less frequently than

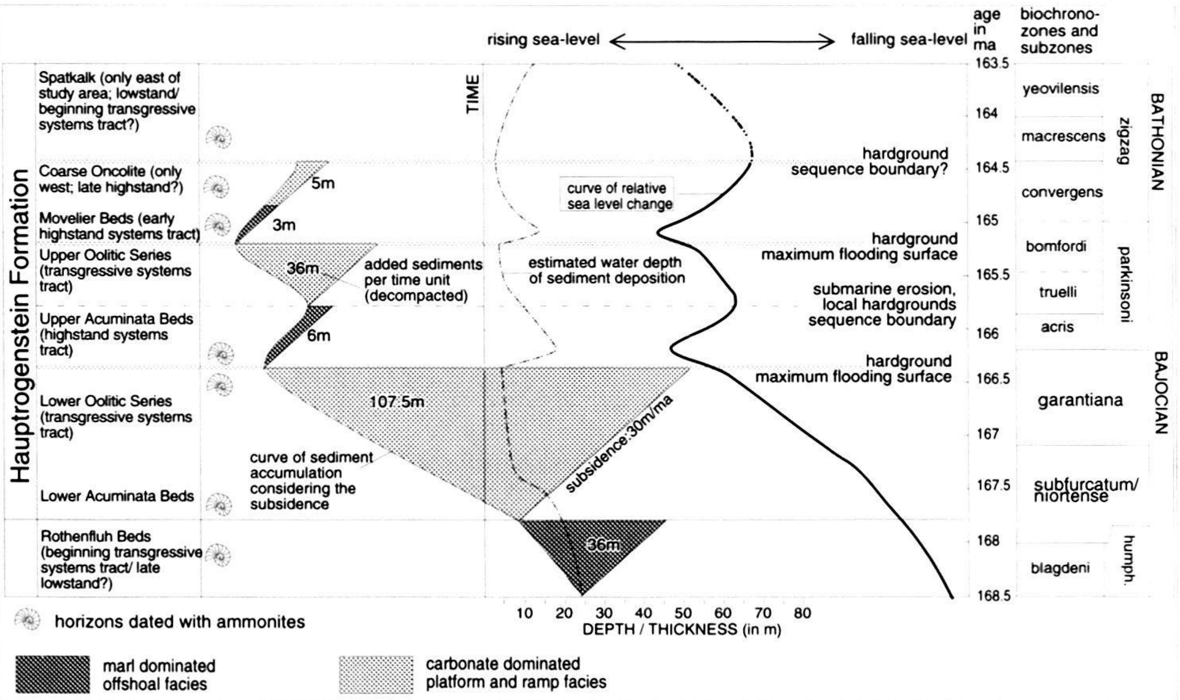
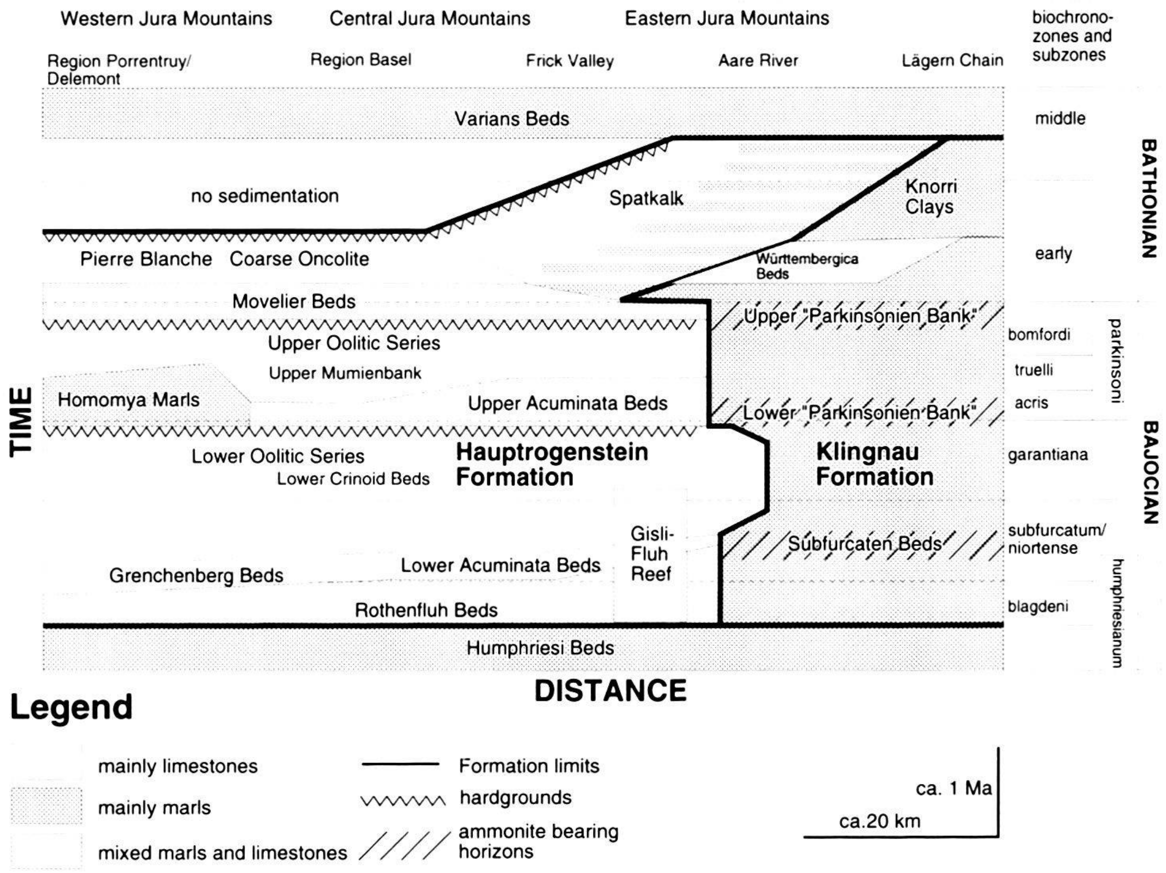


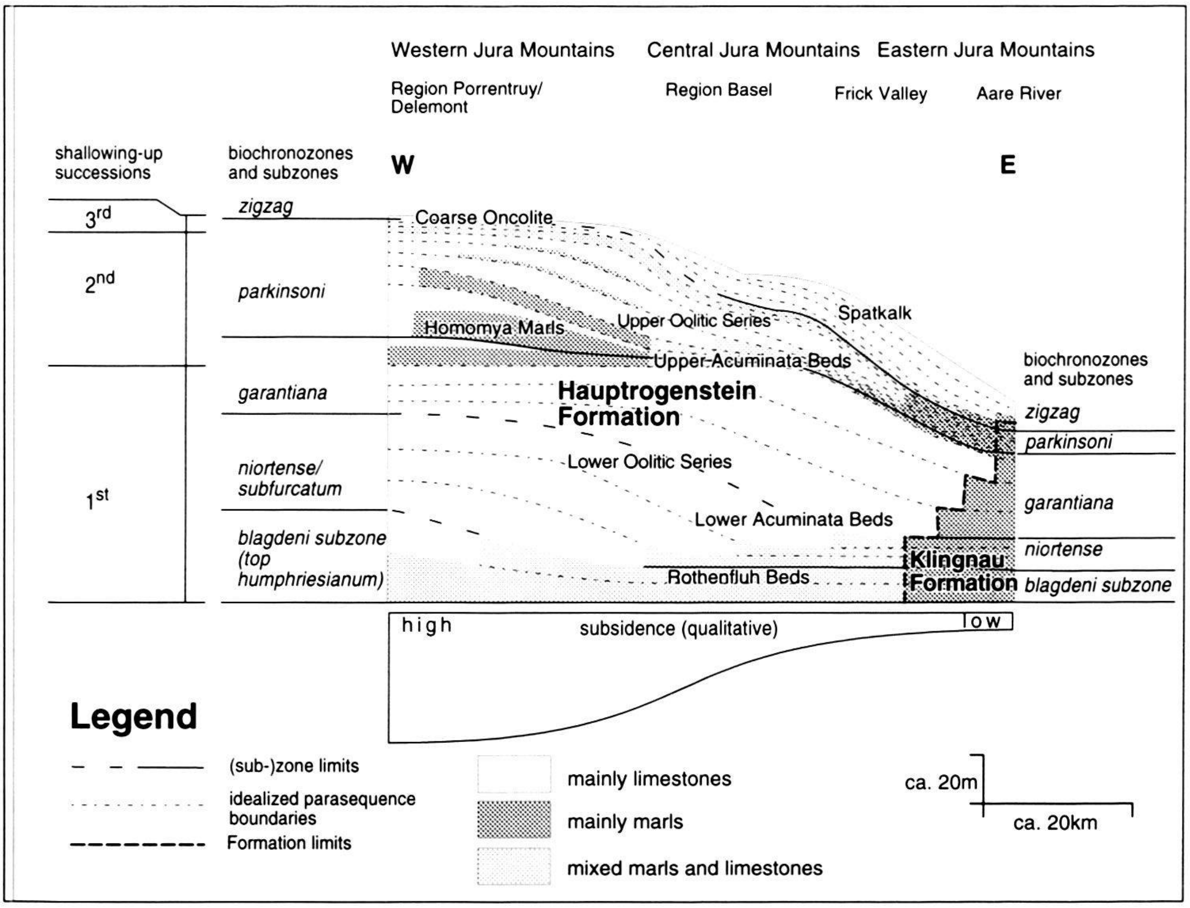
Fig. 3. Tentative qualitative evaluation of relative third-order sealevel changes in northern Switzerland during the late Bajocian to early Bathonian. Thickness of decompacted sedimentary units and estimation of depositional depths refer to the Schleifenberg section (see Fig. 2a). Age was interpolated from regional values. The absolute ages refer to data from Haq et al. (1988).

eustatic variations (Posamentier et al. 1988). Tectonic activity in northern Switzerland was probably confined to well-defined areas during the deposition of the Hauptrogenstein Formation, as evidenced locally by abrupt changes in thickness and facies (Wetzel et al. 1993; Gonzalez 1993).

Sediments used for interpretation of sea-level were decompacted following data from Matter et al. (1975), Hamilton (1976), Enos & Sawatsky (1981), Garrison (1981) and Shinn & Robbin (1983), assuming an initial porosity of 40–67% for pack- and grainstones (average porosity 55%, decreasing to 30% in the first tens of meters of burial, then changing only slowly), 64–78% in marls (decreasing to 50–60% within the first 200 m of burial) and 80% in micrites (decreasing to 40% within the first 100 m of burial).

Fig. 4. Correlation of lithostratigraphic units of the Hauptrogenstein and Klingnau Formations.
(top) Based on biostratigraphic dating of sections and additional lithologic correlation of time levels.
(bottom) Simplified, schematic west-east cross-section through the Hauptrogenstein Formation, showing the architecture of some lithostratigraphic units. Time-lines cut in an oblique, sigmoidal way through the platform, reflecting the progradation of oolitic units towards east during the evolution of the platform and ramp system.


Western Jura Mountains
Central Jura Mountains
Eastern Jura Mountains
biochrono-zones and subzones
Region Porrentruy/ Delemont
Region Basel
Frick Valley
Aare River
Lägern Chain
Varians Beds
middle
no sedimentation
Spatkalk
Knorri Clays
BATHONIAN
Pierre Blanche
Coarse Oncolite
Württembergica Beds
early
Movelier Beds
Upper "Parkinsonien Bank"
bomfordi
Upper Oolitic Series
Upper Mumienbank
truelli
parkinsoni
Homomya Marls
Upper Acuminata Beds
Lower "Parkinsonien Bank"
acris
TIME
Lower Oolitic Series
Lower Crinoid Beds
Hauptrogenstein Formation
Klingnau Formation
garantiana
BAJOCIAN
Gisli-Fluh Reef
Subfurcaten Beds
subfurcatum/ niortense
Grenchenberg Beds
Lower Acuminata Beds
Rothenfluh Beds
blagdeni
humphriesianum
Humphriesi Beds
DISTANCE
Legend
mainly limestones
mainly marls
mixed marls and limestones
Formation limits
hardgrounds
ammonite bearing horizons
ca. 1 Ma
ca.20 km


Western Jura Mountains
Central Jura Mountains
Eastern Jura Mountains
Region Porrentruy/ Delemont
Region Basel
Frick Valley
Aare River
shallowing-up successions
biochronozones and subzones
W
E
3rd
2nd
1st
zigzag
parkinsoni
garantiana
niortense/ subfurcatum
blagdeni subzone (top humphriesianum)
Coarse Oncolite
Homomya Marls
Upper Oolitic Series
Spatkalk
Upper Acuminata Beds
Hauptrogenstein Formation
Lower Oolitic Series
Lower Acuminata Beds
Rothenfluh Beds
Klingnau Formation
biochronozones and subzones
zigzag
parkinsoni
garantiana
niortense
blagdeni subzone
high
subsidence (qualitative)
low
Legend
(sub-)zone limits
idealized parasequence boundaries
Formation limits
mainly limestones
mainly marls
mixed marls and limestones
ca. 20m
ca. 20km

Biostratigraphy

To establish a biostratigraphic framework, newly found ammonites as well those housed in various museums in northern Switzerland were re-determined by Dr. G. Dietl (Stuttgart, Germany). The taxa names, locations, horizons, ages and repositories are listed in an appendix, which is made available on request from the Bibliothek, Geologisches Institut der Universität Basel (address as given above).

However, the occurrence of ammonites in shallow-water carbonates is very sparse, and biostratigraphic information is not continuous. To bridge this gap, several sections were sampled for dinoflagellates. Even in medium- to high-energy, oolitic carbonates, cysts were found to be sufficiently frequent to provide a stratigraphic age. The sections sampled for dinoflagellates are indicated on Figure 2a. The range charts of dinoflagellates are available on request from the Bibliothek, Geologisches Institut der Universität Basel (address as given above).

Lithostratigraphy of the Hauptrogenstein and Klingnau Formations

The sediments of the middle Bajocian to early Bathonian of northern Switzerland were subdivided by Gonzalez (1993) into two lithostratigraphic formations (Fig. 4): the **Hauptrogenstein Formation** ("Celtic realm" in Trümpy 1980) consists of shallow-marine carbonates and occurs west of the Aare River in the Jura Mountains. The **Klingnau Formation** is of the same age and consists of marls with intercalated bioclastic limestone beds. It is localized east and south of the Aare River ("Swabian realm" in Trümpy 1980; Figs. 2a, 4). Table 3 provides a translation into German and French of all stratigraphic terms used in this paper.

Klingnau Formation

The lower limits of the Klingnau Formation (synonymous: Parkinsoni Beds; Mühlberg 1900; Schmassmann 1945; Voss 1969) are the Humphriesi Beds. The upper limit is the Spatkalk, respectively Varians Beds, where the Knorri Clays occur.

The Klingnau Formation is 50 m thick at its western border and only a few meters in northeastern Switzerland. It consists of alternations of cm to dm thick marls and bioturbated, bioclastic mud- to packstones. Towards east and south the lithology is increasingly dominated by marls and mudstones. The main depositional trend is coarsening and thickening upward.

Three lithologically similar horizons can be discriminated within the Klingnau Formation. They are all a few centimeters to decimeters thick and consist of bioturbated bioclastic beds often containing ammonites: the **Subfurcaten Beds** at the top of the lower third of the succession (Niortense/Subfurcatum Zone), and the **Lower** and **Upper "Parkinsonien Bank"**, found around the base of the upper third of the succession, separated by about one to two meters of marls (Fig. 4). They are early respectively late Parkinsoni Zone in age. The occurrence of these horizons is somewhat patchy, but they serve as excellent correlation horizons where they occur.

The **Württembergica Beds** form a lensoid layer at the top of the Klingnau Formation between the Aare River and the Lägern Chain. The layer can be up to a few meters thick

English	Deutsch	Français
Klingnau Formation	Klingnau Formation	Formation de Klingnau
Württembergica Beds	Württembergica Schichten	Couches à Parkinsonia württembergica
Knorri Clays	Knorri Tone	Argiles à Ostrea knorri
"Hauptrogenstein" Formation	Hauptrogenstein Formation	Formation du "Hauptrogenstein"
Rothenfluh Beds	Rothenfluh Schichten	Couches de Rothenfluh
Subfurcaten Beds	Subfurcaten Schichten	Couches à subfurcatum
Grenchenberg Beds	Grenchenberg Schichten	Couches de Grenchenberg
Iron Oolite (of the Grenchenberg Beds)	Eisenoolith (der Grenchenberg Schichten)	Oolite Ferrugineuse (des Couches de Grenchenberg)
Lower Acuminata Beds	Untere Acuminata Schichten	Couches Inférieures à Ostrea acuminata
Gislifluh Reef	Riff der Gislifluh	Récif de Gislifluh
Lower Oolitic Series	Untere Oolithische Serien	Séries Oolitiques Inférieures
Nerinea Beds	Nerinea Schichten	Couches à Nerinea basilensis
Lower "Mumienbank"	Untere Mumienbank	"Mumienbank" Inférieure
Lower Crinoid Beds	Untere Crinoiden Schichten	Couches Inférieures a crinoides
Meandrina Beds	Meandrina Schichten	Couches à Cidaris meandrina
Homomya Marls	Homomyen Mergel	Marnes à Homomyes
Upper Acuminata Beds	Obere Acuminata Schichten	Couches Supérieures à Ostrea acuminata
Upper Oolitic Series	Obere Oolithische Serien	Séries Oolitiques Supérieures
Upper "Mumienbank"	Obere Mumienbank	"Mumienbank" Supérieure
Wittnau Reef	Riff von Wittnau	Récif de Wittnau
Movelier Beds	Movelier Schichten	Couches de Movelier
Upper Crinoid Beds	Obere Crinoid en Schichten	Couches Supérieures à Crinoides
Coarse Oncolite	Grober Onkolith	Oncolite Grossiere
"Pierre Blanche"	"Pierre Blanche"	Pierre Blanche

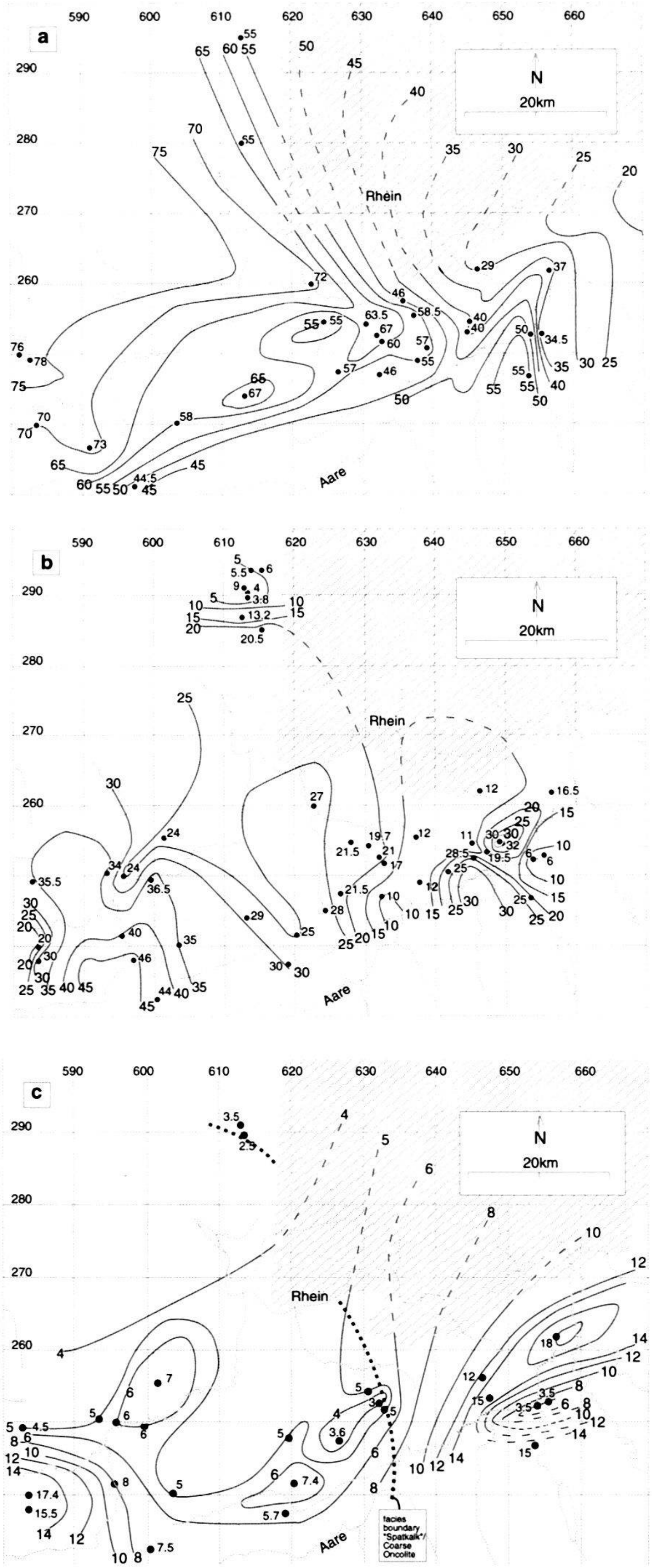
Tab. 3. Translation of the lithostratigraphic terms used in this paper into German and French.

and consists of alternations of marls and fine-grained, strongly bioturbated wacke- to packstones, characteristically very rich in mollusks.

The **Knorri Clays** replace the Spatkalk of the Hauptrogenstein Formation (see below) east of the Lägern Chain. They are a few meters thick and consist of dark clays with occasional layers of fine-grained, nodular limestone, locally with accumulations of the oyster *Ostrea knorri*.

Hauptrogenstein Formation

The Hauptrogenstein Formation occurs west and north of the Aare River, in the Tabular and Folded Jura (Fig. 4; synonyms: "Oolithe Subcompacte" and "Grande Oolithe", "Älterer Rogenstein", "Hauptrogenstein"). Its lower limits are the Humphriesi Beds,


a
b
c
590
600
610
620
630
640
650
660
290
280
270
260
N
20km
Rhein
Aare
facies boundary "Spatkalk"/ Coarse Oncolite

the upper limits are the Varians Beds. The thickness of the formation is 40–50 m in the eastern and up to 130 m in the western Jura, with local variations (Fig. 5).

The shallow-marine carbonates of the Hauptrogenstein Formation form three shallowing-upward successions, each capped by a hardground, synchronous in terms of biostratigraphic resolution (Fig. 2b, 4). Each succession starts with marls and marl/carbonate alternations. These are overlain by large scale (0.5–2 m, in some cases 4–5 m thick), oblique-stratified, oolitic grainstones in the central Jura. The oblique-stratified beds show convex-upward reactivation surfaces, climbing-upward current ripples and other sedimentary structures characteristic of tidal sediments. In the western Jura a large number of facies associations, such as oolites, coral-rich beds, small patch-reefs, tempestites, oncoidic and micritic sediments are found. In the eastern Jura, oolites gradually are replaced by marls and alternating marls and bioclastic sediments. An exception from this pattern is found within the third shallowing-up succession, where oncolites in the west are replaced by bioclastic carbonates in the east. The following members can be recognized within the Hauptrogenstein Formation (Fig. 4):

The **Rothenfluh Beds** occur throughout the Jura (synonyms: "Blagdeni Schichten", "Blaue Kalke" *sensu* Quenstedt 1856/57). They consist of marly, bioclastic mud- and wackestones interbedded with fine-grained, often quartz-bearing (up to 25%), nodular limestones. The unit is approximately 25 m thick in the western and 10 m in the eastern Jura.

The Rothenfluh Beds can be considered a member of the Hauptrogenstein Formation, if the Hauptrogenstein Formation is defined in a genetic sense as an alloformation. However, in a strictly lithostratigraphic sense the Rothenfluh Beds should not be included in the Hauptrogenstein Formation.

The **Grenchenberg Beds** are an up to 15 m thick unit occurring above the Rothenfluh Beds in the western Jura (synonyms: "Marnes sableuses à sphérites": Rollier 1911; "Kalkige Fazies der Blagdeni Schichten": Lusser 1980).

Typically, lutitic to fine-arenitic, locally coarse arenitic or ruditic, fining-upward bioclastic limestones alternate with a marly background sedimentation. The Grenchenberg Beds may contain 0–25% silty to very fine-sand quartz grains.

The **"Oolite Ferrugineuse"** (Thurmann 1832) (not shown in Fig. 4a) occurs locally within the Grenchenberg Beds. These iron-oolites consist of sparry, bioclastic limestones containing coarse arenitic echinoderm fragments and iron-oolites. Typically, oblique stratifications alternate with centimeter-thick marl layers.

The up to 5 m thick **Lower Acuminata Beds** appear in the central Jura. They are oolitic to oncolitic, bioclastic, bioturbated, with cm to dm thick limestones, separated by marls which decrease upwards in thickness.

Fig. 5. Isopachs for the a) first, b) second and c) third shallowing-upward succession of the Hauptrogenstein Formation. The thicknesses of the Rothenfluh Beds are not included in the values of the first shallowing-upward succession, because the Rothenfluh Beds are not or only partially represented in most studied outcrops. It is estimated to be around 25 m in the west and 10 m in the east.
Only complete sections were considered. Data points in Germany were estimated after Ernst (1989). Values are not decompacted. The equidistance is given in meters. Hatched areas (Black Forest) are eroded. All coordinates are given in Swiss coordinates.

The **Gislifluh Reef** is an east-west striking columnar coral reef, a few hundred meters long, about 100–200 m wide and more than 40 m thick. At the base, marls alternate with coarse, bioclastic layers mainly consisting of echinoderm, brachiopod and mollusk fragments, overlain by coral rubble and other bioclastic material. The upper portion consists of several meter-thick layers of autochthonous corals, mostly head corals such as *Isastrea* and *Thamnastrea*, often one growing on top of the other. The cavities are filled with oolitic or bioclastic wacke- to packstones. Planar, erosional horizons and beds of allochthonous corals interrupt these layers at regular intervals.

The **Lower Oolitic Series** (Fig. 4; synonyms: "Oolithe subcompacte": Thurmann 1832; "Unterer Hauptrogenstein": *sensu* Mühlberg 1900, Ernst 1989; including the "Mittlerer Hauptrogenstein" of Schmassmann 1945) are 70 m thick in the western and 20 m thick in the eastern Jura; typical are values of about 50 m (Fig. 5a). The limestones are composed of oolitic and bioclastic, locally micritic pack- to grainstones. Characteristic sedimentary structures are oblique stratifications. The Lower Oolitic Series is capped by a platform-wide, submarine hardground.

Within the Lower Oolitic Series, several beds can be distinguished: at the base, the **Lower Crinoid Beds** in the central Jura, composed of a few centimeter thick, crinoidal limestones, with autochthonous crinoids (*Chariocrinus andreae* DESOR) and intercalated, up to one centimeter thick, muddy beds (Meyer 1987); the **Nerinea Beds** in the western central Jura, 1–2 m thick, micritic wacke- to packstones, containing large numbers of gastropods *(Nerinea basilensis)*; the **"Lower Mumienbank"** in the central Jura (synonym: "Mumienbank"; cf. Sack 1971; Ernst 1989) is a 0.5–2 m thick, oncomicritic to -sparitic limestone containing oncoids with a diameter of 6–60 mm (Ernst 1989); the **Meandrina Beds** in the eastern Jura consist of marly, bioturbated, partly oolitic and oncolitic, fossil-bearing layers at the base of the upper third of the Lower Oolitic Series.

The **Homomya Marls** separate the Lower from the Upper Oolitic Series in the western Jura, forming the base of the second shallowing-upward succession (Fig. 4). Their thickness varies between 5 and 15 m (values included in Fig. 5b). They consist of alternations of cm to m thick marls with bioclastic, sometimes oolitic and oncolitic limestones. Characteristic are large bivalves, such as *Homomya* and *Pholadomya*.

The 0.2–3.5 m thick **Upper Acuminata Beds** form the base of the second shallowing-upward succession in the central and eastern Jura (Fig. 4). Outcrops show a thickening-upward succession of cm to dm thick, oncoidic and bioclastic marl beds alternating with cm to dm thick, bioturbated wacke- to grainstones, often containing bioclasts, intraclasts, iron-ooids and oncoids.

The **Upper Oolitic Series** (synonyms: "Grande Oolite": Thurmann 1832; "Upper Hauptrogenstein": e.g. Mühlberg 1900; Schmassmann 1945) are 5–7 m thick in the eastern and up to 30 m thick in the western Jura (Fig. 4, 5b). They consist of oolitic mud- to grainstones with fine-sand sized oolites, which are usually smaller than those found within the Lower Oolitic Series. The matrix can be micritic, especially in the western Jura. Typical sedimentary structures are oblique stratifications, ranging from centimeter-thick ripple laminae to large foresets with a thickness of several meters. The top of the Upper Oolitic Series is a platform-wide hardground.

Within the oolitic succession the **Upper "Mumienbank"** in the area of Laufen, and the **Wittnau Reef**, a 5 m thick and 1–2 km broad coral reef between Säckingen (Germany) and Olten can be distinguished.

The up to 1 m thick **Movelier Beds** form the base of the third shallowing-upward succession (Fig. 4; values included in Fig. 5c). They consist of marls alternating with lenticular limestones, both rich in complete as well as destroyed biogenous components, such as corals, brachiopods and mollusks.

The **"Spatkalk"** dominates the top of the Hauptrogenstein Formation from the eastern Jura to the Lägern Chain (Fig. 4). Its thickness varies between 2 and 12 m (values included in Fig. 5c). Characteristic are bioclastic (usually coarse echinoderm fragments), often strongly limonitic pack- to grainstones with mm to dm thick marls as background sediments.

The **Coarse Oncolite** replaces the "Spatkalk" in the western and central Jura (Fig. 3, 4; synonyms: "Ferrugineus-" or "Ferruginea-Oolith": e.g., Ernst 1989; "Grober Oolith"; "Oolite cannabine": Rollier 1911). It has a thickness of less than 1–3 m (values included in Fig. 5c). The lithology consists of oncomicritic wacke- to packstone.

The **"Pierre Blanche"** gradually replaces the Coarse Oncolite in the westernmost Swiss Jura. It is a few to tens of meters thick and consists of light-colored, cm to dm thick, micritic mudstones. Rare components are small foraminifera and gastropods.

Biostratigraphy based on ammonites

The deposition of the Rothenfluh Beds started during the Blagdeni Subzone. In the western Jura, these were covered during the late Blagdeni Subzone by the bioclastic Grenchenberg Beds. Both *Teloceras multinodum* QUENSTEDT and *Teloceras coronatum* SCHLOTHEIM were found at the base of the Grenchenberg Beds. The sedimentation of ooids started in the eastern Jura during the latest Niortense/Subfurcatum, respectively earliest Garantiana Zone as indicated by *Spiroceras orbignyi* BAUGIER & SAUZÉ.

The top of the Lower Oolitic Series lies probably within the latest Garantiana Zone. Only one ammonite – *Bigotites* sp. – was found within these sediments in the Jura north of Delémont and it is attributed to the late Garantiana Zone, based on comparisons with other ammonites in the collection of the Museum am Löwentor (Stuttgart, Germany; pers. comm. Dr. G. Dietl 1993).

Within the Homomya Marls and, respectively, the Upper Acuminata Beds a rich ammonite fauna is found. Characteristic are *Parkinsonia acris* WETZEL and *Parkinsonia subarietis* WETZEL, both of which are attributed to the Acris Subzone (early Parkinsoni Zone).

No ammonites are known from the Upper Oolitic Series. However, the ages of the over- and underlying units indicate a deposition during the late Parkinsoni Zone.

The basal Movelier Beds were deposited during the latest Parkinsoni Zone as indicated by several finds of *Parkinsonia planulata* QUENSTEDT and *Parkinsonia parkinsoni* SOWERBY. The sedimentation of the Coarse Oncolite started during the latest Parkinsoni Zone, and ended at the earliest Bathonian (early Zigzag Zone) as documented by many finds, for example *Parkinsonia württembergica* (OPPEL) or *Siemiradzkia aff. aurigera* (OPPEL). Therefore, the Bajocian/Bathonian boundary has to be set within the Coarse Oncolite. A few fossils document that the upper Movelier Beds could be of earliest Bathonian age (e.g. *Prinsonia* sp., from Les Malettes, Canton Jura). However, these finds have all been made by private collectors and are not exactly located in sections. Representatives of the late Zigzag Zone have not been found within the Coarse Oncolite.

The base of the "Spatkalk" in the eastern Jura lies within the late Parkinsoni Zone. Sedimentation until the late Zigzag Zone (lower Bathonian), possibly until middle Bathonian is documented for example by *Parkinsonia convergens* BUCKMAN or *Parkinsonia fretensis* WETZEL from the top of the Spatkalk in several outcrops east of the Aare River.

Discussion and paleoenvironmental interpretation

Blagdeni Subzone (Humphriesianum Zone; Fig. 6a)

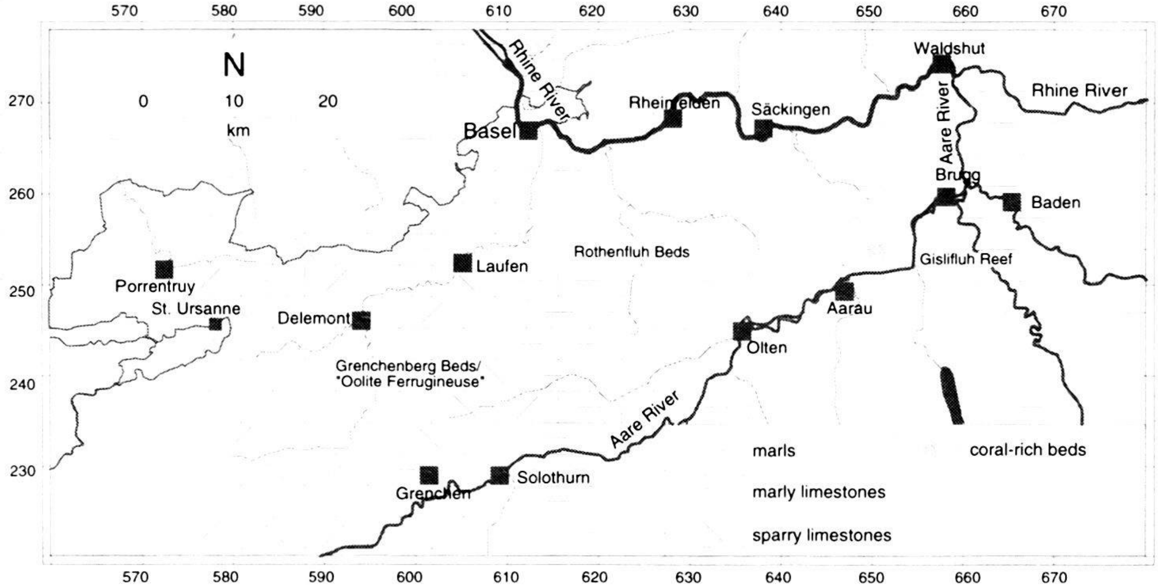
Marls and bioclastic quartzitic bioturbated limestones were deposited in the northern Swiss realm (Rothenfluh Beds). The high percentage (up to 25%) of quartz grains within the lower sedimentary units – the highest amount within the Hauptrogenstein Formation – is interpreted as an influence from possible nearby land areas (e.g. the Rhenish Massif, Fig. 1).

During the late Blagdeni Subzone oblique stratified bioclastic limestones were deposited in the western Jura (Grenchenberg Beds), while the facies did not change in the central and eastern areas. This transition from non-bioturbated limestones in the west to bioturbated marls in the east was supposedly related to a bathymetric gradient with an increase in the estimated water depth from 10–20 m in the west to 15–30 m in the east. Within the Grenchenberg Beds, iron-oolitic patches with coarse-sand sized, sparry bioclasts, transported from N to S were deposited ("Oolite Ferrugineuse"). They were supposedly deposited within broad, submarine channels produced, for example, by rip currents (Ingle 1966).

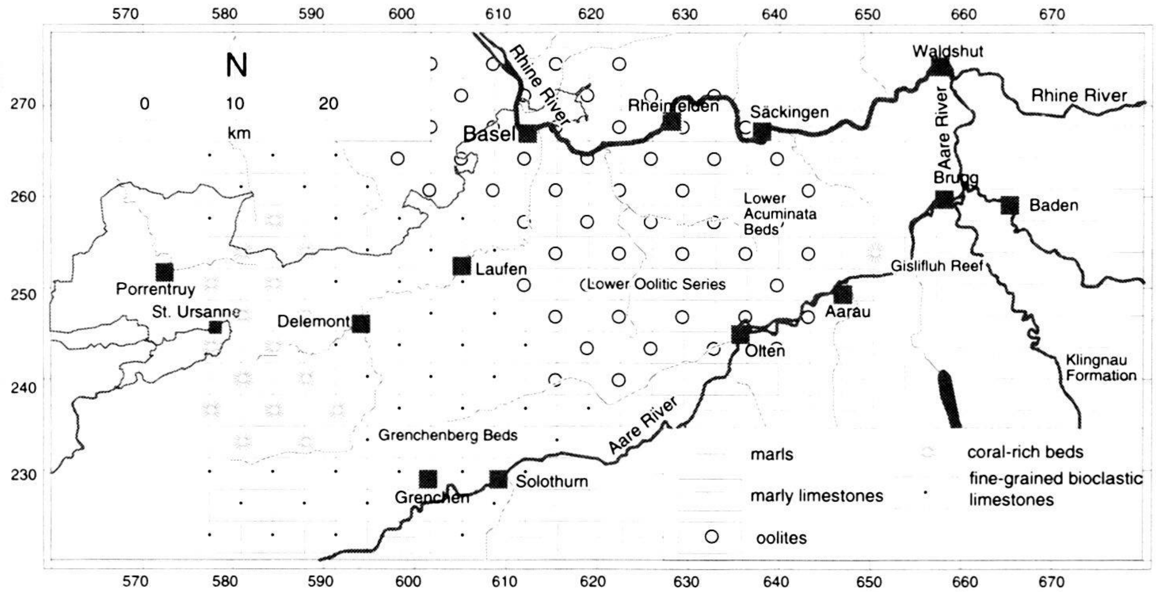
Around this time, the Gislifluh Reef nucleated in the southeastern-most Jura (cf. Mühlberg 1908; Schmassmann 1945), probably on a morphologically elevated zone (Gonzalez 1993; Wetzel et al. 1993) as indicated by thickness from the reef to surrounding units and abrupt lateral facies transitions. The spatial pattern of the facies belts and varying sediment thicknesses in this part of the Swiss Jura were probably affected by synsedimentary tectonic movements (Wetzel et al. 1993).

Subfurcatum/Niortense Zone (Fig. 6b)

In the central part, a broad area was covered by oolites (Lower Oolitic Series). A relative slow rise in sea-level combined with a steady subsidence (cf. Wildi et al. 1989; Loup 1992) continuously provided new accommodation space for the oolitic sediments (Gonzalez 1996). The oblique stratification of the oolites is interpreted to be related to tidal sand waves that were formed on a shoal (estimated water depth 1–10 m), documenting the establishment of a broad north-south trending oolitic barrier. Sediment transport was mainly from north to south, indicating an ebb-tide dominance. The barrier migrated eastwards during the Subfurcatum/Niortense Zone, as evidenced by the paleontological data. Simultaneously, the area that was covered by oolitic sediments became broader during the late Subfurcatum/Niortense and Garantiana Zones. This broadening of the oolitic belt could have been caused by a redistribution of ooids during storm events. In modern oolitic environments such as the western Bahamas, the large-scale shape of most oolitic sand bodies is determined by currents produced by storms (Ball 1967; Hine et al. 1981a, b), whereas the smaller-scale structures of these sand bodies are controlled by tidal cur-



a) late Blagdeni Subzone (latest Humphriesianum Zone)



b) Niortense/Subfurcatum Zone

Fig. 6. Palinspastic, paleoenvironmental reconstructions of Northern Switzerland at different times: a) Late Blagdeni subzone (late Humphriesianum zone). Deposition of the Grenchenberg and Rothenfluh Beds. Nucleation of the Gislifluh Reef in the southeastern Jura. East of the Aare River, deposition of the Klingnau Formation. b) Niortense/Subfurcatum zone. Evolution of the central oolitic shoals (Lower Oolitic Series). To the west, deposition of the upper Grenchenberg Beds in a low-energy sedimentary environment. To the east, with increasing water-depth, the high-energy oolites are transported into areas of lower energy and bioturbated (Lower Acuminata Beds). Full development of the Gislifluh Reef as a bioherm.

rents (Hine et al. 1981a). The areas of effective ooid production are relatively small. This was probably also true for the oolites of the Hauptrogenstein Formation.

In the western Jura, a protected platform with patch reefs and coral meadows developed. East of the barrier, cross-bedded oolites graded laterally into alternations of bioturbated oolites and marls (Lower Acuminata Beds), as the oolitic shoal merged into the relatively deeper marine (water depth ca. 20–40 m), epicontinental central European sea. Ooids were transported by storm-currents into these low-energy areas and subsequently bioturbated. Thin sections from these sediments show irregular algal growths on an oolitic nucleus, documenting the transition from high- to lower-energy environments.

East of the Aare River marls prevailed, but with some intercalations of bioclastic layers (Klingnau Formation). In the area of the Gislifluh, the reef had fully evolved into a bioherm.

Garantiana zone (Fig. 6c)

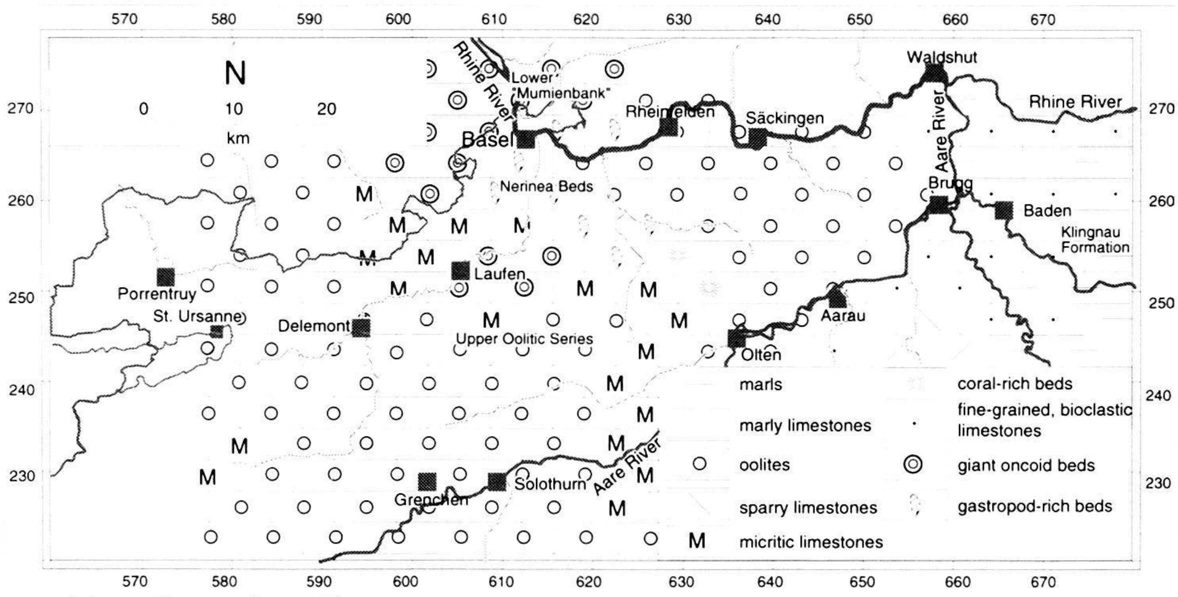
During this time, oolites covered almost the whole Jura realm (Lower Oolitic Series). The ooid sedimentation was occasionally interrupted by extensive bioclastic layers, some of which can be correlated over distances of more than 50 km (e.g. Meandrina Beds). Such layers can be explained with small-scale changes in sea-level, that interrupted the deposition of ooids and allowing the growth of extensive coral meadows (Gonzalez 1996).

In the western Jura, micrites accumulated on a large, protected platform with low water energy. Episodic oolitic layers within these micrites possibly were deposited by storms. Giant oncoids formed immediately in the back of the oolitic barrier in zones of moderate energy (e.g. Lower "Mumienbank") along the eastern border of the modern Rhine valley, possibly near broad, subtidal inlets that connected the platform interior with the epicontinental sea. Accumulations of *Nerinea* (Nerinea Beds) formed in a similar stratigraphic and paleogeographic position. These gastropods probably took advantage of favorable ecological conditions at the back of the oolitic barrier.

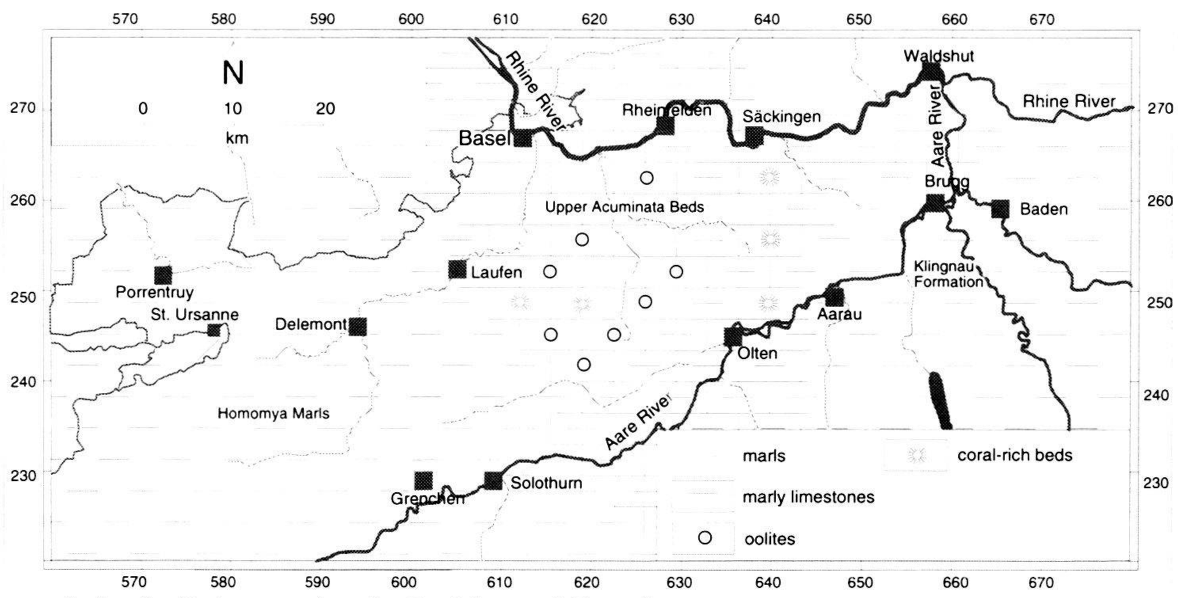
The eastern Jura was dominated by oolitic sedimentation. While these sediments were strongly bioturbated in the northeast, oblique stratified, massive oolites were predominantly deposited the southeastern Jura. The Gislifluh Reef ceased to exist, as the corals were covered by ooids. East of the Aare River the deposition of marls continued (Klingnau Formation).

Acris Subzone (early Parkinsoni Zone; Fig. 6d)

During the Acris Subzone, the sea-level reached a relative, possibly even eustatic highstand (Vail et al. 1984; Haq et al. 1988; Hallam 1988; Rioult et al. 1991; Gonzalez 1996). The formation of ooids in northern Switzerland ceased during this time. The water was deepest in the western Jura (ca. 25–40 m or even more); there subsidence was faster than in the eastern areas (Gonzalez 1993) as documented by the deposition of the Homomya Marls. The relatively large water depths were deduced from up to 15 m thick distal marly deposits, locally interrupted at their top by large-scale bioclastic and oolitic oblique-stratified sand bodies (thickness of 4–5 m and more without considering post-depositional erosion and compaction). In contrast, in the central Jura shallower marine (water depth



c) late Garantiana Zone



d) Acris Subzone (early Parkinsoni Zone)

Fig. 6. c) Garantiana zone. Top of the first shallowing-upward succession within the Hauptrogenstein Formation. Largest extension of the oolitic platform. In backbarrier areas, several zones with characteristic components are found: the giant oncolites of the Lower "Mumienbank" and the gastropods of the Nerinea Beds. The Gislifluh Reef is drowned in oolites. d) Acris subzone (early Parkinsoni zone). Relative highstand of sealevel (Gonzalez 1996). Sedimentation of the Homomya Marls in western, fast subsiding areas and of the Upper Acuminata Beds in the morphologic high area of the former oolitic shoals in the central Jura. The eastern rim of this previous shoal is occupied by a reef (Wittnau Reef).

15–25 m), marly and bioclastic deposits (Upper Acuminata Beds) accumulated which in places only reached a thickness of 50 cm. The change in lithology between the facies belts of the Upper Acuminata Beds and the Homomya Marls occurred within a few kilometers along a more or less north-south trending line near Laufen.

In the east, a very similar set-up marks the transition from the Upper Acuminata Beds to the deeper marine Klingnau Formation (water depth 25–40 m). Both deposition areas were separated by the Wittnau Reef, situated along a well defined narrow north-south line between Säckingen (Germany) and Olten.

The Upper Acuminata Beds were deposited approximately in the same geographical position as the oolitic barrier of the Lower and Upper Oolitic Series. The Homomya Marls in the west occupied more or less the position of the back barrier lagoon. Consequently, a central north-south trending morphologic high separated faster subsiding areas in the east and west and had large influence on the large scale distribution of facies belts. Such a pattern has also been observed for older sediments: Trümpy (1949, 1980) postulated a similar morphological high ("Sissacher Barre") for the Liassic. The differences in sediment thickness resulted from the differences in subsidence rates which were not greater than several tens of meters per million years.

Beginning Parkinsoni zone (Fig. 6e)

A relative sea-level fall during this period (Gonzalez 1993) led to the re-establishment of the shallow-marine, high energy oolitic barrier (Upper Oolitic Series). The main transport direction produced by tides continued to be from the north to the south. The size of ooids is typically smaller than their older counterparts. The oolitic sediments did not prograde as far to the east as during the Garantiana Zone, passing into marly deposits already in the Frick Valley area. These observations could reflect 1) lower water energy level, due to changes in water circulation or greater water depths than during the deposition of the Lower Oolitic Series, 2) changes in local climate, or 3) possibly a combination of both factors.

In the southeastern Jura, up to ten meter thick bioclastic sediments were deposited, probably in deeper water areas (water depth > 10–20 m?) produced by an increased local subsidence (Gonzalez 1993). In the western Jura, micritic lenses were deposited in low energy, back-barrier areas. Around Laufen (BL), similar conditions as during the Garantiana Zone favored the formation of giant oncoids (Upper "Mumienbank").

Terminal Parkinsoni zone

On top of the hardground that sealed the Upper Oolitic Series, a diverse fauna lived in marly background sediments (Movelier Beds). The substitution of oolites by marls was interpreted by Gonzalez (1996) as a relative highstand of sea-level. The sedimentation was controlled by storms in bathymetrically deeper areas in the east and west and might have been influenced by tides in some areas in the western and central Jura (Gonzalez 1993). The dominant transport directions were again from north to south, showing a dominance of ebb-tides. In some western areas coral agglomerations occur. The deposition of the Spatkalk began in the eastern Jura.

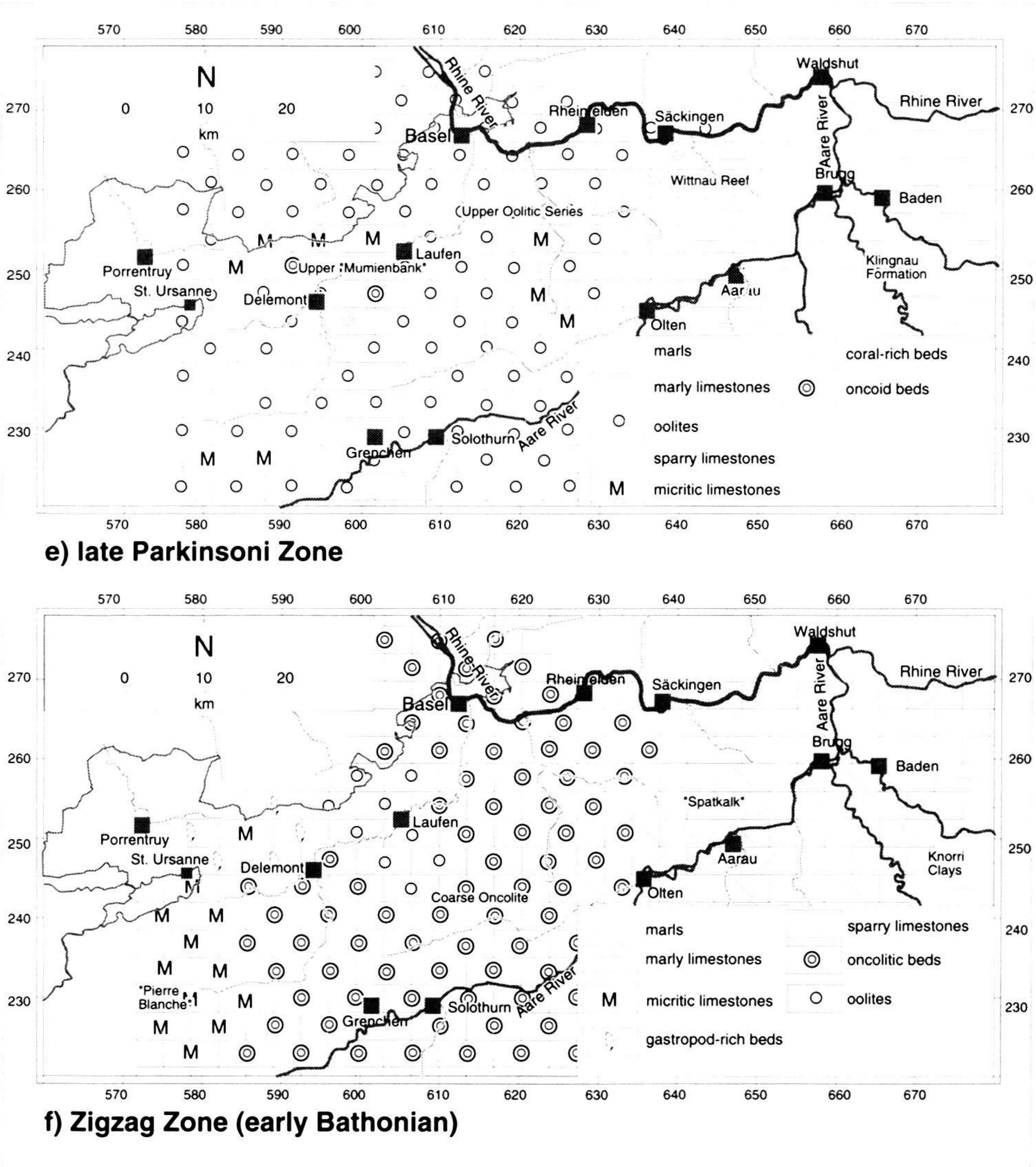


Fig. 6. e) Late Parkinsoni zone. Re-establishment of the oolitic platform. Deposition of the Upper Oolitic Series. Note that it does not prograde as far to the east as its older equivalent. f) Early Zigzag zone (basal Bathonian). The end of the oolitic platform. Deposition of oncolites in a micritic matrix on the area of the former platform, possibly with deepening upward trend (cf. Gonzalez 1996). In the eastern Jura, the "Spatkalk" progrades over the Aare River and covers the western units of the Klingnau Formation. The "Spatkalk" is replaced towards east by the deeper marine Knorri Clays.

Zigzag zone (to middle Bathonian; Fig. 6f)

In the western and central Jura, moderate energy conditions favored the formation and deposition of oncoids in a micritic matrix (Coarse Oncolite), passing into purely micritic beds towards west ("Pierre Blanche"). The water depth is difficult to interpret because of a lack of diagnostic sedimentary structures. Rare ooids have been found in north-south trending channel systems between Delémont and Laufen. In the eastern Jura, towards the open epicontinental sea, a wedge of coarse-grained bioclastic material, mostly echinoderms, prograded towards east and south (Spatkalk). In shallow-marine areas (water depth around 10 m?), oblique stratifications have probably been formed by tides, but most deposits lack the typical characteristics of tidal sediments (e.g. reactivation surfaces, bundles) and have been attributed to episodic storm deposition in deeper water environments (10–20 m).

The trend in the change of lithology, already visible in the Upper Oolitic Series was accentuated during the Zigzag Zone. The transition from oolites to bioclastic carbonates in northern Switzerland might be a response to a climatic change as suggested by Fritz (1965). An increasing influx of waters from the north led to the appearance of boreal elements in the ammonite fauna (Enay & Mangold 1982; G. Dietl, Stuttgart, FRG, pers. comm. 1993) and dinoflagellate flora (Smelror 1993; W. Wille, Tübingen, FRG, pers. comm. 1994). This increase in cold water currents could be explained by the widening of the connection to the Arctic Sea during the Middle Jurassic (cf. Ziegler 1988). Furthermore, these currents from the north were supplied by rivers with nutrient-rich waters in northern Europe, causing a change from facies related to nutrient-poor waters, characterized by ooids and corals (cf. Shinn et al. 1990), to echinoderm- and brachiopod-rich sediments which are believed to reflect high nutrient levels.

Conclusions

1. Based on a well founded biostratigraphic framework, several facies belts can be recognized within the Hauptrogenstein Formation. The central Jura is dominated by a shallow-marine, high-energy oolitic barrier system, controlled by tidal currents. The backbarrier facies assemblage to the west with micrites, oncolites, patch reefs etc. and the off-barrier facies assemblage to the east, characterized by tempestites and basinal marls, can be considered as low-energy environments with occasional influence of storms.

2. These facies belts migrated three times from west to east during Middle Bajocian to Middle Bathonian times forming three shallowing-upward successions. Each succession was capped by a hardground which developed synchronously in terms of biostratigraphic resolution.

3. The progradation of facies belts indicates, that sediment production exceeded accommodation space as made available by subsidence and sea-level changes. Hardgrounds formed when sea-level rise was fastest and the increase in accommodation space exceeded the sediment production (cf. Schlager 1992; Hanford & Loucks 1993). The result was a reduction of sediment motion and a stop of ooid production. Subsequent periods of highstand were dominated by sedimentation in deeper water.

4. In the course of the three shallowing-upward successions, sediment production decreased as is evident from comparison of 1) isopach maps of the successions (cf. Fig. 5),

2) the duration of successions (Fig. 3, 4), estimated from biostratigraphic age and the time scale provided by Haq et al. (1988) and 3) considering the estimated relative change in sea-level and subsidence (Gonzalez 1993, 1996). Sedimentation rates decreased from 40 m/Ma over 25 m/Ma to 13 m/Ma from the first to the third succession. The decrease in sediment production is also reflected by the size of facies belts; during the first shallowing-upward succession an about 40 km broad oolitic belt developed (Fig. 6b, c); during the second succession this belt was only about 20 km wide, but the width of the back-barrier lagoonal zone increased (Fig. 6e); during the deposition of the third succession, a short-lived, fastly migrating oolitic belt narrower than 20 km was immediately replaced by a shoal, mainly consisting of echinoderm detritus (Fig. 6f).

5. Decrease in carbonate production is believed to have been caused by changes in water circulation and in local climate. An increase of colder, nutrient-rich water influx from the north could also have been responsible for a change from facies dominated by ooids and corals (nutrient poor) to facies dominated by echinoderms and brachiopods (nutrient rich).

6. Local and regional differencial subsidence is evidenced by more or less abrupt lateral changes of facies and differences in thickness of deposits. The differences in subsidence probably did not exceed several tens of meters per million years. However they strongly influenced the large-scale distribution of facies belts within the Hauptrogenstein and Klingnau Formations. The central Jura was dominated by a morphological high, covered by an extensive oolitic belt. While sedimentation towards the central European sea in the east was mainly dominated by marls, micritic and bioclastic sedimentation prevailed in the protected lagoon in the western Jura. Several smaller areas in the southeastern Jura seem to have been influenced by more local changes in subsidence, responsible, for example, for the nucleation of the Gislifluh Reef.

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