2 What Can Be Measured, Calculated, or Quantified by Comparison

2.1 Sediment Thickness

The first step in quantifying sedimentation in this regional study was to measure and sample 221 detailed sections which are spaced as closely as possible. The longest of these sections is RG 307 at Péry in Canton Bern, which is represented in Pl. 22 in Gygi (2000a). The section has a length of 357 m, and it includes 246 individually numbered units. Exact thickness of a massive and very thick unit can be difficult to measure. For instance, the Balsthal Formation in its type section RG 438 in Steinibach Gorge north of Balsthal is tectonically in near-vertical position. The lower, mostly massive part of the Holzflue Member is intersected by the road leading through Steinibach Gorge at a very acute angle. Measurement of thicknesses in this part of the Holzflue Member was therefore prone to error.

This is why the thickness of the Balsthal Formation as measured in Steinibach Gorge was checked by measuring the cliff of Chluser Roggen south of Balsthal in the unpublished section RG 450 using a rope. A photograph of the cliff is shown in Gygi (2000a, Fig. 37 on p. 64). The massive limestone strata in this perfectly vertical cliff dip with 8° north. No correction of the measured thicknesses was necessary at this degree of dip. The total thickness of the Balsthal Formation at Balsthal was measured in section RG 438 in Steinibach Gorge to be 90.0 m (Gygi 2000a, Pl. 44), and 90.6 m in section RG 450 descending with a rope from Point 702 on Chluser Roggen. Massive strata of mainly the St-Ursanne Formation crop out in the cliff of Peute Roche 1 km southwest of the village of Vellerat in Canton Jura. The cliff was measured on the rope as section RG 451. The cliff is exactly vertical and 92.8 m high. The strata intersected dip with 13° north. The thicknesses measured are by 3% greater than real because of the dip, or by 2.8 m. The true thickness of the strata measured is consequently 90 m. Section RG 451 is drawn on Pl. 24 in Gygi (2000a). No correction of the measured thicknesses was made in the plate.

It is evident from Figs. 1.5 and 4.15 in this study that there are extreme regional discrepancies in thickness of coeval sediments, both in succession no. 1 and no. 2. The results of measurement of detailed sections and descriptions of lithostratigraphic units are to be found in Gygi (1969a, 2000a, b). The 221 sections measured are assembled in Fig. 1.5 of this study. This figure is the frame of reference for all further work, especially for ammonite biochronology. Thicknesses were measured as accurately as possible in order to quantify synsedimentary tectonics and to discern endogenic from exogenic basement subsidence. *Endogenic* basement subsidence included regional and equable subsidence and in some cases superimposed differential subsidence varying by tens of meters in a short time span over short lateral distances. Such differential endogenic subsidence is evident in carbonate members of the shallow water realm. The thickness of the St-Ursanne Formation varies by 60 m between approximately 95 m in section RG 306 near Liesberg (Gygi 2000a, Pl. 31) and 35.2 m in the unpublished section RG 397 near Kleinlützel over a palinspastic distance of 5 km (see below and Gygi 1990c, Fig. 5). Thicknesses of the Verena Member vary by as much as 27 m between approximately 59 m in section RG 431 in the quarry at Gänsbrunnen (Gygi 2000a, Pl. 40, supplemented on August 30, 2008), 57.2 m in section RG 404 near Mervelier (Gygi 2000a, Pl. 36), and 31.6 m in section RG 429 near Welschenrohr (Gygi 2000a, Pl. 39). Substantial variation in thickness in coeval lithostratigraphic units from shallow water over short horizontal distances was probably caused by endogenically driven normal faults. It is discussed in Sect. 11.2 that neither depth of sedimentation nor facies of carbonate units from very shallow water were affected to a significant degree directly above such synsedimentary faults.

Endogenic uplift amounted to less than 10 m, for instance in the latest *Hypselum* Chron when the top of the calcareous oolite of the Steinibach Member was raised above sea level

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in the unpublished section RG 4 near Waldenburg (see Fig. 1.4 and mainly 4.3) and south of Aedermannsdorf in the unpublished section RG 15. Local endogenic uplift above sea level of marine calcarenite at the top of the Balsthal Formation near Balsthal amounted to more than 4 m. *Exogenic subsidence* of adjacent basement blocks varied by amounts in excess of 100 m. It can be read from Fig. 4.15B, C that the effect of great regional variation in loading of the seafloor with coeval sediments and water caused the basement to subside differentially below the thickest part of the shallowing-upward succession no. 1 and later below the thickest part of shallowing-upward succession no. 2.

2.2 Direct Time Calibration of Sediments

2.2.1 Radiometric Ages

The first attempt at dating pure pellets of submicroscopic glauconite crystals in sediments of Late Jurassic age in northern Switzerland with the K–Ar method was made by Gygi and McDowell (1970). Fischer in Fischer and Gygi (1989) measured some of the same glauconite pellets again with an improved technique. These authors assigned the calculated ages to well-preserved, figured ammonites excavated from the same strata as glauconite. All of the numerical ages which were published in the two papers proved later to be too young. Smith et al. (1993) showed that dating of glauconite *can* be successful, but only if the ^{40}Ar-^{39}Ar method is used.

2.2.2 Geomagnetic Polarity Scale

An attempt at establishing an Oxfordian and early Kimmeridgian chronology of reversals of the Earth's magnetic field based on sediments on land was made by J. Ogg in 1987, when the author of this study guided him through sections in the Swiss Jura Mountains. Ogg then collected a complete set of oriented samples from fine-grained sediments. No results of this work were published.

2.3 Relative Time Calibration of Sediments

2.3.1 Biochronology of Ammonites and Ammonite Zones

Ammonites are the organisms with the highest rate of evolution which became fossilized in the sediments investigated. Establishing a reliable ammonite biochronology is an extremely time-consuming procedure. Almost 10,000 casts of ammonites in a state of preservation sufficient for study were collected over the years from *in situ,* some in existing outcrops, but most of them in systematic, bed by bed excavations. The well-preserved specimens among these were prepared, measured, identified, and many of them were figured in several publications. The ammonites were organized into zones, as far as possible according to the comprehensive volume coordinated by Cariou and Hantzpergue (1997). The ammonite zone in the present study is the taxon-range zone of the International Stratigraphic Guide, second edition by Salvador (1994, p. 57). The ammonite zone in this study is equivalent to the subzone in earlier publications by the author of the present study. Since most of the ammonites lived preferentially in water deeper than about 30 m (see below), the 28 ammonite zones which are defined in Sect. 7.3 below were conceived in sediments that were laid down in the deeper part of the epicontinental Rhodano-Swabian Basin. The duration of ammonite chrons, or the time span which is represented by ammonite zones, is probably unequal. Only an average duration of the chrons in the Oxfordian and Kimmeridgian Age could therefore be calculated. This was done by dividing the aggregate duration of the two ages of 10.4 million years, according to Gradstein et al. (2004, p. 310), by the number of the 28 ammonite chrons which are listed in Fig. 1.6 of the present study. One of the listed chrons consequently lasted on average approximately 370,000 years. This is close to, for instance, the 380,000 years which were calculated by Weedon et al. (1999, p. 1800) to be the average time represented by what they rated to be a subzone of the Pliensbachian Stage in England. The similarity is remarkable, because such a subzone in England is temporally and geographically distant from northern Switzerland. There are possibly gaps or overlaps between ammonite zones used in this study, because ammonites in sediments laid down at a *normal* rate in deeper water are uncommon. For instance, the *Hypselum* Zone is represented in northern Switzerland by a single specimen of the zonal index taxon.

2.3.2 The Three Principal Marl-Limestone Successions in the Swiss Oxfordian

Gygi in Gygi and Persoz (1986, Pl. 1A) subdivided the Oxfordian sediments in northern Switzerland into three principal marl-limestone successions. The term marl was then, and is used in this study in the sense of Barth, Correns and Eskola (1939) in Pettijohn (1975, Fig. 10–41). The partially argillaceous sediments of the Bärschwil Formation in succession no. 1, of the Wildegg Formation in succession no. 2, and of the Bure Member in succession no. 3 were initially mixtures with widely varying percentages of clay minerals and of mud-grade carbonate minerals like aragonite and calcite. Such mixed rocks and all of the limestones are classified in the present study using the terminology in Fig. 10–41 in Pettijohn (1975). The sediment with the highest content of clay minerals is the clayey marl of the *Renggeri* Member in the lowermost part of the Bärschwil Formation. The Buix Member in the upper St-Ursanne Formation is a pure limestone with a carbonate content of up to more than 99%.

Succession no. 1 in Fig. 1.5 is thick in its proximal part. Below is clayey marl and marl of the Bärschwil Formation. Above is limestone of the St-Ursanne Formation, which can be extremely pure in the Buix Member. The Bärschwil Formation represents approximately 6.4 ammonite chrons of on average 370,000 years each, which amount to a total of almost 2.4 million years. The St-Ursanne Formation was sedimented during about 1.6 ammonite chrons. This is equivalent to close to 600,000 years on the assumption of an equal duration of ammonite chrons. The total time represented by succession no. 1 is 8 ammonite chrons or nearly 3 million years.

Succession no. 2 represents the 6 ammonite chrons from the *Schilli* Chron to the *Berrense* Chron. The Effingen Member is the thick, lower part, where the succession was sedimented in deeper water. The member is mostly marl with some intercalations of marly limestone or of limestone. The Effingen Member represents the *Schilli* to the *Hypselum* Chron, or 5 chrons. The limestone in the uppermost part of succession no. 2 in Canton Aargau is the Geissberg Member, which represents the greater part of the *Berrense* Chron. The Effingen Member was sedimented in a time span of about 1.8 million years and the Geissberg Member during probably approximately 300,000 years. Succession no. 2 then represents a time span which can be calculated at 2.1 million years.

Succession no. 3 in Canton Schaffhausen includes in its lower part the upper, partially marly Hornbuck Member of the *Bimammatum* Chron, and above the limestones of the Küssaburg Member (*Gredingensis* Chron) and of the Wangental Member (*Planula* and *Galar* Chron). The four ammonite chrons represented by succession no. 3 amount to a total time span of about 1.5 million years. Succession no. 3 in northwestern Switzerland includes the marl of the Bure Member below and the limestones of the La May and of the Porrentruy Member above (Fig. 1.5). The Bure Member probably represents the *Bimammatum* Chron or 370,000 years. No ammonites were found in the three members in northwestern Switzerland. Time correlation with Canton Aargau was made using the mineral-stratigraphic correlations by Persoz in Gygi and Persoz (1986, Pl. 1A). Time correlation between Canton Aargau and Canton Schaffhausen could be made with ammonites.

The times of sedimentation of successions no. 1–3 calculated above differ from those which can be read from chart 6 by Hardenbol et al. (1998): 2.63 ma for succession no. 1, 1.58 ma for succession no. 2, and 1.17 ma for succession no. 3. The time represented by each of the three principal Oxfordian marl-limestone successions in northern Switzerland is unequal, whether according to the calculations mentioned above or following Hardenbol et al. (1998, chart 6). The proportions of time of marl to limestone sedimentation diverge within successions no. 1–3 even more than the total time represented by each of the successions. The proportion of time between marl and limestone sedimentation can be calculated to be in succession no. 1 approximately 2.4:0.6 ma, or 1.8:0.3 ma in succession no. 2, and 0.3:1.2 ma in succession no. 3.

2.3.3 Elementary Marl-Limestone Cycles

The limestone member representing the *Planula* Zone and the *Galar* Zone in southern Germany is called Wohlgeschichtete Kalke (well-bedded limestones). Seibold (1952) analyzed the carbonate content of the thick, micritic limestone tiers and of the thin marly intercalations in between. He found that the carbonate content of the marly intercalations separating the limestone tiers or beds was on average 13% less than that of the limestone layers. Seibold concluded from this that the supply of clay minerals to the deeper part of the Rhodano-Swabian Basin in southern Germany was slight and continuous in the pertinent time span. He presumed that the carbonate mud was chemically precipitated intermittently within the basin. Seibold (1952, p. 368) presented evidence that the variation in the carbonate content between limestone beds and thin, marly intercalations was primary, not caused by diagenesis. The bedding rhythm was constant and could be followed in southern Germany over a great horizontal distance.

Being inspired by Seibold (1952), Gygi (1969a, Pl. 17) published the result of calcimetry in a bed by bed set of analyses through the entire micritic limestone succession of the Villigen Formation in section RG 62, which was measured in 1960 west of Villigen in Canton Aargau. The average content of $CaCO_3$ of the limestone tiers in the Letzi Member in section RG 62 is 96%. The $MgCO_3$ content of the limestone tiers analyzed for magnesium in the Villigen Formation does not exceed 3% in the section. The partings with an elevated content of clay minerals between limestone tiers in the Letzi Member are a few millimeters thick and were not analyzed. Marly intercalations with a substantial thickness between limestone beds were found in section RG 62 only in the Geissberg Member. The carbonate content of these intercalations, where analyzed, is at most 15% lower than that of the limestone beds. This confirms the results of Seibold (1952, p. 368). Marly intercalations weather back and thereby produce the distinct bedding as it appears in weathered, natural cliffs of the Villigen Formation.

Section RG 62 was measured in the small valley west of the ruin of Besserstein castle located above the village of Villigen. The road from Villigen upward to the table mountain of Mt. Geissberg is leading through the valley. Section RG 62 was assembled from minor outcrops on both sides of the valley. The location of these partial sections was sketched from two viewpoints on the brink of the table mountain, each viewpoint overlooking the steep slope and cliff on the opposite side of the narrow valley. The sketches were drawn early in March, before the trees in the deciduous forest had sprouted their foliage. The minor sections in the valley partially overlap. Their overlapping parts could be correlated using the pattern of successive beds with varying thickness in a similar way as the succession of unequal growth rings in the trunk of trees is correlated in dendrochronology. Section RG 62 being thus assembled was checked against the overlapping part of the nearby, unpublished section RG 63 which was measured on the rope descending at a vertical cliff 300 m northwest of the ruin of Besserstein castle on the northeastern slope of Mt. Geissberg. The neighboring sections RG 62 and 63 are shown at a reduced scale in the upper composite section on Pl. 19 in Gygi (1969a).

The Letzi Member in Canton Aargau includes the *Planula* and the *Galar* ammonite Zone. The *Galar* Zone possibly represents significantly less time than the *Planula* Zone. The assumption can therefore be made that the Letzi Member was sedimented in a time span of around 600,000 years instead of the 740,000 years, which are the average duration of two entire ammonite chrons in the Late Jurassic. The Letzi Member in section RG 62 near Villigen includes 61 elementary marl-limestone cycles. Fifty-seven such cycles could be counted in the Letzi Member at Mellikon in section RG 70 (Gygi 1969a, Pl. 17). The fact that the numbers of elementary cycles are so close together over the considerable distance of 12 km between sections RG 62 and RG 70 in the Tabular Jura is an indication that the marl-limestone cycles were caused by short-term variations of climate. If this is so, then the average length of such an elementary climatic cycle would have been approximately 10,000 years during sedimentation of the Letzi Member.

The Pichoux Formation is a succession of well-bedded micritic limestone much like the Villigen Formation. It can be read from Fig. 1.5 that the formation is a wedge when imaged in cross-section perpendicularly to depositional strike. In the most proximal part of the wedge, in Pichoux Gorge near Sornetan in Canton Bern, the lower half of the formation includes 44 elementary marl to limestone cycles. The lower half of the Pichoux Formation at Sornetan ranges from the formation's base in section RG 314 to the marly boundary bed no. 22 of section RG 315 in Gygi (2000a, Pl. 21). The boundary beds between the top of the Sornetan Member and the base of the Pichoux Formation do not crop out in section RG 314 in Pichoux Gorge. They were excavated in a trench. The time span represented by the lower Pichoux Formation is about one third of the *Antecedens* Chron, and it can be estimated to be around 120,000 years. Provided that this estimate is of the right order of magnitude, the average duration of one of the 44 elementary marl-limestone cycles in the lower Pichoux Formation at Sornetan would be about 2,730 years. Notwithstanding the uncertainties of how much time is represented by the Letzi Member and mainly by the proximal part of the lower Pichoux Formation, the duration of elementary cycles in the lower Pichoux Formation at Sornetan is certainly less than that of elementary cycles in the Letzi Member of the Villigen Formation. Further down in the wedge of the Pichoux Formation perpendicularly to depositional strike, in section RG 307 at Péry in Gygi (2000a, Pl. 22), the coeval lower part of the Pichoux Formation includes only 17 marl-limestone couplets. The conclusion to be drawn from this is that long-distance time correlation using the bedding rhythm of micritic limestone is unfeasible.

The time equivalent of the lower Pichoux Formation in the adjacent carbonate platform of the St-Ursanne Formation is the lithostratigraphic unit that Gygi (2000a, p. 55) re-defined and named Delémont Member. The name of the member was challenged since and is therefore replaced here by the new name **Chestel Member**. Chestel is the name of the ridge which is formed by limestone of the St-Ursanne Formation south of the village of Liesberg in Canton Basel-Landschaft. A photograph of Chestel ridge is presented in Fig. 24 on p. 41 in Gygi (2000a). The name Chestel is shown on the topographic map Landeskarte 1:25,000, sheet no. 1086 Delémont. The type section of Chestel Member is bed nos. 107–110 in section RG 306 in Chestel ridge, which is represented in Gygi (2000a, Pl. 31). A photograph of Chestel Member near St-Ursanne is Fig. 4.19B in the present study. The member is at that locality massive calcareous oolite with only one parting in its upper part. The time equivalent of the micritic, well-bedded Letzi Member in the upper Villigen Formation in Canton Aargau is in northwestern Switzerland the Verena Member in the upper part of the carbonate platform of the Balsthal Formation. The Verena Member is massive calcareous oolite in most places, like for instance in the rock of Rouge Pertuis north of the village of Undervelier in Canton Jura. Strata are tectonically perpendicular in this landmark rock. No partings are visible in the Verena Member on this rock which is shown in the photograph of Fig. 1.7.

The Paulin Member in the lowermost Reuchenette Formation in the northern Jura Mountains includes 62 beds of pure or marly limestone in section RG 350 near Courgenay, 65 such beds in section RG 340 in the quarry of La Rasse south of Porrentruy where the top of the member does not crop out, and 56 limestone beds in section RG 443, where the member is complete in an exploration well near St-Ursanne.

The three sections are shown in detail in Pl. 17, 19, and 20 in Gygi (2000a). There are on average approximately 60 limestone beds or tiers in the Paulin Member of Ajoie region. The member represents a time of 1.4 million years according to Hardenbol et al. (1998), or 1.5 million years following Gradstein et al. (2004, p. 310). The thickness of the limestone tiers in the member is very unequal. The duration of an elementary cycle with a thin layer of marl below and a thick limestone tier above can be calculated, following the authors cited above, to have been on average approximately 25,000 years in this lagoonal sediment from very shallow water. The time represented per elementary cycle in the Paulin Member is probably about as unequal as the widely varying thicknesses of the individual cycles. When the average duration of one of the seven ammonite chrons represented by the Paulin Member is assumed to have been about 370,000 years as it was calculated above, then the average duration of an elementary cycle in the Paulin Member would have been as much as approximately 43,000 years, or almost twice as much as the time of around 25,000 years (see below) to be concluded from Hardenbol et al. (1998).

2.3.4 Comparison of Marl-Limestone Cycles with Milankovitch-Type Periodicity

The most probable cause of change between marl and limestone sedimentation in the region investigated is variation between humid and drier climate at the source of terrigenous sediment on neighboring land in the north. This was suggested by Cecil (1990). It is not yet known whether the principal marl-limestone successions no. 1–3 in the Oxfordian of northern Switzerland reflect variation in temperature of the pertinent climate. Milankovitch (1941) calculated the periodicity of precession of the Earth's axis and periodicities in the eccentricity of the Earth's orbit around the Sun. He quantified the intensity of solar radiation arriving on the surface of the Earth which he called insolation, and he calculated the variation in insolation with time. Milankovitch summarized the results of his calculations in the form of curves in Fig. 51 on p. 549, and he assigned certain insolation minima to particular glaciations of the Pleistocene. The calculations by Milankovitch had subsequently to be revised. For instance, Milankovitch (1941, p. 186) calculated the period of Earth's axial precession to be 25,735, or approximately 26,000 years. According to Hinnov in Gradstein et al. (2004, p. 56 and Fig. 4.3 on p. 58), the average periodicity of precession of the Earth's axis is 21,000 years, and the eccentricity of the Earth's orbit around the Sun varied over the past 10 million years with the principal periodicities of 100,000, 400,000, and 2,360,000 years. Variation in the intensity of insolation of the Earth affects the temperature of land, air, and surficial ocean water, and thereby causes the volume of ocean water to wax and wane slightly, as it was pointed out by Schultz and Schäfer-Neth (1997).

The question arises from this whether minor sea level fluctuations and variation in the rate of climate-sensitive carbonate sedimentation in the area investigated in this study was tuned by variation in insolation of the Earth according to Earth's precessional and orbital periodicities. Orbital time calibration of sedimentation is at the present time possible, according to Hinnov in Gradstein et al. (2004, p. 61), not further back than the Miocene-Oligocene time boundary at 23 million years before present. Data in Sect. 5.2 of this study are evidence that some of the rises of sea level documented in sediments from shallow water in northern Switzerland were indubitably rapid (Fig. 5.1). Observations described in Sect. 5.3 indicate that probably all of the sea level falls were slow. The curve of sea level fluctuation was therefore in these cases probably asymmetrical much like the curve of variation in temperature during the Quaternary which was derived from ice cores drilled in Antarctica (Mcmanus 2004). The principal marl-limestone successions no. 1–3 of the Oxfordian in Fig. 1.5 represent an unequal number of ammonite chrons. A list of Late Jurassic ammonite chrons is in Fig. 1.6 in this study. It was indicated above that the proportion of time represented by marl and by limestone sedimentation is different in every one of the three principal Oxfordian marl-limestone successions. The elementary marl-limestone cycles in units of micritic limestone from deeper water were averaged in every unit. The averaged elementary cycles represent widely different time spans: about 2,730 years in the lower Pichoux Formation and approximately 10,000 years in the Letzi Member. The average duration of an elementary cycle in the lagoonal Paulin Member was calculated to be at least 25,000 years.

Recognizing elementary cycles in the shallow-water realm which represent about as much time as elementary cycles in sediments from deeper water was impossible, especially in units of mostly massive calcareous oolite like for instance the Chestel or the Verena Member. It is stated below that it was necessary to revise several correlations between sections which Gygi (2000a) had measured in the shallow-water realm. This illustrates how difficult it is to correlate sections within carbonate platforms in detail. Time correlations are prone to error especially within the Günsberg Formation. It is therefore at least premature to calibrate shallow-water sedimentation of the Oxfordian in northern Switzerland with Milankovitch-type cycles. Both Olsen and Kent (1999) and Weedon et al. (1999) claimed that they could recognize Milankovitch cycles in Jurassic sediments. Strasser (2007, p. 427) concluded from sections of Late Jurassic sediments in the Swiss Jura Mountains that "it can be shown that Oxfordian and

Kimmeridgian platform and basin carbonates hold a record of orbital (Milankovitch) cycles" of 20,000, 100,000, and 400,000 years. Milankovitch (1941) clearly distinguished periods of precession of the Earth's *axis* from longer periods of eccentricity of the Earth's *orbit* around the Sun. Some of the sections shown in Strasser (2007) were measured by the author of this study and are represented in plates by Gygi (2000a). The above conclusion of Strasser (2007) is scrutinized in Sect. 11.6.2 below.

2.4 Rates of Sedimentation

Meaningful, net sedimentation rates can as a rule be calculated only in deposits from deeper water on the basin floor, where erosion, transportation, and re-deposition of fine-grained sediment by bottom currents were of a minor scale. The situation is different in the shallow-water realm. Much calcareous mud was chemically precipitated for instance in the peritidal area in which the Vorbourg and the Röschenz Member were sedimented in the lower Vellerat Formation landward of the Günsberg carbonate platform, or in the shallow lagoon where the Courgenay Formation was laid down landward of the Balsthal carbonate platform. Some of the calcareous mud which was produced in very shallow-marine water initially settled from suspension in the environment where it was precipitated. Currents driven by tides and by occasional storms then stirred the mud up from the bottom, and it was carried away by currents in suspension along with the mud which never settled, across the carbonate platform of the Günsberg Formation, or across the wide sand bank of calcareous ooids of the Balsthal Formation. Both terrigenous and calcareous mud were resedimented in deeper water of the Rhodano-Swabian Basin. This is indicated in Sect. 4.14.3. Varying rates of sedimentation on the carbonate platform of the St-Ursanne Formation are calculated in Sect. 8.1.

2.5 Provenance and Quantity of Calcareous Mud

Calcareous mud was quantitatively the most important primary constituent of the Late Jurassic sediments and bioconstructions investigated. Gygi (1969a) figured on Pl. 11, Fig. 41 part of a coccolith and on Pl. 5, Fig. 17 an unidentified organism of nannoplankton. Such nannoplankton is refigured in this study in Figs. 4.16 and 4.17. Gygi (1969a) showed in Fig. 1 on p. 24 that he found coccoliths only in micritic limestones which were sedimented in deeper water. The abundance of coccoliths increases in the Oxfordian sediments investigated with growing depth of deposition. 150,000 coccoliths were calculated to occur in 1 cm^3 of micritic limestone of the Letzi Member from a water depth of about 50 m in bed no. 88 of section RG 70 at Mellikon. Approximately 1,000,000 coccoliths per cm^3 occur in a limestone sample of the Wangental Member from around 100 m depth in bed no. 101 of section RG 91 at Immendingen in southern Germany. This is equivalent to about 0.004% of the rock volume. The sample from Immendingen was the richest of all out of the limestones searched for nanoplankton. Gygi (1969a, p. 24) therefore concluded that the contribution of nannoplankton to sedimentation of calcareous mud in the deeper part of the Rhodano-Swabian Basin was negligible *in the Oxfordian Age*. Pittet and Strasser (1998, p. 161) arrived at a similar conclusion.

Bioerosion can produce fine-grained calcareous sediment. This was documented in Bermuda by Neumann (1966) and by Gygi (1969b, 1975, Fig. 11). A substantial amount of the fine-grained calcareous sediment produced by various organisms, possibly mainly by regular sea urchins, on coral reefs in the lagoon in the internal part of the calcareous platform of the upper St-Ursanne Formation is included in the Buix Member (Fig. 1.5). It is shown in Sect. 4.14 that the quantity of calcareous mud produced on carbonate platforms was less than what was at the same time laid down in the deeper part of the basin like for instance in the Effingen Member. The Effingen Member is a mixture of on average about 60% lime mud and of 40% of clay minerals and some silt of mainly detrital quartz. The Effingen Member includes much more $CaCO_3$ than the entire volume of the coeval carbonate platform of the Günsberg Formation, from where calcareous mud spilled into deeper water. This is evidence that most of the lime mud in the Effingen Member was produced in the peritidal environment landward of the Günsberg Formation, where the lower Vellerat Formation with the Vorbourg and the Röschenz Member was sedimented. Currents transported mud from there across the carbonate platform of the Günsberg Formation and into the deeper part of the basin, where it was incorporated into the Effingen Member. The carbonate platform of the Balsthal Formation is much wider than that of the Günsberg Formation below. Nevertheless, the great amount of calcareous mud in the Villigen Formation, which is adjacent to and coeval with the Balsthal Formation, cannot possibly have all been produced on the sand bank of calcareous ooids of the Balsthal Formation. The Villigen Formation extends far into adjacent southern Germany and grades southeastward into the coeval part of the lower, micritic Quinten Formation. Most of the pertinent calcareous mud was probably chemically precipitated in very shallow water landward of the Balsthal Formation, where the micritic limestone of the Courgenay Formation was sedimented (Fig. 1.5). All of this is approximately quantified and discussed in Sect. 4.14.

2.6 Water Depth and Sea Floor Topography

There is no evidence that the tidal range was more than a few decimeters during deposition of the sediments investigated. The position of mean sea level can therefore be inferred based on stromatolites from the upper intertidal zone. Such stromatolites are shown in Figs. 4.4–4.6 and 5.8. Water depth above Oxfordian sand banks on which calcareous ooids were accreted was probably as slight as that on the Recent ooid sand bank which is shown in the photograph of Fig. 4.7. The greatest water depth above the top of a carbonate platform was calculated to have been 10 m. This depth was reached after rapid sea level rise no. 5 (see Fig. 5.1) in the internal part of the carbonate platform of the St-Ursanne Formation. The initial depth of the lagoon, into which the Buix Member was sedimented (Fig. 1.5), is calculated in Sect. "Rise no. 5" in part 1 of Chap. 5. Rankey (2004) concluded that no "deterministic link" exists between depositional facies and water depth in shallow water on carbonate platforms. Hermatypic corals could live in the environments investigated in a paleobathymetric range which probably nowhere exceeded approximately 20 m. This is calculated based on section RG 307 at Péry in Canton Bern, which is represented in Pl. 22 in Gygi (2000a). The pertinent calculation is in the middle of Chap. 6. The paleobathymetric interval between 20 and 30 m is characterized by a macrofauna with large bivalves of the genus *Pholadomya*, which can be very abundant in the *Crenularis* Member of Canton Aargau, in the Reuchenette Formation near Olten (Gygi 1986, Fig. 6B), and that are fairly abundant in the upper half of the Sornetan Member.

The thin marker bed with a rich macrofauna of mainly ammonites, which separates the lower half of the distal part of the Sornetan Member from the member's upper half, was sedimented at a water depth of between 30 and 35 m. This is calculated in Sect. 4.2. Water depth at the time boundary between the Middle and the Late Jurassic near Blumberg in southern Germany, 18 km north-northwest of Schaffhausen, was 100 m. The depth is calculated semiquantitatively in Sect. 4.1.1. This is an important mark of paleobathymetry which can be observed in both vertical and lateral facies boundaries. Water depth at the beginning of the Oxfordian in northwestern Switzerland and in Canton Aargau can only be estimated. The depth was probably about 80 m (see Figs. 1.5 and 4.15). The argumentation of how this estimate was arrived at is to be found in the last part of Sect. 4.2.

The grain size of sediments is undiagnostic of water depth. Mud-grade sediment occurred from tidal flats down to the greatest water depth of up to well over 100 m on the floor of the epicontinental basin (Fig. 4.9). On the other hand spherical, primarily hard oncoids of calcium carbonate with a diameter of up to 36 mm were periodically rolled at the sediment surface of calcareous mud by currents of bottom water driven by exceptionally violent storms on the floor of the epicontinental basin at the water depth of as much as approximately 120 m (see Sect. 4.3.2). Ellipsoidal nodules of limestone with a diameter of up to 30 cm occur in a matrix which was originally mud in sediments from a water depth approaching 100 m. Such nodules are the product of subsolution (or corrosion, see below) of initially continuous limestone beds. Nodules formed by subsolution at a water depth of close to 100 m are represented in Fig. 8.3. Allenbach (2002, p. 336) thought that large nodules at the base of the Oxfordian like those shown in Fig. 8.3 of this study were formed "beyond doubt . . . in an agitated environment close to storm-wave-base". The term wave base is avoided in this study, because fair weather wave base varies within days or even hours between sea level on an exceptionally calm summer day and a depth of at most a few meters. Storm wave base during exceptionally violent cyclones could reach down to the floor of the epicontinental basin at the greatest water depth of well over 100 m, which was concluded from the sediments investigated. This is discussed in Sect. 4.3. The vertical scale in Fig. 1.5 is exaggerated a hundred times. It can be read from this that the inclination of the slope of the Pichoux Formation (PIC in Fig. 1.5) and of the Villigen Formation between Villigen and Siblingen was very slight. Sea floor topography was subdued at any stage of sedimentation in the region investigated.

2.7 Subsidence

Endogenic subsidence is caused by processes deep in the interior of the Earth. *Exogenic subsidence* of the basement is caused by the weight of sediments or of additional water after a sea level rise. Gygi (1986, p. 472) calculated exogenic subsidence to have been approximately two-thirds of the partially compacted thickness of Oxfordian sediments in northwestern Switzerland. This is in agreement with Ziegler (1982). According to Ziegler (1982, p. 106), a eustatic rise of sea level causes the basement to subside by 40% of the rise. Differential exogenic subsidence of neighboring basement blocks caused by the lateral shift of belts with maximal sedimentation was imaged first by Gygi (1986, Fig. 3). A revision of that is shown in Fig. 4.15 in the present study.

2.8 Synsedimentary Tectonics

Synsedimentary tectonics were documented with photographs of normal faults in outcrops by Gygi in Gygi and Persoz (1986, Figs. 2 and 8). Such normal faults were active and caused a displacement of as much as 60 m in the St-Ursanne Formation between section RG 306 at Liesberg in Canton Basel-Landschaft (Gygi 2000a, Pl. 31) and the unpublished section RG 397 at Kleinlützel in Canton Solothurn (Gygi 1990c, Fig. 5), or of the same amount near Riniken in Canton Aargau (Gygi 1990c, Fig. 6). Synsedimentary faulting caused the substantial differences in thickness of coeval carbonate members in formations of the shallow-water realm. This becomes evident when loose foldout plates in Gygi (2000a) are laid out side by side. Synsedimentary faulting ceased almost entirely when the Hauptmumienbank Member and the coeval Steinibach Member were sedimented. Thicknesses within these members differ only slightly.

2.9 Sea Level Variations

Rises of sea level can be quantified, and their rate could be proved in many cases to have been geologically speaking rapid. Falls could be documented qualitatively, but quantification was impossible. This is discussed in Chap. 5. Rapid relative sea level rises were quantified with different methods. According to Sect. 5.2, they were driven by eustatic, global rises. Rapid relative rise no. 10 in Fig. 5.1 occurred at the end of the *Gredingensis* Chron. It is the smallest of all of the rapid rises which could be documented in sediments of Late Jurassic age in northern Switzerland. The eustatic component of rise no. 10 was quantified in the following way. The amount of relative rise no. 10 was so small that it had no visible effect on the vast shoal of calcareous ooid sand which is now the Holzflue Member in Fig. 1.5. Nevertheless, the rise left distinct traces in micritic limestones of the Villigen Formation from deeper water in the Rhodano-Swabian Basin. The rise can be quantified thanks to *lack* of traces of it in the oolitic Holzflue Member of the Balsthal Formation, and using the mineral-stratigraphic correlation J by Persoz in Gygi and Persoz (1986, Pl. 1A). Calcareous ooids are *accreted* in Recent marine environments in water no deeper than 6 m, according to the concurring results of several authors. This is stated in Sect. 4.1.3. Rise no. 10 left no traces on the sand bank of calcareous ooids of the Holzflue Member, because it amounted to less than 6 m and therefore did not interrupt ooid accretion.

The load of additional water brought into a basin by a eustatic sea level rise causes the basement to subside isostatically by 40% of the rise according to Ziegler (1982, p. 106). Isostatic equilibration of the basement is shown in Sect. 11.3 to be prompt as compared with sedimentation rates. Relative sea level rise no. 10 had consequently a eustatic component of 60% of at most 6 m, or of not more than 3.6 m. In spite of the small amount, the rise caused temporal omission (non-deposition) and thereby a distinct, corroded transgressive surface directly below the base of the slightly glauconitic Knollen Bed in the Villigen Formation at Villigen in Canton Aargau. This is well visible in Fig. 12 in Gygi et al. (1998). The corroded surface is above sequence boundary O8 in Gygi et al. (1998, Fig. 2). The Knollen Bed is a thin marker bed which can be used in long-distance time correlation of micritic limestones in the Villigen Formation. The limestones of this formation were sedimented in the deeper part of the Rhodano-Swabian Epicontinental Basin (Fig. 1.5). Omission at the base of the Knollen Bed and formation of some glauconite within the bed (Fig. 4.1E) because of a very low sedimentation rate were the effect of rise no. 10, because the rise thoroughly reduced or even interrupted for a short time export of calcareous mud from the lagoon of the La May Member of the Courgenay Formation. According to the text at the end of Sect. 4.15.1, most of the calcareous mud sedimented in the Villigen Formation was produced in the very shallow lagoon of the Courgenay Formation landward of the carbonate platform of the Balsthal Formation. Tidal and occasional storm-driven currents transported most of the mud produced in the lagoon out of the environment and in the distal direction across the vast shoal of calcareous ooid sand of the Balsthal Formation, from where the mud spilled into deeper water of the basin (see Fig. 1.5).

2.10 Oxygen Content and Salinity of Bottom Water

Optimal oxygenation of bottom water in the deep part of the Rhodanian-Swabian Basin is indicated by the abundant and diverse assemblage of benthic organisms thriving while the Birmenstorf Member was sedimented at a low rate. The oxygen content of the pertinent bottom water is estimated in Sect. 4.4 by comparison with the Recent northwestern Gulf of Mexico. The clayey marl of the *Renggeri* Member was sedimented in a time span when the lower part of the water column above the sea floor was *permanently* dysaerobic. This is investigated in Sect. 4.4 judging from a comparison of the diameter of burrows in the lower part of the member (Gygi 2000a, Fig. 7 on p. 19) with trace fossils of the Recent. Bottom water was *intermittently* dysaerobic when the Effingen Member was laid down. This was documented by Gygi (1969a, p. 107) with less than millimeter-size casts of iron sulfide of bivalves and of gastropods in marl. Above-average salinity in shallow water is documented by dolosparite (Gygi 2000a, Fig. 16 on p. 26), dedolomite (Fig. 3.3 in this study), calcite pseudomorphs after sulfate minerals (Fig. 3.3), and occasionally by gypsum in calcareous oolite of the Verena Member (Gygi 2000a, p. 45, and Pl. 35, bed no. 113 in section RG 400). A mass occurrence of the worm *Cycloserpula socialis* (Goldfuss) in shallow-water limestone of the Laufen Member (Gygi 2000a, Fig. 19 on p. 29) is probably an indication of sedimentation in water with a salinity below the normal level.

2.11 Paleoclimate

An either tropical or subtropical climate can be concluded from coral reefs which occur mainly in the St-Ursanne Formation and in the boundary beds between the Effingen Member and the Günsberg Formation. Distinctly delimited accretion bands with a regular thickness in the skeletal part of hermatypic corals in the Liesberg Member and in the St-Ursanne Formation which were figured for the first time by Gygi in Gygi and Persoz (1987, Fig. 3), then by Insalaco (1996b), and which are shown in Fig. 3.1 in this study, are annual. The accretion bands in Fig. 3.1 are by comparison with Recent corals in subtropical Bermuda an indication that the temperature of shallow water varied substantially between summer and winter during growth of the reefs investigated in northern Switzerland. This is explained in detail in the following Chap. 3. Oxfordian climate in the region investigated was consequently *subtropical*. The growth rate of Oxfordian hermatypic coral colonies in northern Switzerland can be calculated from the thickness of their accretion bands. The lower limit to the paleobathymetric range of Oxfordian hermatypic corals is calculated in Chap. 6 to be at the water depth of approximately 20 m.

The principal marl-limestone succession nos. 1–3 of the Oxfordian Age (Fig. 1.5) are diagnostic of a long-term transtion from humid to drier climate. When rainfall and runoff on adjacent land in the northwest and north grew plentiful, weathering on land and supply of terrigenic sediment to the area investigated increased a great deal. Siliciclastic silt in succession no. 2 was concentrated by elutriation mainly in tidal currents in some beds in the peritidal Röschenz Member and in small, distal turbidites and possibly in tempestites of the Effingen Member in deeper water. Evidence of humid climate on land is gyrogonites of characean algae and shells of limnic ostracods from freshwater ponds (Oertli and Ziegler 1958, Pl. 1) as well as lignite coal seams from freshwater swamps. Dolomite, calcite pseudomorphs after sulfate minerals, and some gypsum in sediments from very shallow-marine water are evidence of a drier climate. Supply of fine-grained terrigenic sediment of mainly clay minerals and of some siliciclastic silt diminished to a minimum in times of drier climate. This was the case when the extremely pure limestone of the Buix Member in the St-Ursanne Formation was sedimented into a lagoon in uppermost succession no. 1. No detrital quartz at all was found in the Verena Member, neither in thin section nor by x-ray diffractometry. The Verena Member is the youngest Oxfordian sediment on the carbonate platform of the Balsthal Formation (see Sect. 11.5.2).

Evidence of a *long-term* tendency of increasingly drier climate throughout the Oxfordian Age is absence of dolomite and of calcite pseudomorphs after sulfate minerals in the St-Ursanne Formation of succession no. 1. Some dolomite first appears in the Günsberg Formation (Gygi 1969a, Pl. 7, Fig. 30), and the earliest calcite pseudomorphs after sulfate minerals were found at some localities in the Hauptmumienbank Member in uppermost succession no. 2 (this study, Fig. 5.5C). A semiarid climate in the late Oxfordian during sedimentation of the Balsthal Formation of succession no. 3 (see above) is indicated by pervasive dolomitization (Gygi 2000a, Figs. 16 and 30), by abundant calcite pseudomorphs after sulfate minerals (this study, Fig. 3.3), and by some gypsum found in the Verena Member at one locality (Gygi 2000a, Pl. 35, thin section Gy 7706). The climate did not only become drier, but possibly also warmer during the Oxfordian Age. Measurements of paleotemperature listed by Rais (2007, Chap. 4, Table 1) based mainly on belemnites from the author's collection at Basel, gave no unambiguous evidence of rising temperature of bottom water from middle Callovian to late Oxfordian time. A strong argument that bottom water *did* become warmer from early Oxfordian to early Kimmeridgian time is the paleobathymetric distribution of ammonites of the boreal genera *Cardioceras* and *Amoeboceras*. This is discussed in Sect. 11.5.5.

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