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Sedimentary Geology 150 (2002) 323–342

Sedimentary Geology

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The ups and downs of "Tectonic Quiescence"—recognizing differential subsidence in the epicontinental sea of the Oxfordian in the Swiss Jura Mountains

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Received 27 August 1999; accepted 5 September 2001

Abstract

Recent studies in northern Switzerland have shown that epicontinental areas thought to have been tectonically stable during the Mesozoic were not necessarily as rigid as presumed. By comparing Oxfordian facies boundaries and depocenters in their palinspastic position with known faults in the basement, a direct relationship between the two can be demonstrated. Previously, the lack of obvious synsedimentary tectonic features has lulled scientists into believing that the realm of the Swiss Jura was tectonically stable during the Mesozoic. However, it can be shown that facies and sedimentary structures are largely influenced by tectonics. Subsurface data provide evidence for the presence of Paleozoic troughs in the basement which, apparently, were prone to reactivation during the Pan-European stress-field reorganization taking place in the Late Jurassic. This led to differential subsidence along pre-existing lineaments within the study area, which can be recognized in the distribution of Oxfordian epicontinental basins and their coeval shallow-water counterparts. Eustatic sea-level fluctuations played an important role in the development of shallow-water facies patterns, but a subordinate role in the control of accommodation space in basins. While tectonic activity is often recorded in the sedimentary record in the form of platform break-ups and associated sedimentary debris, more subtle indicators may be overlooked or even misinterpreted. Sedimentary structures and isopach maps, as well as subsurface data in the study area suggest that subtle synsedimentary tectonic movements led to the formation of two shallow, diachronous epicontinental basins during the Late Jurassic. It becomes possible to recognize and differentiate the combined effects of local and regional tectonism, eustasy and sedimentation.

Keywords: Oxfordian; Subsidence; Facies; Jura Mountains

1. Introduction

Whereas the sedimentological and paleontological aspects of the Jura Mountains have been thoroughly studied over the last two centuries, the effects of subtle tectonic movements on the epicontinental marine environments have only recently been approached (Allia, 1996; Burkhalter, 1996; Wetzel et al., 1993; Wetzel and Allia, 2000). Even though the relationship between tectonism and basin formation has been known for some time and has been extensively studied by the oil and gas industry, it remained virtually unrecognized in the Jura Mountains. Inasmuch as the

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PII: S0037-0738(01)00202-0

Jurassic epicontinental sea of northern Switzerland has been regarded as a tectonically stable cratonic area (Laubscher, 1986; Thury et al., 1994), pre-existing structures were scarcely considered. Seismic and drilling campaigns for oil and gas in the 1960s and 1970s provided evidence for the structuring of the basement, yet data remained largely inaccessible to academia and the general public until recently. During the 1980s and 1990s, further subsurface exploration was undertaken, to explore the possibilities for the sub-terrain deposition of low to medium grade nuclear waste (Matter et al., 1987, 1988; Diebold et al., 1992; Thury et al., 1994).

With the accessibility to these subsurface data, the potential relationship between the (hitherto unknown) basement structuring and the isopach anomalies of various Mesozoic formations could be studied. The effects of regional tectonism on a local depositional system have been demonstrated in various areas around the world (e.g., central USA: Lowe (1985); Ireland: Keeley (1996); southern England: de Wet (1998)). These studies share the common goal of looking for the answer to a very basic question: How was the accommodation space for sediment accumulation in the basin formed? Given biostratigraphic constraints, basin deposits and their coeval platform deposits can be correlated, revealing that facies and thickness from platform to basin change abruptly within a given time-frame, and that these abrupt changes and accompanying isopach maxima are controlled by structuring within the basement. The effects of basement remobilization on shallow epicontinental seas have already been demonstrated, proving synsedimentary tectonics on a scale below seismic resolution (Allia, 1996; Dromart et al., 1998). The goal of the present study was to demonstrate that mainly tectonic elements governed the complex facies patterns, which include carbonate deposits, mixed carbonate-siliciclastic deposits and non-deposition, as seen in the Oxfordian of northern Switzerland.

Primary sedimentological structures and paleoecology give some indication of paleo-waterdepth, while gravitative sediment transport indicates the direction

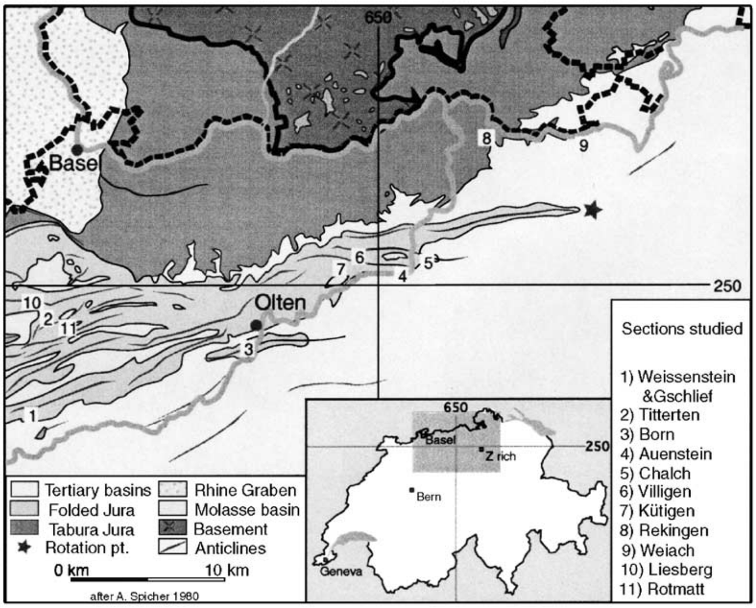


Fig. 1. Geological overview of the study area situated in northern Switzerland. Numbers refer to the location of sections and localities mentioned in the text. The star marks the point around which the locations west of this point were rotated counter-clockwise to attain palinspastic positioning (after Laubscher, 1965). Inset shows the location of the study area in northern Switzerland and adjoining France and Germany.

to the depocenters and the persistence of relief along the basin margin. Subsidence plots showing local pulses of differential subsidence in northern Switzerland have been calculated by Wildi et al. (1989), Loup (1992) and Allia (1996).

In this study, the emphasis is on the Mid Oxfordian basin evolution. Lack of surface exposure and subsurface data of the Lower Oxfordian basin precludes a detailed analysis, but evidence in favor of differential subsidence being the leading cause in the development of the Mid Oxfordian basin can also be found in the Lower Oxfordian basin.

2. Geological setting

During the Late Jurassic, the study area (Fig. 1) was submerged in a shallow epicontinental sea (Fig. 2) north of the Tethys ocean (Ziegler, 1990). The shelf was differentiated into basins, swells and platforms. Periodically, parts of the study area experienced subaerial exposure as is documented by the flora and fauna (Pittet, 1996; van Konijnenburg-van Cittert and Meyer, 1996; Allenbach and van Konijnenburg-van Cittert, 1997; Meyer et al., 1997) as well as sedimentary structures (Gygi, 1986; Pittet, 1996). Carbonate deposits dominate the sedimentary history of the platform, with influxes of siliciclastics, especially during the Mid to Late Oxfordian (Gygi and Persoz, 1986). The neighboring basin is filled with mudstones.

As the relief defining the local sea-floor topography is supposed to be linked to the reactivation of Paleozoic structures in the basement, a short outline of the tectonic history of the study area is given. During the Late Carboniferous and Early Permian, crustal extension led to the formation of troughs along strike-slip and normal faults. Surface exposures of Permo-Carboniferous troughs in the general vicinity of the study area are known from eastern France (Debrand-Passard and Courbouleix, 1984), southern Germany (Geyer and Gwinner, 1991) and the Swiss Alps. Identical structures from underneath the Swiss Molasse Basin and eastern Jura Mountains were only recently discovered by the National Swiss cooperative for the disposal of radioactive waste (e.g., Diebold and Naef, 1990). Orientation of the trough axis is generally ENE–WSW, with trough widths of 10–20 km (e.g., von Raumer, 1998). To date, however, only a relatively small area of the basement underneath the eastern Jura Mountains and northern Molasse Basin has been explored.

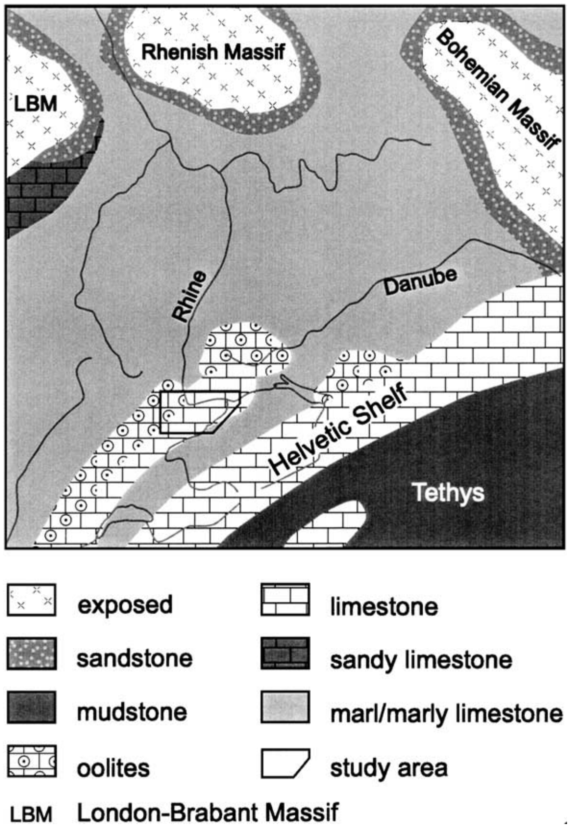


Fig. 2. Paleogeographic map of central Europe during the Mid Oxfordian. The London-Brabant, Bohemian and Rhenish Massifs are exposed and supply the widespread siliciclastics found in the Oxfordian deposits. The study area is situated within the rectangle. Carbonates and marls, as well as some siliciclastics, dominate the Oxfordian lithofacies of northern Switzerland (after Debrand-Passard and Courbouleix, 1984; Ziegler, 1990).

These Late Paleozoic troughs are defined by deep-reaching masterfaults (Diebold and Naef, 1990). They were filled with continental deposits, mainly lacustrine and fluvial sediments, and a peneplain was formed by erosion of the surrounding Variscan Mountains (Diebold, 1990). By the late Permian, the troughs had undergone phases of uplift, subsidence and extension (Diebold, 1990). During the Mesozoic, deformation of the troughs appears to have been reduced to the reactivation of the masterfaults in response to the prevailing crustal stress-

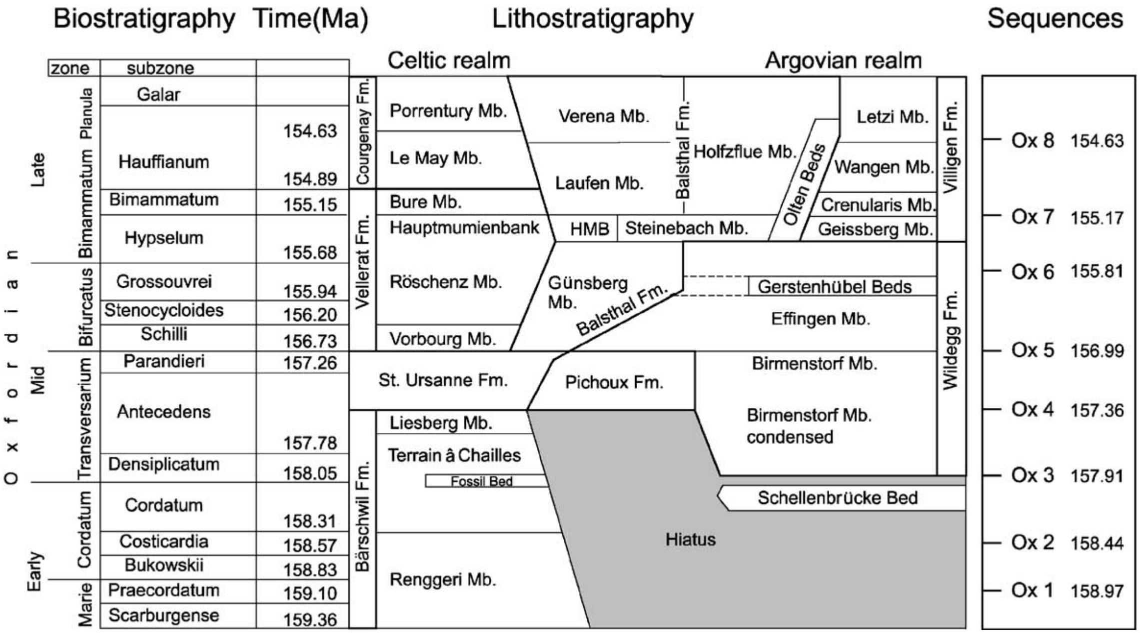


Fig. 3. Oxfordian stratigraphy of the northern Swiss Jura Mountains; litho- and biostratigraphy after Gygi (1995), sequence boundaries and their absolute ages after Hardenbol et al. (1998).

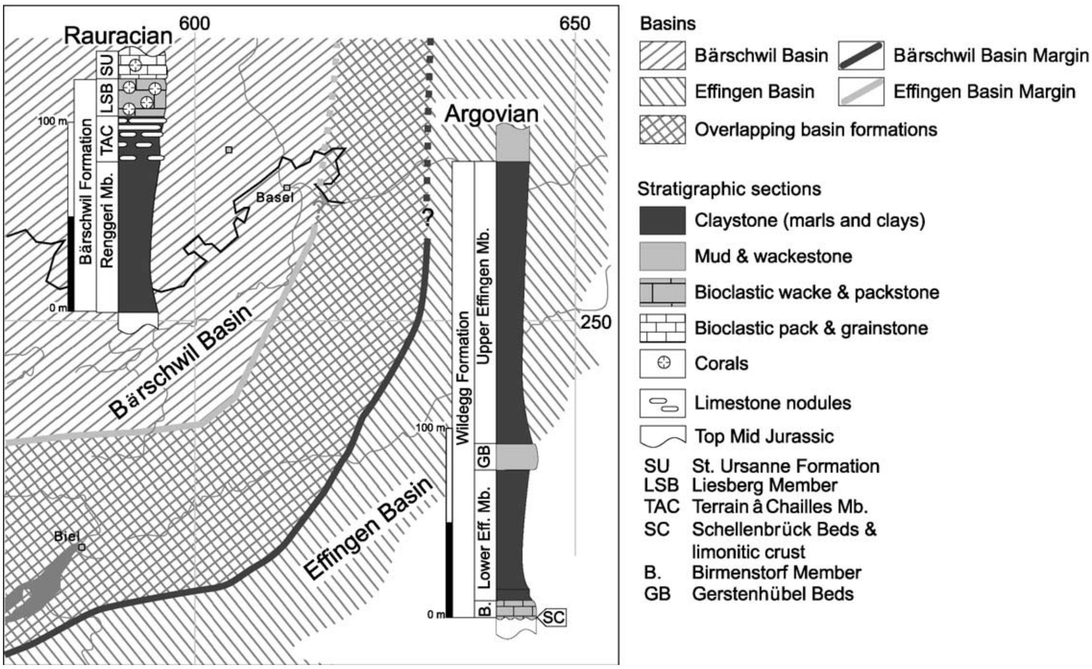


Fig. 4. Spatial relationship of the Early and Mid Oxfordian basins in the study area with representative sections. The Bärschwil basin depocenter is situated in the northwest within the Rauracian realm, the Effingen basins situated in the Argovian realm and extends from the east to the southwest. Note that the basin margins of these diachronous basins overlap.

fields (Wetzel et al., 1993; Allia, 1996; Wetzel and Allia, 2000). Recurring fault reactivation and changing eustatic sea-level led to the facies variations seen in the Mesozoic sedimentary stack of the Jura Mountains.

During the Early and Mid Oxfordian, the study area was separated into two basinal domains characterized by marly deposits (an overview of the local biostratigraphy is given in Fig. 3): the first one, Early Oxfordian in age, in the northwest and the second, roughly Mid Oxfordian in age, in the remaining study area (Fig. 4). These two domains are referred to as the "Rauracian realm" in the northwest and the "Argovian realm" in the eastern and southern part of the study area. Within the Rauracian realm, the Early Oxfordian deposits constitute the Bärschwil Formation made up of the Renggeri Member, Terrain à Chailles Member and Liesberg Member (Fig. 4). Coeval with these deposits condensation prevails in the Argovian realm (Schellenbrücke Bed and the Limonitic crust). The earliest platform deposits in the Rauracian realm are the succeeding patch-reefs and oolites of the St. Ursanne Formation. After a hiatus during the Early Oxfordian in the Argovian realm, sedimentation commenced during the Mid Oxfordian with the marl–limestone succession of the sponge-bearing Birmenstorf Member. To the west, the marl and fossil content decreases within the Birmenstorf Member. Upsection, marl content increases and the marl–limestone alternations become more pronounced as the fossil content decreases to nearly sterile conditions in the Effingen Member.

A monotonous succession of bioturbated micrites with thin, marly partings (Gerstenhübel Beds) overlies

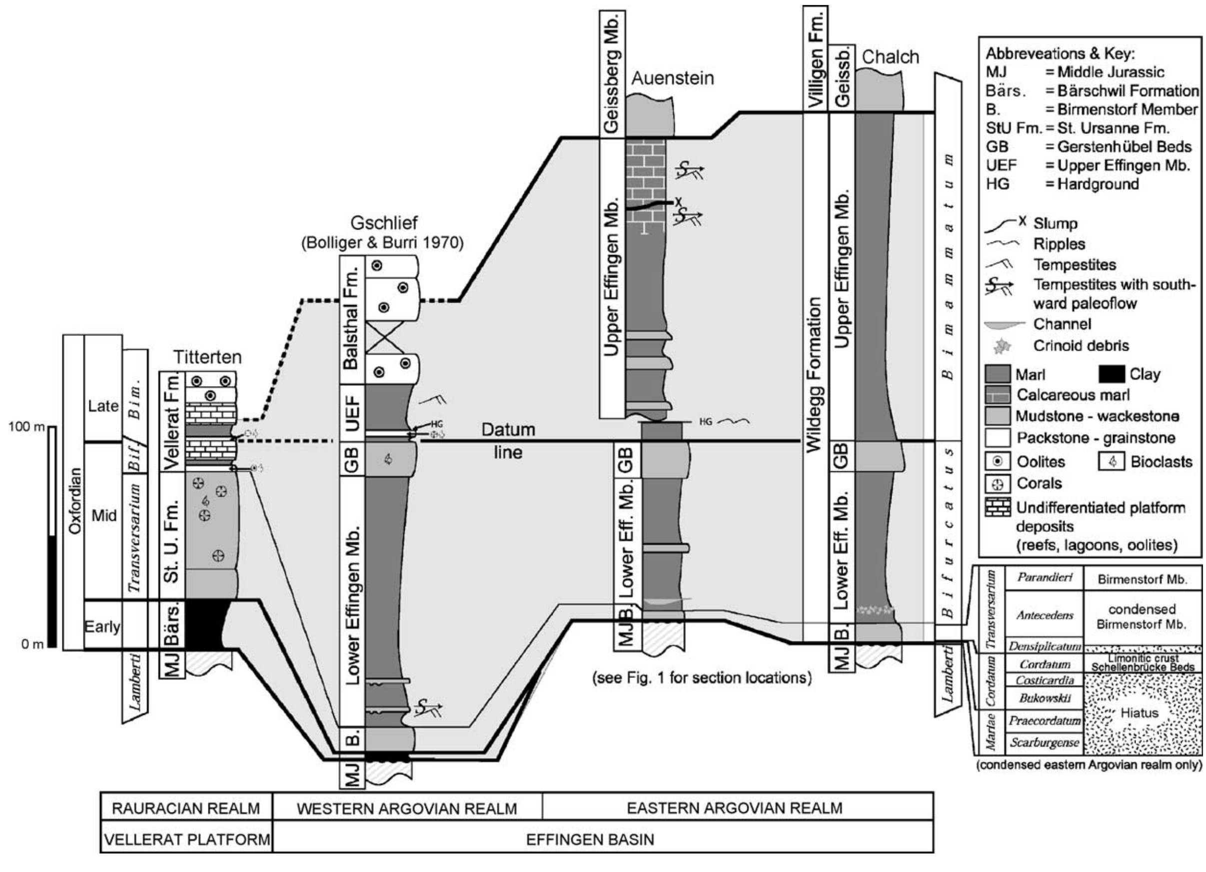


Fig. 5. Selection of simplified sections from the platform, platform margin and basin. The studied time interval is shaded in gray. Note the changes in thickness of the Upper and Lower Effingen Members, which already suggest important changes in differential subsidence within the study area. Biostratigraphy according to Gygi (1995).

the Lower Effingen Member and separates it from the Upper Effingen Member.

Towards the platform, the Gerstenhübel Beds become thinner, more bioturbated and contain more bioclasts and platform debris (wackestones) in contrast to the more distal areas dominated by mudstones. The Upper Effingen Member is similar to its lower counterpart, but with a slightly higher carbonate content (Matter et al., 1988). Coeval with the marl–limestone deposition occurring in the Effingen basin, a carbonate platform established itself in the Rauracian realm (Fig. 5) and prograded to the south and east (Gygi, 1986). To the northeast, the marl–limestone deposits of the Effingen basin grade into the shales of southwest Germany. Towards the south, the basin deposits continue into the marls and limestones of the Helvetic shelf (Debrand-Passard and Courbouleix, 1984; Kugler, 1987). The continuation of relatively deep-water facies towards the northeast and south leaves the Effingen basin without a distinct northeastern and southern basin margin.

The Mid Oxfordian offers an ideal time slice to study the effects of differential subsidence in northern Switzerland. Since the sediments were deposited during a relatively stable (Haq et al., 1987) or generally falling (Pittet and Strasser, 1998) eustatic sea-level, accommodation space must have formed by subsidence. Furthermore, coeval platform deposits crop out in the study area, thereby allowing the northern contour of the basin to be mapped.

3. Material and methods

3.1. Isopach maps

Within the biostratigraphic framework, isopach maxima and facies boundaries highlight areas which potentially experienced higher and lower rates of subsidence. The isopach maps used in this study are based on a compilation of Bitterli (1992), with supplemental data gained in this study. Because several localities are situated in the folded Jura Mountains, it is necessary to use palinspastically restored maps to determine where a given stratigraphic section was located at the time of deposition. Only then can the relationship between the Late Jurassic facies and the basement be recognized. Palinspastic correction was accomplished in accordance to Laubscher's (1965) model. Since the Jura Mountains are the result of thin-skinned tectonics, the basement underneath the study area remained stationary during the Alpine orogeny.

3.2. Paleoflow

Primary sedimentary structures indicative of gravitative flow occur with varying frequency throughout the marl–limestone alternations of the Effingen basin. Current ripples in tempestites and turbidites roughly reveal the orientation of the paleoslope along the Effingen basin. Since flow is influenced by gravity, paleoflow will be from shallow to deep, or more precisely towards the depocenter, although potentially affected by some geostrophic balancing (e.g., Duke et al., 1991).

To determine the paleoflow directions, samples were taken with in situ top, magnetic north and dip orientation. This was measured on polished surfaces, if sufficiently steep ($\geq 2°$) laminae or foresets were preserved, using the method described by Illies (1949). With this method the inclination of individual foreset dips on two sides of the sample are measured and their poles plotted (with respect to the sample azimuth) onto a Lambert grid. Samples which are bioturbated and do not allow for a precise determination of the paleocurrent direction, yet still have enough recognizable structuring to determine the compass-rose quadrant in which the current flowed, were used qualitatively. The same applies for nearly horizontal laminae ($<2°$).

In the Upper Effingen Member, tempestites are encountered near the top of the member, before the facies grades into platform deposits (Weissenstein and Born; Fig. 1) or distal shelf deposits (Auenstein; Fig. 1). In the Lower Effingen Member, tempestites are found only along the platform margin (Weissenstein; Fig. 1). Tempestites are rarely more than 5 cm thick and are unidirectional.

3.3. Subsidence

Geohistory calculations were made using several well-logs and show a distinct increase in subsidence in the Effingen basin at the onset of the Oxfordian interval (Allia, 1996). Other geohistory calculations

(Wildi et al., 1989; Loup and Wildi, 1994) across the European part of the Tethyan continental margin in Switzerland substantiate this trend. Since paleobathymetry and biochronology can only be determined within a certain range of error, these results are regarded semi-quantitatively only. In spite of these inaccuracies the general pattern of increased rates of differential subsidence can be recognized as the epicontinental basins were formed and filled. Rates of subsidence in the studied basins are between 2 and 15 cm/ka (Allia, 1996).

4. Studied sections

All studied sections, a selection of which is shown in Fig. 5, share the same basic trilogy of a marly base (Lower Effingen Member), a calcareous interval (Gerstenhübel Beds) and calcareous marls (Upper Effingen Member or its equivalents), even if the platform equivalents of the marl series are only present as thin layers on the platform. In the case of the Gerstenhübel Beds, calcareous muds characterize the deeper basin and bioclastic muds the basin margin. In the Argovian realm, the sections measured at Villigen, Auenstein and Chalch (Figs. 1 and 5) represent the most distal depositional environments relative to the platform and share a nearly identical development.

Cores obtained from a well near Kütigen (Figs. 1 and 6) include an eroded surface a few centimeters above the top of the Callovian. Lithoclasts of up to 7 cm across with moderately rounded edges (Fig. 6) occur over the condensed Callovian–Oxfordian boundary. Lithologically the clasts are iron-oolitic wackestones, mudstones and iron-encrusted stromatolitic clasts. Some clasts also feature stromatolitic growth around the whole clast. In the Auenstein section, iron-oolitic lithoclasts measuring only a few millimeters were also recovered from above the condensed series. Upsection these are overlain by sponge-dominated marly limestones of the Birmenstorf Member. Within the basal Lower Effingen Member, a series of channels crops out in the Auenstein section (Fig. 7). These are defined by asymmetrical, convex down, limestone beds. Each of these channels is characterized by an erosive base which cuts into the underlying marls. The basal limestone bed (Fig. 7a) consists of a bioclastic wackestone containing reworked sponges as well as some ammonites, brachiopods and echinoderm debris. The overlying marl layer shows some lag deposits as most of the bioclasts accumulated at the base. The succeeding layers do not show any internal structuring and contain far fewer bioclasts. Internal, sigmoidal structuring can only vaguely be recognized in some channels (Fig. 7b). In the Chalch section (Figs. 1 and 5), a 50-cm-thick succession of

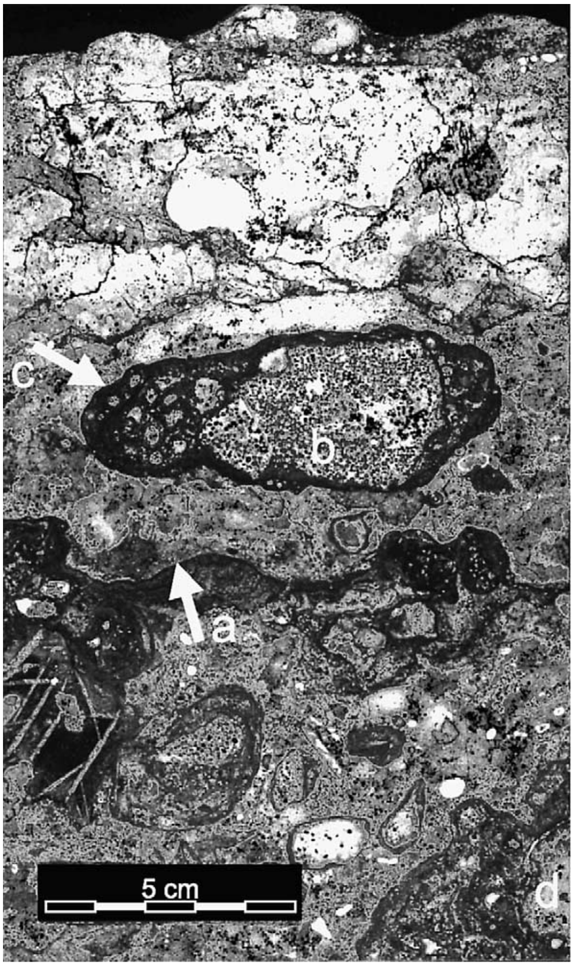


Fig. 6. The condensed top of the Early Oxfordian remnants of the Argovian realm overlain by the condensed lower Birmenstorf Member. The limonitic crust (a) is a ferroan stromatolitic crust which is also exposed in the Auenstein section. This sample was taken from a core (KTG; in Fig. 1) west of Auenstein. Above the limonitic crust an iron–oolitic clast (b) encrusted by ferroan stromatolites (c) floats in an iron–oolitic matrix (wackestone). Below the limonitic crust identical clasts (d) are in a bioclastic and iron–oolitic wackestone matrix.

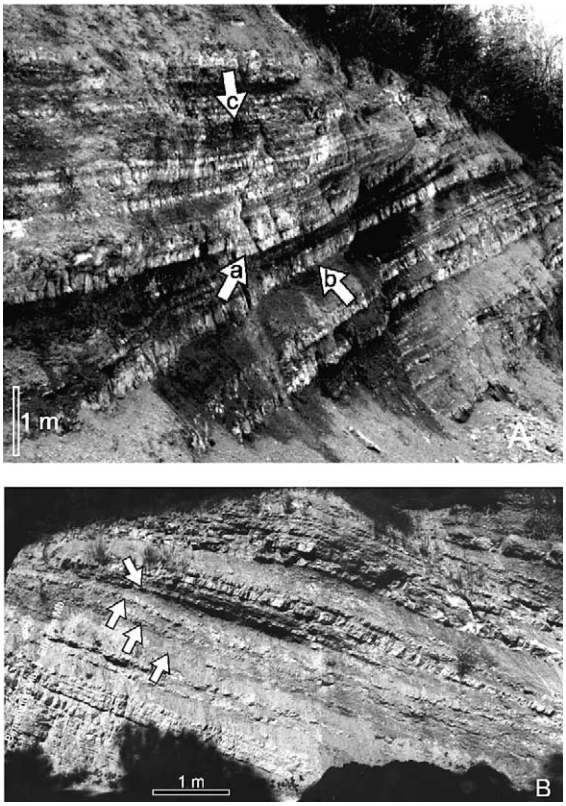


Fig. 7. The channel facies of the Lower Effingen Member in the Auenstein section (see Fig. 1 for location). (A) Arrow "a" points to the channel base, while the others point to horizontal beds below and above the channel. (B) The lower arrows point to internal structuring within a second channel. The top arrow points to the first horizontal bed over the channel. The top of the Birmenstorf Member is exposed in the lower left corner.

crinoid detritus forming two beds lies within the lowest Effingen Member (Fig. 8). The only moderately abraded clasts are arranged in thin layers covered with limonite drapes. The remainders of these sections are marl–limestone alternations typical of the Effingen basin.

The Gschlief section situated near the platform margin includes both basinal and platform margin facies (Fig. 5). The condensed series (Schellenbrücke Bed) is not developed and the Birmenstorf Member contains only sparse occurrences of sponges and ammonites as is typical for the western Argovian facies. Other macrofauna is absent. In the overlying marl–limestone alternations (base of the Lower Effingen Member), tempestites containing ophiurids (Meyer, 1984) have been recovered from the Weissenstein section (Fig. 1). The Gerstenhübel Beds contain platform debris (ooids and bioclasts) at this location and a bed containing corals (Bolliger and Burri, 1970) at their top. A further section (Rotmatt in Fig. 1) contains reworked and bored lithoclasts in the micrites of the Gerstenhübel Beds. These are rounded micrite clasts up to 5 cm in diameter. The uppermost marl–limestone alternations of the Upper Effingen Member rapidly grade into the platform deposits of the Balsthal Formation as documented by the sudden occurrence of ooids within the uppermost meters of the basin deposits (sections Gschlief and Rotmatt).

A section representative of the coeval platform, with oolites, patch-reefs and other shallow-water carbonate deposits, is found at Titterten (Figs. 1 and 5).

5. Field data

5.1. Paleocurrents

Paleocurrent indicators are eminent in determining the spatial orientation and persistence of the slope. Maintaining flow direction into a basin, which is

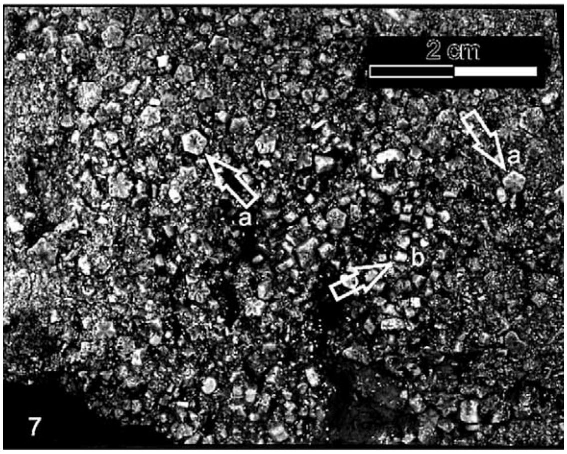


Fig. 8. View of the top of a sample obtained from the crinoid debris layer in the Chalch section (see Fig. 1 for location). Arrows point to stem fragments (a) and ossicles (b). This combined occurrence indicates nearly in situ disintegration of the crinoids and only minor subsequent transport.

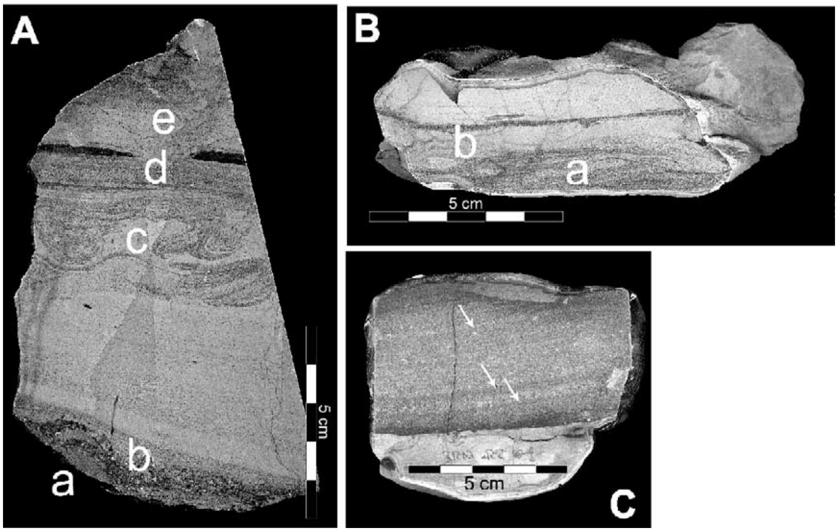


Fig. 9. Tempestites of the Effingen Member. (A) Born section (see Fig. 1 for location), Upper Effingen Member. The sample begins with a curved, erosive lower surface (a) followed by a graded, bioclastic interval (b) and laminae. The middle portion of the sample (c) contains ripples deformed by dewatering (convolute bedding). A second event is recorded by laminae (d). Post-event micrites form the top of the sample (e). (B) Tempestite sample from the Auenstein section (see Fig. 1 for location). The base is nearly flat. Current ripples (a) show low-angle lamination dipping to the left. The remainder of the sample consists of micrite interrupted by a thin sandy layer (above b). (C) A nearly horizontally laminated (arrows) tempestite (Born section; see Fig. 1). The calcareous portion of the sample below the tempestite may have formed diagenetically.

continuously being filled, proves the persistence of relief. Paleocurrents are usually revealed by current ripples found in association with tempestites having an erosive base overlain by laminae and/or foresets (Fig. 9). Further qualitative paleocurrent directions are given by the channels found at two locations (Auenstein and Limmern; Fig. 1). The channels of the Lower Effingen Member in the Auenstein quarry

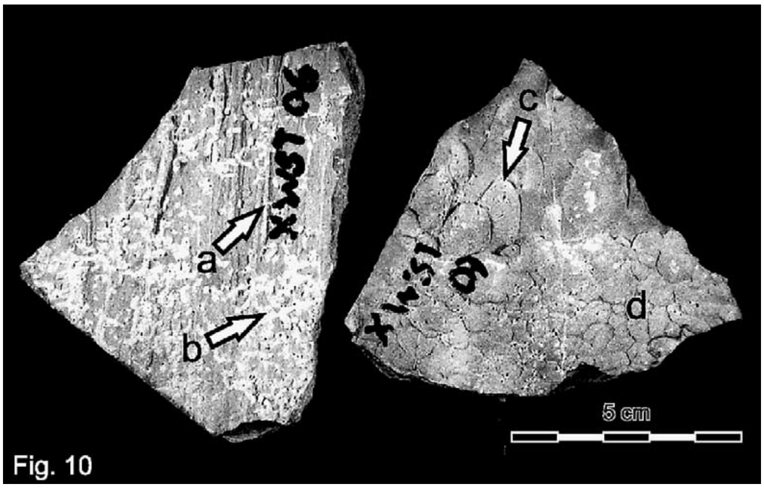


Fig. 10. Groove casts (a) and flute casts (c) recovered from the scree of the Gschlief section (see Fig. 1 for location). Small burrowing traces (b; *Chondrites*?). In the right-hand sample load casts (d) lie a few millimeters above the flute casts (c). Current direction is from top to bottom in both samples.

indicate a paleoflow to the west, whereas the ripples in the Upper Effingen Member show dominant current directions towards the northwest. Groove-casts described by Meyer (1984) from the northern basin margin (Weissenstein; Fig. 1) have a north–south orientation (Fig. 10).

5.2. Distality trends

Due to the lack of indicative fossils and sedimentary structures in the Effingen Member, paleo-water-depth and distality trends could only be estimated. However, primary sedimentary structures are found mainly in the lowest and uppermost reaches of the member in the form of tempestites. Frequency of tempestites and their degree of bioturbation will only give a qualitative indication of distality trends (Seilacher and Aigner, 1991), yet these are the only available structures which can be used to differentiate deeper from shallower areas within the Effingen basin. Samples from the deeper basin (sections Auenstein and Villigen; Fig. 1) commonly contain numerous paleoflow directions within one sample. Within single beds, episodes of deposition and erosion can be determined which have been related to tempestites (e.g., Aigner, 1985). However, on a larger scale covering several meters laterally, the beds do not resemble hummocky cross-stratification as defined by Johnson and Baldwin (1996) because amplitudes and relief are too low. Yet the erosive and depositional features within individual beds, as well as locally chaotic paleoflow directions, suggest that these beds are tempestites deposited above the storm wavebase.

The earliest and latest deposits of the Effingen basin, which contain the most tempestites, are interpreted to represent the shallowest parts of the basin (e.g., Pittet, 1996). This distality trend is further substantiated by the far lower frequency of tempestites in the more distal sections of the Effingen basin (sections Rekingen; Villigen in Fig. 1) in comparison to the proximal sections (sections Weissenstein; Gschlief in Fig. 1). Due to sorting of the suspended matter during transport, only the fine-grained detrital quartz will be carried into the basin. Coarser material remains on the deeper platform.

The stromatolite-enveloped clasts found at the base of the Oxfordian deposits of the Argovian realm suggest recurring high energetic conditions capable of eroding the clasts from the condensed series (sections Auenstein and Kütigen; Fig. 1) and periodically overturning these to enable the enveloping stromatolite growth. The accompanying iron-encrustation indicates a period of very slow sedimentation. Similarly, the smaller iron-oolitic lithoclasts found above the condensed series (section Auenstein; Figs. 1 and 5) are interpreted to be reworked clasts.

The moderate abrading and presence of both ossicles and stem fragments (poor sorting) in the crinoid debris-beds of the lower Effingen Member suggest a short transport; and the accumulation of limonite indicates a period of slow deposition during the formation of these beds. Tempestites containing exceptionally well-preserved ophiurids of the lower marl–limestone alternations of the Effingen basin (Weissenstein; Fig. 1) were interpreted by Meyer (1984) to have been deposited in a depth between 50 and 100 m.

Earlier authors (Bolliger and Burri, 1970; Gygi and Persoz, 1986) have placed the occurrence of current ripples and laminae of the Effingen Member in deep water ($\geq$100 m) based on observations from the Recent. However, Hallam (1999) has recently suggested that the lack of polar ice-caps during the Late Jurassic reduces the likelihood of marine currents capable of reworking consolidated rock in epicontinental seas.

5.3. Interpretation of the depositional environment

Based on the distality trends of tempestites and the occurrence of sedimentary structures such as channels and crinoid debris accumulations as well as reworking, some qualitative interpretations on the paleo-waterdepth of the Effingen basin can be made. The oldest deposit found in the eastern Argovian realm is the Schellenbrücke Bed which contains evidence of a shallow environment based on the reworked deposits and stromatolites. Geographically, this bed is restricted to the eastern Argovian realm. This same area has been recognized as a swell during the Callovian (Bitterli, 1977). The condensed nature of this bed is interpreted as an effect of sediment bypassing on a structural high rather than starvation as suggested by Gygi (1986). Also, the omission of the Bärschwil Formation (i.e. thinning out of the Early Oxfordian basin to the east and south) in this area suggests a structural high rather than a basin. Towards the northwest, evidence for reworking and condensation is lacking in the Birmenstorf Member. This implies non-bypassing in the western Argovian realm, and thus a slightly deeper environment in the western as opposed to the eastern realm.

The channels, crinoid debris beds and tempestites of the Lower Effingen Member are approximately synchronous (Fig. 5), revealing that this is a shallow, basin-wide interval within the Effingen basin.

A second more proximal horizon is found in the carbonate-rich Gerstenhübel Beds which document a shallowing-up trend in the basin. Again, reworked deposits indicate shallow conditions.

The final proximal interval containing tempestites is found in the Upper Effingen Member, before this member grades into the overlying micrites (Geissberg Member). Based on tempestite frequency and the presence of current ripples, this interval is regarded as the most proximal one (e.g., Pittet, 1996). Along the northern basin margin (sections Gschlief and Weissenstein; Fig. 1) the influx of platform debris further documents this proximity.

The intervals within the Upper and Lower Effingen Members which do not contain any primary sedimentary structures are regarded as the most distal and deepest intervals (below the storm wave base) within the Effingen basin.

5.4. Intraformational truncations

Angular unconformities within the Effingen basin are found at three localities—all of them marl quarries in the eastern part of the study area. In one location (Rekingen; Fig. 1) four successive unconformities were identified. The steepest measured angles of the unconformity relative to the local dip of the strata are 5° to 7°. Dip of the truncation surfaces is consistently to the south. Along the base of one bed lying just over the unconformity numerous mudclasts indicate reworking.

In a second quarry (Auenstein; Figs. 1 and 5), a further unconformity was identified (Fig. 11; Gygi and Persoz, 1986) overlain by a 20-cm-thick debris flow. This unconformity is cut by a small synsedimentary reverse fault which displaces the unconformity by a few meters. Upsection the fault ends without further disturbing the sedimentary stack.

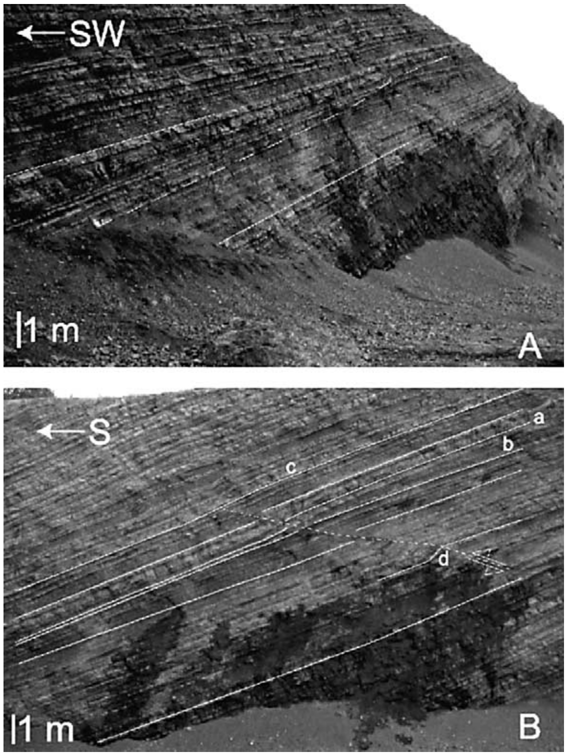


Fig. 11. Angular unconformity found in the Upper Effingen Member of the Auenstein section (Figs. 1 and 5). (A) The dashed line highlights the unconformity; the sediment stacks both below and above the unconformity are cut. Solid lines indicate the normal dip of the strata. (B) Frontal view of the unconformity shown in (A); the unconformity "a" cuts the underlying stack "b". Normal dip of the strata is shown by "c". A blind thrust displaces the unconformity and also produces small "kinks" (d).

Another large-scale structure, yet without an intraformational truncation, crops out in the Upper Effingen Member of the central study area (Born; Fig. 1). An approximately 10- to 15-m-thick interval of marl–limestone alternations is folded into a small anticlinal structure. Beds found below and above this structure lie parallel to the dip measured in the remainder of the quarry.

Generally, the unconformities of the Effingen Member bear a very close resemblance to the Permo-Pennsylvanian slumps of Ellesmere Island (Cook and Mullins, 1983). These structures were interpreted by Davies (1977) to be seismically induced, in part because they are situated near the fault-bounded basin rim. The Born quarry structure is reminiscent of the folds encountered in a slump toe or more likely a "skin slump'' (Seilacher, 1991) and is as such interpreted to be triggered by similar shocks as are the slumps encountered in the other two quarries.

Ball-and-pillow structures were found in the Auenstein section. These structures are interpreted by Aigner (1985) and Dugué (1995) to be of seismic origin. The beds show convolute tempestites around which carbonate was preferentially concentrated during diagenesis.

5.5. Basement structures

Seismic analysis and core data (Diebold and Naef, 1990) show that the Variscan basement is separated into deep troughs, shallow troughs (both with Permo-Carboniferous infill) and trough shoulders (without Permo-Carboniferous sediments). These authors stated that the troughs are intensely structured by numerous faults leaving a veritable ''block-mosaic'' in the basement (Fig. 12). The Permo-Carboniferous trough fill is entirely continental dominated by fluvio-lacustrine sediments capped by red beds (e.g., Matter, 1987). In the eastern Jura Mountains, the Molasse Basin and along the southern foot of the Jura Mountains trough orientation is ENE–WSW. Along the northern foot of the Jura Mountains, however, trough orientation is east–west (Pfiffner, 1993). This slight change in strike orientation takes place along the Rhenish lineament (Boigk and Schöneich, 1974) which corresponds to the eastern Rhinegraben masterfault. This lineament, as well as the Wehra-Zeininger fault, appears to have been active during the Mesozoic and repeatedly played a major role in defining N–S striking facies boundaries during the Mesozoic and especially during the Oxfordian.

Two Paleozoic troughs are of importance in the development of the Bärschwil and Effingen basins: the Olten Trough and the Constance-Frick Trough (Fig. 12).

6. Eustasy and accommodation space

According to Sarg (1988), carbonate environments are controlled by four factors: tectonic subsidence which creates accommodation space; eustatic change,

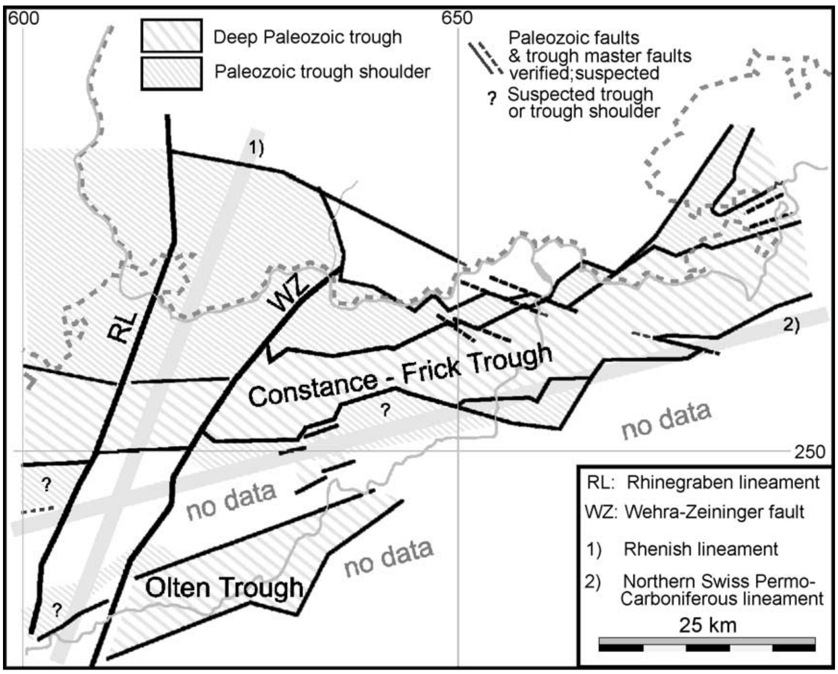


Fig. 12. The two major Permo-Carboniferous Troughs (PCTs) situated in the study area: the Olten and Constance-Frick PCTs, both of which form part of the westward continuation of the Constance-Frick trough situated under Lake Constance.

which may create or reduce accommodation space and also influences carbonate production and/or siliciclastic input; the volume of sediment, which controls paleo-waterdepth; climate, which affects sediment production. Infiltration of siliciclastics into a carbonate system occurs during falling and low sea-levels during which carbonate production is reduced on the platform and distant crystalline rocks and coastal facies belts become exposed and are eroded (Talbot, 1973; Pittet, 1996).

In the case presented here, the four controlling factors are as follows: during the Oxfordian, sea-level describes a general long-term rise of approximately 30 m, interrupted by eight short-term sea-level drops of up to 10 m (Haq et al., 1987; Ponsot and Vail, 1991). Sediment thickness in the Effingen basin is quite substantial: 260 m (maximum value) of compacted marls were deposited in 1.5 Ma (Pittet and Strasser, 1998), while paleo-waterdepth remained deep relative to the platform. The climate was favorable for weathering subaerially exposed rocks (Gygi and Persoz, 1986; Pittet and Strasser, 1998) thereby introducing siliciclastics into the environment.

Sedimentation rate was high in the basin and paleo-waterdepth was probably slightly below the storm-wave base as documented by the lack of obvious shallow-water indicators such as oscillation ripples. Since rates of deposition were high and eustatic sea-level variations negligible in relation to the needed accommodation space, only tectonic subsidence could have produced the necessary accommodation space. Sediment thickness, especially when decompacted, exceeds all estimates of depositional water-depth. As the Effingen basin was gradually being filled (early Bimammatum zone), the carbonate factory on the platform started up again during a slight rise in sea-

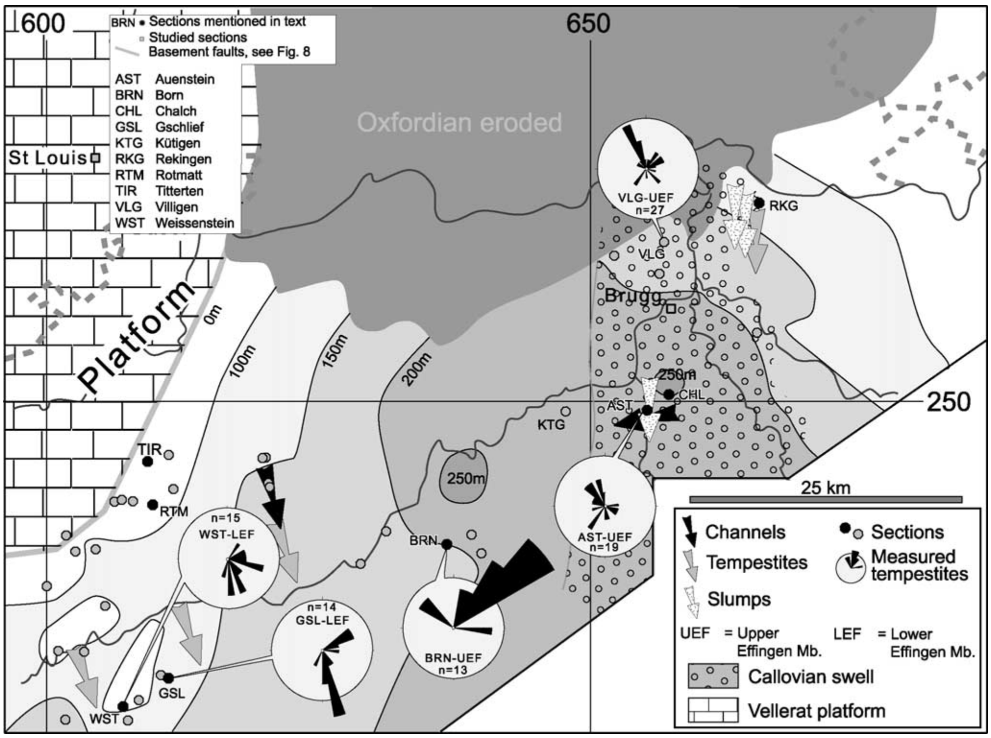


Fig. 13. Paleocurrents in relation to isopach maxima of the Effingen Member. The majority of paleocurrents shows a distinct preferential flow towards the depocenters, indicating continuing paleorelief despite continuous basin infill. On all maps included in this study, only the localities from which Oxfordian data were recovered are palinspastically restored, whereas present-day geography remains in its present position in order to demonstrate the effect of the palinspastic restoration relative to familiar topographic elements (towns, rivers, etc.) and the basement. For further details see text.

level (Pittet and Strasser, 1998). This increase in carbonate is seen along the northern basin margin in the form of patch-reefs and oolites. In the eastern basin, however, subsidence remained too rapid for the platform to be able to prograde and marl–limestone deposition continued, albeit with a higher carbonate content as carbonate was washed off the platform and into the basin. The facies boundary between the calcareous marls of the basin and the platform lies parallel to Paleozoic faults in the basement. Thus, the facies boundary also differentiates areas with higher and lower rates of subsidence.

The reworked and encrusted clasts found in the eastern Argovian realm show beyond doubt that the earliest preserved Oxfordian deposits of this facies were formed in an agitated environment close to the storm-wave-base. Based on the distribution of tempestites, the upper- and lowermost parts of the Effingen basin fill are considered to represent the shallowest periods in the basin (e.g., Seilacher and Aigner, 1991). Therefore, the remainder of the formation, without recognizable tempestites, represents the relatively deepest facies within the Effingen basin. As this period coincides with an eustatic fall during the early Bifurcatus zone, a local increase in subsidence is necessary in order to maintain the waterdepth and accommodation space needed for the deposition of the basinal sediments. Although reworked deposits on the coeval platform are known from the Titterten locality (Figs. 1 and 5), suggesting that the wave-base on the platform was sufficiently low to cause erosion, there is no evidence for karstification on the platform.

7. Paleorelief and the basement

When all the data regarding paleocurrents and slumps are brought into context with the isopach

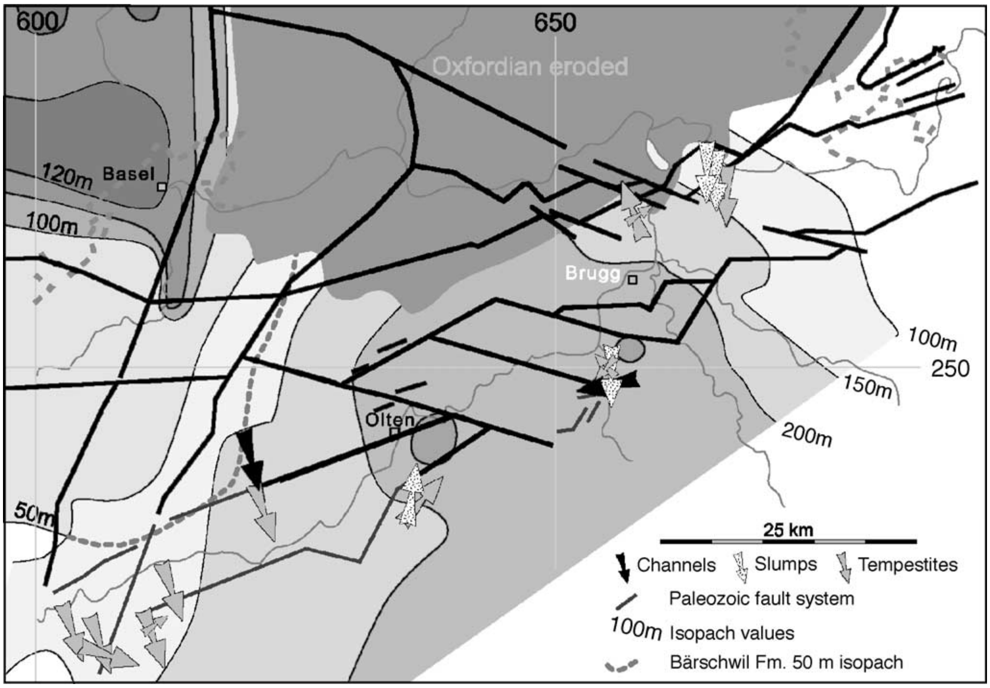


Fig. 14. Synopsis of paleocurrent data, depocenters and basement structures of the Effingen Member (see also Figs. 8 and 13). Depocenters occur preferentially along the southern trough margins and slumps occur on either northern or southern trough margins. Sections situated over the trough (VLG, WST and GSL) may contain tempestites, but not slumps. The northwestern basin margins are largely influenced by the Rhenish Lineament and Wehra-Zeininger fault. Also included are the thicker (> 50 m) isopachs of the Bärschwil Fm. (see also Figs. 4 and 8). Only the localities from which Oxfordian data were recovered are palinspastically restored, whereas present-day geography remains in its present position.

map of the Effingen basin, it becomes evident that paleoflow and slumping was preferentially towards the local depocenters (isopach maxima; Fig. 13). Along the southern foot of the Jura Mountains, most of the paleocurrents indicate a flow towards the south–southeast, the only exceptions being the Born and Villigen localities (Fig. 1). The Born section displays a flow towards the Olten depocenter situated to the northeast (Fig. 13), whereas the Villigen section displays a paleocurrent trend with dominant flow to the northwest and northeast. Superimposing the structural data onto isopach maps reveals that the Late Jurassic depocenters occur in the spatial vicinity of Paleozoic fault systems (Fig. 14). This occurrence of depocenters above the Permo-Carboniferous troughs and trough margins suggests a direct relationship between the depocenters and the Paleozoic troughs. The depocenter located in the eastern study area (south of Brugg) lies south of the deep trough, but above the trough shoulder and, hence, appears to be related to deep-reaching Paleozoic faults. The variable thickness of the marl–limestone alternations of the Effingen basin provides a further valuable clue to differential subsidence. As shown in Fig. 5, the thicknesses of both the Lower and Upper Effingen Members change from distal to proximal. The Lower Effingen Member is thickest along the platform edge, whereas the Upper Effingen Member is thickest over the distal basin. This change in thickness of the Lower Effingen Member is attributed in part to the topographic swell inherited from the Callovian. Due to the persistence of this swell, accommodation space in the Argovian realm was reduced in comparison to the remainder of the basin. Therefore, it seems unlikely that the variations in thickness are to be attributed to an effect of prograding clinothems in the basin as postulated by Gygi (1986) and Gygi and Persoz (1986). Lithostratigraphic and biostratigraphic data (Fig. 5) suggest that the basin subsided more rapidly along the platform margin than in the central part during the early Mid Oxfordian. During the later Mid Oxfordian, subsidence rates in the eastern part of the basin increased, leaving a thick stack of calcareous marls in the eastern Argovian realm. The increase in carbonate content within the basin is the effect of increasing carbonate production on the platform during a sea-level highstand, the surplus of which was deposited in the basin.

In the eastern Argovian facies, the condensed section indicates a shallow environment affected by storm-waves (30–50 m waterdepth; Tucker and Wright, 1990) which inhibited deposition. Norris and Hallam (1995), who examined the Middle-Upper Jurassic boundary, mention paleo-waterdepths of 20 to 50 m for this type of facies. Also, the sponge facies of the Birmenstorf Member is regarded as a relatively shallow environment (Gaillard, 1983; Ricken, 1985) situated on a swell already observed in upper Mid Jurassic facies patterns (Bitterli, 1977). Paleocurrents are found to flow towards local depocenters, which proves that these are not contourites as suggested by Kugler (1987) or basin-floor currents as proposed by Bolliger and Burri (1970).

8. Interpretation of the lower Oxfordian basin

Despite the lack of exposure of the Lower Oxfordian Bärschwil Formation, parallels to the Mid Oxfordian Effingen basin can be found. Some evidence suggests that the Lower Oxfordian deposits were also deposited in a basin defined by basement structuring. Laterally, the Bärschwil Formation thins out to the east, south and southwest (Debrand-Passard and Courbouleix, 1984; Gygi, 1990) leaving only the coeval condensed series in the eastern study area. Isopach maps reveal an isopach maximum throughout the Lower Oxfordian in the area of the southern Rhinegraben (Bitterli, 1992). Depocenters of the Triassic (Bitterli, 1992) and Aalenian (Allia, 1996) are also found in this area. This recurrence of depocenters already suggests repeated reactivation of basement structures in order to form the accommodation space. Indeed, Allia (1996) demonstrated that reactivated Paleozoic faults were the main factor in developing accommodation space for the Aalenian epicontinental basin. Subsidence plots of the southern Rhinegraben show a rapid increase in subsidence rates during the Early Oxfordian (Allenbach, 1997). Based on studies of other Mesozoic epicontinental basins where isopach maxima coincide in both location and time with increased subsidence rates, it is inferred that the Bärschwil Formation was also deposited in a basin formed by the reactivation of Paleozoic basement faults. The condensed Lower Oxfordian deposits were formed on relative high zones which inhibited sedimentation.

Some fossil collectors further suggest that the lower Bärschwil basin is not uniform in age (B. Hostettler, Glovelier, 1998, pers. com.). Based on ammonites collected from the Bärschwil Formation, the impression is gained that accommodation space was formed diachronously on the subzone level, thereby implying differential subsidence.

9. Discussion

During the Late Callovian, a relative high existed in the eastern Argovian realm characterized by condensed shallow-water deposits, in contrast to the basinal clays deposited in the remaining area (Bitterli, 1977). This basin-and-swell architecture of the study area concurs with the findings of Norris and Hallam (1995). Thus, the Early Oxfordian appears to be a continuation of the Late Callovian depositional style (a depocenter above the Upper Rhinegraben while a swell persists in the east). A similar trend has also been recognized by Loup and Wildi (1994) who found that Mid Jurassic subsidence patterns of the Paris Basin continue into the Oxfordian. With the reorganization of the European stress-field in the Late Jurassic (Ziegler, 1990), a shift in the depocenters is recognized; and the Triassic and Mid Jurassic subsidence pattern observed in the Lower Oxfordian Bärschwil basin is replaced by the Late Jurassic subsidence pattern seen in the Mid Oxfordian Effingen basin.

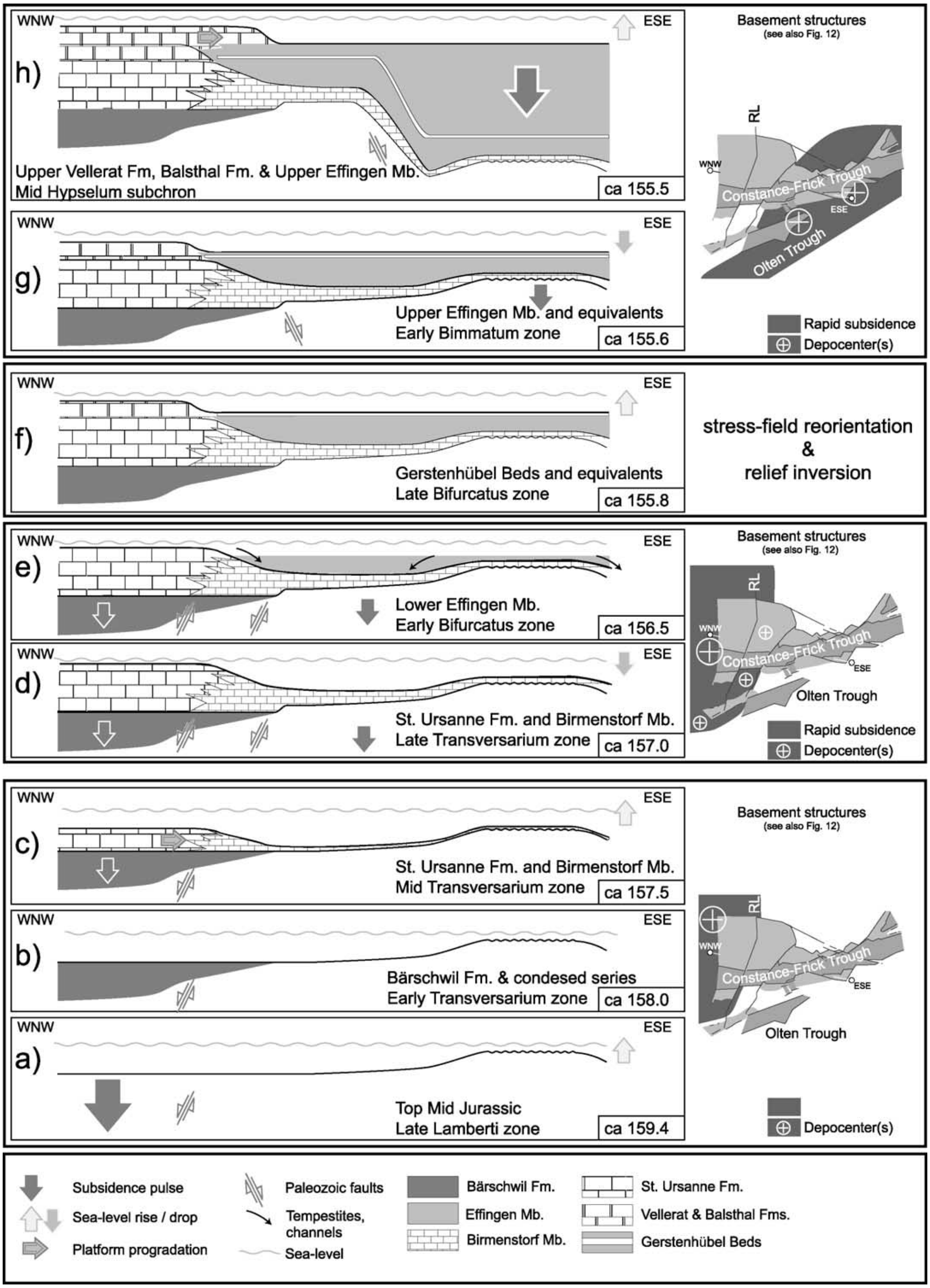
Paleogeographic maps of the Early Oxfordian (Debrand-Passard and Courbouleix, 1984) show that the depocenter of the Early Oxfordian claystone facies continues to the SW into the area of the Bresse Graben in eastern France, with formation thickness decreasing on all sides. This pattern is consistent with a basin and contradicts the model of Gygi (1986) who interpreted the Early Oxfordian Bärschwil Formation as "prodelta mud with a positive physiographic structure". With this "hill" sufficient relief was formed, which doubled as the northern margin of the Mid Oxfordian basin.

Facies analysis by itself already shows that a shallow basin bordered the carbonate platform in the northwestern study area during the Mid and Late Oxfordian (Fig. 13), but there has been little discussion to date on the formation of this basin. Subsidence in the Gygi model is assumed to be uniform with some additional isostatic subsidence (Gygi, 1986; Gygi et al., 1998). Because eustatic sea-level rise (Haq et al., 1987) is not sufficient to form the needed accommodation space, subsidence is the only factor which provided the space to accommodate the sediments of the two basins discussed here. Based on the observation that the Effingen Member attains a compacted thickness of over 260 m within 1.5 Ma (130 m in 1.5 Ma for the Bärschwil Formation), the interpretation is made that deposition was rapid and available accommodation space was promptly filled. Sediment was readily available, be it in the form of siliciclastics, carbonates or a mixture of both.

Comparison of the Oxfordian isopach maps with those of the Triassic (Bitterli, 1992) and Aalenian (Allia, 1996; Bitterli, 1992) shows that depocenters occur above Permo-Carboniferous troughs. The continuous south–southeasterly paleoflow along the northern Effingen basin margin reflects the relief in this area, and the northeasterly directed tempestites of the Born quarry show a distinct preferential flow towards the depocenter situated over the Paleozoic Olten trough.

As can be seen in Fig. 14, the palinspastically restored localities featuring slumps along with other indicators of seismic activity are situated over major

Fig. 15. Cartoon of the model proposed in this study. Differential subsidence along reactivated Paleozoic faults in the basement is the main cause of the development of the Effingen and Bärschwil basins. In the early stages of the basins (a–c), the northwestern study area experienced the highest rates of subsidence bordered by the Rhenish lineament and Wehra-Zeininger fault to east of the Bärschwil basin. The Argovian swell remained somewhat elevated. During the late Transversarium and early Bifurcatus zones, the subsiding area extended somewhat to the east and south (d–e) and lowstand deposits of the first marl–limestone alternation were laid down. By the end of the Bifurcatus zone (f) the Lower Effingen Member was deposited and the calcareous interval of the Gerstenhübel Beds were formed as carbonate production on the platform increases due to sea-level rise. With a drop in sea-level taking place during the early Bimammatum zone (g) siliciclastics were again brought into the Effingen basin. During the Hypselum subzone (h), a major subsidence pulse took place in the central Effingen basin and the second marl–limestone series was deposited. Rising sea-level allowed carbonate production on the platform to pick up again while rapid subsidence in Effingen basin formed accommodation space that rapidly filled with marls. The absolute ages are estimated from Gradstein et al. (1995). Despite their potential for inaccuracy, the absolute ages convey a perspective on the amount of time involved in the processes illustrated here.


WNW
ESE
h)
Upper Vellerat Fm, Balsthal Fm. & Upper Effingen Mb.
Mid Hypselum subchron
ca 155.5
Basement structures
(see also Fig. 12)
RL
Constance-Frick Trough
Olten Trough
g)
Upper Effingen Mb. and equivalents
Early Bimmatum zone
ca 155.6
Rapid subsidence
Depocenter(s)
f)
Gerstenhübel Beds and equivalents
Late Bifurcatus zone
ca 155.8
stress-field reorientation
&
relief inversion
e)
Lower Effingen Mb.
Early Bifurcatus zone
ca 156.5
d)
St. Ursanne Fm. and Birmenstorf Mb.
Late Transversarium zone
ca 157.0
c)
St. Ursanne Fm. and Birmenstorf Mb.
Mid Transversarium zone
ca 157.5
b)
Bärschwil Fm. & condesed series
Early Transversarium zone
ca 158.0
a)
Top Mid Jurassic
Late Lamberti zone
ca 159.4
Subsidence pulse
Sea-level rise / drop
Platform progradation
Paleozoic faults
Tempestites, channels
Sea-level
Bärschwil Fm.
Effingen Mb.
Birmenstorf Mb.
St. Ursanne Fm.
Vellerat & Balsthal Fms.
Gerstenhübel Beds

faults known from seismic interpretation. In addition, the depocenters are found to overlie the Permo-Carboniferous troughs or their southern margins. All of these facts suggest that the reactivation of Paleozoic faults during the Oxfordian was probably the driving force behind the formation of the Bärschwil and Effingen basins.

An explanation for the lack of a proper southern basin margin of the Effingen basin is that subsidence increased to the south across the Swiss Plateau to the Helvetic shelf as part of the Tethyan continental margin (Wildi et al., 1989)—subsidence was between 11 and 25 m/Ma (depending on locality) in the Jura Mountains, up to 55 m/Ma in the Swiss Plateau and 16 to 40 m/Ma on the Helvetic shelf.

Subsidence pulses during the Oxfordian linked with the opening of the North Atlantic have been reported from various parts of Europe: Rioult et al. (1991) in Normandy; de Wet (1998) in the Wessex Basin of southern England; Pittet and Strasser (1998) in Spain and Switzerland; Loup and Wildi (1994) in the Paris Basin and Færseth (1996) in the North Sea. Similarly to the basin portrayed here, de Wet (1998) found that the Corallian thickness maximum is situated above a rotated east–west striking Paleozoic trough, with thin coeval beds on the upthrust side. Further evidence for differential subsidence in the Effingen basin is provided by occurrences of indicators for a relatively shallow facies, such as proximal tempestites and channels followed by deeper-water deposits, despite the eustatic lowstand (Haq et al., 1987).

10. Conclusions

Depocenters and paleocurrents in combination with subsurface data show a relationship to pre-existing structures in the basement, which became reactivated. In this study, it is shown that the examined Oxfordian epicontinental basins were directly influenced by reactivation of Paleozoic fault systems. The depocenters of both Oxfordian basins are situated above or near Permo-Carboniferous troughs. The basin margins are parallel to Paleozoic faults, and indicators of seismic activity occur only above Permo-Carboniferous trough masterfaults which are the deepest-reaching and potentially most susceptible to reactivation. Slumps, blind thrusts and ball-and-pillow structures suggest seismic activity, thereby further strengthening the evidence for fault reactivation during the Oxfordian. Paleocurrent indicators show a preferential direction towards the depocenters during the early and final stages of sedimentation in the Effingen basin, thereby indicating that the relief was never completely leveled out during deposition of these sediments. The formation of an epicontinental basin and its infill during a eustatic lowstand (Haq et al., 1987) also shows that eustatism cannot be responsible for forming the relatively deep basins. All of these observations strongly suggest that differential subsidence formed the depositional environments shown here (Fig. 15). Because the nearest known tectonic activity taking place at the time is the opening of the North Atlantic and Tethys Oceans, these movements are seen as the driving force behind fault reactivation. Similar effects are also known from the North Sea in which Paleozoic fault systems were reactivated by Late Jurassic extension in the Atlantic and thereby caused differential subsidence (Færseth, 1996; Ziegler, 1990). Also, the basins portrayed here fit the subsidence histories of Mesozoic European epicontinental basins as shown by Loup and Wildi (1994): a continuation of the Mid Jurassic subsidence pattern into the Oxfordian. This change in subsidence patterns has also been observed by Wildi et al. (1989) who found that the Late Jurassic is the first subsidence phase with a WSW–ENE striking zone of subsidence. Thus, it can be shown that distant tectonic forces may be identified in regions where they are not expected and their resulting structures are only subtly developed. The implication is that the Oxfordian in central Europe was a period of widespread basement remobilization and not of tectonic quiescence.

Acknowledgements

I am indebted to A. Wetzel and B. Pittet for the numerous discussions as well as for improving an earlier version of this manuscript. A. Strasser, T. Aigner and K.A.W. Crook are thanked for their helpful reviews and comments to improving the manuscript. I would also like to thank the Holderbank AG and the Jura Zement AG for allowing access to their quarries. This study was funded by the Swiss

National Science Foundation (grants 20-37269.93, 21-43103.95 and 20-50484.97 to A. Wetzel).

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