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Autor: Bachmann, Gerhard H. / Müller, Manfred
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Sedimentary and structural evolution of the German Molasse Basin

By GERHARD H. BACHMANN & MANFRED MÜLLER [1])

ZUSAMMENFASSUNG

Die sedimentäre Entwicklung des süddeutschen Molassebeckens gliedert sich in die Abschnitte Permokarbon, Mesozoikum und Tertiär, die durch Schichtlücken voneinander getrennt sind.

Die tertiäre Molasse besteht aus zwei großen, transgressiv/ regressiven 'shallowing-upward' Megasequenzen (Priabon bis Ober-Eger, Eggenburg bis Pannon), die durch eine ausgedehnte Diskonformität getrennt werden und in weitere kleinere transgressiv/regressive Sequenzen untergliedert werden können. Die Sequenzen scheinen mehr oder weniger gut mit der Kurve eustatischer Meeresspiegelschwankungen von Haq et al. (1988) zu korrelieren, ein Hinweis auf einen möglichen eustatischen Einfluß auf die Molasse-Sedimentation, der sich zusätzlich zu Subsidenz und Sedimenteintrag bemerkbar macht.

Die für die süddeutsche Molasse charakteristischen beckenparallelen syn- und antithetischen Abschiebungen sind auf die flexurartige Dehnung des Vorlandbeckens zurückzuführen. Die synsedimentäre Aktivität der Störungen wird von Süden nach Norden jünger. Dies kann durch die nordwärtige Verlagerung des Bereichs maximaler Verbiegung des Vorlandes während des alpinen Deckenvorschubs erklärt werden.

ABSTRACT

The sedimentary evolution of the German Molasse Basin is characterized by three stages of Permo-Carboniferous, Mesozoic and Tertiary age, which are separated by major unconformities.

The Tertiary Molasse can be subdivided into two major transgressive/regressive shallowing-upward sequences (Priabonian to Late Egerian, Eggenburgian to Pannonian) which are separated by an extensive unconformity. These megasequences can be subdivided into a number of smaller sequences of generally transgressive/ regressive character which are separated by further unconformities. These units seem to correlate more or less wiht the Haq et al. (1988) curve of eustatic sea-level changes suggesting there was an eustatic control of Molasse sedimentation in addition to those provided by subsidence and sediment influx.

The characteristic basin-parallel antithetic and synthetic normal faults are caused by flexural extension. Their synsedimentary activity becomes younger from south to north. This is explained by the northward shift of the zone of maximum flexure due to the advance of the Alpine nappes.

1. Introduction

The Molasse basin is a typical asymmetric foreland basin. It is filled with predominantly clastic sediments of Tertiary age, the so-called Molasse, which are up to 5000 m thick at the Alpine thrust front in SE Bavaria. The Molasse is underlain by Mesozoic shelf sediments, local Permo-Carboniferous graben sediments and the Variscan basement.

This paper gives a brief outline of the sedimentary and structural evolution of the German Molasse basin in the Tertiary. The Paleozoic to Cenozoic paleogeographical history and its significance for oil and gas has recently been described in some detail by

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[1]) Deilmann Erdöl Erdgas GmbH (Preussag AG), Karl-Wiechert-Allee 4, 3000 Hannover 61.

Bachmann et al. (1987) and Bachmann & Müller (1991). A thorough description of the German Molasse basin and its oil and gas fields can also been found in Lemcke (1988), who also made the first attempt to correlate the Molasse sediments with the Haq et al. (1988) curve of sea-level changes.

2. Sedimentary evolution

The sedimentary evolution of the German Molasse basin can clearly be subdivided into three stages separated by major unconformities:

- Tertiary foreland sedimentation ("Molasse")
  foreland unconformity
- Triassic to Cretaceous epicontinental or shelf sedimentation
  shelf unconformity
- Permo-Carboniferous graben sedimentation
  rift unconformity
- Variscan basement

A similar subdivision is also characteristic of other foreland basins (Bally 1991).

2.1. Permo-Carboniferous

In the late Carboniferous a system of grabens or troughs began to form in the Variscan basement. Genetically they are related to an extensive late Hercynian wrench-fault system (Arthaud & Matte 1977, Ziegler 1990). Most troughs trend ENE-WSW, with the exception of the ESE-WNW trending Giftthal Trough in SE Bavaria (Bachmann et al. 1987, Lemcke 1988). In Germany only five wells have been drilled to any significant depth into graben fills showing that most of them are filled with several 100 m to over 1000 m Rotliegend and Upper Carboniferous clastic sediments. Little is known about the internal structure of the troughs in Germany. Seismic sections show extensional faults.

The feather edge of the marine Zechstein is at the southern margin of the Kraichgau trough in central Württemberg.

2.2. Mesozoic

During the Mesozoic the area belonged to an epicontinental basin on the northwestern margin of the Tethys. Triassic and Early and Middle Jurassic sediments gradually overstepped the basement and the Permo-Carboniferous trough fills in a southeasterly direction (Bachmann et al. 1987). The area became fully inundated and connected with the Tethys in Late Jurassic times. Then, after a temporary regression around the Jurassic-Cretaceous boundary, sedimentation began again in the Early Cretaceous, whereby marine sediments transgressed northwards from the Tethys realm in the south. Extensional normal faulting is characteristic of this period (Fig. 3).

From the end of the Cretaceous until earliest Tertiary times, the area of South Germany became uplifted and the Bohemian Massif as well as the Landshut-Neuötting High were upthrown along NW-SE trending reverse wrench faults (Bachmann et al.

1987). Extensive denudation took place during this period. The compressional deformation which affected much of Central Europe is thought to have been caused by the collision of Africa and Europe (Ziegler 1987).

2.3. Cenozoic Molasse Basin

The Late Eocene underthrusting of Europe below the Adriatic-African Plate caused the Molasse Basin to develop in front of the advancing Alpine nappes. The basin is characterized by northward expansion, and its fill consists primarily of the erosion products of the nappes (Fig. 1). The total thickness of the Molasse sediments is up to 5000 m at the present-day Alpine thrust front. Seismic and well data show that the basement, the Permo-Mesozoic and the lowermost Molasse dip southwards underneath the Alpine nappes for a distance of 30–50 km (Bachmann et al. 1982, Bachmann & Koch 1983). Thus the Molasse Basin extends much further south than its present surface expression.

The Molasse can be divided into two major transgressive/regressive sequences of Priabonian to Late Egerian and Eggenburgian to Pannonian age, which are separated by a major unconformity (Fig. 2). Each sequence consists of several smaller transgressive/regressive sequences, which are also separated by unconformities (Bachmann & Müller 1991). Some of the thick sequences can be readily recognized in seismic sections. The sequence boundaries are characterized by toplap and onlap of the seismic reflections.

On the basis of currently available data some of the transgressive/regressive sequences seem to correlate more or less with the EXXON curve of eustatic sea-level changes (Haq et al. 1988) suggesting there was eustatic control of Molasse sedimentation in addition to that exerted by subsidence and sediment influx.

2.4. Late Eocene

The first megasequence starts in the Late Eocene (Priabonian). The Basal Sandstone and Ampfing Sandstone comprise sands derived from the Landshut-Neuötting High. These sandstones interfinger with the red algal Lithothamnium Limestone – all being typical shelf sediments.

These shelf sediments grade to the south into the deep-water Stockletten Marls and, finally, into so-called "Helvetic Flysch", which represents an early deep-water deposit of the Molasse basin. The presence of Helvetic Flysch of Middle Eocene to Early Oligocene age was proved for the first time in Germany beneath the Helvetic Nappes by the Hindelang 1 well (Huber & Schwerd 1993).

2.5. Early Oligocene

During the Early Oligocene the basin deepened rapidly. The Fish Shale is overlain by "Heller Mergelkalk" and "Bändermergel" – coccolith-rich beds of Rupelian age. They grade upwards into thick Rupelian Marls which pass upwards into the littoral Baustein beds. The younger strata overlap each other progressively northwards indicating rapid expansion of the basin. Towards the south the deposits of Rupelian age grade into

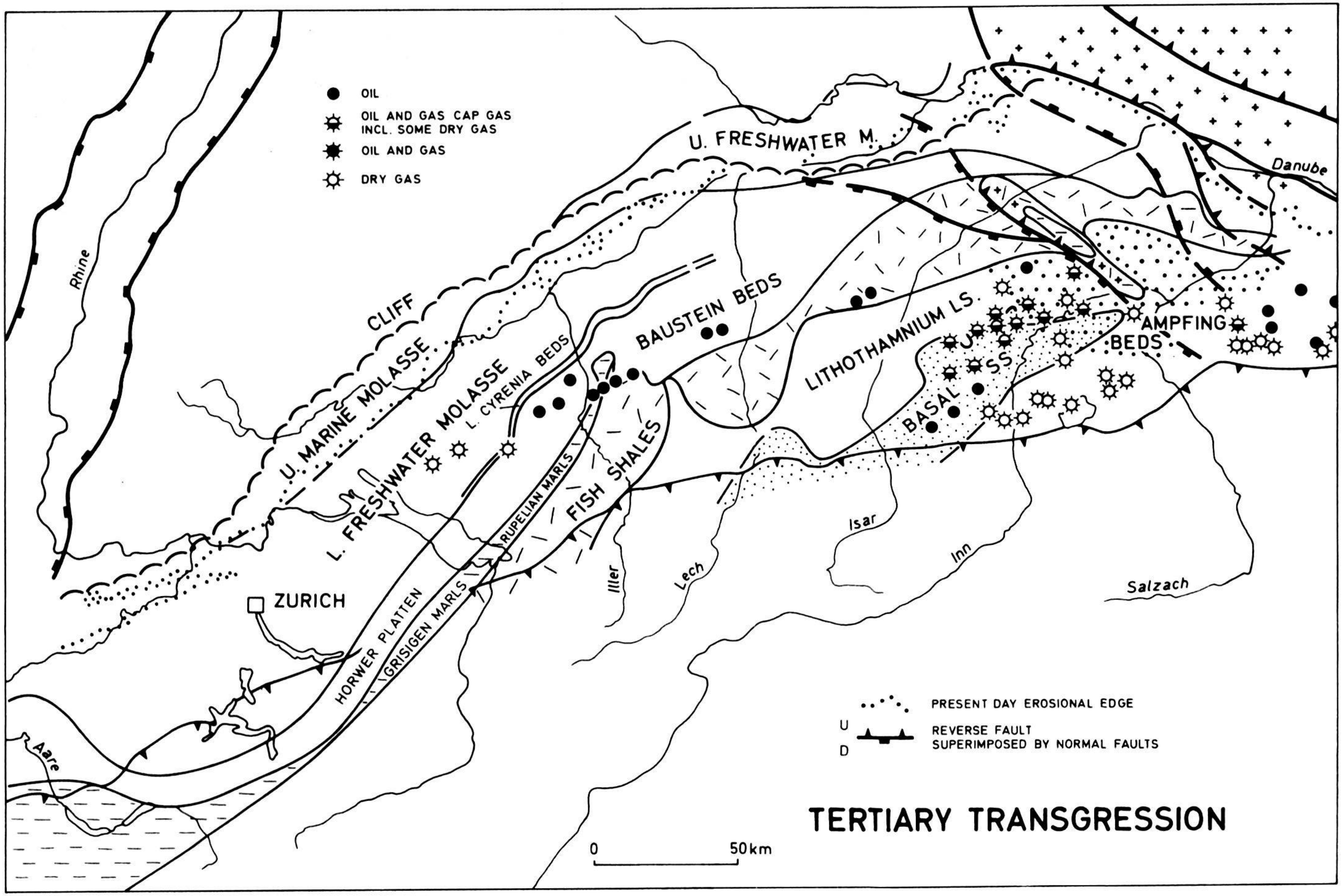


Fig. 1. Onlap of transgressive Tertiary lithostratigraphic units (after Bachmann et al. 1987, modified).

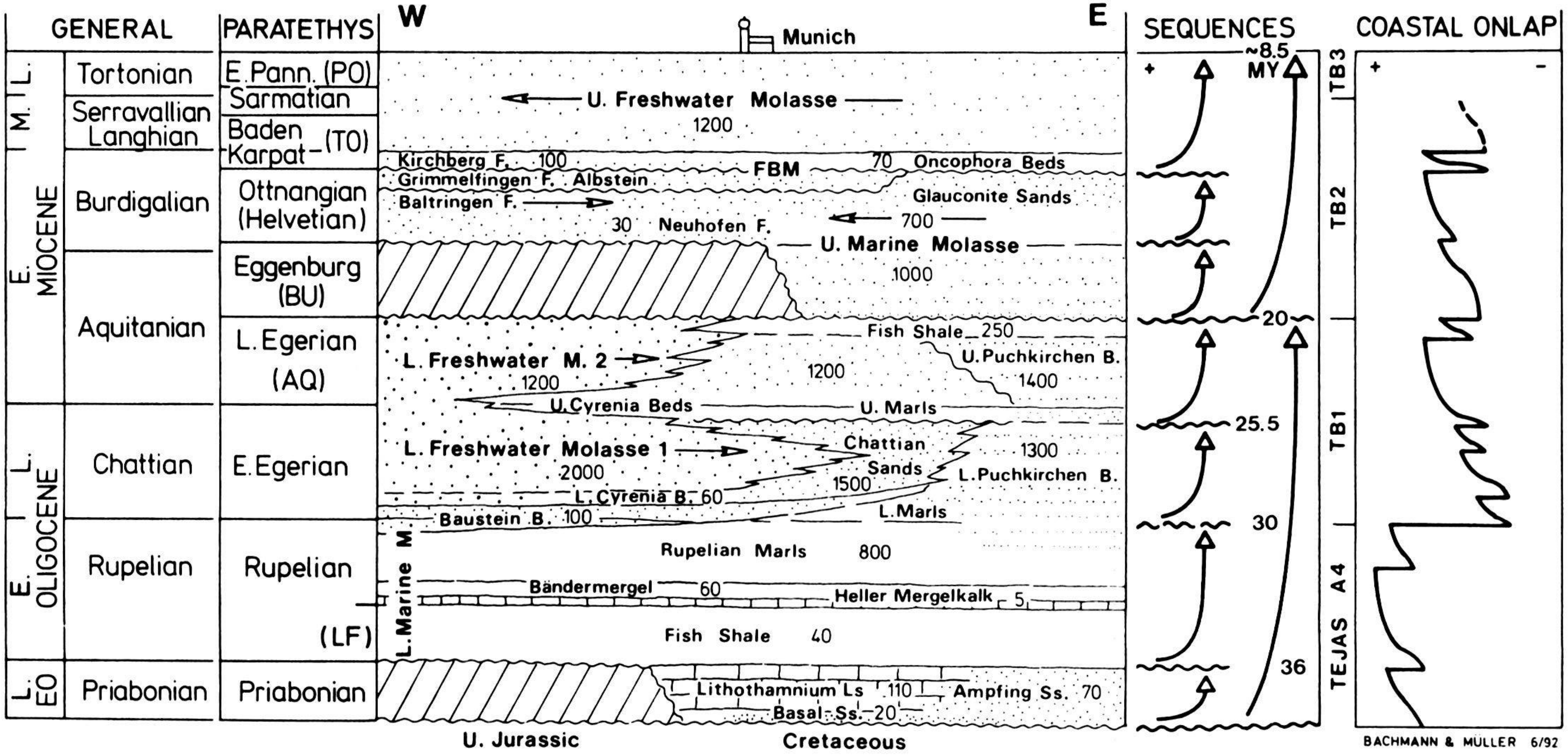


Fig 2. Schematic W-E cross-section of the Molasse basin showing (on the right) the successive transgressive-regressive sequences (vertical arrows) and their possible correlation with coastal onlap curve (Haq et al. 1988). Old, now obsolete stages in brackets: (LF) Latdorfian, (AQ) Aquitanian, (BU) Burdigalian, (Helvetian), (TO) Tortonian, (PO) Pontian. Lithostratigraphy (centre panel) modified from Lemcke (1988). FBM: Freshwater-Brackish Molasse. Numbers refer to average thicknesses in meters; horizontal arrows show general direction of transport. (After Bachmann & Müller 1991 modified).

turbiditic Deutenhausen beds, which are also characteristic for the early deep-water stage of the Molasse Basin.

2.6. *Late Oligocene*

The continental Lower Freshwater Molasse was deposited in front of the nappes in the Late Oligocene – thick alluvial conglomerates and sandstones, which grade basinwards into multicoloured sandstones and shales. To the east of Munich they give way to the deltaic Chattian Sands and, further east, to the deep-water turbiditic Puchkirchen Beds. An erosional unconformity with a broad valley was incised into the top of the Chattian Sands (Müller 1991). This is overlain by the "Hangende Tonmergel" or Upper Cyrenia Beds, indicating a new marine ingression from the east around the Early/Late Egerian boundary.

2.7. *Early Miocene (Late Egerian)*

After the transgression, the depositional environments evolved similarly to those of the Early Egerian: Continental Lower Freshwater Molasse in the west, shallow marine sands east of Munich, and turbiditic Puchkirchen beds east of the River Inn. The incised valley was drowned to form a broad submarine canyon, which funneled shelf sediments into the deep water area.

A regression during the latest Egerian produced an extensive unconformity which marks the end of the first Molasse megasequence (Lemcke 1988, fig. 22).

2.8. *Eggenburgian*

The second megasequence started in Eggenburgian times with a transgression from the south. Shallow marine sands and shales overlie the unconformity.

2.9. *Ottnangian, Karpatian*

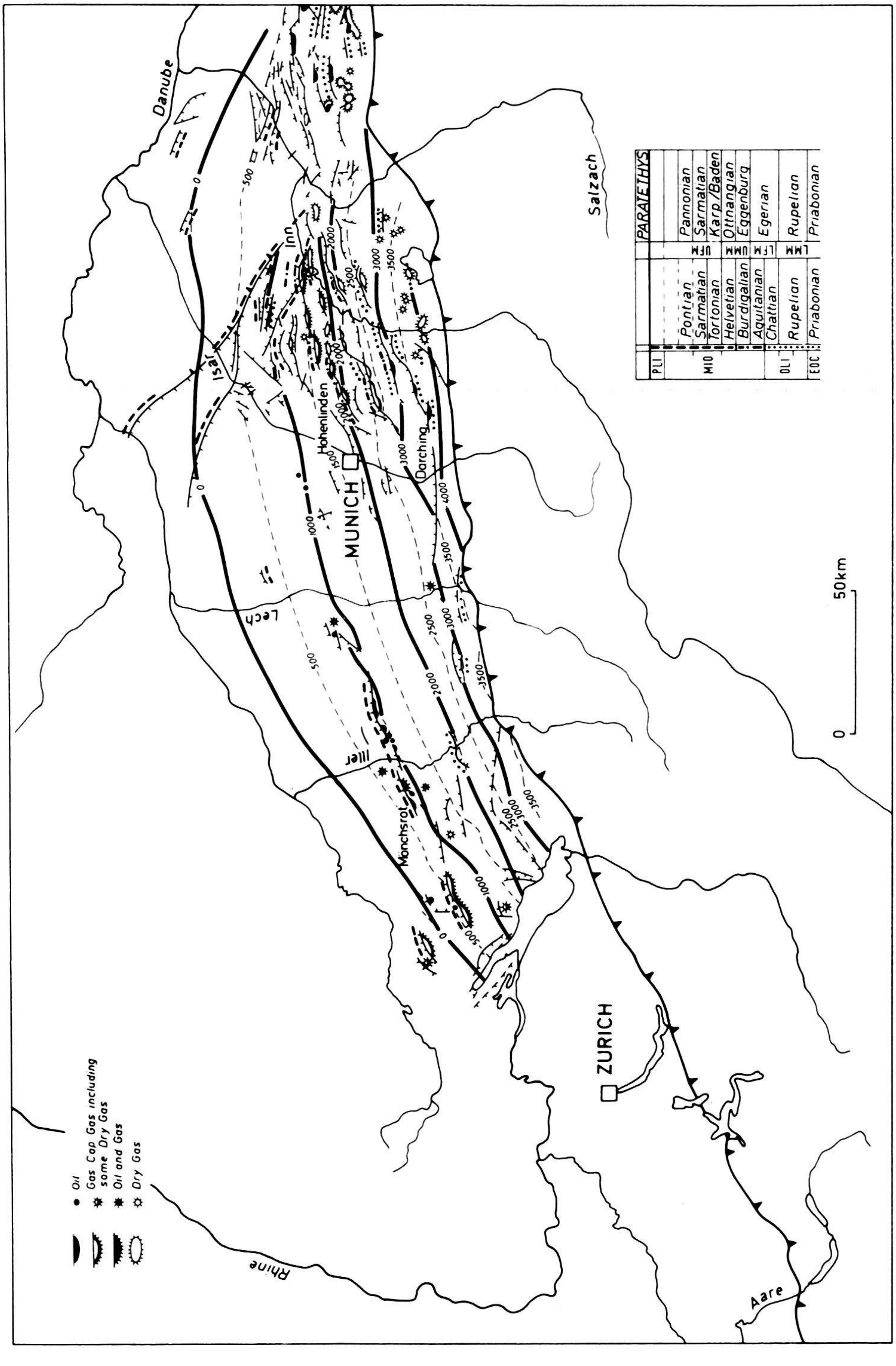
A further transgression occured in Ottnangian times. Marine sands and shales lie unconformably on those older deposits that were not covered by the Eggenburgian sediments. In Ottnangian times the famous "cliff" was cut into the Upper Jurassic Limestones along the northern shore of the basin.

The Late Ottnangian and Karpatian sediments are also referred to as the "Freshwater-Brackish Molasse" because of their variable depositional environment.

2.10. *Middle/Late Miocene*

The continental Upper Freshwater Molasse represents the final filling stage of the basin during the Middle and Late Miocene. Afterwards the Molasse basin was subject to erosion. It is for this reason that the original thickness and extension of the Upper Freshwater Molasse cannot be reconstructed with certainty.

Fig. 3. Depth of the Molasse base below sea level in meters (after Schröder 1991, modified). Synsedimentary activity of synthetic and antithetic normal faults is indicated by code (inset).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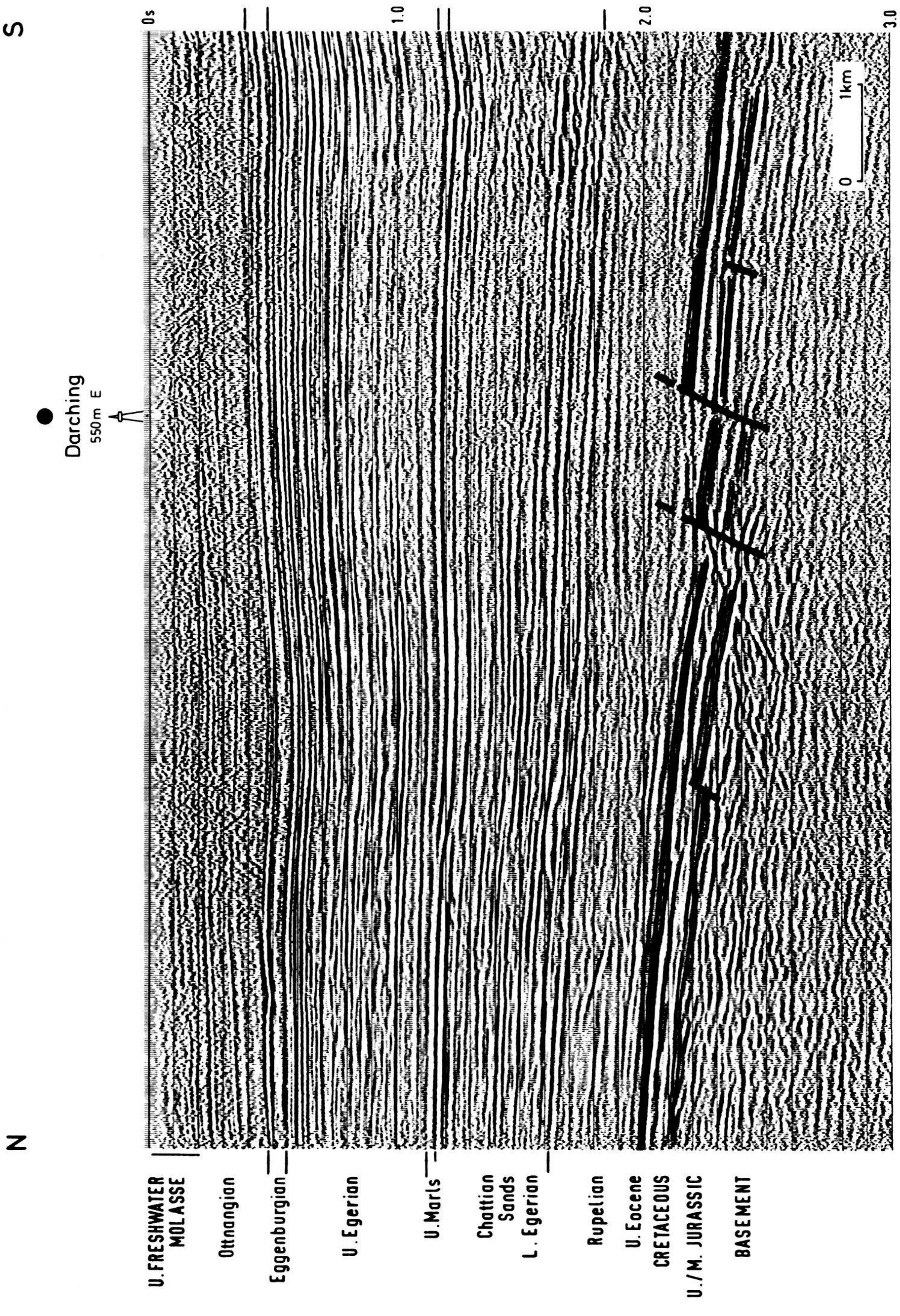
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L. Egerian
Rupelian
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3. Structural evolution

Antithetic and synthetic faults parallel to the long axis of the basin are characteristic of the entire basin (Fig. 3). They form lineaments several tens of kilometers long and have a displacement of several tens of meters, rarely as much as 100–200 m. The faults planes are usually curved in plan with alternating concave and convex segments. Antithetic normal faults dominate. Their concave segments provide the traps for most of the oil and gas fields that have been found in both Mesozoic and Tertiary strata. Generally, the number of faults and the displacement is larger in the eastern part of the German Molasse Basin as compared with the western part. This seems to be due to less subsidence in the western part (Fig. 3).

Interestingly, the synsedimentary activity on the normal faults becomes younger from south to north (Fig. 3). Up to some 30 km to north of the present day Alpine thrust front, the faults are not younger than Early Egerian (Chattian). A good example are the antithetic faults of the Darching oil field (Fig. 4).

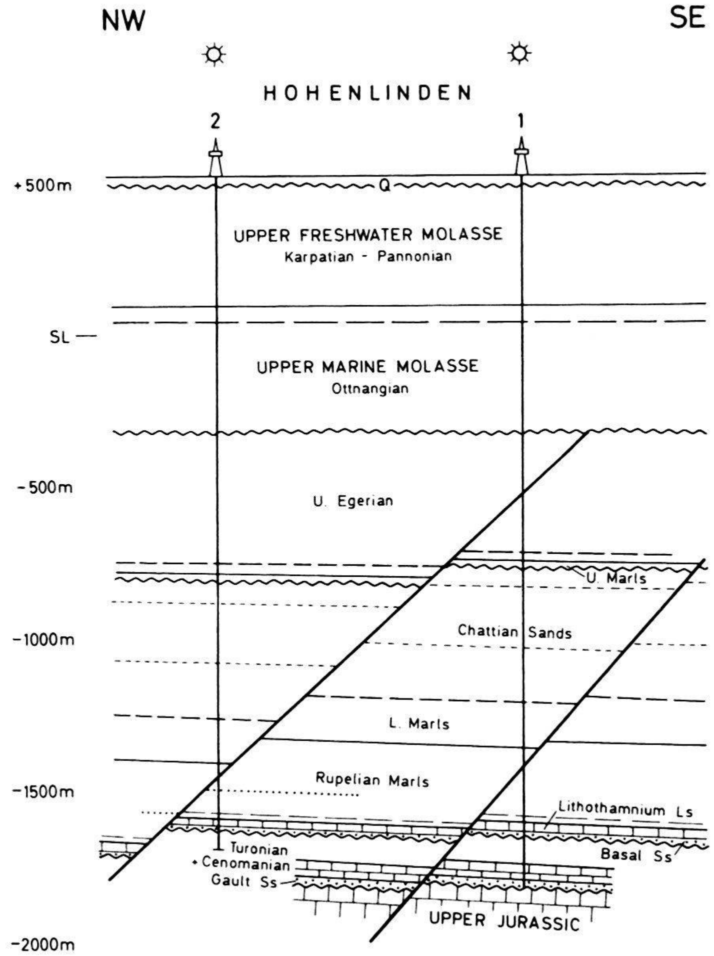

Fig. 5. Hohenlinden gas field, which produces from the Lithothamnium Limestone and Rupelian Sandstone (Kraus 1968, modified). Synsedimentary faulting ceased in Late Egerian to Eggenburgian times.

Fig. 4. Darching oil field, which produces from the Basal Sandstone. Synsedimentary faulting ceased in Rupelian times. Two further faults of Cretaceous age.

Further north, some faults were active until Late Egerian and Eggenburgian times. These faults do not cut the unconformity at the base of the Ottnangian ("Helvetian") (Fig. 5).

Beyond a distance of 40–50 km north of the Alpine thrust front, the faults may be as young as Late Miocene (Fig. 6).

The successively younger synsedimentary activity of the faults towards the north is in good accordance with the northwardly expansion of the foreland basin. Subsidence of the Molasse basin was initiated and controlled by the tectonic loading of the foreland by the advancing Alpine nappes. The flexural downbending of the lithosphere caused extensional stress resulting in synthetic and antithetic normal faults. The zone of maximum flexure shifting north due to the advancing nappes resulted in the northward propagation of the extensional fault system. As a further consequence, the system of synthetic and antithetic faults is restricted to the Molasse basin. The process of "flexural extension" is characteristic of many collisional foredeeps (Bradley & Kidd, 1991). However, according to Bradley & Kidd synthetic normal faults seem to dominate in most other basins. Alternatively, maximum flexure might be associated with a northwardly shifting foreland bulge.

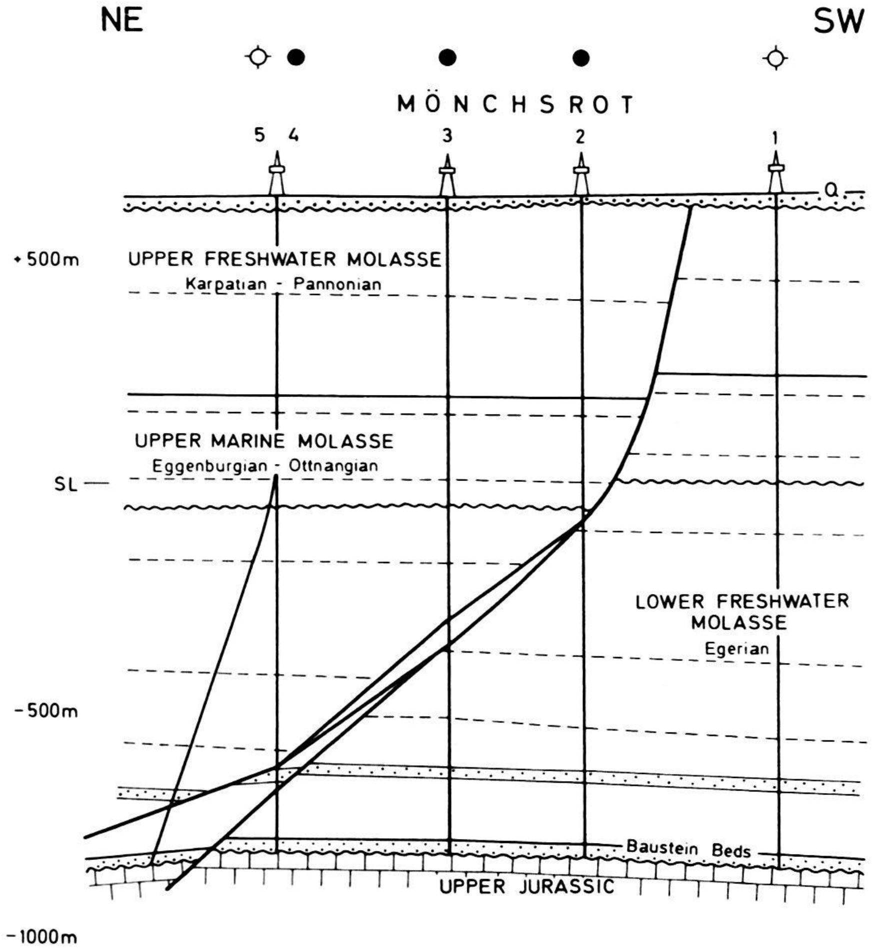

Fig. 6. Mönchsrot oil field, which produces from Baustein Beds (Haus 1960, modified). Synsedimentary fault were active until Late Miocene times.

Thrusting and synsedimentary faulting continued until late Miocene times, when the present-day so-called Folded Molasse became incorporated into the Alpine nappe system. Particularly in the western part of the German Molasse Basin it is characterized by a complex duplex structure similar to the Triangle Zone in the Rocky Mountains of Canada (Müller et al. 1988).

Schrader (1988) describes pressure-solution on Molasse-pebbles indicating compression generally perpendicular of the Alpine border. Significantly, compressional anticlinal structures rarely occur in the German sector of the Molasse Basin north of the Folded Molasse (Bachmann et al. 1982) – in contrast to the broad anticlines of the Mittelländische Molasse in Switzerland (Brink et al. 1992). This appears to be due to the lack of a decollement medium such as the Muschelkalk evaporites in Switzerland.

The youngest structural features comprise a system of SE-NW and SW-NE conjugate wrench faults which transsect the normal faults (Betz & Wendt 1983, Brink et al. 1992).

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