"The Early Miocene Upper Marine Molasse of the German part of the Molasse Basin - a subsurface study. Sequence Stratigraphy, Depositional Environment and Architecture, 3D Basin Modeling"

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Zusammenfassung

Die Untersuchung der Oberen Meeresmolasse (unteres Miozän) im Untergrund des deutschen Anteiles am nordalpinen Molassebecken beruht vor allem auf der Analyse von 72 Bohrungen und 14 seismischen Profilen, die von der deutschen Erdölindustrie zur Verfügung gestellt worden sind.

Traditionell wird der deutsche Teil des Molassebeckens in die Westmolasse zwischen München und dem Bodensee und die sich von München bis an die österreichische Grenze erstreckende Ostmolasse unterteilt (Fig. 2). Die Qualität und die Anzahl der Daten aus dem Untergrund der Ostmolasse ist für eingehende Untersuchungen ausreichend. Die Exploration in der Westmolasse erfolgte vor allem in den fünfziger und sechziger Jahren; entsprechend sind die Daten sehr viel spärlicher und oft von ungenügender Qualität. Aus dem Untergrund des Grenzbereiches zwischen der West- und der Ostmolasse standen keine Daten zur Verfügung.

Die zweite Megasequenz der Molasse (Obere Meeresmolasse und Obere Süsswassermolasse) beginnt in Ostbayern im frühen Burdigal (Eggenburg) mit der Transgression mariner Ablagerungen aus dem Puchkirchen-Trog in Oberösterreich entlang der alpinen Front nach Westen. Mehr oder weniger gleichzeitig erfolgt eine marine Transgression aus dem Gebiet der Westschweiz nach Osten in den Bereich der südlichen Westmolasse. Die beiden marinen Vorstösse vereinigen sich schliesslich zu einem durchgehenden Meeresarm. In einem zweiten Vorstoss greift die Obere Meeresmolasse auf den Südrand der Schwäbischen und Fränkischen Alb bis hin zur Klifflinie. Die brackischen Kirchberger Schichten der Westmolasse und die Oncophoraschichten der Ostmolasse markieren den Übergang zur Oberen Süsswassermolasse. Am Ende des Burdigals (Ottnang) hat sich das Meer vollständig aus dem Molassebecken zurückgezogen.

Stratigraphische Einheiten der Oberen Meeresmolasse

Die hier verwendeten pragmatischen stratigraphischen Einheiten entsprechen der in der Exploration mehrheitlich angewandten Bezeichnung der Schichtglieder.

Die Obere Meeresmolasse der Westmolasse lässt sich in einen transgressiven litoralen grobkörnigen unteren Teil (Basisschichten, 20-35m), einen vorwiegend subtidalen feinkörnigen mittleren Teil (Sandmergelserie I und II, 10-110m) und einen wiederum litorales vorwiegend grobkörnigeren regressiven Teil (“Baltringer Schichten” und “Feinsandserie”, 15-40m) unterteilen.

In dem N-S verlaufenden Querprofil (Fig. 11) bleibt die Mächtigkeit der einzelnen Einheiten recht konstant.

Die einzige in der Westmolasse zur Verfügung stehende seismische Linie (Fig. 13) ist von eher schlechter Qualität, so dass sich die Ablagerungsmuster innerhalb der verschiedenen stratigraphischen Einheiten nicht eindeutig erkennen lassen.

Auch in der Westmolasse lassen sich in der Molasse fünf Sequenzgrenzen erkennen (Jin 1995, Zweigel 1998). Die Sequenz 4, die dem obersten Teil der Unteren Süsswassermolasse und der Oberen Meeresmolasse entspricht, wird in 5 Subsequenzen untereilt (4a: oberer Teil der Unteren Süsswassermolasse, 4b: Basisschichten, 4c1: Sandmergelserie I, 4c.2: Sandmergelserie II und 4d: Baltringer Schichten).

Die Ostmolasse wird in einen flachmarinen westlichen und in einen östlichen Teil, der im Oligocaen und im frühen Miocaen dem Übergang zum tiefer marinen Bereich in Oberösterreich bildet, getrennt.

Die Obere Meeresmolasse lässt sich wie in die Westmolasse in eine untere transgressive Abfolge mit den Aquitan-Fischschiefern, der Obing Folge und dem "Burdigal", ein mächtiges mittleres Paket mit den Neuhofener Schichten I und II und einen oberen regressiven Teil mit den Glaukonitsanden und Blättermergeln unterteilen. Die Obing Folge ist nur in im östlichen Teil vorhanden.

Im N-S verlaufenden Querprofile (Fig. 17 und 19) nehmen alle stratigraphischen Einheiten mit Ausnahme der Glaukonitsande und Blättermergel nach Süden hin an Mächtigkeit zu. Das "Burdigal" transgrediert mit einer ausgeprägten Winkeldiskordanz auf die Aquitan-Fischschiefer. Das "Burdigal" und die "Neuhofener Schichten keilen nach Norden mit progressivem "Onlap" aus. In fast allen Einheiten nimmt der Sandgehalt nach Süden zu.

Im W-E Querprofile (Fig. 21 und 23) zeigen das "Burdigal" und die Neuhofener Schichten einen nach Westen progressiven "Onlap" auf die Aquitan-Fischschiefer. Das "Burdigal" nimmt nach Osten stark an Mächtigkeit zu, während die Neuhofener Schichten I und II, die Glaukonitsande und Blättermergel nur geringe Mächtigkeitsschwankungen zeigen.

In den seismischen Linien aus dem westlichen Teil der Ostmolasse (Figs. 25 bis 31) lagern die Aquitan-Fischiefer (Subsequenz 4a) mit "Onlap" auf den an ihrer Obergrenze erodierten Aquitan-Sanden. Die mächtige Subsequenz 4b ("Burdigal") weist in ihrem unteren Teil recht einheitliche grossflächige Ablagerungsmuster auf. Im mittleren und oberen Teil finden sich Anzeichen einer von Westen nach Osten progradierenden deltaischen bis prodeltaischen Sedimentation. In der mit erosiver Grenze auflagernden Subsequenz 4c.1 (Neuhofener Schichten I) nimmt die Amplitude der erosiven Muster nach Westen hin zu. Subsequenz 4c.2 (Neuhofener Schichten II) weist vorwiegend parallele bis subparallele Muster auf, die auf einheitliche Ablagerungsbedingungen hinweisen. In den Subsequenzen 4d-e (Glaukonitsande und Blättermergel) dominieren wiederum parallele Reflektoren. Sie werden durch einen sehr konstanten starken Reflektor getrennt.

Im N-S Querprofil des östlichen Teiles der Ostmolasse (Fig. 32) sind die lateralen Wechsel komplexer als im westlichen Teil. Die Mächtigkeit der Obing Folge nimmt nach Süden hin ab. Relativ einheitliche Mächtigkeiten finden sich in den Glaukonitsanden und Blättermergel, den Neuhofener Schichten I und dem

"Burdigal". In den Aquitan-Fischschiefern und den Glaukonitsanden nimmt der Sandgehalt nach Süden hin ab, während er in den Neuhofener Schichten I und II recht konstant bleibt.

In den seismischen Linien aus dem untersuchten östlichen Teil der Ostmolasse (Figs. 34 bis 37, 41 und 44) lassen sich die gleichen Subsequenzen wie in deren westlichen Teil erkennen. Die Subsequenz 4b enthält hier zusätzlich die Obing Folge (4b.1), die nach Nordwesten auf die Aquitan-Fischschiefer (4a) greift. Das transgressive "Burdigal" (4b.2) progradiert nach Nordosten. Die vorwiegend parallelen Reflektoren zeigen einheitliche Ablagerungsbedingungen an. Die Subsequenzen 4c.1 (Neuhofener Schichten 1) und 4c.2 (Neuhofener Schichten II) entsprechen der grössten Ausdehnung der Oberen Meeresmolasse. Sie werden durch eine geringe Erosionsphase getrennt. Die Subsequenz 4c.2 wird durch einen ausgeprägten doppelten Reflektor zweigeteilt, der als Oberfläche der maximalen Flutung interpretiert wird. Die Subsequenzen 4d und 4e (Glaukonitsande und Blättermergel) bestehen aus mehr oder weniger parallelen Reflektoren, in welchen die Ablagerungsmuster schlecht abgebildet sind. Sie konnten nicht voneinander getrennt werden und werden deshalb als eine Einheit behandelt.

Zeit-, Geschwindigkeits- und Isopachen-Karten (Figs. 48 to 55)

Zeit-, Geschwindigkeits- und Isopachen-Karten ("grid maps") wurden in MapView mit den Programm SeisVision in einem GeographixDiscovery Project konstruiert. Die Grenzen und der Wahrscheinlichkeitsgrad dieser Karten werden durch die Dichte und die Verteilung der zur Verfügung stehenden Bohrungsdaten und seismischen Linien bestimmt. In der Ostmolasse wurde ein Gebiet im Westen südlich und südöstlich von München sowie ein weiteres Gebiet im Südosten in der Nähe der österreichischen Grenze ausgewählt in welchen die Datendichte ausreichend ist. Die Dichte und die Qualität der in der Westmolasse zur Verfügung stehenden Daten ist ungenügend.

Geschwindigkeits-Karten (Figs. 50-51): Im westlichen Teil der Ostmolasse wird die in den Glaukonitsanden und Blättermergeln nach Norden zunehmende Geschwindigkeit durch erhöhten Sandanteil verursacht. Die Geschwindigkeits-zunahme im mittleren Teil des Gebietes in den "Neuhofener Schichten I und II" sowie dem "Burdigal" ist vermutlich ebenfalls auf Zunahme des Sandanteiles zurückzuführen. In den Aquitan-Fischschiefen und dem Aquitan nehmen die Geschwindigkeiten im zentralen Bereich und nach Süden bedingt durch die grössere Abteufung und den ebenfalls ansteigenden Sandgehalt zu.

Im östlichen Teilgebiet der Ostmolasse sind die nach Norden zunehmenden und nach Osten abnehmenden Geschwindigkeiten in den Glaukonitsanden und Blättermergeln vor allem auf den unterschiedlichen Sandgehalt zurückzuführen. Die Neuhofener Schichten I und II, das "Burdigal" und die Aquitan-Fischschiefer weisen die höchsten Geschwindigkeiten im zentralen Bereich des Gebietes auf. Die trotz grösserer Tiefe im Süden niedrigeren Geschwindigkeiten zeigen wohl geringeren Sandgehalt an. In der Obing Folge werden die im Westen höheren

Geschwindigkeiten durch den sich in proximaler Richtung erhöhenden Sandanteil verursacht. Im "Aquitan" finden sich die höchsten Geschwindigkeiten und vermutlich auch der höchste Sandgehalt im Südosten.

Tiefen-Karten (Figs. 52-53): Im westlichen Teil der Ostmolasse nimmt die Tiefe aller stratigraphischen Einheiten wie zu erwarten mit geringen Variationen nach Süden zu. Die Aquitan-Fischschiefer und das "Aquitan" weisen im zentralen Teil eine leichte Abnahme der Tiefe auf. In der östlichen Ostmolasse finden sich die grössten Tiefen im Südosten in der Nähe von 5 Ost.

Isopachen-Karten (Figs. 54-55): In der westlichen Ostmolasse erreichen die Glaukonitsande und Blättermergel ihre grösste Mächtigkeit im zentralen Bereich. Die Mächtigkeit der Neuhofener Schichten II nimmt nach Südosten zu und vermindert sich nach Norden und Westen, während diejenige der Neuhofener Schichten I und des "Burdigal" im zentralen Bereich am geringsten sind und sich sowohl nach Süden als auch nach Norden zu erhöhen. Die Isopachen der Aquitan-Fischschiefer zeigen ein komplexes Muster.

Im östlichen untersuchten Gebiet der Ostmolasse reduzieren sich die Mächtigkeiten der Glaukonitsande und Blättermergel sowie der Neuhofener Schichten II im Süden und nehmen nach Norden zu, während die Neuhofener Schichten I und daas "Burdigal" im Süden und Südosten am mächtigsten sind. Die Isopachen der Obing Folge und der Aquitan-Fischschiefer verlaufen recht unregelmässig. In beiden Einheiten trennt ein zentraler Bereich mit reduzierten Mächtigkeiten einen nördlichen und südlichen Bereich mit Mächtigkeiten von mehreren hundert Metern.

Abstract

The detailed investigation of the early Miocene Upper Marine Molasse of the German part of the Molasse Basin is based on the study of the logs from 65 wells which have been digitized with LogScan® (Briere Engineering) and on the reinterpretation of 14 seismic sections. The interpretation program Geographix® (Landmark Graphics) has been used to integrate all data into facies maps and cross sections in order to reach an improved interpretation of the paleogeographic configuration, paleobathymetry and facies-distribution of the Upper Marine Molasse. These interpretations have been complemented by data available from literature. An extended abstract is given in Chapters 4 and 5.

Resúmen

El detallado estudio de los datos del subsuelo de la Molasa Marina Superior de la parte alemana de la Cuenca Molásica durante el Mioceno temprano está basado en el re-estudio de los perfiles eléctricos de 65 pozos los cuales han sido digitalizados con el software LogScan® (Briere Engineering) y en la re-interpretación de 14 perfiles sísmicos. El programa de interpretación Geographix® (Landmark Graphics) ha sido usado para integrar todos los datos en mapas de facies y cortes geológicos. La gran mayoría de datos de pozos y de perfiles sísmicos no se han no publicados antes. Su

análisis se ha completado por los datos disponibles de la literatura para así poder obtener una interpretación mejorada de la configuración paleogeográfica, paleobatimétrica y distribución de facies de la Molasa Marina Superior. Un resúmen más ampliado es dado en los capítulos 4 y 5.

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"Cualquiera que sea mi suerte en lo adelante, mi último suspiro será por mi país".

"Ansío por respirar el aire que formó mi vida y ver los primeros objetos que ejercitaron mis primeros sentidos; yo deliro por Caracas, ahora que la aflicción me la ha hecho más interesante; ahora que, libre de mis primeros deberes de la guerra y de la libertad puedo consagrarme todo por entero a aliviar los dolores de una patria que ha gemido tanto tiempo".

Simón Bolívar

Bolívar, 1829

Firma de Simón Bolivar

La Patria es del tamaño del corazón de quién la quiere.

Renny Ottolina

1. INTRODUCTION

1.1 Aims of this study

A sequence stratigraphic subdivision of the Upper Marine Molasse was suggested by Jin (1995) and Zweigel (1998) in the area of Eastern Bavaria. Five second order sequences modified from Jin (1995) have been recognized by Zweigel (1998). The aim of this work is to study in detail the Sequence 4, which was deposited during the early Miocene.

The objectives of this study are:

1) to extend the restudy of subsurface data and the sequence stratigraphic interpretation to the area between Munich and Lake Constance.

2) to extend and refine Jin's (1995) 2-dimensional interpretation and Zweigel's (1998) 3-dimensional interpretations to a revised 3-dimensional reconstruction by the use of the Geographix® program, with the aim to obtain an improved representation of the spatial development of the Molasse basin during the Early Miocene.

1.2 Geological Overview

1.2.1 Introduction

The term „molasse" was introduced by De Saussure (1740-1799) at the end of the 18th century to describe Oligocene to Miocene grey sandstones and associated sediments of the Alpine Foreland of western Switzerland. Initially, it has been mainly used for the syn- and postorogenic deposits of the North Alpine Foreland Basin, but today the term is used for deposits formed by the erosion of rapidly uplifted orogens, regardless of their deposition in continental or marine environments and regardless of the geological area or age.

The Alpine Molasse Basin or North Alpine Molasse Basin (NAFB) is a classical example of a peripheral foreland basin (e.g. Allen and Homewood, 1986). As in other foreland basins, its sedimentary infill records the interaction between the growth of the thrust wedge, the isostatic adjustments of the cratonic lithosphere to thrust loading and additional bending moments, eustasy and the surface processes that redistribute material from the mountain belt into the surrounding basins (Sinclair 1997).

The NAFB extends from the south of Lake Geneva in the west to Lower Austria in the east over a distance of approximately 700 km. The generally accepted southern limit of the basin is the frontal thrusts of the Alpine Belt. Its northern feather-edge margin is found in the Jura Mountains, the Swabian and Franconian Alb and the blocks of crystalline basement of the Bohemian Massif. The basin widens substantially to the east, attaining a maximum present-day width of about 150 km in southern Germany (Lemcke, 1973; Jin, 1995) (see Fig. 1).

I will concentrate on the interval corresponding to the Upper Marine Molasse. The deposition of the Upper Marine Molasse (OMM) was initated by a basin wide transgression during the Early Miocene (~ 20 Ma) that flooded the Alpine foredeep, generating shallow marine conditions between southeastern France and Eastern Austria via Switzerland and Southern Germany (e.g. Bieg, 2005).

The OMM transgression opened the approximately 100km wide "Burdigalian Seaway" connecting the Paratethys with the western Mediterranean. The seaway was reaching from the Rhone Valley via the northern Alpine Molasse Basin to the Vienna Basin (e.g.Rögl et al., 1978). Shallow marine conditions became established in the entire area during this transgression. The start of this transgression was diachronous, because of the interaction of the radial dispersal systems draining the Alpine Orogen. At the end of the Eggenburgian, some areas within the Paratethys became subaerially exposed and the seaway was closed again (Nagymarosy and Müller, 1988).

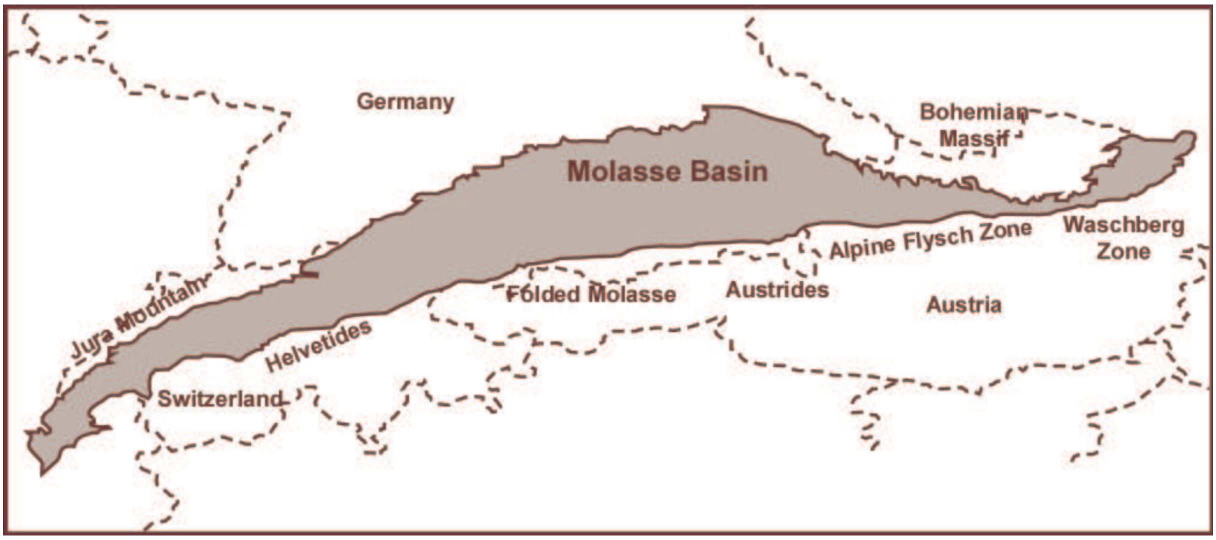


Figure 1. Location of the Molasse Basin.

1.2.2 Pre-tertiary History of the Alpine foreland

The basement of the German Molasse Basin consists of gneisses and Variscan granites, which outcrop in the Black Forest and the Bohemian Massif. They have also been encountered in numerous wells in the Molasse Basin (Bachmann et al., 1991). The part of the Variscan Orogen which underlies the Molasse Basin became uplifted during the late Visean Sudetic diastrophism and was subject to erosion during the Late Carboniferous. Following the Late Westphalian-Early Stephanian consolidation of the Variscids, a system of mostly SW-NE-striking grabens and troughs began to subside in the area of the Molasse Basin. The subsidence of the basins can be related to the development of the Late Hercynian wrench-fault system which transected the Variscan fold belt and its European foreland during the Stephanian and Autunian (Arthaud and Matte, 1977; Reading, 1980; Ziegler, 1982; Jin, 1995).

During Triassic to Middle Jurassic times, the area of the German Molasse Basin was part of the Franconian platform which was connected with the North German Basin, the Paris Basin and the Tethys shelf (Bachmann et al., 1987). A basement high, the so-called Vindelician High, existed in the area and acted as a source of clastic rocks. The basement high and the Permo-Carboniferous grabens were gradually overstepped from north-west to south-east by up to 1000 m thick Triassic to Jurassic sediments (Bachmann et al. 1987). All Mesozoic formations become increasingly sandy towards their distal margins. North-east of Munich the pinch-out limits of the Upper Triassic and the Lower Jurassic show a bulge to the south-east. This suggests that a Permo-Carboniferous graben was still active in Triassic times (Bachmann and Müller, 1991).

During the Late Jurassic to Late Cretaceous, the uplifted Rhenish-Bohemian Massif separated the North German basin from the Franconian Platform and the southward adjacent area of the Molasse Basin which now formed part of the vast Helvetic Shelf. Upper Jurassic carbonates subsequently covered the whole are and extended still further to the south, thus connecting the area with the Tethys realm (Bachmann et al., 1987). After a temporary regression around the Jurassic-Cretaceous boundary, shallow marine sedimentation resumed during Early Cretaceous times. The transgression advanced from the Helvetic shelf area in the south; therefore Cretaceous strata become thicker and more complete towards the south (Lange and Paulus, 1971).

At the end of the Cretaceous and the beginning of the Tertiary, the collision of the Alpine orogenic system with the passive margin of the Helvetic Shelf was accompanied by the transmission of compressional stresses onto the Alpine foreland (Ziegler, 1982, 1987). The area of southern Germany was uplifted, resulting in a north-westward truncation of Cretaceous and Upper Jurassic strata. At the same time, the Bohemian massif and the Landshut-Neuötting High were upthrown along NW-SE trending reverse faults, causing 1000 m of Mesozoic strata to be eroded from the latter area (Bachmann et al., 1987; Jin, 1995).

1.2.3. Structural units of the Molasse Basin and its adjacent thrust belt

The foreland basin of the so-called "Unfolded Molasse" ("ungefaltete Molasse") is a typical asymmetric basin (Jin, 1995). The basin is filled with predominantly clastic sediments, which thicken from north to south and reach their greatest thickness of over 5000 m at the present-day Alpine thrust front. Seismic and well data show that the basement, the Permo-Carboniferous and the Mesozoic, as well as the lowermost Molasse, dip southwards underneath the Alpine nappes up to a distance of at least 50 km (Bachmann et al., 1982; Bachmann and Koch, 1983; Müller, 1984; Müller et al., 1988). Thus the Molasse Basin extends much further south than its present surface expression. In the foreland basin, compressional structures are rare. However, basin-parallel synthetic and antithetic normal faults are characteristic of the entire basin (Jin, 1995). They form lineaments several tens of kilometres long and have a displacement of several tens of meters.

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 (Bachmann et al., 1982; Bachmann and Koch, 1983). It is believed that the flexural downbending of the foreland plate caused extensional stress resulting in the synthetic and antithetic normal faults (Bradley and Kidd, 1991).

The “Folded Molasse” (“gefaltete Molasse”) is the northernmost and deepest tectonic unit of the Alpine nappe system. It consists of the clastic sediments of Oligocene to Miocene which were deposited in the southern part of the Molasse Basin, thus generally consisting of similar but overall coarser grained rocks than those of the “Unfolded Molasse” of the foreland basin (Bachmann, et al., 1982). It was part of the Molasse Basin until Late Miocene when the progressive thrusting incorporated it into the thrust belt. In the younger Miocene, the “Folded Molasse” was sheared off and thrust to the north, forming several long, west-east-striking thrust units which commonly have synclinal shape (Jin, 1995). Normally two to three, in places up to five, of these units are thrust upon each other. The basal thrust plane of the “Folded Molasse” gradually becomes parallel to the bedding of the subthrust. The subthrust consists of the lowermost part of the “Unfolded Molasse” and the underlying Mesozoic, which dip beneath the “Folded Molasse”. Most commonly, the thrust plane is within the incompetent Rupelian or Chattian marls. The southern edge of the “Folded Molasse” is overthrust by the tectonically higher “Helvetic” or “Flysch” units (Müller, 1970, 1975, 1978).

1.2.4 Structural evolution and dynamics of the Molasse Basin

The present-day Alps/Molasse basin system is the result of the Late Cretaceous-Miocene continent-continent collision between the Adriatic promontory of Africa and the European plate. This collision resulted in a total of 120 km of post-Eocene shortening (Schmid et al., 1996), based on the geological interpretation of geophysical data, Laubscher (1990), Pfiffner (1992), and Schmid et al. (1996) showed that the collision between the two plates occurred by insertion of the Adriatic lower crust into the interface between the south-dipping European lower crust and the European upper crust (Schlunegger, 1997).

The development of the Molasse Basin was initiated on the southern (Helvetic) margin of the European shelf by the Late Eocene underthrusting of the European Plate under the Adriatic-African Plate (Frisch, 1979) and the transgression of the Tethys Sea over the northern foreland. Subsidence of the Molasse Basin was controlled by the flexural loading of the advancing thrust sheets and nappes of the Alpine orogenic front, which, from Late Eocene times onward, were successively thrust over the southern part of their foreland. The weight of these allochthonous masses caused the elastic downbending of the thick and cold foreland crust which resulted in the development of the foredeep basin. In addition, the subsidence of the basin was affected by the isostatic adjustment of the crust due to water-loading and the continuous input of sediments. At times of the flexural downbending of the subducted foreland plate, tensional blockfaulting took place, which generally trends sub-parallel to the basin axis (east-west) (e.g. Jin, 1995).

The structural evolution of the Molasse Basin can be subdivided into three major phases, which mainly reflect the development of the Alpine mountain belt and to minor extent also the influence of global events (e.g. eustatic sea level changes, plate tectonic configuration) affecting the foreland.

The first phase (Upper Eocene to Aquitanian/upper Egerian) is characterized by uplift beginning in the Western Alps and by the movements of the Savic dislocation phase. The Rupelian/Chattian boundary is marked by the greatest eustatic lowering of the sea level since the Cambrian period. During the second phase (Burdigalian / Eggenburgian to lower Pannonian), the main uplift shifts to the Eastern Alps, causing in the foreland the large E-W directed fluvial accretion of the Upper Freshwater-Molasse. The third phase (lower Pannonian to Pliocene) is dominated by denudation of the previous accumulations driven by the continuing uplift of the Alps with its centre shifting back to Western Switzerland. This denudation is initiated by the Danube System which is extending from Lower Austria into the Molasse Basin.

1.2.5. Overview of the lithostratigraphy and the sedimentological development of the Molasse Basin

The sedimentological development of the North Alpine Foreland basin can be described in terms of an early deep-water stage and a later shallow-water/continental stage; in the classic Alpine literature, these stages are referred to as the Flysch and Molasse, respectively.

The basin was primarily filled with the erosional products of the advancing nappes in the south. Traditionally, the Molasse basin fill has been divided into two thick, generally shallowing-upward, transgressive-regressive mega-sequences, which are separated by an extensive unconformity (e.g.Eisbacher, 1974). Each mega-sequence starts with marine sedimentation, the so-called "Marine Molasse", and ends with continental sedimentation, the so-called "Freshwater Molasse" ("Untere Süsswassermolasse" or USM, Chattian to Aquitanian)/ and Lower Marine Molasse ("Obere Meeresmolasse" or OMM, Burdigalian)/Upper Freshwater Molasse ("Obere Süsswassermolasse" or OSM, Langhian to Serravallian) can be followed from Switzerland into Bavaria (e.g. Matter et al.,1980,; Keller,1989). However, east of Munich, the depositional facies remain marine to even deep-marine from the Oligocene to the middle Miocene and therefore this fourfold subdivision is no longer applicable (e.g. Fuchs, 1976; Betz and Wendt, 1983). Only the OMM will be discussed in more detail in 1.3.6.

Lower Marine Molasse (UMM):

The first megasequence starts with the development of the 35- to 30-Ma-old Lower Marine Molasse Group (UMM) (e.g. Lemcke, 1988; Bieg, 2005). This unit forms the transition from the underfilled to the filled stage of basin evolution, presumably as the increase of sediment supply rates was larger than the creation of accommodation space (cf. Kuhlemann 2000).

Lower Freshwater Molasse (USM):

The UMM is overlain by fluvial clastics of the 30- to 20-Ma-old Lower Freshwater Molasse Group (USM). This unit consist of several kilometres of alluvial fan conglomerates at the thrust front (cf. Kempf & Matter 1999). Towards the more distal parts of the basin, the conglomerates interfinger with meander belt sandstones, floodplain mudstones and lacustrine depositional systems (e.g. Bieg, 2005).

Upper Marine Molasse (OMM):

The second megasequence starts with a marine transgression at approx. 20 Ma, resulting in the establishment of the shallow marine depositional systems of the Upper Marine Molasse Group (OMM), which in the German part of the basin last between 20 and 16.5 Ma (Bieg, 2005). At the Alpine thrust front, the marine deposits interfinger with fan delta conglomerates, which were sourced in the Central Alps (e.g. Schaad et al. 1992, Keller, 1989).

Upper Freshwater Molasse (OSM):

The OMM is overlain by the continental Upper Freshwater Molasse Group (OSM). Deposition of the OSM started at ca. 16.5 Ma. (Bieg, 2005), the youngest deposits of this unit display ages between 13 Ma (proximal position, Kempf et al. 1999) and 10.5 Ma (distal position, Berger 1992). At present, the Molasse basin is uplifted and eroded, and no deposits younger than Tortonian are preserved (Bieg, 2005).

1.2.6. Sedimentary Evolution of the Upper Marine Molasse

After the deposition of the USM, basin-wide marine conditions were re-established during the Eggenburgian (e.g. Kuhlemann and Kempf, 2000). This regional transgression started in the Bavarian Molasse (Zweigel et al., 1998) and propagated diachronously westwards (e.g. Berger, 1985), probably before the onset of a global sea-level rise (see Haq et al., 1988; Berggren et al., 1995). In the Bavarian Molasse, fossil-rich shales were deposited during latest Upper Egerian. This indicates regional starvation of the foreland basin (Zweigel et al., 1998), despite a previously strong sediment supply. Moreover, supply of conglomerate-rich mass flows to the Puchkirchen Trough from the palaeo-Inn stopped. The supply of sandy turbidites from southwestern sources intercalated with marls continued (Haller Schlier; Herbst, 1985). In the Lower Inn Valley, marine sandstones were deposited (Hagn, 1976), indicating a strong retreat of alluvial deposits rich in conglomerates (Kuhlemann, 2000).

In the western NAFB, the marine transgression started likewise during the latest Egerian (Berger, 1985). Sandstones intercalated with mudstones formed in a wave- and tide-dominated (micro- to mesotidal) shallow marine environment (Homewood & Allen, 1981; Keller, 1989). At the southern basin margin, shallow marine sandstones interfinger with large fan deltas (e.g. Keller, 1989; Schaad et al., 1992). This so-called “Burdigalian Transgression” followed a regional erosional unconformity (e.g. Lemcke, 1988). Important reworking and erosion of Molasse sediments at its base of up to 250 is observed in eastern Bavaria (Zweigel et al., 1998) and of about 50m in western Switzerland (Morend, 2000). Between Lake Constance in the west and the Landshut-Neuötting Basement High in the east, the northern basin margin shifted southward by several tens of kilometres during the earliest Eggenburgian (Doppler, 1989; Bachmann and Müller, 1991). This southward shift of the northern basin margin was most pronounced in the area of Munich, where the narrowest marine gate of the "Burdigalian Seaway" is situated (Bachman and Müller, 1992). North of Munich, an area of low relief parallel to the Alpine front became established. However, this emerged area is not identical with the Landshut-Neuötting basement high, located ~ 30 km east of Munich. This latter region was a local zone of relatively low subsidence and reduced sediment thickness from ca. 18 Ma onward (Lemcke, 1988).

Close to the thrust front, a shallow and narrow marine trench formed, connecting the Paratethys with the Western Mediterranean Sea (Kuhlemann & Kempf, 2002).

According to Sinclair (1997a), the USM reflects a filled or overfilled stage of basin evolution. However, with the beginning of the Burdigalian transgression, accommodation space formed at higher rates than sediment accumulation. Hence, the transgression of the OMM marks a change in the domain of the central and western NAFB from overfilled to underfilled conditions. During the OMM, the wedge-shaped basin geometry changed to a tabular geometry (e.g. Unger, 1983; Schlunegger et al., 1997). Towards the end of marine sedimentation, the basin geometry again changed towards a wedge-shaped type (Schlunegger et al., 1997). These transformations occurred within 3 million years.

The NAFB remained underfilled during deposition of the OMM for about three million years, although fan deltas in the central and western parts of the NAFB evidence continuous discharge of coarse Alpine debris. Despite the decreasing sediment discharge of the Alps during deposition of the OMM, dissolved load and an important part of the suspended load may have been held in suspension drifting south-westwards into the Rhone fan (Kuhlemann, 2000).

The Ottnangian times were characterized by fast and multiple changes in facies and environment in the NAFB; shallow marine and brackish deposits, which are very sensitive to even minor sea-level fluctuations, dominate at that time. In response to a rising sea level, the initially narrow marine seaway became much wider.

Shallow marine conditions coinciding with a global sea-level highstand (see Haq et al., 1988; Berggren et al., 1995) prevailed. The northern margin of the NAFB shifted tens of kilometres northward and the basin widened particularly in its central parts. A sea cliff developed in southwestern Germany along the northern basin margin probably during the Ottnangian sea-level highstand ("Klifflinie"; e.g. Geyer & Gwinner, 1991). At that time, an unconformity is evident in the proximal part of the central NAFB (Schlunegger et al., 1997). The marine transgression flooded a southwestward draining river valley north of the foreland bulge, before it fell dry again for a short period of time, forming an erosive channel ("Graupensandrinne"; e.g. Kiderlen, 1931; Lemcke, 1988; Geyer & Gwinner, 1991). Shallow marine and tidally influenced deposits formed in the former Puchkirchen trough of the eastern NAFB, which rapidly became filled (Malzer et al., 1993).

Between 18 and 17 Ma, several short-lived facies and basin geometry modifications in the South German Molasse (e.g.Doppler, 1989) are partly related to eustatic sea-level fluctuations (Zweigel et al., 1998).

At the Ottnangian-Karpatian boundary (ca. 17.2 Ma), the marine environment of the central and eastern NAFB changed into temporally isolated brackish lakes (Lemcke, 1988; Doppler, 1989). Later on, these lakes were filled with clastic debris and a large, gravel-rich, westward-directed transverse drainage system developed at the northern margin of the Upper Austrian and Bavarian Molasse basin (Unger, 1983; 1989). Following this regression, a final, short brackish ingression from the west, in the early Karpatian, marked the end of the OMM period and started the overfilled phase of the OSM.

Despite a decreased clastic supply from the Alps after ~ 17 Ma, the marine environment was rapidly replaced by isolated brackish residual lakes and, later on, by a terrestrial environment (Lemcke, 1988; Doppler, 1989). Around 17 Ma, the eastern part of the Eastern Alps collided with the stable European continental margin, which induced a slow rise of the Amstetten Swell at the southern tip of the Bohemian Massif (Kapounek et al., 1965). At about the same time, further retreat of the marine to brackish environment (Doppler 1989; Reichenbacher et al. 1998) established a large west-directed river system (Glimmersande), termed Palaeo-Rhone by Kuhlemann et al. (2001). The regression of the "Burdigalian Sea" of the OMM is mainly due to an increase of sediment supply into the NAFB caused by important uplift in the Eastern Alps. This uplift is caused by the termination of thrusting along the eastern part of the Alpine front (Decker & Peresson 1996).

1.2.7. Miocene orogenic evolution of the Alps and its implication on the depositional history of the OMM

The orogenic evolution of the Alps combined with the global eustasy governed the the development of the basin fill in the NAFB mainly by modifying the available accommodation space and the sediment supply. There are fundamental differences in the topographic evolution of the Central and the Eastern Alps. The generally higher relief in the Central Alps is linked to Miocene to recent crustal thickening (Schmid et al., 1996), whereas the Eastern Alps are mainly undergoing Late Tertiary lateral extrusion (Ratschbacher et al., 1991), i.e. a combination of gravity-driven orogenic collapse and crustal escape driven by tangential forces. This lateral extrusion occurred mainly in the Early and Middle Miocene (ca.23-13 Ma). The metamorphic core complexes of the Eastern (Tauern Window) and Central Alps (Lepontine Dome) were subaerially exposed at approximately 14-13 Ma (Spiegel et al., 2000) as a consequence of tectonic unroofing during the Miocene lateral extrusion (Frisch et al.,2000; Steck and Hunziker, 1994). In contrast to the Eastern Alps, the

Penninic basement units had already been exposed between 25 and 20 Ma in the Central Alps. At about 21 Ma the sediment discharge of the Alps dropped dramatically. This event is coeval with the reduction to at least one-third of thrust-advance rates in the Swiss sector (Homewood et al., 1966). In the easternmost part of the orogen, thrusting continued until about ~ 17 Ma (Decker and Peresson 1996).
The decrease of the Early Miocene erosion rates is in general considered to be the result of changes in rate and pattern of crustal uplift, exposed lithologies and palaeoclimate (Schlunegger 2001, Whipple & Tucker 1999, Kühni & Pfiffner 2001).

At approximately 20 Ma, average erosion rates in the Alps decreased by 25-40%, as the crystalline core of the Alps became exposed. This also resulted in a reorganisation of drainage pattern from orogen-normal to orogen-parallel orientation. It appears that erosion rates decreased more rapidly than crustal uplift rates (Schlunneger et al. 2001). Schlunegger & Pfiffner (2001) propose that a climate change caused in an almost instantaneous decrease of sediment discharge and vertical topographic growth. In contrast, Kuhlemann (2000) found no detectable influence of a Miocene "climate change" on the Alpine erosion rates and thought that these are mainly conditioned by the lateral extrusion. The underfilling of the NAFB at ca. 20 Ma coincides with a significant modification in the structural evolution of the Alps from a period of crustal thickening in the central part of the orogen to a phase of frontal accretion in the foreland. According to Schlunegger (1997), the marine ingression of the "Burdigalian Sea" was triggered by this decrease of the average erosion rates. A more extensive discussion of this significant decrease in the discharge of sediment from the Central Alps at approx. 20 Ma as compared to the preceding 10 Ma and its influence on the structural evolution of the Alps can be found in Schlunegger (1999), Schlunegger & Willett (1999), Kuhlemann (2000).

During the Early Miocene, the area of the western Eastern Alps was already mountainous, whereas the eastern part was occupied by lowlands or hilly terrains (Frisch et al., 1998). The main period of extrusion was from the Ottnangian or the Karpatian until the early Badenian (ca. 18 to 15 Ma). A number of intramontane basins formed as pull-apart or transtensional structures along major strike-slip fault zones (Ennstal, Mur-Mütztal, Lavantal) (see e.g. Bieg, 2005, and literature therein). Enhanced block movement during tectonic extrusion led to the rearrangement of the north-directed drainage pattern east of the Tauern Window (Frisch et al., 2000). The deposition of the Augenstein sediments, a paleosurface and paleosoil formation of Early Miocene age (Frisch et al., 2000), was interrupted at ca. 18 Ma by a tectonic event during which fault-bounded valleys dissected the "Augenstein" peneplain. Between 18 and 17 Ma, a short drastic increase in the sediment discharge rates is observed (Bieg, 2005). At this time, the final thrusting phase in Lower Austria resulted in the collision of the Alpine nappes stack with the Bohemian Spur (Decker and Peresson, 1996), which formed a rigid indenter of the European continental margin in Lower Austria. The Amstetten Swell (Kapountek et al., 1965) became a drainage divide and forced the NW-trending East-Alpine rivers towards westerly directions (Kuhlemann, 2000). The closure of this gateway between the Central Paratethys and the Western Mediterranean led to the final retreat of the "Burdigalian Sea" to the west.

2. Database and Methods

2.1. Study Area

The studied area reaches from Tuttlingen to the west to the Inn River to the east (see Fig. 2). The area to the west of Munich (“Westmolasse”) is characterized by the interplay of continental and marginally marine to lacustrine deposits during the Oligocene, whereas to the east of Munich (“Ostmolasse”), marine and in part deep-water deposits prevailed during the same time. The area intermediate between the two major depositional realms of the Westmolasse and the Ostmolasse is well suited to investigate transgression/regression cycles, shifts in the position of the shoreline position, onlap, etc., in order to analyse the stratigraphic signatures of tectonics, eustasy and sedimentation (Vail et al., 1991; Jin, 1995; Zweigel, 1998).

Unfortunately, subsurface date from the critical area between Munich and the Lech River, which is intermediate between the “West”- and the “Ostmolasse” are very scarce.

2.2. Database

The present study of the OMM in the German sector of the Molasse Basin is mainly based on a large number of subsurface data made generously available by the German oil companies. A considerable amount of these data has not been published previously. Additional surface and subsurface data have been drawn from literature.

The German Sector of the Molasse Basin has been explored intensively from the 1950’s to the early 1990’s and a wealth of surface and subsurface data are available, but only part of it has been published until now (e.g. Lemcke, 1988; Bachmann & Müller, 1991; Fertig et al., 1991, Jin 1995, Zweigel 1998). Since the exploration has been carrried out by different oil companies over several decades, the stratigraphic terminology changes considerably not only between different companies, but also with time from older to younger data. Therefore, it became necessary to use a pragmatic unified stratigraphic subdivision which is based on Lemcke (1988) and Bachmann & Müller (1991).

2.2.1. Borehole analysis

The interpretation of the lithologies, the depositional environments and other petrophysical properties is based on the wireline logs and completion reports of a total of 65 wells; which have been reinterpreted. In a second step, the borehole data are included in the seismic sections, thus allowing the direct correlation of the interpretations based on the well logs with the seismic facies and the application of sequence stratigraphy (see e.g. Jin 1995, Zweigel 1998).

The criteria used for the original subdivision into stratigraphic units are not uniform. Many of the wells were later subdivided by other authors using different methods

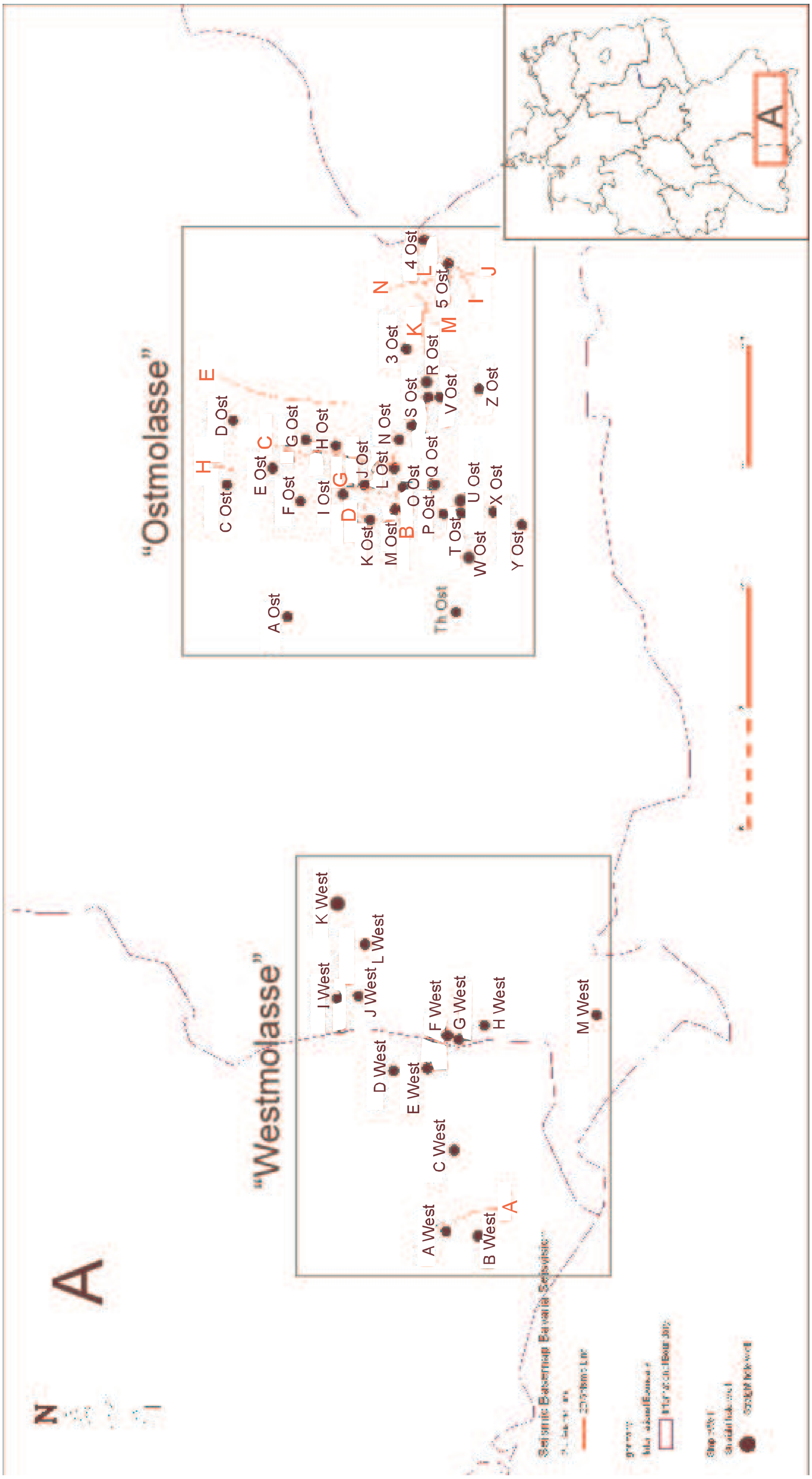


Figure 2. Location of the studied areas and wells in the German part of the Molasse Basin.

(e.g. Lemcke, 1955, 1956; Jin, 1995; Zweigel, 1998). As far as possible, I have tried to standardize the subdivisions of all studied wells. However, the available data are of different vintage, completeness and quality. Older wireline logs usually lack sonic and gamma logs.

2.2.2. Seismic Data

A grid consisting of 14 seismic lines parallel and perpendicular to the basin axis and intersecting the studied wells was selected. The studied seismic lines are of variable quality; those from the western part of German Molasse Basin generally being considerably older than those from the eastern part.

Generally, the contacts between most lithologies have impedance contrasts which are sufficiently high to produce good seismic reflectors. Most reflectors represent a composite signal from several reflecting horizons.

The interval of interest, i.e. the Miocene part of the Molasse is often very close to the surface, especially in the western part of the study area. This results in a low signal-to-noise ratio that may obscure the reflectors (Derer, 2003). The interpreted seismic lines often show zones of diffuse reflectivity; which affects particularly the "Glaukonitsande-Blättermergel", "Neuhofener Schichten", "Baltringer Schichten" and the "Sandmergelserie". It is not possible to state unequivocally if this disturbance is caused by (a) a bad signal transmission due to unconsolidated Quaternary sediments at the surface and/or noise from other disturbances (e.g., electric power lines), (b) fault zones with small movements on many faults that destroy the impedance contrasts between beds, or (c) lithologies with diffuse reflectivity behaviour due to small scale facies changes (Morend, et al. 1998; Watney, 1996).

2.3. Methods

2.3.1. Well logs

I have compiled and analysed all data available for the studied 65 wells with the help of the program Geographix® and the LogScan® software (see figs. 3 and 4).

The well logs are digitalized with the LogScan® software. LogScan ® is an on-screen well log digitizing software for the petroleum industry. Both the original bitmap image and the final trace curve are displayed on the same screen and can be compared at the same scale. The well logs were first scanned into the computer as bitmap picture files, subsequently the log curves were traced on the bitmap picture.

Some of the available logs could not be scanned satisfactorily because of the poor quality of the prints or the poor resolution of the shape of the traces. In some cases, the grid lines were stronger than the curves, in others the gridlines and the curves were very thin and could not be read with confidence.

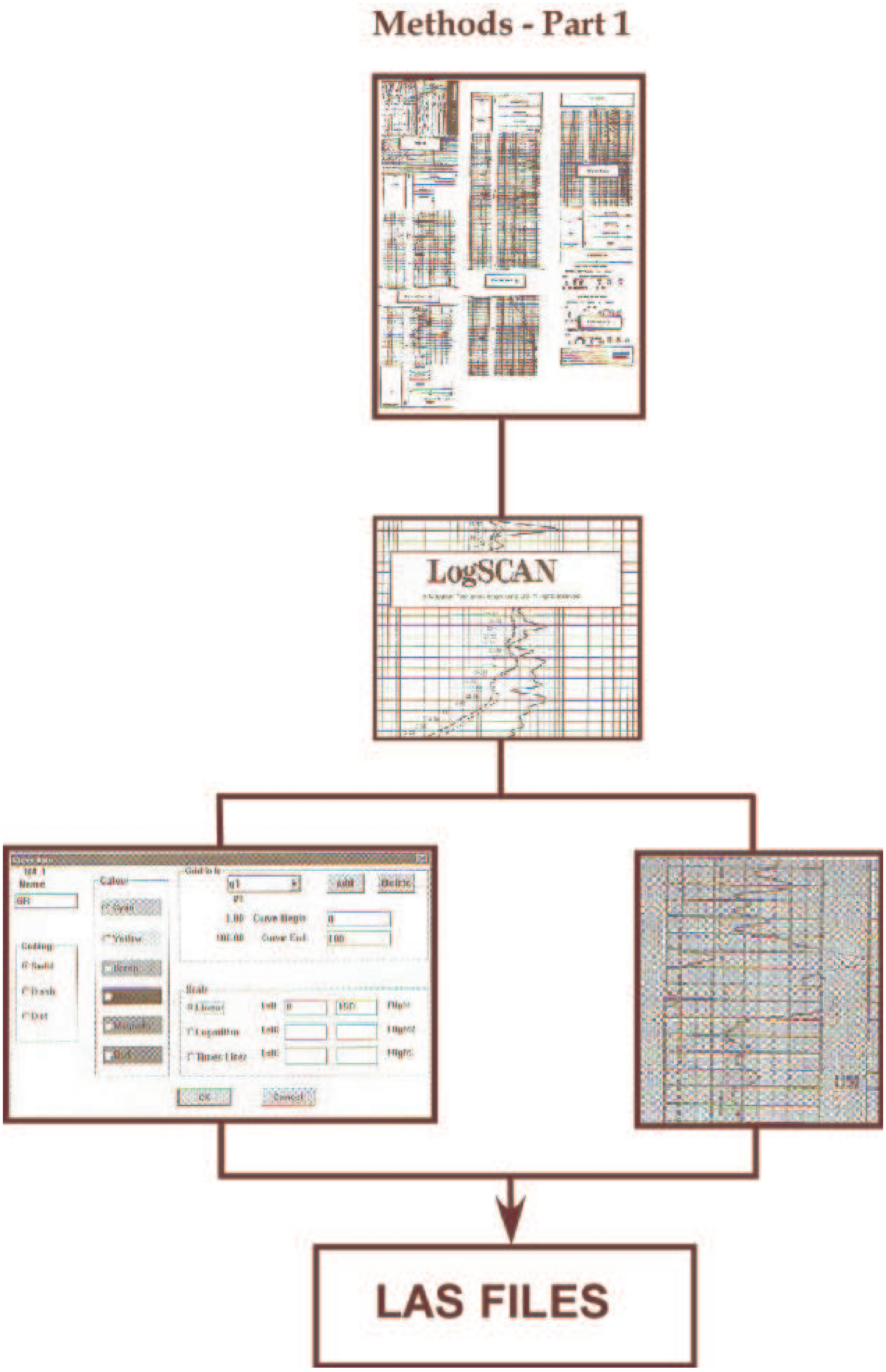


Figure 3. Digitization of the well logs with the LogScan® software.

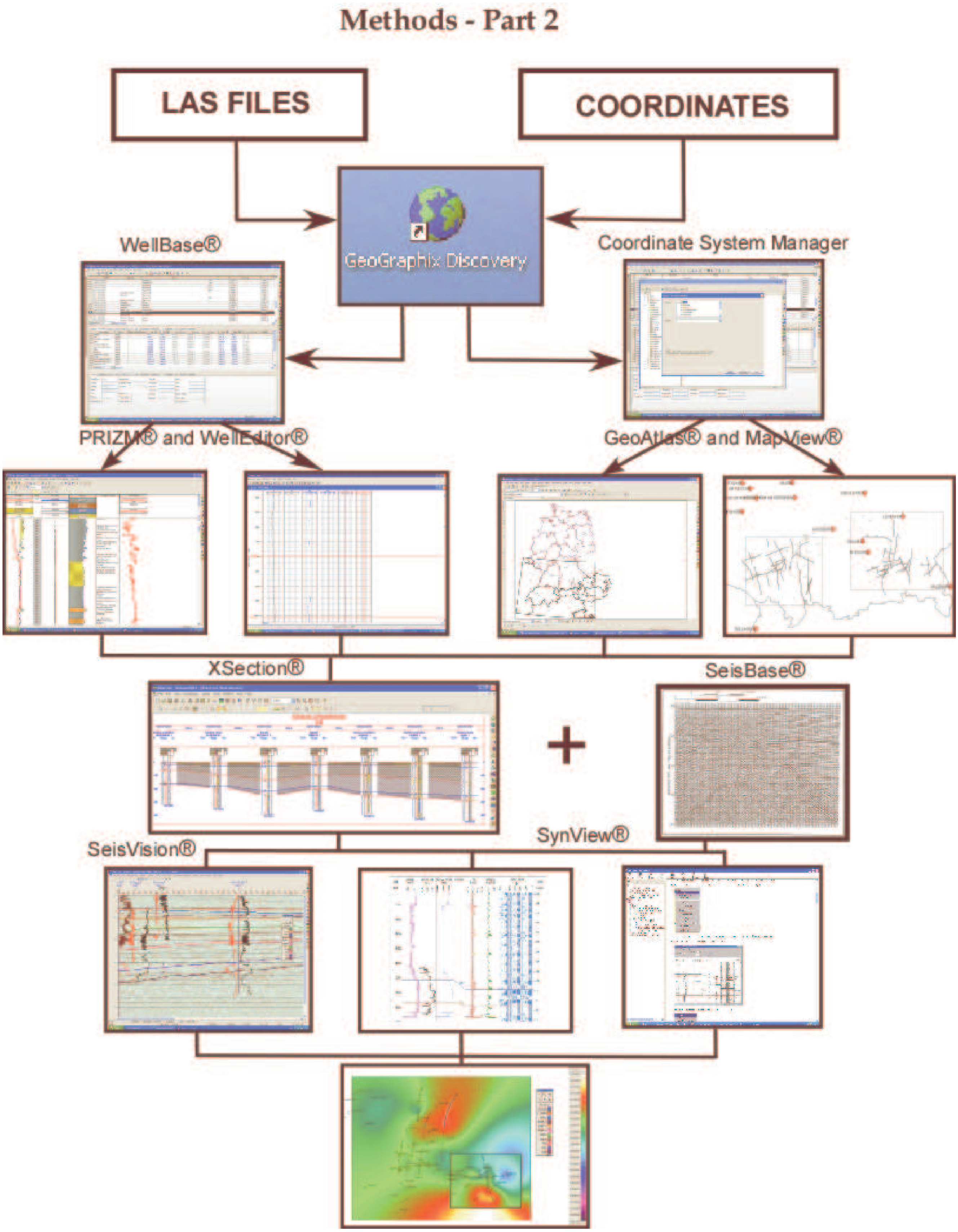


Figure 4. Compilation, integration and analysis of the data with the program Geographix ® and the LogScan® software.

Some curves did not fit into the main scale because of the engineering values (the engineering values are defined as the numbers on the left and right edge of the track) chosen by the logger and went off-scale in some rock formations. The same engineering values are maintained throughout the entire length of the log. However, in some cases, scale changes have not been indicated by the logger.

2.3.2. Seismic data

The interpretation of the seismic lines was achieved in several steps (see e.g. Mitchum & Vail, 1977; Vail et al., 1977, 1991). In the first one, I traced the prominent base of the Miocene and its consistency was checked by correlating all analysed lines. The second step consisted in the subdivision of the Miocene into units with similar reflection behaviour. The boundaries between these units are either visible directly by more or less continuous reflectors, or indirectly by the accumulation of truncated reflectors in the interval below and/or onlap and downlap of the reflectors in the interval above. In a few lines, the boundaries between units are drawn based on similarities of the reflection patterns.

2.3.3. Integration of well logs and seismic sections

All well logs and seismic sections have been compiled in a comprehensive data base. The well log data (GR-gamma ray, SP-self potential, caliper, resistivity and sonic measurements) include also the palaeontologic data, description of cores and cuttings of the completion reports. The interpretation of the seismic data is based on the correlation with the well information. Significant surfaces identified in wells were tied to the seismic lines using velocity data. These and the results of a stacking pattern analysis are part of the sequence stratigraphic interpretation.

All data were integrated with the help of the Geographix® program. This program is user friendly and among other applications allows generating facies maps and cross sections.

The digitized well logs were transferred to the Geographix® program from LogScan® as LAS files. The Geographix® program allows the rapid construction of the database and the systematic processing of the available data. The following of its applications have been used step by step:

- Coordinate System Manager: Definition of the coordinate systems, map projections and data for use in GeoGraphix® projects and in SeisVision®.

- GeoAtlas® and MapView®: Generation of maps, modification of the map attributes and the definition of the areas of interest. All interpretated surveys, including wells, faults and 2D seismic line locations were displayed in MapView®.

- WellBase®: This program provided access to a relational database management system for the geologic well data, including formation tops and deviation surveys. In this step, the stratigraphic units were defined and the lithological and palaeontological information obtained in the completion reports have been integrated.

- PRIZM ® is a well log analysis system I used to interpret key wells. The same interpretation was then extended to all other wells. With the help of this software, I selected and improved the digitized curves. The curves were displayed together with the corresponding lithological and palaeontological information. This application allows the correction of the polarity of the Spontaneous Potential caused by the variable salt content in the formation water.

- WellEditor ® it is a multi-purpose geophysical application used to edit, to correct and standardize the well log curves.

- XSection®: after selecting wells and log templates, I designed the layout of the cross sections, including the spacing of the wells, horizontal and vertical scales, datum and the depth ranges to be displayed. The wells were shown as a vertical wellbore using a true vertical depth scale. The stratigraphic datum to create the several stratigraphic sections was specified.

- SeisBase® allowed to import seismic survey location data along with selected attributes associated with the interpreted seismic horizons.

- SeisVision® was used to interprete, analyze, manage, and manipulate seismic data in order to define the structure and the stratigraphy.

In this application, I defined the horizons to be analyzed, carried out the correlation of the seismic lines with the well data and the created interpretative maps. An interpretation in SeisVision® is a combination of seismic, well, and geographical data together with the interpreted horizons, faults, and velocities in a specific geographic area. The area of interpretation is determined dynamically by the geographic extension of the seismic and well data added to the interpretation.

In spite of the advantages offered by the program Geographix®, the processing of the seismic lines was hampered by several factors. Several seismic lines are affected by noise, whereas in others the resolution is low because of the interference of reflections from closely spaced reflectors. For these reasons, the synthetic seismograms were generated to compare with the seismic data and identify the reflectors with layers and formations already known in the analyzed wellbore.

In SeisVision software with Map View were displayed all interpretation surveys, including wells, the 2D seismic line locations and the grid times, grid velocity and depth surface data for each lithological unit.

The following programs and applications have been used to improve the interpretation of the seismic lines:

- SynView® window provides tools to compute the time-depth curves (velocity surveys) and the generation of the synthetic seismograms for the wells. However, sonic logs have not been run routinely in the older wells. The synthetic seismograms of the studied wells were used to identify the several horizons in each well and thus was produced a more realistic seismic model.

- SeismicModelling® is an interactive editing platform for producing single well log synthetic trace responses in addition to multi-well cross section trace modelling. It allows to model synthetic sonic logs.

Finally, published data were integrated and contrasted with the results of the stratigraphic analysis.

3. Regional palaeogeography of the Upper Marine Molasse in the South German Molasse Basin

3.1. Introduction

At the base of the Burdigalian (Eggenburgian), a new chapter in the paleogeographic history of the Molasse Basin begins. After a short time of uplift and erosion, the sea invades the basin in a new transgression which originates from both the southwest and the east. The thickest sequences (1200-1500m) are deposited in the inherited zones of subsidence (Switzerland, area of Lake Constance, Eastern Bavaria). The transgression spreads over the exposed fluvial and lacustrine series of the USM and reaches the Swabian/Franconian Alb and the "Tafel Jura" (e.g. Geyer & Gwinner, 1991). At the end of the early Burdigalian, the entire Alpine foreland is flooded.

In the area to the east of Munich, the cycle of the OMM begins with a transgression progressing from east of the Chiemsee along the present-day Alpine front and finally floods the entire basin. The base of the transgression is marked by a weak unconformity with the basal horizons of the OMM getting younger to the north. In the area between the Enns and Inn rivers, the OMM contains an ENE-WSW striking series of sand lenses shed from the East (e.g. Kollmann & Malt 1980). The input of coarse terrigenous material from the South and from the Moldanubian is insignificant and sporadic only.

In Bavaria, the Burdigalian coast turns to the SW and reaches in Peißenberg the northern margin of the "Faltenmolasse", which it follows more or less to the area of Lake Constance (e.g.Lemcke 1970).

The Amstetten Antiform establishes itself as an important paleogeographic element. At the end of the middle Eggenburgian, the sea retreats westward into NE-Switzerland and most of the Austrian and German parts of the Molasse Basin fall dry (e.g. Lemcke, 1972). In the area between Lake Constance and the Lech River, the "Albstein", interpreted as a calcareous desiccation crust by Lemcke et al. (1953) is developed. To the South of it, the fluvial deposits of the "Hochgrat-Fan" are prograding. The regressive phase of the second cycle culminates in the deposition of the "Süssbrackwasser-Molasse" (SBM, freshwater to brackish Molasse).

A renewed invasion of the sea proceeding from NE Switzerland via the "Graupensandrinne" reaches into Eastern Bavaria as far as the Chiemsee and the Salzach River. (e.g. Lemcke 1972, Boigk 1981) depositing the brackish "Kirchberger Schichten" in the western part and the "Oncophora-Schichten" in Lower Bavaria as well as in Upper and Lower Austria (Grimm 1964; Schlikkum & Busch 1968, Steininger et al. 1976).

In the area of the "Faltenmolasse", and its adjacent parts, alluvial fans continue to shed alluvial and fluvial deposits during the deposition of the OMM and the SBM.

3.2. Stratigraphic Units of the OMM

Traditionally, the OMM is subdivided into two cycles: (a) the thick and predominantly pelitic "Sandmergelserie" / Neuhofener Schichten") which constitute 4/5 of the total thickness of the OMM (Lemcke, 1953) and (b) the shallow-water sandstones of the "Baltringer Schichten" / "Glaukonitsande + Blättermergel". Both cycles begin with an increase in grain size with gravel reaching fist size in the W (e.g. Lemcke et al., 1953) (see Fig. 5). In the following I will describe the sedimentary facies of the OMM – unit in more detail.

In the Allgäu (SW-Bavaria, SE Baden-Württemberg), the Upper Marine Molasse (OMM) of the southern part of the Molasse basin is subdivided into 3 lithological units: a lowermost coarse grained transgressive sequence rich in bioclasts, a sandy and marly unit in the middle part with a very poor fossils record and an upper coarse grained regressive unit again rich in clasts. To the south, these marine sediments interfinger and pass into the alluvial fans at the mouth of big Alpine river systems (e.g. Scholz, 1989).

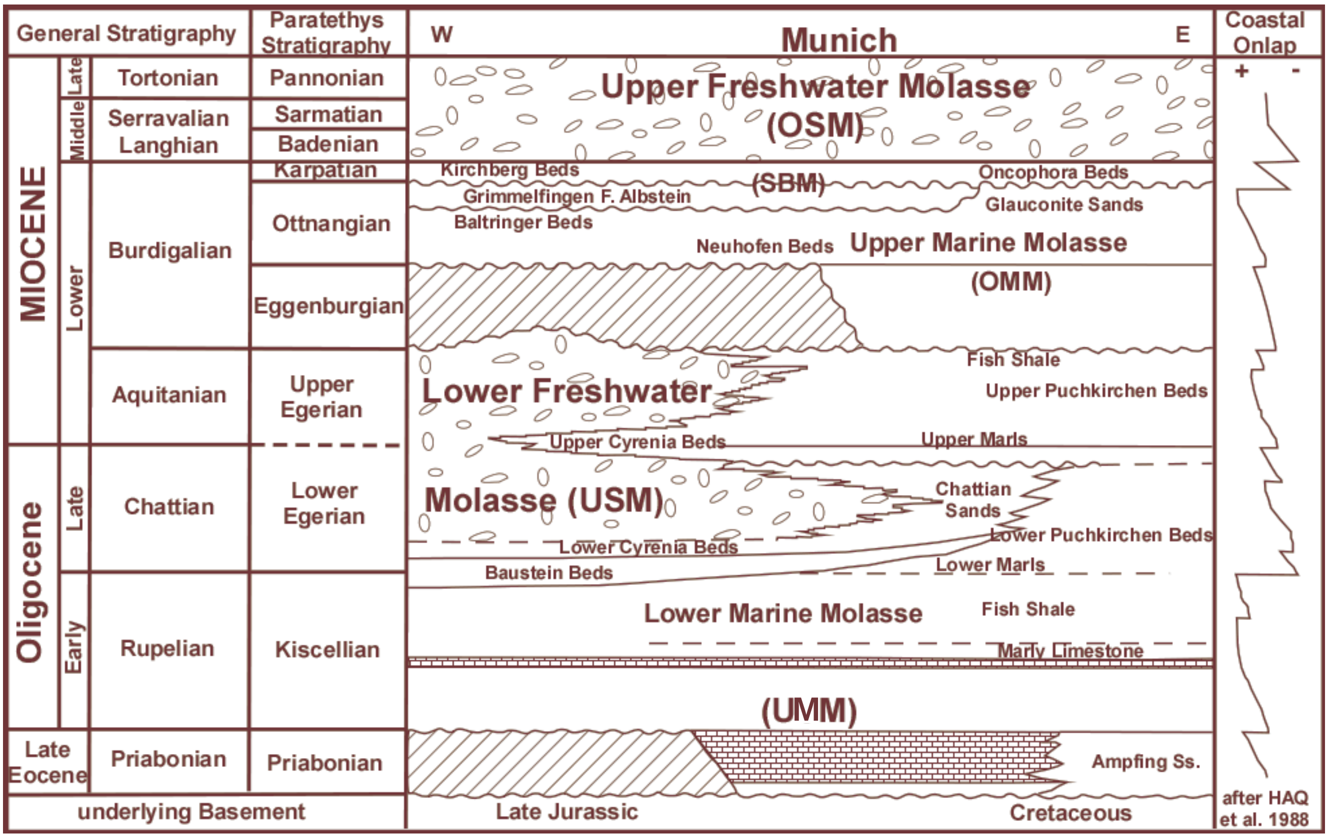


Figure 5. Schematic east-west chart showing generalized stratigraphic and facies evolution of the central North Alpine Foreland Basin (NAFB) (after Lemcke, 1988; Bachmann and Müller, 1991), modified according to Zweigel et al. (1998). Coastal onlap curve after Haq et al. (1988). Taken from Kuhleman and Kempf (2002).

3.3. Western part of the German Molasse Basin "Westmolasse"

3.3.1. I. Cycle

3.3.1.1. "Basisschichten"

The "Basisschichten" at the base of the OMM are well developed from eastern Switzerland to Upper Bavaria (e.g. Hagn, 1976; Scholz, 1989). Their thickness varies from 10 to 50m. Their lithofacies ranges from well bedded, often coarse-grained to pebbly sandstone, in places pebbly and rich in skeletal material (e.g. "Bryozoensandstein") to more friable, thin-bedded middle- to coarse-grained glauconitic sandstone (e.g."Gyrolitessandstein"), which may contain frequent marl intercalations (Scholz, 1989).

The name „Bryozoenschichten "or "Bryozoensandstein " was used by Gümbel (1861) and Miller (1877). The "Bryozoensandstein" consists of grey, yellowish to brownish weathering coarse calcareous sandstones to sandy limestones, which are very hard in fresh outcrops. Usually, they include poorly sorted coarse sandstones to fine conglomerates (Scholz, 1989; Scholz & Zacher, 1983.

The friable, glauconitic "Gyrolitessandstein" which is poor in fossils and often contains marly interlayers is named after the frequent occurrences of root traces called "Girolites". They generally underlie the "Bryozoensandstein" and are transitional to the USM (Scholz, 1989).

Scholz (1989) observed two facies of the "Basisschichten". The top of this unit contains green-grey coarse-grained glauconite-rich gravels sandstones. In the eastern part, the base of the transgression is often represented by green-grey fine- to middle-grained calcareous sandstones with marl and silt intercalations. They contain some feldspar and in places display hummocky stratification.

3.3.1.2. "Sandmergelserie"

The coarse-grained "Basisschichten" change upward into a thick marly succession, which is named "Sandmergelserie". The term "Sandmergelserie" was introduced by Lemcke et al. (1953) for the uniformly grey fine-grained sandy to silty sandstones between the "Basisschichten" and the "Baltringer Schichten" in the northern Swabian part of the Molasse Basin (Lemcke, 1953; Scholz, 1989).

In the entire area, the "Sandmergelserie" is surprisingly monotonous and rather poor in macrofauna. Scholz (1989) described the "Sandmergelserie" as green-grey, fine- to medium-grained friable sandstones with intercalations of clay, marls, and sandy marls. The content in glauconite is high, except in the upper part of the unit. In many sections, a few 10 to 30cm thick levels of poorly sorted coarse sand with numerous rounded pebbles are observed. Flaser- and lense-bedding are frequent.

The “Sandmergelserie” is further subdivided into two facies: “Sandmergelserie I” and “Sandmergelserie II”. The “Sandmergelserie I” consists of grey marly fine to coarse-grained sandstones with occasional coal debris, whereas the “Sandmergelserie II” is composed by grey sandy marls, claystone, siltstone and flasers of fine-grained sands.

The thickness of the Sandmergelserie represents more than 50% of the total thickness of the OMM.

3.3.2. II. Cycle

3.3.2.1. “Baltringer Schichten”

The basal layer of the “Baltringer Schichten”, which marks the beginning of the second depositional cycle of the OMM, consists of coarse sandstone which may contain locally pebbles of Alpine origin (limestones, radiolarites, quartzites, granites; Lemcke, 1953). Very characteristic is a 0.3 to 2.5 thick mollusc-bearing bed which is usually associated by an up to 10m thick coarse sandstone; 76% of its grains are of crystalline material, 24% from limestones (Berz,1915). Intensive cross-bedding is frequent. In places, a few burrows are observed (Lemcke, 1953).

Scholz (1989) described two facies in this stratigraphic unit:

• The “Muschelsandstein” together with the “Muschelkonglomerat” is observed in almost all sections. The sudden appearance of skeletal material, the abrupt increase in grain-size and the intensive cross-bedding and ripples mark the base of the renewed transgression at the top of the “Sandmergelserie”.

• The “marines Konglomerat” at the boundary towards the OSM contains shell fragments (mainly of oysters) in its sandy cement.

The transition into the overlying “Feinsandserie”, which contains no marine fossils, is gradual.

3.3.2.2. “Feinsandserie”

The “Baltringer Schichten” change upward rather rapidly into a sequence of green-grey fine sandstone and siltstone with varying mica content, whose thickness varies within a wide range (from 14 to 50 m; Lemcke, 1953). In some wells, intercalations of green-grey sandy marls were observed, which reach a thickness of 2-3 m. The fine-grained to dust-size sandstones to siltstones are always calcareous and in part argillaceous, in part clay-free (Lemcke, 1953).

This unit was named “Deckschichten” by Kiderlen (1931), Hagn (1961) and Schreiner (1966), whereas Lemcke et al. (1953) used the name “Feinsandserie” (Scholz, 1989).

3.4. Eastern part of the German Molasse Basin

3.4.1. I. Cycle

3.4.1.1. "Aquitanian Fish Shales"

The Aquitanian Fish Shales are composed of grey and grey-brown, often slightly sandy, in part thin-layered claystone. The content in fine-grained sand is poor. An increase in sand content is limited to the distal part of the slope and is expressed in the logs by an increase of resistance. The lime content is subject to weak variations; only the brown-colored tops of the layers are clearly lime-free. Accessories are mica as well as occasionally abundant glauconite (Müller, 1978).

The microfauna is abundant in the lower and poor in the upper part. Oschmann (Internal report of Ampfing 4, in Müller, 1978) reported the following microfauna: *Uvigerina aff. semiornata, Cibicides dutemplei, Bathysiphon filiformis, Robulus aff. Inornatus, Gyroidina soldanii, Nodosaria longiscata, Nonionella liebusi, Chilostomella, Bulimina pupoides, Allomorphina trigona, Cyclammina gracilis, Plectofrondicularia striata, Uvigerina farinosa, Bulimina elongata, Bulimina pyrula* and *Cancris auriculus,* in addition to frequent echinoid spines, serpulids, snail and fish debris.

3.4.1.2. "Obing Folge"

The "Obing Folge" is recognized in the well logs by an abrupt shift to high resistivity and low SP values. It is characterized by abundant sharp peaks in the SP and resistivity logs, being arranged into a general fining-upward trend. The "Obing Folge" (Zweigel, 1998) differs from the underlying Aquitanian Fish Shales by an increase in fine-grained sand. Their depositional environment is probably similar, but in the "Obing Folge" it was more distal with fewer slumps and turbidites beds and a generally more sand-dominated sediment supply (Zweigel; 1998).

3.4.1.3. "Burdigal"

The sea, which retreated at the end of the Aquitanian to the South, reached again the southern part of the area of Mühldorf at the end of the "Burdigalian" (Müller, 1978).

The informal name "Burdigal" is used by Zweigel (1998) for the light-grey claystones of Eggenburgian age in order to differentiate them from the brownish-grey claystones of the Aquitanian. Intercalations of sandy marls and siltstones are rare. Silt-size mica and glauconite are mentioned as accessories by Müller (1978).

3.4.2. II. Cycle

3.4.2.1. "Neuhofener Schichten"

In the southern and central part of the "Burdigalian Seaway", the transition into the Neuhofener Schichten is gradual, whereasto the north they are transgressive on the

Aquitanian. Therefore, the most complete sections of the Neuhofener Schichten are in the South, whereas in the North, the lower part was not deposited (Müller, 1978).

The „Neuhofener Schichten“ are subdivided in two units: „Neuhofener Schichten I“ and „Neuhofener Schichten II“. The “Neuhofener Schichten I” constitute the subsequence “SQ4b” of Zweigel (1998). This lithostratigraphic unit can be easily differentiated on the logs (SP and Resistivity) by the increase in sand content.

According to Müller (1978), the Neuhofener Schichten consist of a few differentiated packages of grey claystone with changing silt to fine sand content, which is often enriched in irregularly shaped streaks. Fine mica, which forms frequently films on the bedding surfaces, is always present. Some glauconite and pyrite occur consistently, whereas chlorite is rare. Occasionally indistinct stratification and lamination are observed.

The “Neuhofener Schichten I” are composed of grey claystone rich in glauconite with intercalations of coarse sandstone, limestone and coarse sandy marl. Some gravels are reported. The total thickness of this unit is between 5m to 135 m. The unit contains: benthonic foraminifera (*Lenticulina sp., Cibicides dutemplei, Pullenia bulloides, Bulimina sp., Robulus inornatus, Spiroplectammina carinata, Sigmoilina tenuis, Nonion sp*.), rare planktonic foraminifera, ostracodes and shell debris.

The “Neuhofener Schichten II” consist of grey claystone with intercalations of grey sandy marl and marl. They are characterized by the following microfauna: *Cibicides dutemplei, Robulus inornatus, Spiroplectammina pectinata, Sigmoilina asperula, Rotalia beccarii and Nonion soldanii*. The thickness of this unit varies between 30m and 295m.

Zöbelein and Weiler (1940) reported the following macrofossils: *Nucula cf. ehrlichi, Nucula cf. nucleus, Laternula cf. fuchs, Angulus cf. ottnangensis, Astarte cf. neumayeri, Leda sp.*, and *Buccinum sp.*

3.4.2.2. “Glaukonitsande” and “Blättermergel”

These stratigraphic units were described and defined by Neumaier & Wieseneder (1939).

The “Blättermergel” consist of light-grey, weakly sandy and silty micaceous claystone, which in the middle part is rich in sand with some glauconite (Neumaier & Wieseneder, 1939; Müller, 1978).

According to Müller (1978) the “Glaukonitsande” generally consist in the whole area of clays and marls with intercalated sand layers. The claystones are light-grey, also bluish grey and green always with some medium-grained sand content. The more or less marly sand layers cover the spectrum from fine to coarse grained. Isolated small pebbles and multicoloured quartz grains are described. Glauconite may be very frequent. Frequent additions are mica, lignite and abundant shell debris. The

"Glaukonitsande" are poorly solidified and often indistinctly laminated. The microfauna is poor and dwarfed.

4. Sequence Stratigraphic Interpretation of the “Westmolasse”

4.1. Introduction

In this chapter I will present a new sequence stratigraphic framework of the Molasse in the area between the Lech River and Lake Constance (“Westmolasse”) based on the interpretation of the available seismic line and fourteen wells from this area. Exploration in the “Westmolasse” has been mainly active during the 1950’s and 1960’s. The quality and completeness of the data acquired by different companies mainly during the first phase of the exploration of the Molasse Basin are in part incomplete and of variable quality (see Figures 6, 7 and table 1).

4.2. Lithostratigraphy

I have used the spontaneous potential (SP) and the resistivity (Rs) curves because they were the only ones available for all wells.

4.2.1. “Untere Süßwasser Molasse” (USM)

In the “Westmolasse”, the uppermost part of the Lower Fresh Water Molasse (Eggenburgian) corresponds to the so-called “Aquitanian Fish Shales” of the Ostmolasse.

This unit consists lithologically of green-gray claystone grading into green-gray sandy marl, of gray marls with gradation into grey fine sandstone, gray fine sandstone grading into sandy marl and coarse sand. Some intercalations of grey limestone and siltstone are observed in this unit. The unit has a thickness of 150 m. On the electric logs, it is characterized by low to moderate values with strong peaks. In E West, D West and L West, moderate to high values with very pronounced and strong peaks are observed. They disappear towards K West to the NE. In the SP traces, a slight decrease of grain size towards the base of the unit is observed.

The microfauna contain fish teeth and scales, plant debris and coal particles, fragments of mollusc shells, and the ostracods: *Darwinula cylíndrica*, *Ilyocypris gibba*, *Candona praecox* (In all descriptions, the names of the fossils are given as in the original completion logs and their taxonomy has not been revised.)

4.2.2. “Basisschichten”

The “Basisschichten” are easily identified on the electrical logs by moderate to high values with characteristic peaks at the base marking the strong contrast between this unit and the underlying USM as well as with the overlying Sandmergelserie I. On the SP log, the curve is very homogenous, but with a very characteristic and prominent blocky shape, which differentiates this layer from the underlying and overlying units. An increase of grain size towards the base can be observed.

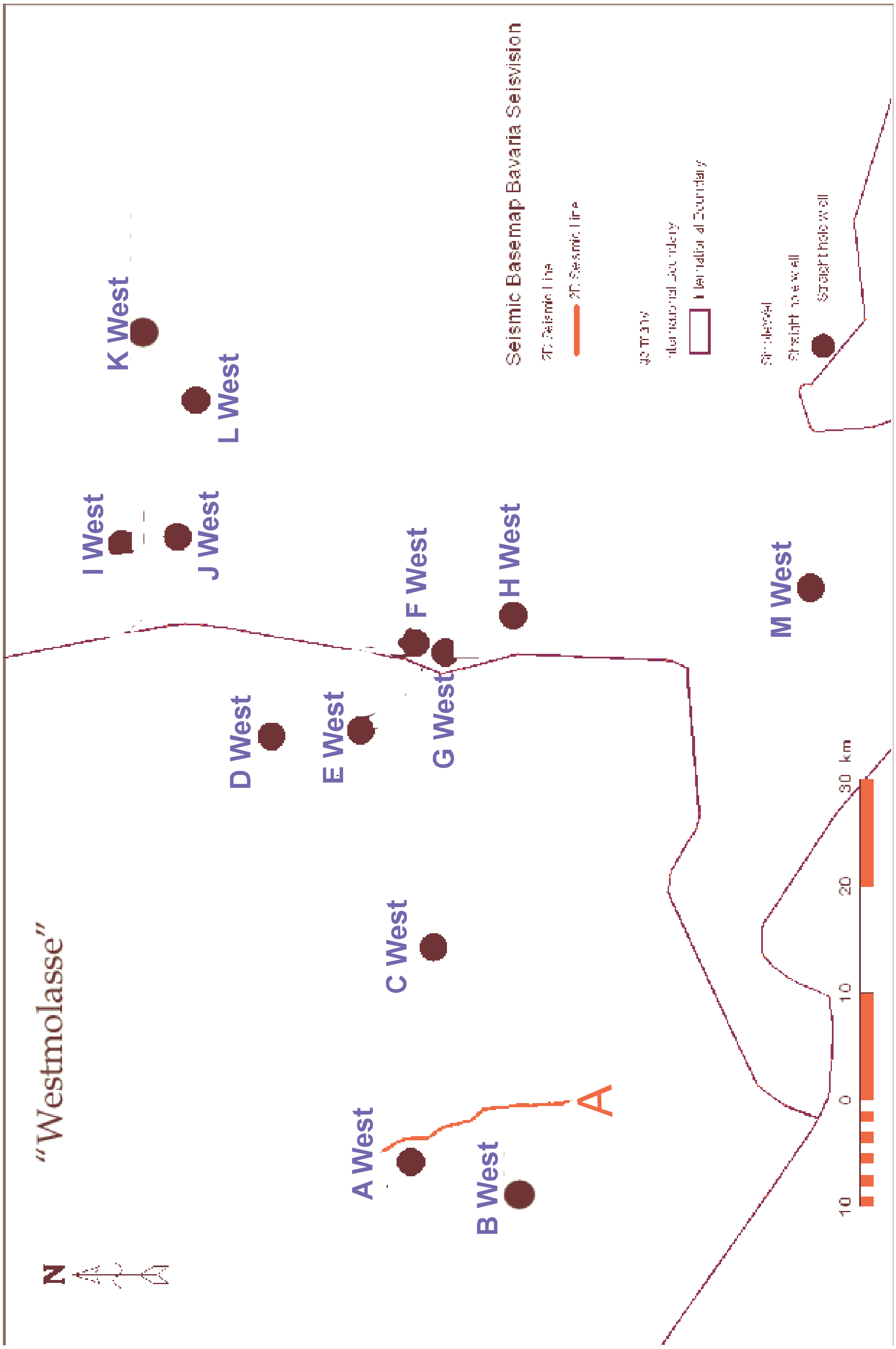


Figure 6. "Westmolasse" – location of the studied wells and of seismic line A.

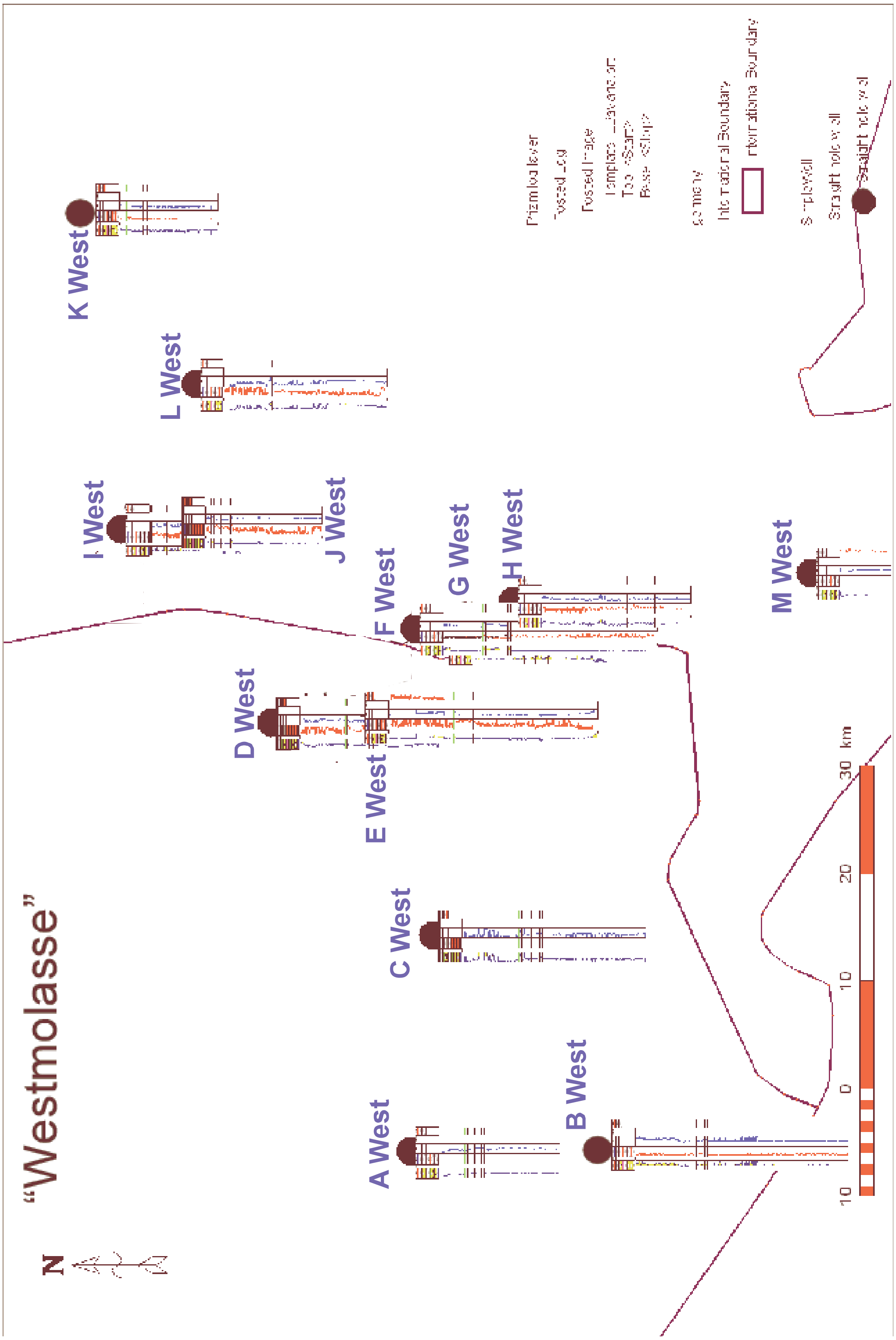


Figure 7. "Westmolasse" - Logs of the studied wells.

Lithological Unit	Description	Fossils	Interpretation
Feinsandserie (Ottnangian)	Green-gray marly sandstone which may grade into sandy marls. Thickness: 2-8 m.	Mollusc debris, echinid spines, Rotalia beccarii, Elphidium sp., Cibicides sp.and globigerinids.	Shallow ponds and lagoons.
Baltringer Horizon (Ottnangian)	Green-gray fine- to middle-grained glauconite-rich sandstones which may grade into sandy marls and into coarse sandstone to gravel or pebbles. Pyrite concretions and coal fragments. Thickness: 10-30 m.	Fragments of oysters and other molluscs, lucinids, echinoid spines, ostracods, radiolarians and Rotalia beccarii.	High-energy near-shore to shore environment.
Sandmergel II (Ottnangian)	Gray sandy marls, silt and claystone and glauconitic sandstone with flaser structures. Thickness: 60 - 110 m.	Rare shell debris, foraminifera, carbonized plant remains, fragments of coal.	Probably subtidal, e.g. Bieg 2005.
Sandmergel I (Ottnangian)	Gray glauconitic sandy marls which grade into fine sandstone and, less frequently, grey-green fine to coarse glauconitic sandstone. Thickness: 60 -120 m.	Generally barren of fossils except rare coaly plant remains.	Probably subtidal, e.g. Bieg 2005.
Basisschichten (Eggenburgian)	Gray marls grading into dark gray-green coarse to fine sandstone rich in glauconite. In places small quartz pebbles. Thickness: 20-35 m.	Debris of mollusc shells, carbonized plant remains, coal particles, echinid spines, fragments of spatangids, Aloidis ("Corbula") sp., A.(Vari-corbula) gibba, Rotalia beccarii, Nonion commune, Elphidum sp., Cibicides sp., globigerinids, Bulimina pupoides, Pullenia quinqueloba, Robulus inornatus, Spiroplectammina sp., Cyclammina sp.	Marine nearshore high-energy environment (e.g. Homewood 1981).
Untere Süßwasser Molasse (late Upper Egerian)	Layers of green-gray claystone, green-gray sandy marl, interlayers of gray marls with gradation into gray fine sandstone; layers of gray fine sandstone gradding to sandy marl and coarse sand. Some intercalations of gray limestone and siltstone. Thickness:150 m.	Marine microfaunas with fish teeth and scales, plant debris and coal particles, fragments of molluscan shells, plant debris and the ostracods: Darwinula cylíndrica STRAUB 1952, Ilyocypris gibba (RAMDOHR 1808), Candona praecox STRAUB 1952 , Ostracoden.	Flood plain with meandering streams.

Table 1. Lithological Units distinguished in the „Westmolasse"- description and paleoenvironmental interpretation.

This unit consists of gray marls grading into dark gray-green coarse to fine sandstone rich in glauconite. It contains a larger amount of coarse sandstone, in places small quartz pebbles, and less shale than the overlying Sandmergelserie I. Its thickness varies between 20 and 35m.

The macro- and microfossil remains listed from the Basisschichten are debris of mollusc shells, carbonized plant remains, coal particles, echinid spines, fragments of spatangids, *Aloidis ("Corbula")* sp., *A.(Varicorbula) gibba, Rotalia beccarii, Nonion commune, Elphidum* sp., *Cibicides* sp., globigerinids, *Bulimina pupoides, Pullenia quinqueloba, Robulus inornatus, Spiroplectammina* sp., *Cyclammina* sp.

The "Basisschichten" are overlain by the bulk of the Upper Marine Molasse (Ottnangian) which is subdivided into the "Sandmergelserie I", "Sandmergelserie II", "Baltringer Schichten" and "Feinsandserie".

4.2.3. "Sandmergelserie I"

This unit is composed of gray glauconitic sandy marls which grade into fine sandstone and, less frequently, gray-green fine to coarse glauconitic sandstone.

The electric log pattern of the "Sandmergelserie I" show moderate to high values with marked and strong peaks. At its base, it is clearly differentiated from the Basisschichten. Its SP curve is homogeneous, due to the presence of sandstone-shale packages in which a slight increase of grain size is observed towards the base. Its thickness varies from 60 to 120 m. This unit is generally barren of fossil remains except rare coaly plant remains.

4.2.4. "Sandmergelserie II"

Gray sandy marls, silt and claystone and glauconitic sandstone with flaser structures compound this unit. The electrical logs display moderate to high values of resistivity with some peaks, but their proportion is smaller than in the underlying units. The "Sandmergelserie I" have a thickness of 60-110 m. Fossil remains are rare and described as shell debris, foraminifera, carbonized plant remains and fragments of coal.

4.2.5. "Baltringer Schichten"

This unit reaches a thickness of 10 to 30m. It consists of green-gray fine- to middle-grained glauconite-rich sandstones which may grade into sandy marls and into coarse sandstone to gravel or pebble beds. A characteristic bed is the "Muschelschillbank" rich in fragments of oysters and other molluscs. Pyrite concretions and coal fragments are mentioned in the descriptions.

In both the W-E and the N-S directions, the characteristic electrical log pattern of this unit presents high values of resistivity with very characteristic peaks at the base and the top. The shape of the Rs trace is a well defined block with a single peak from the base to the top of the unit. The very characteristic SP curve clearly diffentiates this unit from the underlying and the overlying ones. An increase in grain-size towards the base is observed.

Fragments of oysters and other molluscs, lucinids, echinoid spines are frequent. Ostracods, radiolarians and *Rotalia beccarii* are mentioned in some of the descriptions.

4.2.6. “Feinsandserie”

The thickness of this unit varies between 2 and 8 m. It consists of green-gray marly sandstone which may grade into sandy marls.

The electrical logs display moderate to high values with a very characteristic shape at the base and the top of this unit. The resistivity values increase towards the contact with the overlying unit. On the SP log, the unit is well defined by the characteristic shape of the curve.

Fossils mentioned from the Feinsandsserie are mollusc debris, echinid spines, *Rotalia beccarii*, *Elphidium* sp., *Cibicide*s sp.and globigerinids.

4.3. Correlations by wireline logs

Two representative cross sections based on the SP- and resistivity logs have been constructed in order to document the lateral lithologic changes and the variations in thickness (for locations, see Fig. 8). The W-E correlation (figs. 9 and 10) reaching from B West in the West to K West in the East is more or less parallel to the axis of the basin, whereas the N-S correlation from I West to H West (figs. 11 and 12) follows the depositional dip of the basin.

4.3.1. W-E cross section (figs. 9 and 10)

The thicknesses of all units are relatively uniform, except in the “Baltringer” and the “Basisschichten” which increase to the east. In the same direction, a slight increase in the sand content is shown in the “Feinsandserie”, the “Baltringer Schichten” and the Untere Süßwasser Molasse, whereas it decreases in the same direction in the “Basisschichten” and the “Sandmergelserie I”. The maxima of thickness and sand content of the “Sandmergelserie II” are found in D West.

4.3.2. N-S cross section (figs. 11 and 12)

As in the W-E cross section, the total thicknes of the individual units remains relatively uniform with the exception of the “Baltringer Schichten”, the “Sandmergelserie II” and the “Basisschichten”, which increase in thickness towards the south.

The sand content in the “Feinsandserie” decreases towards the centre of the cross section and to the south in the “Basisschichten” and the “Untere Süßwasser

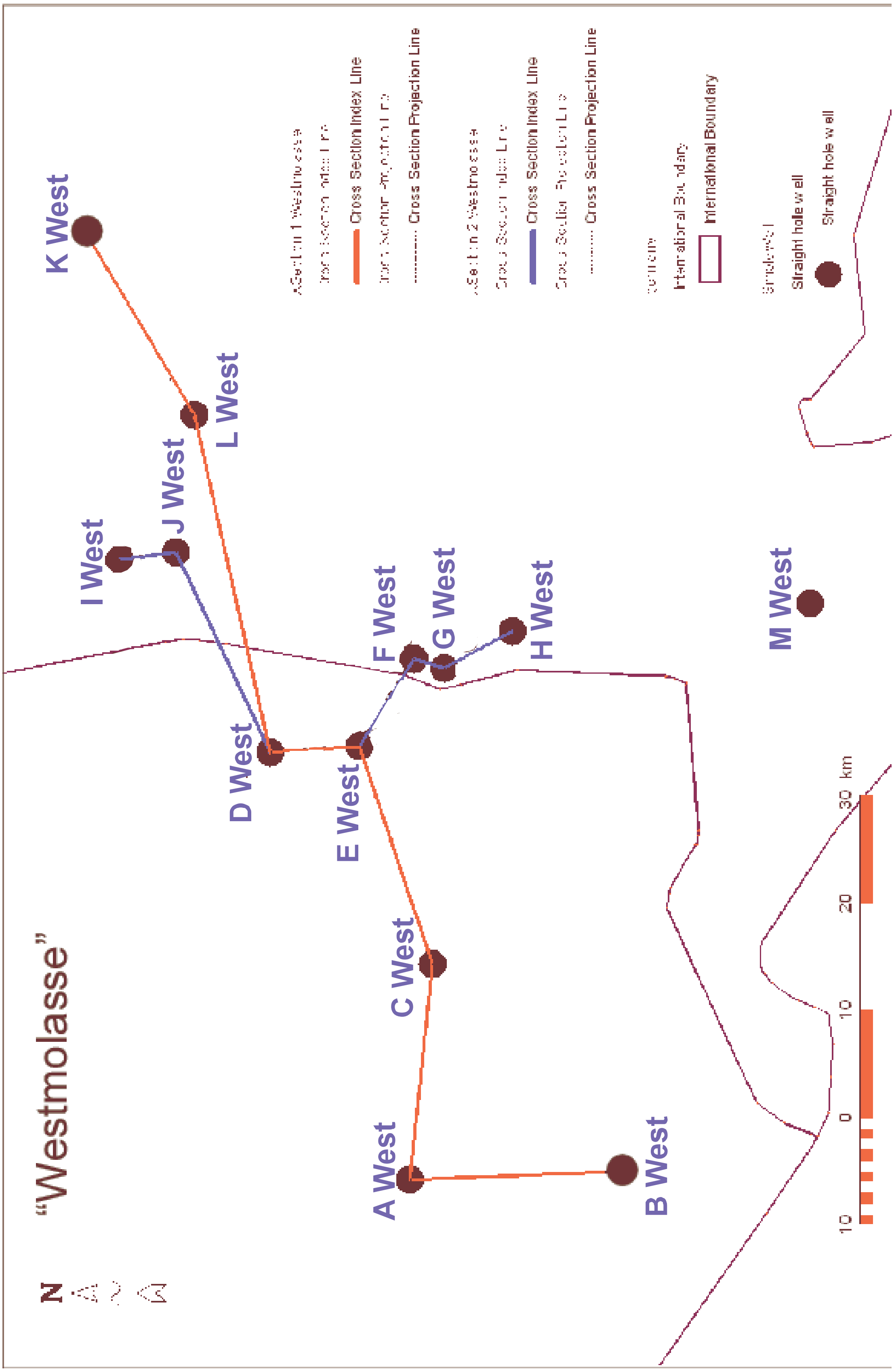


Figure 8. "Westmolasse" – location of cross sections 1 and 2.

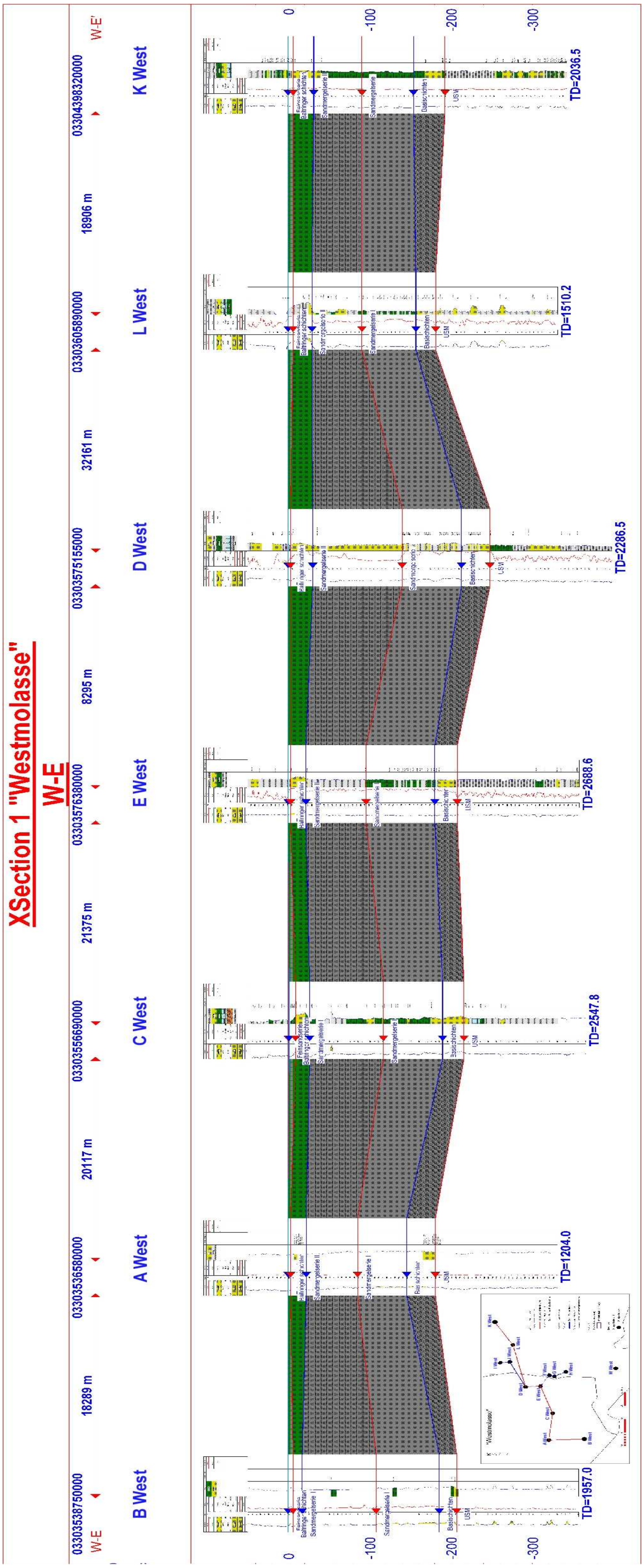


Figure 9. "Westmolasse" –W-E cross section 1, correlation based on SP and resistivity logs.

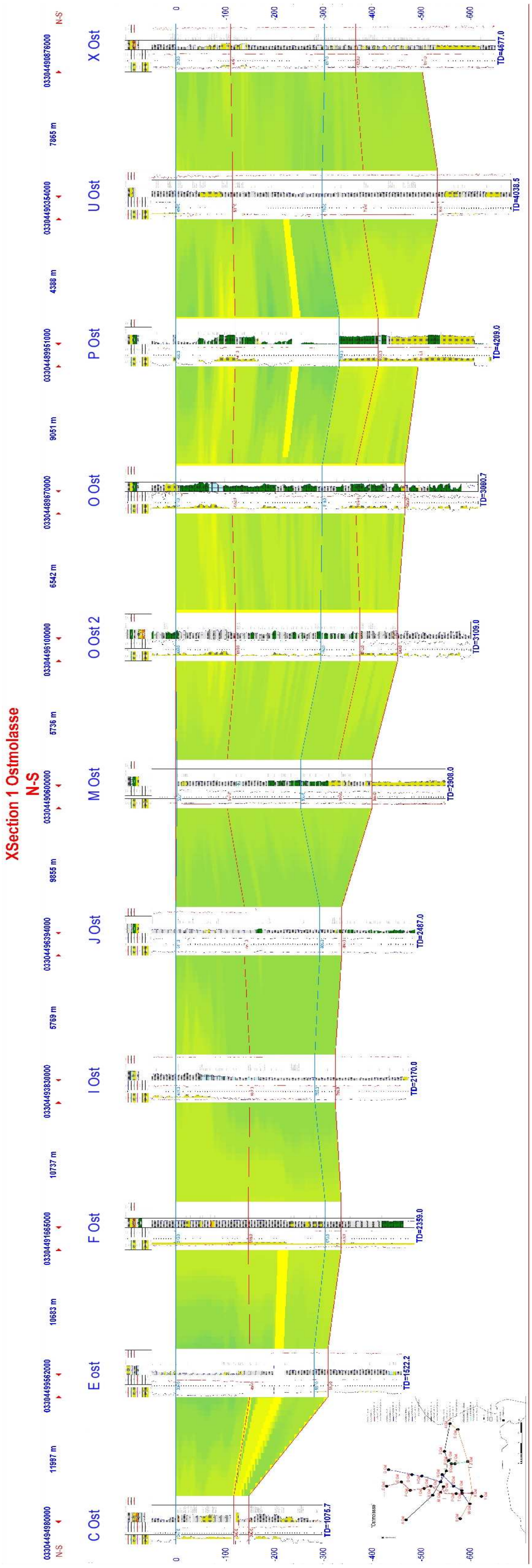


Fig.10. "Westmolasse" - W-E cross section 1, correlation based on SP log.

Molasse”, whereas that of the “Sandmergel II” increases in the same direction. In the other units, the sand content shows only minor changes.

4.4. Seismic stratigraphy

4.4.1. Seismic sequence boundaries

The log patterns of the studied wells have been integrated with the seismic lines with the help of the Geographix ™ program. The analysis of the seismic lines and the well data allow the identification of the five seismic sequence boundaries recognized in the area of the Ostmolasse (Jin 1995, Zweigel 1998):

- SB1: at the base of the Tertiary
- SB2: at the base of the “Baustein Schichten”,
- SB3: at the base of the “Upper Chattian Marls” and their western equivalents in the Lower Freshwater Molasse.,
- SB4: at the base of the “Aquitanian” part of the “Lower Freshwater Molasse”, and
- SB5: at the base of the “Upper Freshwater Molasse”.

4.4.2. Seismic Sequences

In this study, I have analyzed the sequence SB4, which includes the uppermost part of the “Untere Süßwasser Molasse” and the Upper Marine Molasse (Eggenburgian and Ottnangian, early Miocene). In the Westmolasse, this sequence is subdivided in the following way:

a) Subsequence 4a: “Untere Süßwasser Molasse” (upper part)
b) Subsequence 4b: “Basisschichten”
c) Subsequence 4c.1: “Sandmergelserie I”
d) Subsequence 4c.2: “Sandmergelserie II”
e) Subsequence 4d: “Baltringer Schichten”
f) Subsequence 4e: “Feinsandserie”

The only seismic reflection line available from the Westmolassse is the NW-SE running Line A (see Fig. 13). It is of rather poor quality and the depositional patterns within the different units could not be recognized clearly. The “Feinsandserie” could not be recognized. The log of A West has been integrated with the aid of the Geographix program. The different units – with the exception of the “Feinsandserie” – are recognized based on differences in the reflectors and the correlation with F West 2. In this line, all sequences dip towards NW.

4.4.2.1. Subsequence 4a – “Untere Süßwasser Molasse” (upper part)

Towards the top of this sequence of uniform thickness the reflectors tend to become parallel. At its base, a group of reflectors are onlapping towards NW on the top of the underlying sequence. Toplap towards NE is observed in some places.

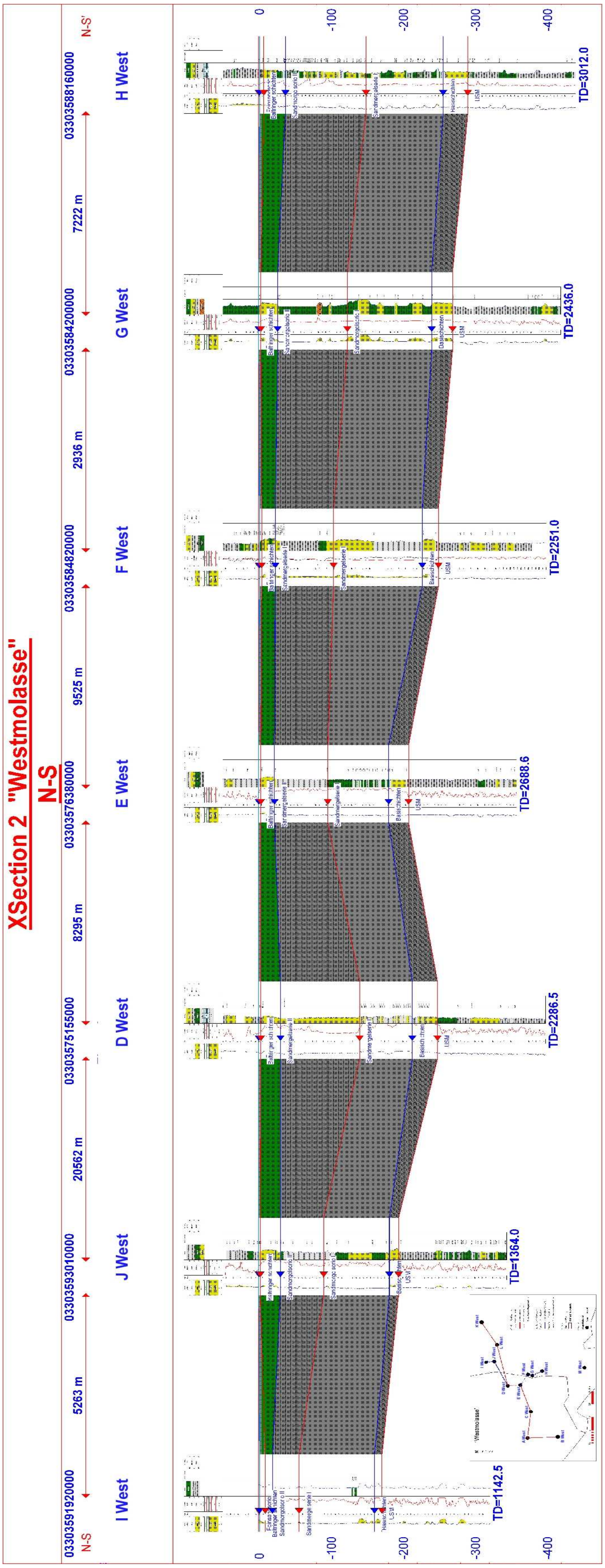


Figure 11. "Westmolasse" – N-S cross section, correlation based on SP and resistivity logs.

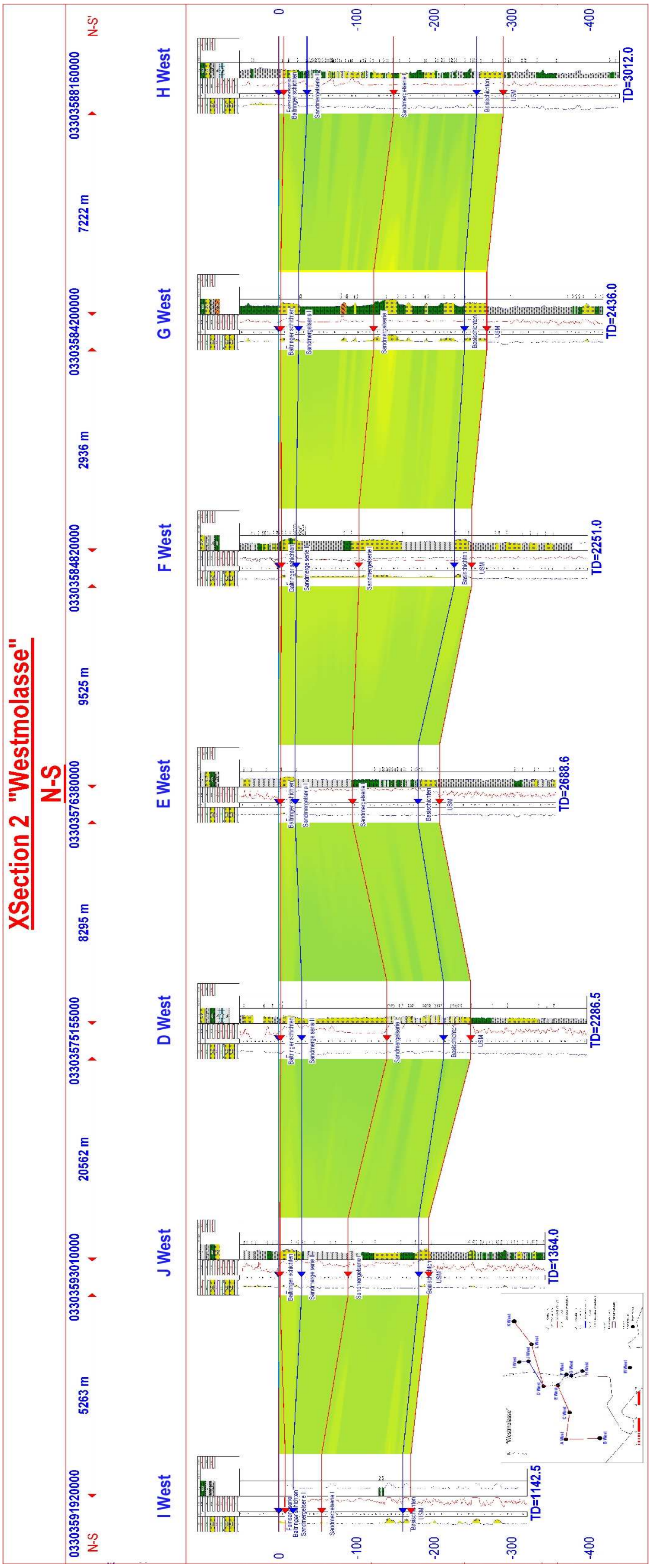


Figure 12. “Westmolasse” – N-S cross section, correlation based on SP logs.

4.4.2.2. Subsequence 4b - "Basisschichten"

The considerable thickness of this sequence remains more or less the same throughout the entire line. Towards the top, erosional channels and toplap in both directions may be present, but their resolution is rather poor. The base shows some onlap patterns in NW direction.

4.4.2.3. Subsequence 4c.1 - "Sandmergelserie I"

This subsequence has a very uniform thickness and predominantly parallel reflectors. At its base, onlap towards NW and some toplap towards SE are observed.

4.4.2.4. Subsequence 4c.2 - "Sandmergelserie II"

This sequence is very thick. Its volume decreases slightly towards NW.

The base is marked by many onlap groups with NW direction. Some toplap in both directions are observed.

4.4.2.5. Subsequence 4d - "Baltringer Schichten"

At its base, onlaps in NW direction are observed. The top displays some channels and toplap in SE direction.

4.4.2.6. Subsequence 4e - "Feinsandserie"

This unit could not be recognized.

4.5. Depositional Environments

4.5.1. Subsequence 4a – « Untere Süßwasser Molasse »

In the upper part of the Lower Freshwater Molasse (USM), the input of sandstones into the multicoloured and nearly barren pelitic deposits increases. Probable these sandstones have been deposited in channels of a meandering river system of a slowly submerging flood plain (Lemcke 1973).

4.5.2. Subsequence 4b - "Basisschichten"

A package of fine to medium-grained sandstones with intercalations marls and siltstone at the base of this transgressive unit displays hummocky stratification patterns. The top consists of coarse-grained sandstones to gravels with abundant glauconite. The base of this transgressive unit is composed by fine to middle-grained sandstones with intercalated calcareous silts and marls with some feldspars. Some of the reflectors display hummocky stratification. The large amount of marine organisms (abraded fragments of bivalve shells, shark teeth) and the sedimentary structures and textures indicate deposition in a marine nearshore high-energy environment (e.g. Homewood 1981).

4.5.3. Subsequences 4c.1 - "Sandmergelserie I" and 4c.2 - "Sandmergelserie II"

The marine "Burdigalian" (of Zweigel, 1998) is subdivided into the two cycles: the thick and more pelitic "Sandmergelserie I and II" (Ottnangian) and the glauconitic coarser-grained "Baltringer Schichten" (Ottnangian). Both cycles start with an increase in grain-size which in the West may reach gravels of fist-size in the younger cycle (Lemcke et al. 1953).

The "Sandmergelserie I" consists mainly of marly fine- to coarse-grained fine to medium-grained sandstones with occasional coarser intercalations and coaly debris. The typical "Sandmergelserie II" includes predominantly grey claystones, sandy marls and siltstones and sand flasers. In some layers, coaly debris are observed.

As already indicated by Lemcke et al. (1953), the "Sandmergelserie" has been deposited in greater water-depths (probably subtidal, e.g. Bieg 2005) than the other units of the Upper Marine Molasse.

4.5.4. Subsequence 4d - "Baltringer Schichten"

The coarse sandstones at the base of Subsequence 4d mark the onset of the second depositional cycle of the Upper Marine Molasse. Locally, they contain pebbles of alpine origin. Characteristic of the Baltringer Schichten is a 0.3 to 2.5 m thick bed composed by coarse fragments of molluscs. The generally 10m thick coarse sandstones contain layers in which the components may reach gravel-size. The rather rapid transition to the overlying Feinsandserie is gradual and contains no marine fossils. The "Baltringer Schichten" have been deposited in a high-energy near-shore to shore environment.

4.5.5. Subsequence 4e - "Feinsandserie"

The thickness of the green-grey siltstones and fine-grained sandstones with variable mica content of the Feinsandserie is very variable. In a few wells, intercalations of up to 2-3m of grey to green-grey sandy calcareous marls are described. Thin beds of glauconitic and calcareous fine to dust-size sands alternate with clayey and argillaceous ones (Lemcke et al. 1953). They may correspond to sediments deposited in shallow ponds and lagoons.

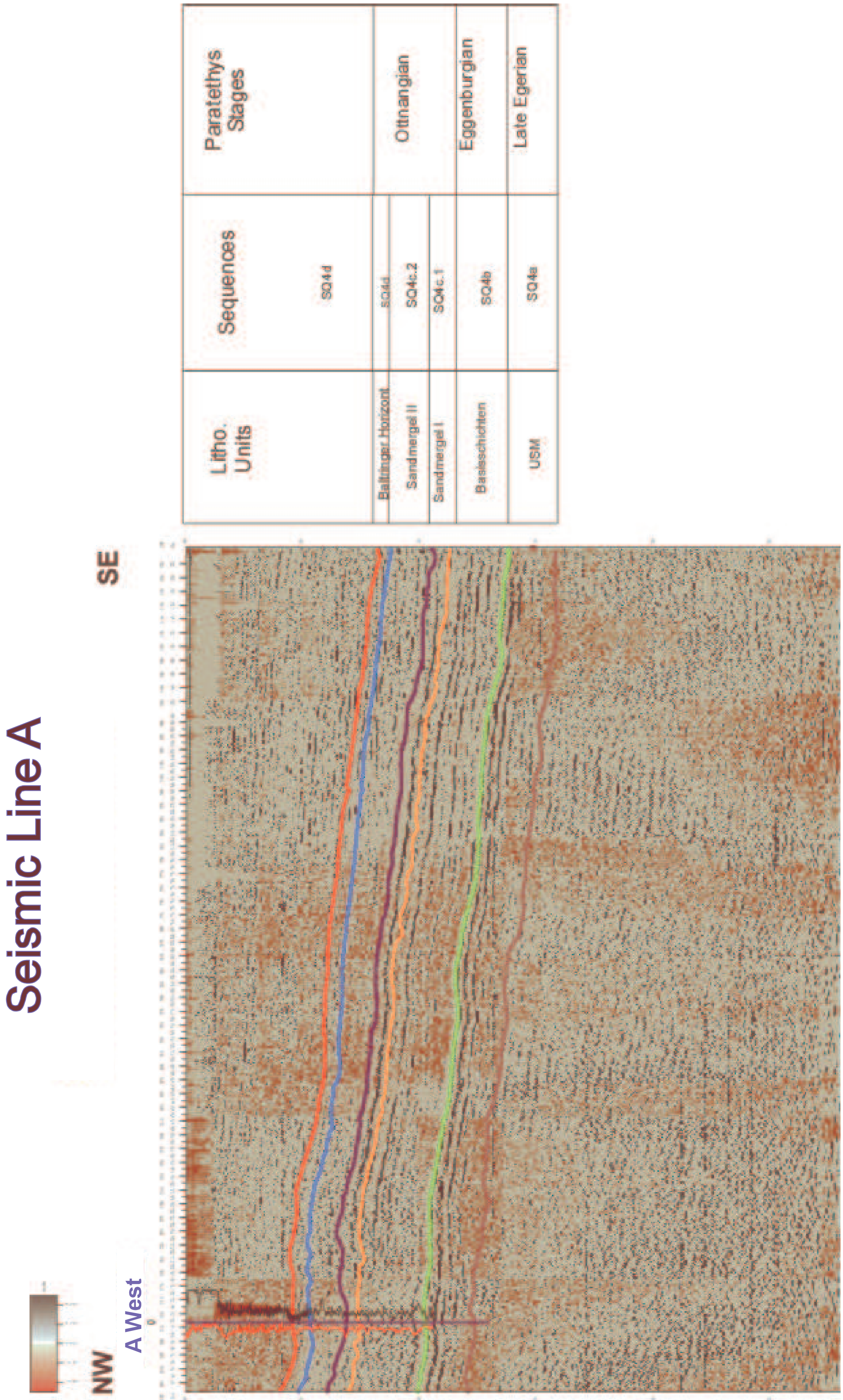


Figure 13. "Westmolasse" – seismic line A.

5. Seismic Stratigraphic Interpretation of the OMM in the "Ostmolasse"

5.1. Western Part of the "Ostmolasse"

5.1.1. Introduction

Thirty-one wells and eight seismic lines were available in the area between the region of Munich and the Inn River corresponding to the so-called "Ostmolasse" (see Figs. 14 and 15). A N-S and a W-E regional composite seismic section have been constructed and a number of wells on or close to these regional seismic lines have been selected as constraints for the interpretation (Figs. from 25 to 31 and 34 to 47). As in the "Westmolasse", the quality of the available data varies considerably from older to younger wells and seismic lines, but in part also between different companies. As in the "Westmolasse" the log patterns of the studied wells were integrated into different seismic lines with Geographix ™.

The typical well log characteristics of the lithological units are shown on Figs. 17 to 24 and 32 to 33. The SP, Resistivity and the Sonic logs were chosen because they were available in most wells.

5.1.2. Lithostratigraphy (see Table 2 and fig. 5)

5.1.2.1. "Aquitaine Fish Shales"

In the eastern part of the area, the uppermost Aquitanian is formed by the "Aquitaine Fish Shales" (thickness: 0-120 m). They are characterised by extremely low resistivity values. The SP log shows high content of shale and an increase of the grain size towards the top. The low values observed in the GR log at the base are possibly due to a decrease in the sand content. The sonic log shows a pattern of moderate values and strong peaks indicating packages of sand and shale. Towards the base, the sand content diminishes as indicated by the low values of the curve. Some peaks in the sandstones may be interpreted as possible presence of calcareous components in the sandstones. In general, the values are moderate as characteristic of packages of sands and shales. Towards the base, the velocity values decrease; this could mean the absence of sands.

The "Aquitaine Fish Shales" have been deposited in a quiet oxygen-deficient marine environment.

5.1.2.2. "Burdigal"

The thickness of this unit varies from 2 m in G Ost 2 to 857 m in 5 Ost**.**

The rather monotonous log response with abundant small peaks of the "Burdigal" is typical of a uniform sandy and marly succession. On the resistivity log moderate to

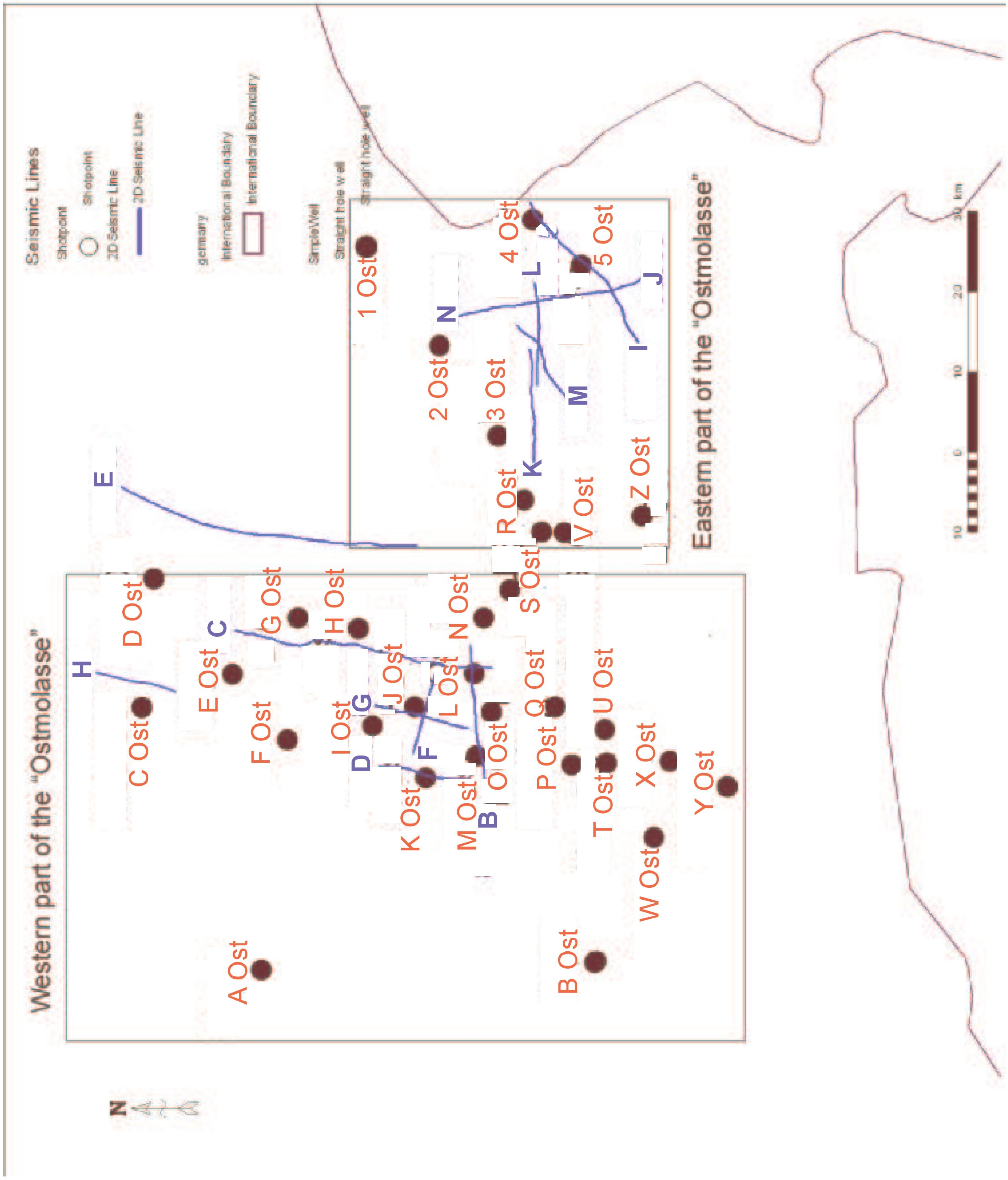


Figure 14. Location and studied area of the „Ostmolasse".

Lithological Unit	Description	Fossils	Interpretation
Glaukonit + Blättermergel (Ottnangian)	Both units consist of gray claystones and marls with gradations into gray sandy marls, fine to coarse glauconitic sandstones and some limestone beds. Thickness: 90 to 190m.	Bivalves (among others Cardium, Pecten), gas-tropods, balanids, wood fragments, lignitic and coaly debris and a shallow-marine micro-fauna with: Elphidium crispum, Nonion sp., Cibicides dutemplei, Robulus Inornatus, Rotalia beccarii, and Spiroplectammina pectinata.	Shallow-marine environment with a shallowing upward trend.
Neuhofener Schichten II (Ottnangian)	Gray claystones which may grade into sandy marls and into marly sandstones and a few intercalations of light gray cal-careous marl and limestone. Thickness: 30-205m.	Robulus inornatus, Cibicides dutemplei, Sigmoilina asperula, Nonion soldanii, N.commune, Spiroplectammina sp., Rotalia beccarii).	Shallow-marine environment
Neuhofener Schichten I (Ottnangian)	Gray claystone, gradding into sandy marl; light gray sandy marl, with gradation into marly sandstone, fine gravel debris and fine to coarse sandstone, calcareous. Thickness: 5-135 m.	Benthonic foraminiferal fauna with Lenticulina, Cibicides dutemplei, Pullenia bulloides and Bulimina sp.; planktonic foraminifera; shell and snail debris; Robulus inornatus, Sigmoilina spiroplectammi-na tenuis, ostracode, Cibicides dutemplei and Nonion sp.	Shallow-marine environment
Burdigal (Eggenburgian)	Green-gray fine-medium grained sand-stones, siltstones, and marls with interca-lations of claystone, limestones and coarser sandstone to gravels with variable glauco-nite content. Thickness: 2-857 m.	Rotalia beccarii, Cibicides dutemplei, Elphidium crispum, Uvigerina semiornata, Robulus inornatus.	Shallow-marine to intertidal depositional environment.
Obing Folge (Eggenburgian)	Gray sandy claystones, in places grading into sandstones and with intercalations of sandy marls and limestones. Thickness: 110m to 270m.	Shell debris and Aquitanian microfauna	Deeper marine, turbiditic.
Aquitanian Fish Shales (uppermost Egerian)	Gray clay and marly siltstones which grade into sandy marls, fine to medium-grained sandstones, occasionally coarse sand-stones, including some layers with fine gravels. Thickness: 0-120m.	Robulus inornatus, Uvigerina urnula, Cibicides dutemplei, C.inornatus, Chilostomella czjzeki, Bulimina ovata, B. elongata, Rotalia beccarii, Nonion commune, Sphaeroidina bulloides, Cyclammina gracilis, globigerinids, fish scales and teeth, fragments of bivalves and gastropod as well as a few debris of brown coal.	Quiet oxygen-deficient marine environment.

Table 2. Lithological units of the "Ostmolasse" – lithology and environmental interpretation.

high values with some sharp peaks due to alternating packages of sandstones and shales are observed.

The SP log indicates an increase in grain-size towards the base. The GR log displays moderate to high values with some peaks in layers with increased shale content, whereas some not very pronounced lower than average values could indicate a slight increase in sand. Some low values at the base of the unit are probably due to the increased presence of sands. The sonic log shows moderate to low values with very few peaks. The values are moderate in the more sandy intervals and low in the more shaly ones. In N Ost, the uppermost part of the "Burdigal" is marked by strong peaks of high and low values caused by the pronounced alternation of sand and shale layers. The caliper curve shows a lot of peaks, but the number of the ones pointing to the right side indicates a smaller number of shale and clay layers than in the Aquitaine Fish Shales.

In the southern part of the area, conglomeratic beds are found at the base and at the top of the "Burdigal". Probably, they are part of fan deltas which built out from the Alpine front during the "Burdigalian Transgression" (e.g. Lemcke 1988), whereas in the axial area a shallow sea with strong tidal influence existed (Zweigel 1998, Bieg 2005).

These "Helvetian" strata of older authors are subdivided into the "Neuhofener Schichten I and II" (defined by Zweigel as sequence SQ4b in her regional analysis (1998)), the "Blättermergel" and the "Glaukonitsande".

5.1.2.3. "Neuhofener Schichten I"

The electrical log is characterized by moderate to high values with strong peaks. It differentiates this unit from the "Neuhofener Schichten II" and the "Burdigal" strata. On the SP log, a characteristic grain-size decrease towards the base is observed. The GR log shows moderate values with some peaks, indicating shale content in this unit. Toward the base low values can be observed due to the increase of sand. The sonic curve presents moderate to high values due to the increased presence of sand. Strong peaks at the base are caused by the presence of sand beds.

5.1.2.4. "Neuhofener Schichten II"

The "Neuhofener Schichten II" are grey claystones which may grade into sandy marls and into marly sandstones, in addition to a few intercalations of light grey calcareous marl and limestone. The thickness of this unit varies between 30m and 205 m. They contain contain shells and fragments of bivalves and gastropods, of coal and lignite and a shallow-marine microfauna (*Robulus inornatus*, *Cibicides dutemplei*, *Sigmoilina asperula, Nonion soldanii*, *N.commune*, *Spiroplectammina* sp., *Rotalia beccarii*).

On the resistivity log, moderate to low values with strong peaks, which are strongest in the well W Ost are observed. The SP pattern is not well defined, except a possible increase in grain-size towards the base. The GR log shows moderate values and greater shale content than in the underlying unit. Some shallow peaks towards the base and the top indicate an increase in sand content. On the sonic log, moderate to high values with some strong peaks towards the base are observed. They probably indicate the predominance of shales with some intercalations of sands. In the middle part of the unit, some conspicuous peaks may correspond to layers richer in carbonates in the shale packages. The absence of peaks in the caliper log towards the top and the base of the unit is due to the presence of massive sands. In its middle part, thick layers of sandy marls cause an accumulation of peaks towards the right.

5.1.2.5. "Glaukonitsande" and "Blättermergel"

These two units are discussed together because their lithology and other characteristics are very similar. Both units consist of grey claystones and marls with gradations into grey sandy marls, fine to coarse glauconitic sandstones and some limestone beds. Their thickness varies from 90 to 190m.

On the resistivity log, moderate to high values with blocky intervals as well as pronounced and characteristic peaks are observed. On the SP log, a thick intercalation of shales and sand with an increase in grain-size is present towards the top. On the GR log, strong peaks of low values towards the top are probably due to the alternation of shales with sands, whereas the high values towards the base indicate the predominance of shales. The sonic log shows moderate values, with strong peaks of high and low values caused by the intercalations of shales and sands. The sand content increases slighly to the south. The caliper response shows strong peaks to the right and to the left caused by the pronounced intercalation of clays and marls. At the base, a prominent sand layer causes a distinct peak to the right.

The "Glaukonitsande and Blättermergel" contain bivalves (among others *Cardium*, *Pecten*), gastropods, balanids, wood fragments, lignitic and coaly debris and a shallow-marine microfauna with: *Elphidium crispum*, *Nonion* sp., *Cibicides dutemplei*, *Robulus inornatus*, *Rotalia beccarii*, and *Spiroplectammina pectinata*.

The presence of a "kümmerfauna" indicates a restricted shallow-marine environment with a shallowing upward trend.

5.1.3. Correlations by wireline logs

Representative W-E and N-S cross sections (Fig. 15) based on electrical, SP, GR, Sonic and Caliper logs are shown on Figs. 16 to 23.

In the cross sections 20, 21, 22 and 23, the western and the eastern part of the Ostmolasse are correlated in order to document the changes in thickness and lithology. The subdivisions of the Burdigalian are most clearly seen in the Puchkirchen area of the eastern Ostmolasse.

5.1.3.1. N-S cross section 1 (figs. 16 and 17)

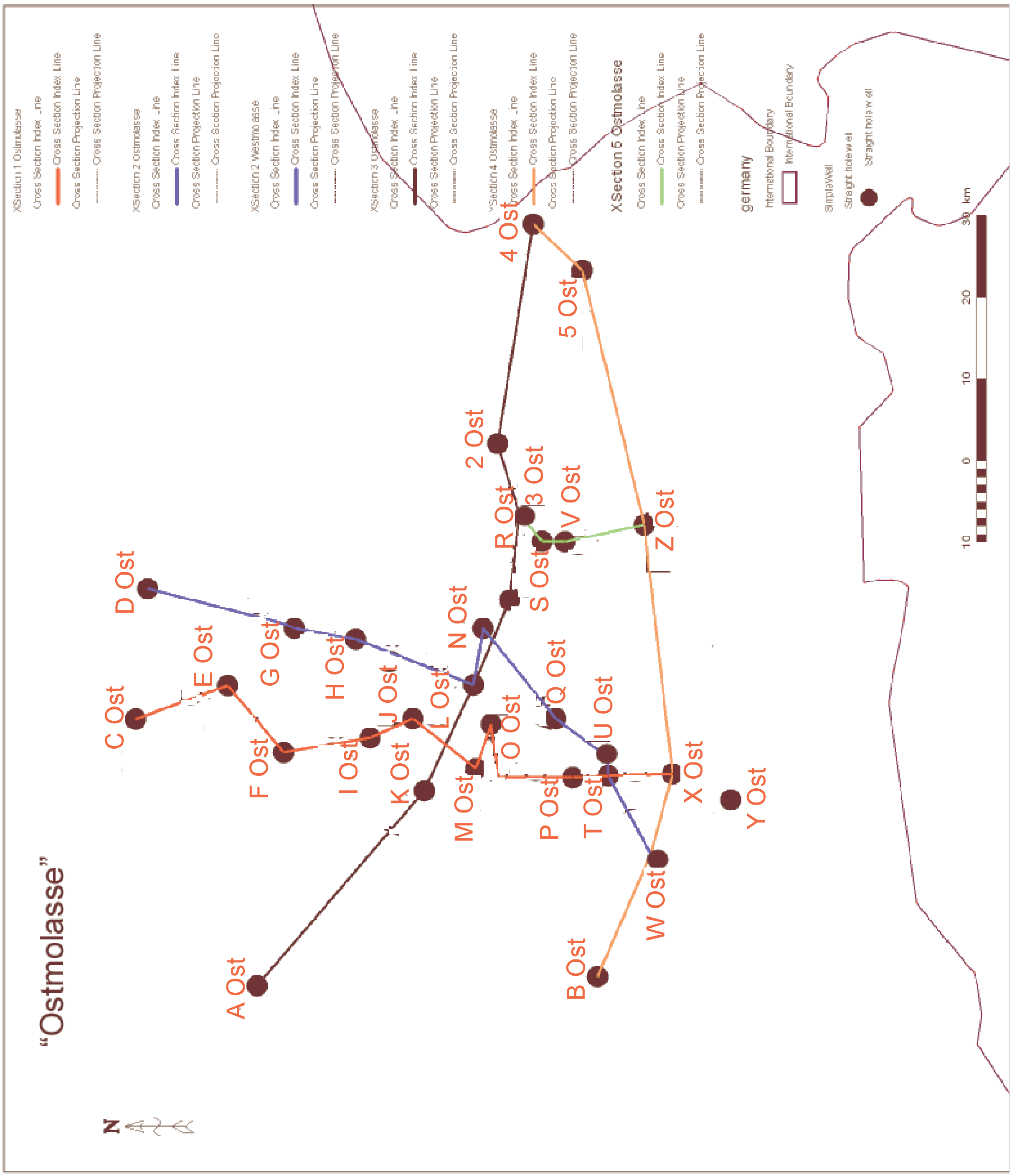


Figure 15. Location of the cross section of the western and eastern part of the "Ostmolasse"

All units increase in thickness towards the south, except the "Glaukonitsande" and the "Blättermergel" which have a relatively uniform thickness. A pronounced angular unconformity is developed between the "Aquitanian Fish Shales" and the "Burdigal". The "Burdigal" and the "Neuhofener Schichten I" disappear towards the North.

The "Neuhofener Schichten I" and the "Burdigalian" both display progressive northward onlap. The "Burdigalian" pinches out at M Ost. The "Neuhofener Schichten II" are thinning towards the north; the "Glaukonitsande" and "Blättermergel" have a relatively uniform thickness and the "Neuhofener Schichten I" and the "Burdigal" are onlapping progressively towards the north.

The "Burdigal" pinches out at M Ost, the unit "Neuhofener Schichten I" at E Ost.

The sand content increases in all units towards the south.

5.1.3.2. N-S cross section 2 (figs. 18 and 19)

This cross section runs eastward of the N-S cross section 1 and is more or less parallel to it. It shows the same southward increase in thickness of all units as cross section 1. The thicknesses of the "Neuhofener Schichten I", the "Neuhofener Schichten II", the "Glaukonitsande" and the "Blättermergel" are relatively moderate. The angular unconformity between the Aquitaine Fish Shales and the "Burdigal" is well developed.

The "Burdigal" pinches out at H Ost 2. The sand content increases in all units from the north towards the center of the line (N Ost, Q Ost) and then diminishes again towards the south.

5.1.3.3. W-E cross section 1 (figs. 20 and 21)

The changes in the thickness of the different units are related to the direction of the cross section which has a NNW-SSE direction and to shifts in the axis of the basin.

The "Burdigal" and the Neuhofener Schichten I show a progressive westward onlap onto the Aquitaine Fish Shales.

The "Burdigal" is increasing substantially its thickness towards the east. The thicknesses of the "Glaukonitsande" and "Blättermergel", the "Neuhofener Schichten II" and the "Neuhofener Schichten I" are relatively stable.

The following units pinch out towards west: the "Neuhofener Schichten I" at K Ost and the "Burdigal" at L Ost.

In all units, the sand content increases moderately towards the east.

5.1.3.4. W-E cross section 2 (figs. 22 and 23):

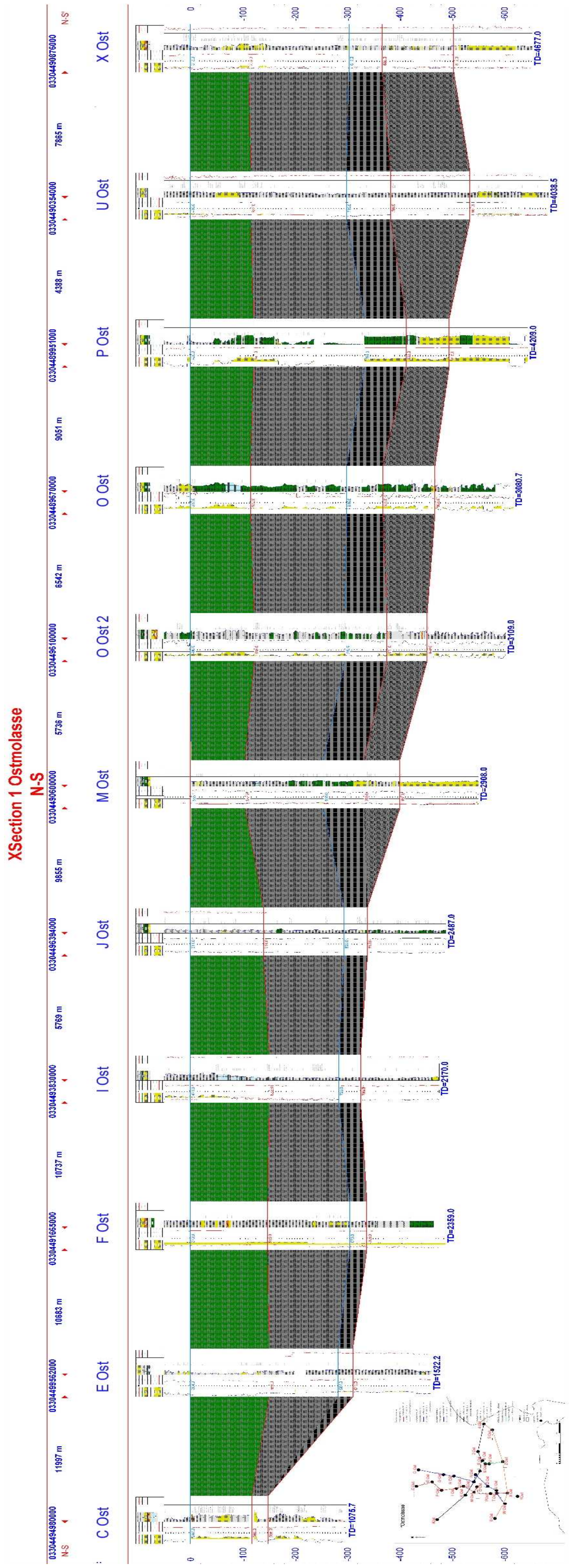


Figure 16. Lithostratigraphic correlation of wells based on, SP, Resistivity, Sonic and Density logs.

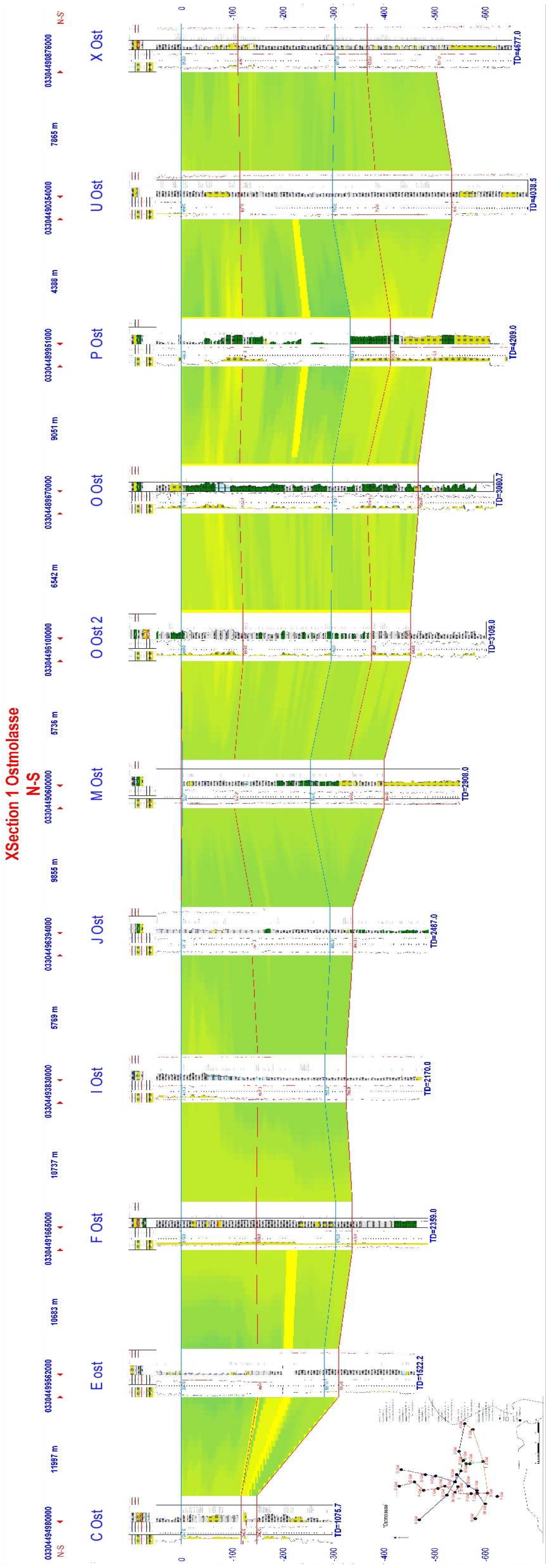


Figure 17. Lithostratigraphic correlation of wells based on SP logs.

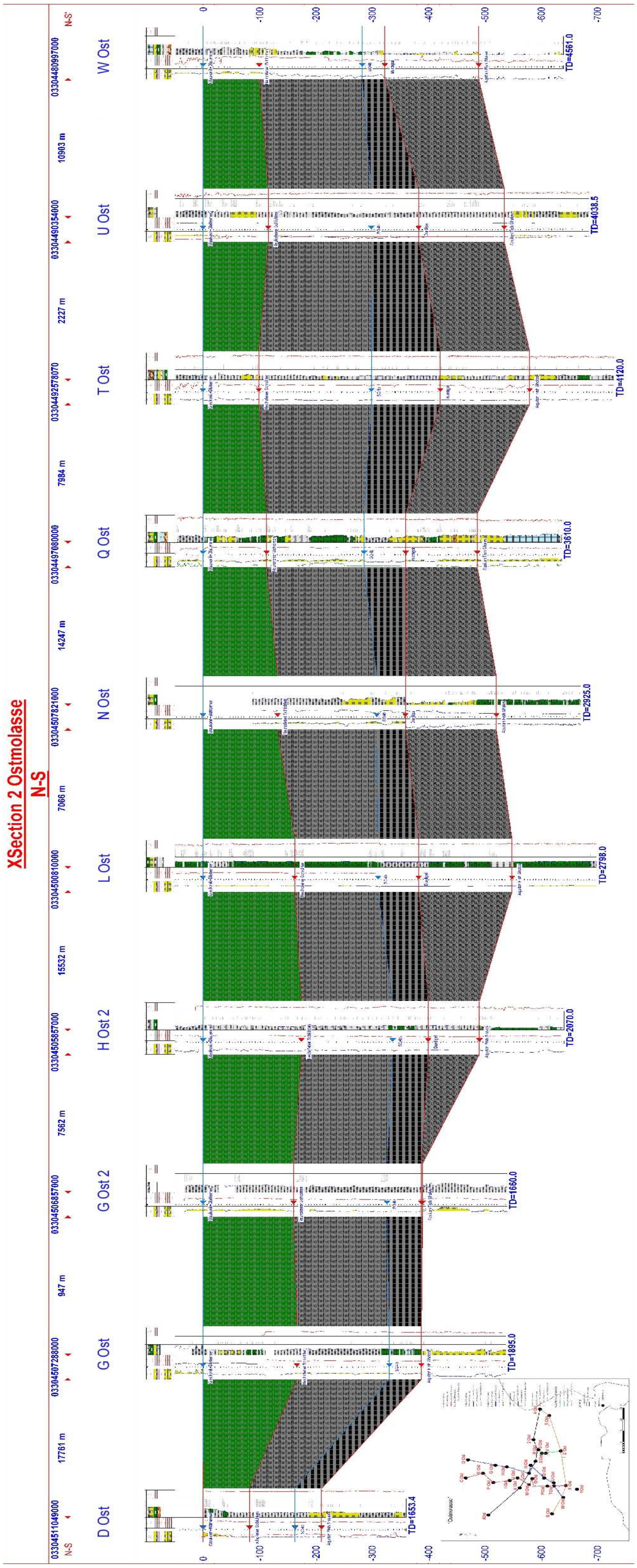


Figure 18. Lithostratigraphic correlation of wells based on SP, Resistivity, Sonic and Density logs.

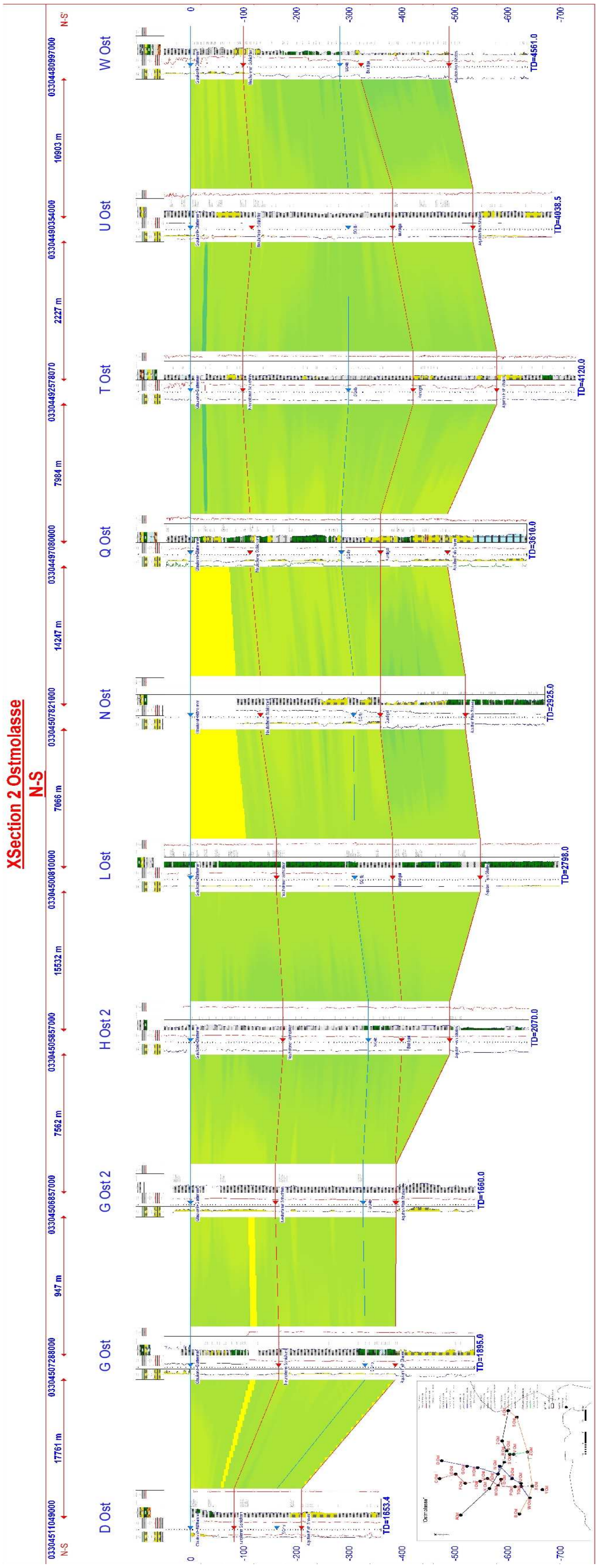


Figure 19. Lithostratigraphic correlation based on SP logs.

All units increase in thickness towards the south, except the "Glaukonitsande" and the "Blättermergel" which have a relatively uniform thickness. A pronounced angular unconformity is developed between the "Aquitanian Fish Shales" and the "Burdigal". The "Burdigal" and the "Neuhofener Schichten I" disappear towards the North.

The "Burdigal" shows again a progressive westward onlap onto the "Aquitaine Fish Shales".

In the "Glaukonitsande" and "Blättermergel" and the "Neuhofener Schichten I", the sand content remains relatively constant, whereas it increases slightly towards the east in the "Neuhofener Schichten II", the "Burdigal" and "the Aquitaine Fish Shales".

5.1.4. Seismic Stratigraphy

The boundary between the Lower Freshwater Molasse and the Upper Marine Molasse is marked by reflections that are associated with truncation and onlap, whereas the boundary between the Upper Marine Molasse and the Upper Freshwater Molasse is characterized by continuous high-amplitude reflections (e.g. Schlunegger et al., 1997).

5.1.4.1. Seismic facies

In this study, we have used the subdivision into the ten types of seismic facies recognized by Zweigel (1998) and extended it to all available seismic sections. I am mainly dealing with her seismic facies 6 to 8 which she described from the interval between the base of the Aquitaine Fish Shales and the base of Upper Freshwater Molasse.

These seismic facies are illustrated on figs. 24 to 30 together with their characteristic SP, resistivity, gamma ray and sonic logs. The corresponding lithofacies and depositional environments have been calibrated by well data.

The Seismic Facies 6 corresponds to the Aquitaine Fish Shales. According to Zweigel (1998), this seismic facies represents starved sedimentation. After the interval of submarine erosion during the late Egerian, a time of quiet sedimentation in relatively deep water followed. The observed hummocky to chaotic reflection patterns are probably related to slumping and re-sedimentation during infilling of the erosive paleorelief.

Where the base is not erosive, the "Aquitaine Fish Shales" are characterized by Seismic Facies 7 (Zweigel, 1998). The lithological character of the deposits is the same, but a smooth base inhibited slumping and thus the disturbance of the parallel bedding.

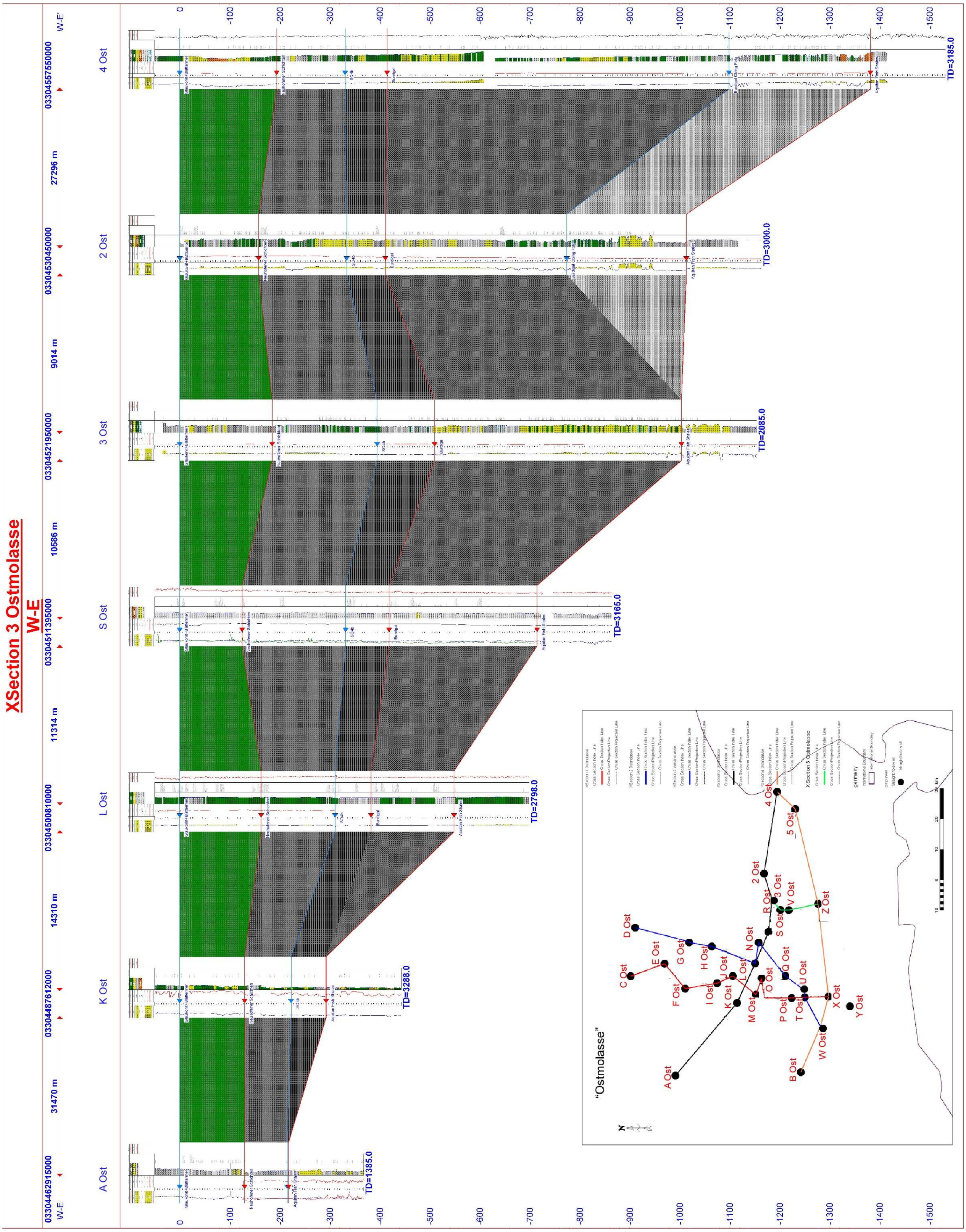


Figure 20. Lithostratigraphic correlation of wells based on SP, Resistivity, Sonic and Density logs.

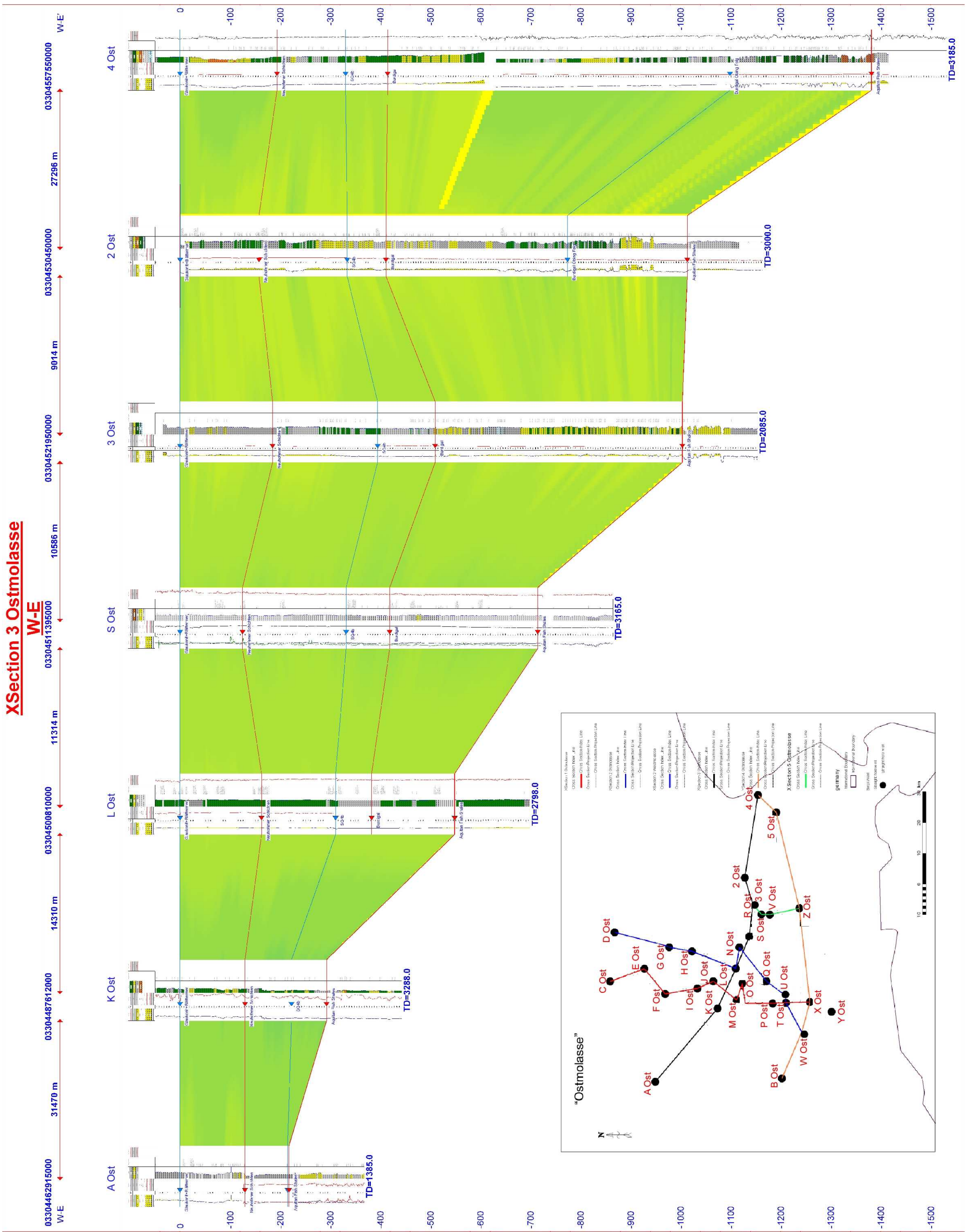


Figure 21. Lithostratigraphic correlation based on the well SP logs.

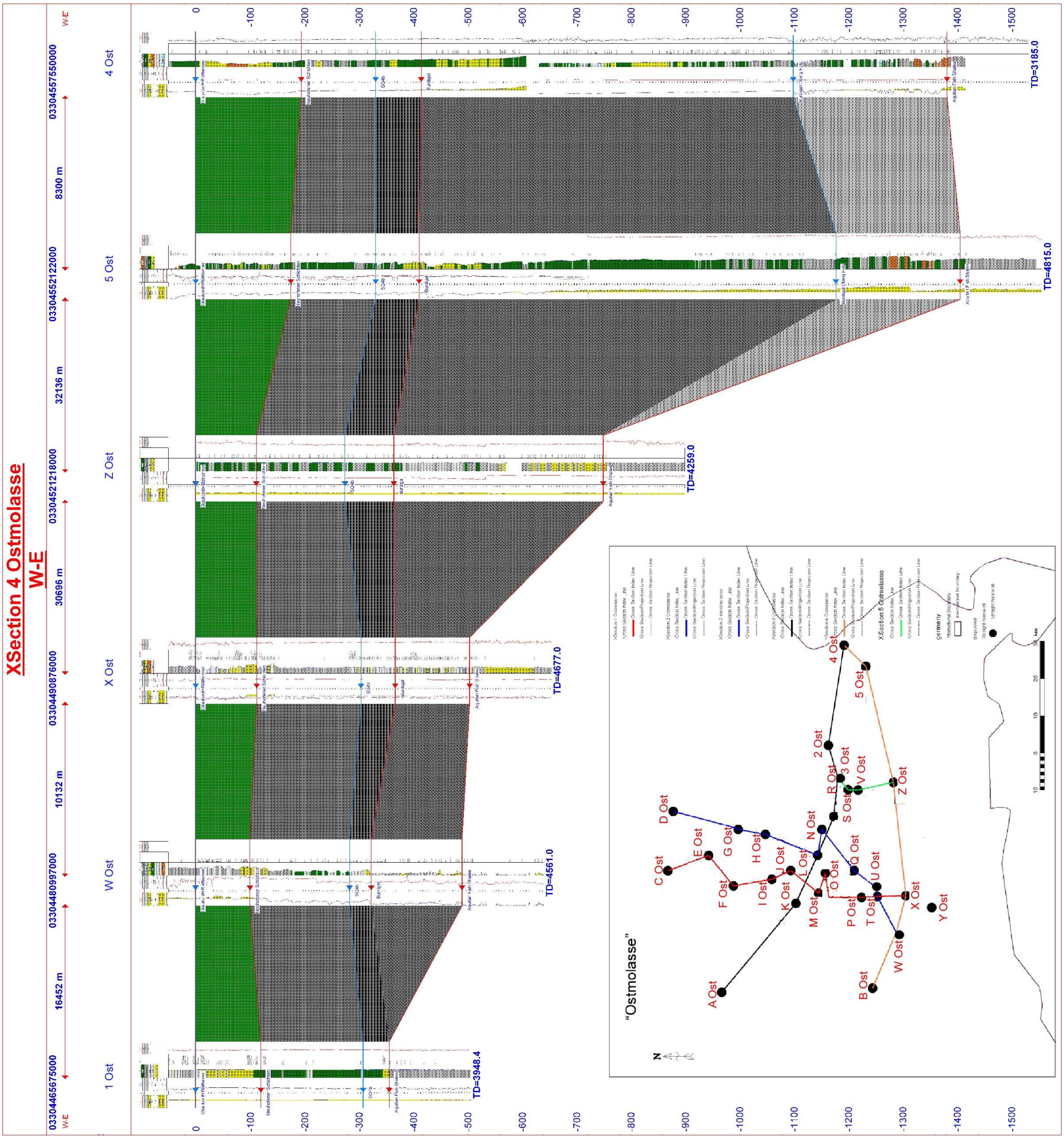


Figure 22. Lithostratigraphic correlation of wells based on SP, Resistivity, Sonic and Density logs.

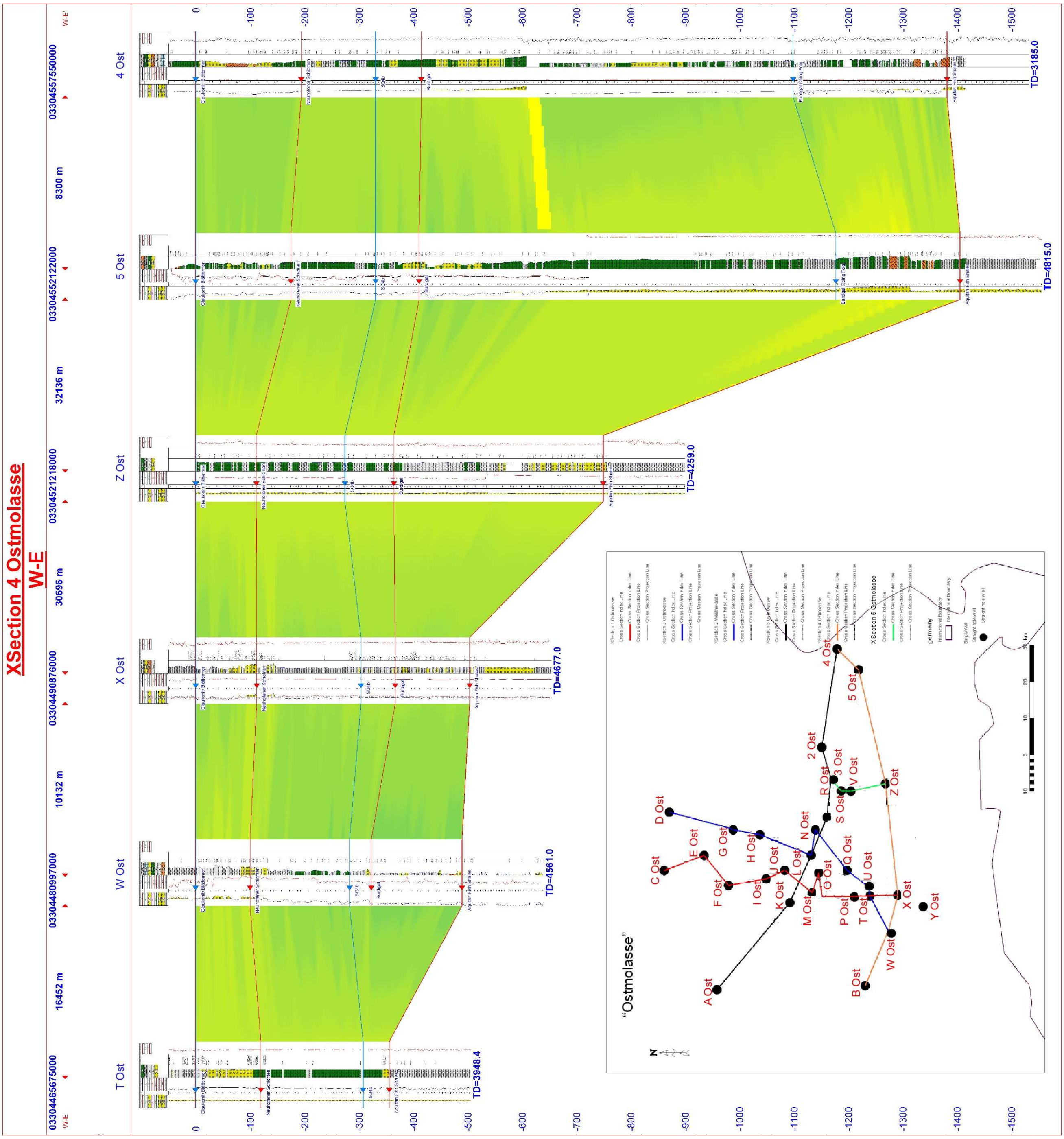


Figure 23. Lithostratigraphic correlation based on SP log for each well.

Seismic Facies 8 occupies the thick interval corresponding to Upper Marine Molasse up to the base of the "Upper Freshwater Molasse". This facies with its predominantly parallel reflectors is typical of an in generally well bedded shallow marine environment (Zweigel, 1998).

5.1.4.2. Seismic sequences

Based on the studies of Jin (1995) and Zweigel (1998) and the correlation of the seismic lines and the well date, the following five subsequence boundaries have been identified in the western part of the Ostmolasse:

- SB1: at the base of the Tertiary,
- SB2: at the base of the "Baustein Schichten" and their equivalents
- SB3: at the base of the "Upper Chattian Marls"
- SB4: at the base of the "Aquitanian Fish Shales"
- SB5: at the base of the Upper Freshwater Molasse.

I have studied and analyzed only Sequence 4 (SB4) which corresponds to the "classic" transgressive-regressive cycle of the Upper Marine Molasse. It is subdivided into the following subsequences:

Subsequence 4a: "Aquitaine Fish Shales"
Subsequence 4b: "Burdigal"
Subsequence 4c.1: "Neuhofener Schichten I" (defined by Zweigel as "SQ4b", 1998)
Subsequence 4c.2: "Neuhofener Schichten II"
Subsequences 4 d-e: "Glaukonitsande and Blättermergel"

The subdivision into the second order sequences is best seen in the eastern part of the study area (figs. 24 to 30). Below I will present a more detailed interpretation of individual lines and sequences.

5.1.4.3. Interpretation of seismic lines B (SW-NE) (fig. 24) and C (SE-NW) (fig. 25)

Subsequence 4a - "Aquitaine Fish Shales":

B: towards the top, the incision of channels and some toplap in opposite directions is observed. The base is marked by some SW directed onlaps and incised channels.

C: The "Aquitaine Fish Shales" increase their thickness towards the SE. The upper boundary of Subsequence 4a has some toplaps towards NW. They display onlap in S direction onto the Aquitaine Sand, the top of which is marked by deep erosive channels.

Subsequence 4b.2 - "Burdigal":

B: The thickness of this subsequence is uniform. The top and the base show intensive channeling. Some downlaps and toplaps in a NE direction are observed.

C: Subsequence 4b.2 onlaps towards the NW onto the "Aquitaine Fish Shales", which have an eroded surface cut by some channels. Some toplap with a SE direction is observed. The "Burdigal" increases slightly its thickness towards the SE.

Subsequence 4b.1 - "Neuhofener Schichten I":

B: sequence of uniform thickness which laps onto the "Burdigal". Towards its base, a NE directed channel is observed.

C: This subsequence decreases its thickness towards the SE. It laps onto the eroded surface of the "Burdigal". Some downlaps and onlaps to the SE are observed. Toplaps to the SE are frequent.

Subsequence 4c - "Neuhofener Schichten II":

B: Inspite of the parallel pattern of the reflectors, the thickness of this subsequence diminishes towards SW. Onlap and toplap are directed SW.

C: The subsequence onlaps onto the erosive top of "Neuhofener Schichten I". At the base, downlap and onlap to the SE, towards the top, erosive channels and toplap in the same direction are observed. The thickness of this subsequence is uniform.

Subsequences 4d-e - "Glaukonitsande" and "Blättermergel":

B: Subsequence of uniform thickness with onlap at the base and some toplap towards the NE. The reflectors of this subsequence are parallel.

C: The subsequence diminishes its thickness slightly towards the SE. Some toplap and basal onlap with a SE direction are observed.

5.1.4.4. Interpretation of seismic line D (SW-NE) (fig. 26)

Subsequence 4a - "Aquitaine Fish Shales":

Subsequence of rather uniform thickness which increases only slightly towards SW. Some basal onlaps towards SW and some toplaps towards NE and SW are observed.

Subsequence 4b.2 - "Burdigal":

The "Burdigal" increases slightly its thickness towards the SW. In this line, the reflectors are parallel. Some basal onlap towards NE and SW is observed. The toplaps are directed to NE. In the middle part of the subsequence, a group of internal onlaps towards SW occur.

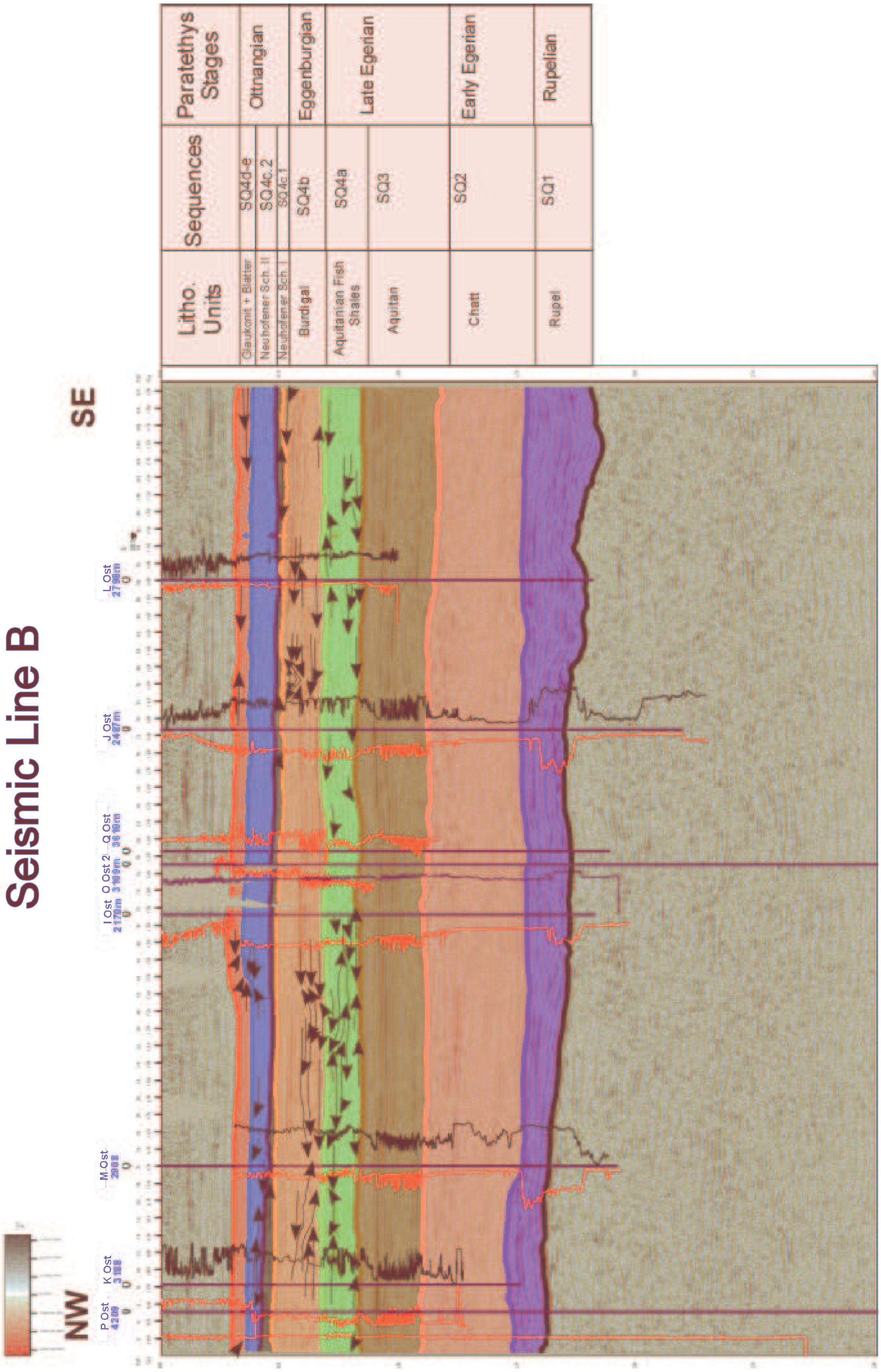


Figure 24. Seismic line B of the western part of the "Ostmolasse" area.

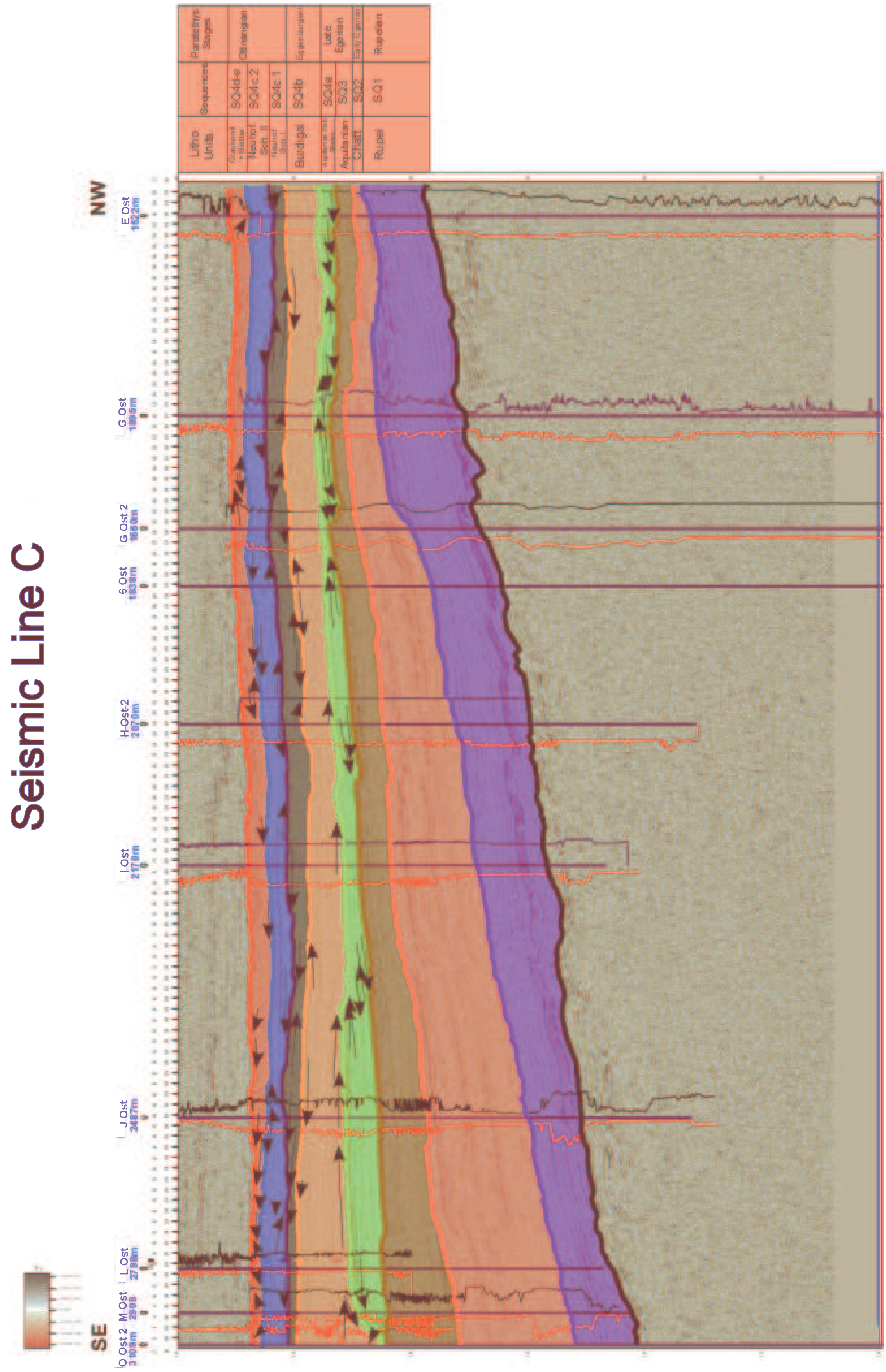


Figure 25. Seismic line C of the western part of the "Ostmolasse".

Subsequence 4b.1 - "Neuhofener Schichten I":

This sequence is of minor thickness with parallel reflectors. To the base some onlap towards the SW and toplap to the NE are observed.

Subsequences SQ4c-e - "Neuhofener Schichten II", „Glaukonitsande" and „Blättermergel":

All three subsequences present parallel reflectors and have uniform thicknesses throughout the entire line.

In the "Neuhofener Schichten II", basal onlap towards the SW and some toplap to the NE are observed.

In the Glaukonitsande" and "Blättermergel", basal onlap and toplap have a SW direction. The top is eroded by channels.

5.1.4.5. Interpretation of seismic line E (SW-NE) (fig. 27)

Subsequence 4a - "Aquitaine Fish Shales":

This subsequence increases slightly its thickness towards the South and laps onto the Aquitaine Sands. The base is marked by S directed onlap and some downlap. Towards the top, some erosive channels and toplap towards NE are observed.

Subsequence 4b.2 - "Burdigal":

The "Burdigal" Subsequence is of uniform thickness throughout the seismic line. The top displays erosive channels and toplap directed towards South. At the base, some onlaps towards the NE are present. In the middle part, some channels and internal downlap are observed.

Subsequence 4b.1 - "Neuhofener Schichten I":

The thickness is uniform. Towards the top some, channels and toplap with a southward direction are observed. At the base and in the middle part, downlap, channels and onlap in NE directions occur.

Subsequence 4c - "Neuhofener Schichten II":

This subsequence increases slightly its thickness towards the South. Some toplap, bidirectional downlap and onlap are observed.

Subsequences 4d-e - "Glaukonitsande" and "Blättermergel":

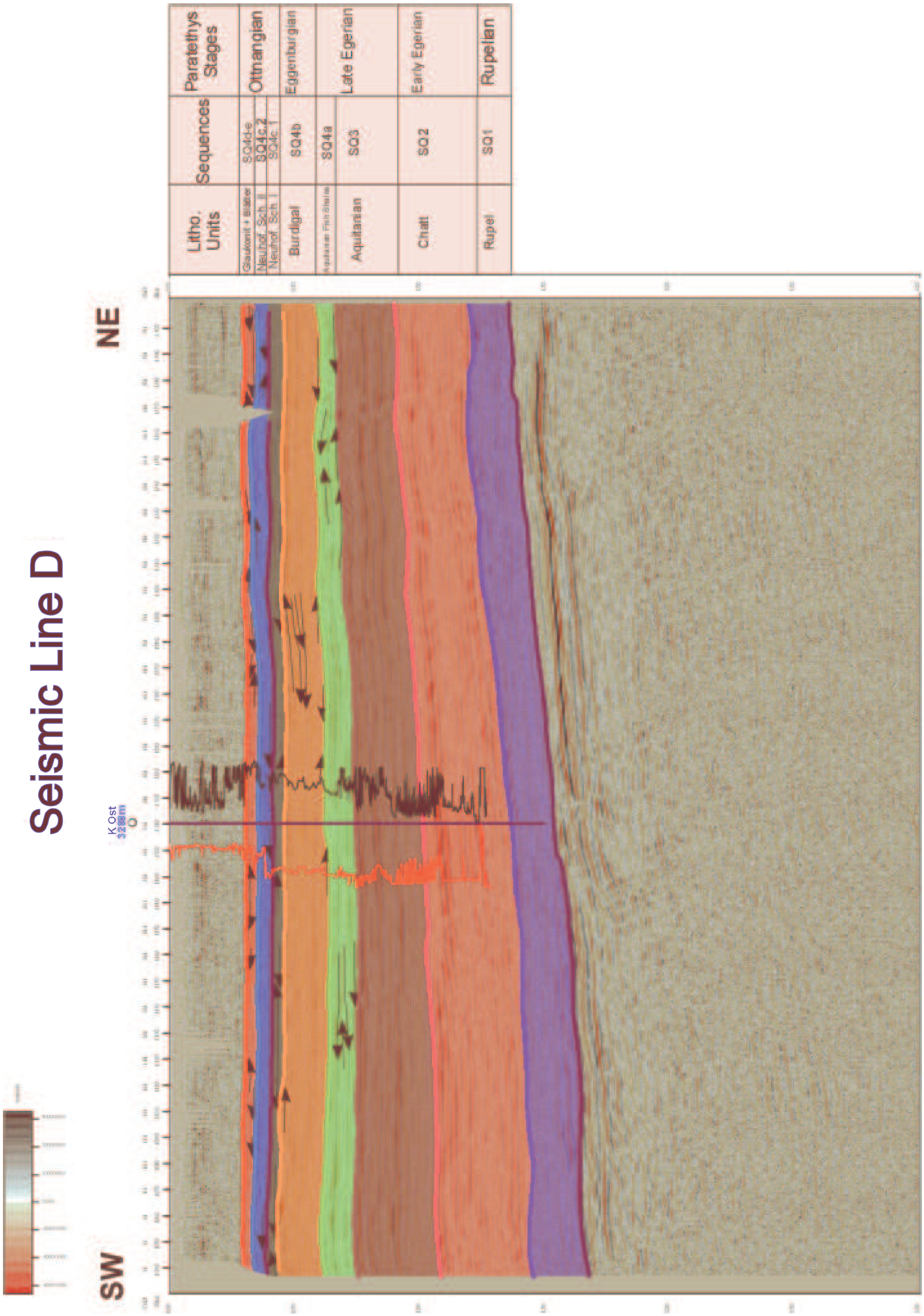


Figure 26. Seismic line D of the western part of the "Ostmolasse".

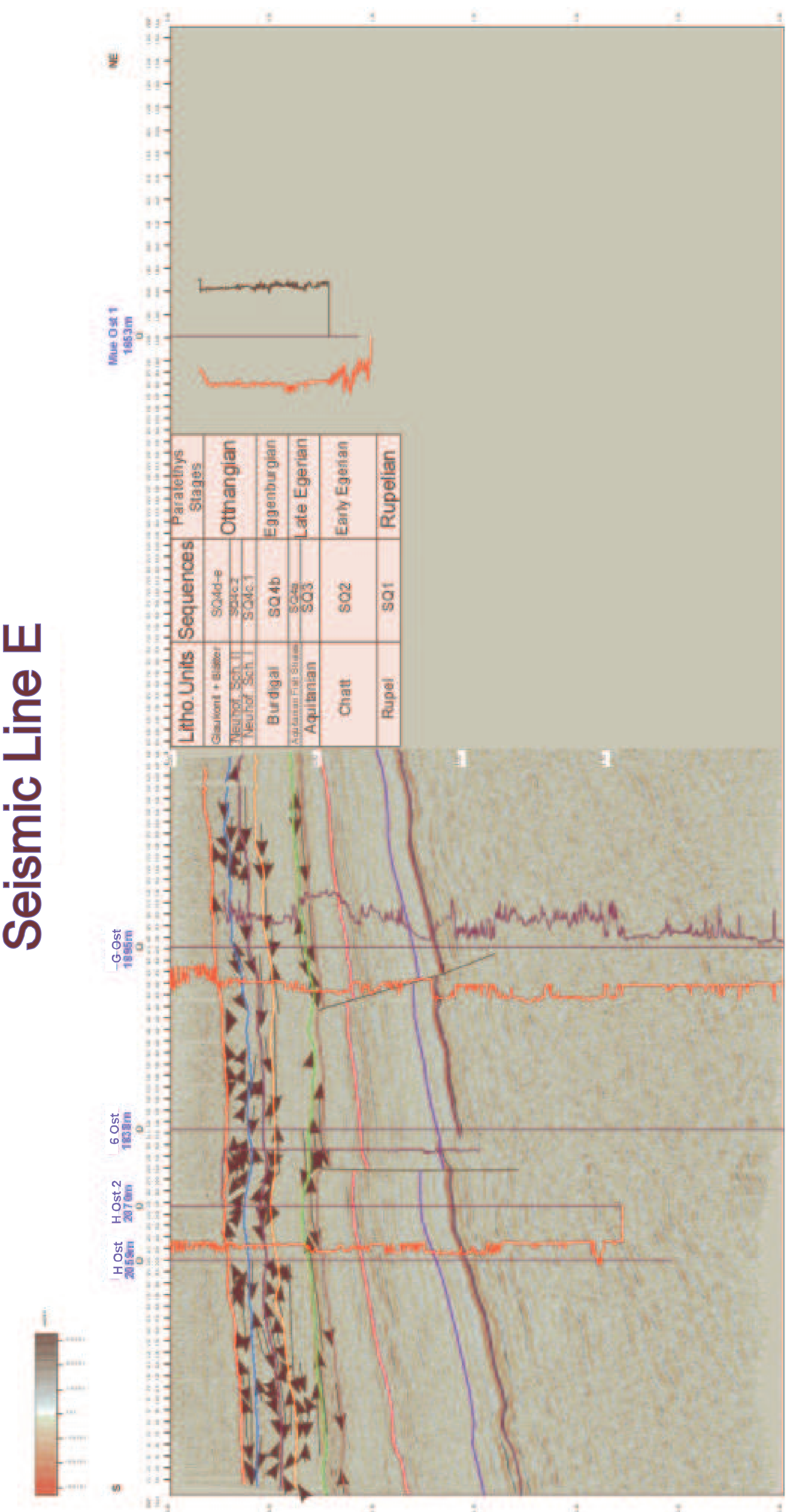


Figure 27. Seismic line E of the western part of the "Ostmolasse".

The thickness of this subsequence is uniform throughout the seismic line. The base is marked by some downlaps, the top by erosive channels and NE directed toplap.

5.1.4.6. Interpretation of seismic lines F (NW-SE) (fig. 28) and G (SW-NE) (fig. 29)

Subsequence 4a - "Aquitaine Fish Shales":

F: The reflectors within this uniformly thick subsequence are parallel. Some toplap towards the NW and some basal onlap to the SE .

G: The thickness increases slightly to the SW. Some toplap towards SW and some basal onlap towards NE and a few internal erosive channels.

Subsequence 4b.2 - "Burdigal":

F: The reflectors within this subsequence of uniform thickness are in their majority parallel. Some toplaps in both directions.

G: The thickness increases slightly towards SW. The reflectors are parallel. The basal onlap is directed towards the SW, whereas the top shows some erosive channels and NE directed toplap.

Subsequence 4b.1 - "Neuhofener Schichten I":

F: The thickness is uniform. The basal onlap points into both directions.

G: The thickness of this subsequence diminishes towards the SW and it is missing in the southernmost part of the line. At the base, some channels and SW directed onlap.

Subsequences 4c-e - "Neuhofener Schichten II", „Glaukonitsande" and „Blättermergel":

F: Both subsequences present parallel reflectors and uniform thicknesses. In the Neuhofener Schichten II, some basal onlap and toplap occur towards the NW.

In the Glaukonitsande and Blättermergel, some basal onlap in both directions can be observed, some toplap to the NW and erosive channels are present.

G: Thicknesses of both subsequences remain unchanged throughout the entire line. Their reflectors are parallel.

In the "Neuhofener Schichten II", toplap towards the NE and basal onlap towards SW are observed.

In the "Glaukonitsande" and "Blättermergel", some basal onlap and toplap both towards the SW are present.

5.1.4.7. Interpretation of seismic line H (SW-NE) (fig. 30)

The quality of this line is not optimal and the internal patterns of the subsequences could not be recognized.

Subsequence 4a - "Aquitaine Fish Shales":

This sequence laps onto the irregularly eroded surface of the "Aquitaine Sands", but its thickness is nevertheless rather uniform. Some poorly defined NE directed toplaps and a few equally blurred SW directed basal onlaps and downlaps may be present.

Subsequence 4b.1 - "Burdigal":

The poor quality allows to recognize only some SW directed basal downlaps and toplap in both directions within this thick subsequence.

Subsequence 4b.1 - "Neuhofener Schichten I":

This subsequence progressively increases its thickness towards the SW. Only some basal onlaps with a NE direction are recognized.

Subsequence 4c - "Neuhofener Schichten II":

This subsequence has a uniform thickness in spite of its irregular surface. Only some basal onlap in both directions and toplap to SW can be discerned.

Subsequence 4d-e "Glaukonitsande and Blättermergel":

Similar to the "Neuhofener Schichten II", this subsequence has a rather uniform thickness in spite of its irregular surface. Some basal onlap and toplap towards the NE are distinguished.

5.1.5. Discussion

Sequence 4a "Aquitaine Fish Shales"

On the W-E as well as on the N-S running seismic lines, this subsequence laps onto the erosive surface of the Aquitaine Sands, which are incised by deep erosive channels at the top.

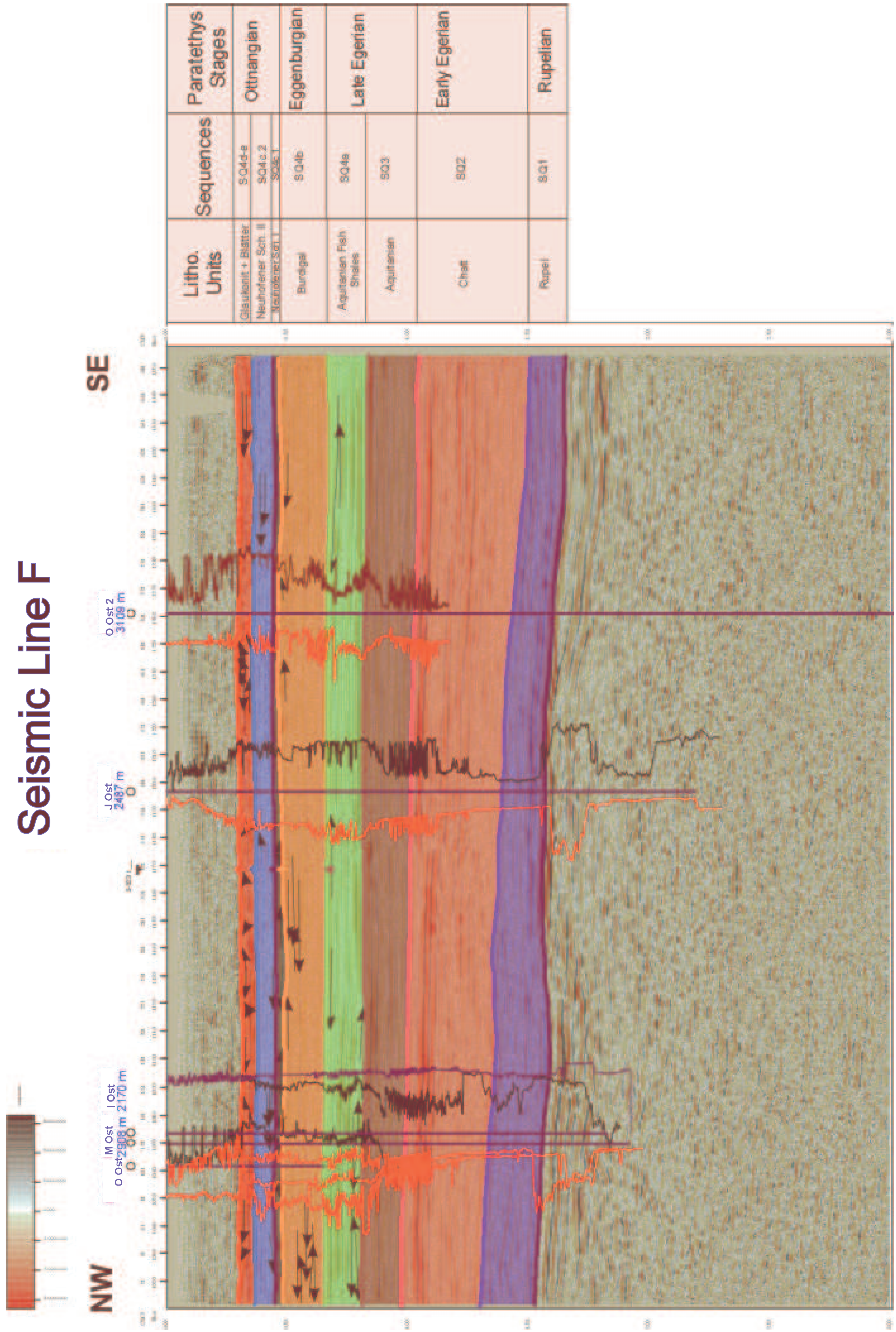


Figure 28. Seismic line F of the western part of the "Ostmolasse".

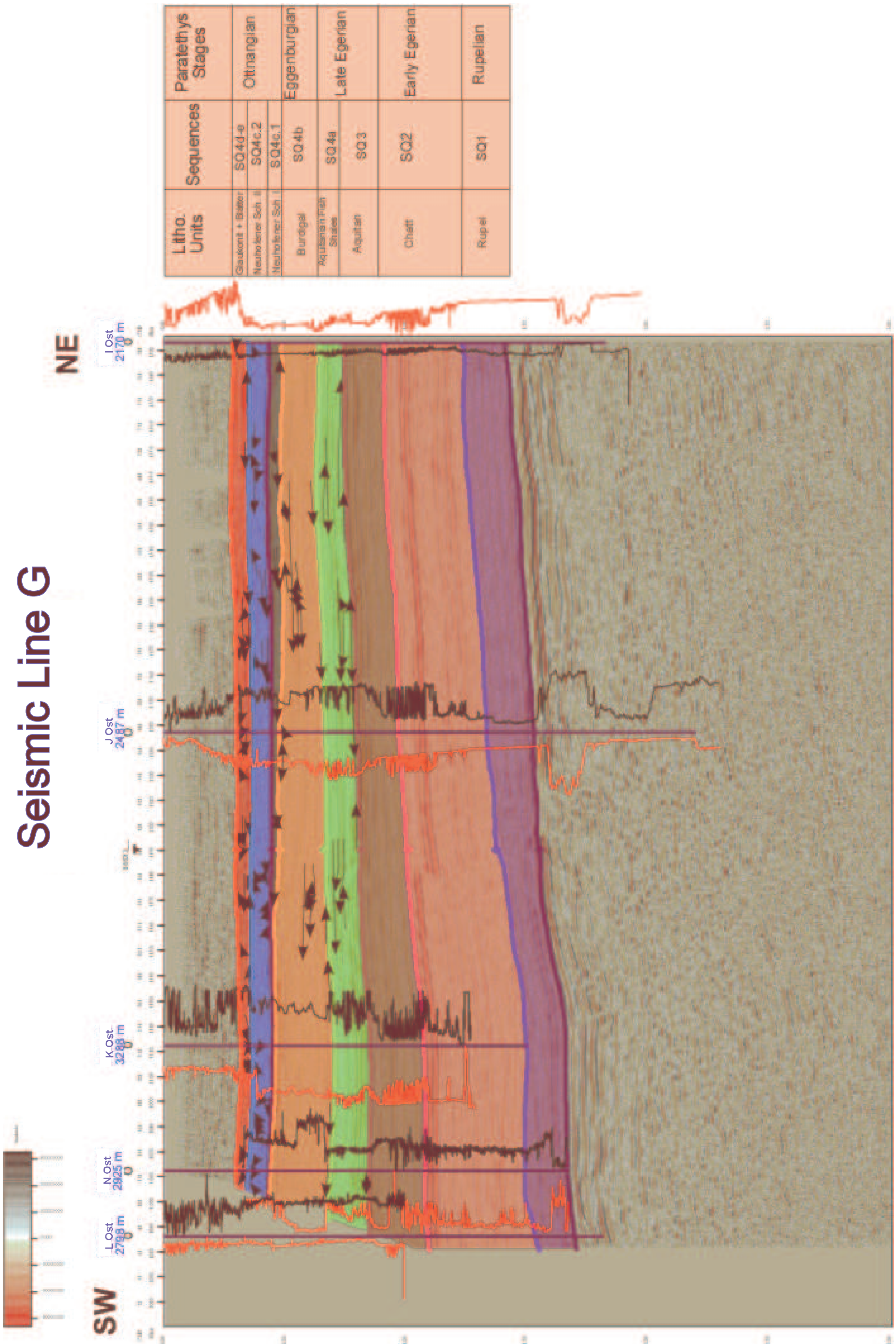


Figure 29. Seismic line G of the western part of the "Ostmolasse".

Sequence 4b "Burdigalian":

This sequence onlaps on the eroded surface of the "Aquitaine Fish Shales", which has some erosive channels. The lower portion of Sequence 4b is composed of a low amplitude facies which corresponds to a sand-rich interval. It is interpreted as lowstand deposits while the inclined reflectors are thought to represent W-E delta progradation (Zweigel, 1998).

Subsequence 4c.1 - "Neuhofener Schichten I" :

This subsequence was defined by Zweigel (1998) as sequence 4b in her regional analysis and it can be best seen in the eastern part of the Ostmolasse and the Puchkirchen area. Its erosive lower boundary laps onto the "Burdigal" Subsequence. The amplitudes of the erosive incisions increase westward.

Subsequence 4c.2 - "Neuhofener Schichten II":

The Subsequence 4c.2 laps onto the Subsequence "Neuhofener Schichten I" and consists of parallel reflectors of variable amplitude. The sediments are interpreted as shallow- marine lowstand deposits based on the interpretation of the well data and correlation with the Puchkirchen area.

Subsequences 4d-e - "Glaukonitsande" and "Blättermergel":

The subsequence is dominated by parallel reflectors. They are separated by a very continuous high amplitude reflector into a lower low amplitude and an upper high amplitude facies. They are interpreted to represent lowstand and highstand deposits respectively, whereas the continuous reflector is the maximum flooding surface (Zweigel, 1998).

5.2. Eastern part of "Ostmolasse"

5.2.1. Introduction

Five seismic reflection lines and eight wells have been available from the easternmost German part of the Molasse Basin (Figs. 31, 32 and 33 to 39). Unfortunately, the poor quality of the seismic data available from this area prevented a direct correlation with the western and central part of the Ostmolasse. Only a rather small number of wells were available from the area occupied by the Puchkirchen Trough during the Oligocene and earliest Miocene. However, the well logs are of good quality and could be correlated to the seismic reflection lines I (fig. 2.18B; P6, Zweigel 1998) and J (fig. 2.18A; P5, Zweigel 1998) with the help of Geographix.

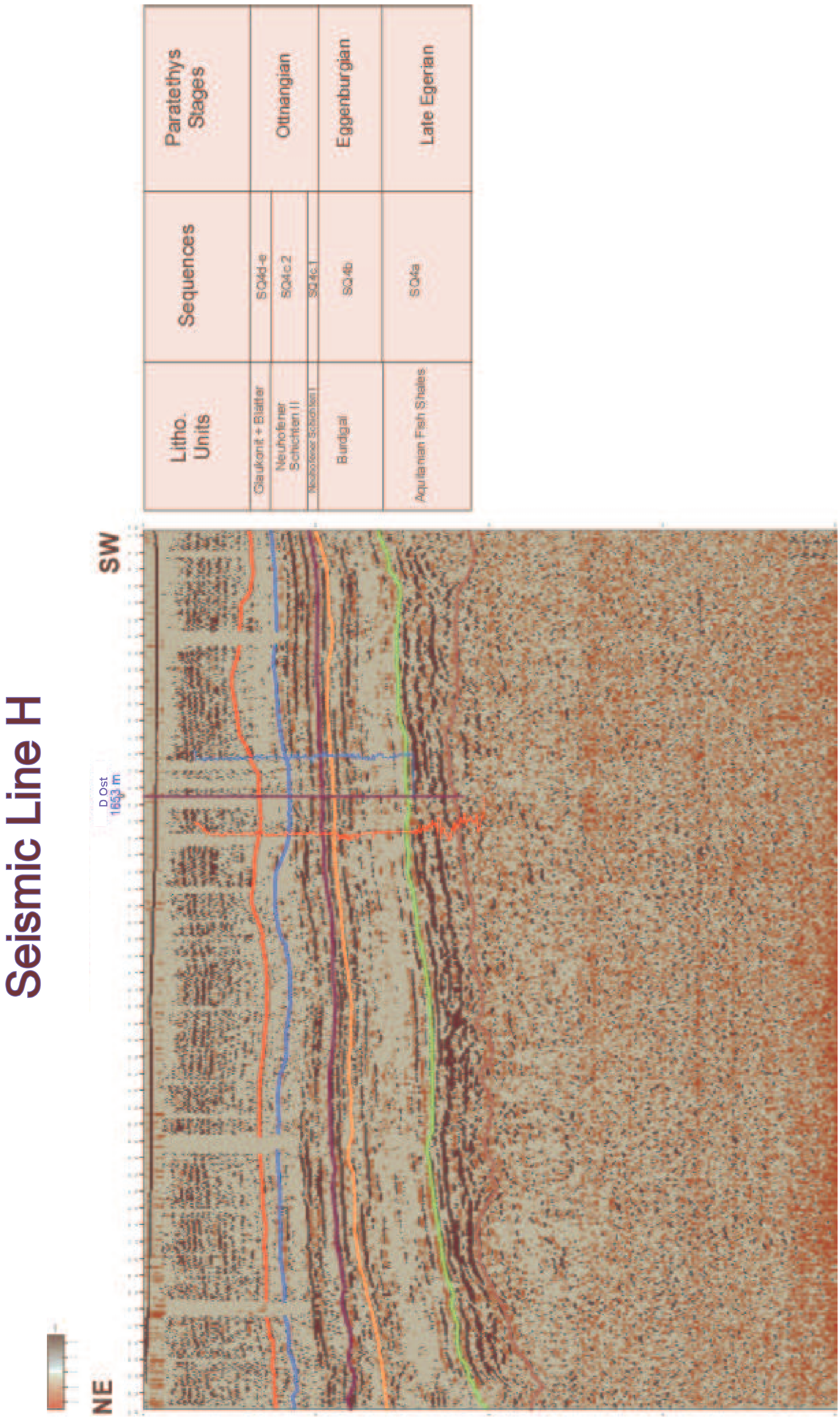


Figure 30. Seismic line H of the western part of the "Ostmolasse".

5.2.2. Lithostratigraphy

5.2.2.1. "Aquitaine Fish Shales"

This unit is composed of grey sandstone with intercalations of shales. Its thickness is approximately 120m. Their electrical response shows low resistivity values. The SP log indicates a possible increase of grain size towards the base. The persistent high velocities shown on the sonic log are caused by the shale packages.

5.2.2.2. "Obing Folge"

The thickness of the grey sandy claystones, in places grading into sandstones and with intercalations of sandy marls and limestones varies from 110m to 270m. In 4 Ost, moderate to high values with strong peaks are observed. The SP curve shows an alternation of shales and sands and a possible increase of grain size towards the base.

5.2.2.3. "Burdigal"

The 335m to 850m thick "Burdigal" is composed of grey claystones which grade into sandy marls and sandstones. The glauconitic sandstones are in part coarse and may contain chips of gravel ("Kiessplittter").

The electrical response shows moderate to high values with some peaks in 4 Ost. The SP log indicates a decrease in grain size towards the base. The high values observed near the top in the GR response are due to the presence of great amounts of shale.

5.2.2.4. "Neuhofener Schichten I"

This unit is composed of grey claystones, very sandy marls and fine sands with thin intercalations of limestones. Its thickness varies from 70m to 110m. A few beds contain shell debris.

The resistivity log shows moderate values; a possible decrease in grain size towards the base is observed on the SP log.

5.2.2.5. "Neuhofener Schichten II"

The grey claystones to sandy marls with intercalations of fine to medium-grained glauconitic sandstones have a thickness of 135m to 295 m, occasionally, shell fragments are observed.

The moderate values of the rather smooth electrical log are due to the predominance of shaly sediments.

5.2.2.6. "Glaukonitsande" and "Blättermergel"

This unit consists of grey claystones and sandy marls grading into glauconitic fine to middle-grained sandstones. A few layers with gravels are present. The thickness of the unit varies considerable from 20m to 260m. Only shell debris is reported.

The values observed on the electrical logs are moderate to high with strong and characteristic peaks, in particular at the base, because of the increase in sand content. However, a possible decrease of the grain size towards the base is observed in the SP log. The thick packages of sand and claystone in the middle part of the unit cause strong peaks with high and low values in the sonic log.

5.2.3. Correlation by wireline logs

5.2.3.1. N-S cross section 5 (figs. 31 and 32)

The patterns of the lateral changes are more complex than in the western part of the Ostmolasse. The "Obing Folge" diminishes its thickness southwards and pinches out at 2 Ost and V Ost. The "Glaukonitsande" and "Blättermergel", the "Neuhofener Schichten I" and the "Burdigal" have relatively uniform thicknesses.

In the in "Glaukonitsande" and "Blättermergel" as well as the "Aquitaine Fish Shales", the sand content diminishes towards the South, whereas in the "Neuhofener Schichten II" and the "Neuhofener Schichten I" it remains relatively constant. The "Burdigal" has its lowest sand content in the central part of the cross section.

5.2.4. Seismic stratigraphy

I discuss here only Sequence 4 of Zweigel (1998), i.e. the interval corresponding to the depositional cycle of the Upper Marine Molasse which reaches from the "Aquitaine Fish Shales" to the base of the equivalents of the "Kirchberger Schichten".

The lower boundary of Sequence 4 is a conformable surface with some onlap. In 4 Ost, it corresponds to a fining upward trend. In the eastern part of the Ostmolasse, it is composed by the following subsequences (see figs. 33 to 37):

Subsequence 4a - "Aquitaine Fish Shales"
Subsequence 4b.1 - "Obing Folge"
Subsequence 4b.2 - "Burdigal"
Subsequence 4c.1 - "Neuhofener Schichten I"
Subsequence 4c.2 - "Neuhofener Schichten II".
Subsequences 4d-e - "Glaukonitsande" and "Blättermergel".

Figures 35, 36, 37, 38 and 39 illustrate the sequence stratigraphic subdivision of the lines P5 (N-S) (Zweigel, 1998) and P6 (SW-NE) (Zweigel, 1998) and their correlation with the wells R Ost, 3 Ost, V Ost, Z Ost, 2 Ost, 1 Ost, 4 Ost and 5 Ost. Here I will describe in detail the seismic line K.

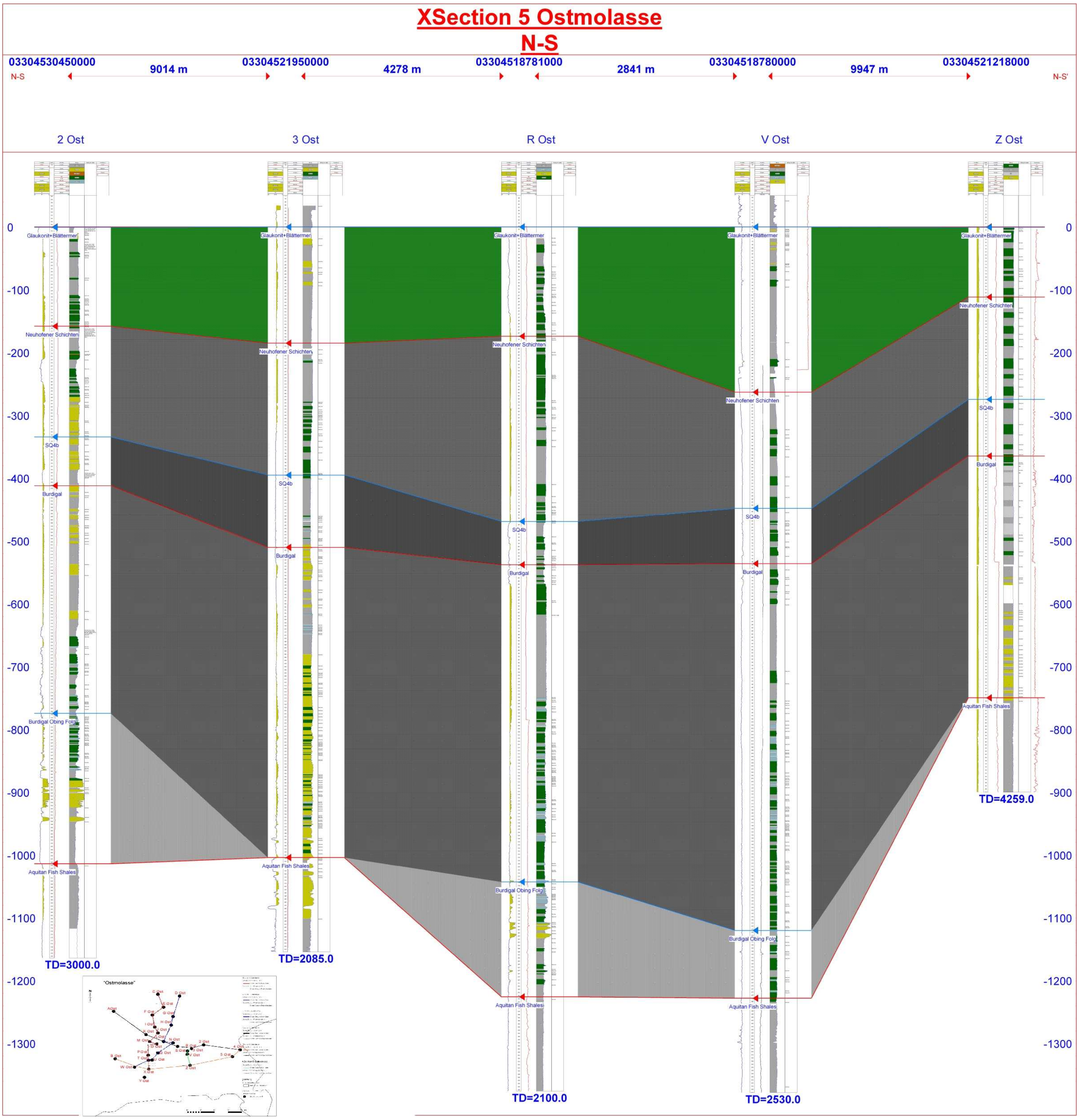


Figure 31. Lithostratigraphic correlation of wells based on SP, Resistivity, Sonic and Density log.

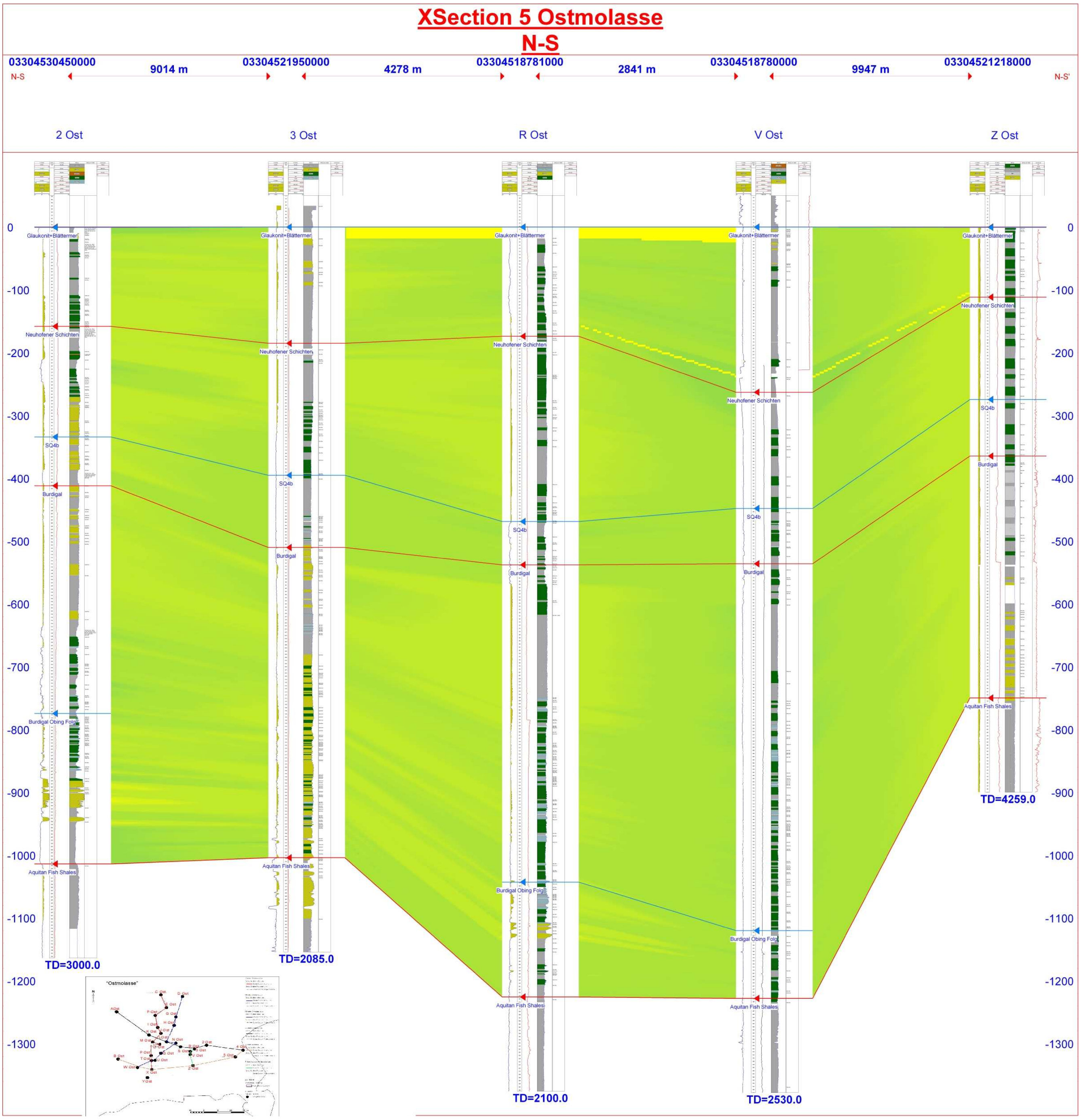


Figure 32. Lithostratigraphic correlation based on the SP logs of the studied wells.

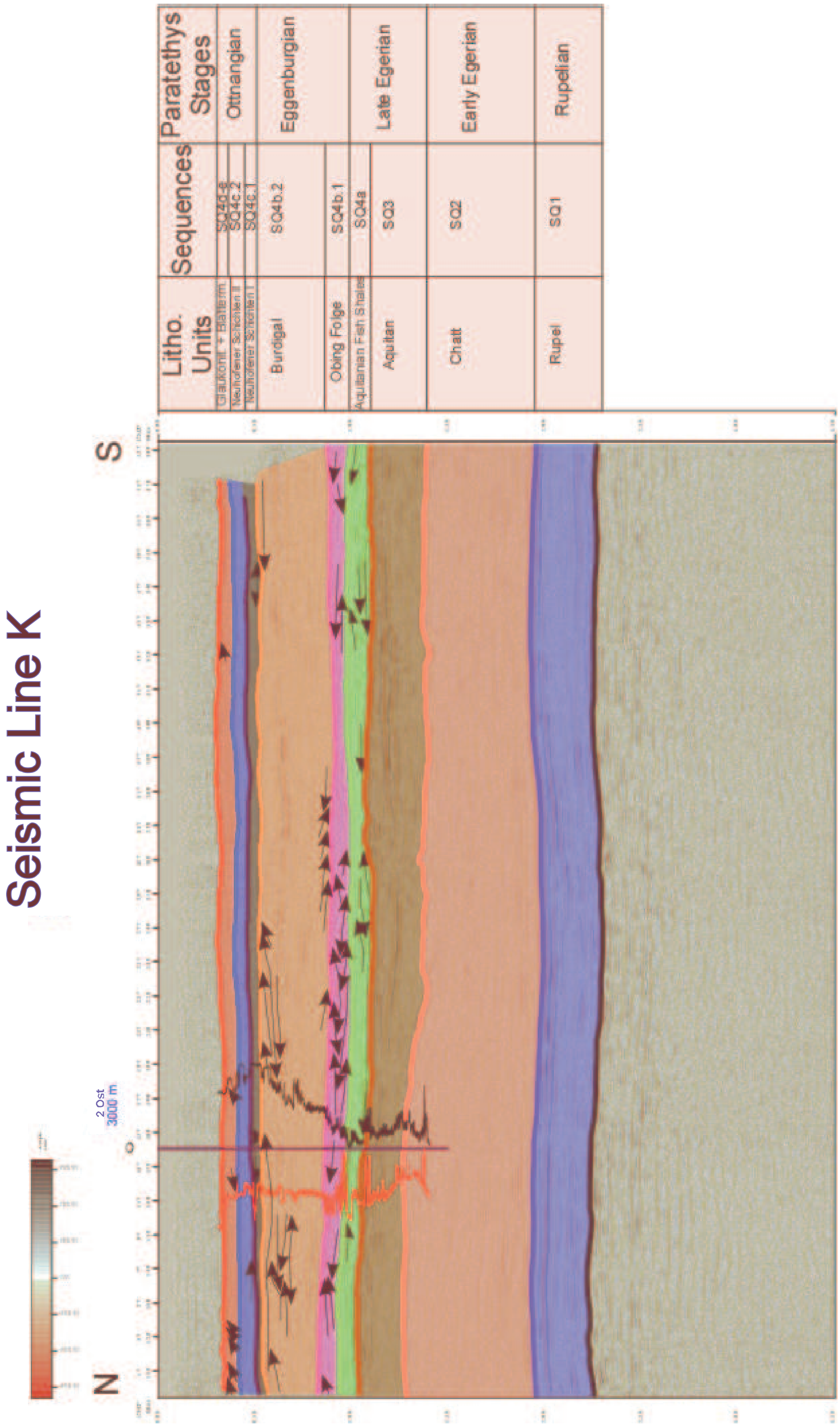


Figure 33. Seismic line K of the eastern part of the "Ostmolasse".

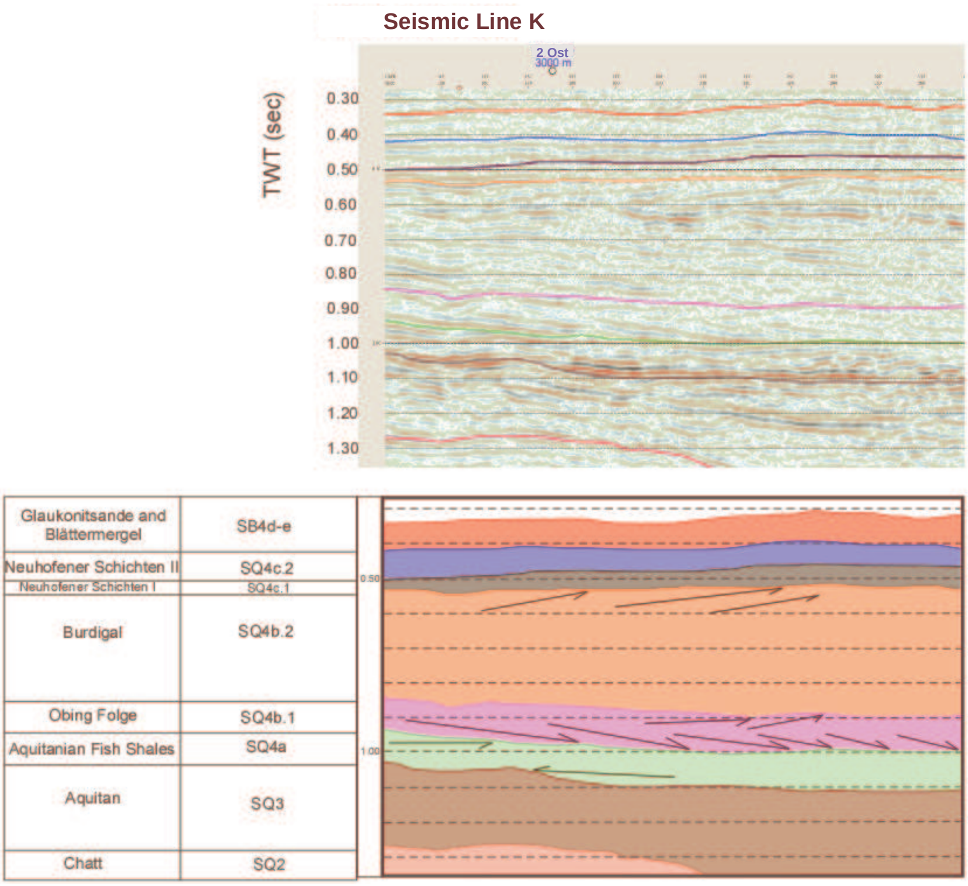


Figure 34. Details from seismic line K

5.2.4.1. Seismic line K (fig. 33, 34)

Subsequence 4a – "Aquitaine Fish Shale"

The "Aquitaine Fish Shales" onlap the eroded surface at the top of the "Aquitaine Sands" in a north-westward direction. Their thickness is more or less uniform throughout the entire line. The eroded top is marked by distinct toplap. The eroded surface of this sequence is onlapped by the "Obing Folge".

Subsequence 4b.1 – "Obing Folge"

The "Obing Folge", which has not been differentiated by Zweigel (1998), appears below a group of eastward directed downlap patterns of the "Burdigal". Its thickness is uniform throughout the entire seismic line.

In 2 Ost, the two units are also clearly differentiated by their SP curve. In the "Burdigal", it has a blocky and more homogenous shape without numerous peaks corresponding to thick sand layers with shaly intercalations. In the "Obing Folge", the SP curve starts quite irregularly with a large number of peaks due to the reduced sand content and grain size towards its base. The "Obing Folge" consists of packages of clay and sandy marls. Within this subsequence, a group of internal onlap patterns directed to the east can be observed. Its upper boundary is marked by toplap.

Subsequence 4b.2 - "Burdigal"

To the west, the "Burdigal" displays the slight incision of a channel. Some toplap patterns are directed to the east.

Subsequence 4c.1 - "Neuhofener Schichten I"

In this subsequence, channel-like incisions are observed in the western and in the eastern part.

Subsequences 4c.2-d-e - "Neuhofener Schichten II", „Glaukonitsande" and „Blättermergel"

These subsequences are dominated by parallel reflections. They are separated by a very continuous higher amplitude reflector into a lower low amplitude and an upper high amplitude facies. The "Glaukonitsande" and "Blättermergel" present some toplap towards the East, although the reflectors are rather parallel.

5.2.4.2. Interpretation of seismic lines J (NE-SW) (fig. 35, 36) and I (NW-SE) (fig. 37-38 and 39)

The seismic lines J and I were analyzed by Zweigel (1998). I have used these lines to calibrate the location of the stratigraphic subsequences studied.

Subsequence 4a - "Aquitaine Fish Shales"

The base of this subsequence is characterized by some onlap onto topographic highs, whereas the top is marked by erosion. In the seismic line I, the highstand deposits only are preserved in the SW. In the west, the top of the subsequence is eroded. The well logs indicate an abrupt coarsening upward.

Subsequence 4b.1 - "Obing Folge"

This subsequence which laps onto the "Aquitaine Fish Shales" is restricted to the easternmost part of the study area. Because of its turbiditic character, it is interpreted as lowstand deposits. Higher up in the subsequence, strong parallel reflections with southward onlap mark the transgressive systems tract.

Subsequence 4b.2 - "Burdigal"

Strong parallel reflections with onlap towards the south mark the transgressive systems tract above the "Obing Folge". The "Burdigal" decreases in thickness towards the NE. In the upper part, a thick interval of north-eastward prograding downlapping surfaces is observed. They are interpreted as a highstand prograding delta complex (Zweigel, 1998).

Subsequence 4c.1 - "Neuhofener Schichten I"

The upper subsequence boundary (sequence boundary 4b of Zweigel, 1998) is conformable in the south but in the northern part of line I, onlap, toplap, and some minor erosive patterns are visible. The well logs indicate minor upward coarsening.

Subsequences 4c.2 - "Neuhofener Schichten II" and 4d-e - "Glaukonitsande" and „Blättermergel"

Channel-like, W-E oriented features are best seen in line J. They are filled with northward onlapping strata. This fill is terminated by a very continuous medium to high amplitude reflector, which can be followed from the shelf area into the area of the Puchkirchen Trough. As already mentioned above, it has been interpreted by Zweigel (1998) as a transgressive surface separating highstand and lowstand deposits. The interval above this surface is characterized by unspecific parallel reflectors.

5.2.4.3. Interpretation of seismic lines L (W-E) (fig. 40, 41 and 42) and M (NE-SW) (fig. 43, 44 and 45)

Zweigel (1998) analized the seismic lines L and M. The seismic lines have been used to calibrate the location of the stratigraphic subsequences studied.

Subsequence 4a - "Aquitaine Fish Shales":

L: Throughout this line, the subsequence maintains a uniform thickness. The top is marked by erosive channels and some toplap towards NE, whereas the base shows some onlaps.

M: This subsequence progressively increases its thickness towards the SW. Towards the top it presents toplap in NE direction and some channels. At the base some NE-directed onlaps are observed.

Subsequence 4b.1 - "Obing Folge":

L: The thickness of the subsequence is very irregular. The basal onlaps on the erosive surface of the Aquitaine Fish Shales are in part directed towards E. The top shows some channels and toplaps directed to W. The upper surface of the sequence is rather uniform.

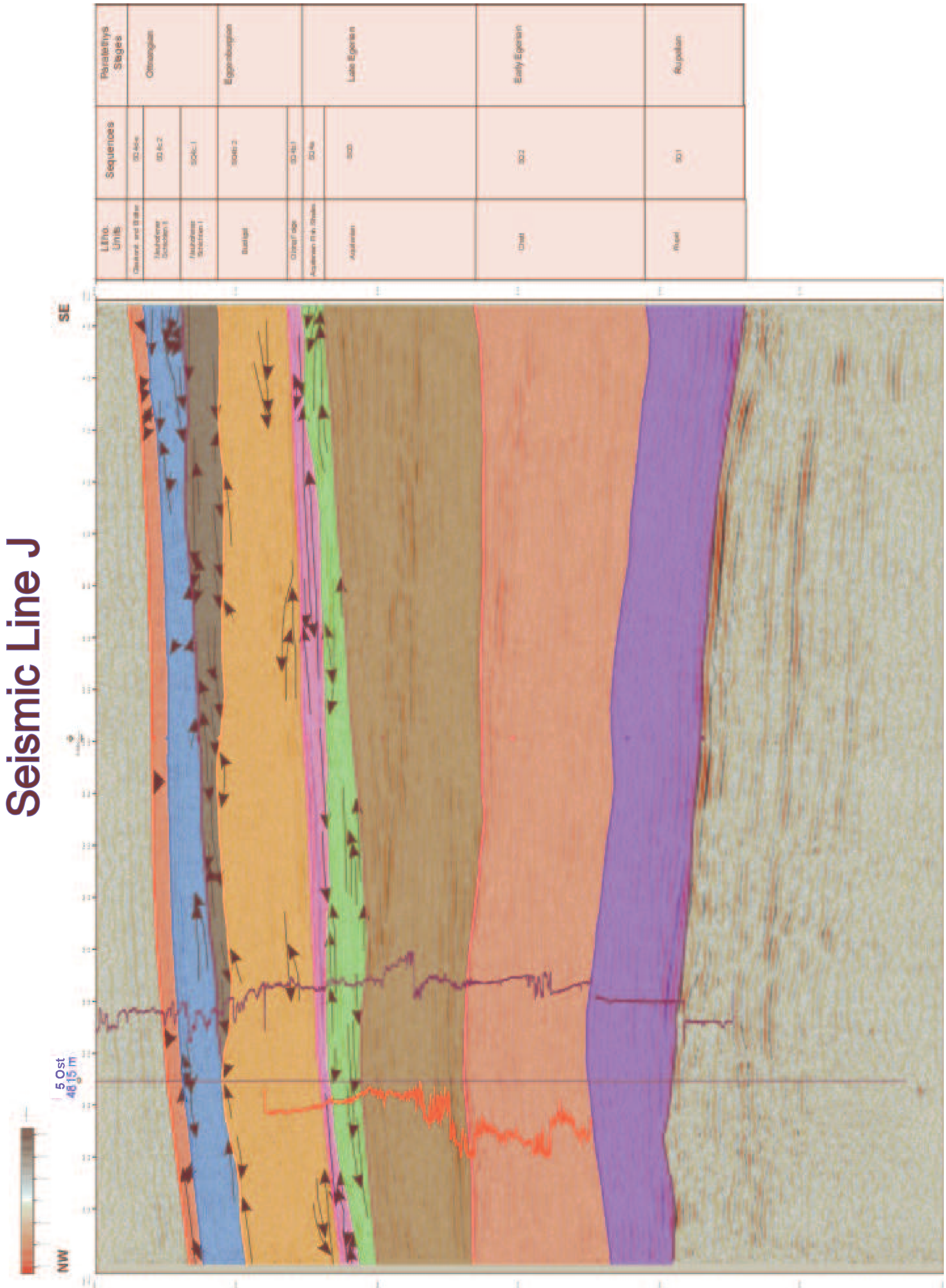


Figure 35. Seismic line J of the eastern part of the "Ostmolasse"

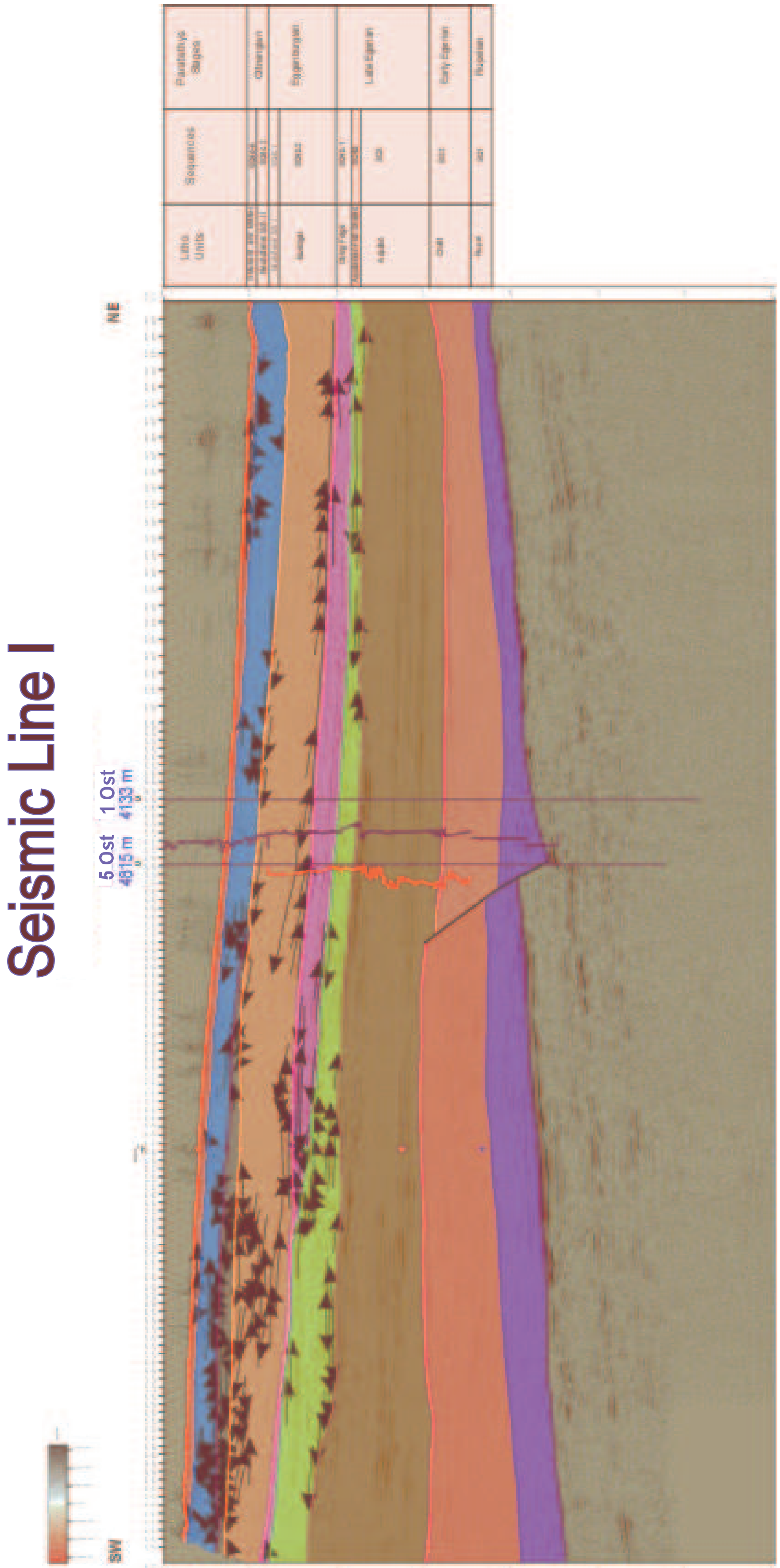
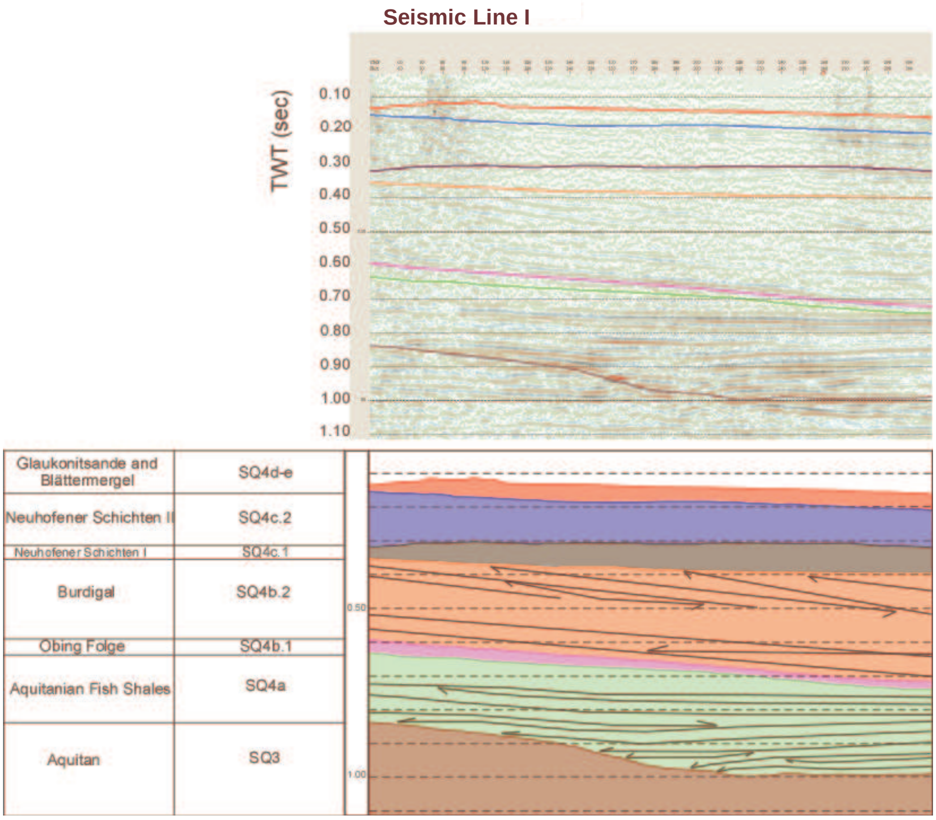
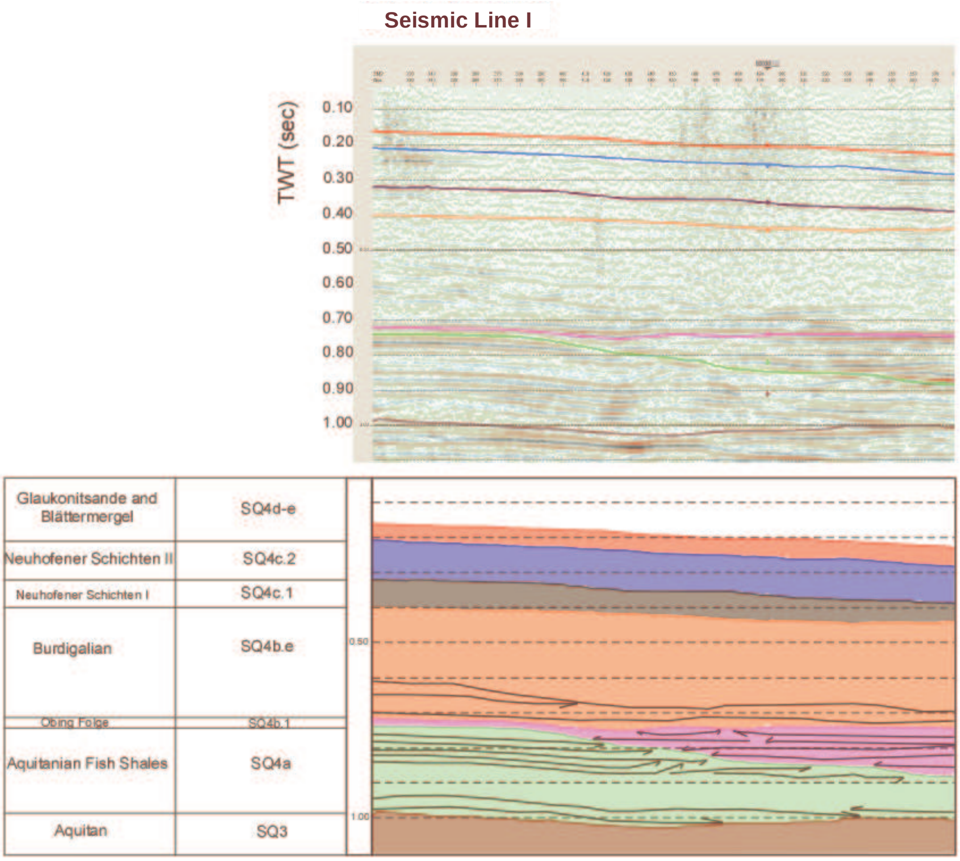


Figure 36. Seismic line I of the eastern part of the "Ostmolasse".





Figures 37 and 38. Details from seismic line I of the eastern part of the "Ostmolasse".

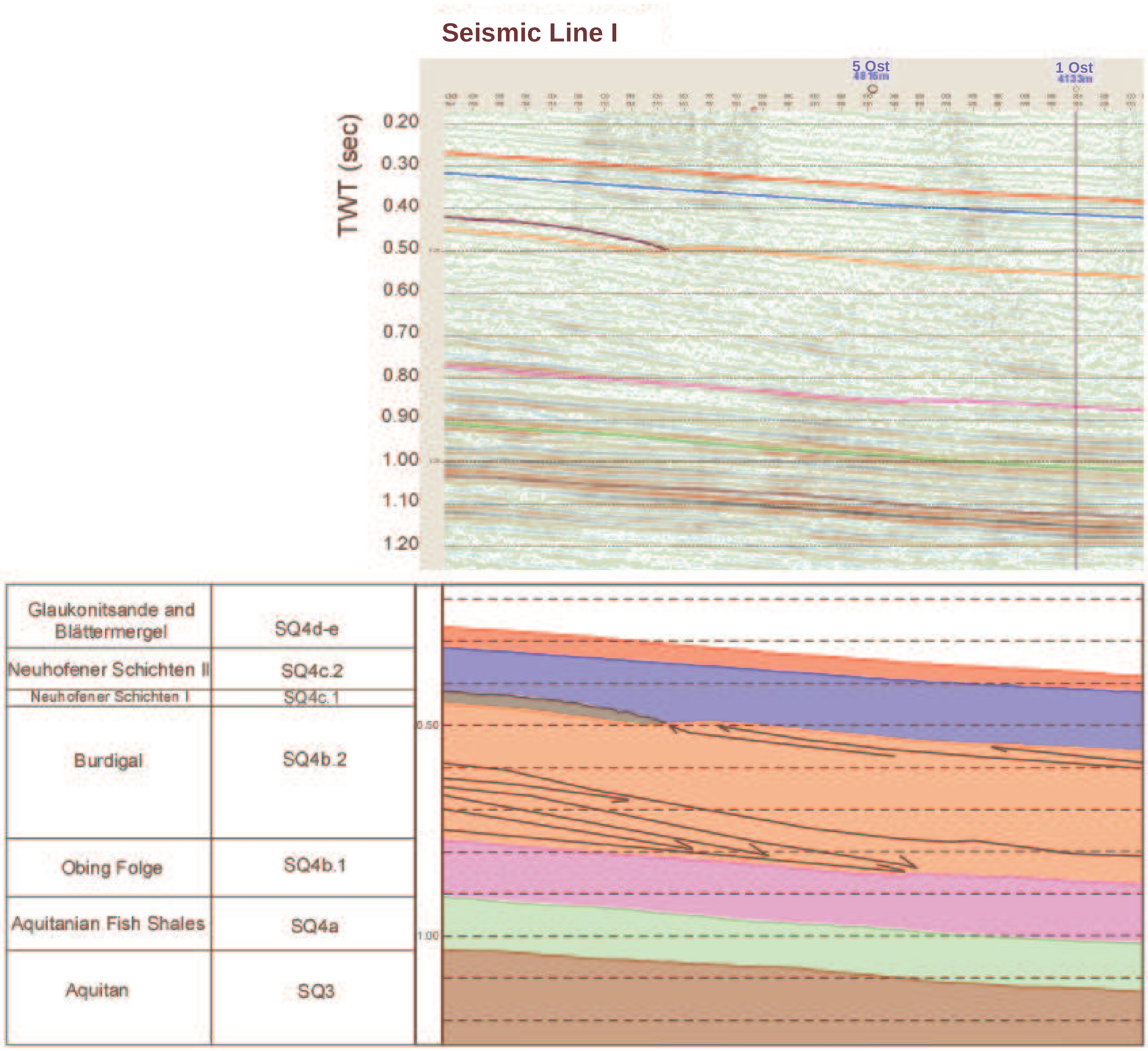


Figure 39. Details from seismic line I.

M: The subsequence diminishes in thickness towards the SW. Near the top, a group of erosive channels is observed.

Subsequence 4b.2 - "Burdigal":

L: The subsequence maintains a considerable thickness throughout the entire line. The toplap and the onlap at its boundaries are both directed to the E. A few erosive channels are observed. A group of reflectors in the middle and lower part are gently inclined towards E.

M: The toplaps of this thick subsequence are directed towards SW, whereas the onlaps at the base point in the opposite direction. A few erosive channels are observed. The topmost part contains mainly parallel reflectors, whereas the middle and the basal parts contain a thick package of reflectors with a marked inclination to NW. The boundary surfaces and the thickness of the subsequence remain uniform thoughout the entire line.

Subsequence 4c.1 - "Neuhofener Schichten I":

L: Thickness and boundaries of this subsequence are unchanged throughout this line. The few onlaps and toplaps are directed towards W. In addition, the top shows some erosive channels.

M: The thickness diminishes towards NE and SW. The basal onlap has a SW direction. The top is marked by some erosive channels.

Subsequences 4c.2-d-e -"Neuhofener Schichten II", „Glaukonitsande"and „Blättermergel"

L: The subsequences are composed by parallel reflectors, although the "Neuhofener Schichten II" show a slight increase in thickness towards W and some E-directed onlap. The "Glaukonitsande" and "Blättermergel" display a few onlaps directed to the E.

M: The subsequences consist of parallel reflectors, in which depositional signatures are only very poorly expressed. In the "Neuhofener Schichten II", some onlap and toplap patterns are both directed towards the SW, whereas in the "Glaukonitsande" and "Blättermergel" some onlap and some NE-directed toplap are observed.

5.2.4.4. Interpretation of seismic line N (NW-SE) (fig. 46)

Subsequence 4a - "Aquitaine Fish Shales":

The "Aquitaine Fish Shales" increases their thickness toward the SE. The reflectors are parallel and some toplaps in direction SE and basal onlaps to the NW are observed.

Subsequence 4b.1 – "Obing Folge":

The thickness of this subsequence increases towards SE. Some toplaps towards NW and SE are observed. Downlaps and basal onlaps are observed in direction NW.

Subsequence 4b.2 - "Burdigal":

In this line, toplaps in both directions (NW – SE) are observed as well as some basal onlaps and downlaps toward the NW. The Burdigal has uniform thicknesses throughout the entire line.

Subsequence 4c.1 - "Neuhofener Schichten I":

The "Neuhofener Schichten I" increase their thickness to the SE. To the base, some onlap towards the NW and toplap to the SE is observed.

Subsequence SQ4c.2 - "Neuhofener Schichten II":

This subsequence shows parallel reflectors and its thickness decreases slightly toward the SE. Some toplap to the SE is observed.

Subsequences SQ4d - e "Glaukonitsande" and "Blättermergel":

In the "Glaukonitsande" and "Blättermergel", basal onlap to the NW and toplap in direction SE is observed. These subsequences show a uniform thickness throughout the entire line.

5.2.5. Summary and Discussion

In the easternmost part of the Ostmolasse which is influenced by the Puchkirchen Trough, the sequence 4 is subdivided in seven subsequences, labelled 4a to 4e.

5.2.5.1. Subsequence 4a - "Aquitaine Fish Shales":

The base of Subsequence 4a displays some onlap onto topographic highs, whereas the erosion of channels at its top implies a relative fall of the sea level. The distribution of the "Aquitaine Fish Shales" is restricted to the axial part of the basin; they pinch out and onlap to the north and the south.

The "Aquitaine Fish Shales" are sediment-starved and almost sand-free. Coarser sands occur only in 4 Ost, which is situated in the marginal area of this subsequence close to its pinch-out onto the shelf (seismic line I).

A strong continuous reflection separates the strata into a lowstand and a highstand systems tract. According to Zweigel (1998), the seismic facies of the lowstand deposits is similar to that of the turbidites in the Puchkirchen Trough.

5.2.5.2. Subsequence 4b.1 - "Obing Folge":

The base of the "Obing Folge" is characterised by onlap onto the erosive top of the "Aquitaine Fish Shales" or older horizons. Because of its seismic facies which is identical to that of the turbidites of the Puchkirchen area, Zweigel (1998) interpreted the "Obing Folge" as a lowstand deposit. This subsequence is confined to the eastern part of the Ostmolasse.

5.2.5.3. Subsequence 4b.2 - "Burdigal":

The strongly parallel reflections with S-directed onlap above the "Obing Folge" mark the transgressive systems tract (see line I). The distribution of the "Burdigal" is limited to the southern and central part and it pinches out to the N.

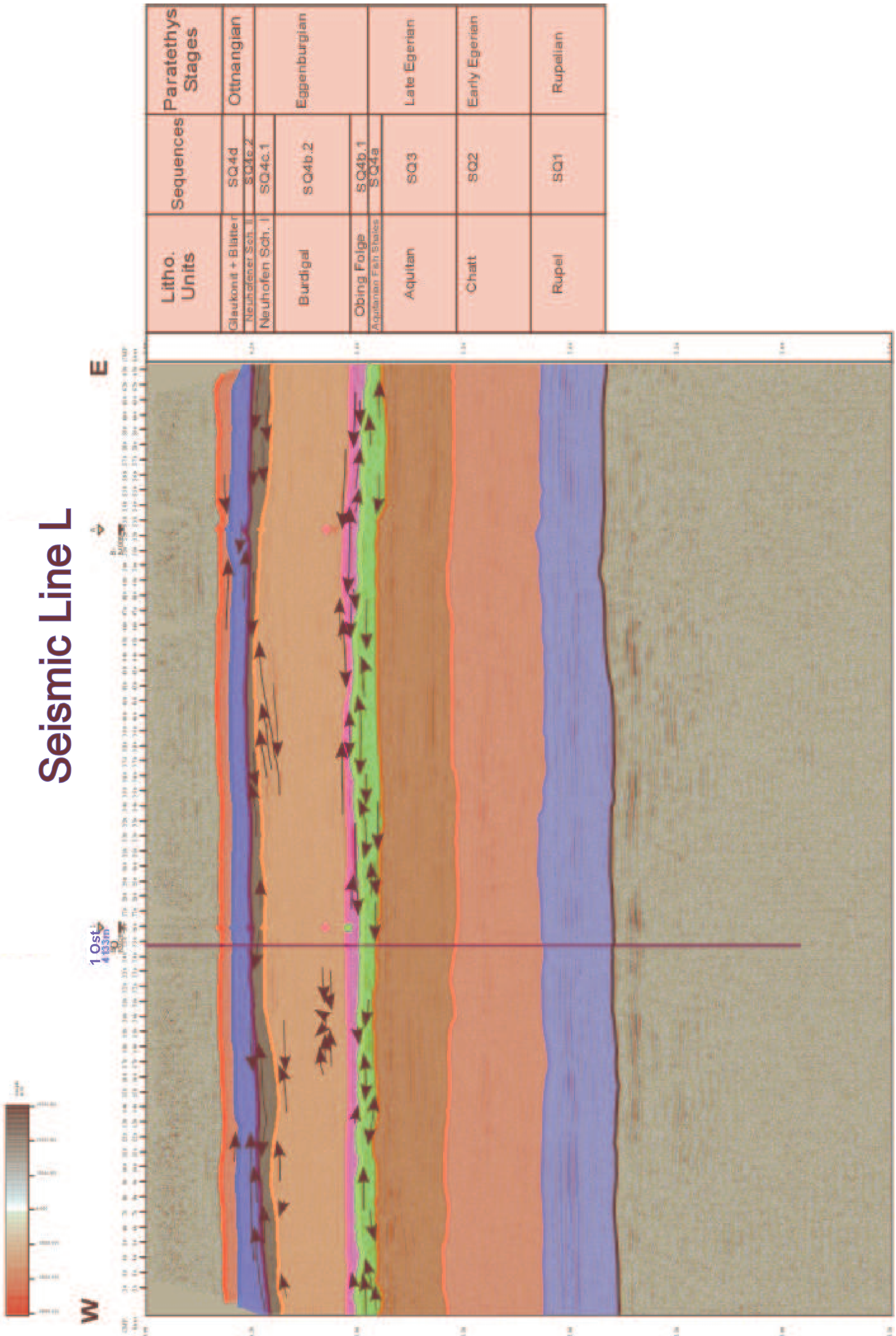
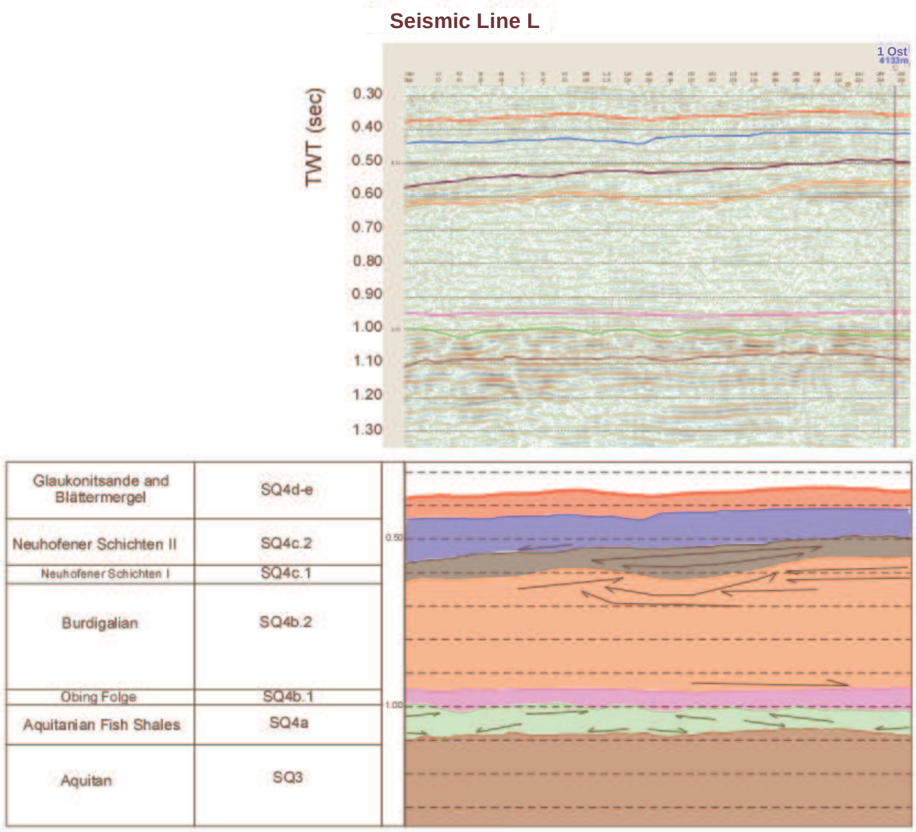
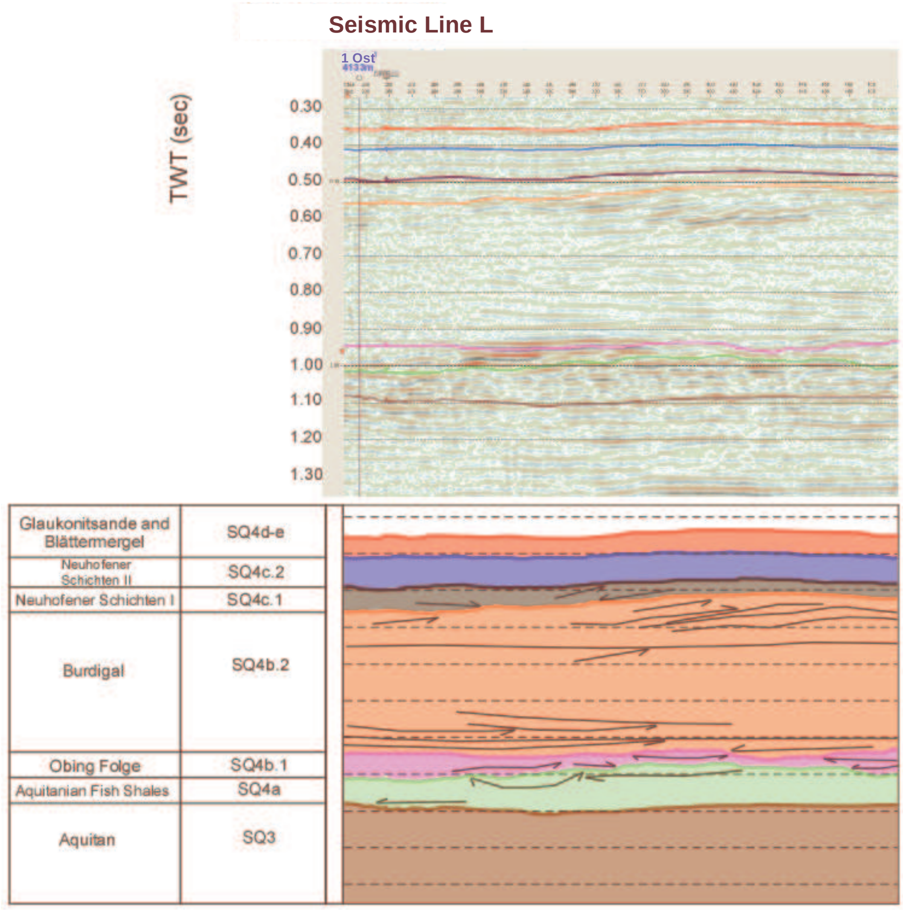


Figure 40. Seismic line L of the eastern part of the "Ostmolasse".





Figures 41– 42. Details from the seismic reflection L.

Its lower boundary is recognized by down- and baselaps as well as by the truncation of the underlying strata. The bulk of the subsequence consists of a thick interval of strong parallel reflections. Above it, a thick interval of NE-prograding downlapping surfaces is observed. This interval decreases in thickness towards NE. It may be interpreted as a prograding highstand delta complex. Within the prograding wedge, internal reflection terminations may indicate episodic delta progradation caused by delta-lobe switching and/or higher-order sea level fluctiations (Zweigel, 1998).

In the subsequences 4b.1 and 4b.2 ("Obing Folge" and "Burdigal"), the sand-rich interval is interpreted as lowstand deposits, while the oblique reflectors are thought to represent W-E delta progradation.

The "Burdigal" may correspond to a lowstand wedge which thickens toward the east and pinches out toward the west.

5.2.5.4. Subsequence 4c.1 - "Neuhofener Schichten I":

The bulk of the widespread marine sediments of the Upper Marine Molasse (Ottnangian, "Helvet" of older authors; "Neuhofener Schichten I and II", "Glaukonitsande" and "Blättermergel") was again deposited in a highstand setting and corresponds to a new transgression.

The lower boundary of subsequence 4b.1 is conformable in the S, but displays onlap and minor erosive patterns in the N (e.g. line P6 of Zweigel, 1998). On the well logs, only minor coarsening is observed. The upper boundary is marked by toplap and truncation as well as down- and baselap in the overlying subsequence.

5.2.5.5. Subsequence 4c.2 "Neuhofener Schichten II":

This subsequence is subdivided into a lowstand and a highstand systems tract (line I) by a strong double reflection interpreted as the maximum flooding surface. The contact with the underlying subsequence is erosive. The highstand systems tract is formed by low amplitude parallel reflections and shows a coarsening upward trend on the well logs.

5.2.5.6. Subsequences 4d-e - "Glaukonitsande and Blättermergel":

The interval overlying the Neuhofener Schichten II is characterized by rather featureless parallel reflections which could not be subdivided into subsequences. The boundary between sequences 4 and 5 at the base of the "Kirchberger Schichten" and their equivalents is based on correlation with the western part of the Ostmolasse and with well data.

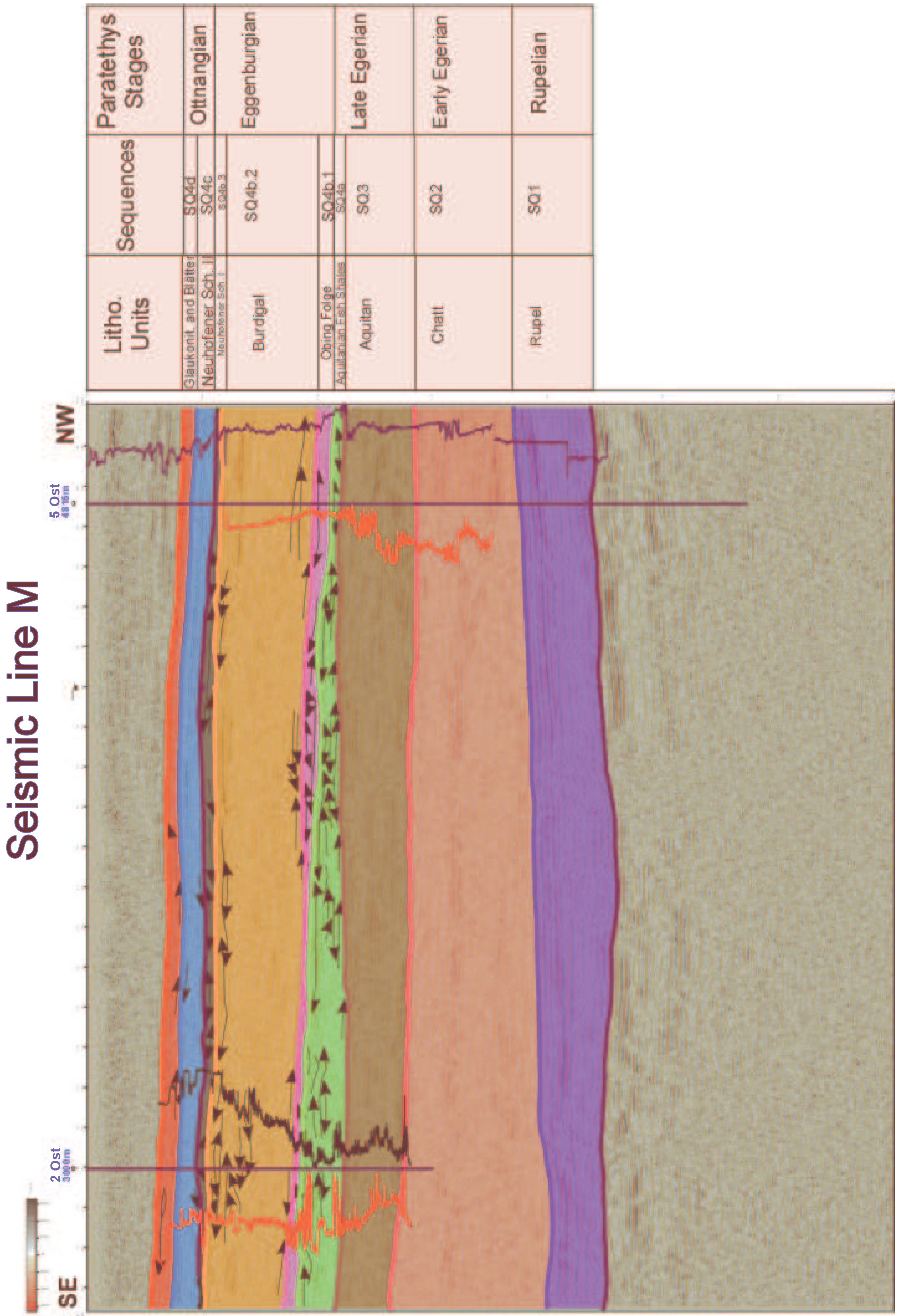
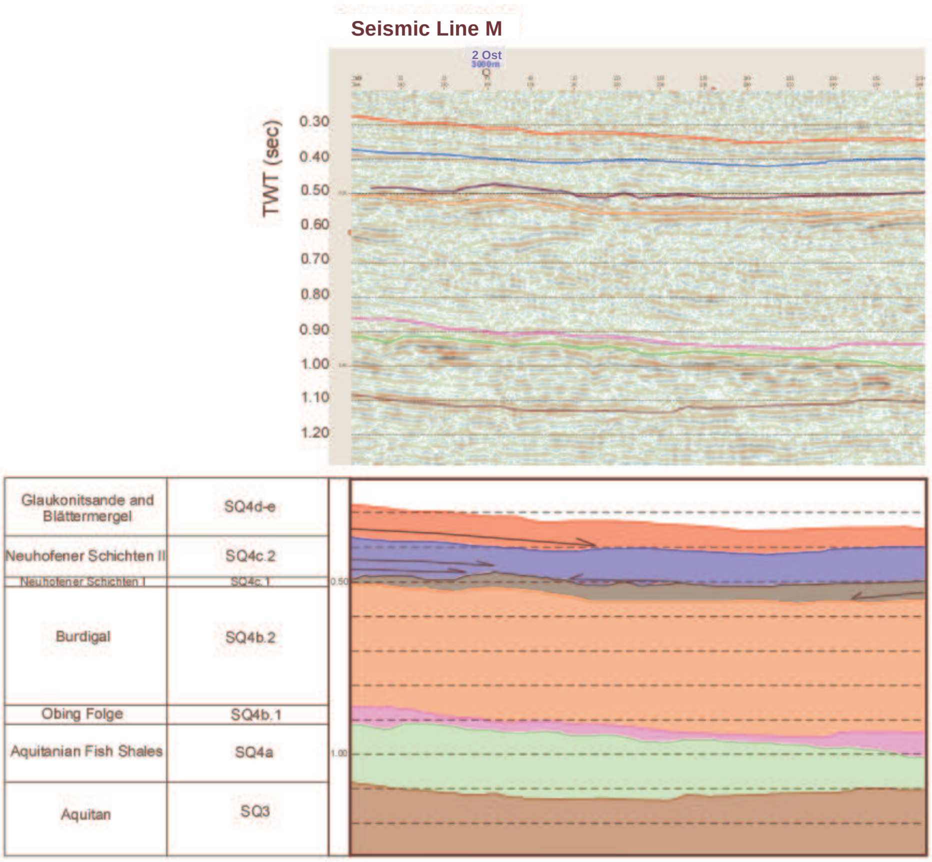
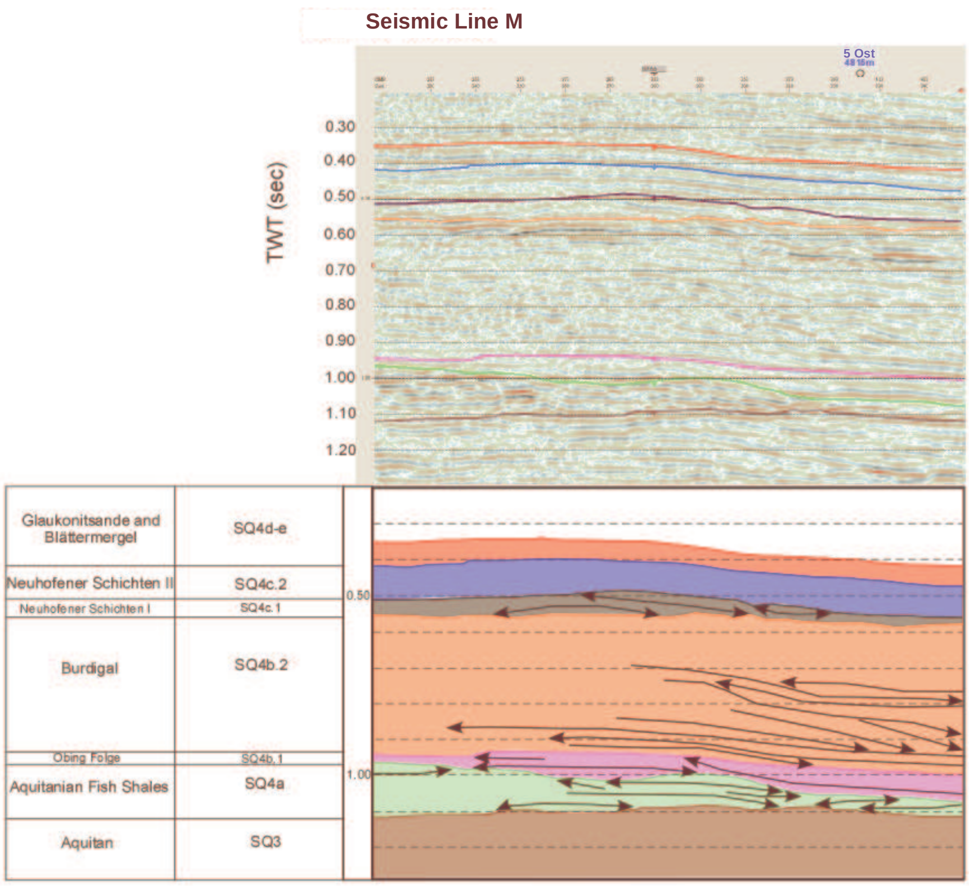


Figure 43. Seismic line M of the eastern part of the "Ostmolasse".





Figures 44 – 45. Details from seismic line M.

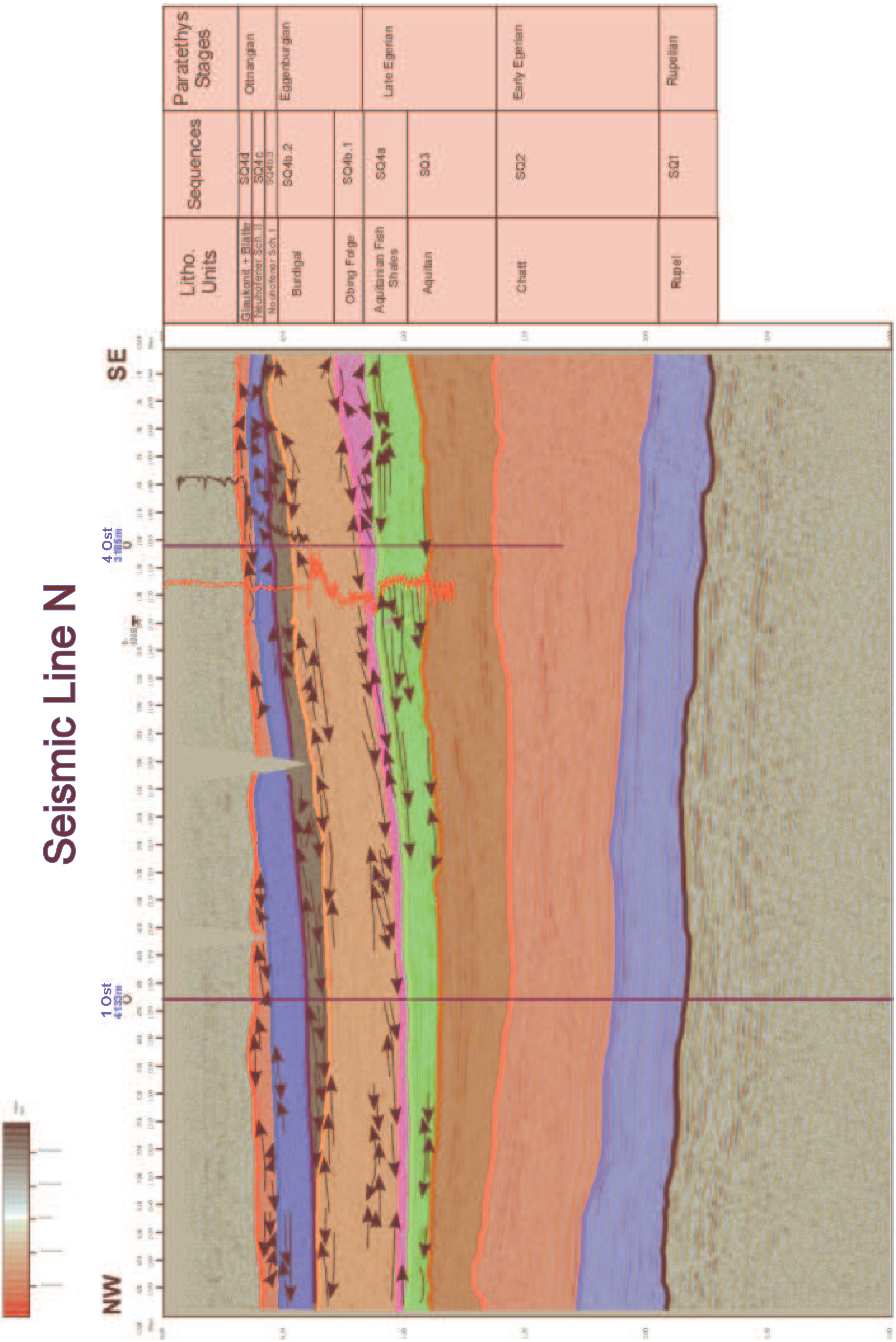


Figure 46. Seismic line N of the eastern part of the "Ostmolasse".

6. Construction of time, velocity, depth and isopach maps

6.1 Time, velocity and depth horizon surfaces in MapView

In this step of the analysis, I interpreted selected stratigraphical horizons with the program SeisVision. It is used to compute and create the time-depth curves (velocity surveys) and isopach maps of the defined horizons and to generate the synthetic seismograms for the wells with available sonic logs.

The interpretation in SeisVision is a collection of seismic and well data of the interpreted horizons and of the velocities in a specific geographic area within a GeoGraphix Discovery Project. The area of interpretation is determined dynamically by the geographic extent of the seismic and well data added to the interpretation.

The tops of the stratigraphic units are added to the results of the interpretation of the well logs with WellBase. Together with the single available velocity survey this allows a more realistic interpretation of the seismic surveys.

The surfaces of each unit are displayed in MapView and the seismic attribute maps are generated on any 2D surface within a time or depth interval. The map view is oriented with north to the top.

The obtained data are filtered, sampled and stored in a regular 3D grid; the two horizontal axes are the geographical coordinates of the seismic traces, and the vertical axis indicates the recording time, velocity and depth surfaces. Each cell of this grid contains a property value equal to the signal amplitude recorded at the captor and at the instant associated with the cell coordinates.

The figures 47, 48, 49, 50, 51 and 52 display the time, velocity and depth surface grids for each stratigraphic unit. All maps are shown in a horizontal cut.

In the depth maps, the colour scale indicates the depth in meters of the surface which is equidistant to the top and the base of each unit.

6.2 Time and velocity surface (figs. 47 - 50)

The time horizon surface is defined as the average of the minimum and maximum curvature and is usually dominated by the maximum curvature. Visually, it may not convey any additional information, but it is useful as velocity, depth and other attributes are derived from it. The time horizon surface is the base of the velocity and depth attributes presented in this study.

The conversion of time to depth uses the well time/depth function and then generates a velocity map.

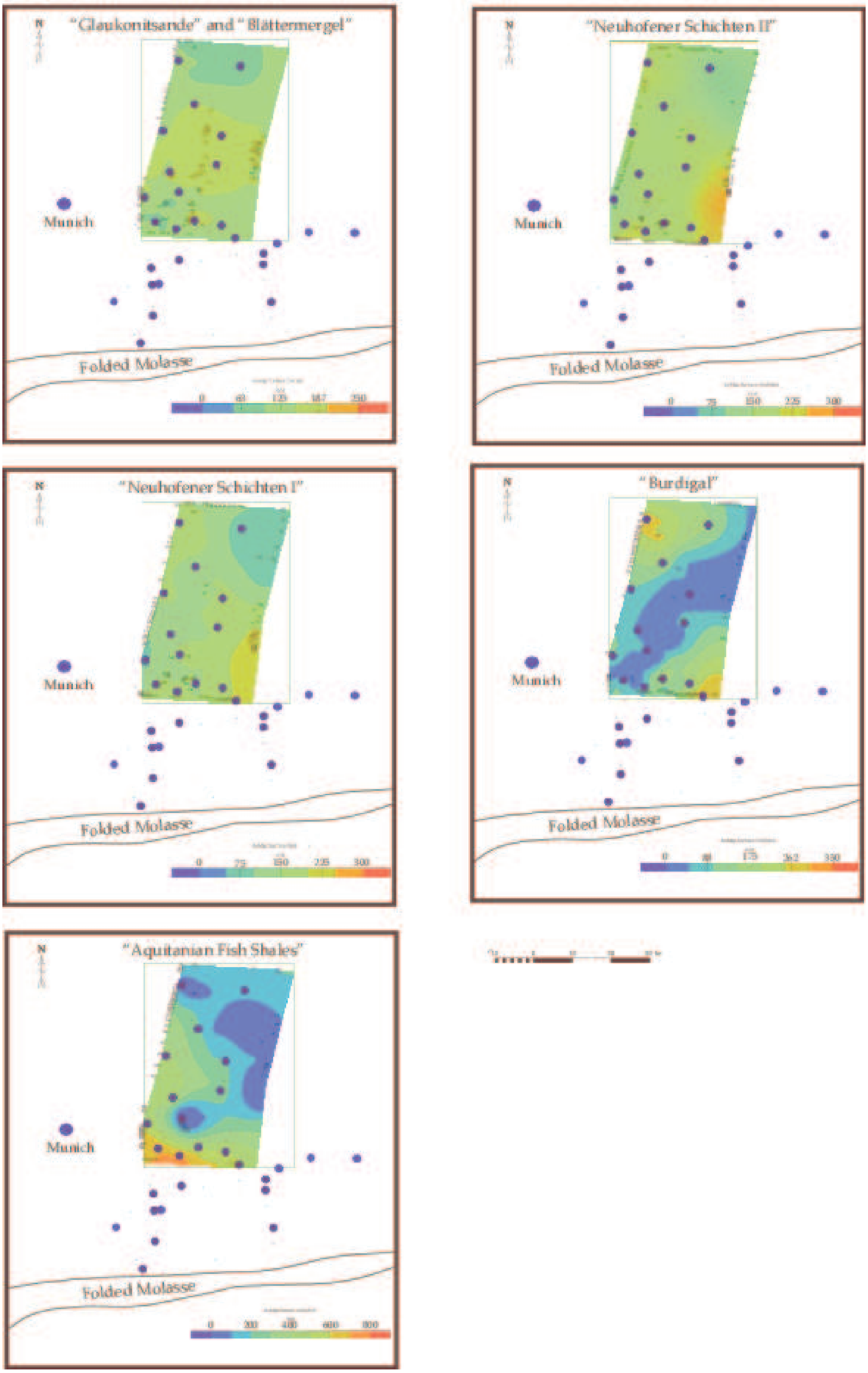


Figure 47. Time surface maps, western part of "Ostmolasse"

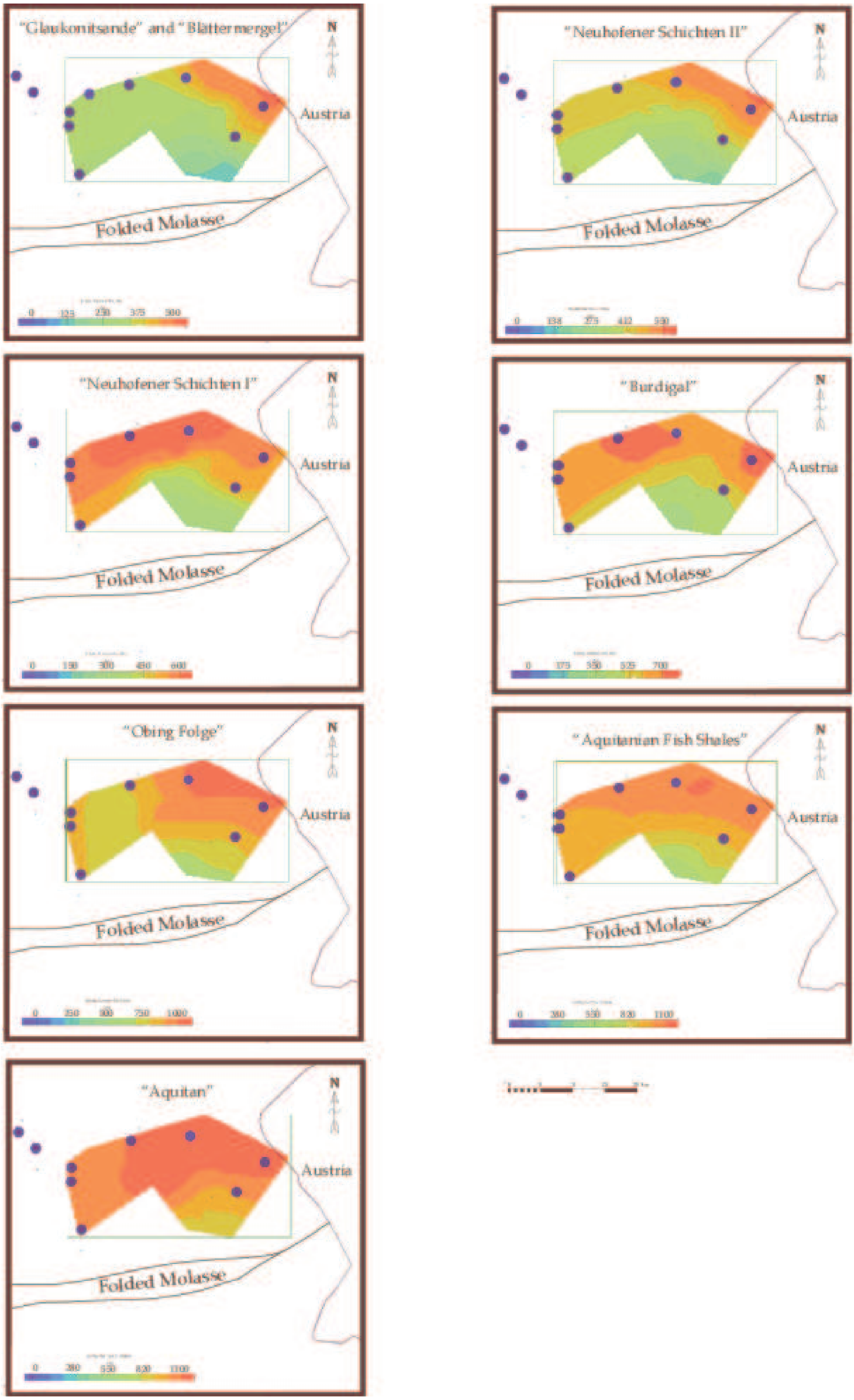


Figure 48. Time surface maps, eastern part of "Ostmolasse".

In this study, the velocities maps have been used to obtain a more accurate conversion to depth of the seismic data. The velocities maps can be optimized at the well locations during the velocity modelling process. The data can be viewed from any perspective to reveal complex spatial relationships in a 3D visualization.

The gridded time and velocity surfaces are based on the interpretation of seismic horizons that are interpolated on seismic grids. The first step is the selection of the extended mapping of the grids in SeisVision. In the "Ostmolasse", two separate polygonal areas corresponding to its western and eastern part include all available 2D seismic data.

The second step is to generate velocity surfaces that provide the information of the interval average velocities down to the interpreted horizon. During this process, SeisVision requires at least one well-based velocity survey to guide the interpretation of seismic horizons from which the tie times were derived. This velocity survey is also needed to allow the plotting of the well bores on the vertical seismic sections. The velocity survey can be a checkshot survey, a user-defined velocity survey (either manual or automatic), or derived from a synthetic seismogram. In this study, checkshot surveys and synthetic seismograms are used as the velocity surveys.

SeisVision used the following formula to calculate the velocity:

- Velocity = (depth2 - depth1)/ [0.5(time2 - time1)].

where the velocity between two horizons is the difference between well top depths divided by one half the difference between 2-way horizon tie times. The upper depth can be the reference datum and then the formula applies to average velocities.

In this study, I use the average velocity option for performing depth conversions. It allows to interpret and to convert to depth the selected horizons without being concerned with their stratigraphic order. If the average velocity option is selected, SeisVision determines depth values for a specific horizon based on its project datum and velocity as well as the interval average velocity of this horizon. This is the only option available, if velocity surveys are selected as the data source or if a horizon is selected as the reference datum.

The velocity grid system calculates average velocities from well top depths and seismic tie times. When displaying a velocity surface for a horizon, SeisVision posts the calculated velocities at the wells and uses these velocities to interpolate the velocity of the surface. Until the velocity surface is gridded, SeisVision displays colour-coded velocities only at entered well locations.

The third step is to generate a depth surface. SeisVision multiplies one-half of each grid value of the time surface by the corresponding grid value of the velocity surface. Due to the selected average velocity option, a single layer velocity model is obtained when converting each time surface to depth.

6.3 Interpretation of the Velocity Surface maps (see figs. 49, 50)

Knowledge of velocity values is essential in determining the depth, dip and horizontal locations of reflectors and refractors.

The sand content of the "Glaukonitsande and Blättermergel" (see fig. 49) and therefore its velocity values decrease in the northern part (region of the well C Ost). To the south, the highest velocity values corresponding to a higher percentage of sands are found in the area between N Ost and L Ost. In the eastern part of the "Ostmolasse", the highest velocity values for thi unit (fig. 50) can be observed near to the well 2 Ost. The sand content increases in the same direction. It decreases to the eastern part between the wells 5 Ost and 4 Ost.

The highest velocity values of "Neuhofener Schichten II" (see fig. 49) in the western part of the "Ostmolasse" are observed to the south, in an area between 4 Ost and L Ost. This is due to a higher sand content but also to the greater burial depth in this region. The smallest velocities and the lowest sand content are found close to D Ost. In the eastern part, the sand content in the "Neuhofener Schichten II" (fig. 50) decreases to the south at Z Ost and it increases to the centre of the area near 2 Ost, where the highest velocity values are observed.

In the western part of the "Ostmolasse", the sand content of the "Neuhofener Schichten I" (fig. 49) increases towards the centre of the study area in the region of J Ost and N Ost which displays the highest velocity values. In the eastern part of the "Ostmolasse", the velocity of this unit (fig. 50) increases to the north-west near the wells R Ost and 2 Ost. Possibly, there the sand content is higher than in the region of the wells Z Ost and 5 Ost.

The highest velocity values of the "Burdigal" (fig. 49) are observed in the centre of the western part of the "Ostmolasse" (between H Ost 2, H Ost, G Ost 2 and G Ost). As the values decrease towards the south, the relatively high velocities in the central area may be caused by an increased sand content. Toward the eastern part of the studied area, the highest velocities of the "Burdigal" (fig. 50) are found in the central and the north-western part. The sand content increases in the same direction. The velocity values decrease toward Z Ost and 5 Ost.

In the unit "Obing Folge" (fig. 50), the sand content increases to the west. The highest velocity values are observed at V Ost. These values decrease to the east near 4 Ost.

The highest velocities and sand content of the "Aquitanian Fish Shales" (see fig. 49) are found in the region between H Ost 2 and G Ost 2 and in the area of N Ost and S Ost, in the western part of the "Ostmolasse". The decrease of the velocity to the north (C Ost) is probably linked to the shallower burial depth, but also to a decrease of the sand content. To the eastern part, the velocity for this unit (fig. 50) increases toward 5 Ost, R Ost and V Ost, where the highest values of this

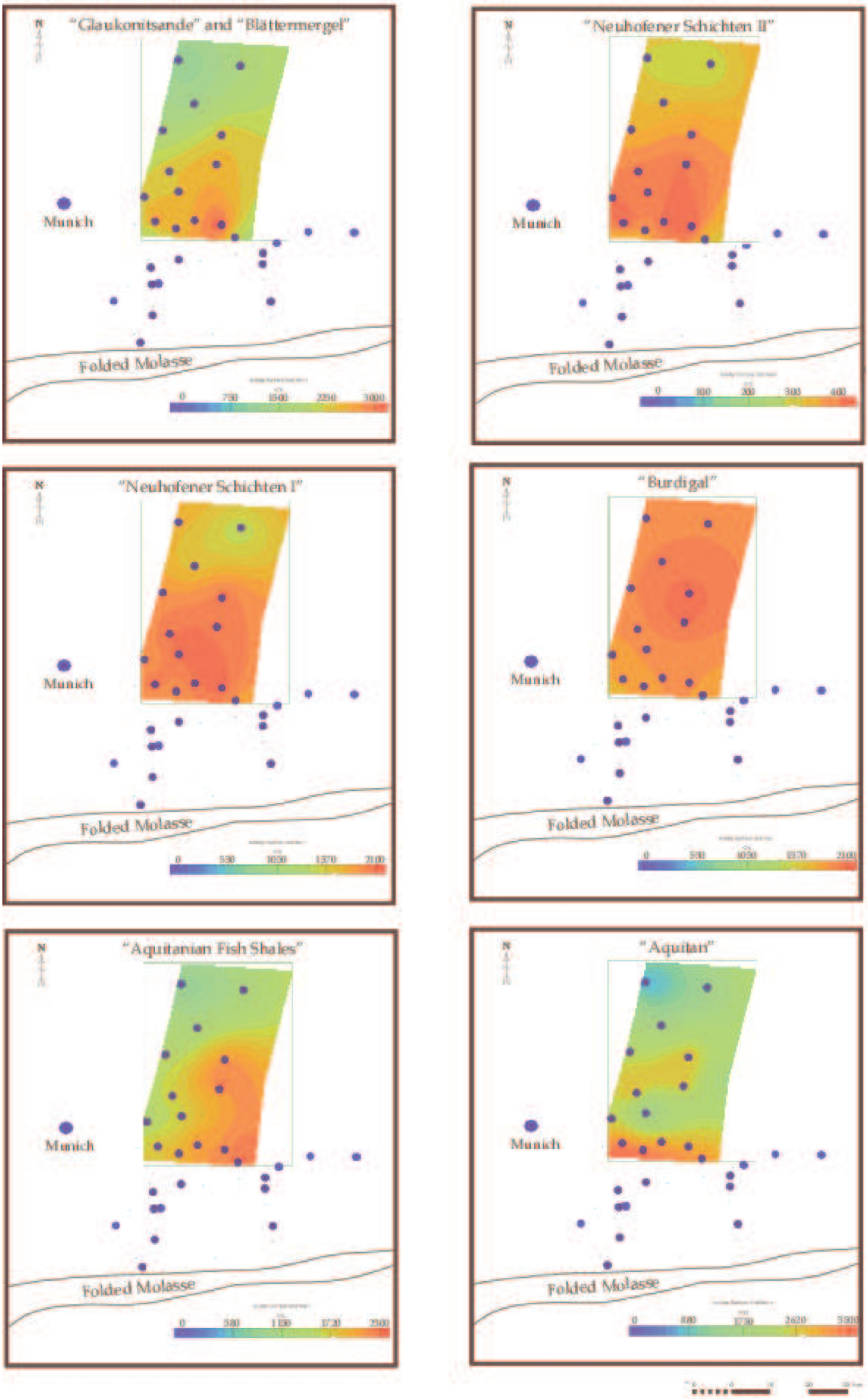


Figure 49. Velocity surface maps, western part of "Ostmolasse".

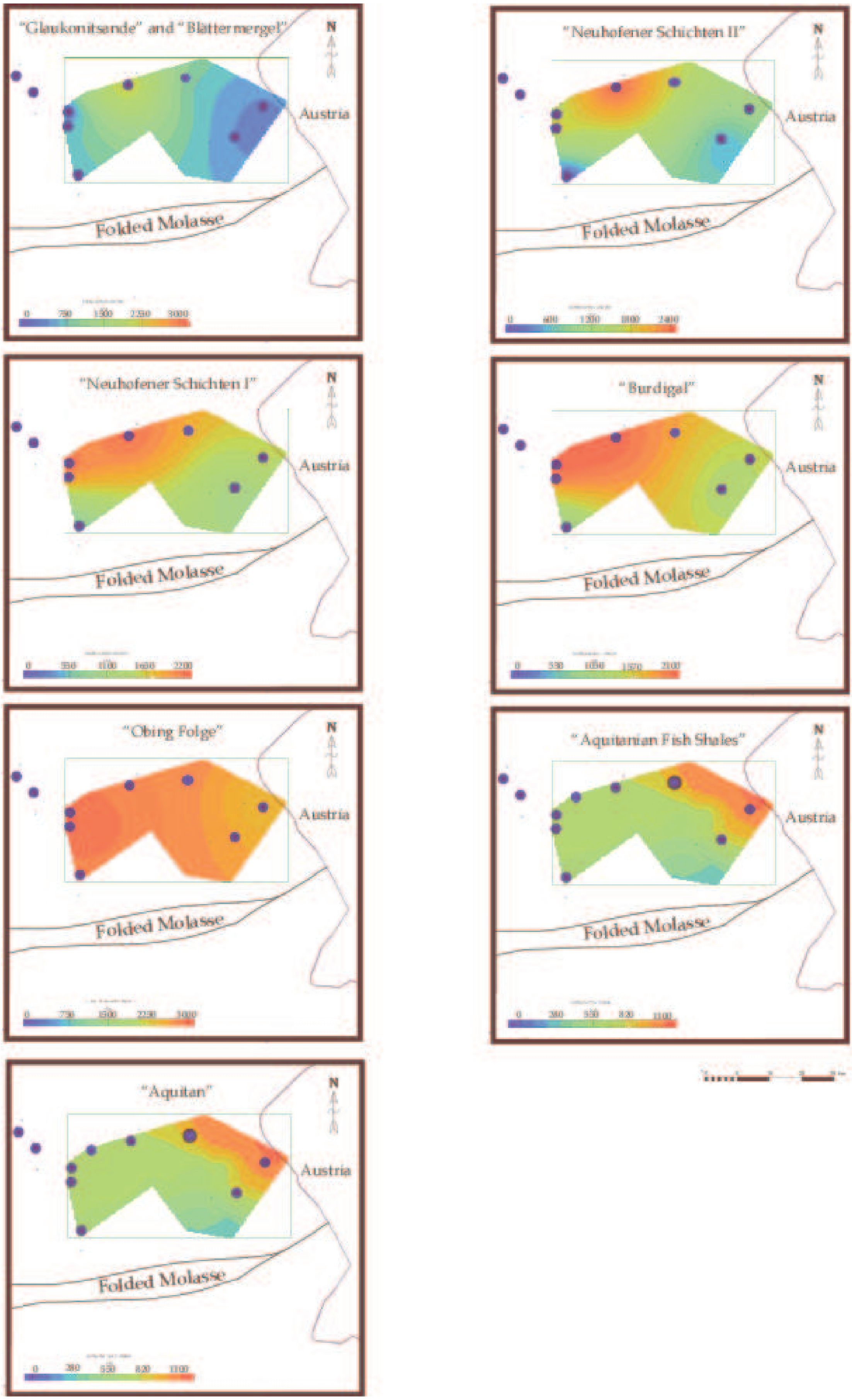


Figure 50. Velocity surface maps, eastern part of "Ostmolasse".

unit are found. They decrease in direction of Z Ost in the south of the “Ostmolasse”.

The highest velocity values within the “Aquitanian” (fig. 49) are observed toward the south in the area of M Ost, O Ost and O Ost 2. They decrease towards C Ost in the northern part. This pattern is again caused by an increase of both the sand content and the burial depth to the south of the basin. In the eastern part of the “Ostmolasse”, the velocities and the sand content of the “Aquitanian” (see fig. 50) increase to the southeast towards 5 Ost and they decrease toward Z Ost in the south.

6.4 Interpretation of the Depth Surface maps (figs. 51-52)

In the western part of the “Ostmolasse” the greatest burial depths for the “Glaukonitsande” and “Blättermergel” (fig. 51) are near C Ost and the shallowest ones in the area of N Ost. In the eastern part, the deepest occurrences of the “Glaukonitsande“and “Blättermergel” (fig. 52) units are at 5 Ost in the south-eastern part of the “Ostmolasse”. The burial depth decreases to the area of 2 Ost and 3 Ost in the centre of the “Ostmolasse”.

The grid map of the depth surface for the “Neuhofener Schichten II” (fig. 51) unit is similar to that of the overlying unit “Glaukonitsande and Blättermergel”. The shallowest values are observed near N Ost and the deepest ones in the area between C Ost and D Ost. Toward the eastern part, the greatest burial depth of “Neuhofener Schichten II” (fig. 52) is again near to 5 Ost and Z Ost in the southtern part of the “Ostmolasse” and its shallowest occurrences are in the centre of the “Ostmolasse” at 2 Ost.

The depth of the “Neuhofener Schichten I” (fig. 51) decreases toward the centre of the “Ostmolasse” in the area between H Ost and N Ost. This unit has its deepest burial at D Ost. The depth of this stratigraphic unit (fig. 52) decreases toward 2 Ost, i.e. the northeastern part of the centre of the analysed area. It increases toward the southern part in direction of 5 Ost.

The burial depth of the “Burdigal” (fig. 51) unit decreases towards the central part close to N Ost and L Ost. The greatest burial depth of this unit (fig. 52) is in the southern part of the “Ostmolasse” near 5 Ost and Z Ost, whereas its depth decreases to the area of 2 Ost, 4 Ost, R Ost and V Ost.

The deepest occurrence of the “Obing Folge” (fig. 52) is in the southwestern at 5 Ost and the shallowest one in the northern part at 1 Ost.

The depth of the “Aquitanian Fish Shales” (fig. 51) increases to the north of the basin in the area of C Ost and it decreases toward the centre close to S Ost. In the eastern part of the “Ostmolasse”, the burial depth of this stratigraphic unit (fig. 52) decreases toward 1 Ost and R Ost and it increases toward the south in the area of 5 Ost and Z Ost.

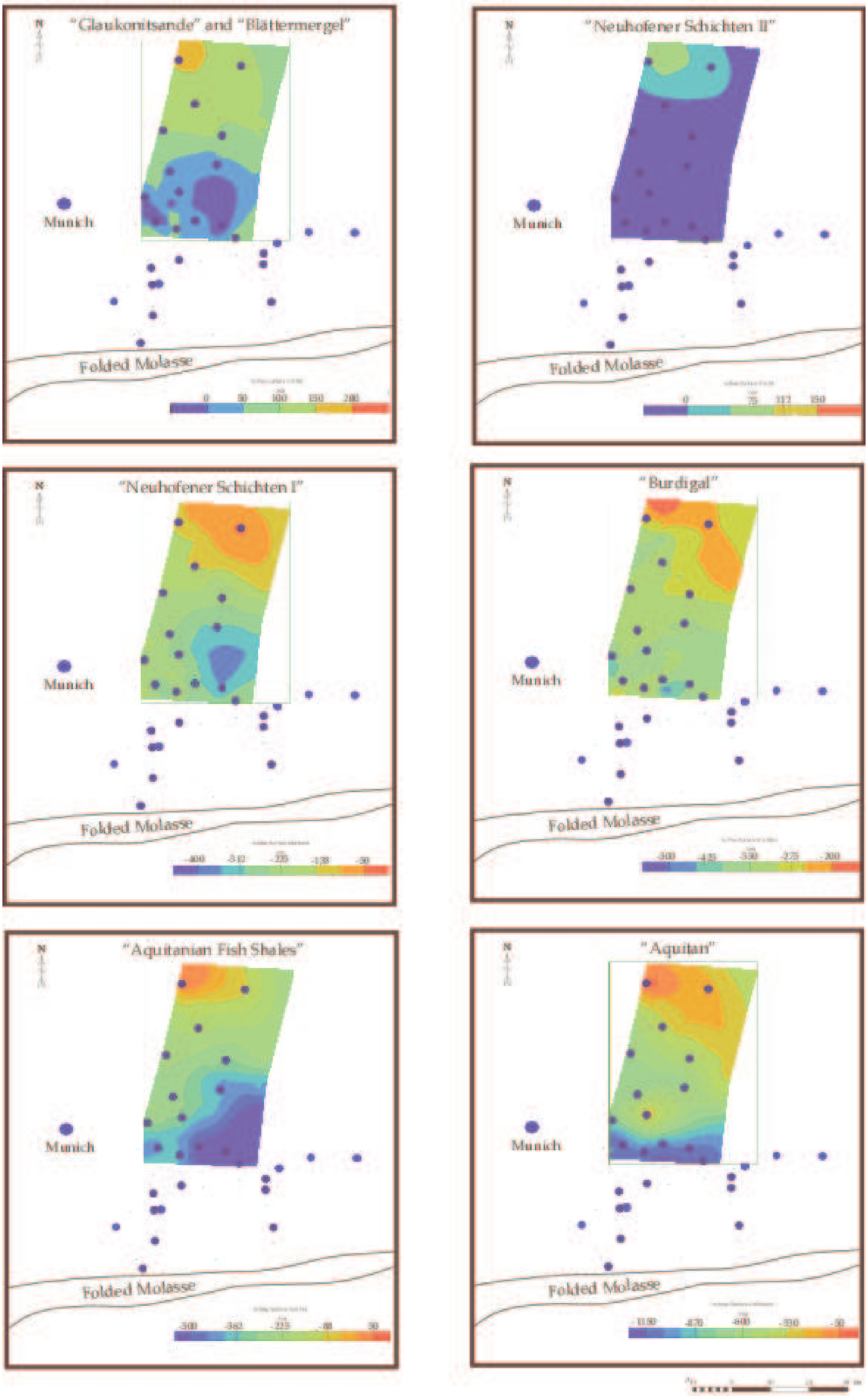


Figure 51. Depth surface maps, western part of "Ostmolasse".

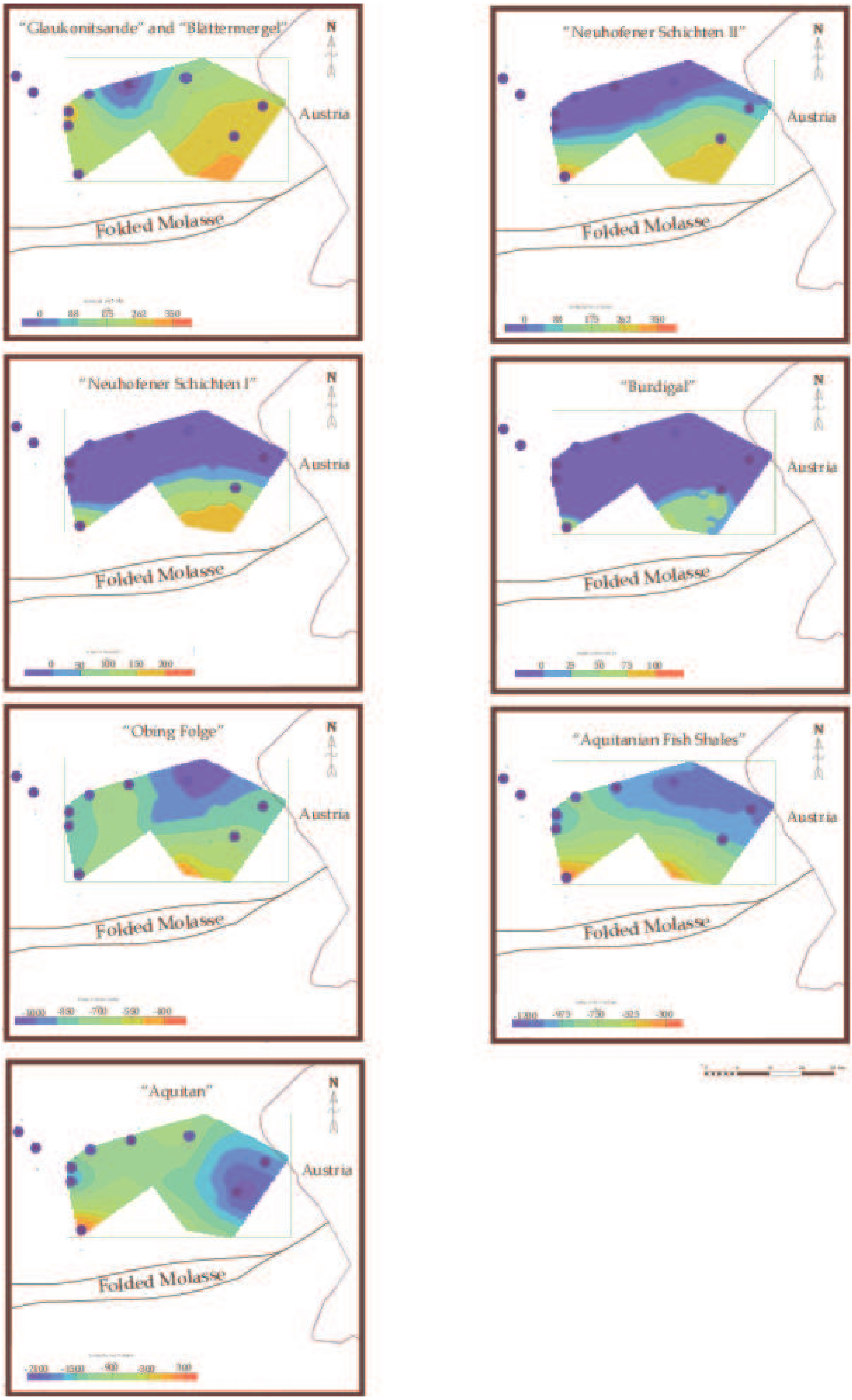


Figure 52. Depth surface maps, eastern part of "Ostmolasse".

In the "Aquitanian" (fig. 51), the burial depth increases northward in direction of C Ost and it decreases toward the centre in the area of O Ost, O Ost 2 and S Ost. The burial depth for this unit (fig. 52) decreases at 5 Ost and 4 Ost in the eastern part. The deepest occurrence is in the area of Z Ost.

According to the surface depth maps, the greatest burial depth of the stratigraphic units in the western part of the "Ostmolasse" is observed in the north-western area of the basin and it decreases toward the south-center area. In the eastern part of the "Ostmolasse", the burial depth pattern is more complex, it increases to the South and decreases to the North, due to the tectonics differences present in the area. This area is very close to the allochthonous Folded Molasse.

6.5 Interpretation of the Isopach Maps (figs. 53-54)

The horizon isopach maps for the various stratigraphic units have been calculated in SeisVision to extract an isopach surface between a selected shallower and a deeper horizon, whose data are included in the calculation. For this extraction, it was necessary to interpret a velocity surface for the deeper horizon.

In the western part of the "Ostmolasse", the greatest thickness of these two units, "Glaukonitsande" and "Blättermergel" (fig. 53) is observed close to the well G Ost 2 where it exceeds 110m. It decreases to less than 100m to the north, towards the well D Ost and to the southwestern corner of the area. In the eastern part, the combined thickness of these two units (fig. 54) increases to the centre and northwest of the gridded area. In the vicinity of V Ost, it reaches more than 250m. It is less than 100m in the southern part.

The "Neuhofener Schichten II" (see fi. 53) reach their greatest thickness (< 225m) in the southeastern part. An average thickness between 150 and 175m is observed in the central part of the study area. It decreases to less than 100m in the north-eastern part close to D Ost and to the southwest near M Ost. The thickness of the "Neuhofener Schichten II" (fig. 54) in the eastern part is less than 150m in the area south of 5 Ost and in the vicinity of 4 Ost, whereas it increases its thickness in the northwestern part to more than 250m near Gr Ost 1.

The pattern of the changes in thickness of the "Neuhofener Schichten I" (fig. 53) is rather different from that of the "Neuhofener Schichten II". Their thickness decreases towards the center and the southeast (< 100m), whereas the greatest thicknesses (<210m) are observed in the north at E Ost and near D Ost. As in the area studied in the western part of the "Ostmolasse", the "Neuhofener Schichten I" in the eastern part of the "Ostmolasse"(fig. 54) tend to reach their greatest thicknesses in areas in which the "Neuhofener Schichten II" are relatively thin. They reach a maximum of more than 150m in the southeastern corner, south of 5 Ost and south of 2 Ost, whereas they thin to less than 50m to the northeast of 4 Ost.

The thickness distribution of the "Burdigal" (fig. 53) is somewhat comparable to that of the "Neuhofener Schichten II". The lowest values of less than 75m are found in a

NE-SW stretch with G Ost 2 in its center, the highest ones occur in the NW near E Ost (<260m) and in the southeastern corner near R Ost (<280m). The thickness of this unit (fig. 54) increases to the north of 5 Ost and to the southwest at Z Ost to more than 800m and it decreases toward the north-western part of the eastern part of the "Ostmolasse" to less than 450m.

The isopachs of the lowstand deposits of the "Obing Folge" (see fig. 54) show a very irregular pattern. Its greatest thickness (>500m) is found in the southwest near Z Ost. It exceeds 250m east of 4 Ost, 200m near 2 Ost and 150 m at V Ost 1, whereas as a stretch with thicknesses of less than 50m runs from east to west in the southern central part of the analysed area.

The thickness of the "Aquitanian Fish Shales" (fig. 53) increases to the south of the western part of the "Ostmolasse" (region of the wells O Ost and O Ost 2), where it reaches more than 680m. It decreases to less than 200m towards northeast, but the isopachs display a rather complex pattern. The thickness of this unit in the eastern part of the "Ostmolasse" (fig. 54) increases to more than 500m to the east with its maximum exceeding 1000m at B Ost 1 and to the southwest. The areas of Z Ost with more than 600m and of V Ost with up to 500m are separated by a rather narrow area with less than 125m. The "Aquitanian Fish Shales" thin to less than 50 to the north.

The isopach maps of the two areas studied in the "Ostmolasse" show quite different patterns. In the western area, the thicknesses of all stratigraphic units except the "Neuhofener Schichten" increase toward its southeastern corner and decrease to the northwest in agreement with the asymmetric architecture of a typical foreland basin. The eastern part displays a more complex pattern due to its location at the western margin of the late Oligocene/early Miocene basin centred in Upper Austria. "Glaukonitsande "and "Blättermergel", "Neuhofener Schichte I and II" are thicker in the northern and the central part of the area, whereas it decreases eastward. The greatest thicknesses of the "Burdigal" and the "Aquitanian Fish Shales" are observed in the east and southwest, whereas they thin northward. The "Obing Folge" thickens in the proximal western part and thins toward the center of the area.

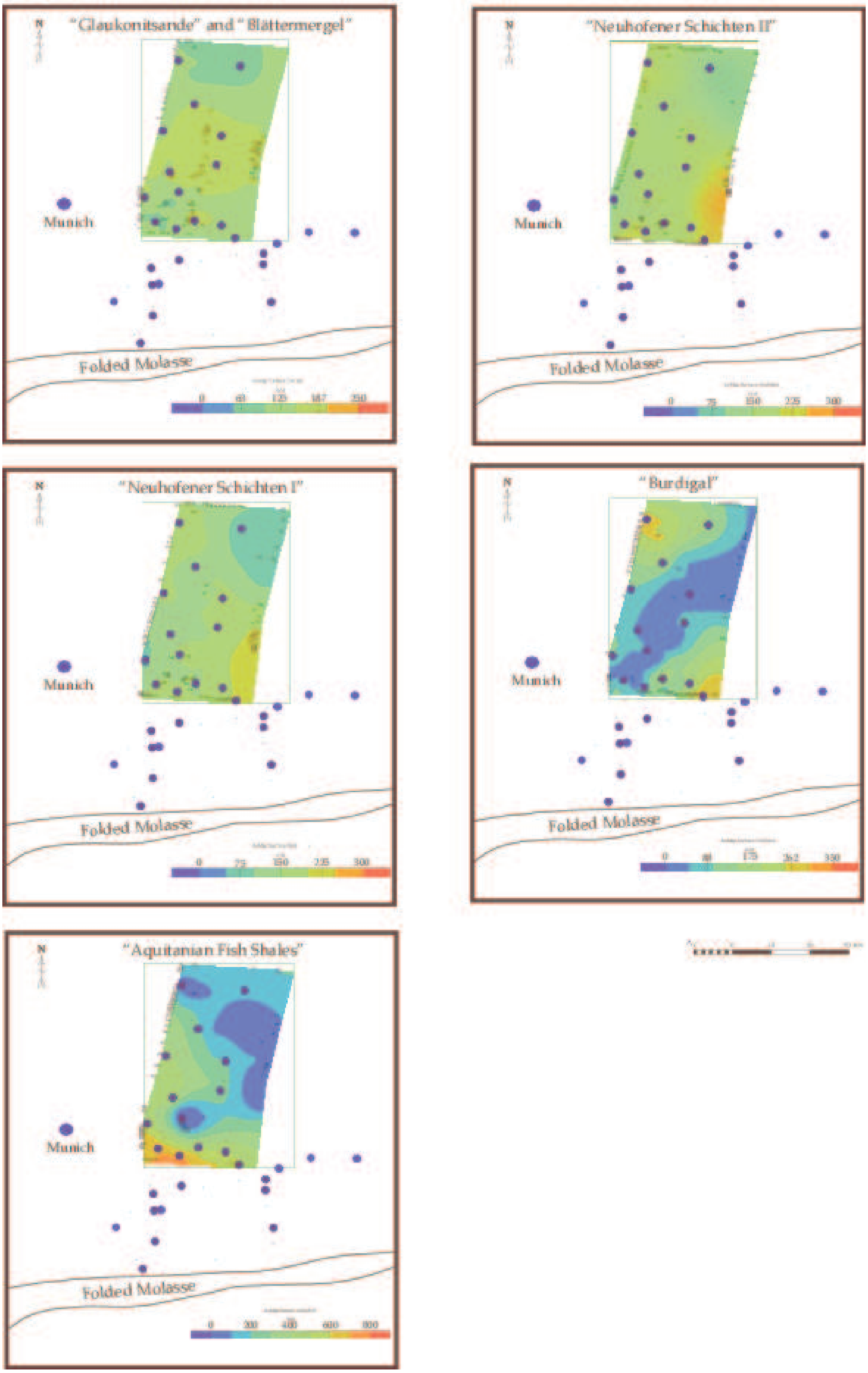


Figure 53. Isopach maps, western part of "Ostmolasse".

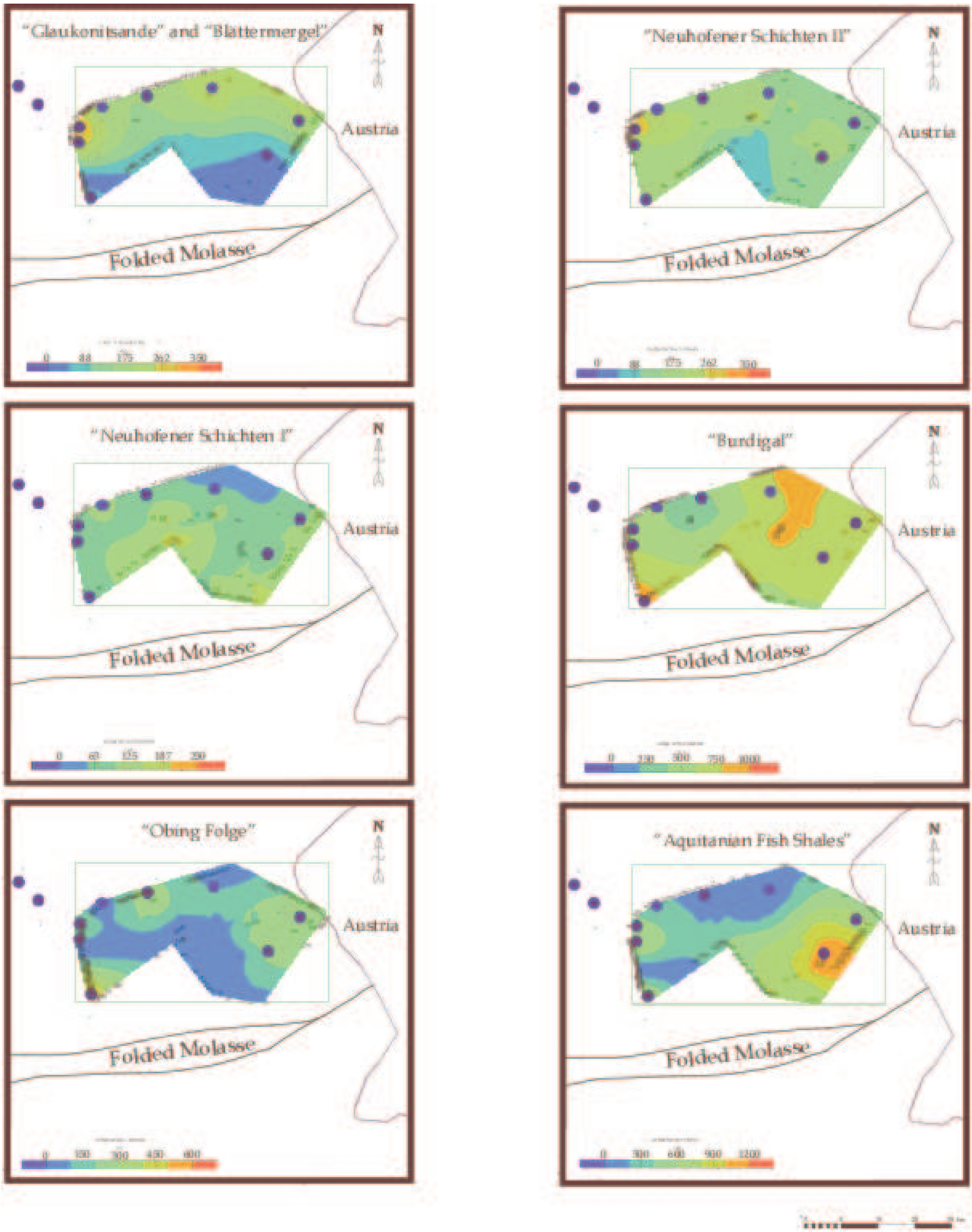


Figure 54. Isopach maps, eastern part of "Ostmolasse".

7. CONCLUSIONS

The present investigation of the Upper Marine Molasse (early Miocene) of the German part of the Northalpine Molasse Basin is mainly based on a large number of subsurface data (72 wells and 14 seismic lines) made generously available by the German oil companies. The subsurface data have been digitized with LogScan® (Briere Engineering) and reinterpreted with the program Geographix® (Landmark Graphics). This interpretation program has been used to integrate all data into cross sections and maps. A considerable amount of these data has not been published previously.

The German part of the Molasse Basin, which reaches from Lake Constance in the west to the Inn River to the east, is traditionally subdivided into the "Westmolasse" and "Ostmolasse". During the Oligocene, the region to the west of Munich ("Westmolasse") is characterized by continental and marginally marine to lacustrine deposits. In the area of the "Ostmolasse" which is transitional to the basinal area of Upper Austria ("Puchkirchen Trough"), marine and in part deep-water deposits prevailed during the same time. The transitional area between the two realms is characterized by a shifting coastline. At the Oligocene/Miocene boundary, brackish lagoonal facies reach as far to the west as the Iller River dividing the Lower Freshwater Molasse into a lower and an upper part. More uniform conditions return to both the "West-" and most of the "Ostmolasse" with the deposition of the shallow-marine Upper Marine Molasse. The scarcity of subsurface data from the area intermediate between the "Westmolasse" and "Ostmolasse" prevents a detailed correlation of the two depositional realms.

Depositional History of the Upper Marine Molasse

The second megasequence of the Molasse (Upper Marine Molasse and Upper Freshwater Molasse) starts in E Bavaria during the early Burdigalian (Eggenburgian). In E Bavaria, a marine transgression on fluvial to brackish deposits progresses westward out of the area between Chiemsee and the Salzach River. The axis of the depositional trough is close to the present-day Alpine Front. In this area, the lower part of the Burdigalian contains in part deposits which are comparable to the deeper marine "Upper Puchkirchen Schichten" in Upper Austria. According to Zweigel (1998), this marine transgression is caused by a rather sudden cessation of thrusting in the Eastern Alps combined with the viscoelastic relaxation of the European Plate. The foreland basin changes from the overfilled status during the deposition of the Lower Freshwater Molasse and its equivalents to the underfilled status during the deposition of the Upper Marine Molasse (Zweigel 1998).

The transgression extends to N and NW, but the thickness of the marine Burdigalian decreases rapidly (e.g. Lemcke 1988, Wagner 1982). At its northern edge, it is unconformably overlying the Aquitanian. South and east of Munich, the coastline bends southward and continues westward in the present-day Subalpine Molasse. At the same time, a marine transgression extends eastward out of western Switzerland into the southern part of the "Westmolasse" and finally connects with the marine

Burdigalian of the "Ostmolasse". However, this connection does not take place during the older part of the Burdigalian ("Land-Burdigal" of F.Müller 1980, "Burdigal-Anteil der USM II of authors). During a second transgressive pulse, the shallow sea of the Upper Marine Molasse encroaches on the Swabian-Franconian Alb up to the "Klifflinie" which marks its northernmost extension.

In the late Burdigalian (Ottnangian), the prevailing shallow-marine conditions coincide with a global sea-level highstand. The marine transgression floods a southwestward draining river valley north of the foreland bulge. The sea invades again Eastern Bavaria out of NE-Switzerland via the "Graupensandrinne" reaching initially the area of the Chiemsee and the Salzach River and depositing the "Kirchberger Schichten" in the area of the "Westmolasse" and the "Oncophoraschichten" in Lower Bavaria and Upper Austria (see Lemcke 1984, Bachmann and Müller 1991, Steininger et al. 1976, Schwerd, Doppler and Unger 1996, Kuhlemann and Kempf 2002, Bieg 2005). Before the end of the Burdigalian (Ottnangian), the sea has completely retreated from the German part of the Molasse Basin.

Stratigraphic units of the Upper Marine Molasse

"Westmolasse":

The Upper Marine Molasse of the "Westmolasse" is subdivided into three packages: a lowermost coarse grained transgressive sequence rich in bioclasts ("Basisschichten"), a sandy and marly middle part with a very poor fossils record ("Sandmergelserie I and II") and an upper mainly coarse-grained regressive unit again rich in clasts ("Baltringer Schichten" and "Feinsandserie").

The so-called "Basisschichten" consist of coarse- to medium-grained sandstones with minor intercalations of marls and siltstone. In places, coarse-grained sandstones to gravel with abundant glauconite are found at the top. The base of this transgressive unit is composed by fine to middle-grained sandstones with intercalated calcareous silts and marls with some feldspar. The large amount of marine organisms (abraded fragments of bivalve shells, shark teeth) and the sedimentary structures and textures indicate deposition in a marine nearshore high-energy environment (e.g. Homewood 1981). The thickness of the Basisschichten varies from 20 to 35 m in the studied wells.

The middle unit, the "Sandmergelserie" has been subdivided into two units: the "Sandmergelserie I" consists mainly of marly fine- to medium-grained sandstones with occasional coarser intercalations and coaly debris, whereas the "Sandmergelserie II" predominantly includes grey claystones, sandy marls and siltstones and sand flasers. In some layers, coaly debris are observed. The "Sandmergelserie I and II" have been deposited in greater water-depths than the other units of the Upper Marine Molasse (e.g.Lemcke, 1984) in predominantly subtidal environments. The observed combined thickness of the "Sandmergelserie I and II" varies from only 10m up to 110 m.

The regressive unit is composed by the "Baltringer Schichten" and the "Feinsandserie".

The "Baltringer Schichten" typically consists of well-bedded rather coarse sandstones with layers in which the components may reach gravel-size and, in places, pebbles of Alpine origin and fragments of oysters and other molluscs ("Muschelschillbank"). They have been deposited in a high-energy nearshore to shore environment. The average thickness of the "Baltringer Schichten" does not exceed 30 m.

The transition into the overlying siltstones to fine-grained sandstones of the "Feinsandserie" is gradual but rapid. In a few wells, intercalations of up to 2-3m of grey to green-grey sandy calcareous marls are described. They may correspond to sediments deposited in shallow ponds and lagoons. The thickness of the "Feinsandserie" is 2 to 8m.

In the W-E cross section (figs. 9, 10), the thickness of stratigraphic units remains relatively constant. The sand content increases in the "Feinsandserie" and the "Baltringerschichten" from west to east, in the "Sandmergelserie II" to the south. The thicknesses of all units remain relatively uniform in the W-E and also the N-S transect.

Seismic stratigraphy

The only seismic line available from the Westmolassse is the NW-SE running Line A. It is of rather poor quality and the depositional patterns within the different units could not be recognized clearly. The different stratigraphic units – with the exception of the "Feinsandserie" – are recognized based on differences in the reflectors and the correlation with A West.

In the "Westmolasse", the same five seismic sequence boundaries established by Jin (1995) and Zweigel (1998) in the "Ostmolasse" (Jin, 1995; Zweigel, 1998) could also be recognized in the "Westmolasse". I have analyzed the sequence SB4, which includes the uppermost part of the "Untere Süßwasser Molasse" and the Upper Marine Molasse. This sequence is subdivided into 5 subsequences:

Subsequence 4a: "Untere Süßwasser Molasse" (upper part)
Subsequence 4b: "Basisschichten"
Subsequence 4c.1: "Sandmergelserie I"
Subsequence 4c.2: "Sandmergelserie II"
Subsequence 4d: "Baltringer Schichten".

All subsequences lap onto the Lower Freshwater Molasse, the top of which is marked by erosive channels indicative of a relative sea-level fall. The "Sandmergelserie" is in turn onlapped by the "Baltringer Schichten". Channelings observed at its top indicate the beginning of the regression of the Burdigalian Sea.

"Ostmolasse"

The "Ostmolasse" has been divided into a western and an eastern part (Fig.14). The western part corresponds to the shelf area of the Oligocene, whereas the eastern part is transitional to the outer neritic and bathyal succession in Upper Austria.

Stratigraphic Units

The Upper Marine Molasse of the "Ostmolasse" is again subdivided a basal transgressive part with the "Aquitanian Fish Shales", the "Obing Folge" and the "Burdigal", a middle part with the "Neuhofener Schichten I and II" and an upper regressive part with the "Glaukonitsande" and "Blättermergel".

"Aquitaine Fish Shales": Approximately 120m of dark sandstones with intercalations of dark shales deposited in a quiet oxygen-deficient marine environment.

"Obing Folge": The sandstones and sandy claystones with intercalations of sandy marls and limestones of the 110 to 470m thick "Obing Folge" are outer neritic to bathyal deposits with turbidites. The "Obing Folge" is restricted to the eastern part of the "Ostmolasse".

"Burdigal": The 335m to 850m thick "Burdigal" is composed of grey claystones which grade into sandy marls and sandstones. The glauconitic sandstones are in part coarse-grained or even gravelly at the base and the top close to the fan deltas of the Alpine front. The axial area corresponds to a shallow sea with strong tidal influence (Zweigel, 1998; Bieg, 2005).

"Neuhofener Schichten I": The grey claystones and sandy marls with intercalated fine to coarse sandstones have been deposited in a shallow-marine and tidally influenced environment. Thickness: 5-210 m.

"Neuhofener Schichten II": The "Neuhofener Schichten II" consist of grey claystones which may grade into sandy marls and into marly sandstones and a few intercalations of light grey calcareous marl and limestone. The thickness of this unit varies between 30m and 210 m. The shells and fragments of bivalves and gastropods and the shallow-marine microfauna are indicative of a shallow-marine predominantly subtidal environment.

"Glaukonitsande" and "Blättermergel": these two units are discussed together because their lithology and depositional environment are very similar. Both units consist of grey claystones and marls with gradations into grey sandy marls, fine to coarse glauconitic sandstones and some limestone beds. Their thickness varies from 90 to 260m. The unit shows an overall shallowing-upward trend. The presence of a "kümmerfauna" indicates a restricted shallow-marine environment.

In the N-S cross section (Figs. 16 to 21), all stratigraphic units increase in thickness towards the south, except the "Glaukonitsande" and the "Blättermergel" which have a relatively uniform thickness. A pronounced angular unconformity is developed between the "Aquitanian Fish Shales" and the "Burdigal". The "Burdigal" and the "Neuhofener Schichten I" disappear towards the North and both display progressive northward onlap. The "Neuhofener Schichten II" are thinning towards north. In all units, the sand content increases units towards the south.

In the W-E cross section (Figs. 22, 23, 31 and 32), the "Burdigal" and the "Neuhofener Schichten I" show a progressive westward onlap onto the "Aquitaine Fish Shales". In all units, the sand content increases moderately towards the east. The "Burdigal" increases its thickness substantially towards the East, whereas the "Glaukonitsande and Blättermergel", the "Neuhofener Schichten II" and the "Neuhofener Schichten I" have rather uniform thicknesses in all wells of the cross section.

Seismic stratigraphy

Western part of "Ostmolasse" (Figs. 24 to 32)

The "Aquitaine Fish Shales" (Subsequence 4a) lap onto the erosive surface of the Aquitaine Sands, which are incised by deep erosive channels at the top. This subsequence 4a dips to the SW and it displays some toplaps towards N. Its boundary with Subsequence 4b is marked by erosive channels caused by a relative sea-level fall.

The parallel to sub-parallel reflectors at the base of Subsequence 4b ("Burdigal") lap onto the eroded surface of Subsequence 4a ("Burdigal") and indicate uniform and undisturbed sedimentation. In its middle part, some internal onlaps, downlaps and channels are frequent. The subsequence increases its thickness southward. The top is again characterized by channels which may indicate another minor sea-level fall. Subsequence 4b is interpreted as transgressive unit while the inclined reflectors are thought to represent W-E delta progradation (Zweigel 1998).

Subsequence 4c.1 ("Neuhofener Schichten I") laps with an erosive boundary onto the "Burdigal". The amplitudes of the channels increase westward. The thickness of Subsequence 4c.1 increases rather abruptly to both the S and the SE and decreases to the NE.

The Subsequence 4c.2 ("Neuhofener Schichten II") is interpreted as a shallow-marine lowstand deposit based on the interpretation of the well data and correlation with the Puchkirchen area. Its bulk consists of parallel to subparallel reflectors of variable amplitude which suggest uniform sedimentation on an even bottom topography. Subsequence 4c.2 laps onto the Subsequence 4c.1 and its thickness decreases southward. A few reflectors dip in the same direction.

The Subsequences 4d-e ("Glaukonitsande" and "Blättermergel") are dominated by parallel reflectors. They are separated by a very continuous high amplitude reflector into a lower low-amplitude and an upper high-amplitude facies. They are interpreted to represent lowstand and highstand deposits respectively, whereas the continuous reflector is the maximum flooding surface (Zweigel, 1998).

Subsurface data, eastern part of “Ostmolasse”:

In the N-S cross section of the eastern part of the “Ostmolasse” (Figs. 31 and 32), the patterns of the lateral changes are more complex than in the western part. The “Obing Folge” decreases its thickness southwards. The “Glaukonitsande and Blättermergel”, the “Neuhofener Schichten I” and the “Burdigal” have relatively uniform thicknesses. In the “Glaukonitsande” and “Blättermergel” as well as in the “Aquitaine Fish Shales”, the sand content diminishes towards S, whereas in the “Neuhofener Schichten II” and the “Neuhofener Schichten I”, it remains relatively constant. The “Burdigal” has its lowest sand content in the central part of the cross section.

Seismic stratigraphy (Figs. 33 to 36)

The Subsequence 4a (“Aquitaine Fish Shales”) onlaps the eroded surface at the top of the “Aquitaine Sands” in a northwestward direction. Its thickness increases to the S. The eroded top is marked by distinct toplap in NE and SE direction and erosive channels. Within the “Aquitaine Fish Shales”, a strong continuous reflection separates the unit into a lowstand and a highstand systems tract. According to Zweigel (1998), the seismic facies of the lowstand deposits is similar to that of the turbidites in the Puchkirchen Trough.

The Subsequence 4b.1 corresponding to the “Obing Folge” is onlapping in NW direction the underlying Subsequence 4a. This subsequence, which has not been differentiated by Zweigel (1998), appears below a group of eastward directed downlap patterns of the “Burdigal” (Subsequence 4b.2) and its thickness decreases to the SW. Higher up in the subsequence, strong parallel reflectors with southward onlap and erosive channels mark the transgressive systems tract.

Strong parallel reflectors with pronounced onlap towards NW mark the transgression of the Subsequence 4b.2 (“Burdigal”). In its upper part, a thick interval of NE prograding downlapping surfaces is observed. The parallel reflections indicate the uniform sedimentation on a stable bottom topography following the relative lowering of the sea-level at the boundary between sub-sequences 4b.1 and 4b.2. The oblique reflectors are thought to represent W-E delta progradation.

The Subsequence 4c.1 corresponding to the “Neuhofener Schichten I” laps westward onto the “Burdigal”. It increases its thickness towards S. The subsequences 4c.1 und 4c.2 correspond to the bulk and the maximum extension of the Upper Marine Molasse. They are probably separated by a rather insignificant erosional phase. The Subsequence 4c.2 or “Neuhofener Schichten II” is subdivided into a lowstand and a highstand systems tract (line I, Fig. 36) by a strong double reflection interpreted as the maximum flooding surface. Its eroded top indicates the relative fall of the sea-level which finally leads to the end of marine sedimentation.

The "Glaukonitsande" and Blättermergel" (sub-sequences 4d and 4e) are characterized by rather featureless more or less parallel reflections in which depositional signatures are only poorly expressed. They could not be divided into sub-sequences. They display some NW directed onlap onto the "Neuhofener Schichten II and minor toplap in NE direction.

Time, velocity, depth and isopach grid maps (Figs. 47, 49, 51 and 53)

The grid maps of the time, velocity, depth and isopachs have been constructed in MapView with the programs SeisVisions within a GeographixDiscovery Project. The delimitation of the selected areas is conditioned by the distribution of the available well data and seismic lines. The resulting grid maps are affected by the uneven spacing and quality of the input data.

In the "Ostmolasse", grid maps have been generated for an area in its western part to the south and southeast of Munich and one in its southeastern part adjacent to the border with Austria. In these two areas, the distribution and number of the available wells and seismic lines allow the generation of meaningful grid maps. The data available from the "Westmolasse" lack the density and quality necessary for the construction of grid maps.

The time horizon surfaces are used to generate the grid maps of the velocity surfaces of the selected horizons and the conversion to depth of the seismic data. The main factors affecting the velocities are thought to be the lithology (mainly changes in the sand content) and the burial depth.

Grid maps of the velocity surfaces

Western part of the "Ostmolasse" (Fig. 49)

In the "Glaukonitsande" and "Blättermergel", the velocity increases towards north is caused by an increase of the sand content. The increase in velocity in the central area in the "Neuhofener Schichten I and II" and in the "Burdigal" probably corresponds to the higher concentration of sand in this part. The velocities of the "Aquitanian Fish Shales" and the "Aquitan" increase towards the center and to the south. This may be mainly due to the increase in burial depth and of the sand content.

Eastern part of the "Ostmolasse" (Fig. 50)

As in the western part, the increase of the velocities in the "Glaukonitsande and Blättermergel" towards north and their decrease towards east are probably linked to changes in the sand content. The "Neuhofener Schichten I and II", the "Burdigal" and the "Aquitanian Fish Shales" have their highest velocities induced by a higher sand content in the central area. The lower velocities in the south in spite of the increased burial depth are likely to indicate a decrease in sand. In the "Obing Folge", the westward increase of the velocities is caused by the increase of sand in proximal direction, whereas they decrease in the more distal eastern part. In the “Aquitan”, the velocities and probably also the sand content are highest in the southeast.

Grid maps of the depth surfaces

Western part of the “Ostmolasse” (Fig. 51)

The burial depths of all stratigraphic units increase with minor variations southward except those of the “Aquitanian Fish Shales “and the “Aquitan” which display a slight decrease in the central part.

Eastern part of the “Ostmolasse” (Fig. 52)

As to be expected, the greatest burial depths are found in the southeastern part of the area close to 5 Ost.

Grid maps of the isopachs

Western part of the “Ostmolasse” (Fig. 53)

The “Glaukonitsande and Blättermergel” reach their greatest thickness in the central part of the area. The thickness of the “Neuhofener Schichten II” increases toward southeast and decreases to the north and west, whereas those of the “Neuhofener Schichten I” and of the “Burdigal” are smallest in the central part and greater to the south and the north of it. The isopachs of the “Aquitanian Fish Shales” show a rather complex pattern.

Eastern part of the “Ostmolasse” (Fig. 54)

The thicknesses of both the “Glaukonitsande and Blättermergel” and the “Neuhofener Schichten II” are reduced in the southern part of the area and increase northward and westward. The “Neuhofener Schichten I” and the “Burdigal” reach their greatest thickness in the south and southeast. The isopachs of the “Obing Folge” and the “Aquitanian Fish Shales” display rather irregular patterns. In both units, a central area with reduced thicknesses separates a northern and southern part with thicknesses of several hundred meters.

8. References

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