Tectono-sedimentary Evolution of the NE German Variscan Foreland Basin

Dissertation

zur

Erlangung des Doktorgrades (Dr. rer. nat.)

der

Mathematisch–Naturwissenschaftlichen Fakultät

der

Rheinischen Friedrich–Wilhelms–Universität Bonn

vorgelegt von

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Ptuj

Bonn 2004

Angefertigt mit Genehmigung der Mathematisch–Naturwissenschaftlichen Fakultät der Rheinischen Friedrich–Wilhelms–Universität Bonn

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Tag der Promotion: 31.01.2005

Diese Dissertation ist auf dem Hochschulschriftenserver der ULB Bonn
http : //hss.ulb.uni − bonn.de/diss_online elektronische publiziert.

Erscheinungsjahr: 2005

Abstract

The present study focuses on the tectono-sedimentary evolution of the NE German Variscan foreland basin that is genetically part of the Mid-European Variscides. Within these Mid-European Variscides, the situation considering Carboniferous-age strata is considerably complicated because the Carboniferous is buried under the thick young Permian and Mesozoic/Cainozoic-age sequences of the NE German Basin that contains sediments and volcanics of up to 7000 m thickness. The study is based on a network of 34 boreholes that were drilled into Carboniferous strata in the course of oil and gas exploration. The sedimentary Carboniferous succession of seventeen wells was documented and sampled in detail for this study. In addition, further seventeen wells were investigated in part; information from the literature and unpublished well reports was also incorporated. These wells provide the database for a facies analysis that examines the evolution of the depositional environments in time and space. The evolution of the depositional environments facilitated the spatial reconstruction of the evolving foreland basin which resulted in the compilation of a tectono-sedimentary model. This reconstruction (*i.e.* the tectono-sedimentary model) is presented in a series of nine cartoons which correspond to nine time-slices that demonstrate the evolution of the basin from Viséan (Asbian) to Stephanian times.

The oldest sediments (Asbian) that were cored in the basin's foredeep area are characterised by a deep-marine depositional environment with typical deposits of gravity flows, *i.e.* turbidites. Subsequent, progressive shallowing is recorded from the foredeep area which included the burying of the Viséan carbonate platform remains during the Namurian A. The deep-marine sedimentation in the foredeep area ceased at the beginning of the Namurian C. Subsequently, the foredeep area was uplifted and eroded from Westphalian B times onward while the foreland sedimentation continued in the area further to the north.

The passive continental northern margin of the Rheno-Hercynian Basin was occupied by the Tournaisian/Viséan "Kohlenkalk"-carbonate platform that preceded the initiation of foreland basin sedimentation. The initial effects of Variscan shortening were noted in the northern basin area during the Asbian when the carbonate platform collapsed, leading to the deposition of a clastic series in an intraplatform basin in the Rügen area. This break-up included the change from the autochthonous carbonate platform sedimentation to a siliciclastic shelf depositional environment. The northern shelf is characterised by a progressive shallowing from shallow-marine over coastal- to alluvial depositional environments. Moreover, a continuous northward shift of the basin axis and a progressive

narrowing of the basin from Westphalian times onward were deduced from the tectono-sedimentary reconstruction. Cessation of Variscan shortening was noted during the Westphalian D. This period is characterised by a progressive shallowing of the basin and an overall coarsening of the sediments. The Stephanian evolution of the area introduced the "Post-Variscan" period. This included the change from a peripheral foreland basin to an intracontinental basin, *i.e.* the NE German Basin. Therefore, the NE German Variscan foreland basin is regarded as the precursor of the NE German Basin. The tectono-sedimentary reconstruction of the basin could not identify any area that could be interpreted as an area of forebulge uplift. It is presumed that the studied basin did not develop a forebulge due to the considerable age and tectonic history of the underlying Avalonian lithosphere.

Zusammenfassung

Die vorliegende Arbeit untersucht die tektono-sedimentäre Entwicklung des Nordostdeutschen variszischen Vorlandbeckens, das genetisch den mitteleuropäischen Varisziden zugeordnet wird. Das Karbon wird im Arbeitsgebiet von den mächtigen spätpaläozoischen und meso- bis känozoischen Folgen des Nordostdeutschen Beckens überlagert, deren Sedimente und Vulkanite eine Mächtigkeit bis zu 7000 m aufweisen. Diese Arbeit basiert auf einem Netzwerk von 34 Bohrungen, die das Karbon im Rahmen von Kohlenwasserstoff-Exploration erreicht oder durchteuft haben. Von 17 ausgewählten Bohrungen wurde das sedimentäre Karbon im Detail beschrieben und dokumentiert. Zusätzlich wurden weitere 17 Bohrungen in Teilen untersucht sowie Informationen aus der Literatur und unveröffentlichten Bohr-Berichten verwendet. Diese 34 Bohrungen liefern die Grundlage für eine Faziesanalyse, welche die Entwicklung der Ablagerungsbedingungen in Raum und Zeit untersucht. Die Entwicklung der Ablagerungsbedingungen ermöglicht die Erstellung eines tektono-sedimentären Modells, das eine räumliche Rekonstruktion des Beckens zu neun verschiedenen Zeiten aus der Periode Visé (Asbian) bis Stephan veranschaulicht.

Die ältesten Sedimente (Asbian) der Vorlandbecken-Vortiefe sind einem tiefmarinen Ablagerungsraum zuzuordnen. Nachfolgend wurde eine fortschreitende Verflachung der Vortiefe festgestellt, infolge deren die Reste der vorgelagerten Karbonatplattform (Kohlenkalk) unter tiefmarinen Schüttungen im Laufe des Namur A begraben wurden. Die tiefmarine Sedimentation im Bereich der Vortiefe kam zu Beginn des Namur C zum erliegen. Danach wurde dieser Bereich des Vorlandbeckens, beginnend im Westphal B, gehoben und erodiert während sich die Beckenachse in nördlicher Richtung verlagerte.

Der passive Kontinentalrand des rhenohercynischen Beckens wurde während des Tournai/Visé von der Kohlenkalk-Karbonatplattform eingenommen, die der Vorlandbecken-Sedimentation zeitlich vorausgeht. Erste Auswirkungen der variszischen Einengung erreichten den nördlichen Beckenrand während des Asbian als die Karbonatplattform zusammenbrach. Dieses Zusammenbrechen führte zur Ablagerung einer klastischen Sedimentserie in einem Intraplattformbecken im Bereich von Rügen. Dies entspricht dem Wechsel von einer autochthonen Karbonatplattform-Sedimentation zu Sedimentation auf einem siliziklastisch geprägten Schelf. Dieser nördliche Schelf ist durch eine fortschreitende Verflachung des Ablagerungsraumes von flachmarinen über Küsten- zu alluvialen Bedingungen gekennzeichnet. Darüber hinaus wurde anhand der tektono-sedimentären Rekonstruktion, beginnend mit dem Westphal, ein kontinuierliches Verschieben der Beckenachse in nördlicher Richtung und eine fortschreitende Verengung (in N-S Richtung) des Vorlandbeckens beobachtet. Das Ende der variszischen Einengungsbewegung wurde für das

Westphal D beobachtet. Dieser Zeitabschnitt ist von fortschreitender Verflachung des Beckens und einer Vergröberung der Korngrössen gekennzeichnet. Das Stephan läutet die "post-variszische" Entwicklung des Arbeitsgebiets ein. Dies beinhaltet den Wechsel von einem peripheren Vorlandbecken zu einem intrakontinentalen Becken, dem Nordostdeutsche Becken. Demzufolge wird das Nordostdeutsche variszische Vorlandbecken als Vorläuferbecken des intrakontinentalen Nordostdeutschen Beckens angesehen.

Anhand der tektono-sedimentären Rekonstruktion des Vorlandbeckens konnte keine "Forebulge"-Struktur identifiziert werden. Als Grund hierfür sind das beträchtliche Alter und die tektonische Geschichte der unterlagernden avalonischen Kruste zu betrachten.

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Chapter 1

Introduction

The aim of this study is to compile an overall picture of the structural development of the Variscan foreland basin and the evolution of its sedimentary infill respectively depositional environments in the area of NE Germany. This study is part of the German Research Council (DFG) Priority Programm (SPP 1135) "Dynamik sedimentärer Systeme unter wechselnden Spannungsregimen am Beispiel des zentraleuropäischen Beckensystems" (Dynamics of sedimentary basins in alternating stressfields: The Central European Basin).

The Variscan foreland basins of Europe - and in terms of this study in the area of North-eastern Germany - evolved from the Rheno-Hercynian Basin of Western and Central Europe as successor basins, *i.e.* the transition from an early trench - fore-arc respectively remnant ocean basin setting to a foreland basin setting during the Tournaisian/Viséan period (Ricken et al. 2000). The Rheno-Hercynian Basin, with its Devonian to Lower Carboniferous fill, is over 2500 km long and extends in a double arc from southern Ireland, England and Belgium through northern Germany, northern Poland and eastern Czech Republic being divided into a series of sub-basins. The subduction of the Rheno-Hercynian Basin under the Normannian - Mid German Crystalline High began in the late Devonian (Ziegler, 1990) forming the Variscan orogenic front and therefore initiate a nearly 60 Ma record (from late Devonian to late Westphalian) of convergent processes in central Europe that were related to subduction and collision (Ricken et al. 2000). The Variscan foreland basins of Europe evolved north of the Variscan Orogenic Front and are thus coupled genetically to the geodynamic processes along this zone of plate- subduction and collision. In much of Western Europe, the formation of peripheral foreland basins to the Variscan Orogen is well-established (Franke and Engel, 1988; Gayer et al. 1993). The basins strike east-west across from south Wales to northern Germany (Fig. 1.1). This trend continues eastwards along the northern margin of the Bohemian Massif and swings NNE-SSW along the eastern flank of the massif in the Czech Republic (Hartley and Otava, 2001). These foreland basins have been mainly characterized by their foredeep areas that are often referred to as the Subvariscan Foredeep named the Culm, South Wales, Namur, Aachen, Ruhr, NE German and Upper Silesian basins (Hartley, 1993; Dzordzdewski and Wrede, 1994; Gaitzsch et al. 1998; McCann, 1999; Burgess and Gayer, 2000; Ricken et al. 2000; Hartley and Otava, 2001; Süss et al. 2001; Kopp et al. 2002).

Furthermore, these foreland basins can be divided into two zones 1) the Rheno-Hercynian Zone, comprising the earliest phase of parautochtonous foreland basin sedimentation in the young evolving foredeep largely including deep-marine sediments and 2) the northerly-situated Variscan foreland zone, which includes later coal-bearing sediments (Hartley and Otava, 2001). Ricken et al. (2000) also recognized a comparable partition for a well-described portion of the Mid-European Variscides - the area of the eastern Rhenish-Massif and the Harz Mountains. They divided the evolving peripheral foreland basins into the Rheno-Hercynian Turbidite Basin (Rheno-Hercynian Zone *sensu* Hartley and Otava, 2001) and a younger molasse stage called the Sub-Variscan Molasse Basin (Variscan Foreland Zone *sensu* Hartley and Otava, 2001).

The Evolution of the peripheral Foreland Basin of NE Germany took place during the final phase of the Variscan Orogenic cycle leading to the deposition of the Viséan to Stephanian sedimentary and volcanic succession of NE Germany. This NE German Variscan foreland basin is bounded to the north by the stable Precambrian-age shield area of Baltica. The Variscan orogenic front forms the southern boundary (Fig. 1.2). It thus straddles two different tectonic domains with the advancing Variscan front to the south and the tectonic activity along the Tornquist - Teisseyere Zone (TTZ) to the north. The TTZ is a prominent lineament inside the Trans-European suture zone (TESZ) that separates ancient lithosphere of the Baltic shield and the East European Craton from younger lithosphere of western and southern Europe (Pharaoh, 1999). In terms of foreland basin geometry, this framing is of great significance because foreland basins can be simple or asymmetric, *i.e.* linked to a single thrust front, or composite, with thrust fronts on each side of the basin (Jordan et al. 1988). The tectonic events along the northern margin of the basin are not of the

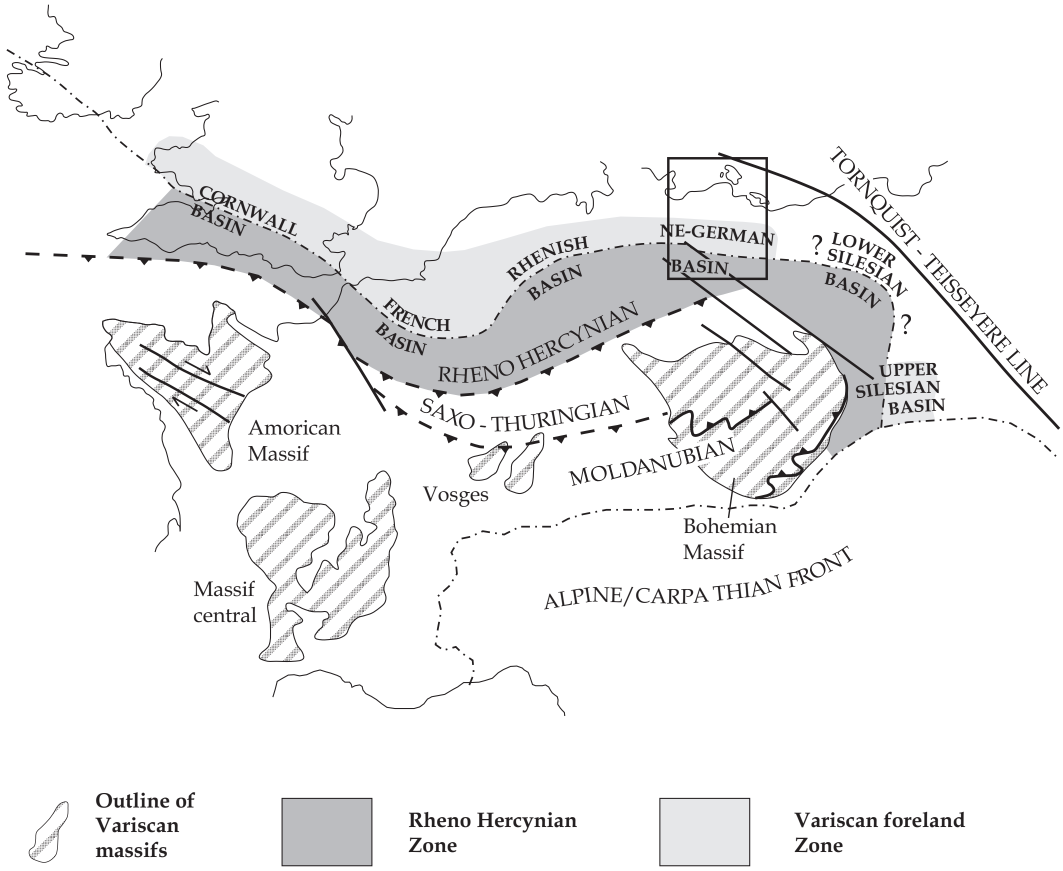

Figure 1.1: Variscan foreland basins of Europe (modified from Franke and Engel 1988; Ziegler, 1990; Hartley and Otava 2001 and this study). The study area is outlined.

same magnitude especially regarding compressional activity than a thrust front linked to a subduction zone, but it must be kept in mind that the tectonic events along the TTZ must have affected the basin geometry and sedimentary infill of the region in some way - the Variscan foreland basin cannot be exclusively regarded as a simple foreland basin linked to a single thrust front and a stable craton. Thus, the advancing Variscan orogenic front to the south and the complexity of the region to the north led to the development of a pseudocomposite basin (McCann, 1999).

A compressional tectonic regime governed the evolution of this part of the Variscan foreland basin throughout the Carboniferous until the cessation of the Variscan orogeny. A change in basin style from a foreland basin to an intracratonic basin was established at the Permo-Carboniferous transition introducing the post-Variscan period when western and central Europe was dominated by crustal instability and reequilibration. This crustal reorganisation took place under an alternating transtensional and transpressional tectonic regime and the combined effect of reequilibration and tectonic activity controlled the kinematic patterns and subsidence of approximately 70 intramontane basins that are combined to the Central European Basin (CEB). All of these intramontane basins are characterised by a major strike-slip component in their deformational history and some of them were accompanied by an extensive and significant phase of Permo-Carboniferous magmatism. Therefore, the Variscan foreland basin is regarded as the precursor of the CEB.

The study area is situated below the North East German Basin (NEGB) - a segment of the Central European Basin - and is genetically part of the Mid-European Variscides (Fig. 1.2). Within these Mid-European Variscides, the situation considering Carboniferous-age strata is considerably complicated because the Carboniferous is buried under the thick young Permian and Mesozoic/Cenozoic-age rocks of the NEGB that contains sediments and volcanics of up to 7000 m thickness. For this reason, data in this area is restricted to a series of wells that have been drilled in the course of oil and gas exploration (Hoth et al. 1993). This exploration focused mainly on the Permian-age strata but even super deep wells were drilled in the central part of the basin (up to 8000 m deep). The number of wells extending into the Carboniferous-age strata decreases to the south, with their density being much lower in the central and southern areas (see Fig. 2.6).

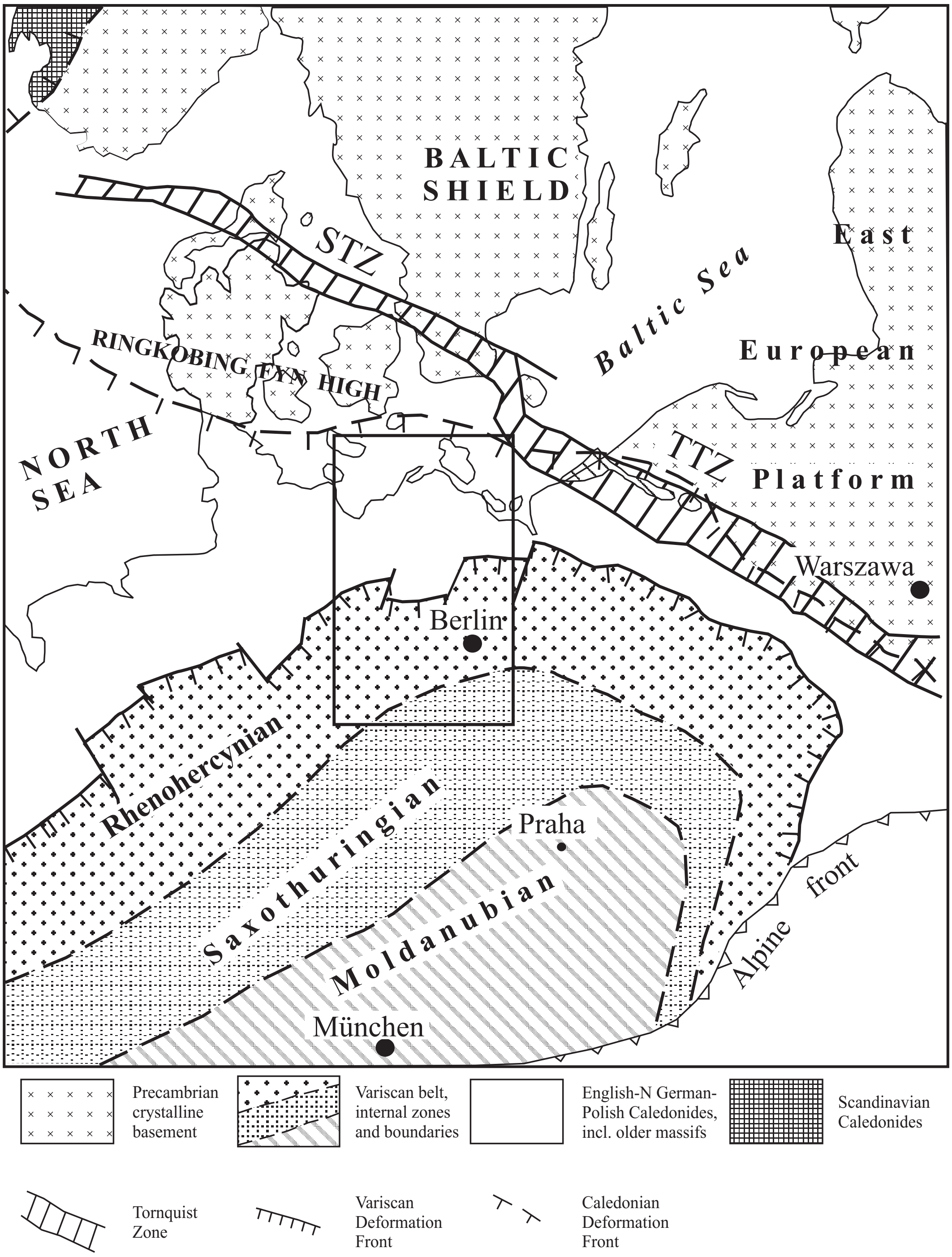

Figure 1.2: Structural subdivision of the European Variscides (from Franke, 1992). The study area is outlined.

Chapter 2

Geological Background

2.1 Foreland Basins

Foreland basins are generally defined as an elongate region of potential sediment accumulation that forms on continental crust between a linear contractional orogenic belt and the stable craton. They develop mainly in response to tectonic loading of a foreland plate by the emplacement of large thrust sheets on their margin (Dickinson, 1974; Jordan, 1981; Allen et al. 1986; DeCelles and Giles, 1996). The foreland plate reacts to this emplacement of loads by flexural bending leading to the formation of an asymmetric basin (Miall, 1995).

Collision-related foreland basins can be divided into two genetic classes. 1) Peripheral foreland basins, which form on the extensional continental downgoing plates in front of the thrust belt, and 2) retroarc foreland basins which lie on the overriding plate and occur behind the thrust belt (Miall, 1995). Peripheral foreland basins - the subject of this study - result from arc-arc, arc-continent and continent-continent collisions.

An example for an arc-arc related peripheral basin is the central part of Honshu Island where the collision of the Izu-Bonin Arc with Honshu during the late Cenozoic led to the formation of a series of small peripheral basins (Ito and Masuda, 1986 in Miall, 1995). The western part of Taiwan constitutes a fold-and-thrust belt and an associated peripheral foreland basin that developed from successive arc-continent collision. The largest peripheral foreland basins, however, result from continent-continent collisions, the Swiss Flysch-Molasse basin being the classic example (Homewood et al. 1986). These continent-continent collision-related peripheral foreland basins form above the extensional continental margins of subducting plates that developed during a preceding cycle of ocean opening and closing.

The main sedimentological trend in an evolving peripheral foreland basin is the progressive shallowing of the basin and coarsening of the sediment. Deep-water sediments are typically the oldest series encountered in the basin. Commonly, as a consequence of sediment starvation, the stratigraphic section is condensed at the beginning. The basin is successively filled with turbidites followed by shallow-water and nonmarine sediments (Ricci-Lucci, 1986; Sinclair and Allen, 1992; Zoetemeijer, 1993; Sinclair, 1997). This stratigraphic succession pattern was originally termed the "geosynclinal shale-flysch-molasse cycle" (Clark and Stearn, 1960 in Miall, 1995). Initial loading of the overriding margin onto the continental slope generally takes place below sea-level, so little sediment is available to be transported into the basin. When the overthrust masses, as a consequence of continued shortening, begin to rise above sea-level, the amount of sediment shed into the basin increases rapidly, forming a deep-marine clastic wedge. This is the so-called "Flysch-Phase". As crustal shortening continues the accreted arc or continent climb beyond the thinned edge of the rifted margin. This leads to more pronounced topographic uplift and an increase in sediment supply. The conditions within the basin change from shallow-marine to nonmarine; the so-called "Molasse-Phase". As thrust activity decreases, erosion reduces the lithospheric load and the basin undergoes lithospheric uplift and erosion (Miall, 1995).

The stratigraphic record of a foreland basin reflects a two-type hierarchy of the controlling mechanisms on basin formation. The first-order control is the subsidence pattern governed by flexure of the lithospheric plate on which the basin is located. Two types of loads were distinguished by Jordan et al. (1988): 1) the thickening pile of thrust sheets in the thrust belt and 2) subcrustal buoyancy contrasts (negative buoyancy of the cold subducting lithosphere) or mantle dynamic loads. The rheological properties of the lithosphere and the relative impact of the affecting loads determine the basin geometry, whereas the chronology of loads controls timing and the magnitude of subsidence. The second-order controls include the lithology of the thrust belt, climate, and eustatic sea level variations. These second-order controls can influence the stratigraphic record of a foreland basin but cannot generate a basin (Jordan et al. 1988). The abovementioned controlling mechanisms determine the structural evolution of the basin, its stratigraphy, facies, petrographic characteristics and the nature of the stratigraphic sequences (Miall, 1995).

The rheological properties of the lithosphere on

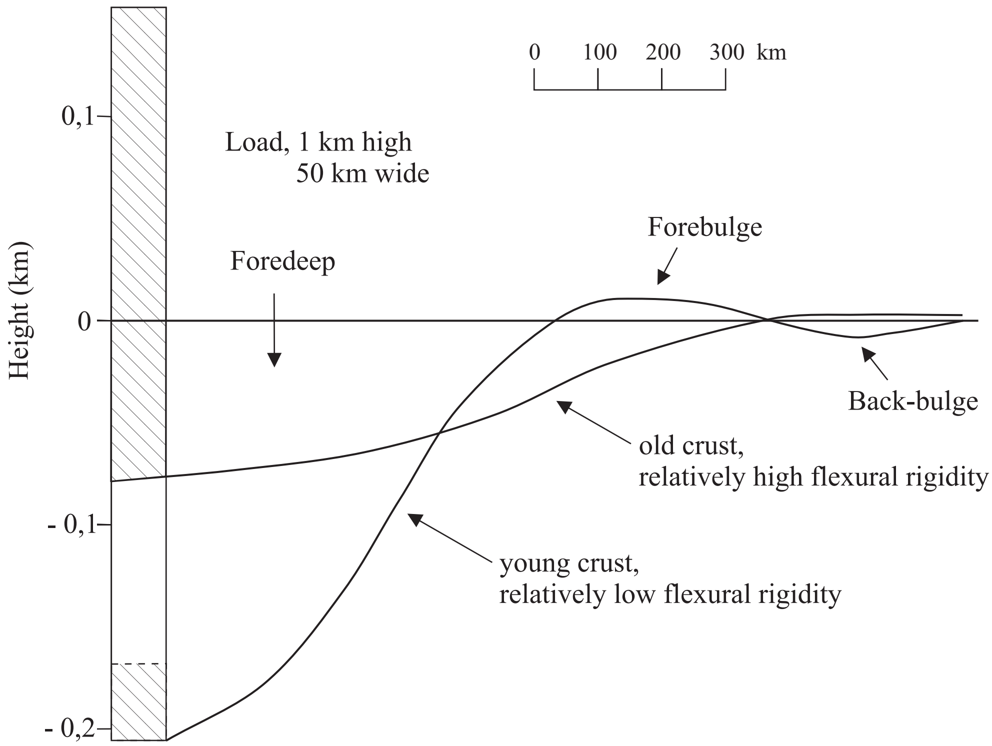

Figure 2.1: Cross section of a deformed elastic beam in response to a load 1 km high and 50 km wide, with a density of 2400 kg/m^3. Sediments of same density fill each basin. Two cross sections are shown, corresponding to two values of flexural rigidity. Each basin has approximately the same cross-sectional area but differs in degree to which load is spread over greater surface areas of crust (modified after Beaumont, 1981).

which a foreland basin will develop have a significant amount of influence on its evolution. To describe the behaviour of a lithospheric plate under an emplaced load, modelling studies have been applied. These have shown that the lithosphere behaves approximately as an uniform elastic plate (Beaumont, 1981; Jordan, 1981). Important variables of the underlying crust are its thickness and age. These two variables determine the thermal properties, buoyancy and flexural strength of the crust and the variations strongly influence the palaeogeographical evolution of the basin (Stockmal et al. 1986; Stockmal and Beaumont, 1987). The impact of crustal age and crustal rigidity to the geometry of an evolving foreland basin can be seen in Fig. 2.1. When foreland basins form above young, relatively warm, buoyant and weak lithosphere with relatively low flexural rigidity, they tend to be narrow and deep. Young crust has a low flexural strength, and the foreland basin increases rapidly in depth. Basin evolution above old lithosphere will lead to the formation of a foreland basin that is initially relatively deep, but tends to deepen more slowly under the influence of the emplaced load. The resultant basin tends to be relatively wide because of the greater rigidity of the old basement (Miall, 1995).

Flexural bending of relatively young crust produces uplift on its distal margin. This so-called forebulge and the associated area between the stable craton and the forebulge (*i.e.* back-bulge) can be seen in Fig. 2.1. The forebulge uplift has an amplitude of tens up to a few of hundred meters and its position and elevation are linked to the supracrustal load and the advancing thrust front (DeCelles and Giles, 1996). Because the forebulge is an elevated feature, it is generally considered to be a zone of nondeposition or erosion. The resulting unconformity can be used to track its position through time (Stockmal et al. 1986; Flemings and Jordan, 1989; Sinclair et al. 1991). The back-bulge area comprises the mass of sediment that accumulate in the shallow but broad zone of potential flexural subsidence cratonwards of the forebulge. Most of the sediment within the backbulge area is derived from the orogenic belt, but contributions from the craton may also be significant. Relatively low rates of subsidence in the backbulge area produce stratigraphic units that are much thinner than those in the fordeep (Flemings and Jordan, 1989; DeCelles and Burden, 1992).

The primary cause of subsidence in a foreland basin setting is the flexural response to the topographic loads of the adjacent thrust belt and sediment loads within the foreland basin. However, many modern and ancient foreland basins exhibit subsidence that is greater and/or more widespread than that expected from the observable topographic load, sediments and water that occupy the basin. For example, the Po-Adriatic Basin is three to four times deeper than expected from the mass of the ad-

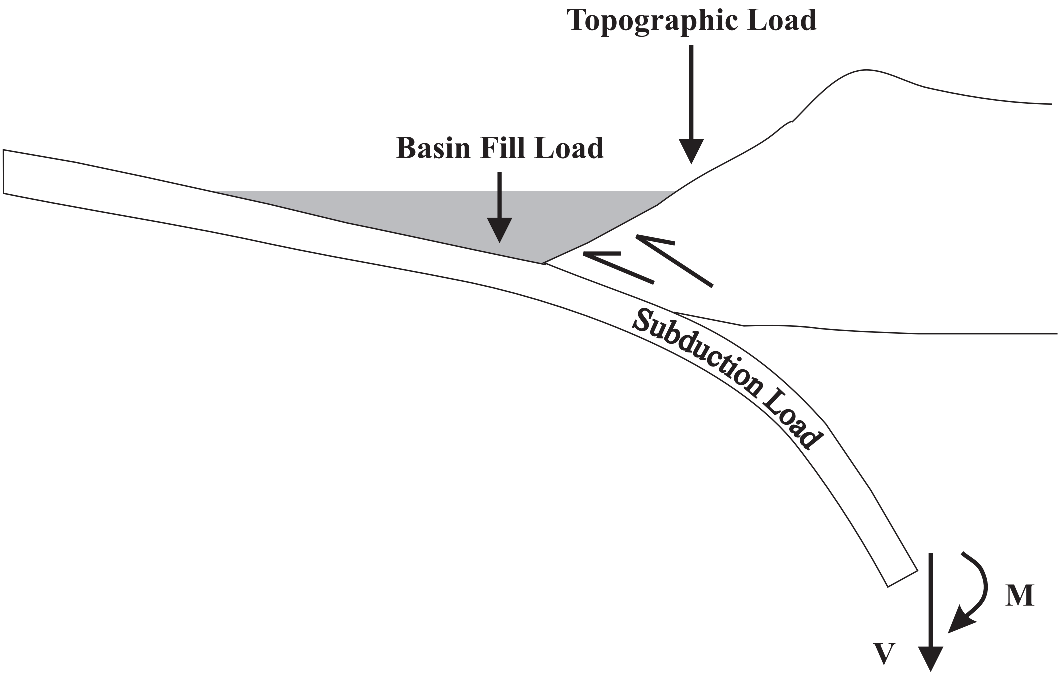

Figure 2.2: Schematic diagram showing the principal loads in peripheral foreland basins. In addition to the topographic and sediment load, a subduction load, due to a vertical shear force (V) and bending moment (M) on the end of the subducted slab, may exist at depths of 50-200 km (Royden, 1993).

jacent fold-thrust belt; the likely cause of most of the flexural subsidence in this foreland basin is the downward pull of a dense subducted oceanic slab 50-150 km beneath the Apennines (Royden, 1993). This so-called subduction load can contribute to the total amplitude of subsidence. Subduction load results from the dense, subducting oceanic slab exerting a vertical shear force and a bending moment (Fig. 2.2). With prograding continental collision and subduction of transitional, following continental lithosphere, the portion of subduction loads decreases and topographic loads will dominate the subsidence profile (Karner and Watts, 1983).

The pattern of subsidence at any single point in a foreland basin is distinctive (Burbank et al. 1986; Cross, 1986; Homewood et al. 1986). In the beginning the subsidence rate in a peripheral setting is slow. The rate increases as the shortening of the overriding plate proceeds and climbs the underlying continental margin. It reaches its maximum when the basin is overridden by the emplaced load. The subsidence rate then decreases as the basin itself is uplifted by post-tectonic erosional rebound (*c.f.* Miall, 1995). In foreland-basin subsidence curves sharp inflection points mark a sudden increase or decrease in subsidence rate. These changes in the subsidence pattern maybe responses to specific thrust-load events and can, therefore, be used in dating fold-thrust belt tectonism (Burbank et al. 1986; Cross, 1986; Homewood et al. 1986; Jordan et al. 1988). Thrust motion can be recognized in the stratigraphic record either through measurement of its subsidence impact on the basin (*i.e.* the creation of new accommodation space) or through the impact that thrust motion might have on the characteristics of the basins sediments.

2.2 Historical background to the Variscan Orogeny, Classification and terminology

The European Variscan fold-and-thrust belt can be traced on the basis of geological and geophysical data as a broad arc extending from southern Ireland and the adjacent offshore areas across central Europe into Poland (Fig. 2.3). Variscan Europe was traditionally subdivided into four distinct zones which can be differentiated by their sedimentary-magmatic and tectono-magmatic development. From north to south these are the Westphalian, the Rheno-Hercynian, the Saxo-Thuringian zones and the Moldanubian region which together comprise the western Variscan foldbelt between the rivers Maas and Elbe (Kossmat, 1927).

Kossmat's Westphalian Zone, interpreted as an axial depression to north of the Variscan Orogeny, extends from the southern margin of the London-Brabant Massif into the Ruhr area. The Rheno-Hercynian Zone comprises the Rhenish Massif to the west and east of the Rhine (Ardennes, Rhenish Massif, Hunsrück, Taunus, Harz Mountains and the Flechtingen Block). The crystalline basement outcrops of the northern parts of the Vosges/Black Forest, Kyffhäuser, Saxo-Thuringian Schiefergebirge, Spessart, Odenwald, Fichtel- and Erz Mountains were grouped together to comprise the Saxo-

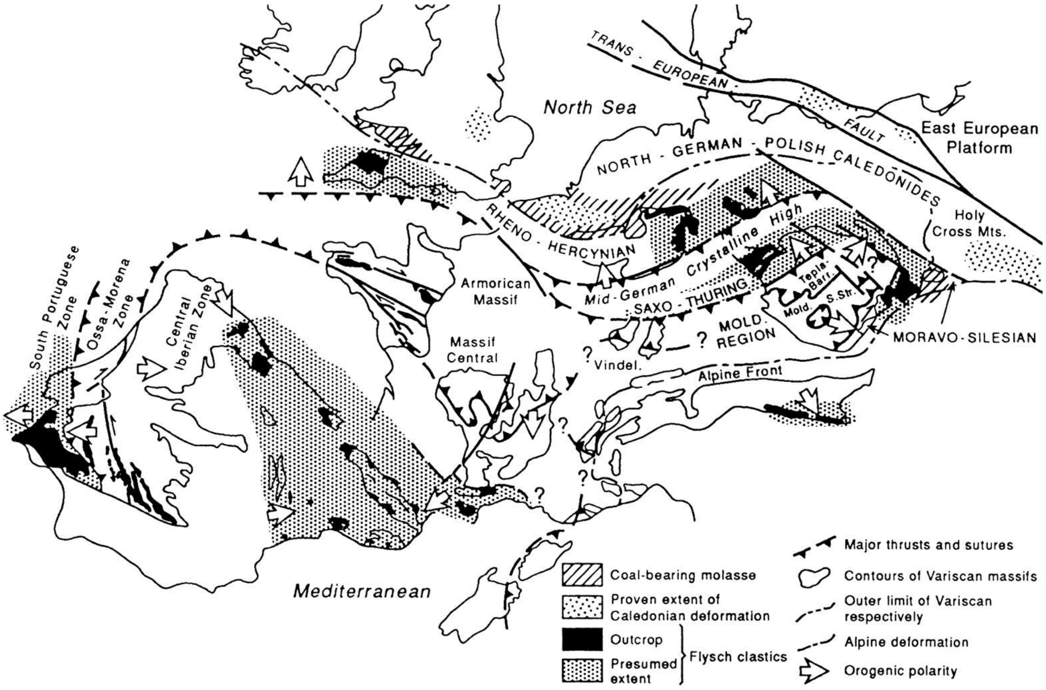

Figure 2.3: Tectonic elements of the European Variscides (Franke 1992).

Thuringian zone. The Moldanubian Region comprises most of the Vosges/Black Forest area and the Bohemian Massif. Subsequent modification of Kossmat's classification included the identification of the Mid-German Crystalline High (MGCH) situated on the northern margin of the Saxo-Thuringian Zone by Schlotz (1930), who distinguished it as the "Spessart-Schwelle", a zone of crystalline rocks located between two zones of Palaeozoic sedimentation, *i.e.* between Kossmat's Rheno-Hercynian and Saxo-Thuringian zones. Behr et al. (1984) excluded the Northern Phyllite Zone (NPZ) on the southern margin of the Rheno-Hercynian Zone. The extension of Kossmat's Variscan zones to the Elbe-Lineament was described by Möbus (1966). Equivalents of Kossmat's zones east of the Elbe-Lineament were identified by Dvořák and Paproth (1969).

Kossmat's original classification has also been extended to the West European Variscides (Ellenberger and Tamain, 1980). The South-Portuguese zone is presumed to be the equivalent of the Rheno-Hercynian while the Ossa-Morena zone has been compared to the MGCH. The Northern- and Central Armorican zones are counterparts of the Saxo-Thuringian though the West Asturian-Leonaise Zone is, in parts, also comparable to the latter. The prolongation of the Moldanubian Zone to the west can be found in the south Armorican Zone and in most parts of the Galician-Castilian Zone (Schöneberger and Neugebauer, 1994).

Using Kossmat's classification as a basis and taking modern plate tectonic theory into account, all of these zones (*i.e.* the original four of Kossmat together with the MGCH and the NPZ) are defined as palaeogeographically coherent units that broadly retained their material integrity throughout the entire orogenic evolution (Oncken, 1997). They can thus be interpreted as former plate fragments which formed the basis for subsequent Palaeozoic development (Franke, 1989; Plesch and Oncken, 1999).

2.3 Plate tectonic history

The Variscan foreland basin of NE German developed on Avalonian basement. It is bounded to the north by the stable Precambrian-age Baltica Shield that is considered to be a Precambrian terrane collage consolidated during the upper Proterozoic Sveco-Norwegian Orogeny (Berthelsen, 1992).

The Palaeozoic evolution of the region commenced with the **Caledonian orogenic cycle** (Late Cambrian to Earliest Devonian) which began with the break-up of the Precambrian supercontinent Rodinia and involved the convergence and collision of Baltica, Laurentia and, more importantly in terms of the study area, the northward convergence and accretion of Gondwana-derived continental fragments (Avalonian, Armorica) to the southern margin of Baltica (Fig. 2.4).

The drift history of these above-mentioned micro- and major-plates began in early Ordovician times when Avalonia moved northwards (Cocks and Fortey, 1982; Lees et al. 2002). Avalonia collided with Baltica in the latest Ordovician from which the closure of the Tornquist Ocean resulted (Figs. 2.4a,b). In late Silurian time, the Iapetus Ocean between Avalonia-Baltica and Laurentia was closed

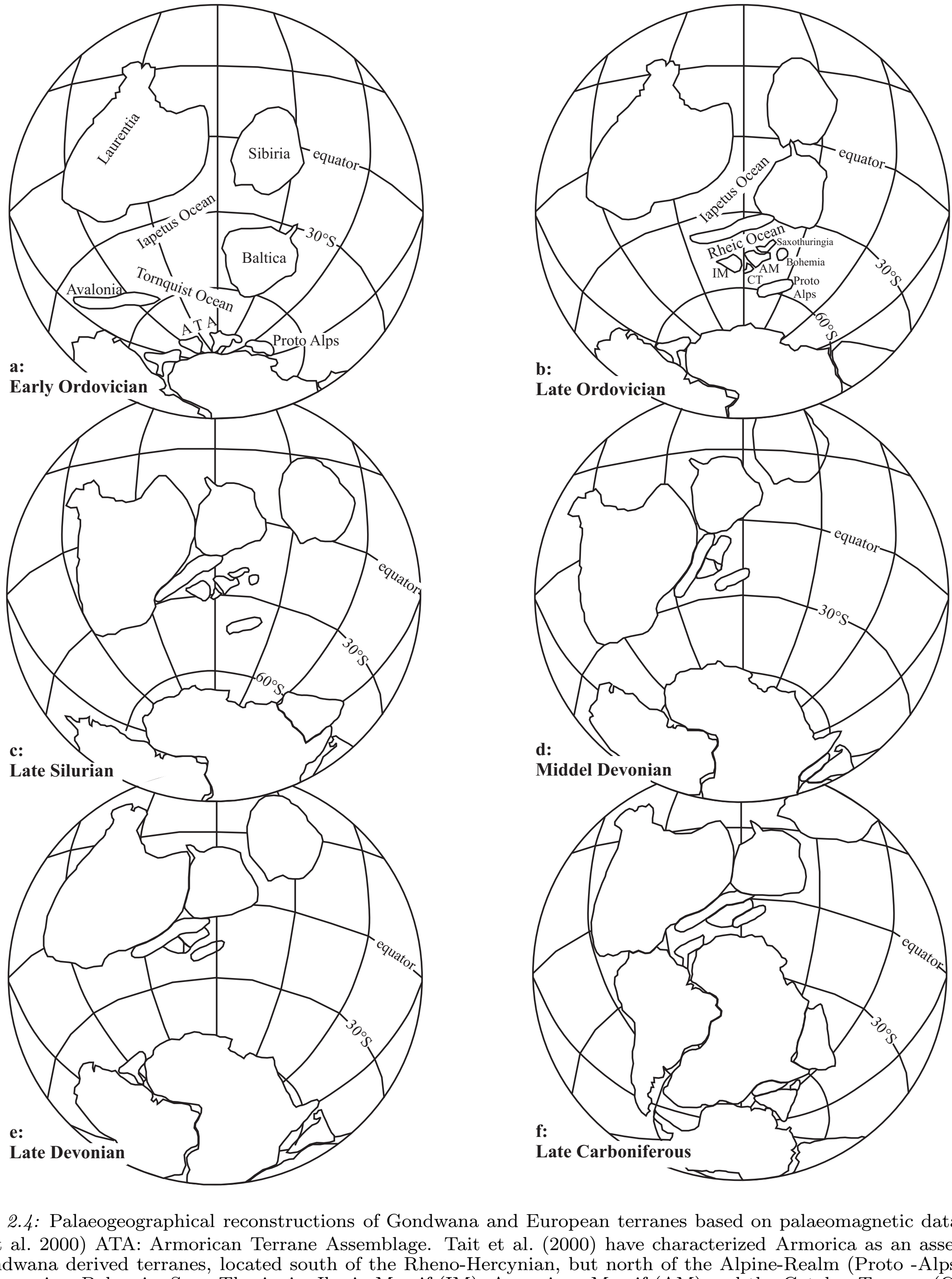

Figure 2.4: Palaeogeographical reconstructions of Gondwana and European terranes based on palaeomagnetic data (after Tait et al. 2000) ATA: Armorican Terrane Assemblage. Tait et al. (2000) have characterized Armorica as an assemblage of Gondwana derived terranes, located south of the Rheno-Hercynian, but north of the Alpine-Realm (Proto -Alps). The ATA comprises Bohemia, Saxo-Thuringia, Iberia Massif (IM), Armorican Massif (AM) and the Catalan Terrane (CT).

(Fig. 2.4c) and the Caledonian orogenic cycle ceased with the formation of Laurussia (Tait et al. 2000). Northern Europe formed part of Laurussia - that is the Old Red Continent - and was covered by Silurian to Devonian, mainly continental sediments (Timmerman, 2003).

The **Variscan orogenic cycle** began when Armorica detached from Gondwana in Middle Ordovician times and drifted northwards (Soffel et al. 1994). The Rheic Ocean (Fig. 2.4b) was formed in middle/late Ordovician times between Avalonia-Baltica and Armorica (Cocks and Fortey, 1982). Narrowing of the Rheic Ocean occurred during the late Ordovician through earliest Devonian, and was accompanied by the formation of an oceanic island arc between Avalonia and Armorica. The closure of the Rheic Ocean (Fig. 2.4c) was completed by early Devonian times (Franke, 1992; Franke et al. 1995).

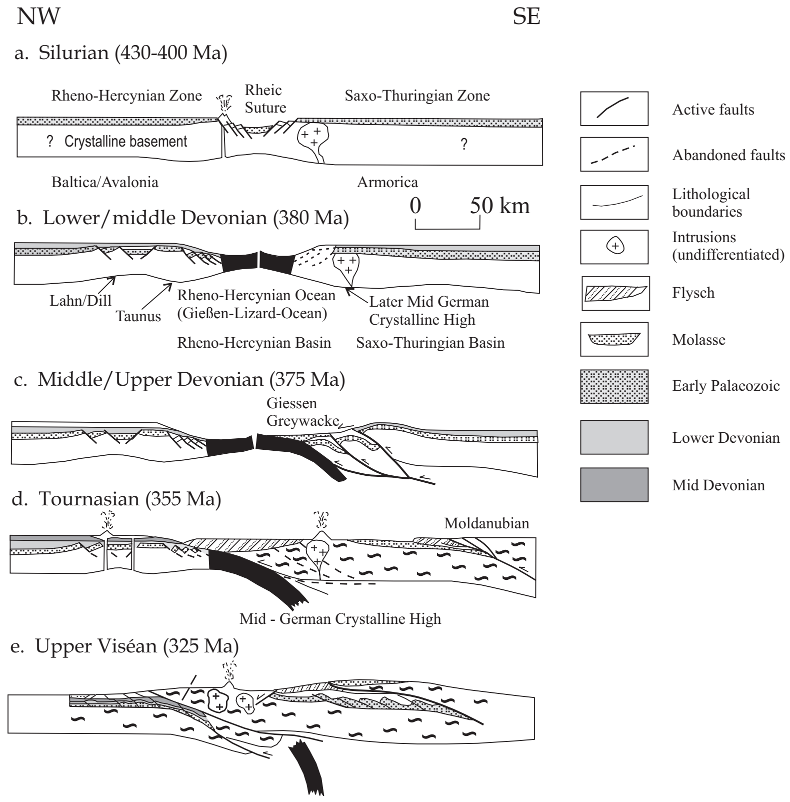

Figure 2.5: Cartoon displaying the opening and closure of the Rheno-Hercynian basin and the closure of the Saxo-Thuringian basin between 430 and 290 Ma ago (Franke, 1992).

Extensional movements along the Rheic suture between Avalonia (*i.e.* Rheno-Hercynian Zone) and Armorica (*i.e.* Saxo-Thuringian Zone) began in late-early to middle Devonian (Fig. 2.5b) leading to the formation of a broadly E-W-trending oceanic or back-arc basin of limited width. Basin formation led to the separation of Avalonia from Armorica to the south; the resultant ocean being termed the Rheno-Hercynian Ocean of Central Europe (Oncken, 1997; Oncken et al. 1999; Warr, 2000). The Rheno-Hercynian basin extended from southern England to an area east of the Harz Mountains and was primarily filled with clastic sediments derived from the Caledonides, located to the north (Franke, 2000; Oncken et al. 2000). Early Devonian volcanic activity (basalts with a tholeitic affinity) confirms the extensional character of the Rheno-Hercynian Basin (Matte, 1986). With continued extension, oceanic crust was generated within the basin (Fig. 2.5b). The resultant Rheno-Hercynian Ocean attained a maximum width of only ca. 400 km and was, therefore, not wide enough to be verifiable by palaeomagnetic methods (Franke and Oncken, 1990).

The closure of the Rheno-Hercynian Basin (Figs. 2.5c-e) took place during the late Devonian-early Carboniferous period with a SE-directed subduction. The decline of volcanic activity within the Rheno-Hercynian Basin (Matte, 1986) and the renewal of basinwide tectonic activity may have been coeval with the onset of the subduction of the Rheno-Hercynian Zone beneath the Saxo-Thuringian Zone (Franke, 1989). Franke (1992) has suggested that subduction of oceanic crust in the region was completed by the end of the Devonian. Subduction resulted in the evolution of a magmatic arc - the Mid German Crystalline High (MGCH) - within the upper Saxo-Thuringian plate (Oncken et al. 2000). The MGCH is considered the core of an orogenic wedge, which showed significant uplift and a north-westward progradation (Oncken, 1997). The closure of the Rheno-Hercynian Basin is associated with the development of the northern Variscan foreland, as a response to the tectonic loading of the thinned Rheno-Hercynian passive margin (Avalonia) by the collision with the MGCH on the leading edge of Armorica (Oncken et al. 2000). The erosion and deposition of MGCH-derived turbidites within the evolving foreland basin in late Tournaisian times marked the ultimate closure of the Rheno-Hercynian Basin. This depositional phase marks the shift from a remnant basin, comprising oceanic crust, to a typical, asymmetric foreland basin with underlying continental crust (Franke, 1992; Franke, 2000). This change in basin style was also noticed on the northern margin (in the Rügen area) of the now evolving foreland basin, where the "Kohlenkalk"-carbonate platform of the Rheno-Hercynian Basin collapsed in the Middle Viséan (Asbian), leading to the deposition of a clastic series in an intraplatform basin at Rügen. Similar sequences have been noted elsewhere within the Variscan orogen, for example the Dublin Basin (Jaeger, personal communication 2003).

The geodynamic evolution of the Mid-European Variscides from early Carboniferous times may be considered as belonging to the collisional stage of the Variscan Orogeny (Henk, 1997). From late-Early Carboniferous times, compression was continuous for ca. 45 Ma, with Variscan deformation advancing northward at a rate of ca. 0.5 cm/yr. (Ahrendt et al. 1983). This is only slightly less than the value of 0.79 cm/yr which characterized Alpine orogenic compression (Schmid et al. 1996). In western Germany, a series of major north- and south-verging, basement-cored nappes were emplaced during Namurian and Westphalian times. The resultant thickening of continental crust by thrusting and stacking ultimately formed the Variscan Orogen (Henk, 1997). The widespread occurrence of low-pressure metamorphic rocks and late- to post-orogenic calc-alkaline intrusives in the internal parts of the Variscan Orogen suggests that a significant amount of crustal shortening, accompanied by crustal delamination, subduction and anatectic remobilization of lower crustal material and partial melting of upper mantle material occurred (Ziegler, 1984; Ziegler, 1986). Rough estimates of total crustal shortening yield a value of ca. 150-200 km (Ziegler, 1990). This is less than half of the crustal shortening recorded from the Alpine Realm during the Tertiary which was estimated around 500 km (Dewey et al. 1989; Schmid et al. 1996). By latest Westphalian time, the Variscan fold and thrust belt of western and central Europe was consolidated and inactive (Ziegler, 1990). However, tectonic activity in the form of transpression continued, as evidenced by the diverse angular unconformities visible on 3D seismics from the Rügen area (Piske et al. 1994), between the Westphalian and Permian deposits (McCann, 1999).

2.4 Reconstruction of depositional sedimentary environments

A depositional sedimentary environment is a geomorphic unit in which deposition takes place. Such an environment is characterised by a unique set of physical, biological, and chemical processes operating at a specific rate and intensity which exert sufficient effect on the sediment, so that a characteristic deposit is produced (Reading and Levell, 1996). The character of a sediment so produced is determined both by the intensity of the formation processes operating on it and by the duration over which such action is continued (Pettijohn, 1975). Some of the geomorphic units (*i.e.* depositional environments) are rather complex in character. In such geomorphic units, physical, biological and chemical variables can vary strongly from place to place, and as a result so does the type of sediment deposited. These units are termed the subenvironments. For example, fluvial environments can be differentiated into channel, levee, and flood-basin deposits. Thus, the study of depositional environments in ancient sediments is essentially in the recognition of geomorphic units. Only the processes, which leave a lasting record in ancient sediments, are useful in the recognition of environments. In this study, the recognition of depositional environments was performed by a facies analysis which, at first, required a thorough description of the available cored rocks and began with the definition of distinguishable sedimentary facies in each stratigraphic unit (see Chapters 3-8). Subsequently, the individual sedimentary facies are grouped into facies associations and sequences which provide further information to the environmental interpretation.

2.4.1 Sedimentary facies

A sedimentary facies is defined as the sum of the entire primary physical (or lithological), biological, and chemical characteristics of a body of rock, *i.e.* composition, sedimentary structures, bedding, texture, fossils and colour. A sedimentary facies should ideally be a distinctive rock that forms under certain conditions of sedimentation, reflecting a particular process, set of conditions, or environment. Thus, a sedimentary facies is a result of deposition under distinct processes in a given environment and, therefore, possesses characteristics of that specific environment. In the study of ancient sediments, it is advisable to study various characteristics of a stratigraphic unit and describe it as facies (Reineck and Singh, 1980).

The interpretation of sedimentary facies at the environmental level should begin with the study and description of the physical factors. The most important physical factors are the deposition medium, current and wave intensity/velocity and water depth. Information about hydrodynamic conditions is best obtained by detailed and careful study of primary sedimentary structures and of size distribution parameters.

In addition, the recognition of minerals that originally precipitated in the environment provides important clues to the conditions during deposition. Biological criteria, *i.e.* palaeoecological information, can provide information about water depth, salinity, temperature, turbulence, rate of sedimentation, etc. The study of physical factors combined with the study of biological and chemical factors provides a more complete picture of the sedimentary depositional environment (Reineck and Singh, 1980).

In this study, the physical criteria were used to reconstruct the depositional environment. Chemical criteria were limited to certain minerals that formed during or shortly after deposition such as pyrite, siderite, and phosphorite. The biological cri-

Table 2.1: Abbreviations for Lithotypes.

Abbreviation	grain size
G	gravel
S	sand
f	fine
m	medium
c	coarse
M	mud (clay and silt)
	bedding type
h	massive
p	planar bedded/ laminated
r	cross-bedded, ripple-bedded
l	lenticular bedded, flaser-bedded
s	soil horizon, soilification

teria could mostly not be studied, since characteristic faunal horizons and other fauna and flora findings were removed from the core material by earlier workers. All palaeontological and palaeoecological information were obtained from the literature or unpublished well reports.

Definition of Lithotypes

The diverse sedimentary facies encountered during core logging were classified by defining certain lithotypes following the criteria as introduced by Miall (1996). The various lithotypes were deduced from the macroscopic characteristics of the rocks, *i.e.* composition, lithology, bedding and texture (for details see Section 2.5 and Appendix 10). One should keep in mind that these lithotypes are simplifications since sedimentary facies are defined by additional features. However, in order to label and compare different sedimentary facies these simplifications are useful.

The lithotypes are labelled with a facies code that comprises a capital letter for the grain size and a small letter for the grain size class (see Tab. 2.1). Additional grain sizes are noted in brackets. These abbreviations are commonly used for the description of clastic sediments (*cf.* Miall, 1996).

2.4.2 Facies associations

Individual sedimentary facies vary in their interpretative value, as most of the sedimentary facies occur in several depositional environments. A rootlet bed or a coal seam indicates that the depositional surface was close to, or above, water level. However, a rippled sandstone implies that deposition took place in the lower part of the lower flow regime from a current that flowed in a particular direction but it indicates little about water depth, salinity or environment. Even a rootlet bed does not indicate a distinct environment (Reading and Levell, 1996). It may have formed in a vegetated swamp area on a floodplain, on a river levee or at a shoreline. Therefore, one has to recognize, from the beginning, the interpretative limitations of individual sedimentary facies, taken in isolation. For example, a graded sandstone bed with an erosional contact to an underlying non-bioturbated mudstone (*i.e.* pelagic) would be interpreted differently from an identical graded sandstone interbedded with a rippled sandstone clearly deposited in current agitated shallow water (Reading and Levell, 1996).

Therefore, it is generally the spectrum of sedimentary facies and their presence in certain combinations that provide direct clues in environmental interpretation. Thus, facies have to be interpreted, at the environmental level, by reference to their neighbours and are consequently grouped together as facies associations that are thought to be genetically or environmentally related.

2.4.3 Facies sequences

In some successions, the sedimentary facies of a facies association are interbedded randomly. In others, the sedimentary facies may lie in a preferred order with vertical transition from one sedimentary facies into another. Thus, we can predict - within known limits - what facies we might encounter as we move upwards or downwards through the succession. A facies sequence therefore is a series of sedimentary facies that pass gradually from one into the other. Most facies sequences are bounded at top and bottom by sharp or erosive contacts, or by a hiatus in deposition indicated by a bioturbated horizon, a rootlet bed, a hardground, or early diagenesis. On the other hand, some sequences may not have such sharp boundaries and the junction has to be taken at an arbitrary point within a progressively changing facies (Reading and Levell, 1996). A sequence may occur only once or it may be repeated (*i.e.* cyclic).

The importance of facies sequences has long been recognized, at least since Walter's *Law of facies* (1894) which states that "The various deposits of the same facies area and, similarly, the sum of rock of different facies areas were formed beside each other in space, but in a crustal profile, we see them lying on top of each other [...] it is a basic statement of far-reaching significance that only those facies areas can be superimposed, without a break, that can be observed beside each other at the present time" (translation from Blatt et al. 1972, pp. 187-188 in Reading and Levell, 1996)). It follows that the vertical succession of facies may reflect the lateral juxtaposition of these facies, representing typical environments. Walter's law applies only to successions without a major gap. A break in the succession, perhaps marked by an erosive contact, may represent the passage of any number of environments whose products were subsequently removed (Middleton, 1973).

2.5 Database

The lithostratigraphy and biostratigraphy of the Carboniferous succession in the studied area is based on a network of 38 boreholes that drilled into Carboniferous strata in the course of oil and gas exploration between 1962 and 1987 (Hoth et al. 1993; Hoth, 1997; Jaeger 1999; several unpublished well reports). These boreholes provide, particularly in the Rügen area, a dense data network (see Fig. 2.6). These wells are stored in the core-stores of the "Landesamt für Umwelt, Naturschutz und Geologie – Mecklenburg-Vorpommern" in Sternberg, the "Landesamt für Geologie und Rohstoffe Brandenburg" in Wünsdorf and the "Geologisches Landesamt Sachsen-Anhalt" in Halle. The cores were obtained using the Rotary-drilling technique using special drilling bits, with an inner and outer metal core barrel each approximately 9 meters in length. A combined core barrel can yield a maximum of 18 m of material. Each core barrel was subsequently divided into segments of approximately 80-90 cm and stored in wooden boxes of one-metre length.

The Carboniferous sedimentary succession of seventeen selected wells were documented and sampled in detail for this study; these provide the database for the performed facies analysis. The cores were investigated in order to deduce the sedimentary facies, sedimentary associations and sequences. These observations were used to reconstruct the sedimentary depositional environment (for details see Section 2.4). Furthermore, additional information from the literature (*i.e.* well-described outcrops and other research wells) were used to provide an overall view of the foreland basin succession. The bio- and lithostratigraphy for the NE German Variscan foreland basin was compiled from various sources and is presented in Fig. 2.7.

The well descriptions were displayed at a scale of 1:50. The macroscopic features of the cored sediments were described onsite and sedimentary logs (following the procedure of Nichols, 1990) were constructed. A selection of these sedimentary logs are included in order to better depict particular observations (*e.g.* Fig. 3.2). The lithologies were separated into gravel, coarse-, medium-, fine sand and mud. Silt and clay frequently appear together but could not be differentiated by macroscopic means. Therefore, clay and silt were combined to mudstones except when a clear differentiation was possible, for example in clay/silt interlayered beds. Moreover, the bedding, primary and secondary sedimentary structures, grain-shape, sorting, tectonic elements, concretions, diagenetic minerals, fossils and various miscellaneous observations were also noted.

The seventeen wells utilised, are - in terms of the performed facies analysis - subdivided into two main groups. The first group comprises the wells that were located on the northern basin margin of the Variscan foreland basin. Due to their marginal position within the basin they were reported separately (see Chapter 3 - 7). These wells are, moreover, characterised by detailed biostratigraphic information and cover a relatively wide stratigraphic range. The second group comprises the wells that characterise the more orogen-proximal sedimentation of the Variscan foreland basin. They are located in northern Brandenburg and Sachsen-Anhalt. These wells are - compared to the wells from the northern margin - relatively short in length (ca. 22 - 170 m) and comprise only one stratigraphic interval. Moreover, the age assignments are in certain cases rather tentative and can only be classified in terms of lithostratigraphic correlations and their position within the basin. Therefore, the description and interpretation of these wells are combined in Chapter 8. In addition to the above noted wells, an additional seventeen wells were investigated in part (see Fig. 2.6) also including published literature (Hoth et al. 1993) and unpublished well reports. This dataset focused both on the formation thicknesses in order to compile isopach maps and also on the overall lithological trends which were utilised to broaden results of the detailed environmental interpretation.

Several outcrops and research wells in the Flechtingen Block provide valuable information. These outcrops and the research wells of the Flechtingen Block were not documented and interpreted in this study but information concerning lithofacies and environmental interpretation were involved into the overall picture of the foreland basin successions. This additional information on outcrops was taken from the literature (see Chapter 8.13). Moreover, the spatial extend of the autochthonous carbonate platform sedimentation (*i.e.* Kohlenkalk) on the northern passive continental margin was derived from Hoffmann et al. (2001) and Hoffmann (2004, personal communication). This work is based on evidence from magnetotelluric and geochemical data. The spatial extend is of special interest in terms of this study since the formation

Table 2.2: List of research wells and according abbreviations that were used in the course of this study. Research wells that were documented and sampled in detail are written in bold letters.

Research well	Abbreviation	Research well	Abbreviation
Rügen 5/66	Rn 5/66	**Pudagla 1/86**	**Pud 1/86**
Dranske 1/68	Dke 1/68	**Parchim 1/68**	**Pa 1/68**
Rügen 2/67	Rn 2/67	Boizenburg 1/74	Bzg 1/74
Dranske 2/68	Dke 2/68	**Eldena 1/74**	**Ela 1/74**
Lohme 2/70	Loh 2/70	**Proettlin 1/81**	**Proet 1/81**
Sagard 1/70	Sagd 1/70	**Gransee 2/67**	**Gs 2/67**
Prerow 1/65	Pew 1/65	**Angermünde 1/68**	**Am 1/68**
Rügen 4/64	Rn 4/64	**Zehdenick 2/75**	**Zeh 2/75**
Gingst 1/73	**Gst 1/73**	**Grüneberg** 2/74	**Gü 2/74**
Binz 1/73	Binz 1/73	**Peckensen 7/70**	**Peck 7/70**
Barth 1/63	Bth 1/63	**Flatow 6/75**	**Flo 6/75**
Richtenberg 4/65	Ric 4/65	**Oranienburg 1/68**	**Ob 1/68**
Greifswald 1/62	Gd 1/62	**Nauen 1/76**	**Na 1/76**
Richtenberg 2/64	Ric 2/64	**Brandenburg 1/68**	**Br 1/68**
Grimmen 6/64	Gm 6/64	**Dreileben 3/70**	**Dren 3/70**
Loissin 1/70	**Loss 1/70**	**Eilsleben 8/76**	**Eil 8/76**
Lütow 1/67	Lto 1/67	Gommern 1	Gomm 1

of the carbonate platform preceded the initiation of foreland basin sedimentation.

2.6 Previous work

Much of the previously published work has concentrated on the bio- and lithostratigraphy of the cored Carboniferous throughout the former German Democratic Republic (GDR) and the correlation between these wells. Knüpfer und Weyer (1967) provided the biostratigraphy for the Rügen area. This work was extended by Hoffmann et al. (1975) who described the Lower Carboniferous lithostratigraphy of the Rügen area based on the cyclicity of the fossil rich calcareous-clayey shelf-sediments. In addition, a broad overview on the palaeogeographical and palaeotectonics was given in this study. Hirschmann et al. (1975) focused on the lithostratigraphy of the Upper Carboniferous of the Rügen-Hiddensee area. The work of Hirschmann et al. (1975) was extended by Hoth et al. (1990) for the Upper Carboniferous of the Rügen area with 10 additional wells from the Vorpommern area.

Initial comments on the central part of the basin were provided by Paech (1973 a-c) who focused on the outcrops and research wells from the Magdeburg and Flechtingen Block. He recognised the turbiditic character of the middle to upper Viséan Gommern Quartzite and the Namurian A deposits of the area. Moreover, he introduced (Paech, 1970) and described the Stephanian Süpling Formation and made valuable comments on its distribution and the environmental characteristics. Hoffmann (1990) described the deepest well in this area (Pröttlin 1/81) and suggested a Viséan age. This was later extended by Hoth (1997) who connected the well Pröttlin 1/81 with the wells Parchim 1/68 and Eldena 1/74 to one section through the entire region and contributed a stratigraphic range from Namurian A to, probably, Westphalian A.

The spatial extent of the Variscan Foreland Basin was defined by Ziegler (1990) including the Rügen area. For the first time parts of the studied basin were assigned to a foreland basin setting. Prior to this work, this particular basin was referred to as the "external Variscan Zone", "Subvariscan foredeep" or even more broadly the "Lower – Upper Carboniferous Basin".

Hoth et al. (1993) contributed a review of 63 deep boreholes in the area of the former GDR including short notes on the lithology and stratigraphic range of each listed well. Some of these wells were utilised by Hoth (1997) who investigated the facies and diagenesis of a transect from Rügen to the Harz Mountains focusing on pre-Permian strata. Gaitzsch et al. (1998) analysed the distribution of potential Carboniferous source-rocks in the Variscan foredeep of NE Germany by focusing on facies distribution, environmental interpretation and palaeogeography especially of the southern margin of the foreland basin while McCann (1999) focused on facies- and thickness distribution along the northern margin of the foreland and, secondarily, on the sedimentation in the basin centre. The interdependence between basin formation and Variscan activity to the south was also outlined in that study.

Jaeger (1999) added on the sedimentology and biostratigraphy of the Gommern Quartzite by a comparison with similar deposits to the east (*i.e.* quartzites from the Hörre-Gommern Zone). He argued that the sediment source of these gravity flows was not the orogenic front to the south but

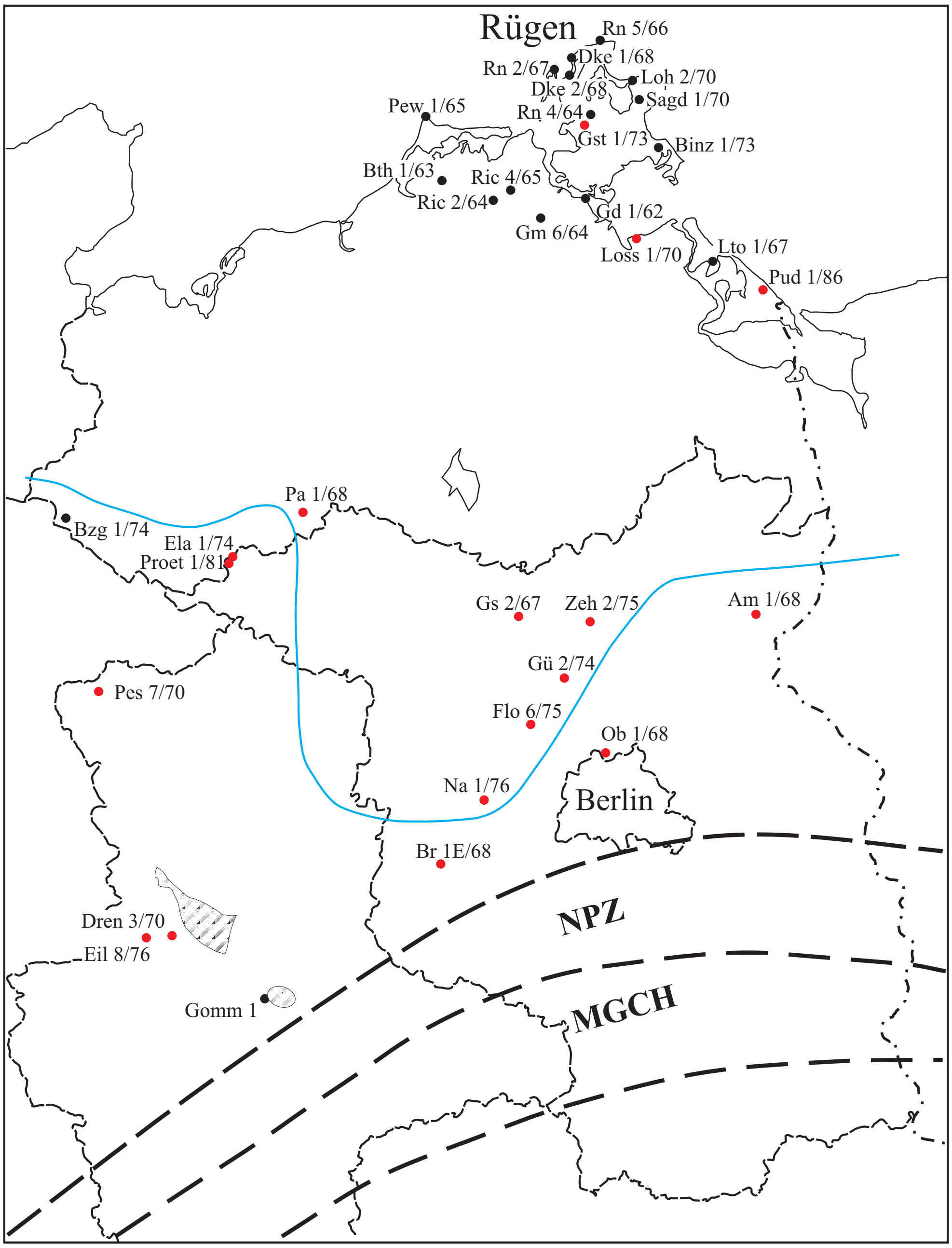

Figure 2.6: Study area and database. The red dots mark the research wells that were documented and sampled in detail for this study. The black dots mark the research wells that were investigated in part. Furthermore, information from the literature (Hoth et al. 1993) and several unpublished well reports were incorporated. The blue line marks the spatial extend of the autochthonous carbonate platform sedimentation (*i.e.* Kohlenkalk) on the northerly situated passive continental margin (Hoffmann et al. 2001; Hoffmann, 2004 personal communication). The hatched areas mark the outcrops of the Flechtingen Block and the outcrops south-east of Magdeburg.

the northern basin margin. Kopp et al. (2002) focused on the facies distribution of Viséan and Namurian strata (in northern Brandenburg) north of the therein called "northern Variscan outer edge" - corresponding to the central part of the foreland basin *sensu* Gaitzsch et al. (1998) and McCann (1999). He identified - from south to north - three facies zones: the Viséan proximal "Flysch-zone" with turbiditic deposits, the Namurian distal "Flysch-zone" also characterised by turbidites and the "Pelagite slack-water" zone. This study does, however, not refer to the structural evolution of the basin. Jaeger (2003, personal communication) provided the latest biostratigraphic classification for the Lower Carboniferous of the northern margin of the Variscan foreland basin. However, an integrated study - as approached in this study - focusing on the Carboniferous foreland basin as an entity was not supplied yet.

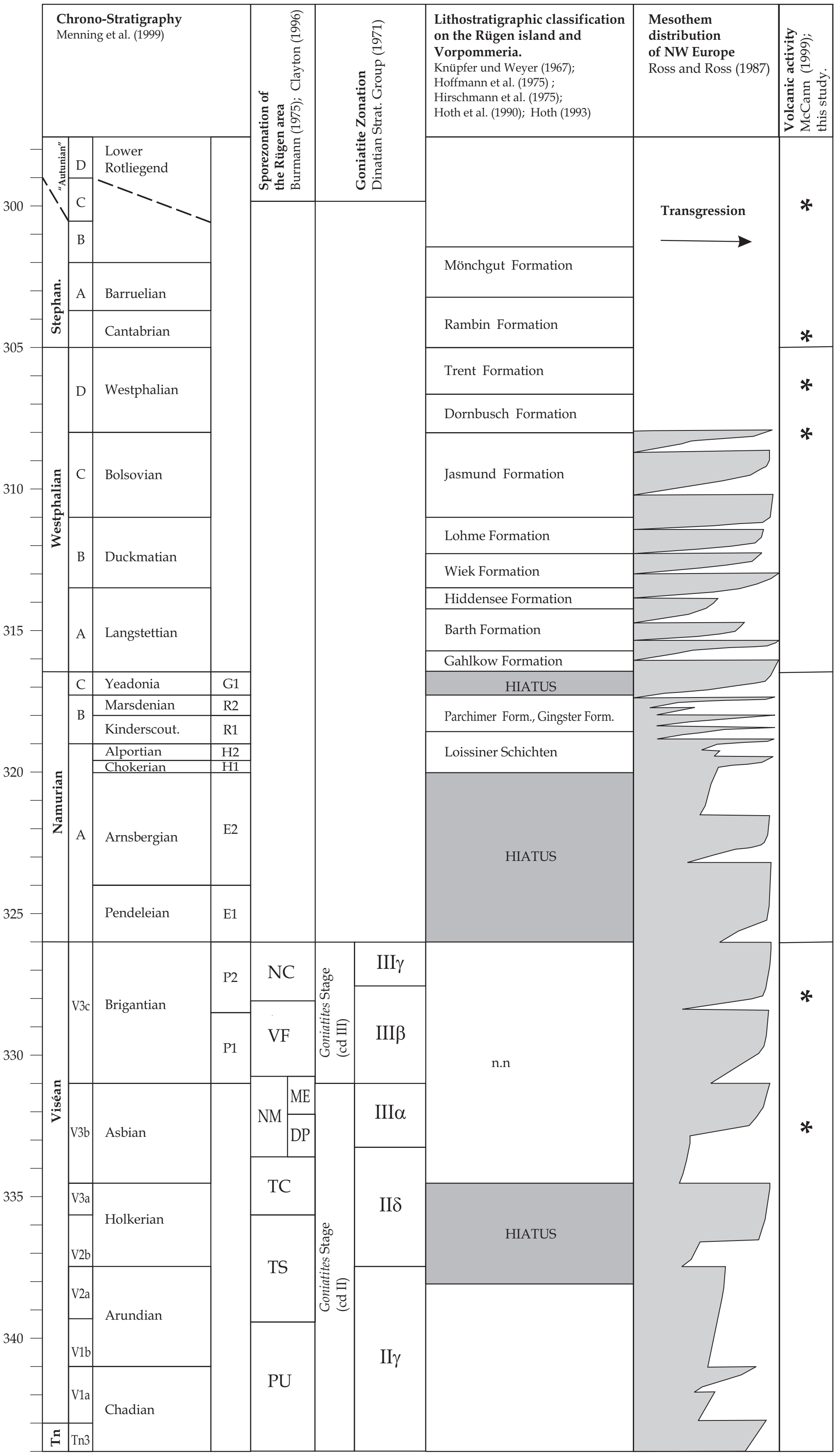

Figure 2.7: Bio - and lithostratigraphy of the NE German Variscan foreland basin. Compiled from various sources.

Chapter 3

Loissin 1/70

This well comprises a Stephanian to Viséan succession that extends from 3285 - 6876 m (see Tab. 3.1). A regional hiatus at 3285 m truncates the uppermost Stephanian at 3285 m depth. A local hiatus at 5336 m depth separates the Westphalian A from the Namurian B. The next hiatus of regional relevance separates Upper and Lower Carboniferous strata. It occurs at 6231 m depth and truncates the underlying Viséan strata. A local fault at 6774 m truncates the Viséan 2b and 3a. Viséan 1a and the Tournaisian are missing due to a regional hiatus at 6876 m. The Upper Carboniferous succession extends from 3285 - 6231 m of which 2946 m (including 550 m of magmatic rocks) were penetrated and 466.8 m core material was recovered (17 %). The Lower Carboniferous succession extends from 6231 - 6876 m of which 646 m were penetrated and 90 m recovered (14 %). 164 m of the Lower Carboniferous succession were magmatic rocks. The complete Carboniferous succession contains a total of 18 % magmatic rocks (714 m). The biostratigraphy and lithostratigraphic classification was adopted from Hoth et al. (1975; 1990; 1993).

3.1 Lower Viséan, Arundian

The Arundian succession extends from 6876 - 6774 m. Five core barrels with a total of 30 m of sediment were cored. The succession is mostly represented by limestones that are assigned to the autochthonous carbonate platform sedimentation of that area. A facies analysis was not performed on this material as the carbonate platform sedimentation on the passive continental margin preceded the initiation of foreland basin sedimentation.

3.2 Lower Viséan, Asbian - Brigantian

The uppermost Lower Viséan siliciclastic series (6231 - 6774 m) is represented by sixteen core barrels that together yield ca. 60 m of clastic material. The upper four core barrels were assigned to the Brigantian while the following twelve core barrels contain Asbian clastics (Hoth et al. 1993). Hoth et al. (1993) recorded three magmatic intrusions (rhyolite, andesite and basalt) during the lower Brigantian (Cv3c inf. 6328m - 6565 m).

3.2.1 Facies description and interpretation:

Mudstone facies; M,h-p: This facies comprises mudstones that are either well laminated (mm-scale) or massive. Rare bioturbated beds, up to 30 cm thick occur within the well laminated mudstones while the massive mudstones lack any biogenetic features. Pyrite precipitation is common. It occurs either as pyrite concretions (0.1 - 1 cm in diameter) or as dispersed pyrite that is aggregated in thin beds. The transition to the surrounding facies is mostly gradational. This facies attains thicknesses of between 2 - 18 m.

Interpretation: No current-generated sedimentary features were observed in this facies. With regard to the facies association, a depositional environment below storm wave base is suggested. The bioturbation of several beds within the laminated parts may denote - at least - temporary aerobic conditions of the depositional environment. This would suggest a shallow water depth with a common exchange of water masses. On the other hand, the massive beds of this facies may represent anaerobic conditions as no biogenic features were noted in these beds. Common pyrite precipitation also suggests anaerobic conditions since a high amount of TOC is a prerequisite for pyrite precipitation (Werne et al. 2002). This mudstone facies may have been deposited in an outer shelf area where the fine-grained sediments were transported by low-energy currents as suspension-load beyond the so-called 'mud-line'. This line separates high-energy shelf areas with a sandstone-dominated environment from a low-energy shelf area in deeper water on the outer shelf (Stanley et al. 1983). The lamination may result from differences in the supplied fined-grained sediments.

Mud/sand interbedded facies; M,h/Sf,p: This interbedded facies comprises massive mudstones and laminated, fine-grained sandstones. The interbedded beds are mostly 1 - 3 cm thick but beds of up to 15 cm may occur. The sandstone interlayers of the Brigantian are the only ones which show any carbonate content. Bioturbation occurs in parts throughout the succession. Two beds of about 5 cm thickness contain only shell-fragments. Pyrite concretions are common while dispersed pyrite is rarely observed. Two siderite concretions of about 3 cm in

Table 3.1: Loissin 1/70 (Loss 1/70): Bio- and lithostratigraphy of the Carboniferous.

Depth (m)	Thickness without magmat. (m)	Biostratigraphy	Lithostratigraphy
regional hiatus			
3285.0 - 3330.0	45	Stephanian	Mönchgut Formation
3300.0 - 3545.0	215		Rambin Formation
3545.0 - 3682.0	137	Westph. D	Trent Formation
3682.0 - 3933.0	251		Dornbusch Formation
3933.0 - 4243.0	310	Westph. C	Upp. Jasmund Formation
4243.0 - 4618.0	276		Low. Jasmund Formation
4618.0 - 4747.5	56	Westph. B	Lohme Formation
4747.5 - 4809.0	56		Wiek Formation
4809.0 - 4885.6	77	Westph. A	Hiddensee Formation
4885.6 - 5009.5	122		Upp. Barth Formation
5009.5 - 5214.0	199		Low. Barth Formation
local hiatus			
5214.5 - 5336.0	83	Nam. A - Westph. A, R2c? - CwA?	Gahlkow Formation
local fault			
5336.0 - 5526.0	190	Namurian B, Kinderscout. R1c	Parchim Formation
5526.0 - 6145.0	322	Namurian B, Kinderscout. R1a-b	Loissin Formation
6145.0 - 6231.0	86	Namurian A, Alportian, H2	n.n.
regional hiatus			
6231.0 - 6328.0	97	Viséan, Brigantian, V3c sup.	siliciclastics
6328.0 - 6565.0	ca. 237	Viséan, Brigantian, V3c inf.	volcanics siliciclastics
6565.0 - 6774.0	209	Viséan, Asbian, V3b V3b	siliciclastics
local fault			
6774.0 - 6876.0	102	Viséan, Arundian, V1b - V2a	carbonate platform sedimentation

diameter were observed in a mudstone bed. Some of the thicker sandstone beds from the lowermost core barrel show graded bedding (from coarse to fine) with a transition into mudstone beds. Synsedimentary dewatering structures were noted from a ca. 30 cm thick bed.

Interpretation: The observed bioturbation suggests an environment that was at least temporarily oxygenated while pyrite precipitation suggests at least dysaerobic conditions (Werne et al. 2002). Therefore, and with regard to the surrounding facies, a depositional environment of outer shelf conditions in a shallow clastic sea is suggested. The fine-grained mudstones may have been transported by even relatively weak currents while the interbedded sandstones may result from stronger currents that caused a resuspension of bottom sediments (proximal sand shelf) and the genesis of turbid plumes that were transported into outer shelf areas. These processes result in a sedimentation pattern - typical for mud-dominated shelves - where mud zones are juxtaposed against sand zones (Johnson and Baldwin, 1996). The graded sandstone beds with their transition into mudstone beds suggest deposition from turbidity currents as several characteristic features gravity flows deposits were recognised, *i.e.* a normal grading and an erosive base combined with a gradational transition to the mud-dominated background sedimentation. These turbidites were classified to the medium-grained turbidite facies according to Stow et al. (1996). The sandstone beds of these turbidites may correspond to the T_{a-b} intervals of the Bouma classification. The shell-beds may be storm related event beds that were reworked in a proximal shelf area and transported by higher-energy currents onto outer shelf areas.

Sandy mudstone facies; M(Sf),p: The sandy mudstone facies is limited to the Brigantian. It is characterised by mm-scale laminated mudstones

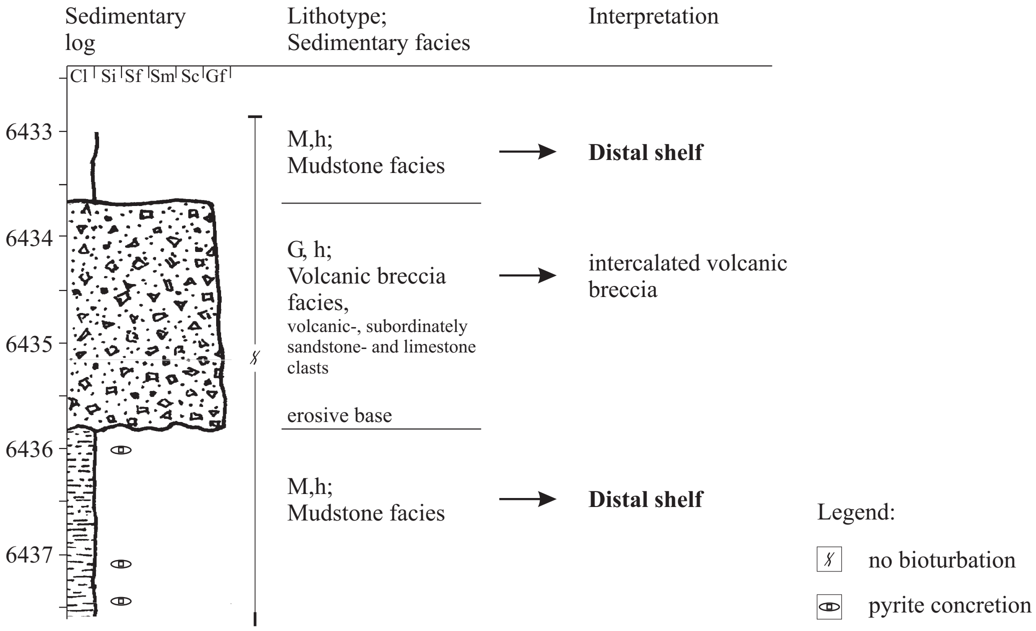

Figure 3.1: Core barrel from 6431 - 6438 m; Brigantian. Sedimentary log of a volcanic breccia. It is characterised by an erosive base and a sharp contact with the upper mudstone bed. The mudstones characterise the not-bioturbated background sedimentation of a distal shelf depositional environment.

with a noticeable amount of fine-grained sand. Moreover, a small amount of calcareous material was noted. Rare bioturbation features, but no pyrite precipitation, were observed. The transition to the surrounding facies is gradational. This facies attains thicknesses of 2 - 6 m.
Interpretation: The lack of any current-generated features may suggest deposition under low-energy conditions, probably below storm-wave base. Some bioturbation was observed which suggests aerobic condition during deposition. The considerable amount of carbonate within the sediments suggests the presence of calcareous rocks in the source area. In comparison to the associated facies this sandy mudstone facies may have been deposited in an outer shelf area where the fine-grained sediments were transported by suspension onto outer shelf areas beyond the so-called 'mud-line'. This line separates high-energy shelf-areas with a sandstone-dominated environment from low-energy shelf-areas in deeper water on the outer shelf (Stanley et al. 1983). The lamination may result from differences in the supplied fined-grained, suspended sediments.

Breccia facies; G,h: A poorly sorted breccia bed of ca. 110 cm thickness was noted from the lowermost Brigantian core barrel (Fig. 3.1). It contains angular to sub-rounded clasts - mostly volcanics with subordinate sandstones and limestones - that are matrix supported. The matrix contains exclusively sand and shows no signs of carbonate content. No sedimentary structures or bedding was observed. This bed has an erosional contact with the underlying mudstone facies and a sharp contact with the overlying mudstone facies.

Interpretation: The breccia bed shows no structures and this may suggest deposition from debris flow. Another process that would create such coarse-grained sediments in a shelf depositional environment would be storm-induced high-energy currents. The deposition due to a storm event can be excluded as the breccia bed shows no internal structures. This debris flow may be interpreted as tectonic origin due to local tectonic movements in the vicinity of volcanic activities. This might have created an increased relief which facilitated the deposition of gravity flows. Such a presumed tectonic movement might correspond to the volcanic activity during the lower Brigantian (V3C inf. see Tab. 3.1). This breccia bed is a part of one core barrel that represents a siliciclastic series which is framed by two volcanic series (overlying andesite, underlying basalt).

3.3 Namurian: Facies description and interpretation

The Namurian sediments of the studied succession comprise the uppermost Namurian A (Alportian) and the Namurian B (Kinderscoutian). Three core barrels (24 m cored) represent the Namurian A. The Namurian B is divided into the Loissin Formation and the Parchim Formation. Five core barrels were cored from the Loissin Formation comprising a total 27.9 m of sediment. Thirteen core barrels from the Parchim Formation were recovered. Eight core barrels contain magmatic rocks while five core barrels contain a total 39.6 m of sediments. Four beds with a marine fauna association were reported (Hoth et al. 1975). This fauna confirms the Namurian age of the sediments between 5336 - 6231 m. Altogether, nine beds with marine- and one brackish fauna provide palaeoecological information for the Namurian succession (Hoth et al. 1975; Hoth et al. 1990).

3.3.1 Namurian A

One bed with a marine fauna (Goniatites: *Homoceras? sp.* and *Homoceratoides?*) indicates the boundary between the uppermost Alportian and the lowermost Kinderscoutian for this section (Hoth et al. 1990). Hoth et al. (1990) classified this section - with regard to the following Kinderscoutian age of the Loissin Formation - to the Alportian. The other fauna yield Productacea, orthoconic Nautiloidea, Crinoidea and other marine genera.

Storm bed facies sequence; G,h - Sf,r: The lowermost core barrel (Fig. 3.2) contains a conglomerate with an erosive base that truncates a massive mudstone. The approximately 3 m thick conglomerate is poorly sorted and both matrix and clast supported. The rounded to well-rounded clasts are fine to medium-grained gravels which are mostly siliciclastic but calcareous clasts also occur throughout the bed. Sandy lenses (ripple bedding) of 5 - 10 cm are common in the uppermost third of the bed. The matrix contains mostly sand (fine to coarse-grained) with a carbonate fraction and subordinately mud. The conglomerate gradually passes into a hummocky cross-stratified sandstone bed (0.5 m thick) and then into dark-grey, laminated mudstones.

Interpretation: This conglomerate can be interpreted as part of a coarse-grained storm-bed sequence. It has a scoured base and a gradational transition to an overlying sandstone bed. The transition from conglomerate over hummocky cross-stratified sandstones to mudstones is typical for coarse-grained storm bed sequences (Cheel and Leckie, 1993) or so-called Tempestite sequences (Walker and Duke, 1983). This overlying mudstone bed records the transition to offshore conditions. Therefore, a near-shore shelf environment above storm-wave base is suggested by these sediments.

Mudstone facies; M,h: The two succeeding core barrels comprise dark-grey, massive mudstones with common pyrite concretions. No bioturbation and sedimentary structures were observed in these beds.

Interpretation: The appearance of massive mudstones with pyrite-concretions that were noted in the upper core barrels would also suggest a marine environment. However, the lack of shallow-water features within these mudstones suggests deposition below storm-wave base.

3.3.2 Loissin- and Parchim Formation

Mudstone–dominated facies; M,h-p; M(Sf),p: The mudstones of the Loissin Formation are mostly thinly interbedded clay/silt beds. These even laminated beds are mostly thinner than 1 mm. Most of these beds show some bioturbation but undisturbed beds, with common pyrite concretions, also occur. A sequential development with a transition from undisturbed, pyrite bearing beds to bioturbated beds is common.

Interpretation: The sedimentation pattern might denote a shelf depositional environment with a transition from oxygen-depleted conditions (no bioturbation, pyrite precipitation) to oxygenated conditions with common bioturbation. Pyrite precipitation may also occur secondarily from diagenetic processes and therefore hinder an environmental interpretation. But in this case, the pyrite is clearly enriched in sections that lack bioturbation and does not appear in bioturbated sections. Thus, an environmental significance is presumed. A deposition below storm-wave base is suggested, since no shallow-water features were observed within these mudstones.

Mud/Sand interbedded facies; M/Sf,l: This facies is characterised by pronounced flaser and lenticular (both connected- and isolated sand lenses) bedding with layer thicknesses varying from a few mm to ca. 5 - 7 cm. Bioturbation is common in this facies while no pyrite precipitation was noted. The thickness of this facies is ca. 2 - 4 m.

Interpretation: Flaser and lenticular structures imply that both, sand and mud were available and that periods of current activity alternated with periods of quiescence. During periods of current activity ripple formation occurs, while mud is held in suspension. During low-energy conditions the mud in suspension was deposited in the troughs or completely covered the ripples (Reineck and Singh, 1980). This is characteristic for tidal-influenced regimes, or where sediment supply is rhythmic or periodic, as in delta-fronts or floodplains (Leeder, 1995). In comparison to the Namurian B successions from other wells of the area (*i.e.* Gingst 1/73, Pudagla 1/86) and the facies association of this well, it is presumably that the overall environment is a shallow marine- to non-deltaic coastal and therefore these flaser- and lenticular structures are interpreted as tidal-influenced.

Sandstone facies; Sf,r: The sandstones of this facies are mostly rippled, ripple cross-bedded and planar cross-bedded and predominately fine-grained. The cross-bedding is mostly small-scale (*i.e.* cros-sets of a few mm up to 5 cm). The thickness of these beds varies from ca. 1 - 4 m. The lower contact is mostly gradational and develops from the mud/sand interbedded facies.

Interpretation: The interpretation of these sandstones in isolation is rather difficult. It has to be interpreted in term of facies associations and sequences as represented in the Section 3.4 from which foreshore or coastal floodplain conditions were deduced.

Soil facies; Sf,s: Two soilified sandstone beds were identified within the preserved succession. Both beds are ca. 80 cm thick. These beds are characterised by disturbed primary bedding due to the activities of rootlets. Plant debris is common within

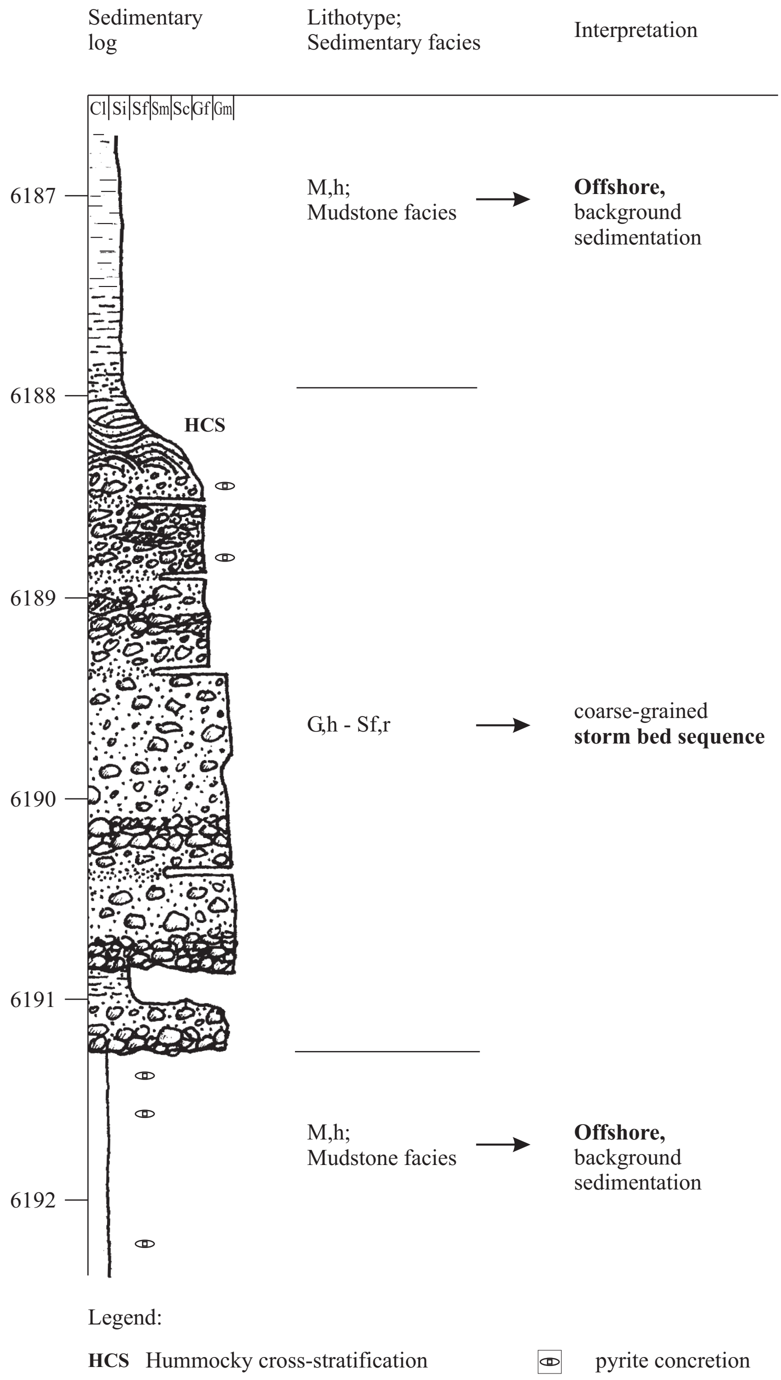

Figure 3.2: Core barrel from 6184.7 - 6192.9 m; Namurian A. Sedimentary log of a storm-bed sequence, characterised by an erosive base and a gradational transition to the upper mudstone bed. Hummocky cross-stratified sandstones mark this transition. The mudstones characterise the non-bioturbated, offshore- to outer shelf background sedimentation.

these horizons. Moreover, these beds are characterised by a brownish grey colour which is in clear contrast to the surrounding facies.

Interpretation: The differentiation between signs of bioturbation or pedoturbation in this facies association is rather difficult. But there are some valuable indicators for the assumption of root penetration. The shape of root burrows differs from those that were assigned to actively burrowing animals; root burrows have a more horizontal component and are commonly arborescent forming a network of traces while animal burrows are commonly isolated. Moreover, rootlets may appear more intense dark grey to black coloured due to a high content of organic matter. In addition, dispersed plant debris is common. Rarely, some signs of tissue structures were observed from bigger rootlets. Furthermore, the colour of the sediments can be involved in the environmental interpretation as these two soil horizons are differentiated by grey brownish colours. The development of a soil horizon indicates that the depositional surface was close to, or above, water level and may denote a backshore subenvironment. This facies has a gradational transition to the underlying sandstone facies.

3.4 Namurian evolution of depositional environments; facies associations and sequences

An overall shallowing of the depositional environment was observed from the Namurian A to the Namurian B. The preserved Namurian A core material lacks of bioturbation while the Loissin- and Parchim Formation (Namurian B) show some bioturbation. This might indicate partly oxygenated conditions during the Namurian B and therefore denotes a shallowing of the presumed shelf environment. The Namurian B is characterised by a sequential development of sedimentary facies (see Fig. 3.3). One possible interpretation might be that the massive or thinly laminated mudstones with common pyrite concretions mark the initial offshore conditions with oxygen-depleted conditions. A gradational transition to bioturbated mudstones occurs as the depositional environment is progressively shallowing. The transition to flaser- and lenticular bedding characterises the influence of tidal currents. The succession then shifts to fine-grained sandstones with current-generated sedimentary structures that may be interpreted as foreshore deposits or - with regard to the subsequent soilification - as fluvial deposits on a coastal floodplain. It has to be discussed if this sequence - with regard to other wells from the area (Parchim 1/68, Eldena 1/74) is part of a barrier-island/lagoonal system (see Sections 6.2 and 7.2). The underlying mudstones would then correspond to a low-energy lagoonal environment. Some observations from the mudstone–dominated facies suggest rather an offshore depositional environment. For example, humid and temperate lagoonal muds are often rich in organic matter and plant debris while soilification - as observed in the lagoonal mudstone facies of the Parchim 1/68 well - might also occur (Reading and Collinson, 1996). In addition, wind-wave generated features as ripples are common in lagoonal deposits as the water depth are considerably low. Such features were not recorded in the mudstone–dominated facies of this well. It is therefore assigned to an offshore depositional environment.

3.5 Westphalian A: Facies description and interpretation

The Westphalian A succession starts with the Gahlkow Formation. It is represented by two core barrels with 4.5 m and 6.6 m of cored sediments. The Gahlkow Formation passes into the Lower Barth Formation from which nine core barrels with a total of 67.9 m were cored. The Upper Barth Formation is documented by four core barrels that contain 18.9 m of sediment. The Hiddensee Formation is represented with two core barrels (11 m of sediment). The facies description and interpretation for the Barth and Hiddensee formations was combined as these formations are characterised by a very similar facies development. One marine fauna horizon at 5028 m depth (Lower Barth Formation) and six non-marine horizons as well as flora-findings provide palaeoecological evidence and a continuous biostratigraphic proof for the Westphalian A age of the sediments from 4809 - 5336 m (Hoth et al. 1975).

3.5.1 Gahlkow Formation

Mudstone dominated facies; M,h - M(Sf),r-l: This facies mostly comprises massive mudstones and subordinate sandy mudstones that are ripple to flaser bedded. A 60 cm thick bed within the sandy mudstones contains abundant coal fragments. Pyrite concretions occur in a ca. 30 cm thick bed of massive mudstone. Bioturbation is rare in the sandy mudstones.
Interpretation: The deposition of coal fragments on the one hand and unbioturbated, pyrite-bearing mudstones on the other side hand a vivid depositional environment. The changes from current-influenced beds to massive beds deposited during slack water conditions suggests a deposition on a coastal floodplain that was partly influenced by probably tidal flat conditions (*i.e.* flaser bedding). But the soil horizon (see below) also suggests deposition at the boundary between water and land.

Soil facies; M,s: A soilified mudstone bed was identified within the preserved succession. The bed is ca. 180 cm thick and characterised by disturbed primary bedding which is caused by the activities of rootlets. Organic matter is enriched in sub-mm thick laminae.
Interpretation: The identification of rootlets besides a characteristic colouring of the sediment suggest a soilified facies. On the environmental level, the development of a soil horizon indicates that the depositional surface was close to, or above, water level. This facies has a gradational transition to the underlying mudstone facies.

3.5.2 Lower- and Upper Barth formations, Hiddensee Formation

Sandy mudstone facies; M(Sf),p-r-l: This facies mostly comprises sandy mudstones and interlayered sand-mud beds. The thickness of this facies ranges between 1 - 9 m (*i.e.* thicker than the length of the core barrel). The commonly observed bedding structures are parallel lamination besides flaser and lenticular bedding. Bioturbation is common throughout this facies. There is a gradational contact with the overlying, rippled fine-grained sandstone beds.
Interpretation: In comparison to the mud/sand interbedded facies of the Loissin and Parchim for-

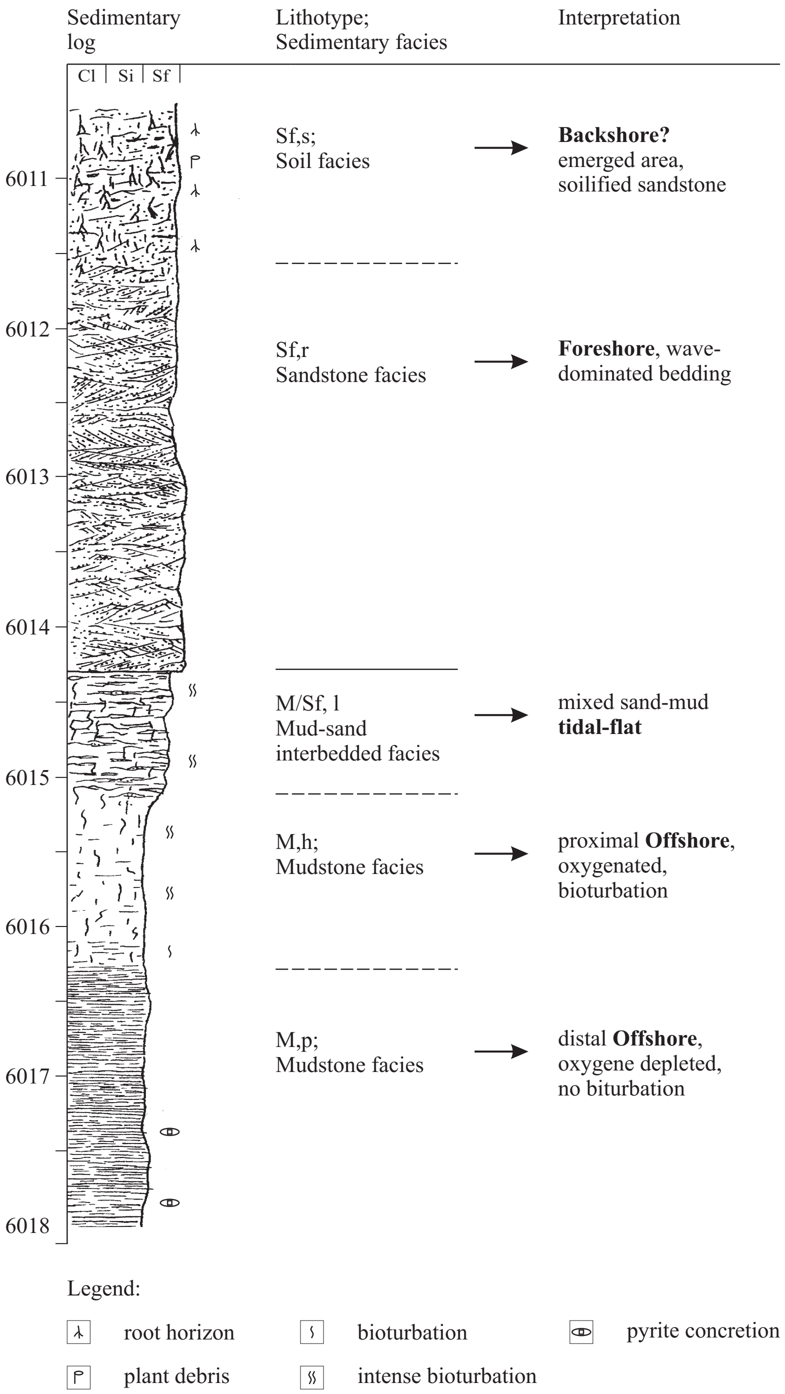

Figure 3.3: Core barrel from 6010.5 - 6019 m; Loissin Formation. Sedimentary log of a coastal facies sequence. It is characterised by transition from offshore to foreshore and, probably, backshore conditions.

mation, the lenticular and flaser bedding are here likewise interpreted as being characteristic for a tidal-influenced depositional environment. Compare Section 3.3.2 for the discussion of these bedding structures and its environmental interpretation.

Soil facies; Sf,s: A 0.8 m thick soil horizon was observed within the sandy mudstone facies. It is characterised by intensively disturbed bedding with patchy siderite-accumulations and brown to grey-brown colours. Siderite is accumulated in the form of well rounded 0.5 - 1 cm thick concretions. These concretions show reddish brown colours.

Interpretation: During the deposition of the sandy mudstone facies the depositional site was emerged and vegetation cover was established. This is interpreted as indicating supra-tidal conditions.

Mudstone facies; M,p: This facies is characterised by thicknesses ranging from 0.2 - 4 m. Both, upper and lower contacts are sharp or gradational. The common bedding type is thin parallel lamination but massive and rippled beds also occur. Plant debris is common within this facies and bioturbation was also observed.

Interpretation: This facies is part of one of two distinct facies sequences which are more carefully discussed below in the interpretation of the sandstone facies. The mudstone facies may form - in association with the sandstone facies (Sf-c;r) - the base of a coarsening-upward sequence or the top of a fining-upward sequence. The rippled bedding of some beds denotes a current-generated deposition. These mudstones - in comparison to the mudstone facies of the Namurian period - have higher silt/clay ratios. These higher ratios are interpreted as indicating a decrease in sediment transport by suspension load. Thus, in contrast to the Namurian, this facies does not represent a shelf or coastal depositional environment but, rather a deltaic environment. Such an interpretation is suggested by the overall facies association which fits more into a vivid change of facies that is typical for deltaic successions.

Sandstone facies; Sf-c,r: The sediments comprise predominantly fine-grained- sandstones while medium- to coarse-grained sandstones occur subordinately. These sandstones are parallel to ripple cross-bedded with small- to medium scale crossets. The thickness varies from 20 cm up to the length of a complete core barrel (*i.e.* 9 m). The lower contacts with the underlying mudstones and conglomerates are gradational, while the upper contact with thin coal seams is predominantly sharp. Plant debris is common throughout this facies.

Interpretation: This sandstone facies is part of a series of facies sequences that are either fining- or coarsening-upward. The **coarsening-upward sequences** are most likely interpreted as interdistributary bay deposits that are characterised by initial shale deposits which are typically rich in organic matter and may be bioturbated. The observed upward increase of grain size is probably caused by an increasing emplacement of crevasse splay deposits as a distributary channel progrades into the bay. This mechanism can be compared with upward-coarsening of fluvial deposits (Diessel, 1992). Horne (1979) also suggests that interdistributary bay-fills of river-dominated deltas may begin with dark grey to black shale clays and finish with silty or fine-grained sandstones from which the coarser upper portion is characterised by current ripple sedimentary structures with the addition of medium and large scale cross-bedding in current-affected sediments. Reading and Collison (1996) point out that in deltaic succession, a series of 3 - 10 m coarsening-upwards sequences represent the repeated infilling of interdistributary areas and where the siltation of the depositional site is commonly marked by peat beds and thin soils.

According to Diessel (1992) an interfingering of fining- and coarsening upward sequences is typical for lower delta plains. **Fining-upward sequences** may correspond to distributary channels that form fining-upward sequences with erosional lower contacts and sharp upper contacts which result from the sudden cessation of sediment supply (Reading and Collison, 1996). This includes the formation of abandoned channel sub-environments that accumulate overbank fines and organic detritus settling out of suspension (Saxena and Ferm, 1976 in Diessel, 1992). These might correspond to the coal seams (see below) that are characteristic for the Barth formation. These coal seams often mark the boundaries between these two sequences. The erosional lower contact of these fining-upward sequences may be marked by conglomerate beds of the conglomerate facies (see below). In general, this lower delta plain environment is characterised by siltation of both coarsening-upward interdistributary bay and fining-upward distributary channels which is indicated by the formation of soils and/or coal seams.

Conglomerate facies; G,h: Four matrix supported conglomerate beds with thicknesses of about 0.1 - 0.3 m form the base of fining-upward sequences. The transition to the overlying sandstone beds is gradational while the lower contact is erosional. The clasts are mostly well rounded quartz gravels and subordinate intraformational muddy rip-up clasts occur. The clast size varies from fine to coarse-grained gravel.

Interpretation: With regard to the facies sequences of the Barth formation (see sandstone facies above), these conglomerates may represent the basal deposits of alternating distributary channels on a lower delta plain.

Coal seams: Eleven coal seams with thicknesses from 3 - 50 cm were noted. They form the top of both coarsening- and fining-upward sequences or appear as boundaries between sandstone beds. A more detailed description of the coal was not possible because the material was mostly removed by earlier workers.

Interpretation: The coal seams are interpreted as having been deposited in vegetated swamp areas or abandoned distributary channels on a - with regard to the facies association - lower delta plain.

3.6 Westphalian A evolution of depositional environments; facies associations and sequences

The Westphalian A begins with the deposition of the Gahlkow Formation. Deposition took place in a coastal floodplain environment that was not influenced by a deltaic system. The mudstone facies of this formation contains some pyrite concretions that might be indicative of anaerobic conditions and with regard to the facies association suggest a marine influence on the depositional area. The Barth- and Hiddensee formations document a deltaic system that is influenced by several processes which results in a vivid change of several sub-environments reflecting *Walther's Law of Facies* (Walther, 1894). Distributary channels (fining-upward sequences) and interdistributary areas (coarsening-upward sequences) are located in direct vicinity to tidal-flat and marsh deposits (flaser- and lenticular bedding, soil horizon). Thin coal seams mark the boundaries between these sequences and represent swamp environments on a delta plain (*e.g.* abandoned channels, floodbasins). The peak of deltaic development is noted during the Lower Barth Formation. The Upper Barth formation is characterised by an overall decrease of sandstones. This might indicate a shift of the deltaic system and an establishment of more fluvial-influenced floodplain conditions, probably, on an upper delta plain. Such a differentiation between lower- and upper delta plain is rather difficult (Diessel, 1992) and in this case tentative. According to Saxena (1979) and Coleman and Prior (1980) (both in Diessel 1992), the upper delta plain occupies the subaerial portion of the delta and merges imperceptibly with the alluvial valley. The lower delta plain is defined as the zone which marks the updip limit of tidal inundation. In ancient delta deposits, this zone is represented by alternating low sinuosity channel sandstones and interdistributary bay shales which may contain brackish to marine fossils, seat earths with rootlets and interspersed coal (Horne et al. 1979 in Diessel, 1992). In this succession only one marine fauna was documented from the Lower Barth formation (5028 m) and another six non-marine fauna for the succession above. This might also indicate a temporary cessation of marine influences from the Lower to the Upper Barth formation and may indicate a shift from lower- to upper delta plain conditions.

3.7 Westphalian B: Facies description and interpretation

The Westphalian B is divided into two formations, *i.e.* Wiek- and Lohme Formation. The Wiek Formation is only documented in one core barrel of 6 m length. The Lohme Formation is documented by two core barrels of together 18 m of sediment.

3.7.1 Wiek Formation

Sandy mudstone facies; M,p: The lower part of the core barrel from the Wiek Formation exclusively comprises a ca. 3 m thick sandy mudstone bed. It can be characterised as a thinly interbedded mud/sand unit with laminae thicknesses between ca. 0.1 - 2 mm. This facies is extensively bioturbated and some pyrite concretions were observed in the non-bioturbated layers.

Interpretation: No current-generated structures suggest deposition during low-energy conditions with alternating sand-mud input (thinly interlayered bedding). Pyrite precipitation also suggests anaerobic conditions since a high amount of TOC is a prerequisite for pyrite precipitation. Such conditions are mostly encountered in marine environments but also lacustrine environments may provide suitable conditions for pyrite precipitation (Werne et al. 2002). The sediments of the Upper Barth formation were prior interpreted as fluvial-influenced floodplain deposition of a, probably, upper delta plain.

With regard to the underlying Upper Barth formation a fluvial-influenced environment is likewise presumed for the Wiek formation. Therefore, this facies is interpreted as representing the deposits of a floodbasin or abandoned channel. The regular alternation of two contrasting sediment types (Rhythmites) is the most characteristic feature of a lacustrine facies (Talbot and Allen, 1996).

3.7.2 Lohme Formation

Sandstone-dominated facies; Sf(M),p-r: This facies is characterised by a muddy sandstone that is mostly parallel laminated to ripple bedded. But also some ripple- and planar cross-bedded beds were recorded. The cross-bedding is small- to medium scale. Most of the sandstone beds have sharp bases and attain thicknesses from 1 - 3 m. Two fining-upward sequences, one with a coal seam (0.25 m thick) on top, were noted. Some interlayered sand-mud beds (ca. 30 - 70 cm) were also observed. One of these interlayered beds is enriched with mud-clasts.

Interpretation: Current-generated sedimentary structures besides an alternation with the sandy mudstone facies (see below) may indicate fluvial conditions. The sandstone beds are all characterised by sharp contacts with the surrounding facies which is characteristic for braided river systems where shallow channels transport the sediment as bedload and the sharp contacts indicate the vivid fluctuation of these channels (Miall, 1996). Two fining-upward sequences contribute to the interpretation as fluvial channel deposits. These fining-upward sequences may be interpreted as deposits of relatively bigger channels within the braided system that are characterised by a gradational transition to the surrounding slack water deposits (*i.e.* overbank fines). This sequence may have resulted from a meandering channel within the channel system. The muddy rip-up clast mark overbank fines that were reworked by alternating channels within the braided system and are therefore classified as intraformational. This characteristic stack of channels and overbank fines was compared to the 16 fluvial styles introduced by Miall (1996) and, as a result, assigned to a "Shallow perennial braided system".

Sandy-mudstone facies; M(Sf),p: The sandy mudstones of the Lohme Formation are characterised by a massive bedding and abundant plant debris. The thickness of this facies varies from 0.5 - 2 m. The upper contacts are exclusively sharp. The lower contact with the sandstone facies is mostly

sharp or gradational within the fining-upward sequences.
Interpretation: These mudstones are interpreted as representing overbank fines of the adjacent braided river system. Abundant plant debris may indicate a proximity to vegetated areas. With regard to the interpretation as a part of a braided river facies association, these overbank fines were assigned to fluvial floodplain environment.

Coal seam: One coal seam with a thickness of 20 cm was noted. It formed on the top a fining-upward sequence. A more detailed description of the coal was not possible because the material was mostly removed from the preserved core-material by earlier workers.
Interpretation: As noted above, the fining-upward sequences were interpreted as relatively bigger, meandering channels. This might suggest that this particular coal seam is indicative of an abandoned channel sub-environment. The depositional site may have been characterised by a vegetated cover which formed during the progressive siltation of the abandoned channel.

3.8 Westphalian C: Facies description and interpretation

The Westphalian C is divided into the Lower- and Upper Jasmund Formation. Seven core barrels containing 45.9 m of sediments were cored from the Lower Jasmund Formation. Two of these seven core barrels yield a volcanic intrusion (graniteporphyr). This intrusion is interpreted as a volcanic sill because it altered both overlying and underlying sediments. The Upper Jasmund Formation is represented by five core barrels containing 41 m of sediment.

3.8.1 Jasmund Formation

Sandstone-dominated facies; Sf-m(M),p-r: This facies comprises sandstone and muddy sandstone beds. Its thickness varies from 1 - 3 m. The facies shows different types of current-generated sedimentary structures. Even planar bedding and ripple cross-bedding (see photo 11) dominate this facies but planar cross-bedding and massive sandstones also occur. The cross-bedding is small- to medium scale. The transition to the surrounding beds within the facies and between the different facies of this formation is mostly sharp. Gradational transitions also occur and often denote a sequential development with a basal sandstone bed as a part of a fining-upward sequence. These sequences have an erosive base.
Interpretation: These sandstone beds are characterised by sharp transitions to the surrounding mudstone facies. This is indicative of distinct shifts from current-generated deposits to low-energy, slack water deposits which are typical for braided streams processes with frequently alternating current energies. This alternation results in the deposition of channel-bar, channel-fill and overbank deposits. The planar-bedded sandstone beds may correspond to channel-fills with alternate bars. In addition, two fining-upward sequences were reported from one core barrel within the Lower Jasmund Formation and with regard to the surrounding facies interpreted as meandering and therefore relatively bigger channel-fill deposits of a braided river (see Fig. 3.4). According to Miall (1996) the facies association of the Upper Jasmund Formation may be assigned to a "Low-sinuosity" braided river system.

Mudstone facies; M,p-r: The mudstone facies is characterised by weakly parallel- to massive bedded mudstones. The mudstone beds attain thicknesses from 0.2 - 5 m but measure mostly ca. 2 - 3 m. These beds are often subdivided into smaller beds that can be distinguished by the clay-silt ratio. Some beds of ca. 0.2 - 0.5 m thickness show a thinly, mud-sand interlayered bedding. Plant debris is very common in this facies while coal fragments appear subordinately.
Interpretation: The mudstones may correspond to overbank fines that were deposited during high-flood stages of the adjacent braided river. These mudstones were mostly deposited from low-energy currents (*i.e.* suspension-load) since current-generated structures were not observed.

Soil facies; M,p-r: Two soil horizons mark the uppermost part of two fining-upward sequences. These soilified mudstone beds are characterised by disturbed bedding, common root burrows and a greyish brown colour.
Interpretation: The depositional site was emerged during the deposition of the mudstone facies as plants could develop on it and a soilification took place. This might indicate emerged and vegetated areas on the floodplain.

Coal seams: Two coal seams (3 cm and 40 cm) were recorded. They form the top of fining-upward sequences. A more detailed description of the coal material was not possible because it was mostly removed from the preserved core-material by earlier workers.
Interpretation: The coal seams are interpreted as deposits of vegetated swamp areas or abandoned channels on a fluvial floodplain. From the scarce preserved material it is not possible to describe this coal forming sub-environment more precisely. The deposition on top of fining-upward sequences may allow the identification of an abandoned channel subenvironment but with regard to the widespread coal seams of this stratigraphic unit in the entire study area (Hoth and Wolf, 1997), such spaciously environments as vegetated swamps must be taken in consideration.

3.9 Westphalian D: Facies description and interpretation

The Westphalian D lithostratigraphy comprises the Dornbusch- and Trent formations. The Dornbusch Formation is documented by three core barrels of together 21.2 m of sediment while the Trent Formation is documented by four core barrels containing 35.5 m of sediment.

3.9.1 Dornbusch- and Trent formations

Sandstone facies; Sf,r: Ripple- and ripple cross-bedded, fine to medium-grained sandstones dominate this facies. A mixture of the grain sizes in one bed is, however, uncommon. The bed thickness varies from 0.1 - 1 m, although the majority of the beds are ca. 0.5 m thick. One fining-upward sequence with an erosive gravel bed that passes into a sandstone bed was observed from the lower part of the Dornbusch Formation. An overall coarsening upward trend from the Dornbusch to the Trent Formation was observed. The sandstone beds from the Dornbusch Formation comprise only fine-grained sandstones. Medium- and coarse-grained sandstones dominate the Trent Formation. Also, the bed thicknesses increase upwards as the two uppermost core barrels of the Dornbusch Formation comprise thick amalgamated sandstone beds (up to 7 m thick sandstone bodies). These can be distinguished by sharp or erosive contacts. The erosive contacts are often marked by thin gravel beds but also mud-pebble conglomerates mark the base of these sandstone beds. The transition to the adjacent mudstone facies is mostly sharp. Gradational contacts of these sandstone beds are limited to some fining-upward sequences. With the onset of the Westphalian D sedimentation, a reddish colouring, in addition to the usual grey colours of the rocks, is observed.

Interpretation: Current-generated sedimentary structures and a comparison with the adjacent facies suggest a fluvial genesis of these sandstone beds. Furthermore, erosive surfaces document the bases of channels within the prominent sandstone beds. The depositional environment suggests the proximity of current-influenced sandstones to the overbank fine mudstones. This proximity is documented by the reworked mud-flakes within sandstone beds. Overbank fine mudstones and current-generated sandstones, particularly the formation of channels, suggest a flood-plain sedimentary environment that was flooded by a braided river system. This facies association - in comparison to the underlying Jasmund Formation - with its amalgamated sandstone beds and intercalated overbank fines suggests a change in the braided river style that is characterised by an overall decrease in overbank intercalations. The observed facies association was compared to the different fluvial systems introduced by Miall (1996) and classified to a "Shallow perennial" braided river system.

Mudstone facies; M,h: The mudstones are predominantly massive and red-coloured. Discontinuous lamination rarely occurs. The bed thickness varies from 0.5 - 1 m. No plant debris was observed throughout this facies.

Interpretation: According to the facies association (see above), these mudstones are interpreted as representing overbank fines of a "Shallow perennial" braided river system that were deposited on a floodplain environment. The lack of plant debris - in comparison to the Westphalian B-C period - may indicate a climatic change that may have caused a decrease in vegetation cover on the floodplain and adjacent areas.

3.10 Westphalian B–D evolution of depositional environments

The Westphalian A–B transition is continuous. The Wiek and Lohme formations document an alluvial sedimentary environment with floodplain and braided river deposits. Furthermore, a floodbasin or abandoned channel subenvironment could also be identified. The onset of the Westphalian C in Vorpommern is marked by the Ägir-Transgression documented by the Ägir-Horizon. Its thickness varies from 2.5 - 16 m. This marine ingression is the final marine influence that could be observed in the Upper Carboniferous foreland basin of NE-Germany (Hoth et al. 1990). In the Loissin 1/70 well, the Ägir-Horizon is not cored but presumed by well-log evidence (Hoth et. al. 1975). The depositional environment of the Jasmund Formation is comparable to the Lohme Formation but a decrease in coal sedimentation was noted. The environmental evolution of the Dornbusch to the Trent Formation (Westphalian D) is characterised by an overall coarsening-upward trend. Alternating braided river and flood-plain sedimentation prevails but sedimentary sequences such as noted in the Westphalian B-C were not developed. The disappearance of plant debris and coal fragments in the mudstone facies of these formations might indicate a climatic change that caused a decrease in vegetation cover. It is not clear whether the red colouring of the Westphalian D sediments is of primary origin or reflects secondary diagenetic changes. A primary cause would favour a climatic change to semi-arid or arid conditions.

3.11 Stephanian: Facies description and interpretation

The Rambin- and the Mönchgut formations represent the Stephanian of the Loissin 1/70 well. Two core barrels of together 16.9 m were cored from the Rambin Formation. The Mönchgut Formation is represented by two core barrels (16.8 m of sediments).

3.11.1 Rambin- and Mönchgut formations

Sandstone facies; M,r: This facies comprises mostly fine- and subordinately medium- to coarse-grained sandstones. The predominant bedding type in the two core barrels of the Rambin Formation is ripple cross-bedding with medium- to large scale crossets. The two core barrels from the Mönchgut Fromation are characterised by mostly rippled- and planar-bedded sandstones (see photo 8). The bed thicknesses vary from 0.5 - 5 m. Reworked mud-fragments are common in some beds. These mud components were characterised as rip-up clasts and thin crinkly muds (ca. 0.1 cm thickness). Granular sandy lenses (coarse-grained sands) were noted within a fine-grained sandstone bed. The transition to the adjacent mudstone facies is mostly sharp but some beds also show a gradational change. Plant debris was noted in one sandstone bed from the Rambin Formation. A reddish colouring prevails throughout the cored succession.

Interpretation: The presence of current-generated sedimentary structures and a comparison with the adjacent mudstone facies suggest a fluvial origin for these sandstone beds. The depositional environment suggests the proximity of current-influenced sandstones and overbank fine mudstones as the sandstone beds contain reworked mud components. As this facies association is very similar to the facies recorded from the Westphalian C-D, an alluvial sedimentary environment with floodplain and braided river deposits is suggested for the Stephanian period of this area. For a detailed discussion of braided river deposits see the sandstone facies interpretations of the Jasmund, Dornbusch and Trent formations above.

Mudstone facies; M,h: The mudstones of this facies are predominantly massive- to weakly planar bedded. Some intercalations of fine-grained sandstone beds with thicknesses from ca. 1 - 10 cm were noted. This facies attains thicknesses from 0.5 - 3 m.

Interpretation: According to the Westphalian C-D period, these mudstones are interpreted as representing overbank fines of a braided river system. They were deposited on a floodplain environment.

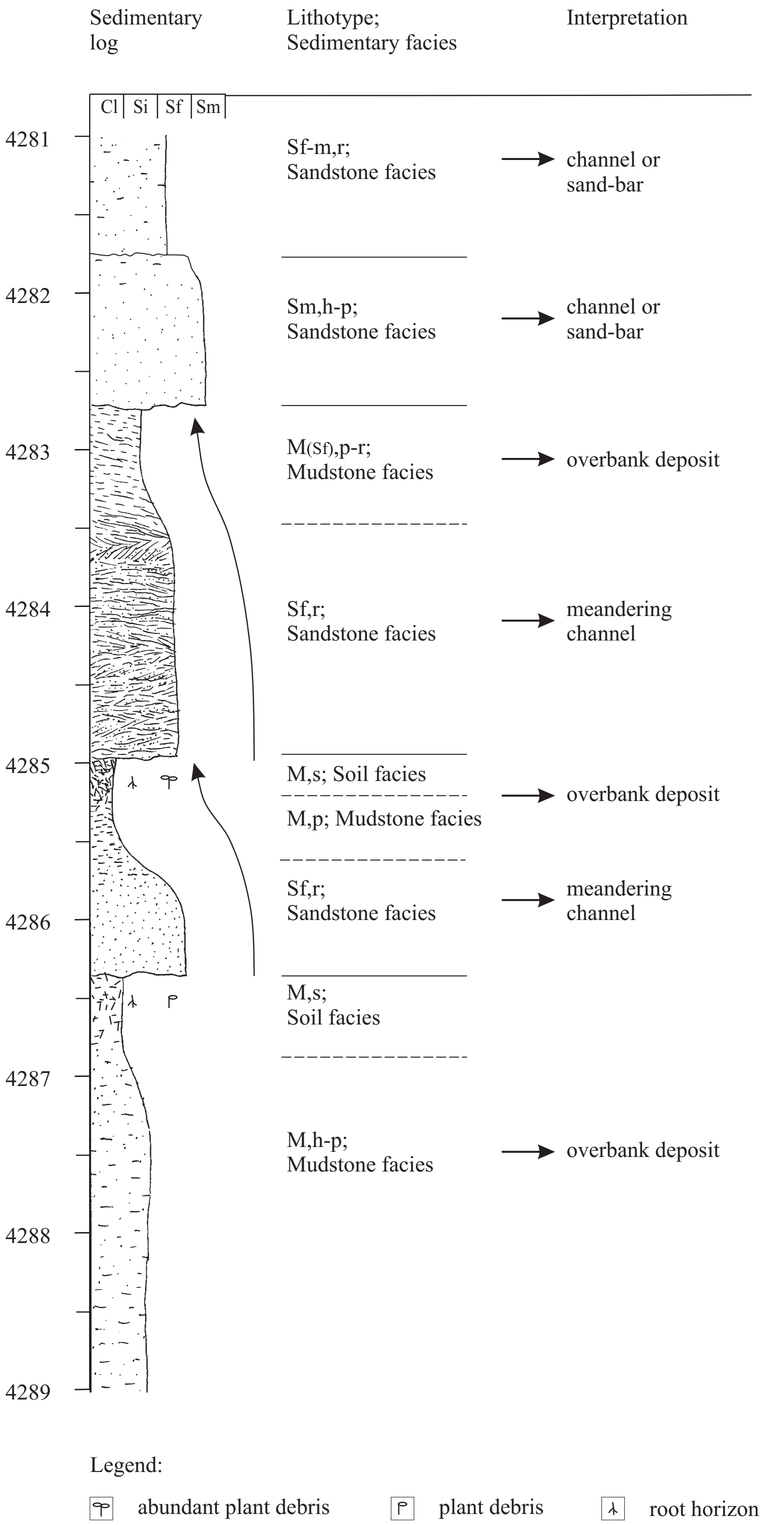

Figure 3.4: Core barrel from 4890.9 - 4289.9 m; Lower Jasmund Formation. This section shows the deposits of a braided river system with alternating sand-bar, channel, meandering channel and overbank subenvironments. Two soil horizons developed from overbank deposits.

Chapter 4

Gingst 1/73

The Gingst 1/73 well comprises a Stephanian to Tournaisian succession that extends from 1954.0 - 4681.0 m (Tab. 4.1. The Upper Carboniferous succession extends from 1954.0 - 3448.9 m of which 389.1 m sediments and 113.8 m magmatic rocks (basalts) were cored. The Lower Carboniferous succession extends from 3448.9 - 4681.0 m. A regional hiatus at 1954 m depth truncates the uppermost Stephanian. A regional hiatus at 3448.9 m depth separates the Upper- and Lower Carboniferous. Within the Lower Carboniferous succession another two hiatuses were recorded. The first hiatus appears between the Asbian and Arundian while the Holkerian is missing. The second hiatus separates the Viséan- from the Tournaisian strata. The biostratigraphy and lithostratigraphic classification was combined from Hoth et al. (1993) and Kurapkat et al. (1977).

4.1 Tournaisian and Lower Viséan

The Lower Viséan (Arundian-Chadian) and Tournaisian successions extend from 3595 - 4681 m. Thirty seven core barrels with sediments and magmatic rocks were cored. The Arundian-Chadian succession is mostly composed of limestones and marls that are assigned to the autochthonous carbonate platform sedimentation of that area. The Tournaisian succession mostly comprises black shales that were deposited in a deep-marine depositional environment. Facies analysis was not performed on these units as the carbonate platform- and the prior deep-marine sedimentation of the area precedes the evolution of the foreland basin sedimentation.

4.2 Lower Viséan, Asbian

The Asbian succession is documented by six core barrels from which only the three upper core barrels yielded interpretable sediments. The three lower core barrels contain basaltic sills that strongly affected the surrounding sediments by contact metamorphosis. Therefore, the description and interpretation of these hornfelses was not possible.

4.2.1 Facies description and interpretation

Mudstone facies; M,h: This facies comprises dark-grey to black coloured, massive mudstones (see photo 3). The dark colour and the overall uniform appearance suggest a high clay/silt-ratio. Organic matter (plant debris) is abundant in this facies and characterised by sub-mm small black components which are dispersed within the mudstones. Bioturbation is common throughout the facies. The facies attains thicknesses of between 2 - 5 m. The transition to the either overlying or underlying sandy mudstone facies is gradual.
Interpretation: The lack of current-generated features and the good sorting of the sediment suggests deposition from suspension load below storm-wave base. No pyrite precipitation was observed although the TOC of this facies seems rather high (dark colour, abundant organic matter). These features - in addition to the common bioturbation - suggest shallow-water depths with a common exchange of water masses, *i.e.* oxygenated conditions during deposition. The suggested depositional environment - in comparison with the Asbian succession of the Loissin 1/70 well - is a distal shelf area where the fine-grained sediments were transported by low-energy currents as suspension load.

Sandy mudstone facies; M(Sf),p: This facies is characterised by thinly-laminated mudstones. These primary sedimentary structures are often difficult to recognise due to intense bioturbation. Organic matter is also common in this facies. The facies thickness varies from 1 - 3 m.
Interpretation: No current-generated features were observed in these core barrels. This suggests deposition below storm-wave base. The common bioturbation suggests an oxygenated environment. With comparison to the other encountered facies this sandy mudstone facies may have been deposited in a distal shelf area where the fine grained sediments were transported by suspension onto outer shelf areas. The lamination may result from differences in the supplied, fined-grained material.

4.3 Namurian - Westphalian A

The Gingst Formation was newly defined because of sedimentological criteria (Kurapkat et al. 1977). An exact age for this formation cannot be given due to sparse biostratigraphic evidence. A Namurian to Westphalian A age seems possible with a Namurian B age most probable (Kurapkat et al. 1977). Compared to the sediments of the Loissin 1/70 and

Table 4.1: Gingst 1/73 (Gst 1/73): Bio- and lithostratigraphy of the Carboniferous.

Depth (m)	Thickness without magmat. (m)	Biostratigraphy	Lithostratigraphy
regional hiatus			
1954.0 - 2045.8	90.3	Stephanian	Mönchgut Formation
2045.8 - 2228.9	183	"	Rambin Formation
2228.9 - 2317.8	88.9	Westphalian D	Trent Formation
2317.8 - 2516.7	154.4	"	Dornbusch Formation
2516.7 - 2916.1	189.8	Westphalian C	Upp. Jasmund Formation
2916.1 - 3177.2	236	"	Low. Jasmund Formation
3177.2 - 3248.6	52.2	Westphalian B	Lohme Formation
3248.6 - 3374.5	41.4	"	Wiek Formation
3374.5 - 3393.5	13.4	Westphalian A	Hiddensee Formation
local hiatus			
3393.5 - 3448.9	51.3	?Namurian B, Kinderscoutian?	Gingst Formation
regional hiatus			
3448.9 - 3595.0	136.5	Viséan, Asbian, V3b	n.n.
regional hiatus			
3595.0 - 4104.5	305.5	Viséan, Arundian - Chadian, 1a-b	n.n.
local hiatus			
4104.5 - 4531.5	247	Tournaisian, Ivorian, Tn3	n.n.
4531.5 - 4681.0	5	Tournaisian, Hastarian, Tn2	n.n.

Pudagla 1/86 wells and to other wells from the area that were dated more precisely, the Gingst Formation is regarded as a marginal equivalent of the Loissin and Parchim formations (Kurapkat et al. 1977). The Gingst Formation is represented by six continuous core barrels that comprise 51.3 m sediments. The uppermost core barrel contains a 4.1 m thick basaltic sill and strongly altered sediments.

4.3.1 Gingst Formation

Conglomeratic facies; G(Sf-c),h-r: This facies comprises matrix supported conglomerates which contain rounded to well-rounded siliciclastic and subordinately calcareous clasts (see photo 22). The matrix comprises mostly fine to coarse-grained sand with a carbonate fraction. This facies is characterised by massive to ripple bedding. Moreover, these beds are characterised by an erosive lower contact and an upper gradational transition to the muddy sandstone facies which indicates a sequential development. The thickness of the facies varies from 0.2 - 4 m.

Interpretation: A fauna horizon is indicative of a marine depositional environment (Kurapkat et al. 1977). The interpretation of this facies is based on the observed sequential development. This facies is interpreted as a transgressive lag of a foreshore depositional environment of a non-deltaic, clastic coast (for detail see Section 4.4 and Fig. 4.1).

Muddy sandstone facies; M(Sf-m),h-r-f: Hummocky cross-stratified to ripple bedded sandstones (2 - 4 m thick) and mud/sand interbeds (0.5 - 3 m thick) are characteristic for this facies. The interbeds have thicknesses from 0.1 - 5 cm and the sandstone interbeds are mostly ripple- to flaser bedded. The transition from one bedding type to another within this facies is mostly sharp. Bioturbation is common throughout this facies. The upper boundary to the conglomeratic facies is discordantly while the lower contact with the sandstone- or conglomeratic facies is gradational.

Interpretation: Current-generated features suggest a deposition above the mean fair weather wave base (FWWB). The hummocky cross-stratification and the ripple- to flaser bedding are interpreted as characteristic wave-dominated structures that are typical for deposits around and above the mean FWWB of a clastic coast depositional environment (Reading and Collison, 1996). The bioturbation may indicate well oxygenated conditions. The interpretation of this facies is based on the observed sequential development. This sequence is interpreted as the foreshore to offshore-transition of a non-deltaic, clastic coast depositional environment (for detail see Section 4.4).

Mudstone facies; M,h: Massive mudstones occur

on top of the muddy sandstone facies. These beds are 0.3 - 5 m thick and bioturbation is common.
Interpretation: The mudstones document the transition to offshore conditions as no wave-dominated bedding was observed.

4.4 Gingst Formation: evolution of depositional environments; facies associations and sequences

The observed sequence is illustrated in Fig. 4.1. It is interpreted as a fining-upward transgressive sequence that includes the transition from foreshore- to offshore conditions. The sequence begins with a transgressive lag (conglomerate) that has an erosive base and shifts into muddy sandstones which are characterised by typical wave-dominated structures. These two facies are both influenced by wave activity. A transition to massive mudstones and the absence of current-generated sedimentary structures denote an increase in water depth which is documented by. Therefore, a non-deltaic, clastic coast depositional environment is suggested for the Gingst Formation.

4.5 Westphalian A: Facies description and interpretation

A local unconformity separates the Hiddensee Formation from the underlying Gingst Formation. Due to this unconformity, the Gahlkow- and Barth formations, as recorded in other wells from the area, are not documented in the Gingst 1/73 well. The Hiddensee Formation is documented by three continuous core barrels comprising 13.4 m sediments and a 5.6 m thick basaltic sill. One brackish fauna horizon was reported (Kurapkat et al. 1977).

4.5.1 Hiddensee Formation

Sand/mud interbedded facies; M/Sf,r-l: This facies is characterised by uniform interlayered bedding with layer thicknesses ranging from 1 - 3 cm. The sandstones are exclusively fine-grained and show internal ripple bedding. Flaser bedding with an estimated sand/mud ratio of ca. 1.5 was observed (see photo 7). Subordinate lenticular bedding (connected lenses) with a lower sand/mud ratio was also noted. Bioturbation is common throughout this facies.
Interpretation: Flaser and lenticular structures imply that both sand and mud were available and that periods of current activity alternated with periods of quiescence. During periods of current activity, the sand is transported as ripples, whilst mud is held in suspension. When the current pauses the mud in suspension was deposited in the troughs or in thicker beds which completely covered the underlying ripples (Reineck and Singh, 1980). This type of sedimentation is characteristic for mixed sand-mud tidal-flats that would suggest a non-deltaic, clastic coast depositional environment (de Raaf and Boersma, 1971; Reading and Collison, 1996). Both flaser and lenticular bedding may also indicate environments in which generally the sediment supply is rhythmic or periodic, as in delta fronts or floodplains (Leeder, 1995). In comparison to the Namurian B from the other wells of the area and the facies association of this well, it is presumably that the overall environment is a shallow marine- to non-deltaic coastal and therefore these flaser- and lenticular structures are interpreted as tidal-influenced.

Mudstone dominated facies; M,h-p: Massive or subordinately wavy laminated mudstones were grouped to this facies. Bioturbation is common. The beds attain thicknesses between 5 - 20 cm. The contacts with the surrounding facies may be sharp or gradational.

Interpretation: With regard to the facies association which implies foreshore-dominates conditions, this mudstones may represent oxygenated offshore conditions characterised by abundant bioturbation. A lagoonal depositional environment could also be presumed but in comparison to other lagoonal facies from the area, this facies lacks of plant debris which is a characteristic feature of lagoonal muds (Reading and Collinson, 1996).

Sand dominated facies; Sf-c(G)-M,r-p-l: This facies is characterised by a wide spectra of grain sizes (sand to gravel) and an erratic interlayered bedding. The layer thicknesses vary from 1 - 20 cm with random variations; no pattern could be identified. Sand interbeds are mostly dominated by fine-grained sandstones. Medium- to coarse grained beds are subordinate. Some 1 - 2 cm conglomeratic beds (coarse-grained sand and gravel) with an erosive base were also noted. These have an upper gradual transition to all of the previously described lithologies (*i.e.* sandstones and mudstones). The predominant bedding type is ripple to ripple cross-bedding while flaser- and wavy parallel bedding were also noted. One approximately 20 cm thick fine-grained sandstone bed with hummocky cross-stratification was noted (see photo 10). Together, this facies is characterised by a vivid change of lithologies with either sharp or gradual transitions. Some bioturbation was noted in this facies.

Interpretation: The combination of the observed sedimentary structures suggest deposition from wave-dominated currents. The hummocky cross-stratification in association with flaser- and wavy parallel bedding are common features of sediments that were deposited above the mean FWWB (Reading and Collison, 1996). The strong variation in wave-energies is indicated by frequent changes in lithologies and bedding, *e.g.* muddy sandstones follow on erosive conglomeratic beds. These interlayers may all represent environments of a clastic coast depositional environment reaching from foreshore (fine to medium-grained sandstones) and shoreface deposits (transgressive conglomerates, ripple cross-bedded coarse sandstones) to, probably, tidal-influenced environments (flaser bedding).

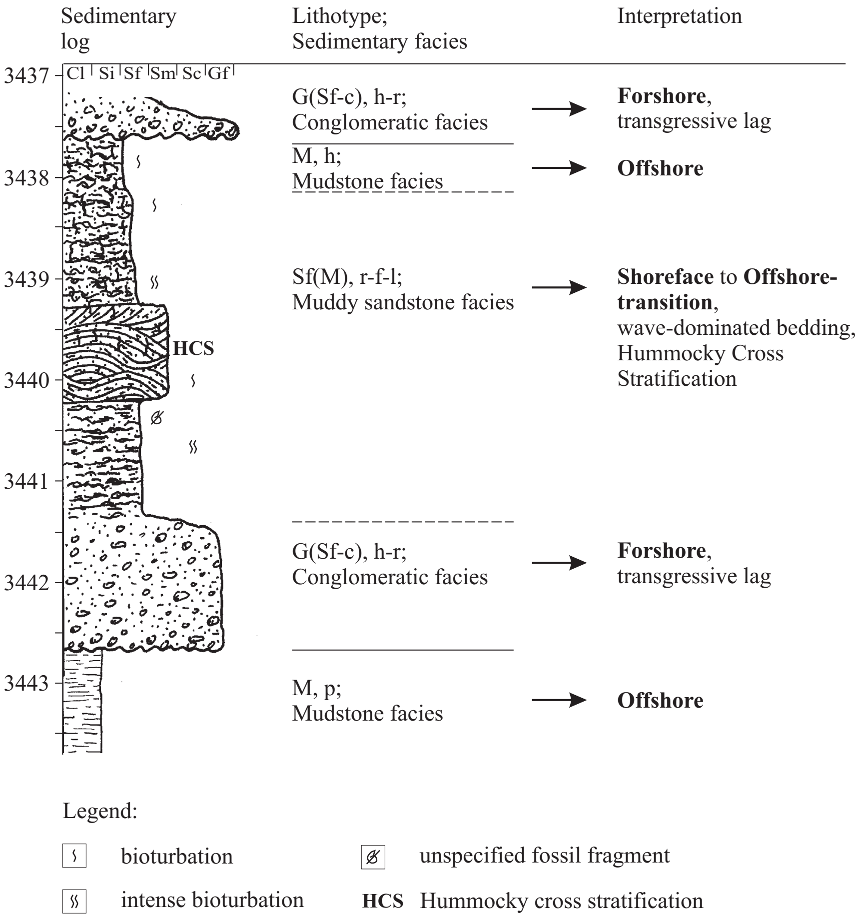

Figure 4.1: Three continuous core barrels from 3431.2 - 3450.9 m contain a transgressive sequence from the Gingst Formation. It includes the transition from foreshore- to offshore conditions.

4.6 Westphalian B

The Westphalian B comprises the Wiek- and Lohme formations. A brackish fauna horizon is recorded within the Wiek Formation which is documented by fourteen core barrels. Only three core barrels contain moderately altered or not altered sediments (16 m) while the remaining core barrels contain several basaltic intrusions that strongly altered the surrounding sediments. The lowermost core barrel comprises a basaltic intrusion but the uppermost part of this core barrel documents a strongly altered mudstone. The mudstones of the succeeding core barrel are also strongly altered due to the thermal impact of the intruded basalt. No primary bedding could be observed within these hornfelsic mudstones. The two uppermost core barrels also contain a basaltic intrusion (ca. 1 m thick). Although the sediments are strongly metamorphosed by the intrusion, the sedimentary structures are still observable. These core barrels comprise parallel-laminated mudstones and a coal layer (60 cm thick). A facies analysis could not be performed with this poorly-preserved section. However, a change in the depositional environment - in comparison with the underlying Hiddensee Formation - is indicated by the absence of sandstones and the development of a rather thick coal seam. This might be indicative of a change to floodplain conditions where laminated mudstones were deposited under slack water conditions and organic matter was probably accumulated in vegetated swamp areas. Such a presumed depositional environment is also indicated by the Wiek Formation of the Loissin 1/70 and Pudagla 1/86 wells (see Chapter 3 and 5).

The Lohme Formation is represented by eleven core barrels that were continuously cored. This section comprises 49.2 m sediments and a 12.3 m thick basaltic sill. The sediments in direct vicinity of this basaltic sill were strongly altered due to the thermal impact. These hornfelses are difficult to describe and interpret and, therefore, only the two lowermost and the six uppermost core barrels were taken in consideration.

4.6.1 Lohme Formation

Mudstone facies; M,h-p: This facies is characterised by massive and discontinuous laminated bedding with bed thicknesses of ca. 0.5 to 5 m. Abundant plant debris was observed. Several soil horizons of the soil facies are intercalated. The transition to this soil facies is gradational.

Interpretation: The lack of current-generated sedimentary structures suggests deposition under low energy conditions while the transition to a soilified facies may suggest a depositional environment close to the water level. Such conditions are characteristic for floodplain environments where floodlakes or abandoned channels of a river system are filled with overbank fines. These overbank fines were presumably provided by adjacent rivers as suspension loads during high-flood stages.

Soil facies; S,h: Several soilified mudstone beds (0.5 to 1 m thick) were identified within the mudstone facies. These beds are characterised by disturbed primary bedding by the activities of rootlets. These rootlets are traced by the preserved organic matter and even some tissue structures could be observed. The lower contact is gradational while the upper contact is sharp.
Interpretation: Abundant evidence of soilification suggests a depositional site that was close to, or above, water level. These soils developed gradational from the underlying mudstones which were interpreted as floodlake or abandoned channel deposits of a floodplain. The formation of soils may be interpreted as indicating a progressive siltation of the subenvironments that ceased with the formation of a vegetated cover.

Sandy mudstone facies; M,r: This facies is characterised by wavy parallel, ripple- to ripple cross-lamination (small-scale cross-bedding). Organic matter is accumulated in thin (0.1 - 0.5 mm) layers. Within the facies association of the Lohme Formation this facies attains thicknesses of 0.2 - 0.8 m.
Interpretation: The sedimentary structures clearly point to current influenced deposition. In comparison to the surrounding facies, this facies might denote a depositional site close to river channels as the deposition might have been influenced by the current energy of the adjacent channels during high-flood stages. During such flooding events, the initial current energy - close to the channel - is sufficient to produce these structures. Subsequently, the flood water submerges wider areas of the floodplain and the turbulence diminishes. This is characteristic for crevasse splays, where suspended sediment is deposited from lower-energy currents (relatively to the channel currents), commonly becoming finer-grained away from the channel (Guccione, 1993).

4.7 Westphalian C: Facies description and interpretation

The Westphalian C is divided into the Lower- and Upper Jasmund formations. The Ägir-Transgression, documented by the so-called Ägir-Horizon, marks the onset of the Westphalian C in the Rügen and Vorpommern area. This is the final marine ingression in the area of Mecklenburg-Vorpommern (Hoth et al. 1990). The lowermost core barrel of the Lower Jasmunder Schichten comprises the Ägir-Horizon. The Lower Jasmund Formation is represented by sixteen core barrels comprising 93.8 m sediment and 25 m of magmatics. Above the Ägir-Horizon, five core barrels of the Lower Jasmund Formation were recovered. These contain three basaltic intrusions that strongly metamorphosed the surrounding sediments. Therefore, no description and interpretation was attempted. The overlying six core barrels contain a continuous succession of sediments (39.5 m). The thermal impact of the surrounding magmatics is marked, but a description and interpretation was carried out. The upper four core barrels are discontinuously cored with magmatics between them. Eight core barrels document the Upper Jasmund Formation. Five of these (42.3 m) contain magmatic intrusions and related hornfels which cannot be interpreted due to the magmatic thermal impact. Three core barrels (29.3 m) contain hornfelsic sediments. The description and interpretation is limited but the metamorphosed sediments show some sedimentary characteristics that can be interpreted.

4.7.1 Ägir horizon

Sandstone facies of the Ägir-horizon; Sf-m,r: The Ägir ingression is documented by a ca. 3.5 m thick sandstone bed. The sandstone's lower base is erosive and the transition to the overlying coal seam is sharp. It is divided in two parts by a ca. 0.3 m thick mudstone. Ripple- and ripple cross-bedding dominate this facies. Organic matter was accumulated in thin (0.1 - 1 mm) laminae. Some indications of bioturbation were noted. Another 0.15 m thick sandstone is assigned to the Ägir-horizon. This bed separates two coal seams and is characterised by a disturbance of the primary sedimentary structures. The cause of this disturbance is discussed below. Moreover, abundant pyrite concretions and dispersed pyrite were noted.

Mudstone facies of the Ägir-horizon; M,h: This 0.3 m thick mudstone bed shows a weak even-wavy parallel bedding and a medium intense bioturbation.

Coal seams of the Ägir-horizon: Two coal seams (5 and 10 cm thick) were noted at the top of the Ägir-horizon. The beds are separated by a 15 cm thick sandstone bed. A more detailed description of the coal was not possible because it was mostly removed from the preserved core-material by earlier workers.

Interpretation: A sedimentary log of the Ägir-sequence is depicted in Fig 4.2. This bed is - based on palaeoecological evidence - assigned to a shallow-marine depositional environment (Kurapkat et al. 1977). Moreover, the sandstones - with their erosive base - show evidence of current-generated sedimentary structures. These structures were interpreted as wave-dominated, shallow marine indicators as suggested by de Raaf et al. (1971). Therefore, this bed documents a marine ingression from the westerly- situated ocean onto the area of prior terrestrial foreland basin sedimentation. Subsequently, the transition to terrestrial conditions is indicated by two coal seams which may have been deposited in a vegetated swamp area on a coastal floodplain. The intercalated and disturbed sandstone may be of marine- or terrestrial origin. Although pyrite precipitation may be an indicator for marine conditions, a fluvial interpretation of this bed is also possible since the sandstone was, perhaps, sealed by the over- and underlying coal-seams and a relatively high TOC in combination with at least dysaerobic conditions may have facilitated the pyrite precipitation. Moreover, the primary sedimentary structures were obliterated due to a medium intense bioturbation. Thus, a shallow-marine or fluvial depositional environment can be suggested.

4.7.2 Lower and Upper Jasmund formations

Sandstone facies; Sf-m,p-r: Several prominent sandstone beds were observed within the Jasmund Formation. Their thickness varies from 3 - 9 m. The sandstones either appear as part of fining-upward sequences with an erosive base and a gradational transition to the overlying mudstone facies or as isolated beds with no grain size trends and sharp contacts with the surrounding mudstone facies. The fining-upward sequences are characterised by a dominant ripple- to ripple cross-bedding while massive- and parallel bedding was seldom observed. The isolated sandstone beds are characterised by planar- to planar cross-bedding (see photo 9). Subordinately, massive and wavy parallel bedding was noted.

Interpretation: The isolated sandstone beds show current-generated structures and are characterised by sharp transitions to the surrounding mudstone facies. This is indicative of distinct shifts from current-generated deposits to low-energy, slack water deposits which are typical for braided stream processes with frequently alternating current energies. This alternation results in the deposition of channel-bar, channel-fill and overbank deposits. Shallow channels transport the sand as bedload and the sharp contacts indicate the vivid fluctuation of these channels (Miall, 1996).

The planar-bedded sandstone beds may correspond to shallow channel-fills with alternate channel-bars while fining-upward sequences may contribute to the interpretation as fluvial channel deposits. These fining-upward sequences may be interpreted as deposits of relatively bigger and deeper channels within the channel-system which are characterised by a gradational transition to the surrounding overbank fines (*i.e.* mudstone facies, see below). The observed fining-upward sequences have erosive bases and soil horizons on top and may result from a meandering channel. This sandstone facies as part of the facies association (compare mudstone- and soil facies below) comprises a mixture of braided- and meandering fluvial characteristics. For further discussion compare the facies description and interpretation of the Lohme and Jasmund formations of the Loissin 1/70 well (see Section 3.7.2 and 3.8.1).

Mudstone facies; M,h: The mudstones are mostly massive. Thin lamination was rarely observed. The upper and lower contacts with isolated sandstone beds of the sandstone facies are mostly sharp. These mudstones may also be part of the above described fining-upward sequences in which the lower contact with the sandstones is gradational. The thickness of these mudstones is mostly between 1 - 5 m but does often exceed the dimensions of a core barrel, *i.e.* 9 m. In contrast to the Jasmund Formation of the Loissin- and Pudagla wells, no plant debris was noted. It is not clear if this presumed material could not be recognised - due to thermal impact of the intruded magmatics - or was primarily not deposited.

Interpretation: The mudstones show no evidence of current-generated sedimentary structures. The association with the above described and interpreted sandstone facies suggest that these mudstones are possibly overbank fines and supplied from the adjacent fluvial channels during high-flood stages. Moreover, the comparably high thicknesses of these mudstone beds may also suggest deposition from floodbasins or lakes; a more specific differentiation of floodplain overbank fines and lacustrine deposits was not possible due to the contact metamorphism of the sediments. In summary, an alluvial depositional environment is suggested. The transition to soilified horizons may denote depositional sites that were progressively shallowing with concomitant aggradation of the subenvironments. Such subenvironments could be, for example, abandoned channels, floodbasins, lakes or swamp areas on a fluvial floodplain.

Soil facies; S,r: Several soilified mudstone beds (0.8 - 2 m thick) were identified within the preserved succession (see photos 20 and 21). These beds are characterised by disturbed primary bedding due to the activities of rootlets and an intense grey-brown colour. Soil horizons mostly appear on top of sandstone beds but also between massive mudstone beds. The lower contact is gradational while the upper contact with the mudstone- or sandstone facies is sharp.

Interpretation: Abundant evidence of soilification suggests a depositional site that was close to, or above, water level. This facies developed from the underlying mudstone facies. This is indicated by a gradational lower contact and therefore might denote the temporary emergence of the depositional site.

4.8 Westphalian D: Facies description and interpretation

The Dornbusch and Trent formations represent the Westphalian D. No biostratigraphic evidence is recorded within these formations. The sediments

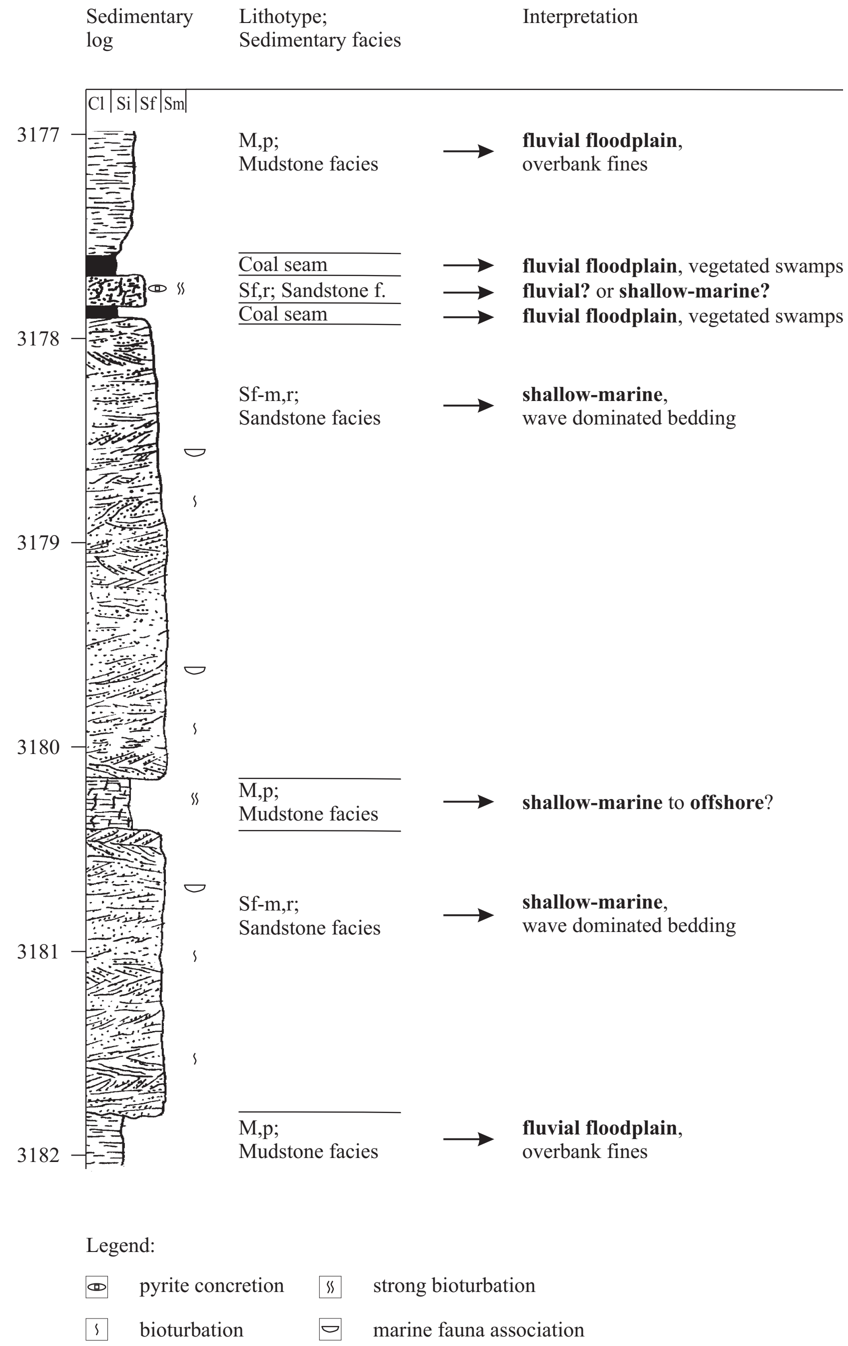

Figure 4.2: Core barrels from 3172.8 - 3186.3 m: The Ägir horizon marks the final marine ingression at the beginning of the Westphalian C. It is characterised by shallow-marine features such as marine fauna and wave-dominated bedding.

were classified on the basis of lithostratigraphic criteria and comparison to other wells in the area (Kurapkat et al. 1977). The Dornbusch Formation is represented by two core barrels that comprise together 18 m of sediment. The Trent Formation is documented by two core barrels comprising 11 m sediment.

4.8.1 Dornbusch- and Trent Formation

Sandstone facies; Sm,h-r: This facies dominates the association of the Dornbusch- and Trent formations. The thick, medium-grained sandstone bodies (amalgamated sandstone beds) are characterised by massive bedding which is intercalated with parallel- to parallel cross-bedded beds. Ripple- and ripple cross-bedding is rare. The cross-bedding is mostly medium-scale. Several mud-flake horizons, with ca. 2 - 7 cm thickness, were noted. The mud-flakes are prolate shaped and about 0.5 - 1.5 cm long.

Interpretation: These sandstones are - in comparison with the Westphalian B-C sediments of the area - interpreted as channel deposits of a braided river system. No features of meandering channels were noted. This characteristic stack of facies may correspond to a "shallow perennial" braided river stream. For further discussion compare the facies description and interpretation of the Lohme and Jasmund formations of the Loissin 1/70 well (see Section 3.7.2 and 3.8.1).

Sandy mudstone facies; Sf(M),h: Two beds, both ca. 1.5 m thick, were observed. They are characterised by massive bedding and sharp contacts with the sandstone facies. Deposition within possible fining-upward sequences was not noted since the contacts with the sandstone facies are exclusively sharp.
Interpretation: These mudstones are interpreted as representing overbank fines of the adjacent channel systems.

4.9 Westphalian B-D evolution of depositional environments

There is a hiatus between the clastic coast sediments of the Gingst Formation and the uppermost Westphalian A (*i.e.* the Hiddensee Formation). The Hiddensee Formation documents a non-deltaic, clastic coast depositional environment with tidal-flat to foreshore subenvironments. The Westphalian A-B transition is continuous. The sediments of the Wiek- and Lohme formations are poorly preserved but the attempted facies analysis suggests an alluvial sedimentary environment - with floodplain and fluvial channel deposits (*i.e.* braided river) - for this stratigraphic unit. No evidence of coal deposition was noted from the preserved core material but in comparison to the other wells from the area (*c.f.* Hoth and Wolf, 1997) pronounced coal deposition can also be presumed for this area as the small amount of core material might not entirely represent this stratigraphic unit. The onset of the Westphalian C is marked by the Ägir-Horizon that is documented by a 4 m thick unit that reveals an initial transgression of shallow-marine sandstones and subsequent shallowing to alluvial conditions. The depositional environment of the overlying Jasmund Formation documents sedimentation on a floodplain with both braided river and meandering river characteristics. The environmental evolution of the Dornbusch Formation through the Trent Formation (Westphalian D) is characterised by a change in the river style. In comparison to the Jasmund Formation an overall decrease of overbank intercalations was noted. This is interpreted as indicating a change to a floodplain and braided river sedimentation.

4.10 Stephanian: Facies description and interpretation

The Rambin and Mönchgut formations document the Stephanian succession. The sediments were classified by lithostratigraphic means. A fauna horizon documents the Stephanian/Autunian transition (Kurapkat et al. 1977). The Rambin Formation is represented by five core barrels containing 39.2 m sediments. Four core barrels with 35.9 m sediments represent the Mönchgut Formation.

4.10.1 Rambin Formation

Sandstone facies; Sf-m,p-r: This facies comprises mostly medium-grained sandstones that are parallel- to parallel-ripple cross-bedded. Beds of up to 1.5 m thickness were amalgamated and form sandstone bodies that exceed the dimensions of a core barrel, *i.e.* 9 m. The bounding surfaces between these distinct beds are sometimes marked by thin micro-conglomerates (coarse-grained sand). One 0.8 m thick bed is characterised by thin (1cm) silt intercalations.
Interpretation: Current-generated sedimentary structures and a comparison with the adjacent mudstone facies suggest a fluvial genesis for these sandstone beds. The contacts with the surrounding mudstone facies is sharp and this might indicate distinct changes from current-generated deposits (*i.e.* sandstones) to low-energy, slack water deposits (*i.e.* mudstones) which are typical for braided river processes. This alternation results in the deposition of channel-bar, channel-fill and overbank deposits. The observed sandstone beds may correspond to channel-fills with alternating channel-bars. Similar to the conditions during the Westphalian D period, an alluvial depositional environment with floodplain and braided river deposits is suggested for the Rambin Formation.

Soil facies; M(Sf),s: A 5 m thick bed of red-coloured and pedoturbated sandy mudstone was recorded from the Rambin Formation. The mudstone facies is characterised by a changing amount of fine-grained sand. Intense pedoturbation is indicated by the presence of disturbed bedding, abundant burrows of rootlets and a crumbly texture. The surrounding sandstone facies is grey-coloured.
Interpretation: In comparison to the environmental development of the Westphalian D, this facies may represent overbank fines that were deposited on a floodplain adjacent to braided river channels. Intense pedoturbation indicates a depositional surface close to, or above, the water level. It is not clear whether the red colouring of the Stephanian sediments is of primary origin or reflects secondary diagenetic changes from the considerably younger Rotliegend surface. A primary cause would favour a climatic change to semi-arid to arid conditions.

4.10.2 Mönchgut Formation

Sand/conglomerate interbedded facies; Sm(Sf-c)/G,h: Four interbedded sandstone/conglomerate beds were noted. The interbeds have sharp contacts (see photo 23). The thickness of these interbeds varies from 60 cm to 3 m. The conglomerates are both matrix- and clast supported with poorly- to well rounded clasts. The clasts are mostly siliciclastics and subordinately volcanics. The thickness of the conglomerate interbeds varies from 5 cm to 20 cm. The sandstone interlayers are massive. A red colouring throughout this facies was noted.

Interpretation: The interpretation of this facies in isolation is rather difficult. A comparison with the underlying formation reveals an overall increase in grain size. This might indicate higher depositional energies. This facies must be considered in terms of the facies association as no mudstones were recorded which is, again, in contrast to the underlying formations. A comparison to the literature was performed in order to deduce probable environments. A "Gravel-bed" braided river system as described in Miall (1996) seems unlikely because the related deposits are characterised by higher bed thicknesses and infrequent sand intercalations of mostly fine-grained sand (Miall, 1996). On the other hand, Diessel (1992) describes sediments from braid-plains which may be compared to the sand/conglomerate interbedded facies of the Mönchgut Formation. According to his description, the facies could be interpreted as channel-fills in a fluvial fan which would imply at least temporary subaerial exposure of the facies. Red colouration is commonly used as a criterion for the recognition of subaerial emergence but it must be applied with care since subsequent secondary reddening can affect sediments of any facies, especially beneath unconformities (Collinson, 1996). With regard to the overall increase of grain size a more proximal depositional site - maybe close to the sediment source - is presumed. Comparable and contemporaneously deposited facies from the Flechtingen Block (see Section 8.13.3) were interpreted as alluvial fan deposits (Paech 1973a). The sedimentary record of the Gingst 1/73 well provides only little environmental evidence but a tentative assignment to an alluvial fan depositional environment is suggested.

Sandstone facies; Sm(Sf,c),h-p: The sandstones of the Mönchgut Formation are mostly massive or parallel laminated; ripple- and cross-lamination was not observed. A red colouring throughout this facies was noted. Beds of up to 2 m thick form amalgamated sandstone bodies that exceed the dimensions of a core barrel, *i.e.* 9 m. The transition to the surrounding facies is mostly sharp.

Interpretation: Current-generated structures may suggest a fluvial origin. With respect to the tentative interpretation of the sand/conglomerate interbedded facies (see above), these sandstones are interpreted as fluvial fan deposits. This might be also supported by a consideration of Miall (1996) who suggested that - in contrast to fluvial fans - gravel-bed braided rivers are characterised by higher bed thicknesses and infrequent sand intercalations of mostly fine-grained sand.

4.11 Stephanian evolution of depositional environments

The evolution of the Stephanian is characterised by an overall increase in grain size. No mudstones were reported from the Mönchgut Formation. Also, the red colouration of the sediments increases from the Rambin- to the Mönchgut Formation. It is not clear if this red colouring is a function of the proximity to the Stephanian-Rotliegend unconformity (secondary colouring) or a signal of the onset of semi-arid to arid climatic conditions. The overall depositional environment probably changes from a floodplain within a braided river system to an alluvial fan depositional environment. This would again indicate an overall shallowing of the depositional area.

Chapter 5

Pudagla 1/86

The Pudagla 1/86 well reached Carboniferous strata from 4147 m - 7120 m (Tab. 5.1 The Upper Carboniferous succession extends from 4147 - 6170 m (2023 m, including 116 m of magmatic rocks) of which 118.5 m were recovered (5.9 %). The Lower Carboniferous succession extends from 6170 m - 7120 m (950 m including 579 m of magmatic rocks) of which 100.6 m were recovered (10.6 %). The biostratigraphy and lithostratigraphic classification was adopted from Schwahn et al. (1990) and Hoth et al. (1993).

5.1 Lower Viséan, Holkerian - Arundian

The Holkerian–Arundian succession extends from 6929 - 7120 m. Six core barrels with together 30 m of sediment were cored. The succession contains mostly limestones that are assigned to the autochthonous carbonate platform sedimentation of that area. A facies analysis was not performed on this material as the carbonate platform sedimentation of the passive continental margin precedes the foreland basin sedimentation.

5.2 Lower Viséan, Asbian

The Asbian succession is documented by two core barrels containing six metres of sedimentary rocks (25 % core recovery). It contains exclusively coarse-grained limestone debris. Calcareous cement or predominates but some clayey cement around grain boundaries was also observed. The clast sizes vary from ca. 1 - 400 mm but a distribution peak was noted around 2 - 15 mm. A facies analysis was not performed on this material as this succession contains exclusively limestones that were deposited on the carbonate platform prior to Asbian times. However, the core description yielded some valuable information on the overall tectonic evolution of the area as this clear shift from primary carbonate sedimentation to secondary, reworked debris sedimentation implies a change in the depositional regime.

5.3 Lower Viséan, Brigantian

The Brigantian siliciclastic series comprises 135 m of sediment and 18.5 m of volcanic rocks (Schwahn et al. 1990). Only two core barrels with together 5.1 m of sediment were recovered (3.3 % core recovery). Sedimentary logs of these two core barrels are presented in Fig. 5.1. Due to the minor amount of recovered material, an interpretation of the environmental level remains rather speculative but some palaeoecological evidence - a marine fauna association - suggests a shallow-marine depositional environment (Schwahn et al. 1990).

5.3.1 Facies description and interpretation

Conglomerate facies, Gf-m(Sf-m),h-p: The conglomerate clasts are fine to medium-grained gravels that are mostly matrix supported. Some layers are characterised by an unusually dense clast-packing. These layers are not matrix supported. The clasts are predominately of volcanic origin with mostly crystalline volcanic rocks but a considerable amount of tuffaceous clasts was also noted. Some of these tuffaceous clasts appear to be secondarily altered as they have a clayey habitus. Siliciclastic clasts were rarely noted. The clasts are rounded to well-rounded. The matrix is fine to medium-grained sand. An internal rhythmical bedding was observed. This interlayering is a consequence of changes in the clast grain size. The upper contact with the surrounding facies is exclusively sharp while the lower contact is characterised by an erosive base. Load casts were observed at a mudstone/conglomerate contact where conglomerate clasts sink into a plastically deformable mudstone.

Interpretation: This facies reveals little palaeoenvironmental information. With regard to the facies association of the Brigantian (compare mud/sand interbedded facies, Mudstone facies below) and the palaeoecological evidence, it is interpreted as a clastic coast deposit. In general, the deposition of conglomerates requires considerable energy. The dominance of volcanic clast implies the vicinity of this depositional site to an area of volcanic activity. Moreover, the considerable amount of tuffaceous clast points to a short transport distance and, consequently, a depositional site in direct vicinity to the sediment source. Therefore, a coastal depositional environment is suggested. The previous and succeeding volcanic series of the Brigantian (see Tab. 5.1) are volcanically active during this period. The literature reveals only sparse examples of conglomerate units in coastal systems.

Table 5.1: Pudagla 1/86 well (Pud 1/86): Bio- and lithostratigraphy of the Carboniferous

Depth (m)	Thickness without magmat. (m)	Biostratigraphy	Lithostratigraphy
regional hiatus			
4147 - 4353	206	Stephanian	Mönchgut Formation
4353 - 4680	225.5	Stephanian Westphalian D	Rambin Formation, Trent Formation
4680 - 4925	245	Westphalian D	Dornbusch Formation
4925 - 5426	501	Westphalian C	Jasmund Formation
5426 - 5458	32	Westphalian B	Lohme Formation
5458 - 5800	342	Westphalian B-A	equivalent Wiek- and Hiddensee Formation
5800 - 5865	65	Westphalian A	Upp. Barth Formation
5865 - 6071	195		Low. Barth Formation
local hiatus			
6071 - 6170	99	Namurian A-B?	equivalent of the Loissin Formation
local hiatus			
6170 - 6340	170	Viséan, Brigantian V3c	n.n, volcanics
6340 - 6494	156	Viséan, Brigantian V3c	n.n, siliciclastics
6496 - 6905	409	Viséan, Asbian V3b	n.n, volcanics
6905 - 6929	24	Viséan, Asbian V3b	n.n, Limestonebreccia
6929 - 7120	191	Viséan Cv1b-Cv3a, Holkerian-Arudian	n.n., carbonate platform sedimentation

Keith (1991) suggested that conglomerates in a presumed foreshore/shoreface environment may be deposited during sea-level lowstands when downcutting rivers could transport coarser material. Another process for the deposition of conglomerates in this presumed clastic coast depositional environment was described by Reading and Collinson (1996); conglomerates of a coarse-grained coastal system may form coarse-grained deltas that were fed by alluvial fans. These fan deltas may have developed during sea-level lowstands in a proximal position to the sea margin and the deposits change from clast-supported conglomerates through matrix-supported debris flow conglomerates to well-sorted granule sandstones.

With regard to the study area and especially to the position of this well within the basin, the appearance of coastal deposits must not imply a depositional site in the area of the main shore. It may also be possible that this "beach" was adjacent to a volcanic isle.

Sandstone facies; Sf(Sm-c),r-p: The fine-grained sandstone beds are poorly sorted with considerable amounts of medium to coarse-grained components. Abundant volcanic fragments were identified within the coarse-grained fraction. Parallel- and ripple-bedding dominate this facies. The upper- and lower contact with the other facies is sharp.
Interpretation: The occurrence of current-generated structures and a comparison to the mud/sand interbedded facies suggest deposition above storm-wave base, *i.e.* foreshore depositional environment. Again, the abundant volcanic components denote an environment that was strongly influenced by volcanic activities.

Mud/Sand interbedded facies; M/Sf,l: This facies is characterised by a mud/sand interbedding with interbeds from a few mm to ca. 5-7 cm. It is moreover characterised by a pronounced flaser- and lenticular bedding. Bioturbation is common throughout this facies while no pyrite precipitation was noted. This facies is ca. 0.1 - 0.5 m thick. The upper- and lower contact with the other facies is mostly sharp.
Interpretation: The abundant bioturbation is characteristic for a well oxygenated depositional environment. Flaser- and lenticular structures are characteristic bedding types for mixed sand-mud tidal-flats that would suggest a clastic coast depositional environment. For further discussion on tidal-flat deposits compare to chapter 3.3.2 of the Loissin 1/70 well.

Mudstone facies; M,h: One mudstone bed with a thickness of 0.6 m was observed. It is characterised

by a high silt/clay ratio and intense bioturbation. The primary bedding could not be deduced due to the intense bioturbation. The upper contact with a sandstone bed is sharp and this contact is characterised moreover by load casts. Clasts from the overlying bed (sandstone facies) sink into the more ductile mudstone.
Interpretation: The intense bioturbation suggests a well-oxygenated depositional site. With regard to the facies association and especially the transition from the underlying interbedded facies, this facies is likewise assigned to tidal-flat depositional environment. Mud is often considered to be a feature of low-energy environments and therefore only able to form in lagoons behind a protecting barrier, but according to McCave (1971) it can also accumulate independent of wave energy when both amount and concentration of mud are high, *e.g.* in tidal-flat environments.

5.4 Namurian: Facies description and interpretation

The interval from 6071 - 6170 m is assigned to the Namurian. Some marine fauna associations suggest the Namurian A-B boundary (H2 - R1a). In comparison to the Loissin 1/70 well, this section is regarded as the equivalent of the Loissin Formation (Schwahn at al. 1990). The transition from the Brigantian volcanics to the siliciclastic series of the Upper Carboniferous is marked by a local hiatus. The Namurian is only represented by two core barrels. Therefore, an interpretation on the environmental level remains rather tentative but some palaeoecological evidence - a marine-brackish macro fauna - suggest a shallow-marine depositional environment (Schwahn et al. 1990).

5.4.1 Loissin Formation

Mudstone facies; M,h: The upper core barrel reveals a mudstone-dominated facies. It contains a 2.9 m long succession of massive to thinly-laminated mudstones. Pyritised burrows of approximately 1 mm thickness were noted. These burrows indicate weak bioturbation. Also, dispersed pyrite is arranged in some laminae. Some 1 - 4 cm thick siderite concretions were noted.
Interpretation: The lack of current-generated sedimentary features denotes deposition below storm-wave base. Dysaerobic conditions are presumed as sparse evidence of bioturbation appears together with pyrite precipitation in one bed (*c.f.* Savrda and Bottjer, 1991). This would suggest an offshore depositional environment that may have been characterised by alternating oxygen conditions.

Sandstone facies; Sf-m,r-p: The lower core barrel contains a fine to medium-grained and a coarse-grained sandstone bed. The transition between these two beds is sharp. A parallel- to parallel cross-bedding was observed. The cross beds are small- to medium scale. Some 2 - 15 mm thick pyrite concretions were noted. The coarse-grained sandstone contains up to 5 mm thick quartz- and 3 mm thick volcanic granules.
Interpretation: Based on the current evidence it is not easy to assign this sedimentary facies to a specific environment. However, based on the sedimentary structures which suggest deposition from vectored current and the pyrite precipitation it would appear that this facies was deposited under the influence of marine conditions. No palaeoecological findings prove the presumed marine depositional environment (Schwahn et al. 1990). With regard to the overlying mudstone facies (see above), this facies could be interpreted as representing a shallow-marine to coastal depositional environment.

5.5 Westphalian A: Facies description and interpretation

A local unconformity separates the underlying Loissin Formation from the Barth Formation. The Westphalian A is represented by three core barrels. The two lower core barrels are classified to the Lower Barth Formation and the upper core barrel is classified to the Upper Barth Formation. The Gahlkow Formation (Lowermost Westphalian A) is missed due to that local hiatus.

5.5.1 Lower Barth Formation

Sandstone facies; Sm,r: Two core barrels contains the so-called "Mecklenburg Sandstone", a local name for the prominent sandstone beds of the Lower Barth Formation (Schwahn et al. 1990). Here, the Mecklenburg Sandstone consists of middle-grained sand and is characterised by a planar cross-bedding. A 0.5 m thick bed of ripple cross-bedded sandstones was also noted. The contact with the surrounding coal seams is often gradational but can also be sharp.
Interpretation: The sandstone facies shows current-generated features. No palaeoecological evidence was observed within the Lower Barth Formation (Schwahn et al. 1990). The abundant interbedding of coal seams might denote a depositional site that was adjacent to emergent areas. The most plausible (but tentative) interpretation is based on the rare core material and its comparison to the neighbouring wells Loissin 1/70 (see chapter 3.5.2) and Boizenburg 1/74 (Bergmann et al. 1979). Therefore, deposition in a deltaic, clastic-coast depositional environment is suggested. These sandstones - in comparison to the Loissin 1/70 well - might correspond to deposits from distributary channel as a fining-upward trend to overlying coal seams was noted. For further discussion compare with Section 3.5.2 of the Loissin 1/70 well. Further evidence for a deltaic environment might be the considerable sand/mud ratio of the Lower Barth Formation. This ratio was deduced from the well logging of this section. Only 6 % of the succession are mudstones. Another 25 % are sand/mud interbeds; a distribution peak is noted for medium-grained sandstones (Schwahn et al. 1990). In contrast, the upper Barth Formation comprises ca. 64%

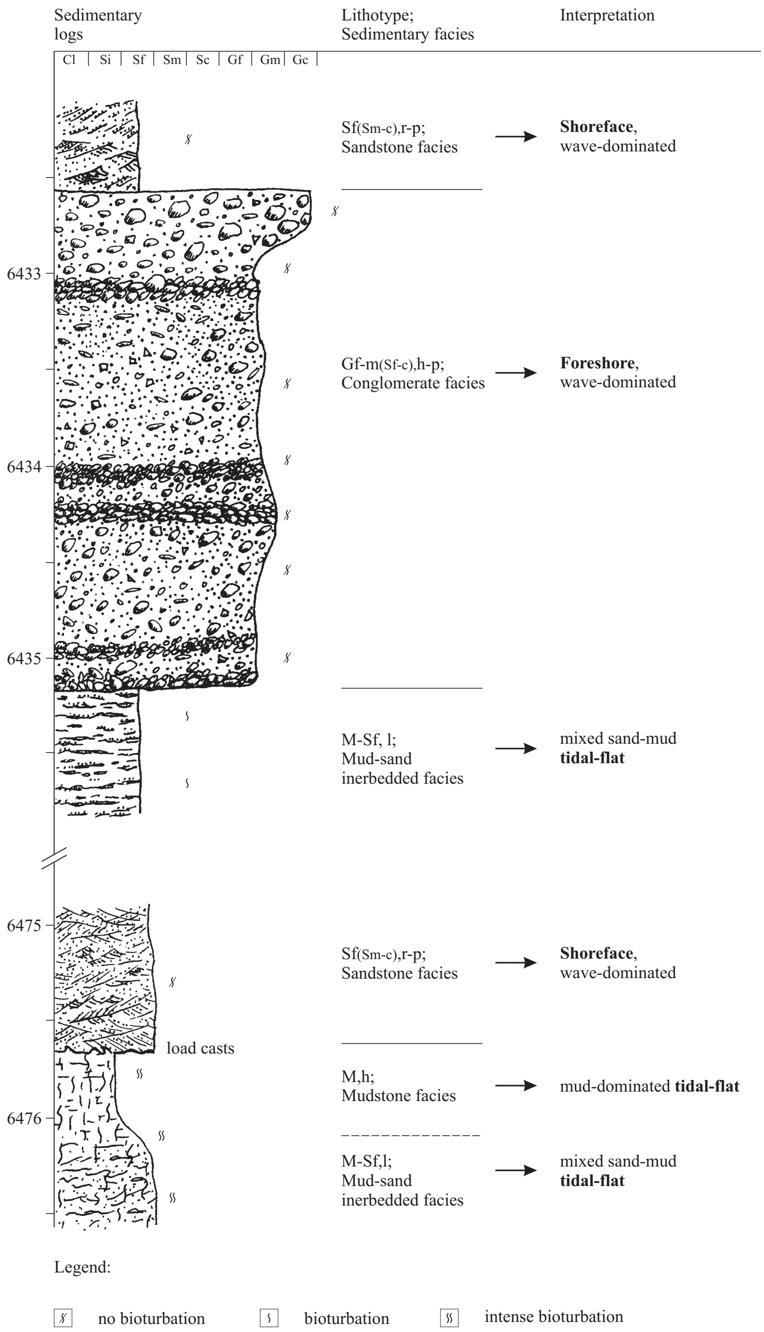

Figure 5.1: Core barrels from 6432.2 - 6435.8 m and 6474.9 - 6476.6 m; Birgantian. Two Sedimentary logs of a coastal facies association. Tidal-flat deposits alter with shoreface and foreshore deposits.

mudstones and 21 % of sand/mud interbeds. According to a presumed deltaic environment, these sandstones might correspond to mouth bar deposits that are characterised by amalgamated sandstones and intercalated distributary channel and interdistributary bay sedimentation on the adjacent delta plain (Diessel, 1992).

Coal seams: Five coal seam (1 - 3 cm thick) were noted. They form the top of fining-upward sequences or appear as boundaries between sandstone beds. A more detailed description of the coal was not possible because the material was mostly removed from the preserved core-material by earlier workers.

Interpretation: The coal seams are interpreted as deposits of vegetated swamp areas or abandoned distributary channels on a - with regard to the facies association - delta plain.

5.5.2 Upper Barth Formation

One core barrel of the Upper Barth Formation was recovered. It reveals a sequential development. Therefore, this sequence is described and interpreted as a whole (see Fig. 5.2).

Mudstone sequence: The sequence starts with a soilified mudstone facies. This bed is characterised by disturbed bedding and an intense brown colour. Abundant rootlets, main roots (*Stigmaria*) and plant debris were identified; even some tissue structures were observed. Moreover, siderite and phosphorite concretions were noted. The transition to the overlying coal seams is sharp. This ca. 0.3 m thick coal seam is interbedded with several thin (2 - 5 cm) sandy mudstone interbeds that are also strongly disturbed by the activities of plant roots. The transition to the overlying mudstone facies is sharp. These mudstones are massive to weakly laminated and some plant debris was noted.

Interpretation: This sequence is interpreted as a "drowning swamp" sequence. This is typical for both, lower delta plain or floodplain depositional environments (Diessel, 1992). This sequence - with regard to the deltaic succession of the Lower Barth Formation - is interpreted in terms of a deltaic environment.

The underlying mudstone (disturbed sedimentary structures) with common rootlets besides *Stigmaria* and siderite-concretions represents a soil-horizon that may be indicative of an emerged area on the delta plain (*i.e.* overbank area). The overlying coal-seam may be indicative of vegetated swamp conditions where repeated flooding of either marine ingressions or high-floods of distributary or fluvial channels may have led to frequent drowning of the vegetation. The thin mudstone intercalations may represent these drowning events. It is not quite clear if these drowning events correspond to marine ingressions onto the delta plain or to flooding-events (*i.e.* crevasse splays) along distributary or fluvial channels. The overlying mudstone facies lacks of current-generated sedimentary structures and may be deposited from slack water in a floodbasin or interdistributary bay subenvironment.

5.6 Westphalian A-B: Facies description and interpretation

The Uppermost Westphalian A and Lowermost Westphalian B (Hiddensee- and Wiek Formation) remain unclassified and are combined to the Westphalian A/B (Schwahn et al. 1990). The upper Westphalian B (Lohme Formation) could not be verified by a cored section. Seven core barrels represent the Westphalian A/B period.

5.6.1 Westphalian A-B

Mudstone facies M,p-r: The Westphalian A/B succession mostly comprises massive to even parallel- and subordinately ripple laminated mudstones which attain considerable thicknesses from 1 - 4 m (length of a core barrel). Plant debris is abundant in several mudstone beds. Occasionally, thin coal laminae (0.5 - 1 mm) are interbedded. The transition to both soil- and coal seams is gradational. The contact with the sandstone facies is exclusively sharp.

Interpretation: These mudstones might have been mostly deposited from low-energy conditions. Subordinate, current-generated features (*i.e.* sandstone facies) imply deposition from higher current energies. With regard to the facies association and especially the formation of soils, an alluvial depositional environment is suggested. On the one hand, these mudstones might indicate overbank fines of adjacent fluvial channels that were deposited during high-flood stages on a floodplain. The ripple bedding might denote a depositional site in the vicinity of channels as the fluvial currents were still strong enough to create this bedding type, for example crevasse splay deposits. In crevasse splays the suspended sediment is deposited from low-energy currents (relatively to the channel currents) and distributed onto the floodplain while commonly becoming finer-grained away from the channel (Guccione, 1993). On the other hand, it is not clear whether some of these mudstones were deposited in a lacustrine environment, *i.e.* floodbasin. The intense soilification of this facies (see below) besides the considerable bed-thicknesses might indicate a final siltation of lakes or abandoned channels. Typical - for lacustrine deposits - thinly laminated mudstones or rhythmites were not recorded but these might be obliterated by the intense soilification.

Soil facies; S,r: Several soilified mudstone beds (0.3 - 3 m thick) were identified throughout the preserved succession. These beds are characterised by disturbed primary bedding due to the activities of rootlets. These dark grey coloured rootlets are traced by the preserved organic matter. Moreover, an intense brown colouring is characteristic for this facies.

Interpretation: Abundant evidence of soilification suggests a depositional site that was close to, or above, water level. This facies developed from the underlying mudstone facies. This is indicated by the gradational lower contact. A gradational downward passage from palaeosols to unaltered sediments is common while the upper contact with the unaltered overlying material may be either erosive or sharp (Collinson, 1996).

Sandstone facies; Sf(Sm),p-r: Some fine to medium-grained, massive to planar and ripple bedded sandstones were observed. Planar- and ripple cross-bedding (small-scale) was also noted. The bed thickness varies from ca. 50-150 cm thick. Moreover, the beds have sharp contacts with the surrounding facies. Some beds are characterised by the accumulation of organic matter that parallels the bedding.

Interpretation: The bed thickness and the sedimentary structures, together with the facies association with overbank mudstones (see above) suggests deposition from fluvial channels. Further discussion on the recognition of fluvial facies is, for example, summarized in Section 3.5.2 and 3.7.2 of the according sandstone facies in the Loissin 1/70 well. No grain size trend was noted within these

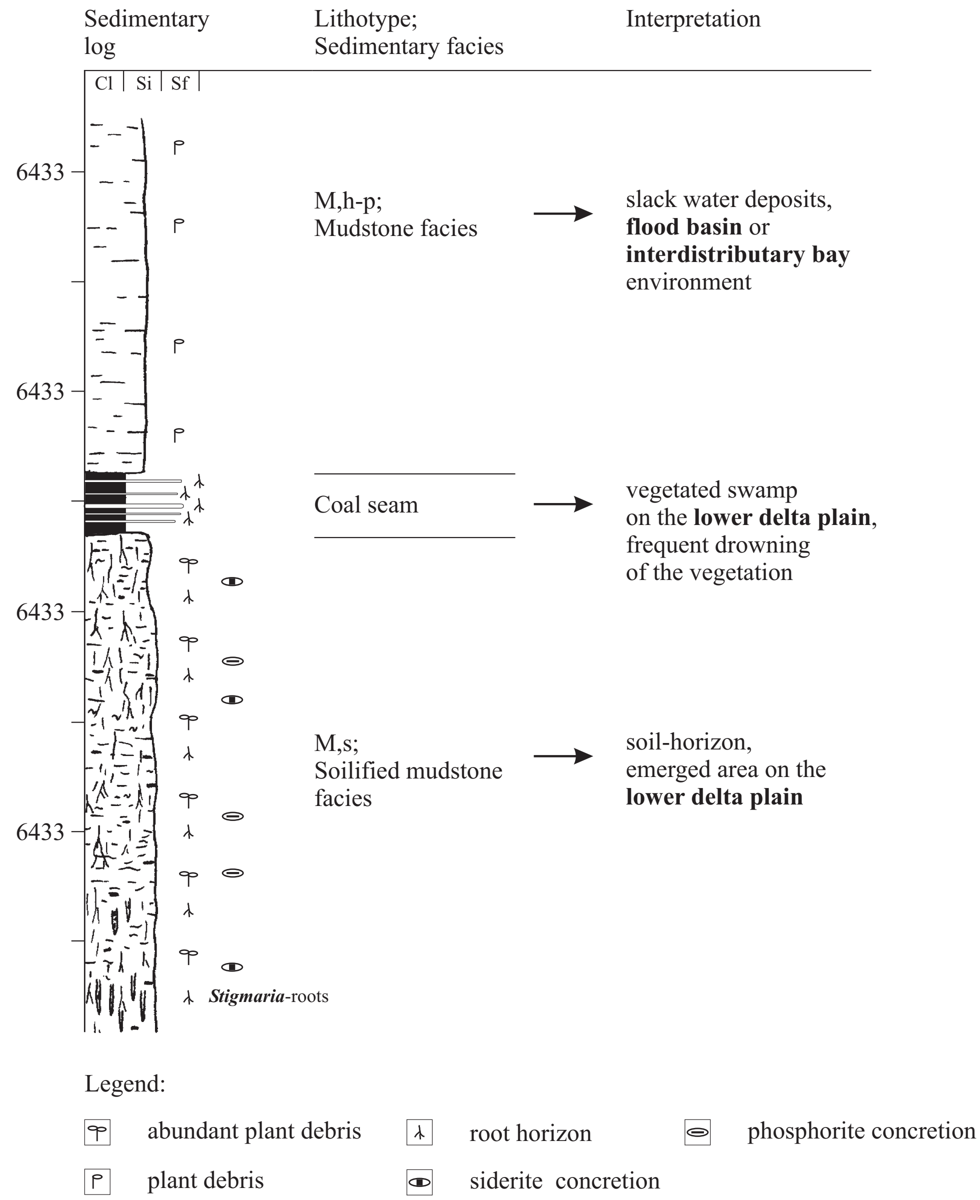

Figure 5.2: Core barrel from 5883.5 - 5887.9 m; Upper Barth formation. Sedimentary log of "drowning swamp"-sequence.

beds. Therefore, these beds might not demonstrate fining-upward sequences of a meandering river but channel-fills and channel-bars of a braided river system.

Coal seams: Several intercalated coal laminae (0.5 - 1 mm) within the mudstone facies were noted. Two thin coal seams (2 and 4 cm) and one prominent, 10 cm thick coal seam form the top of soil horizons.

Interpretation: The coal seams are interpreted as deposits of vegetated swamp areas on a fluvial floodplain. The sequential development from a soilified mudstone facies may suggest progressive shallowing of slack water basins with the formation of a vegetated swamp area during the progressive aggradation of the basins.

5.7 Westphalian A, Westphalian A-B depositional environments

The Barth Formation may document a deltaic system with an environmental trend from delta front to lower delta plain sedimentation. The condensed Westphalian A/B reveals a depositional environment that is predominately characterised by low-energy sedimentation and the pronounced coal formation. This trend corresponds to an overall shallowing of the depositional environment and a decrease in marine influence (Schwahn et al. 1990). The peak of deltaic development is noted during the lower Barth Formation. Subsequently, the younger formations are interpreted as representing more fluvial-dominated depositional environments.

5.8 Westphalian C: Facies description and interpretation

The Westphalian C is represented by the Jasmund Formation that could not be differentiated in Lower and Upper formations as known from other wells in Mecklenburg. Eight core barrels with a total of 30.2 m were cored. The Ägir horizon was identified by well-log evidence. It extends from 5420 - 5426 m (Schwahn et al. 1990).

5.8.1 Jasmund Formation

Soil facies M,s: Numerous soil horizons document the intensive soilification throughout the preserved succession. The four lower core barrels exclusively contain a soilified mudstone facies. These soil horizons are red- to purple brown and mottled grey- to dark grey. One soilified sandstone bed was recorded. Siderite- and phosphorite concretions are common and enriched in distinct layers. The thickness of the soil horizons varies from about 50 cm to the length of a core barrel. Plant debris is less common than in the soil horizons of the older Westphalian units. Rootlets were only observed in one distinct horizon.
Interpretation: The intensive soilification has a different character to that noted from the older Westphalian units. Rare root penetration and the formation of root-mottled horizons are the only apparent differences to the soil horizons from the Westphalian A-B of this well and the other wells from the area (*i.e.* Loissin 1/70 and Gingst 1/73). In the Jasmund Formation of the Pudagla 1/86 well additional mechanisms besides root penetration led to the observed pedoturbation. Here, the intensive pedoturbation may have resulted from swelling and shrinking associated with oxidising and reducing conditions. The swelling and shrinking may have caused the disturbed sedimentary texture, while oxidised and reduced conditions influenced the colour. Oxidised conditions may have generated red-purple brown colours (Fe^{2+}), while reduced conditions lead to greenish-grey colours (Fe^{3+}) (*c.f.* Kraus and Aslan, 1993). The detritial supplied hematite was probably - in an early phase of diagenesis - reduced and siderite was formed. This facies is interpreted as a soilified facies because mass transfer is an elementary process associated with soilification (Duchafour, 1982). This facies may be classified as a "simple alluvial palaeosol" which are rooted and root-mottled and the sediments lack any well-defined horizons and profiles (*c.f.* Kraus and Aslan, 1993).

Mudstone facies M,p: Some few- or undisturbed mudstones that reveal their primary bedding were noted form the four uppermost core barrels. Parallel- and subordinately wavy laminated mudstones dominate this facies. But this facies is still strongly intercalated with soilified sections. Only the uppermost of these four core barrels shows no signs of soilification. The lower contact with the soil facies is sharp, while the upper contact is gradational.
Interpretation: These mudstones were predominately deposited from slack waters. In this facies, no current-generated features were noted. In comparison to the facies association and the sedimentary record of the previous Westphalian A-B section, a lacustrine depositional environment on a floodplain is suggested. It is not clear if these mudstones were deposited in floodbasins (*i.e.* lakes) or abandoned channels; this could not be verified due to the rare core material.

Sandstone facies Sf-m,p-r: The upper core barrels document some medium to fine-grained sandstone beds (1.5 - 2.5 m) that are mostly planar bedded. Planar- to ripple cross-bedding also occurs. The crossets are small- to medium scale. The upper contact is sharp while the lower contact both to the mudstone- and soil facies may be erosional or sharp.
Interpretation: These sandstone beds are characterised by sharp transitions to the surrounding mudstone facies. This might indicate distinct shifts from current-generated deposits to slack water deposits which are typical for floodplain/braided river processes with frequently alternating current energies. These sandstones were also interpreted in comparison to the sandstone facies of the Westphalian A-B of this well (see above) which was interpreted as representing alternating braided channel- and floodplain overbank deposits.

5.9 Westphalian D/Stephanian: Facies description and interpretation

The Dornbusch- and Trent formations represent the Westphalian D while the Rambin- and Mönchgut formations are assigned to the Stephanian (Hoth et al. 1990). The Dornbusch, Trent and Rambin formations were - according to Schwahn et al. (1990) and Hoth et al. (1993) - grouped to the Westphalian D/Stephanian period because no clear biostratigraphic classification was possible. Therefore, these sediments were classified by lithostratigraphic features and a comparison to other wells of the area (Schwahn et al. 1990). The Dornbusch Formation is represented by one core barrel that comprise 1.7 m of sediment. The Trent and Rambin formations are documented by five core barrels comprising 29.2 m of sediment. Subsequently, a 101.5 m thick rhyolithes is intercalated between 4373.5 - 4475 m. Two core barrels (7.5 m of sediment) were preserved above this volcanic rock and assigned to the Mönchgut Formation because a clear change in the overall lithology was noted (see Fig. 5.3). An intense red colouring was observed throughout the succession.

5.9.1 Dornbusch-, Trent-, Rambin Formations

Sandstone facies Sf-m,p-r: The sandstone facies dominates this succession. Medium to fine-grained

sandstones and subordinately coarse-grained sandstones characterise this facies. Cross-bedding (both ripple and planar) and planar bedding is common while massive bedding was also recorded. The single beds are mostly from 0.1 - 2 m thick but amalgamated beds also exceed the length of a core barrel (ca. 5 m). The contact between these beds is mostly sharp but sometimes also erosive. The lower contact with the conglomerate facies (see below) - within a fining upward sequence - is gradational as is the upper contact with the mudstone facies. Sandstone stacks have a sharp lower and upper contact with the mudstone facies. Moreover, these sandstones are characterised by poor sorting.
Interpretation: The characteristic stack of sandstone beds, current-generated sedimentary structures and sharp contacts with mudstones (*i.e.* overbank fines) may indicate channel deposit of a braided river system. Fining-upward sequences are less common than the stacked beds. These fining-upward sequences may begin with an erosive conglomerate bed (*i.e.* conglomerate facies, see below) which changes to the sandstones of this facies. The mudstones of the mudstone facies (compare below) may form the top of these fining-upward sequences. The sandstones which follow the conglomerates may be deposited within relatively larger channels of the braided system, as the initial current energy might be sufficient to transport the gravels of the conglomerate facies. This characteristic sandstone facies (either single beds or within fining-upward sequences) and the facies association may be best compared to a "Deep gravel-bed" braided river system (or Donjek-Type) with major channels (*i.e.* fining-upward), minor channel-fills and alternating channel-bars from which the bed stacking results (*c.f.* Miall, 1996). The thickness of these fining-upward sequences is between 2 - 3.5 m; this indicates that the water depth in the major channels is at least as deep as the channel thickness.

Conglomerate facies Gf-c(Sf-c),p-r: The conglomerates are mostly matrix supported with fine to coarse-grained gravels. Exclusively quartz clasts were noted. Some imbricated lags (01. - 0.2 m) are clast supported. These beds may form the base of fining-upward sequences where imbricated lags mark the erosional surface. Gravel beds were also grouped to stacks with sharp contacts with either conglomerate beds or sandstone beds. Stacked beds have thicknesses from ca. 0.3 - 1 m.
Interpretation: Basis conglomerates of fining-upward sequences are best described in terms of a fining-upward sequence as suggested in the interpretation of the sandstone facies (see above). Single conglomerate beds with lower and upper sharp contacts may correspond to gravel-bar deposits which are characteristic for "Deep gravel-bed" braided rivers (*c.f.* Miall, 1996).

Mudstone facies; M,h: Altogether, four mudstone beds (0.5 - 1.5 m) were recorded within the preserved core barrels. These beds are characterised by a high silt/clay ratio. Massive mudstones predominate while only a few sections show a thin lamination. Thin intercalations (0.5 - 1.5 cm) of fine-grained sand occur frequently; the contact with these interbedded sands is sharp. The upper contact with the surrounding facies may be sharp, gradational or erosive. The lower contact with the sandstone facies is gradational within a fining-upward sequence and sharp in-between single or amalgamated sandstone beds. These mudstones show no signs of pedoturbation and no plant debris was recognised.
Interpretation: These mudstones are interpreted as representing overbank fines of the adjacent braided channels. The thin sandstone beds indicate vivid influx of coarser-grained material into areas of prior slack water conditions. This might indicate a frequent shifting of the adjacent channels. The lack of pedoturbation - compared to the mudstone facies of the Westphalian A-C - may also denote the changeability character of this subenvironment; high sedimentation rates due to the proximity to the channel sources and frequent shifting of channels inhibit the formation of soils.

5.9.2 Mönchgut Formation

Conglomerate facies Gf-m(Sf-c),p: Two clast-supported conglomerates (fine to medium-grained) and two matrix supported beds were noted (see Fig. 5.3). Clast- and matrix-supported beds are stacked and have gradational and sharp transitions. The contact with the sandstone facies is sharp or erosional. The clasts are blocks- and flakes of mudstone, fine- to medium grained sandstone clasts in addition to grey- and white quartz pebbles. Subordinately, some clasts (up to 3 cm) of volcanic origin were recorded.
Interpretation: The obvious difference to the conglomerate facies of the Dornbusch, Trent and Rambin formations is the diversity of clasts. These clasts are interpreted as intraformational which implies - especially for the mudstone clast - a relatively short transport distance. The interpretation of this conglomerate facies in isolation is not easy. However, the interpretation with regard to the facies association of the Mönchgut Formation may be valuable. The facies association and, particularly, the lack of mudstones characterise a change in the depositional environment. Moreover, the lack of a mudstone facies within the association denotes the higher depositional energies, although the muddy interclasts suggest the existence of mudstone beds in the vicinity of the conglomerate facies. It must be presumed that the mudstone facies was not documented due to the rare core material (two core barrels represent 206 m of sediment) and/or the lateral location of the presumed mudstones to the core. However, the well log-evidence suggests that ca. 7% of the Mönchgut Formation is mudstones. This is in clear contrast to the underlying Dornbusch, Trent and Rambin formations which are characterised by 13.5 % mudstone content (Schwahn et al. 1990).

A comparison with the literature and the deposits of the Gingst 1/73 well was performed in order to deduce probable environments. The conglomerates are probably deposits of channel fills in a fluvial fan rather than of a braided stream. This is discussed more detailed in Section 4.10.2 of the Gingst 1/73 well. Comparable and contemporaneous deposited sediments from the Flechtingen Block (see Section 8.13.3) were interpreted as alluvial fan deposits (Paech 1973a).

Sandstone facies, (Sf-c),h-p: The sandstones of the Mönchgut Formation are mostly massive or parallel laminated; ripple-, and cross lamination was not observed. A red colouring throughout this facies was noted. Sandstone beds of up to 1 m thicknesses are amalgamated and characterised by sharp contacts. The transition to the surrounding facies is mostly sharp (see Fig. 5.3).

Interpretation: Again, current-generated structures suggest fluvial origin but with regard to the facies association may be part of a fluvial fan depositional environment as - in comparison - gravel-bed braided rivers are characterised by higher bed thicknesses and infrequent sand intercalations of mostly fine-grained sand (Miall, 1996).

5.10 Westphalian C - Stephanian evolution of depositional environments

The onset of the Westphalian C is marked by the Ägir-Horizon that was not documented by core material. It was identified by well-log evidence (Schwahn et al. 1990). The depositional environment of the Jasmund Formation document the sedimentation of a braided river system and the adjacent floodplain. The dominance of overbank- and lacustrine deposits (accompanied by an intense soilification) was noted for the Westphalian C. The environmental evolution of the subsequent Dornbusch, Trent and Rambin formations is characterised by a change in the river style. In comparison to the Jasmund Formation an overall decrease of overbank intercalations, lack of pedoturbation and an increase in grain size was observed. Conglomerate- and sandstone-channel sedimentation dominates while the proportion of overbank fines decreases considerably. A "Deep gravel-bed" braided river system (or Donjek-Type) with major channels (fining-upward sequences), minor channel-fills and alternating channel-bars was suggested for this period. The transition to the upper Stephanian is characterised by an overall increase in grain size as the proportion of sand increases from ca. 50 % recorded from the underlying Dornbusch, Trent, Rambin formations to ca. 75 % in the Mönchgut Formation (Schwahn et al. 1990). In addition, the red colouring of the sediments becomes more intense from the Rambin to the Mönchgut Formation. It is not clear if this red colouring is a function of the proximity to the Stephanian-Rotliegend unconformity (secondary colouring) or a signal of semi-arid to arid climatic conditions. For the Mönchgut Formation, a change of the overall depositional environment from a floodplain/braided river system to an alluvial fan depositional environment is suggested. This might indicate an overall shallowing of the depositional site.

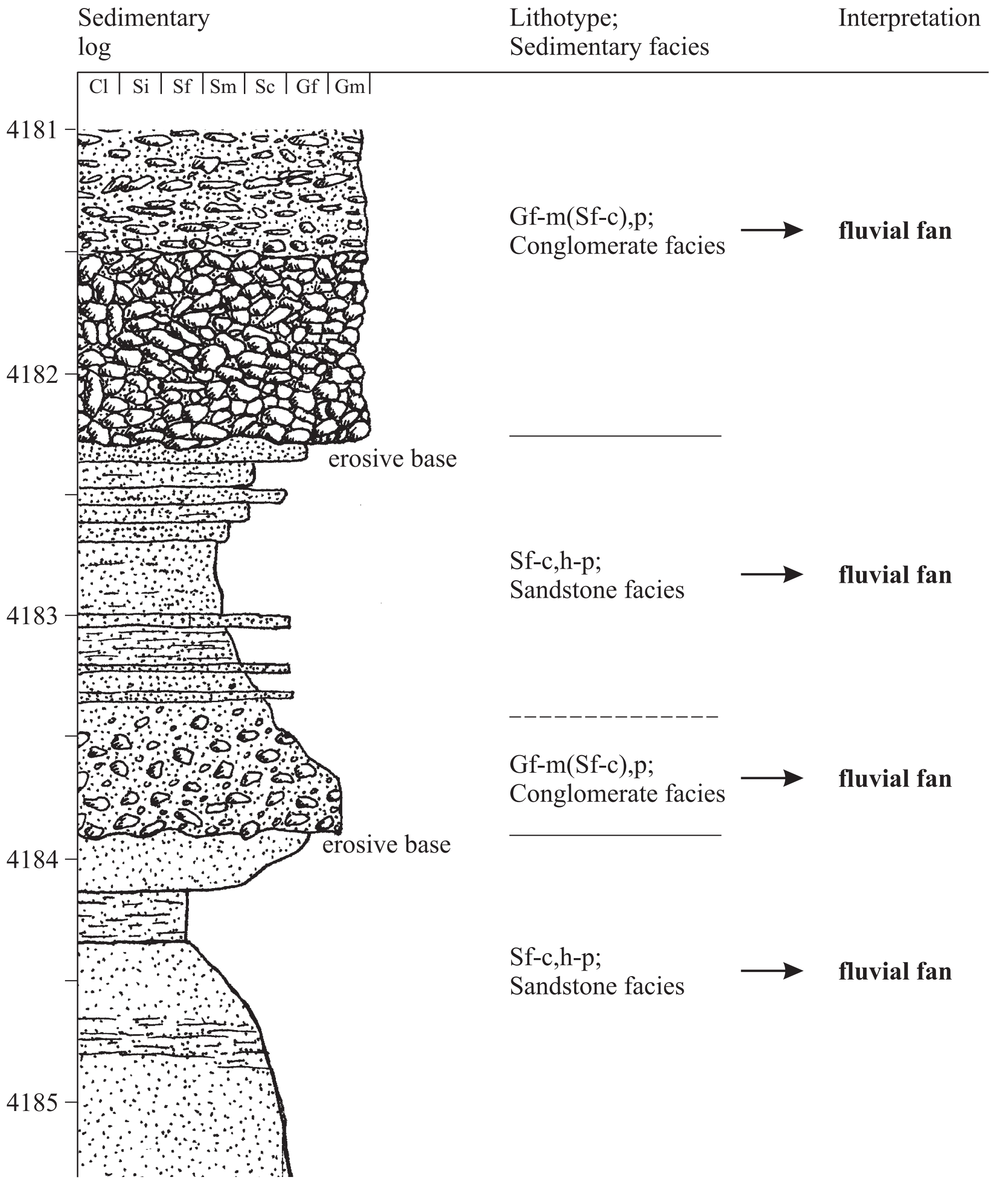

Figure 5.3: Core barrel from 4181 - 4185.3 m; Mönchgut Formation. This sedimentary log represents a fluvial fan depositional environment.

Chapter 6

Parchim 1/68

The Parchim 1/68 well comprises a Kinderscoutian (Namurian B) succession that extends from 6488 - 7031 m (Tab. 6.1). A regional hiatus separates the overlying Rotliegend volcanics from the underlying Carboniferous sediments. This Upper Carboniferous succession is documented by nineteen core barrels. Eighteen of these contain sediments while one core barrel documents a magmatic intrusion. 140.1 m of sedimentary rocks were recovered (ca. 26 % core recovery). The bio- and lithostratigraphic classification was combined from Waldmann et al. (1977), Hoth et al. (1990) and Hoth et al. (1993).

6.1 Namurian B: Facies description and interpretation

The interval from 6488 - 6568 m is assigned to the Marsdenian. Another five marine- and two brackish fauna prove the Kinderscoutian age of the succession. A marine influenced depositional environment can be presumed on the basis of the palaeoecological significance of this fauna (Waldmann, 1977). The below described sediments were assigned to a barrier-island/lagoonal system as discussed in Section 6.2 at the end of this Chapter. Therefore, the described and interpreted facies were divided in three groups which represent the subenvironments of the presumed non-deltaic, siliciclastic coast environment.

6.1.1 Shelf facies

Mudstone facies; M(Sf),h-p: This facies is characterised by massive or thinly interbedded clay/silt beds with laminae smaller than 1 mm. Subordinately, wavy laminated beds were observed. The laminae thickness varies from < 1mm to 1 cm. The facies' thickness varies from 0.5 - 3 m. Both, bioturbated beds and beds with common pyrite concretions or dispersed pyrite occur. A sequential development with a transition from undisturbed, pyrite bearing beds to bioturbated beds is common. Plant debris and unidentified organic matter might be accumulated in thin layers (< 2 mm). A marine fauna was identified in this facies (Waldmann, 1977)

Interpretation: The lack of shallow-water features and a marine fauna association may suggest deposition from suspension load, probably below storm-wave base. The sedimentation pattern might denote a shelf depositional environment with a transition from oxygen-depleted condition (no bioturbation, pyrite precipitation) to oxygenated conditions with common bioturbation.

6.1.2 Lagoonal facies association

Sand/Mud interbedded facies; M/Sf,l: This interbedded facies is characterised by a pronounced lenticular and flaser bedding (see photo 5). The sandstone interbeds are ripple- to flaser bedded. The interbed thickness varies from 0.5 - 5 cm. Some sandstone interbeds might reach up to 20 cm thickness. Moreover, a strong bioturbation was recorded in this facies. Some beds with convolute bedding were also recognised.

Interpretation: Lenticular and flaser bedding are characteristic bedding types for mixed sand-mud tidal-flats (de Raaf and Boersma, 1971; Reading and Collison, 1996). For further discussion of these bedding structures and their environmental interpretation see Section 3.3.2 of the Loissin 1/70 well and Section 4.5.1 of the Gingst 1/73 well. These observations and the common bioturbation would point to a clastic coast depositional environment. Convolute bedding can also indicate a tidal-flat environment (Reineck and Singh, 1980) although it can also develop in turbidites or fluvial sediments (Leeder, 1995). In tidal-flats, convolute bedding is a common feature on steep slopes of sand bars. The origin is a result of liquefaction due to the compaction of sediment during sub-aerial exposure at low-tide (Wunderlich, 1967). This facies is strongly associated with the mudstone facies of the lagoonal facies association (see below).

Mudstone facies; M,h-p: This mudstone facies is characterised by massive to weakly laminated beds of up to 3 m thickness. Pyrite concretions are abundant throughout this facies but intensive bioturbation was also noted (see photo 4). The obvious differences to the shelf mudstone facies are a higher clay/silt ratio and the existence of soilified beds. Moreover, abundant organic matter and plant debris besides the deposition of coal seams is limited to the lagoonal subenvironment. Six very thin coal seams (0.5 - 5 mm thick) were identified in the core barrel from 6560.4 - 6572 m (see Fig. 6.1). Some of these occur on the tops of soil horizons.

Interpretation: On the one hand, the existence of pyrite suggests a relatively high input of organic matter and reducing condition during and shortly after deposition. But on the other hand, intensive bioturbation indicates oxygenated conditions. These are characteristic conditions encountered in muddy tidal-flats, where the large supply of mud can seal the underlying beds and form dysaerobic to anaerobic conditions (Reading and Collinson, 1996). The lack of sandstones might denote a depositional site that was not affected by tidal currents. It is likely to presume that the depositional site was emerged during distinct periods of time. This emergence is documented by the weak soilification of the sediment.

Soil facies; M-Sf,l: Some mudstone beds of 5 - 20 cm thickness show a beginning pedoturbation by the activity of rootlets. The remains of these rootlets are characterised by dark-grey organic matter that traces these rootlets (see photo 19).
Interpretation: This facies denotes a depositional site that was close to, or above, water level. In comparison to the soil horizons that were assigned to a coastal- or fluvial floodplain environment, these present soils are characterised by less disturbance of the primary sedimentary structures and are more grey coloured rather than greyish brown coloured. This might indicate shorter periods of emergence, since the pedoturbation is not as advanced as in alluvial environments. Moreover, most of the alluvial soils (see soil facies of the Loissin 1/70, Gingst 1/73 and Pudagla 1/86 wells) are characterised by a typical brown colouring, which was not observed here.

6.1.3 Barrier-island facies association

Sandstone dominated facies; Sf-m,p-r: Weakly- and massive bedded, fine to medium-grained sandstones dominate this facies. Planar- to planar cross-bedding and, subordinately, ripple cross-bedding also occur. The crossets are micro- to large scaled with predominance on medium and large scale crossets. These sandstones are moreover characterised by weak sorting. Intraformational mud-flakes occur throughout this facies. These mud-flakes might have been accumulated randomly or in distinct layers (1 - 5 cm). The thickness of the sandstone beds may exceed the length of a core barrel. Bed thicknesses are somehow difficult to recognise, as the transition is mostly gradational and marked by changes in the grain size distribution pattern. Sharp contacts between sandstone beds have rarely been recorded. Organic matter is accumulated in thin laminae (< 3 mm). Plant debris and pyrite precipitations are common throughout this facies.
Interpretation: Again, the environmental interpretation of current-generated sandstones with no palaeoecological evidence is rather difficult. It must be interpreted with regard to its surrounding facies. Thus, a depositional environment that is at least influenced by marine processes is suggested. The gradational contacts of sandstone beds and the considerable bed thickness imply a continuous and rapid influx of sediment to the depositional site. Moreover, due to the presumed shallow-marine environment - which was referred from the facies association - one could expect signs of bioturbation, but the presumed rapid sedimentation processes would hinder organisms from disturbing the bedding. Instead, pyrite precipitation may indicate reducing environmental conditions. The recorded characteristics of this facies may be best described as a barrier-island subenvironment of a tide-dominated coast where the sandstones might represent the barrier island deposits. An extended interpretation on this presumed barrier-island/lagoonal system is provided in the Section 6.2.

Sand/mud interbedded facies; Sf/M,p-r: Another sand/mud interbedded facies was identified. This facies contains sand/mud interbeds with layer thicknesses from 1 - 5 cm and bed thicknesses from 0.2 - 1 m. The sandstone interbeds are parallel or ripple- to ripple cross-bedded. The crossets are exclusively micro-scale. Pyrite concretions appear less common than in the shelf mudstone facies (see above) while the bioturbation relatively increases. Plant debris is common in this facies.
Interpretation: In comparison to the shelf dominated mudstone facies and the barrier-island facies as well as the tidal-influenced lagoonal facies, this facies may denote a more wind and wave influenced depositional site. Current-generated bedding and the transport of fine-grained sand suggest a depo-

Table 6.1: Carboniferous Bio- and lithostratigraphy of the Parchim 1/68 well.

Depth (m)	Thickness (m)	Biostratigraphy	Lithostratigraphy
regional hiatus			
6488 - 6568	80	Namurian B, Marsdenian, R2b	n.n
6568 - 6832	264	Namurian B, Kinderscout. R1c-R2a	Parchim Formation
6832 - 7030	198	Namurian B, Kinderscout. R1a-b	Loissin Formation

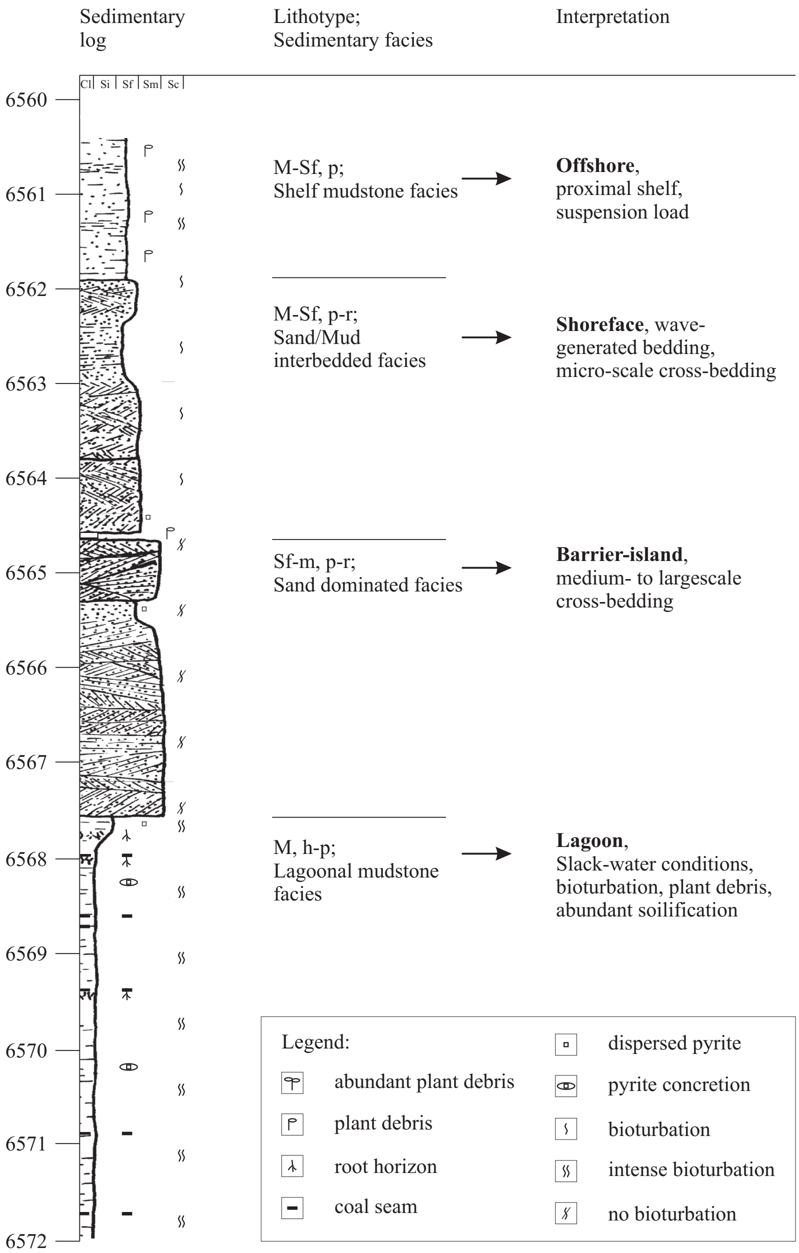

Figure 6.1: Core barrel from 6560.4 - 6572.2. Sedimentary log of a barrier island/lagoonal system. It is characterised by the transition from a lagoonal environment to a barrier island. The depositional environment then changes to the shoreface adjacent to the barrier island. A progressive deepening of the depositional site results in the deposition of mudstones that are assigned to a proximal shelf environment.

sition not only from suspensions but also from vectored currents. This might indicate a deposition above the mean fair weather wave base. In terms of the overall facies sequence, this facies is somehow difficult to interpret. It may appear on the seaward side of a barrier-island and be interpreted as shoreface deposits but also tidal-inlets between barrier-islands may be characterised by this facies. It is associated with the barrier-island facies association as the wave-energy of the shoreface may only be effective on the seaward side of the barrier islands.

6.2 Namurian evolution of depositional environments; facies associations and sequences

The observed facies sequence is assigned to a non-deltaic, siliciclastic coast depositional environment. It is characterised by a sequential succession of depositional environments and is therefore described as a costal sequence. Siliciclastic coastlines are particularly sensitive to relative sea-level changes. Therefore, vertical facies changes are both frequent and complex (Davis and Clifton, 1987). The observed depositional sub-environments change from distal- to proximal shelf over barrier island to lagoonal tidal-flats, *i.e.* barrier-island/lagoonal system. In these systems, the barrier is separated from the land by a shore-parallel lagoon and is built mainly by wave-dominated foreshore/shoreface processes. Barrier-island/lagoonal systems are generally associated with low sediment supply and relative sea-level rise during transgressions (Reading and Collinson, 1996) but may also form during regressions (Diessel, 1992). The succession of environments is depicted in Fig. 6.2. The vivid change of subenvironments within the entire Parchim-succession shows several cycles that were imposed on the probable overall transgression. This presumed transgression was referred from the stratigraphic distribution in the area and the resulting basin's geometry (for detail see Section 9.2.3). A regressive trend as presumed for the upper part of the Eldena 1/74 well (Namurian C) was not noted within the succession (Namurian B) of this well.

It has to be kept in mind that the sequential interpretation of the interval from 6547 - 7030 m is based on only 29 % of recovered core. The lithologies of the uncored sections are based on the correlation with well-log evidence (Waldmann et al. 1977). A sedimentary log of a facies sequence is shown in Fig. 6.1. Here, the facies sequence develops from lagoonal sediments to the thick barrier-island sandstones. Successively, shoreface deposits on the seaward side of a barrier-island were deposited. Subsequently, the change from the sand/mud interbedded facies to a mudstone facies denotes the transition from foreshore-shoreface to offshore conditions. This depicted facies sequence (ca. 22 m) is, in contrast to other preserved successions, relatively thin. From Fig. 6.2 one can see that these sequences may be up to 130 m thick.

In general, the lagoonal tidal-flat facies association is characterised by tidal processes and the formation of soil horizons. No influences of tidal currents were observed in the depicted core barrel (see Fig. 6.1) but, for example, the core barrel from 6840 - 6897 m shows both tidal current influenced deposits that are characterised by a typical lenticular- and flaser bedding besides lower-energy deposits. These core barrels yield a brackish fauna association (Waldmann et al. 1977). Brackish conditions and sediments that are rich in organic matter (including plant debris washed in by rivers) are characteristic for tidal-flats in humid and temperate settings (Reading and Collison, 1996).

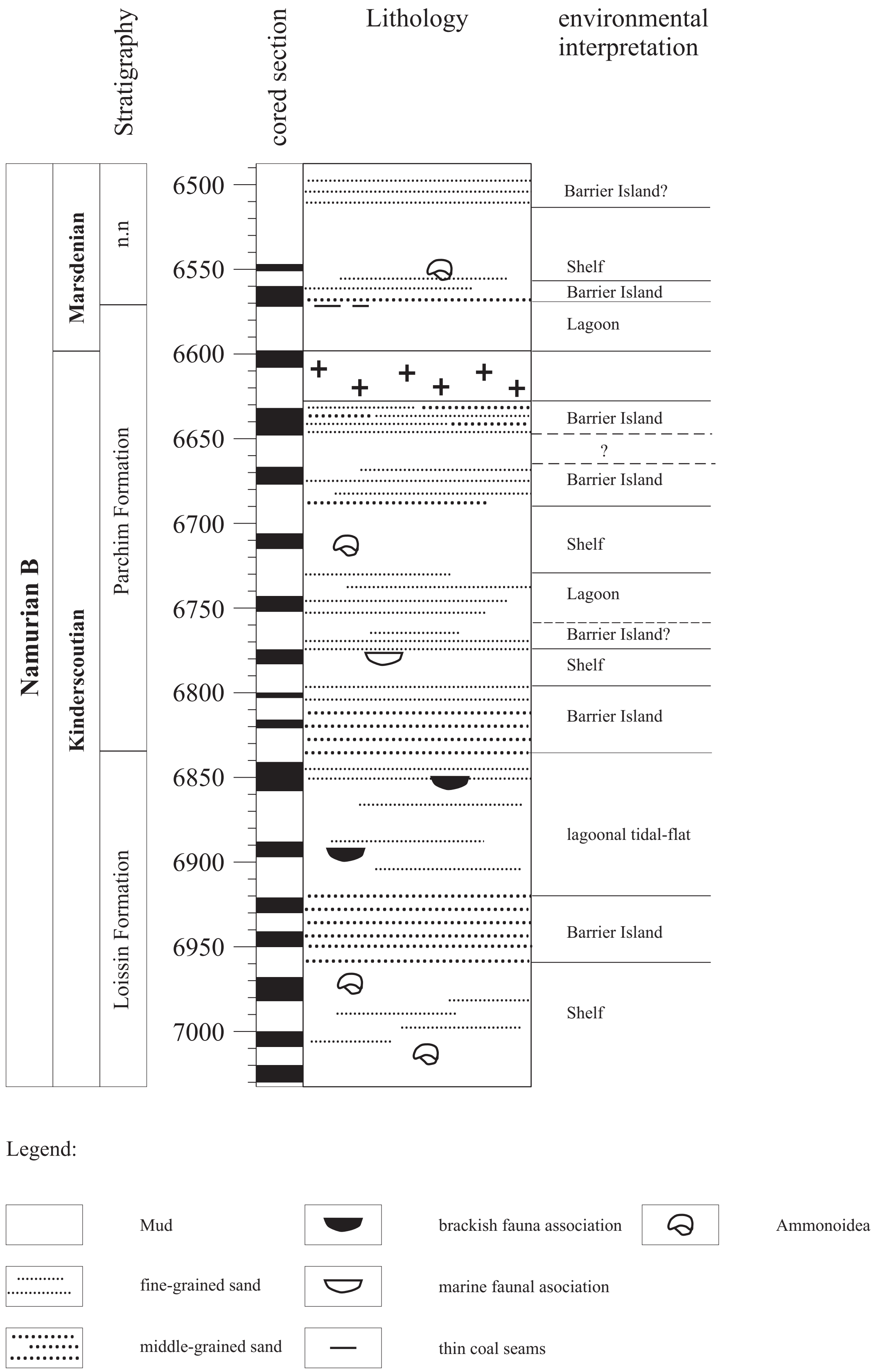

Figure 6.2: The Parchim succession reveals an, probably, overall transgressive sequence of a barrier island/lagoonal system. The vivid change of sub-environments within the succession shows several transgressive/regressive cycles that were imposed on the overall transgressive sequence. Compiled from Waldmann et al. (1977), Hoth et al. (1990) and this study.

Chapter 7

Eldena 1/74

The Eldena 1/74 well (El 1/74) reached Carboniferous strata from 4775,0 - 5206,0 m. Twenty eight core barrels with a total of 173,9 m were recovered (i.e. 40,3 % core recovery). The initial biostratigraphic classification of the Eldena well was performed by Bergmann et al. (1980) who assigned a Namurian A–B, *i.e.* Pendleian (E) - Kinderscoutian (R1), age. Following investigations revised the age assignments; according to Hoth et al. (1993) and Hoth (1997), the sediments of the Eldena 1/74 well encompass the Namurian B to, probably, the lowermost Westphalian A period. In terms of this study a Namurian B–C age seems to be most likely. The Eldena well can be strongly correlated with the Proettlin 1/81 well (see Chapter 8.1). These wells were cored in close distance and correlated with the means of well-log evidence (Bergmann et la. 1980).

7.1 Namurian B-C: Facies description and interpretation

Mudstone facies; M,p-h: The two lowermost core barrels (5187.6 - 5206.2 m) comprise this facies (see Fig. 7.2). It is characterised by laminated and subordinately massive mudstones. The lamination varies from sub-mm scale to 2 cm. Some beds are only weakly or discontinuously laminated. No bioturbation was observed in this facies. Some considerably thin sandy siltstone beds are intercalated (1 - 30 mm). These intercalated beds are characterised by graded bedding and a gradational shift to the overlying mudstone beds. The lower sharp or erosive contact with the mudstone beds is marked by load casts.

Interpretation: The lack of any current-generated features within the mudstones may suggest deposition under low-energy conditions in a marine environment below storm wave base. No bioturbation was observed which suggests anaerobic condition during deposition. These presumed anaerobic conditions did not result in the precipitation of pyrite as observed in other contemporaneous sediments in the area. This might be an effect of an insufficient amount of Total Organic Carbon (TOC).

Two possible depositional environments must be discussed here. On the one hand, these mudstones may have been deposited in a distal shelf area. This assumption is supported by the facies association which implies a possible shift from this facies to the more proximal sandy mudstone facies (see below). The muddy material may have been transported by low-energy currents as suspension-load while the graded, sandy siltstone beds, which are characterised by erosive bases and its gradational transition into mudstone beds, suggest a deposition from turbidity currents; the grain size suggests a classification according to the fine-grained turbidite facies model of Stow et al. (1996). On the other hand, this facies can also be compared to the hemipelagite black shale facies of the Proettlin 1/81 well which was deposited in a deep-marine environment. Therefore, these dark grey mudstones of the Eldena 1/74 well may also be interpreted as hemipelagites with intercalated fine-grained turbidites. This assumption is supported by the fact that these two wells were cored in close distance and encompass in part the same stratigraphic interval (*i.e.* Namurian B). In general, this question cannot be answered satisfactorily; both interpretations seem plausible and were incorporated in Fig. 7.2 and the interpretation of the basin's evolution (see Section 9.2.3).

Sandy mudstone facies; M(Sf),p: This facies is characterised by mm-scale laminated mudstones which have a noticeable amount of fine-grained sand. Some thin, massive bedded sandstone beds (1 - 10 cm) with sharp bases are intercalated. Bioturbation features were observed, but no pyrite precipitation. The transition to the surrounding facies is gradational. This facies attains thicknesses from 2 - 5 m.

Interpretation: The lack of any current-generated features may suggest deposition under low-energy conditions, probably below storm wave base. Bioturbation was observed, which suggests aerobic conditions during deposition. The sandy mudstones may have been transported by even, relatively weak currents while the interbedded sandstones may result from stronger currents that caused a resuspension of bottom sediments - probably shoreface sands - and the genesis of turbid plumes which were transported in offshore areas. In comparison to the associated facies, this sandy mudstone facies may have been deposited in a proximal shelf area (offshore) which is characterised by oxygenated condi-

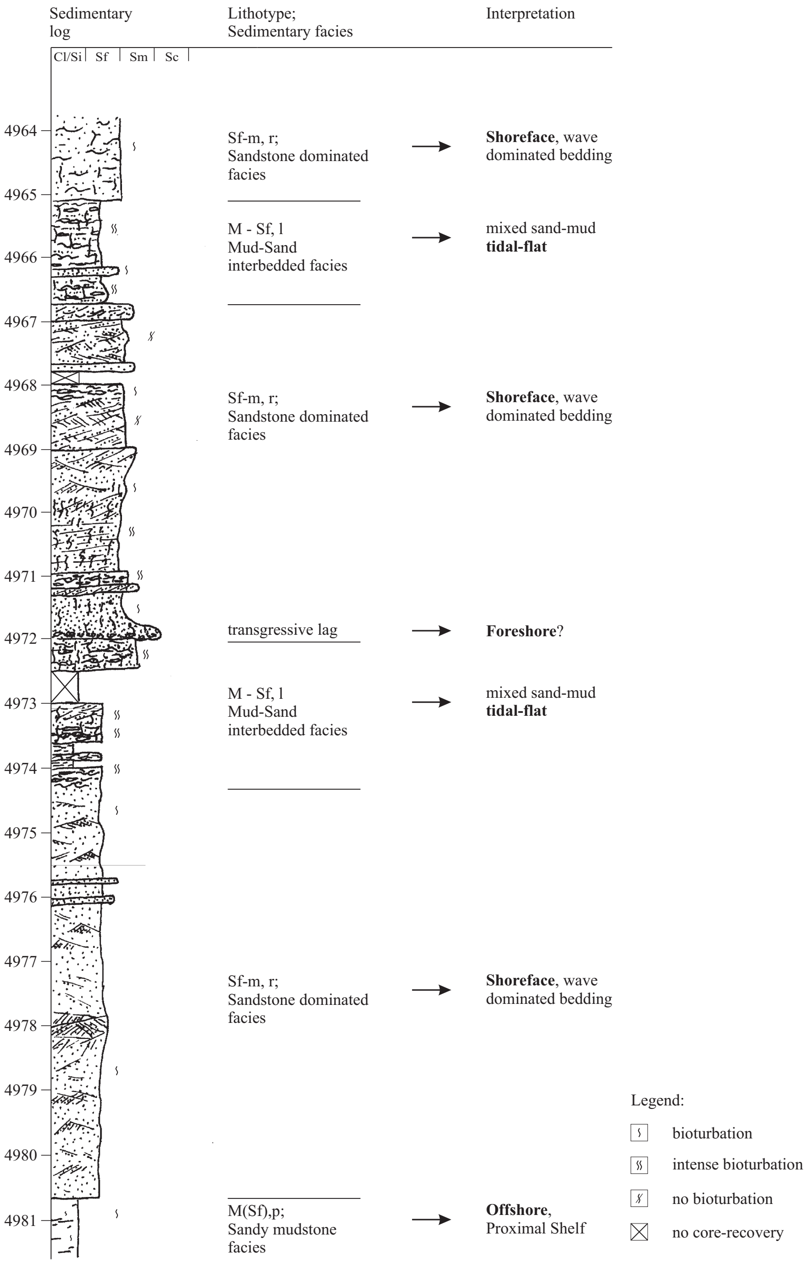

Figure 7.1: Core barrel from 4964.0 - 4981.7; Namurian B. Sedimentary log of a tidal influenced, coastal depositional environment. It is characterised by the transition from offshore to shoreface and tidal-flat environments. In Fig. 7.2, this core barrel corresponds to the tidal influenced shoreface.

tions (abundant bioturbation) and the frequent influx of fine-grained sands. This results in a sedimentation pattern - typical for mud-dominated shelf - where mud zones are juxtaposed against sand zones (*c.f.* Johnson and Baldwin, 1996).

Mud-Sand interbedded facies; M/Sf,l: This facies is characterised by pronounced lenticular (both connected and isolated sand lenses) and flaser bedding with layer thicknesses varying from a few mm to ca. 5-7 cm. The thickness of this facies is between 2 - 10 m. Bioturbation is common in this facies while no pyrite precipitation was noted.

Interpretation: Flaser and lenticular bedding structures imply that both sand and mud were available and that periods of current activity alternated with periods of quiescence. These are characteristic conditions - and the resulting bedding types - for mixed sand-mud tidal-flats (de Raaf and Boersma, 1971; Reading and Collison, 1996). For further discussion on these bedding structures and their environmental interpretation compare Section 3.3.2 on the Loissin 1/70 well and Section 4.5.1 on the Gingst 1/73 well.

Sandstone dominated facies; Sf(Sm),r: The sandstones of this facies are mostly ripple or flaser, ripple-cross bedded and planar-cross bedded and either fine-grained or medium- to fine-grained. The cross-bedding is mostly small-scale (*i.e.* crossets of a few mm up to 5 cm) but also medium-scale (*i.e.* crossets from 5 - 20 cm) were observed. Massive sandstones rarely occur. These sandstone beds are intercalated with the sandy mudstone beds (0.1 - 0.5 m). The contact is mostly sharp but also gradational. The thickness of these sandstone beds varies from ca. 0.5 - 3 m. They might be amalgamated to thick sandstone bodies with up to 10 m thickness. The lower contact is mostly sharp. This facies is often associated with the mud-sand interbedded facies. Some beds contain abundant plant debris and also coal fragments were noted. One layer with pyrite concretions was noted (see photo 18).

Interpretation: In comparison to the surrounding facies, these sandstones may also be assigned to a marine environment. The appearance of wave-dominated structures (in a presumed coastal environment) suggests deposition around and above the mean fair weather wave base (*c.f.* Reading and Collison, 1996). A coastal environment is also suggested from the interfingering with the tidal-flat interbedded facies (see above). Therefore, a shoreface depositional subenvironment is suggested. The intercalation of thin, muddy sandstone beds might denote the frequent shift to lower-energy conditions which, probably, mark the transition to more offshore influenced environments.

Sandstone facies; Sf-m,p-r: Two core barrels contain this facies exclusively. In the uppermost cored section, this facies is associated with the sandstone dominated facies (see Fig. 7.2). Weakly- and massive bedded, medium and subordinately fine-grained sandstones characterise this facies. Planar to planar cross bedding and, subordinately, ripple cross bedding occur. The crossets are medium- and large-scale. These sandstones are moreover characterised by a weak sorting. Intraformational mud flakes were observed in one core barrel. These mud flakes might be accumulated randomly or in distinct layers (1 - 5 cm thickness). The thickness of the sandstone facies may exceed the length of a core barrel. This could be shown with the correlation of well-log evidence and the preserved material from which thicknesses of ca. 15 - 20 m were suggested (Bergmann et al. 1980; Hoth, 1997).

Interpretation: The environmental interpretation of current-generated sandstones with no palaeoecological evidence is rather difficult. This facies was compared to the Namurian succession of the Parchim 1/68 well (for detail see 6.1.1). Here, comparable sandstone beds were assigned to a barrier-island/lagoonal system. Therefore, this facies is best described in terms of a Barrier island/lagoonal system where these sandstones might represent the barrier-island deposits. A more detailed discussion is provided in Section 7.2.

7.2 Namurian evolution of depositional environments

The Namurian succession is characterised by a sequential development of the depositional sedimentary environments (see Fig. 7.2). It starts with mudstones that were interpreted as distal shelf- or, probably, deep-marine deposits. Subsequently, a progressive shallowing of the depositional site is noted. This shallowing might be indicated by a transition to proximal shelf deposits of the sandy mudstone facies; common bioturbation and frequent influx of fine-grained sands mark this mud-dominated shelf. The transition from offshore to shoreface conditions is identified by the increase of wave-dominated features, *i.e.* sand dominated facies. It is interfingered with tidal-flat deposits (*i.e.* mud-sand interbedded facies) which denote the coastal character of the depositional site. As one can see in Fig. 7.2 the changeability of environments within the entire Eldena-succession shows several cycles that were imposed on an initial overall transgressive trend. This transgressive trend might be indicated by a transition form, probably, deep-marine but at least distal shelf conditions to a proximal shelf and coastal conditions. The upper part of the succession may indicate regressive tendencies since barrier-islands and adjacent shoreface and lagoonal tidal-flats subenvironments dominate the succession and the portion of shelf deposits relatively decreases. Such barrier-island/lagoonal systems are generally associated with low sediment supply and relative sea-level rise during transgressions (Reading and Collinson, 1996) but may also form during regressions (Diessel, 1992). Such a presumed regression is supported by a comparison to the Parchim 1/68 well, the spatial distribution of contemporaneous strata in the area and, as an outcome of this, the basin's geometry (for details on the basin's evolution compare with Section 9.2.3).

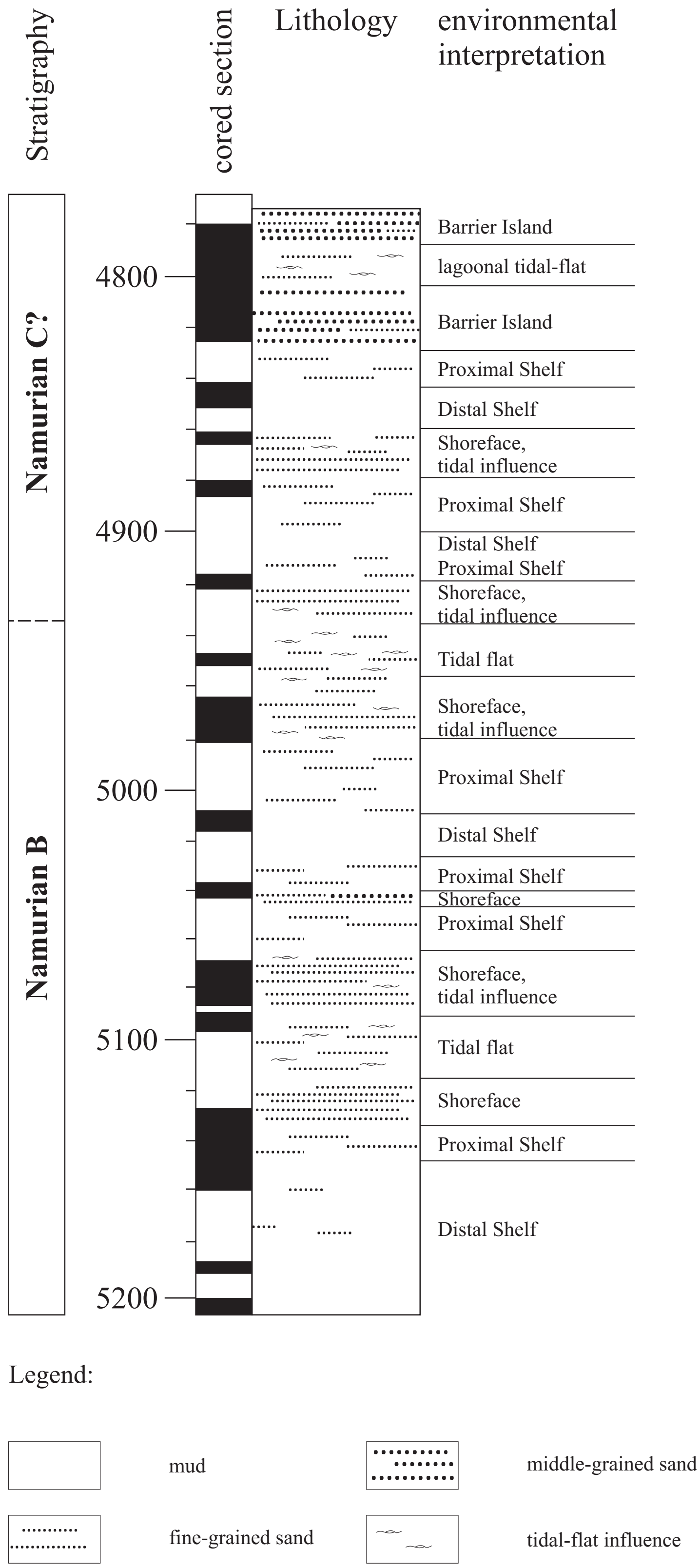

Figure 7.2: The Eldena succession reveals a shallow-marine- to coastal depositional environment. The vivid change of subenvironments within the succession shows several transgressive/regressive cycles that were imposed on the sequence. Compiled from Bergmann et al. (1980) and this study.

Chapter 8

Research wells from northern Brandenburg and Sachsen-Anhalt

The following sections present the description and interpretation of twelve wells that characterise the more orogen-proximal sedimentation of the Variscan foreland basin. They are located in northern Brandenburg and Sachsen-Anhalt (Fig. 2.6). These wells are - in comparison to the wells from the northern basin margin - relatively short in length (ca. 22 - 170 m) and comprise only one stratigraphic interval. Moreover, the age assignments are in certain cases rather tentative and can only be classified in terms of lithostratigraphic correlations and their position within the basin. Furthermore, the outcrops and the research wells of the Flechtingen Block were not documented and interpreted in this study but information concerning lithofacies and environmental interpretation were involved into the overall picture of the foreland basin successions. This additional information on outcrops was taken from the literature and is summarised in Section 8.13 at the end of this Chapter.

8.1 Proettlin 1/81

The Carboniferous of the Proettlin 1/81 well extends from 4752.0 - 7008.0 m (47.8 m of sediments were cored, *i.e.* 2.1 % core recovery. The cored material was assigned to the Namurian A (E1 - E2) – lowermost Namurian B period. This age assignment is based on biostratigraphic evidence (Hoth et al. 1990; Hoth, 1997). The Proettlin 1/81 and Eldena 1/74 wells (see Fig. 9.2a) are close together (1 km distance) in south-western Mecklenburg. The younger, uncored sections were correlated to the Eldena succession on the basis of well-log evidence. Therefore, these wells can be combined (Hoth, 1997) in order to describe the environmental evolution of the area.

The core recovery of 2.1 % allows only a tentative reconstruction of the depositional environment. The recovered core material contains a **black shale facies (M,h-p)**. It is dominated by uniform, dark shales that are interbedded with grey silty mud-laminae. These laminae, respectively beds, are characterised by a higher silt/mud ratio than the surrounding mudstones. The beds are sharp-based, graded and attain thicknesses from < 1mm - 15 mm. Load casts are common along these sharp bases. Some thicker laminae also contain considerable amounts of fine-grained sand. Pyrite nodules of 0.5 - 1 mm are common within the mudstone beds throughout the cored sections. Some indication of an overall grain size trend was noted from the preserved material. The amount of interbedded silt decreases from top to bottom, *i.e.* the portion of the dark grey, uniform mudstones increases. This observation is also supported from well-log evidence. Moreover, the well-log interpretation reveals some rare, up to five meter thick, fine-grained sandstone beds in the interval from 5148 - 5843 m (Hoth et al. 1989). These sandstone beds were not noted from the succession below 5843 m.

The dark grey shales are interpreted as hemipelagites. Hemipelagites are sediments that are deposited in deep-marine environments close to continental margins and in enclosed basins where clastic supply is abundant. The pelagic rain of biogenic debris is further diluted by silt- and clay-sized terrigenous components (*c.f.* Stow et al. 1996). The thin laminae may result either from the settling of dispersed suspended material that was received in pulses, possibly due to seasonal high flooding of distant rivers, or as high concentration sediment clouds, *i.e.* turbidity currents. The intercalated beds of the Proettlin 1/81 well are regarded as "event-beds" (*c.f.* Einsele and Seilacher, 1982) and correspond to fine-grained turbidites *c.f.* Stow et al. (1996). The thinner silt laminae may be described as T_{3-7} mud-turbidites using the terminology of Stow et al. (1996). The laminae with a considerable amount of fine-grained sand, may be described as T_{0-3} fine-grained turbidites. An excellent sample is depicted in Fig. 8.1.

The common precipitation of pyrite suggests an oxygen depleted environment. The oxygen depletion may have resulted from the increased oxygen demand of "surplus" organic matter brought in by the fine-grained turbidity currents in the form of finely-comminuted terrestrial plant matter (Wetzel, 1993). No ichnofossils were noted. This also suggests an oxygen depleted environment. Some rare fossil fragments were noted although these fragments yield no palaeoecological evidence. Some, up to five meter thick, fine-grained sandstone beds

Table 8.1: Research wells in northern Brandenburg and Sachsen-Anhalt.

research well (Abbreviation)	stratigraphic range	depth	recovered core
Proettlin 1/81 (Proet 1/81)	Namurian A-B	4752.0 - 7008.0 m	47.88 m
Peckensen 7/70 (Pes 7/70)	Namurian B-C	4450.0 - 4617.2 m	ca 50.5 m
Gransee 2/76 (Gs 2/76)	Namurian A?	4108.0 - 4180.0 m	48.3 m
Zehdenick 2/75 (Zeh 2/75)	Namurian A-B	4494.5 - 5215.7 m	118.3 m
Angermünde 1/68 (Am 1/68)	Namurian A	4820.5 - 5100.0 m	81.4 m
Grüneberg 2/74 (Gü 2/74)	Namurian A	4408.4 - 4513.3 m	44.3 m
Flatow 6/75 (Flo 6/75)	Namurian A	4335.1 - 4442.8 m	39.2 m
Oranienburg 1/68 (Ob 1/68)	Brigantian	4826.0 - 4996.1 m	149.2 m
Nauen 1/76 (Na 1/76)	Namurian A	4108.0 - 4180.0 m	55.9 m
Dreileben 3/70 (Dren 3/70)	upper Viséan	911.6 - 980.5 m	ca. 35 m
Eilsleben 8/76 (Eil 8/76)	upper Viséan	1333.8 - 1373.7 m	ca. 30 m
Brandenburg 1/68 (Br 1/68)	upper Viséan	3466.7 - 3503.0 m	22.6 m

were noted from well log evidence. These sandstone beds might probably correspond to stacked and individual medium-grained turbidites. The interpretation of the preserved core material may suggest a deep-marine depositional environment for the Namurian A to lowermost Namurian B period. The depositional site was dominated by hemipelagite background sedimentation while the intercalated beds characterise dilute, fine-grained turbidites.

It is not quite clear from where these gravity flows were derived. According to the basin's geometry for that period (see Section 9.2.3) it is plausible to presume that both basin margins might have acted as a source for these turbidites. The increase of turbiditic features in the upper interval (*i.e.* above 5843 m) might correspond to the initiation of sedimentation on the northern basin margin and the probable development of a shelf break from which the turbidites might have been shed into the deep-marine basin.

8.2 Peckensen 7/70

The Peckensen 7/70 well records Carboniferous strata from 4288 - 4617.2 m. It comprises a ca. 167 m thick mud-dominated succession that was assigned to the Namurian B - lowermost Westphalian A (Hoth et al. 1993; Hoth, 1997). This age assignment was performed due to a micro- and macropalaeobotanic flora (unpubl. well report in Hoth, 1997). The uppermost 162 m were assigned to the Stephanian C. These sand- and mudstones discordantly overlie the Namurian sediments. Two core barrels with ca. 3.5 m of sediments were recovered from the Stephanian C period while eleven core barrels comprise Namurian strata (ca. 47 m).

8.2.1 Namurian B–C

The Namurian sediments can be described as a hemipelagite **shale facies (M,h-p)** that was influenced by turbidites (Sf,h-p). According to well-log evidence, 90 % of the overall succession yield mudstones while only 10 % was classified as silt-sandstones (Hoth, 1997). The massive, dark-grey shales are rarely intercalated with some 1-5 mm thick silt-laminae (compare photos 1 and 2). One core barrel contained a **sand/shale interbedded facies (Sf/M,h-p)** with 5 - 50 mm thick silt beds. These beds are graded and characterised by a sharp-based contact with massive shales. Load casts are common features along the bases of these beds. This above described interbedded facies may be interpreted as abundant, fine-grained turbidites that are intercalated with massive shales of the background sedimentation. Another core barrel yielded part of a fine-grained sandstone bed (ca. 0.6 m). This sandstone is characterised by massive bedding and abundant fragments of siltstone that were arranged in a breccia-like appearance. Moreover, organic matter (plant debris) is abundant and characterised by sub-mm small black components that are dispersed within the sandstone. Unfortunately, the core-material below and above of this sandstone was not longer available. Thus, it is not clear if this sandstone bed is part of a turbidite sequence; the appearance of the reworked rock fragments would favour deposition from a gravity flow.

Pyrite precipitation was noted from some beds. The rare appearance of pyrite might be due to the relatively low TOC that varies between 0.8 - 1.4 %. These mudstones are therefore not black shales since black shales contain, by definition, 1 - 15 % TOC (Stow et al. 1996). A full marine fauna was identified throughout the Namurian succession (unpub. well rep. in Hoth, 1997). This palaeoecological evidence and the observed sedimentary features may suggest a marine depositional environment. It is not clear whether these sediments were deposited in an oxygen depleted, deep-marine environment as suggested for the Proettlin 1/81 well (Namurian A–B) or in a more shallow environment probably on a partly oxygenated, distal shelf. No bioturbation was noted within the cored material. However, it is clear that the succession was influenced by turbidity flows. The Peckensen 7/70 well - on the environmental level - has to be further discussed with

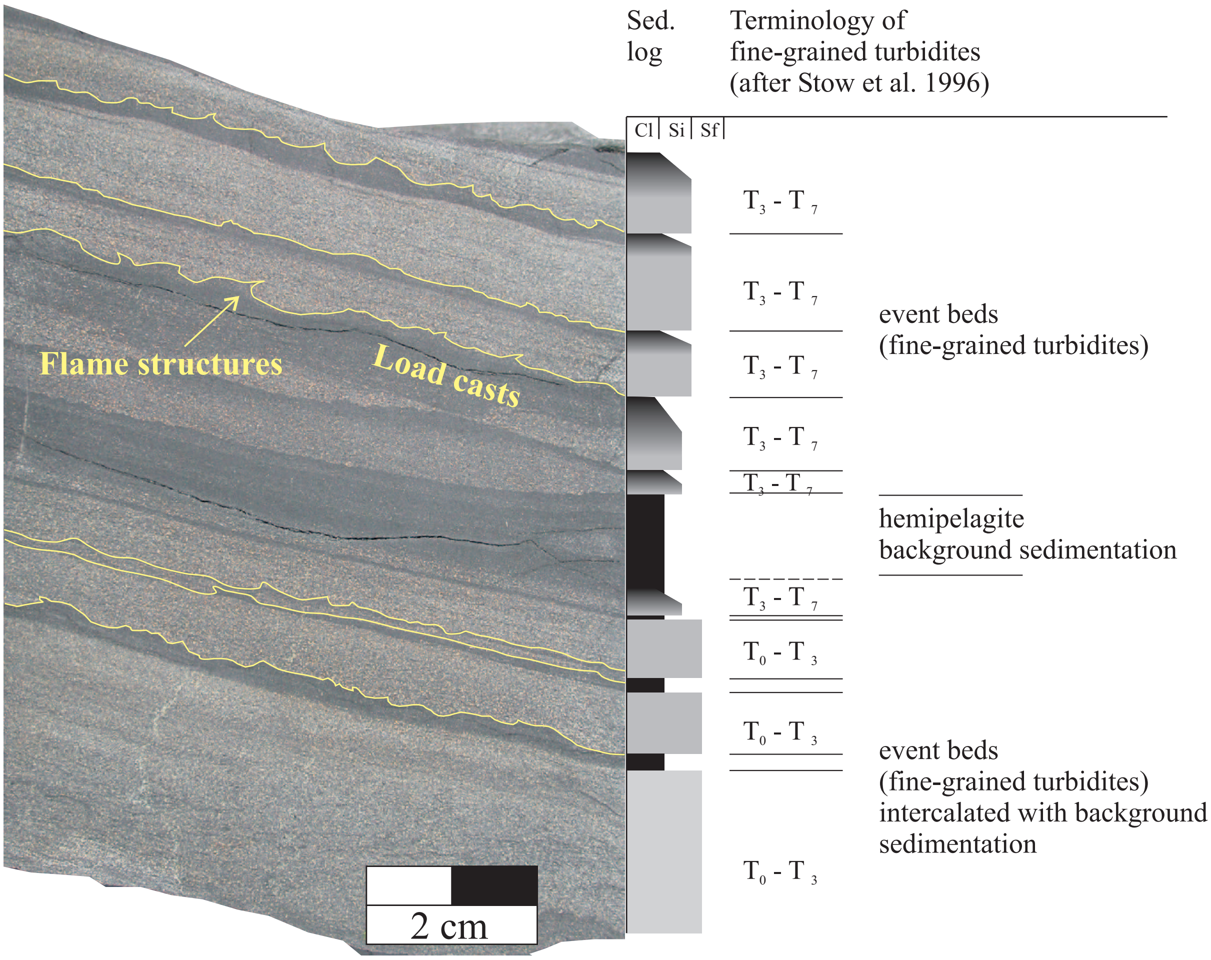

Figure 8.1: Proettlin 1/81: Core barrel from 5399.0 - 5405.6. This sample shows a black shale facies with abundant event-beds that were interpreted as T_{0-3} and T_{3-7} fine-grained turbidites. The yellow lines mark the base of these event-beds.

regard to the overall basins evolution (see Section 9.2.3).

8.2.2 Stephanian A–C

The Stephanian C is only represented by 3.5 m sediment that was assigned to the "Süpling Formation" (unpublished report in Hoth 1997). A sandy mudstone facies was recovered. It is characterised by the interbedding of mud/sand units with laminae thicknesses ranging from 1 - 10 mm. These beds are parallel laminated or massive. Moreover, a 35 cm thick limestone bed was recorded. Organic matter is accumulated in sub-mm thin, discontinuous laminae. Some rootlets were recorded. The rootlets are the only useful environmental indicator suggesting sub aerial exposure of the depositional site. Due to the scarce material, a satisfactory environmental interpretation was not possible. Therefore, the work of Paech (1973c) was used to provide some detail on the sedimentary facies and their environmental interpretation. His work is based on several outcrops and research wells from the Flechtingen Block. A summary of these results is given in Section 8.13.3.

8.3 Gransee 2/67

The Gransee 2/67 well records Carboniferous strata from 5040.5 m to 5241.0 m; eight core barrels with 48.3 m were recovered (*i.e.* 24.1 % core-recovery). The supposed Namurian A age is tentative. It is based on some palaeobotanical material that suggests an upper Viséan- to lowermost Namurian age (Meissner, 1970). Dip variations from 35° - 85° were noted. Thus, a true thickness of ca. 100 m is suggested.

The succession is characterised by a rhythmic sand/mud interbedding of fine- to medium grained sandstones and mudstones. A sand/mud ratio of 4:1 was noted from well-log evidence (Meissner, 1970). Therefore, the succession is described as a **sandstone/shale interbedded facies (Sf-m,h-p-r/M,h-p)**. The mudstones correspond to the shales of the background sedimentation while the sandstones correspond to deposits from turbidity currents (*i.e.* turbidites). These turbidites were assigned to the medium-grained turbidite facies (Stow et al. 1996) which refers to the classical model for medium-grained, sand-mud turbidites following the scheme of Bouma (1962). The individual thickness of turbidite beds ranges from 0.1 - 1.2 m. They are characterised by sharp, mostly erosive bases and an ordered sequence of internal lamination which is comparable to the Bouma-intervals. Complete sequences were not encountered; partial sequences with top-absent or bottom-absent beds are typical for medium-grained turbidites (Stow et al. 1996). Most of these turbidite beds begin with structureless, graded sandstones (*i.e.* T_a-interval). This lowermost interval often contains intraformational mud-flakes that are either orientated or randomly distributed. The overlying T_b-interval (parallel lamination) is sometimes formed on top of the sequence. The T_c-interval (flaser and ripple bedding) was rarely observed. The intervals T_{d-e} are products of settling from suspension and mark the transition to the background (shale) sedimentation.

The hemipelagite shales are up to 3 m thick but on average only a few cm- to dm thick. Intercalated silt- to fine-grained sand beds (0.1 - 2 cm) are common. These intercalated beds are interpreted as fine-grained turbidites (*c.f.* Stow et al. 1996) that are frequently intercalated within the background sedimentation. A sedimentary log with turbidites and hemipelagite shales is depicted in Fig 8.2. Plant debris is common both in the sandstone and mudstone beds. Pyrite precipitation both in the form of concretions and dispersed is noted throughout the succession in sandstones and mudstones. Based on the current evidence it is not easy to assign these sediments to a specific depositional environment. However, based on the abundant deposition of gravity flows and the interbedding with shales besides the comparison to other wells from the area (*e.g.* Oranienburg 1/68) it would appear that this sand/mud interbedded facies was probably deposited in a deep-marine depositional environment.

8.4 Zehdenick 2/75

The Zehdenick 2/75 well records Carboniferous strata from 4494.5 - 5215.7 m; 118.3 m of these 721.2 m were recovered (*i.e.* 16.3 % core-recovery). Dip variations from 32° - 66° were noted. Thus, a true thickness of ca. 450 m is suggested.

Some biostratigraphic material (Spores) was recovered and dated as Namurian A-B (Lindert et al. 1977). This succession resembles the Gransee 2/67 succession. It is also characterised by a rhythmic sand/mud interbedding of fine to medium-grained sandstones and mudstones. A sand/mud ratio of 3:2 was noted from well-log evidence. The ratio of fine- to coarse grained sandstones is 4:1 (Lindert et al. 1977). Moreover, the grain size distribution of the sandstone beds could be referred from the well-log evidence.

Examination of the Gransee 2/67 well suggests that the succession is best described as a **sandstone/shale interbedded facies (Sf-m,h-p-r/M,h-p)**. It is not clear whether these mudstones can be classified as black shales since the amount of TOC is unknown but pyrite precipitation and the dark grey appearance suggest such a classification. The sandstone beds are normally-graded, structureless, parallel- or ripple laminated (Bouma interval T_{a-c}-interval), frequently micaceous and may contain intraformational mudstone-clasts which are arranged in layers or disturbed randomly (see photo 14). Rare, coarse-grained sandstones (T_a-interval) are graded and may contain isolated quartz clasts which measure up to 4 mm in diameter. Bed thicknesses from ca. 1 - 50 cm (in average) were reported from the preserved material. These beds have sharp or erosive bases and form stacked sandstone bodies. These sandstone bodies may exceed the length of a core barrel (*i.e.* 9 m). Furthermore, sandstone bodies of up to 30 m thickness were reported (Lindert et al. 1977); these stacked sandstone beds form the lowermost part of the well (5178 - 5210 m) from which no mudstones were reported; neither from the preserved material nor from well-log evidence. Deposition from gravity flows is still suggested for these sandstones, since they are still characterised by graded bedding and sharp or erosive bases. This section strongly resembles the Brandenburg 1/68 succession (see Section 8.10). The sandstone/mudstone interface shows a variety of post-depositional deformation features as mudstone injections, sandstone dykes, small mud diapirs and rare slump structures. This syn-sedimentary deformation, which occasionally includes small-scale faulting, is predominately confined to individual beds and does neither affect overlying nor underlying beds.

The hemipelagite shales are mostly massive or parallel- to ripple laminated and attains thicknesses from 0.5 - 20 m. Some event-beds of mostly graded, fine-grained sand (1 - 10 cm) are intercalated (see photo 6). Plant debris is common both in the sandstone- and mudstone beds. Organic matter is accumulated in sub-mm thin laminae especially below 5178 m.

Turbidites and shales can also be deposited in outer shelf areas, but the considerable abundance of turbidites and their intercalation with the above described shales besides the comparison to the other wells from the area (see Tab. 8.1) suggest that this sand/mud interbedded facies may be best interpreted as deposited in a deep-marine environment.

8.5 Angermünde 1/68

The Angermünde 1/68 well records Namurian strata from 4820.5 m to 5100.0 m (81.3 m of these 279.5 m were recovered, *i.e.* 29.1 % core-recovery). Dip variations from 15° - 90° were noted. A true thickness of ca. 180 m is suggested.

Some biostratigraphic material was recovered and a Namurian A-age was assigned (Meissner, 1971). A Stephanian sedimentary succession (4693 - 4820 m) unconformably overlies the Namurian. The Stephanian succession comprises sandstones, tuffs and conglomerates (Hoth et al. 1993) but no core

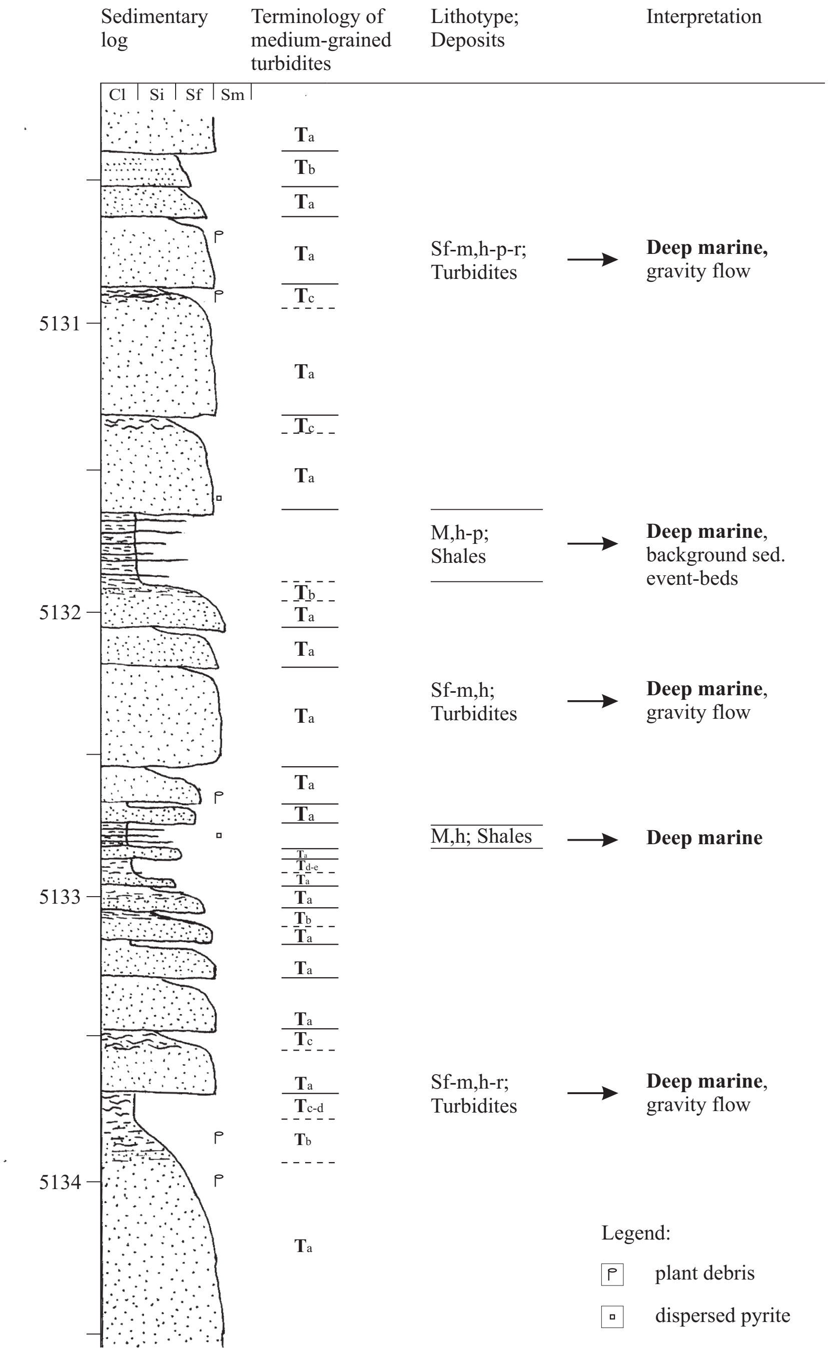

Figure 8.2: Gransee 2/67: Core barrel from 5130.3 - 5139.2. Sedimentary log of a sandstone/mudstone interbedded facies comprising medium-grained turbidites and shales. The sedimentary log is depicted in its true thickness. Terminology of medium-grained turbidites after Stow et al. (1996).

material was available from this interval.

The Namurian succession is characterised by a rhythmic sand/mud interbeds comprising fine to medium-grained, normally-graded sandstones and shales. Therefore, the succession is best described as a **sandstone/shale interbedded facies (Sf/M,h-p)**. A sand/mud ratio of 9:1 was noted from well-log evidence (Meissner, 1971) and the preserved material. The normally-graded sandstone beds are predominantly fine-grained and mostly stacked. These stacked beds attain thicknesses up to 18 m (*i.e.* the length of a combined core barrel). Subordinate, medium-grained sandstone beds with lesser amounts of coarse-grained sand were noted. These medium-grained sandstone beds are also normally-graded and ca. 0.4 - 1.2 m thick. All sandstone beds are characterised by sharp or erosive contact with the underlying beds (either mudstones or sandstones). In general, the sandstones are structureless but parallel bedding occurs to the top of individual units. Mud injection features and mudstone clasts are common features at the base of sandstone beds. The turbidite facies may show evidence of biogenic activity, with a number of ichnofossils, including *Helminthopsis*, *Palaeophycus* and *Planolites* being recognised (McCann, personal communication). The shales are characterised by massive to parallel laminated mudstones that are approximately 20 cm to 200 cm thick. Some interlayers of fine-grained sands (0.05 cm to 7 cm thick) were noted and interpreted as "event-beds" (*c.f.* Einsele and Seilacher, 1982). Some pyrite precipitation was noted from the shale facies.

The interpretation of this sand/mud interbedded facies is rather difficult but based on the current evidence it is likely to suggest that this facies was deposited in a deep-marine depositional environment. This interpretation is based on the considerable high turbidites/shale ratio and the comparison with the other wells from the area (*e.g.* Gransee 2/67, Grüneberg 2/74).

8.6 Oranienburg 1/68

The Oranienburg 1/68 well records Carboniferous strata from 4799.0 - 4996.1 m (149.2 m cored, 87.7 % recovered). The section from 4826.0 - 4996.1 m comprises an uppermost Viséan succession. The age assignment is based on a full marine fauna that was assigned to the *Goniatites granosus* (cuIIIγ) Zone of the German Goniatite Zonation (Meissner and Weyer, 1971). This corresponds to the international chronostratigraphy, the Brigantian period. This Brigantian succession is continuously cored except for the section from 4974.5 - 4996.1 m. Dip variations from 30° - $>$ 90° were noted. Thus, a true thickness of ca. 70 m is suggested. The section from 4799.0 - 4826.0 m comprises a Stephanian succession which unconformably overlies the upper Viséan (Meissner and Weyer, 1971). No core material was available from the Stephanian interval but according to Hoth et al. (1993) the Stephanian comprises sandstones, tuffs and conglomerates.

The Brigantian succession is characterised by a rhythmic sand/mud interbedding of fine to medium-grained (subordinately coarse-grained) sandstones and mudstones. A sand/mud ratio of 1:2 was noted from well-log evidence (Meissner and Weyer, 1971) and the preserved material. The succession is therefore described as a **sand/mud interbedded facies**.

The sandstones are either massive or normally-graded, and may exhibit parallel- or ripple lamination (see photo 13). The beds are up to 1.6 m thick, but in average about 0.2 m thick. The sequential developed of the sandstone beds corresponds to the medium-grained turbidite facies (Stow et al. 1996) Some sandstones show abundant accumulation of mica (both biotite and muscovite); in general the amount of mica decreases when the sandstones grain size increases. Mud injection features are occasionally noted at the base of some sandstone beds. Some beds may contain intraformational mud-flake conglomerates. Some sandstone beds comprise rare micro-conglomerates that form the erosive base of some turbidites. These conglomerate layers are very thin (few centimetres) and show some evidence of normal-grading. These beds were classified to a medium-grained turbidite facies and not to a coarse grained-turbidite facies (*c.f.* Lowe, 1992) because the conglomerate beds do not show any typical features of this facies, *e.g.* traction carpets or dewatering structures. The coarse-grained sandstone beds are particularly dominant in the lowermost part of the cored section. According to the relatively low sand/mud ratio, stacked sandstone beds are being more rarely observed than in other wells (*e.g.* Angermünde 1/68, Gransee 2/67).

The dark-grey shales are characterised by massive to parallel lamination. The bed thickness is in average 0.3 m but up to 2 m thick beds were observed. Frequent event-beds of silty sands were noted. These beds are 0.5 cm to 10 cm thick. Pyrite concretions and dispersed pyrite is common in the shale facies but was also noted from the sandstone beds where they formed in the vicinity of plant debris. An exemplary sedimentary log with turbidites and hemipelagite shales is depicted in Fig. 8.3.

The overall appearance of these sediments is not easy to interpret. Based on the observations, it is most likely to assign this sand/mud interbedded facies to a deep-marine environment rather than to an outer shelf environment. The frequent incursions of turbidites and the interbedding with shales can be well compared to the other wells from the region. Moreover, a full marine fauna with shells, Trilobites, Goniatites, Gastropodes, Brachiopods, Ammonoidea and orthocone Nautiloidea provide palaeoecological evidence which also support the supposition of deep-marine environmental conditions (Meissner and Weyer, 1971).

8.7 Grüneberg 2/74

The Grüneberg 2/74 well reached Carboniferous strata from 4408.4 - 4513.3 m (44.3 m core material was preserved, *i.e.* 42.2 % core recovery). Dip variations from 0° - 50° were noted. Thus, a true thickness of ca. 85 m is suggested. No fossils have been recovered, and thus the given age (Namurian A) is based purely on lithostratigraphic correlation with other research wells from the area (Meissner, 1976).

The succession is characterised by rhythmic sand/mud interbedding and therefore described as a **sandstone/shale interbedded facies (Sf,h-p-r/M,h-p)**. A sand/mud ratio of 8:1 was noted from the preserved material. Fine to medium-grained, massive and normally-graded sandstones dominate the upper part of the succession (4408 - 4480 m). Therein, frequent intercalation of 0.5- to 5 cm thick

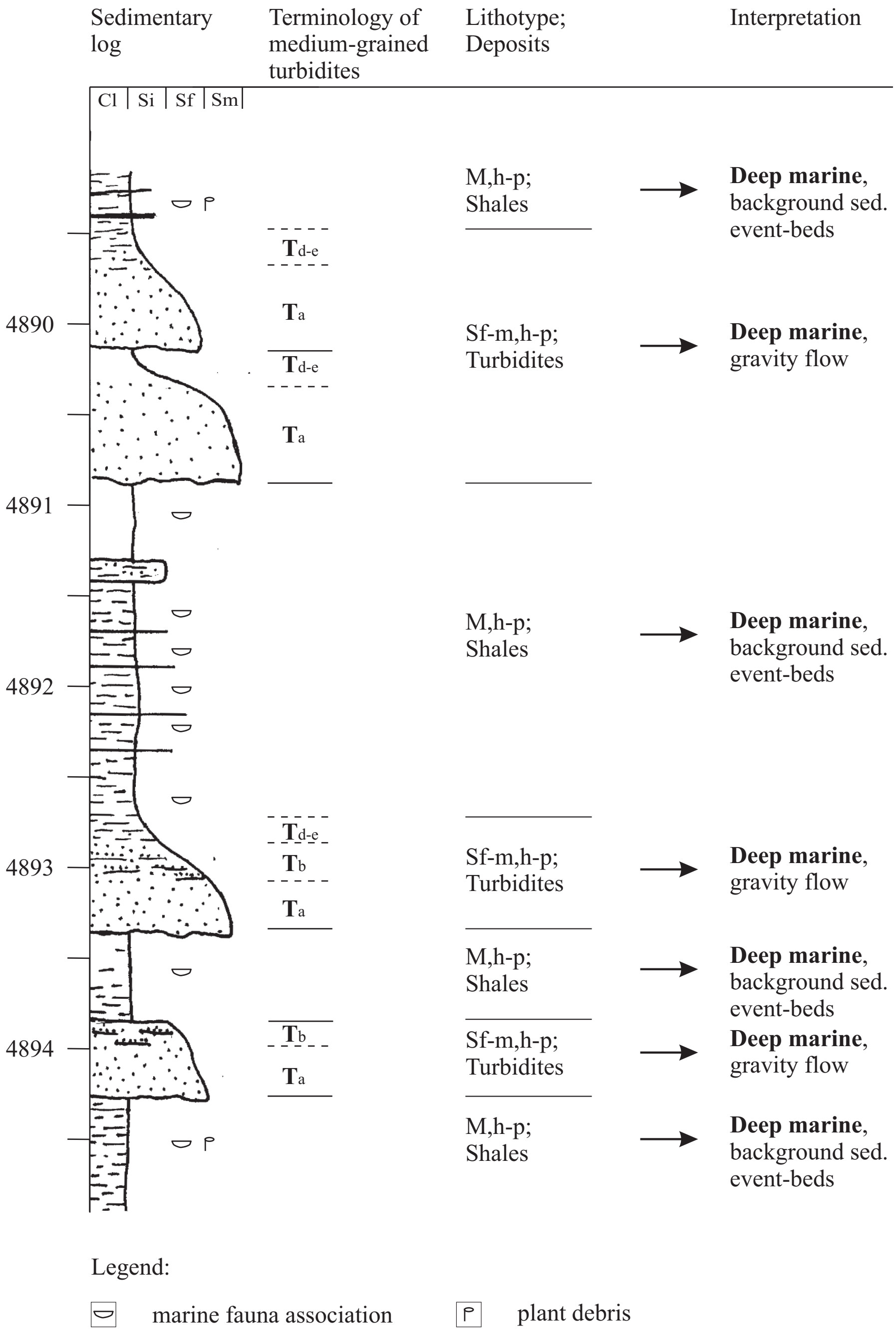

Figure 8.3: Oranienburg 1/68: Sedimentary log of a sandstone/Shale interbedded facies comprising medium-grained turbidites and shales. This sedimentary log is combined from three continously cored core barrels (4881.0 - 4900.8) and depicted in its true thickness. Terminology of medium-grained turbidites after Stow et al. (1996).

shales mark the background sedimentation. The sandstone beds are up to 1.2 m thick but in average about 0.2 - 0.3 m thick. Bed stacking was commonly observed. These stacked beds attain thicknesses of up to 2 m. Within the sandstone beds, isolated, intraformational mud-flakes (1 - 3 cm in diameter) were noted. Interbedded sand/mud beds dominate the lower part of the succession (4480 - 4513 m). These beds are from 0.3 - 4.3 m thick while the interbeds thickness varies from 0.1 cm to 15 cm. These interbeds of fine-grained sandstone show typical features of fine-grained turbidites (normally-graded bedding, erosive base and load casts along its base) and were interpreted as event-beds, *i.e.* dilute, fine-grained turbidites (*c.f.* Einsele and Seilacher, 1982). Moreover, some beds show ripple cross-bedding (micro-scale). Several tectonic breccias and small-scale faulting was observed. This deformation is confined to particular beds (20- 80 cm thick) and interpreted as post-sedimentary effects. The fine to medium-grained, massive or normally-graded sandstones may correspond to the medium-grained turbidite facies while massive mudstones were interpreted as hemipelagite shales. Thinly interbedded sand/mud units may be interpreted as shales that are intercalated with dilute, fine-grained turbidites. The sediments of the Grüneberg 2/74 well resemble the other wells from the area (*e.g.* Gransee 2/67, Angermünde 1/68) and are therefore also assigned to a deep-marine environment.

8.8 Flatow 6/75

The Carboniferous succession extends from 4335.1 - 4442.8 m; 39.5 m of these 107.7 m were recovered (*i.e.* 16.3 % core recovery). Dip variations from 0° - 32° were noted. Thus, a true thickness of ca. 100 m is suggested. No fossils have been recovered, and thus the given age (Namurian A) is based purely on lithostratigraphic correlation with other research wells form the area (Meissner and Lindert, 1980).

The succession is characterised by a rhythmic sand/mud interbedding of fine to medium-grained, normally-graded sandstones and mudstones, *i.e.* a **sand/shale interbedded facies (Sf-m,h-p-r/M,h-p)**. A sand/mud ratio of 4:1 was noted from the preserved material. Fine to medium-grained, normally-graded sandstones dominate the succession. These sandstones are massive, parallel and sometimes ripple bedded. Some bases of these beds may contain considerable amounts of coarse-grained sand- and fine-grained gravel-clasts (up to 4 mm in diameter; see photo 12). The sandstone beds are up to 1 m thick but mostly about 0.2 - 0.3 m thick. Some stacked beds were observed and they attain thicknesses of up to 2.5 m. Within the sandstone beds, isolated, intraformational mud-flakes (1 - 3 cm in diameter) were noted. Most of these sandstones pass over to 5 - 30 cm (in average) thick shales that mark the transition to the background sedimentation. These sequential developed sandstone beds correspond to the medium-grained turbidite facies (*c.f.* Stow et al. 1996).

Some shale beds attain thicknesses of up to 2.3 m. These dark-grey shales are characterised by a massive or parallel- to wavy parallel lamination. Frequent event-beds of fine-grained sands were noted. These beds are 0.5 cm to 5 cm thick and may appear massive, graded or parallel- to ripple bedded. Load casts are common features along bed interfaces both shale/sand and sand/sand contacts (see photo 15). Pyrite concretions and dispersed pyrite were not noted due to a secondary oxidation of the sediment from which an intense red colouring results. Primary precipitated pyrite was altered to haematite (Meissner and Lindert, 1980). Based on the current evidence it is not easy to assign this sand/shale interbedded facies to a specific depositional environment. However, some observations suggest that this facies was deposited in a deep-marine depositional environment. It is the considerable abundance of turbiditic incursions and the interbedding with shales and, moreover, the comparison to contemporaneous wells from the area that suggest a deep-marine depositional environment.

8.9 Nauen 1/76

The Nauen 1/76 well reached Carboniferous strata from 4108 m to 4180 m (55.9 m recovered, 42.2 % core recovery). Dip variations from 0° - 50° were noted. Thus, a true thickness of ca. 85 m is suggested. No fossils have been recovered, and thus the given age (Namurian A) is based purely on lithostratigraphic correlation with other research wells from the area (Lindert et al. 1979).

The succession is characterised by a rhythmic sand/mud interbedding of fine to medium-grained sandstones and mudstones. A sand/mud ratio of 3:2 was noted from the preserved material. Therefore, the succession is described as a **sandstone/shale interbedded facies (Sf-m,h-p-r/M,h-p)**. The sedimentary facies of the Nauen 1/76 well is very similar to the above described Flatow 6/75 well. The normally-graded sandstone beds are predominantly fine to medium-grained, massive, parallel laminated or ripple bedded. The fine/medium-grained sand ratio is 1:1. The sandstone beds are mostly 0.1 - 0.4 m thick. Some stacked beds were observed and they attain thicknesses of up to 5 m. These sequential developed sandstones pass over to 5 - 30 cm (in average) thick shales. An exemplary sample is depicted in Fig. 8.4.

Some shale beds of up to 11 m were observed. The shales are characterised by massive to parallel- and wavy parallel lamination. Frequent intercalations of event-beds (silty fine-grained sand) were noted. These event-beds are 1 mm to 10 mm thick and may appear massive or parallel bedded and correspond to dilute, fine-grained turbidites. Load casts are common features along bed sand/shale interfaces. Pyrite concretions and dispersed pyrite were not noted due to a secondary oxidation of the sediment from which an intense red colouring results. Primary precipitated pyrite was altered to haematite (Lindert et al. 1979). The shales may characterise the background sedimentation while the sandstones correspond to deposits form turbidity currents that were assigned to the medium-grained turbidite facies (*c.f.* Stow et al. 1996). In comparison to the other wells from the area (especially the Flatow 1/75 well) these sediments may appear to be deposited in a deep-marine environment.

8.10 Brandenburg 1/68

The Brandenburg 1/68 well records Carboniferous strata from 3466.7 m to 3503.0 m (22.6 m of 36.3 m recovered, *i.e.* 62.3 % core-recovery). Dip variations from 50° - 100° were noted. These data are rather imprecise due to weak and mostly massive bedding. However, a true thickness of ca. 15 m is suggested. Due to the absence of fossils, the given upper Viséan (Asbian) age is purely based on lithostratigraphic

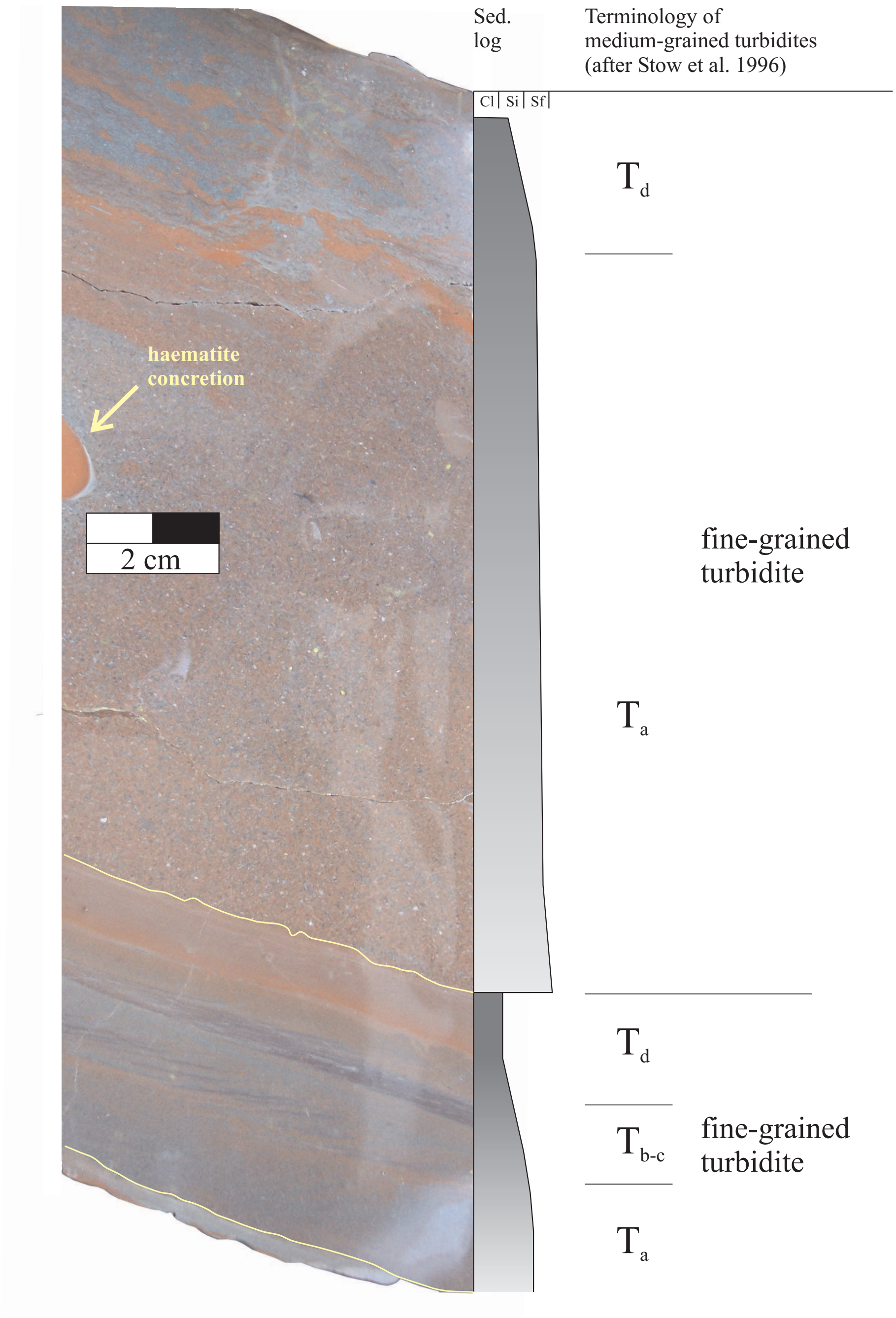

Figure 8.4: Nauen 1/76: Core barrel from 4163.9 - 4169.4. The sample was taken 3.03 m from the top of the core barrel. This sample shows two relatively thin, fine-grained turbidites. Note the haematite concretion which is interpreted to be a secondary altering of primary precipitated pyrite (Lindert et al. 1979).

correlation with the Gommern 1 research well as the lowermost core barrel of the Brandenburg 1/68 well comprises quarzites which may be correlated with the Gommern Quarzite (Jaeger, 1999). Franke and Budzinski (1970) also suggested an upper Viséan age.

The succession comprises a monotone succession of fine to medium-grained, massive and subordinately normally-graded sandstones, *i.e.* **sandstone facies (Sf-c(M),h-p)**. A coarse-grained fraction was also noted and a considerable amount of mudstone is accumulated in the sandstones matrix. Therefore, the sandstones can be described as weakly sorted. The transition between sandstone beds may be gradational and sharp. The normally-graded beds are characterised by a decrease of the medium-grained fraction in fine-grained sandstones. The individual sandstone beds are 0.2 - 6 m thick.

Mudstone beds were rarely noted and are confined to cm-thick intercalations. The interpretation of this monotone succession is rather difficult. Based on the evidence from other wells from the area a deep-marine depositional environment is discussed. According to Stow et al. (1996) thick (> 4 m), structureless beds of sand are quite common in deep-water successions and their interpretation can be problematic. Stow et al. (1994, in Stow et al. 1996)) - on the basis of an extensive worldwide study - concluded that massive sands were most commonly deposited by: (i) freezing of sandy debris flows; (ii) collapse fallout from; or (iii) continuous aggradation beneath a high-density turbidity current with sediment passing through an active basal layer of hindered settling involving grain-flow, fluidized-flow and liquefied flow processes.

8.11 Dreileben 3/70

The Carboniferous extends from 911.6 - to 980.5 m depth. Approximately 34 m of these 68.9 m were cored and ca. 49 % recovered. This well comprises an uppermost Viséan succession. The age assignment is based on a full marine fauna that was assigned to the *Goniatites granosus* (cuIIIγ) Zone of the German Goniatite Zonation. This is, according to the international chronostratigraphy, the Brigantian period (Meissner and Weyer, 1973). This succession was - except for the section from 959.3-971.2 m - continuously cored. Dip variations from 10° - > 90° were noted. Thus, a true thickness of ca. 50 m is suggested. According to the two continuously cored sections, the preserved material can be divided into two parts.

The upper part extends from 911.6 - 959.6 m and is characterised by shales that are frequently intercalated with event-beds, *i.e.* thin silt laminae (1 - 2 mm) and some thick sandy siltstone beds (10 - 20 mm) were noted. The sandy siltstones are characterised by normally-graded bedding and subordinately ripple bedding. The gradational transition to the hemipelagite background sedimentation is common. Load casts commonly mark the erosive bases. These beds were assigned to the fine-grained turbidite facies and may represent T_{3-7} mud-turbidites. The thin lamination may result from the settling of dispersed suspended material. It may contrast the darker, more clay-pronounced background sedimentation. The depositional site was dominated by hemipelagite background sedimentation while the sandy siltstone beds may correspond to dilute, fine-grained turbidites. Pyrite concretions and dispersed pyrite were not noted due to a secondary oxidation of the sediment from which an intense red colouring results. Thus, primary precipitated pyrite may be altered to haematite.

The lower part (971.2 - 980.5 m) very much resembles the Brandenburg 1/68 well. Fine- to coarse- grained, poorly sorted, massive sandstones are stacked together; contacts may be sharp or gradational. Some beds may contain considerable amounts of fine-grained gravel (see photo 17). Seven very thin (1 - 11 mm) intercalations of mud were noted. According to the Brandenburg 1/68 well these sandstones are discussed as deep-marine deposits.

8.12 Eilsleben 8/76

The Eilsleben 8/76 well reached Carboniferous strata from 1333.8 - 1373.7 m (30 m recovered, *i.e.* 75.2 % core recovery). Dip variations from 0° - 30° were noted. Thus, a true thickness of ca. 25 m is suggested. No fossils have been recovered, and thus the given Brigantian age is based purely on lithostratigraphic correlation with the core Dreileben 3/70 (Meissner and Weyer, 1973). The core description of the core material was somehow difficult as most of the core material was not cut into halves. Furthermore, a strong reddish-purple colouring of the rocks and abundant joint systems disguise the primary sedimentary structures. The reddish-purple colour is not a primary one. This secondary colouring results from the Prepremian surface and may include the decomposition of calcareous substances and the oxidation of ferrous material with subsequent formation of hematite (Meissner and Weyer, 1973).

In comparison to the research well further to the east, the succession is characterised by a rhythmic sand/mud interbedding of fine to medium-grained sandstones and shales. A sand/mud ratio of 4:1 was noted from the preserved material. Therefore, the succession is described as a **sandstone/shale interbedded facies (Sf-m/M,h-p)**. The sandstone beds (massive and parallel laminated) are in average 0.1 - 0.5 m thick and show all characteristics of medium-grained turbidite beds as normally-graded bedding and an erosive base that is characterised by common load casts (see photo 16). These sandstones pass over to 5 - 30 cm (in average) thick shales that mark the Bouma T_{d-e} interval and the transition to the background sedimentation. But also two shale beds with 4 m and 3.5 m thickness were observed which may characterise relatively longer periods that were not influenced by gravity flows. Some stacked beds were observed that attain thicknesses of up to 5 m.

The shales are characterised by a massive or parallel- to wavy parallel lamination. Frequent event-beds (silty, fine-grained sands) were noted. These beds are 1 mm to 10 mm thick and may appear massive or parallel bedded. Pyrite precipitation was not noted due to a secondary oxidation of the sediment resulting in an intense red colouring. Thus, primary precipitated pyrite may be altered to haematite. The shales may be hemipelagites while the sandstones correspond to deposits from turbidity currents. The observed features of this facies may correspond to a deep-marine environment although such deposits may also occur in outer shelf areas. The assignment to a deep-marine environment is based on the correlation with the other research wells from the area.

8.13 Flechtingen Block

The database for the description and interpretation of Carboniferous age sediments in the Flechtingen Block is based on several outcrops. They comprise Namurian A-B deposits and discordantly overlying Stephanian C sediments (Paech, 1973a; Paech 1973c). Paech (1973b) described some outcrops near Gommern (east of Magdeburg) and the research well Gommern 1 which are no longer accessible. The so-called Gommern-Quartzite was described and discussed using this data (Paech, 1973b; Jaeger, 1999) The outcrops of the region and the Gommern 1 research well were not documented and interpreted in this study but information from the literature concerning lithofacies and environmental interpretation were involved into the overall picture of the foreland basin successions.

8.13.1 Viséan Gommern Quartzite

The "Gommern Quartzite", a local name for the lower to middle Viséan quartzose sandstone-series of this area was classified to the Kammquartzite-Formation of the Hörre-Gommern Zone (Jaeger, 1999). Since the work of Württenberger (1865), isolated quartzites from the Harz Mountains and the eastern part of the Rhenish massif were correlated and combined to the so-called Hörre-Gommern Zone which is a structural complex over 400 km long but only some kilometres wide (Jaeger, 1999).

Jaeger (1999) critically reassessed all available data (literature, outcrops and well data) and introduced the Kammquartzite-Formation as the quartzose sandstone-series of the Hörre-Gommern Zone. He provided a revised biostratigraphy and a sedimentological model for the Kammquartzite-Formation. For the first time, the quartzites of the Flechtingen Block were dated by biostratigraphic means (Palynology). Generally, the Kammquartzite-Formation is limited to the Viséan. The highest documented stratigraphic level is the ME-spore zone of the upper Viséan. The base is assigned to the PU-spore zone. This encompasses the V1–V3b period (see Fig. 2.7) and the cdIIγ – cdIIIα/β of the German Goniatite Zonation (Jaeger, 1999). The Kammquartzite-Formation of the Flechtingen Block was described from four outcrops south of the city of Gommern (Paech 1973b, Jaeger, 1999) and the research well Gommern 1 (Paech, 1973b; Hoth, 1997; Jaeger, 1999).

Paech (1973b) and Jaeger (1999) described a rhythmic sand/mud interbedding of fine to medium-grained sandstones (quartzites) and shales. The quartzites (well sorted quartzarenites and subordinately quartzwackes) attain thicknesses from 0.5 - 3 m and show grey to dark-grey colours. The beds are separated by mm- to cm thick shales or stacked together. These stacks attain thicknesses of up to 10 meters. A sequential development of the quartzite beds is common. A complete sequence begins with a well sorted quartzarenite. A quartzite with increasing matrix content (quartzwackes) and decreasing grain sizes follows to the top of the sequence. Subsequently, the sequence evolves over a muddy siltstone to a mudstone. This sequence is rarely developed completely, as this ideal sequence is commonly intermittent and only partially preserved. Most of the sequences comprise quartzarenites that pass into quartzwackes. Massive bedding dominates the quartzites. Subordinately, some beds contain faint traces of even-parallel lamination and small-dimensional cross-stratification that is mostly observed at the bottom of a sandstone bed. These laminated beds may also contain fine grained gravels. Frequency grading, *i.e.* a continuous increase of smaller grain sizes (matrix and mud) from the bed bottom to the top is common within the sandstones but graded bedding was also rarely observed. The sandstones are characterised by an erosional contact with the underlying beds. This erosional surface is often associated with load casts. Another observed feature within the sandstones are water-escape structures such as dish structures besides pillar structures and liquefied intrusions. Erosional sole marks, *i.e.* groove casts, flute marks and scour marks, are rare and occur at the undersurface of these sandstone beds. Moreover, mudstone rip-up clasts were observed. The size of these clast ranges from a few millimetres up to 2 meters. The weakly sorted sandstones (quartzwackes) - that contain up to 50 % of silt and clay - attain thicknesses of 10 - 100 cm within a distinct sandstone bed. A gradational upper contact with muddy siltstones and mudstones is common. In some places the mudstones of the Quartzite-facies are disturbed by intrastratal folding and synsedimentary faults, *i.e.* convolute bedding.

According to Jaeger (1999) several characteristics of the quartzites may point to deposition from turbidity currents.

- Frequency grading is a clear evidence of deposition from turbulent suspensions. Gravitational induced sedimentation takes place after the freezing of the turbidity current (*i.e.* cessation of auto suspension).
- A sequential development of beds that are characterised by an erosional surface may indicate the sedimentation of distinct events.
- Erosional sole marks are characteristic sedimentary features within turbidites.
- Load casts, water-escape structures and convolute bedding point to the synsedimentary high water content that is typical for turbidity currents.
- Lack of clear shallow water features such as ripple bedding and characteristic bioturbation.

The massive rocks and the associated sedimentary features of these quartzites may have developed from high-density turbidity currents (Jaeger, 1999). Massive sand that is in parts laminated (*i.e.* traction carpets) is indicative of high-density turbidity currents. Traction carpets are produced under shear stress within an active turbidity current and are commonly interbedded with massive sandstones (Potsma et al. 1988; Kneller & Branney, 1995). These traction carpets may also contain increased amounts of gravel. Water-escape structures in the lower part of a sequence are also features of high-density turbidity currents with varying sediment supply (*e.g.* Kneller & Branney, 1995).

The shales are dark grey and predominantly massive or even laminated. Slumping features are common in distinct beds.

8.13.2 Flechtingen Block; Namurian A

The Namurian succession of the Fletching area was studied in more than 140 outcrops which can be tracked on the length of 35 km between Magdeburg and the city of Flechtingen. The sedimentological interpretation was adopted from Paech (1973a). Several marine fauna prove the Namurian A age of the succession (Weyer, 1975; Weyer and Meissner, 1972) and some ichnofossils provide valuable palaeoecological evidence (Seilacher, 1958; Pfeiffer, 1967; both in Paech, 1973a). These ichnofossils point to non-photic conditions which are characteristic for deep-marine environments.

These extensive information that was provided by the study of these outcrops can be well compared to the interpretation of core material from this study. According to the cored material, the outcrops reveal a deep-marine depositional environment that was strongly influenced by gravity flows resulting in a rhythmic sand/mud interbedding of sandstones- and shales (Paech, 1973a). The shales may be hemipelagite deposits while the sandstones mostly correspond to a medium-grained turbidite facies. Some gravel beds exclusively mark the base of some coarse-grained turbidite sequences and may correspond to the R_{2-3}-interval of coarse-grained turbidite (*c.f.* Lowe, 1982). Furthermore, some imbricated lags were noted that might correspond to deposits from traction carpets (*i.e.* R_1-interval) while the matrix supported conglomerates were deposited from suspension and correspond to the R_{R2}-interval. Sandstones, which are normally-graded, poorly sorted and contain considerable amounts of mud, may form the T_{a-c}-interval of the medium-grained turbidite facies, while mudstones T_{d-e} mark the transition to the background sedimentation. The thickness of turbidite sequences may vary from cm- to m-scale. Paech (1973a) reported a relation between grain size and sequence-thickness; thicker beds tend to contain bigger grain sizes. In addition, further features were noted that point to the deposition from turbidity currents. For example, sole marks were noted on the bottom side of the sequence bases. Groove casts, flute casts and prod marks reveal the direction of the gravity flows which is mostly E-W and subordinately N-S. Moreover, plat debris was accumulated in the T_{b-c} interval and parallels the sole marks. The T_{d-e}-interval may be characterised by post depositional slumping features and convolute bedding.

8.13.3 Flechtingen Block; Stephanian A-C, Süpling Formation

Paech (1970) introduced the Süpling Formation on the basis of a new age assignment that revealed a Stephanian A-C age. The mega flora and spores of this formation were prior assigned to the Namurian but Kahlert (1973) revised the Süpling Formation and provided a Stephanian age. The Süpling Formation discordantly overlies the Namurian deep-marine sediments of the foredeep sedimentation.

The work of Paech (1973a) was used in this study as he contributed some details on the sedimentary facies and depositional environment. His work is based on several outcrops and research wells from the Fletchingen Block. The succession can be characterised as a rhythmic intercalation of conglomerates, sandstones and mudstones. The carbonate content varies from 0 - 100 %; a limestone was likewise recorded in the Süpling formation of the Peckensen 7/70 well. Limestone deposition seems to be characteristic for this period. Carbonate was observed as dispersed grains in the sandstone matrix, Calcareous concretions (Calcite, Dolomite) and limestones. The prevailing colour of the sediment is greenish-grey, red colours appear subordinately. The colouring suggests mostly reducing chemical conditions during deposition. Some well laminated mudstones which bear the megaflora were also noted. Current-generated sedimentary structures are common. Conglomeratic beds often form erosive bases which are followed by a gradational transition to sandstones. Some indications of a beginning soilification also contribute to the environmental interpretation. Bioturbation is common in sediments that were classified as low-energy deposits. Moreover, low-energy conditions are characterised by circular and concentric impressions that were observed on the undersurface of mudstones. These circular marks are associated with other subaqueaceous features and therefore interpreted as traces of gas-bubbles that escaped from the sediment; this would imply a shallow water cover. But also sub aerial deposits were noted; imbricated gravels in a sand/gravel interbedded facies were interpreted as alluvial fan deposits. Paech (1973a) suggests a short route of transport from the sediments source to the depositional site due to the mostly weak rounded clasts of this formation. An analysis of heavy minerals suggested that the Namurian A deep-marine sediments were the source of the Süpling Formation.

In general, the megaflora association and the studied spores provide some palaeoecological evidence that suggests a continental influenced depositional environment, *i.e.* alluvial depositional environment. Paech (1973a) suggests that the sediments of the Süpling formation may be characterised as alluvial fan-/braided river-/floodplain-

/lake deposits. The Süpling Formation may be compared to the Rambin and Mönchgut Formation of the Loissin, Gingst and Pudagla wells. These wells also reveal an alluvial depositional environment with braided-river and alluvial fan deposits. Probably, due to the scarce core-material, no slack-water deposits were noted on the northern basin margin. The mudstones of the Fletching area may correspond to playa deposits with siliclastics and subordinately limestones deposition.

Chapter 9

Basin evolution

Foreland basins and thrust-faulted orogenic belts are genetically linked and, together, constitute the geological record of an orogeny. Foreland basin stratigraphy reflects two main controls: the **first-order control** is the regional subsidence pattern imposed by flexure of the lithospheric plate on which the basin is located. **Second-order controls** influence the character of the strata and include, thrust-belt lithology, adjacent craton lithology, climate and eustatic sea-level controls (Jordan et. al 1988). The evolution of the Carboniferous foreland basin of NE Germany and the development of a characteristic marine-to-continental sedimentary succession, while being predominately controlled by flexure induced by the Variscan Orogen to the south, were strongly influenced by secondary factors.

9.1 Tectono-sedimentary model

9.1.1 Introduction

In this study, the evolution of the NE German Variscan foreland basin (VFB) was reconstructed by incorporating both the first and second order controlling factors into a tectono-sedimentary model. All of the available information on these controls was applied to this conceptual model. Therefore, the phases of deposition, non-deposition, erosion and uplift were interpreted from the reconstruction of the depositional environment, the distribution of the stratigraphic units and the presence of regional and local unconformities. Regional unconformities reveal periods of non-deposition and can, therefore, be interpreted as reflecting regional uplift and/or eustatic sea-level changes. In order to illustrate the influence of tectonics on the sedimentary record and to distinguish between the first-order controls (*e.g.* regional subsidence) and second order control (*i.e.* eustatic sea-level changes), a comparison with a published eustatic sea-level curve was made (see Fig. 9.1). Ross and Ross (1987) described changing depositional sequences for the shallow-marine successions on the stable cratonic shelves of NW Europe and used the presence of sequences as an approximation to eustatic sea-level changes. If the sedimentary succession contains transgression-regression patterns other than those on the eustatic sea-level curve (Ross and Ross, 1987), then other factors - such as the regional subsidence of the foreland basin - may have been responsible for the observed variations. Moreover, local unconformities were linked to localised tectonic activity and pronounced igneous activity is also interpreted as being indicative of tectonic activity. In addition, the evolution of this particular Variscan foreland basin was compared to other Variscan foreland basins of the Mid-European Variscides.

9.1.2 Modelling considerations

The tectono-sedimentary reconstruction of the NE German VFB is based on the variations in both depositional environments and basin events in time and space. The reconstructions presented in this study (*i.e.* the tectono-sedimentary model) are illustrated by a series of nine cartoons which correspond to nine time-slices that demonstrate the evolution of the basin (Fig. 9.3 - 9.12). These cartoons are simplified according to the following assumptions. (i) The form and extent of the Northern Phyllite Zone and the Mid German Crystalline High (see Fig. 9.2a) are taken as an approximation for the Variscan Orogenic Front (VOF) since the NPZ is a zone of Variscan deformed metamorphic rocks that marks the leading edge of Armorica which represents the plate boundary between the upper Armorican- and the lower Avalonian plate (Oncken et al. 2000). (ii) The rate and timing of subsidence of a single point on the subsiding foreland plate is a function of the distance to the emplaced load and that is the distance to the VOF. (iii) the direction of movement of Variscan shortening was approximately N-S.

Based on the above, there are the following considerations: In areas with a comparable distance to the VOF one could possibly expect the development of similar amounts of accommodation space and, likewise, comparable distances to the sediment source areas. Similar depositional environments would have possibly prevailed at the same distances to the VOF. As one can see in Fig 9.2b the five wells of Peckensen 7/70, Proettlin 1/81, Eldena 1/74, Parchim 1/68 and Pudagla 1/87 are all located approximately along strike. Based on the facies analysis within this study, it could be demonstrated that these wells were characterised by a comparable environmental development over

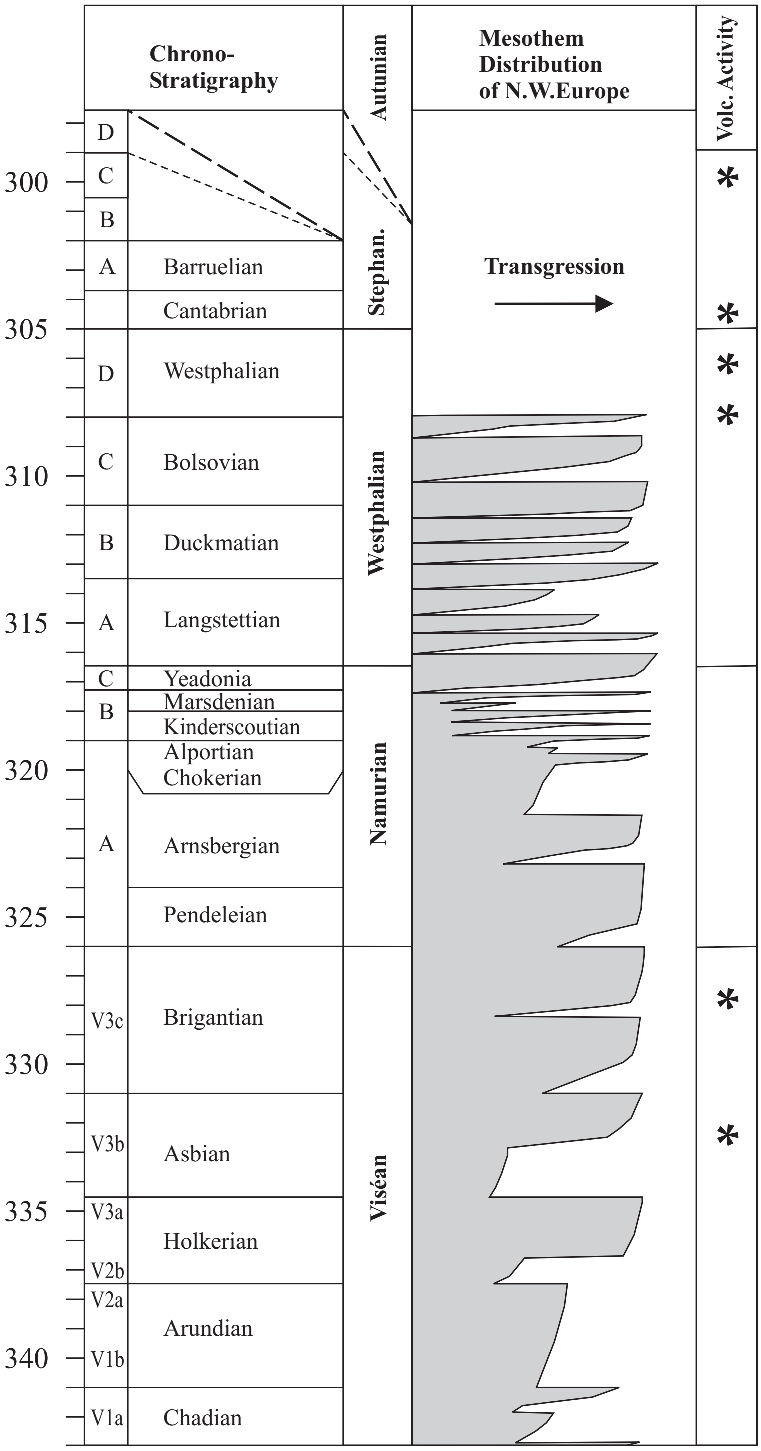

Figure 9.1: The transgressive-regressive depositional sequences of NW Europe - an approximation to eustatic sea-level changes (Ross and Ross, 1987). Chronology after Menning et al. 1999.

time. Thus, the next step in order to depict the geometry of the basin was the following geometric reconstruction which can be followed in Fig. 9.2a-b. Since there was a N-S directed plate movement in Variscan times, a distance function results for the measuring point (*i.e.* well position) to the arcuate line (*i.e.* the VOF). This arcuate line was then simplified into a straight line with an E-W-orientated strike that would subsequently serve as a simplified approximation to the VOF. Therefore, the distance function could be balanced by a standardisation onto this E-W axis in order to depict the relative well position along an E-W strike. This was performed for all of the wells in order to depict their

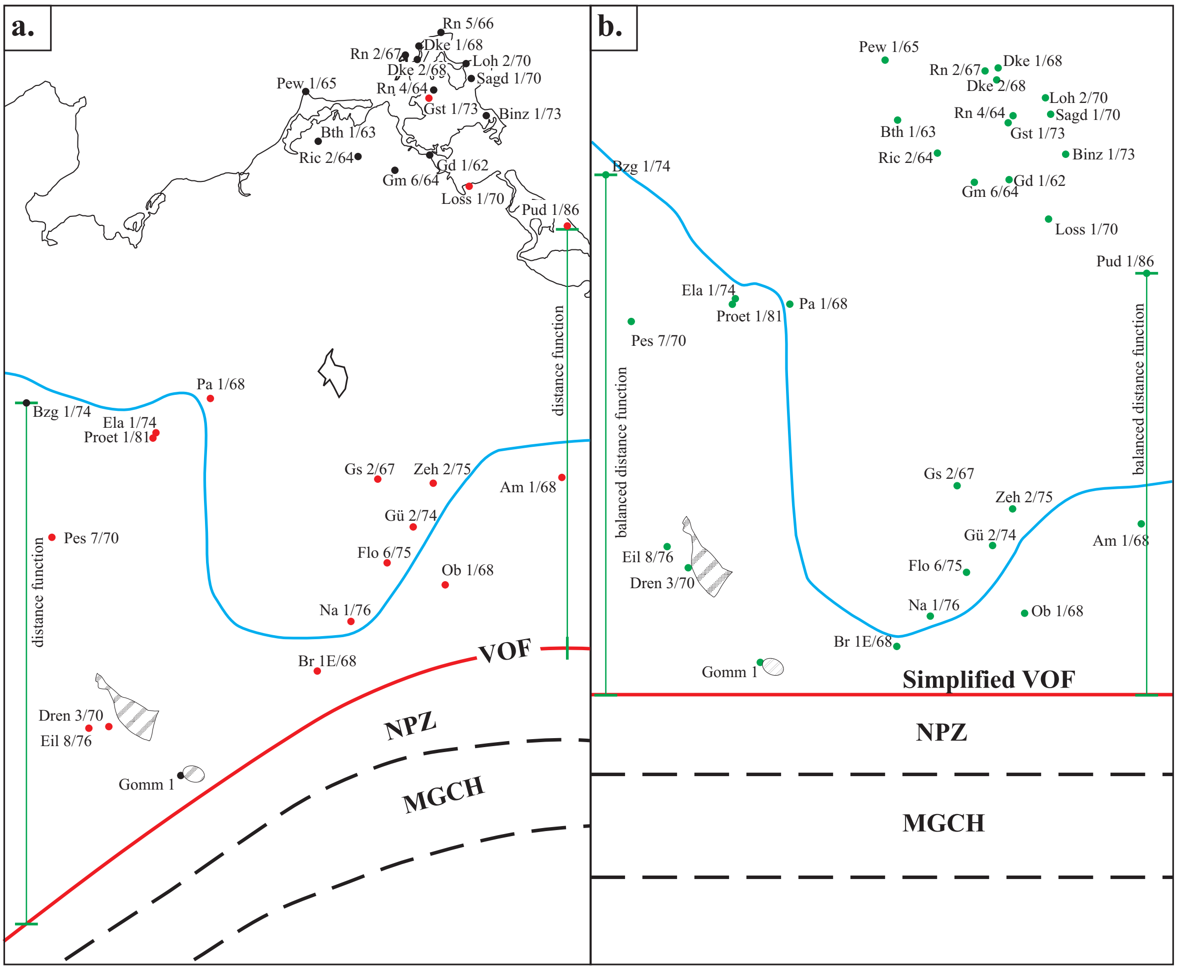

Figure 9.2: Geometric simplification of the foreland basin's geometry. For well abbreviations compare Tab. 2.2.
a.) Present situation: The well positions are marked by red and black dots. The hatched area corresponds to the outcrops of the Flechtingen Block. The blue line marks the extent of carbonate platform sedimentation to the south. The red line serves as an approximation for the VOF. The VOF forms an arcuate line from which a distance function results for every measuring point. Two examples were displayed; Bzg 1/74 and Pud 1/86, the corresponding distance functions are marked by the green straight line.
b.) Geometrical simplification: The calculated well positions are marked by green circles. The simplified VOF is a straight E-W axis on which the distance functions were balanced by a standardisation in order to depict the relative well positions in E-W strike. These balanced distance functions were exemplarily depicted for the wells Bzg 1/74 and Pud 1/86 by the green straight lines. The blue line marks the calculated extent of the carbonate platform sedimentation.

relative distances to each other and to the simplified approximation of the VOF. The resulting simplification facilitates a better graphical demonstration of the tectono-sedimentary reconstruction. While this reconstruction goes some way to facilitate a more unified palaeoenvironmental interpretation for the Carboniferous of the NE German VFB, it does presume that subduction to related orogenic activity was relatively simple. However, some care needs to be taken in the interpretation since this reordering of well location does not account for tectonic complexity in association with possible strike-slip movements along the VOF.

9.2 Correlation between Tectonics and Sedimentation

The following sections present the tectono-sedimentary reconstruction of the NE German VFB. In this study, the evolution of the basin was subdivided into nine time-slices which correspond to the series and stages of the western European Carboniferous time scale, *i.e.* Viséan (Asbian) to Stephanian.

9.2.1 Viséan

By Early Viséan times, carbonate platform deposition was established across the passive northern margin of the study area. This area of carbonate sedimentation was part of an extensive carbonate platform, which stretched in a broad band across Europe from Ireland to Poland (*c.f.* Ziegler, 1990).

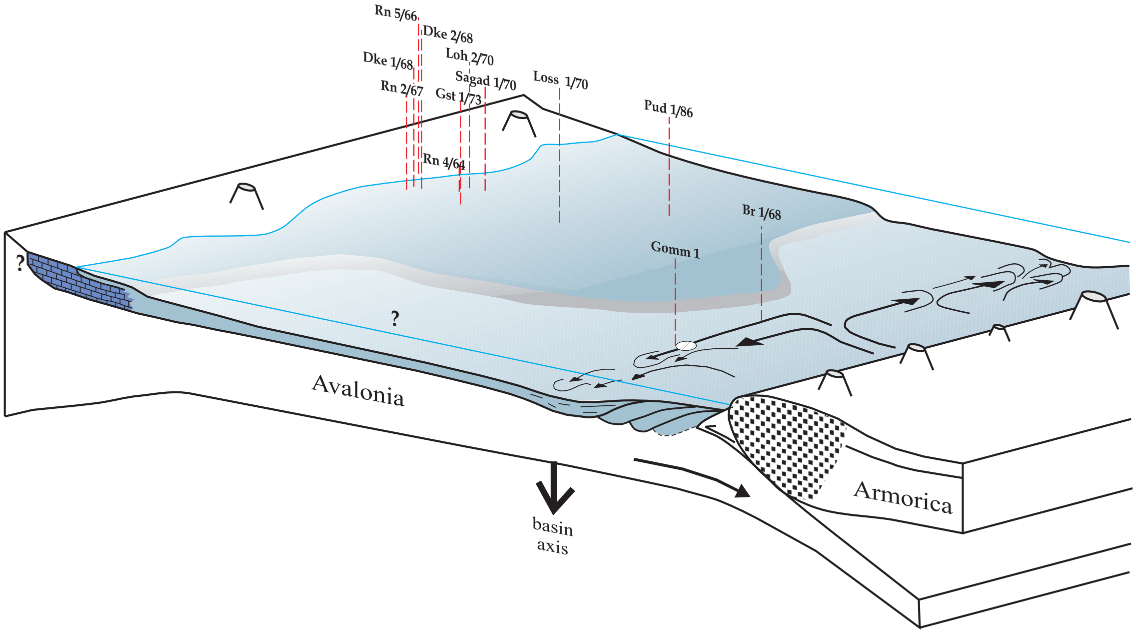

Figure 9.3: Cartoon of the tectono-sedimentary reconstruction for the Asbian. Information on the spatial extent of the autochthonous carbonate platform sedimentation (*i.e.* Kohlenkalk) on the northern passive continental margin was derived from Hoffmann et al. (2001) and Hoffmann (2004, personal communication). The white dot corresponds to the outcrops near Gommern. Tectonic information on the Variscan orogenic front after Oncken (1997). The thickness of Carboniferous strata is not to scale. For well abbreviations compare Tab. 2.2.

The early Viséan sediments in the study area are predominately carbonates (bio-, intraclastics). In the study area, the Middle Viséan is largely missing. This Middle Viséan unconformity together with the presence of an intra-early Viséan angular unconformity and some late Tournaisian tuffaceous intercalations has been interpreted as evidence of localised tectonic activity (Hoffmann et al. 1975; Schmidt and Franke, 1975).

Asbian

From Asbian times onward (Fig. 9.3) a change from carbonate- to clastic sedimentation was noted on the northern basin margin where the development of clastic units, comprising shallow clastic sea deposits, was noted. Clastic units of up to 200 m thickness were observed in the Loissin 1/70 well. Moreover, tectonic activity on the northern basin margin is indicated by local faulting. This tectonic activity is contemporaneous with volcanic activity of alkaline and intermediary character. These observations are interpreted as being indicative of the initiation of the break-up of the carbonate platform. This break-up may have been related to coeval crustal flexure related to the onset of the final phase of the Variscan orogenic cycle.

The approximate spatial extent of the carbonate platform has been deduced from magnetotelluric measurements of Hoffmann et al. (2001). Based on this work, it is possible that there was some kind of shelf break between the northern margin (*i.e.* shelf depositional environment) which overlies the carbonate platform and the foredeep to the south. Crustal flexure - due to the increase in loading related to the Variscan shortening - led to deepening of the area of former platform sedimentation and the foredeep to the south. In comparison to the Harz and Rhenish Massif areas the southerly-situated foredeep of the NE German area has been assigned to the deep-marine Culm-facies (Jaeger 1999, Hoffmann et al. 2001). Therefore, the area south of the carbonate platform - *i.e.* located between the northern shelf and the VOF - is herein interpreted as representing the foredeep of the NE German VFB.

There is a lack of data from the postulated foredeep area of the NE German VFB. Evidence form two wells (Gommern 1, Brandenburg 1/68) and some outcrops suggest that the depositional environment was deep-marine with typical turbidites and a background hemipelagite shale- to black shale sedimentation (see Chapter 8). The distribution pattern of these turbidite flows in the study area (see Fig. 9.3) could not be deduced from these two wells, but a comparison to the area further to the west was made. There, Ricken et al. (2000) described the foredeep-sedimentation pattern of Viséan gravity flows in the Harz and the Rhenish Massif areas. The sediment source for these two areas was identified as being the VOF to the south and the resultant sedimentation took place in sub-basins which developed parallel to the prograding VOF. Thus, the distribution pattern of the turbidites parallels the trend of the VOF. Moreover, progradation of these sub-basins was recorded which suggests that the VOF prograded during this

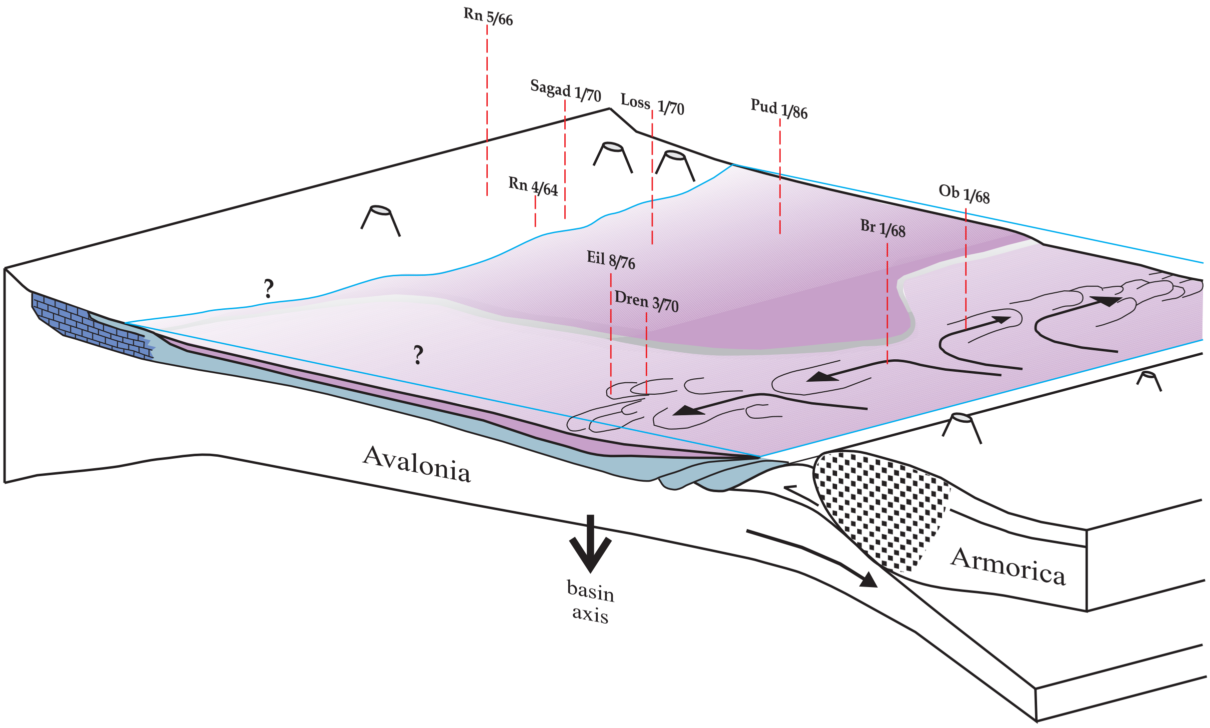

Figure 9.4: Cartoon of the tectono-sedimentary reconstruction for the Brigantian. Information on the spatial extent of the autochthonous carbonate platform sedimentation (*i.e.* Kohlenkalk) on the northern passive continental margin was derived from Hoffmann et al. (2001) and Hoffmann (2004, personal communication). Tectonic information on the Variscan orogenic front after Oncken (1997). The thickness of Carboniferous strata is not to scale. For well abbreviations compare Tab. 2.2.

particular period of basin development. According to Ricken et al. (2000), a similar situation is presumed for the eastern extension *i.e.* within the NE German VFB.

Brigantian

The Brigantian period is characterised by a regressive sea-level trend on the northern basin margin since only the two southernmost wells contain Brigantian sediments (see Fig. 9.4). Sediments from these wells record an increase in grain size in comparison with the underlying Asbian and this is interpreted as evidence of an overall regressive sea-level. A shallow-marine depositional environment is interpreted from the Loissin 1/70 and Pudagla 1/86 wells. The identified subenvironments range from distal shelf to foreshore. The succession from the Pudagla 1/86 well was partly sourced from volcanic activity since the Brigantian sediments are characterised by abundant tuffaceous intercalations and volcanic clasts. Moreover, the Brigantian sediment series is framed by underlying and overlying volcanic units. The volcanic activities along the northern margin may have also increased over time since there is an increase of tuffaceous intercalations and basaltic sills within the succession.

In the southern part of the NE German VFB turbidite sedimentation continued to dominate the succession within the foredeep. The sediments from four wells document this basinal stage: Oranienburg 1/68, Brandenburg 1/68, Eilsleben 8/76 and Dreileben 3/70. The successions were strongly influenced by turbidite sedimentation and the following turbidite facies were recognised in these wells, including:

- coarse-grained turbidites (*c.f.* Stow et al. 1996) in the Brandenburg 1/68 well; only some very thin shale intercalations were also noted.
- medium and fine-grained turbidites (*c.f.* Lowe, 1992) in the Oranienburg 1/68 well.
- fine-grained turbidites (*c.f.* Stow et al. 1996) in the Eilsleben 8/76 and Dreileben 3/70 wells. Most of the succession here comprises hemipelagite shales. This high shale/turbidite ratio may be representative of more distal parts of the basin.

9.2.2 Viséan carbonate platform to clastic transition

The Asbian clastics unconformably overlie the carbonate platform sediments on the northern margin of the studied area. This transition from carbonate platform to clastic sedimentation took place earlier in the studied area than in other Variscan foreland basins. For example, on the northern margin of the Cornwall-, French-, and Rhenish basins to the west of the NE German VFB (see Fig. 1.1), carbonate platform sedimentation prevailed throughout the Viséan with a change of depositional style

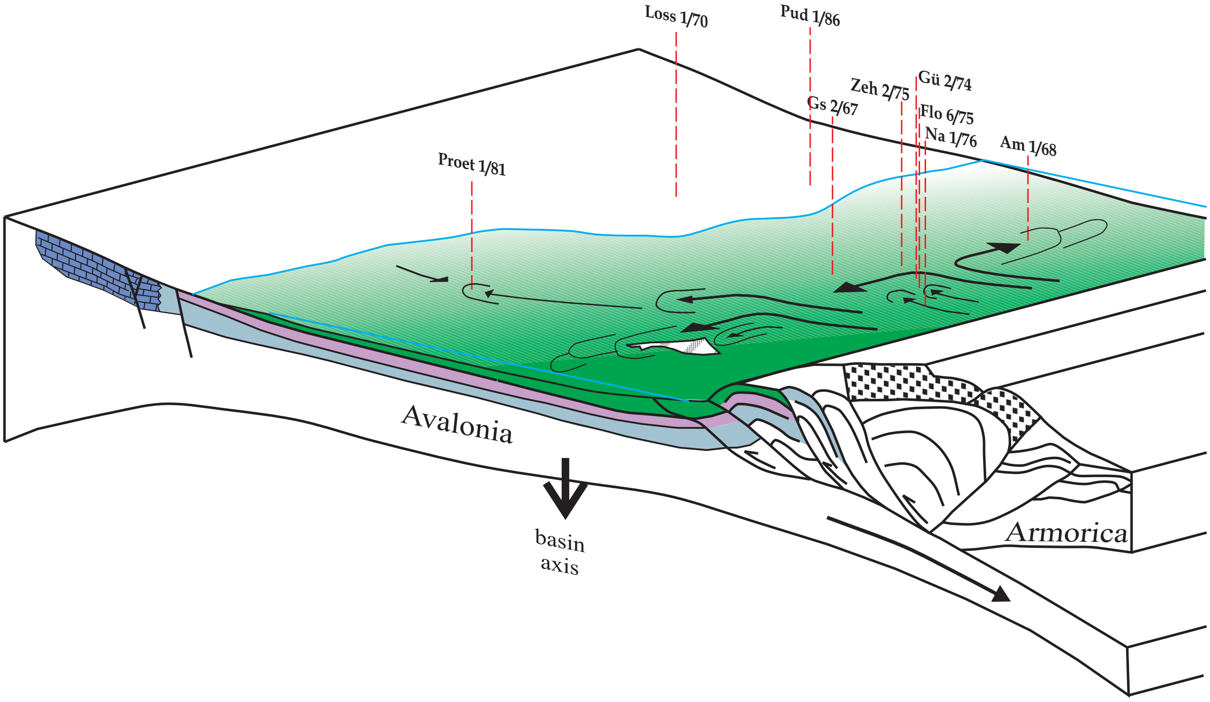

Figure 9.5: Cartoon of the tectono-sedimentary reconstruction for the Namurian A. The hatched area corresponds to the outcrops of the Flechtingen Block. Tectonic information on the Variscan orogenic front after Oncken (1997). The thickness of Carboniferous strata is not to scale. For the well abbreviations compare Tab. 2.2.

at the Viséan/Namurian boundary (Gayer et al. 1993). Therefore, in the NE German VFB, the carbonate to clastic transition occurs ca. 8-6 Ma earlier than recorded in the foreland basins to the west and may be comparable to the Czech Culm Basin which is part of the Upper Silesian Basin that is located further to the south-east (see Fig. 1.1). Here, the transition from shallow-marine carbonate platform to clastic sedimentation took place even earlier, *i.e.* at the beginning of the Viséan. This is approximately 10-15 Ma prior to the Variscan foreland basins to the west, *i.e.* Cornwall-, French-, and Rhenish Basin. The Czech Culm Basin forms the most southerly extension of the Rheno-Hercynian zone in Europe (Fig. 1.1). Therefore, it has been suggested that it was the first area to be affected by the impact of the northwardly-propagating Variscan Orogen (Hartley and Otava, 2001). Subsequently, the studied area was influenced by Variscan shortening while - in the area to the west- the effects of Variscan shortening were felt considerably later. This lack of contemporaneity in the carbonate-clastic transition suggests that the onset of Variscan shortening was not coeval but instead moved from east to west.

9.2.3 Namurian

The Viséan-Namurian boundary coincides with a temporary eustatic sea-level lowstand that is marked by a regional, partly erosional unconformity on the northern margin of the NE German foreland basin (Fig. 9.5). This hiatus encompasses the lowermost Namurian A (Pendleian) to the Upper Namurian A (Chokerian). A Viséan-Namurian hiatus is also recognised on the northern shelves of the French- and Rhenish basin and on the eastern shelves of the Lower and Upper Silesian basins.

Namurian A

According to the late Palaeozoic eustatic sea-level curve (Ross and Ross, 1987), two transgressions are noted for the Namurian A period. However, the observed successions from the northern margin of the NE German VFB show a lack of correlation with the eustatic sea-level curve.

Therefore, possible tectonic activity (*i.e.* uplift) in the area is suggested. This presumed uplift is accompanied by extensive faulting of the Viséan carbonate platform sediments of the area. The work of Hoffmann et al. (1975) would appear to correlate this regional Viséan-Namurian unconformity to the uplift of a fault-bounded NE-SE - trending anticlinal horst during late Viséan - early Namurian times and, according to this, seismic data from the Rügen area clearly shows the extent of post-Viséan-age block-faulting along a series of faults extending from the Ordovician into the Carboniferous (Piske et al. 1994). Contemporaneous block faulting in Pomerania (Western Poland), with uplifts of ca. 1000 m, have also been reported (Ziegler, 1990). Namurian-age rocks are absent in the northern Rügen area where there is an angular unconformity (*i.e.* movement) between the Viséan and Westphalian (compare Fig. 9.8).

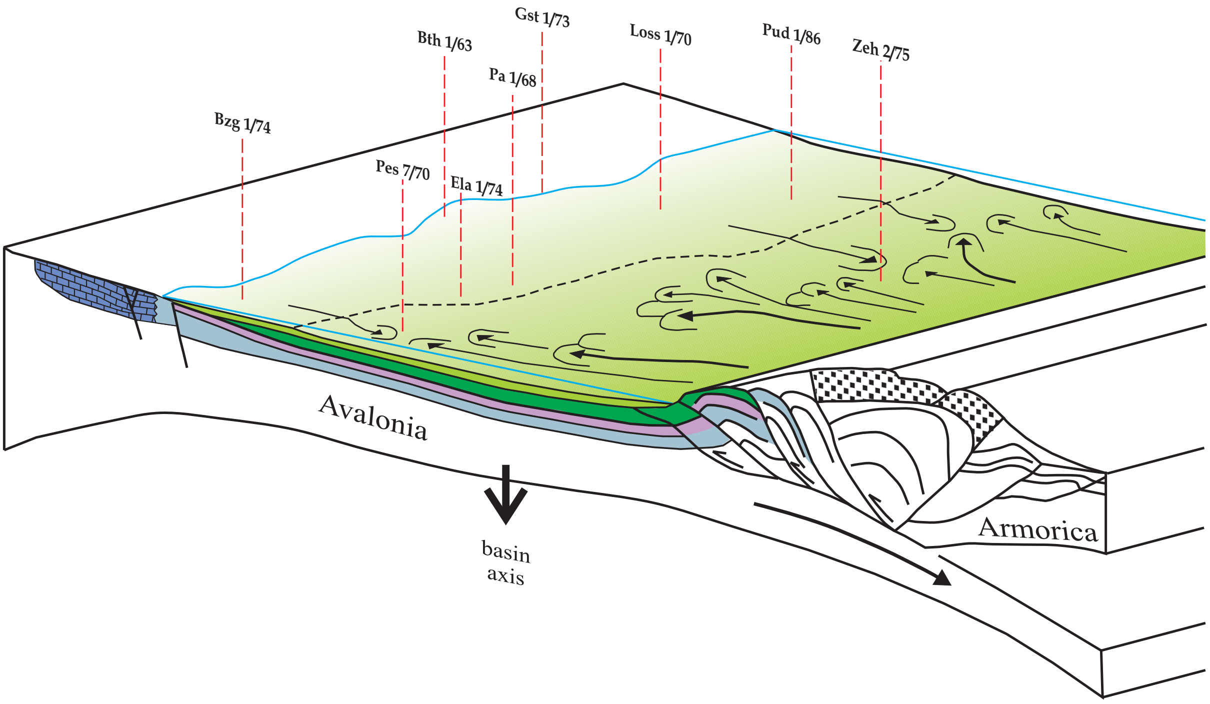

Figure 9.6: Cartoon of the tectono-sedimentary reconstruction for the Namurian B. Tectonic information on the Variscan orogenic front after Oncken (1997). The thickness of Carboniferous strata is not to scale. For well abbreviations compare Tab. 2.2.

A Viséan-Namurian hiatus is not recorded in the southern part of the NE German foreland basin, *i.e.* movement in the Rügen area was localised. During the Namurian A period, the foredeep region was characterised by the development of a deep-marine depositional environment that is comparable to that of the Upper Viséan. The presumed relief of the former carbonate platform to the north relative to the foredeep to the south - which existed prior to Namurian A times - may have been degraded during the Namurian A period by increases in sedimentation and/or erosion which led to the establishment of a more unified area across the region. This may be indicated by evidence from the Namurian A deposits of the Gransee 2/67, Zehdenick 2/75, Grüneberg 2/74, Flatow 6/75 and Nauen 1/76 wells. These wells are all located on the former high area (*i.e.* carbonate platform) but in Namurian A times contain deep-marine sediments.

The outcrops in the area of the Flechtingen Block contain a mainly medium-grained turbidite facies with some erosional sole marks that indicate an E-W-orientated distribution pattern (Paech, 1973a). Such a distribution pattern was already presumed for the upper Viséan turbidites of the area (see Ricken et al. 2000). The Proettlin 1/81 well is located north to the area of the Flechtingen Block. It contains a Namurian A-B succession which is characterised by a black shale facies that is intercalated with some fine-grained turbidites. It is suggested that gravity flows overstepped the external basinal highs of the former prograding sub-basins of the Viséan period and at this time were shedding material into the basin and reached distal positions relative to the VOF. Due to the presumed geometry of the basin (see Fig. 9.5) during the Namurian A period it is presumed that these gravity flows came both from the northern basin margin and the VOF to the south.

9.2.4 Rheno-Hercynian Zone versus Variscan Foreland Zone

The above described observations from the Namurian A in the foredeep region are interpreted as indicating a change in basin style, *i.e.* the change from foredeep sedimentation in prograding, spatial confined sub-basins to a more basinwide distribution. This basinwide distribution resulted in a layer-cake basin infill pattern. This change occurred at the transition from the Rheno-Hercynian Zone to the Variscan Foreland Zone *sensu* Hartley and Otava (2001) who stated that the evolution of the Variscan foreland basins of central Europe can be divided into two main stages. (i) The initial stage comprises the earliest phase of parautochthonous foreland basin sedimentation in the young evolving foredeep and comprises mainly deep-marine sediments of Viséan-Early Namurian age. These sediments characterise the Rheno-Hercynian Zone. (ii) The Variscan Foreland Zone to the north of the Rheno-Hercynian Zone developed during the subsequent molasse stage, which includes sediments of Namurian to Stephanian age (Hartley and Otava, 2001, see Fig. 1.1).

The transition from deep-marine (*i.e.* Rheno-

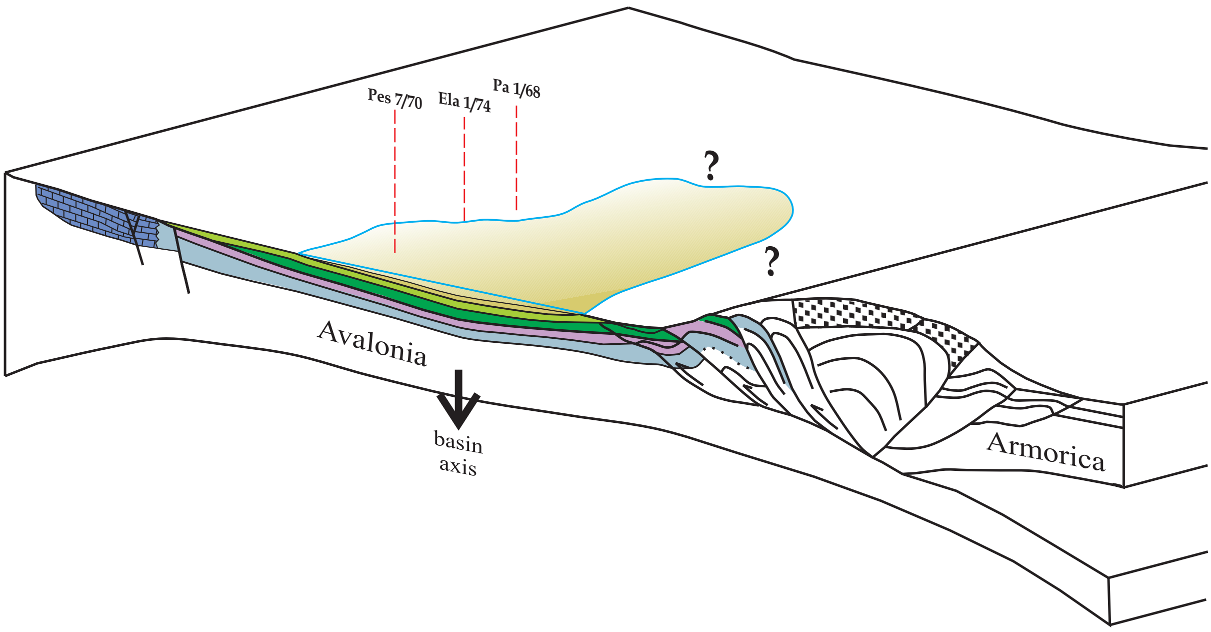

Figure 9.7: Cartoon of the tectono-sedimentary reconstruction for the Namurian C. Tectonic information on the Variscan orogenic front after Oncken (1997). The thickness of the Carboniferous strata is not to scale. For well abbreviations compare Tab. 2.2.

Hercynian Zone) to the shallow-marine and subsequently continental (*i.e.* Variscan foreland zone) sediments characterises the successions of the Variscan foreland basins of Central Europe (*e.g.* Hartley, 1993; Gaitzsch et al. 1998; McCann, 1999; Burgess and Gayer, 2000; Ricken et al. 2000; Hartley and Otava, 2001; Kopp et al. 2002). In the Rhenish Basin to the west of the studied basin, the Rheno-Hercynian- to Variscan Foreland Zone-transition took place during the Namurian A period (Ricken et al. 2000). In the area to the east, such a transition is also recorded from the Czech Culm basin during Lower Namurian times (Hartley and Otava, 2001). This transition is also demonstrated by the successions recorded from the NE German foreland basin, where an increased shallowing of the basin is recorded during the Namurian A when the presumed relief between the former carbonate platform to the north and the foredeep to the south may have been balanced.

A transition from deep-marine over shallow-marine through continental sediments has been observed in many foreland basins around the world. It is described as a change from an, initially, underfilled stage (in an orogen-proximal position) to an overfilled stage (in orogen-distal position). In the underfilled stage, the sediment influx could not overstep the outer basinal highs while in the overfilled stage, the sedimentation outpaces the subsidence (*c.f.* Covey, 1986; Flemings and Jordan, 1989; Miall, 1995; DeCelles and Giles, 1996; Jordan, 1995).

Namurian B

Sedimentation on the northern basin margin recommenced again during the upper Namurian A and continued throughout the Namurian B (Kinderscoutian). The oldest Namurian sediments on the northern basin margin are recorded from the Loissin 1/70 well, where a marine fauna association suggests an Alportian age (Hoth et al. 1975). Comparison with the eustatic sea-level curve shows a pronounced transgression at the beginning of the Alportian. Compared with the Viséan, the eustatic sea-level during the Namurian B is characterised by more frequent sea-level fluctuations with an overall regressive tendency. For the northern basin margin, a clastic coast to shallow clastic sea depositional environment was suggested (Fig. reffig:NamurianB). The sedimentary record does not suggest regressive tendencies and, therefore, a lack of correlation with the eustatic sea-level curve is suggested.

Evidence of post-deformational erosion from the Viséan and possibly older carbonate-dominated successions may be indicated by the presence of the lowermost transgressive conglomerates from the Loissin 1/70 well (see Section 3.3.1). The matrix and some clasts of these conglomerates are calcareous and, therefore, interpreted as reworked older deposits. Comparable deposits are recorded from the Gingst 1/73 well where the Gingst Formation also comprises such transgressive conglomerates with calcareous clasts and matrix.

The Namurian B period of the foredeep depozone is represented by two wells - Proettlin 1/81 and Peckensen 7/70. As noted above, the Lower Namurian B of the Proettlin 1/81 well is interpreted as a deep-marine depositional environment but in contrast to the Namurian A, it is characterised by a considerable increase of turbidites (compare Section 8.1). This observed increase of turbidites might be due to the Namurian B onset of sedimentation

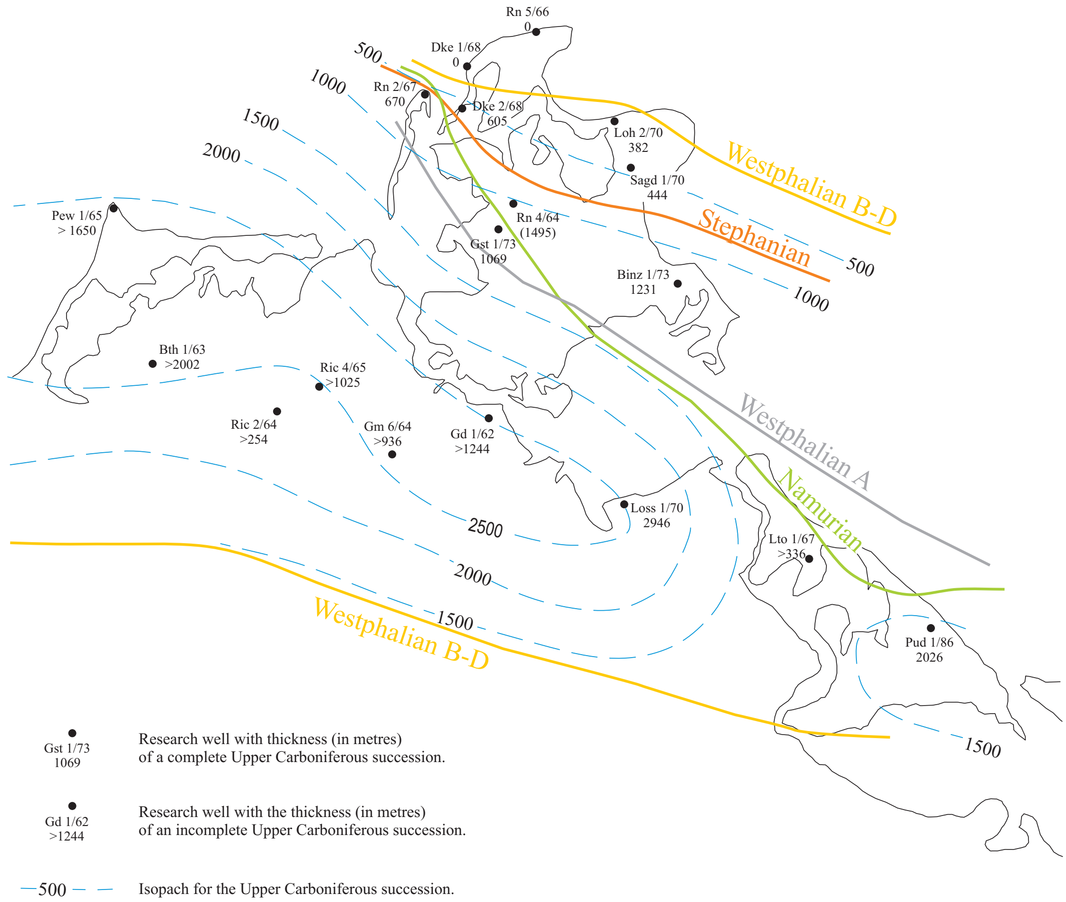

Figure 9.8: Isopach- and strata-distribution map for the Upper Carboniferous of the northern basin margin.

on the northern basin margin, possibly, the development of a shelf break that served as a source for the observed turbidites. The Namurian B of the Peckensen 1/70 well is dominated by a hemipelagite facies with only rare turbiditic incursions. This might be interpreted as indicating a more distal position - relative to the Proettlin 1/81 well - that was less influenced by submarine fans.

Namurian C

During the Namurian C, the northern basin margin is characterised by a regional hiatus which might be interpreted as representing a period of non-deposition. Sedimentation is thus limited to the basin centre where a shallow-marine to clastic coast depositional environment was recorded from the Eldena 1/74 well. Interestingly, the Parchim 1/68 well which is close to the Eldena 1/74 well (ca. 27 km to the east) does not contain any Namurian C strata. The Peckensen 7/70 well, which is - relative to the Eldena 1/74 and Parchim 1/68 wells - located further west (Fig. 9.7), contains sediments which are assigned to a more distal depositional environment, presumably one beyond the shelf break as it contains a hemipelagite facies with little turbiditic influence. The spatial distribution of these three wells would possibly suggest the presence of a spatially-narrow marine basin with a connection to the westerly located ocean during the Namurian C as depicted in Fig. 9.7. The eustatic sea-level curve for the Namurian C shows a pronounced sea-level rise for the Namurian C period but the sedimentary record reveals a lack of correlation with the eustatic sea-level fluctuations. This observed lack of correlation is best explained by uplift of the area that initiated a period of non-deposition and erosion. This uplift may have begun during the latest Namurian B (Marsdenian) that is - on the northern margin - recorded from the Barth 1/63 well exclusively. The Namurian C might have also been deposited in other areas of the northern margin but subsequently eroded due to the proposed uplift. This proposed overall uplift of the northern basin areas may be related to a period of tectonic quiescence in the area to the south, *i.e.* the prograding VOF. Such a discontinuity of Variscan shortening was, possibly, related to a post-tectonic erosional rebound of the foreland crust (*c.f.* Miall, 1995).

9.3 Westphalian

Westphalian A

Evidence of the Westphalian A is restricted to the northern basin margin (see Fig. 9.9). A clastic coast

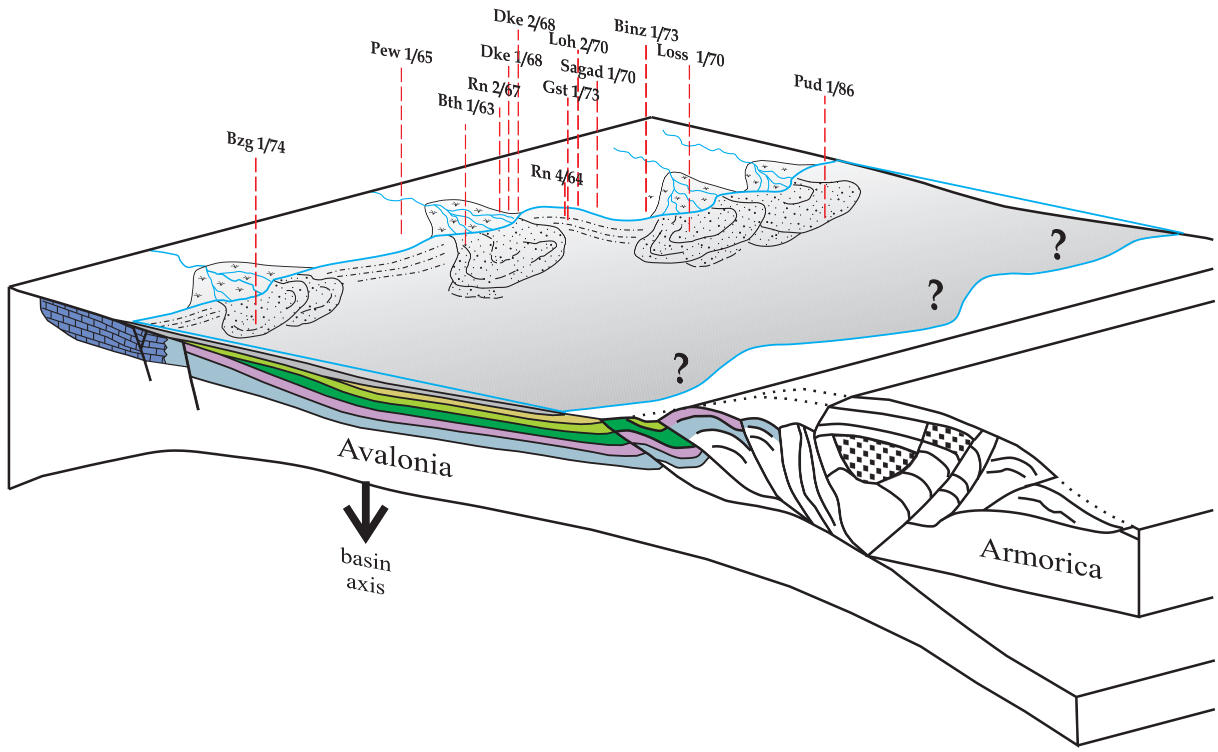

Figure 9.9: Cartoon of the tectono-sedimentary reconstruction for the Westphalian A. Tectonic information on the Variscan orogenic front after Oncken (1997). The thickness of the Carboniferous strata is not to scale. For well abbreviations compare Tab. 2.2.

depositional environment with pronounced deltaic systems developed on this northern margin. Several sub-environments were identified including distributary channels, interdistributary bays and delta plain- as well as floodplain deposits. Moreover, eight marine and brackish fauna horizons document the frequent marine ingressions into the area and onto the delta plains. The Upper Barth Formation of the Pudagla 1/86 well yields a "drowning swamp" sequence which can be interpreted as a consequence of a marine ingression (see Section 5.5.2). The successions of the Westphalian A suggest a regional sea-level rise since sedimentation set in again on the northern basin margin. This suggested sea-level rise also coincides with a eustatic sea-level rise. However, over the same stratigraphic interval, the eustatic sea-level curve shows only four discrete transgressions. This pattern is difficult to correlate with the observed sedimentary record and this may suggest that additional controls may have been imposed on the eustatic sea-level variations. It is not clear if these suggested additional controls were of first-order tectonic origin or may correspond to second-order climatic variations which might have induced storm and flooding events. Ziegler (1989), however, has suggested second-order control for these ingressions. He claimed that short-term glacio-eustatic sea-level fluctuations are responsible for the cyclical, short-lived marine transgressions leading to the deposition of these widespread marine- to brackish bands.

The Westphalian A sediments overstep the Namurian sediment in some areas. This overstep can be seen in the isopach- and strata-distribution map that was compiled from all available data (Fig. 9.8). This would imply a northward progradation of the basin's axis and may be indicative of renewed tectonic pulses from the VOF to the south that might have been accompanied by new subsidence in the foreland basin.

There is some published information on the sediment sources for the Westphalian sediments in the studied area and the area to the west. However, no publication focused on the sediment source of the Namurian sediments of the studied area. According to McCann (1999), the main source area of the sediments was to the north. This is in clear contrast with the Westphalian sandstones, which have been described from the Ruhr area (Rhenish basin) further to the west. Here, Westphalian A (Massone, 1984) and Westphalian A2 (Holl and Schäfer, 1992) sediments were derived from the Rhenish Massif area to the south.

Westphalian B

The Westphalian A-B transition is continuous and the Westphalian B is characterised by a progressive shallowing of the region. The Rügen area was dominated by the development of an alluvial depositional environment with a braided river system, lakes and flood plains (see Fig. 9.10). Four basinwide correlatable coal seams and several local coal seams

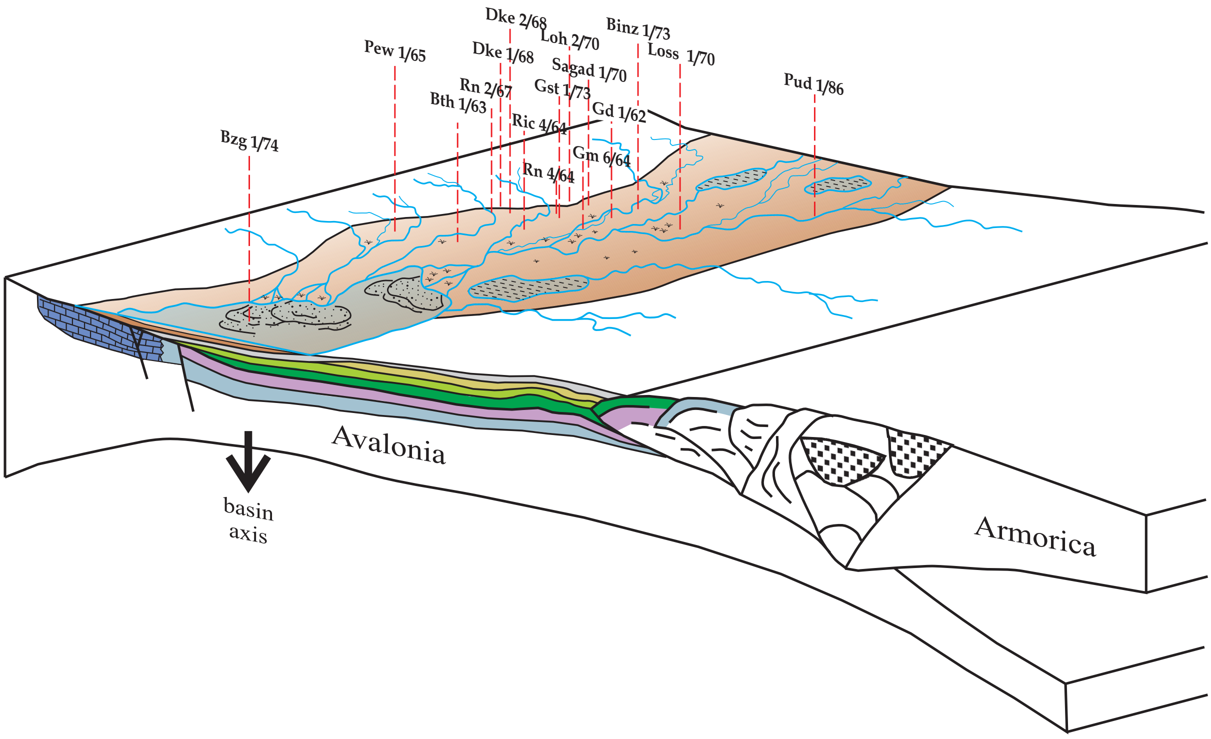

Figure 9.10: Cartoon of the tectono-sedimentary reconstruction for the Westphalian B. Tectonic information on the Variscan orogenic front after Oncken (1997). The thickness of Carboniferous strata is not to scale. For well abbreviations compare Tab. 2.2.

(*e.g.* Hoth and Wolf, 1997) were deposited in this fluvial-lacustrine environment. In the area further to the west, the Boizenburg 1/74 well documents a deltaic succession throughout the Lower Westphalian B (Wiek Formation) suggesting a nearshore depositional position. Two brackish fauna horizons have been noted for the Lower Westphalian B while no marine influences were noted in the Upper Westphalian B (Hoth et al. 1990). For the first time in the Carboniferous, the Rügen area was not influenced by marine processes. The primary sediment sources for the Westphalian B basin are now to the north and the south of the basin. A further northward shift of the area of foreland basin sedimentation is recorded as the Westphalian B sediments overstep the Westphalian A margin. To the north of the Rügen area, the Westphalian B unconformably overlie the Upper Viséan (see Fig. 9.8). The Westphalian A and part of the underlying Namurian succession to the south of the Westphalian B basin were subsequently eroded. This may be indicative of the onset of uplift in this area that continued through to the beginning of the Stephanian.

Westphalian C-D

The beginning of the Westphalian C is marked by a regional transgressive, shallow-marine bed - the Ägir horizon. These marine sediments are indicative of the last marine transgression onto the northern margin of the NE German basin, and correspond to a pronounced eustatic sea-level rise (*c.f.* Ross and Ross, 1987). The Ägir horizon is the final marine influence in this foreland basin. Subsequently, an alluvial depositional environment characterises the area of Westphalian C-D sedimentation (Fig. 9.11) with the development of braided river systems and associated floodplains. Nine coal seams of regional significance with a maximum thickness of 40 cm were deposited during the Westphalian C (Hoth and Wolf, 1997). The spatial extent of foreland basin sedimentation during the Westphalian C-D period is approximately comparable to the preceding Westphalian B (see Fig. 9.8) but several local and basinwide observations from the facies analysis suggest an overall shallowing of the environment. For example, the environmental evolution of the upper Westphalian C (Upper Jasmund Formation) and Westphalian D formations is characterised by a change in the river style that is suggested by an overall decrease of overbank intercalations, lack of pedoturbation and an increase in grain size. Conglomerates and sandstone channel sedimentation dominated while the portion of overbank fines decreased considerably.

The cessation of marine influence and the overall shallowing of the basin may indicate decreased subsidence due to the cessation of Variscan shortening during the Westphalian C-D period. This corresponds to the observations of Ziegler (1990) who suggested that by latest Westphalian time, the Variscan fold and thrust belt of western and central Europe was consolidated and became inactive.

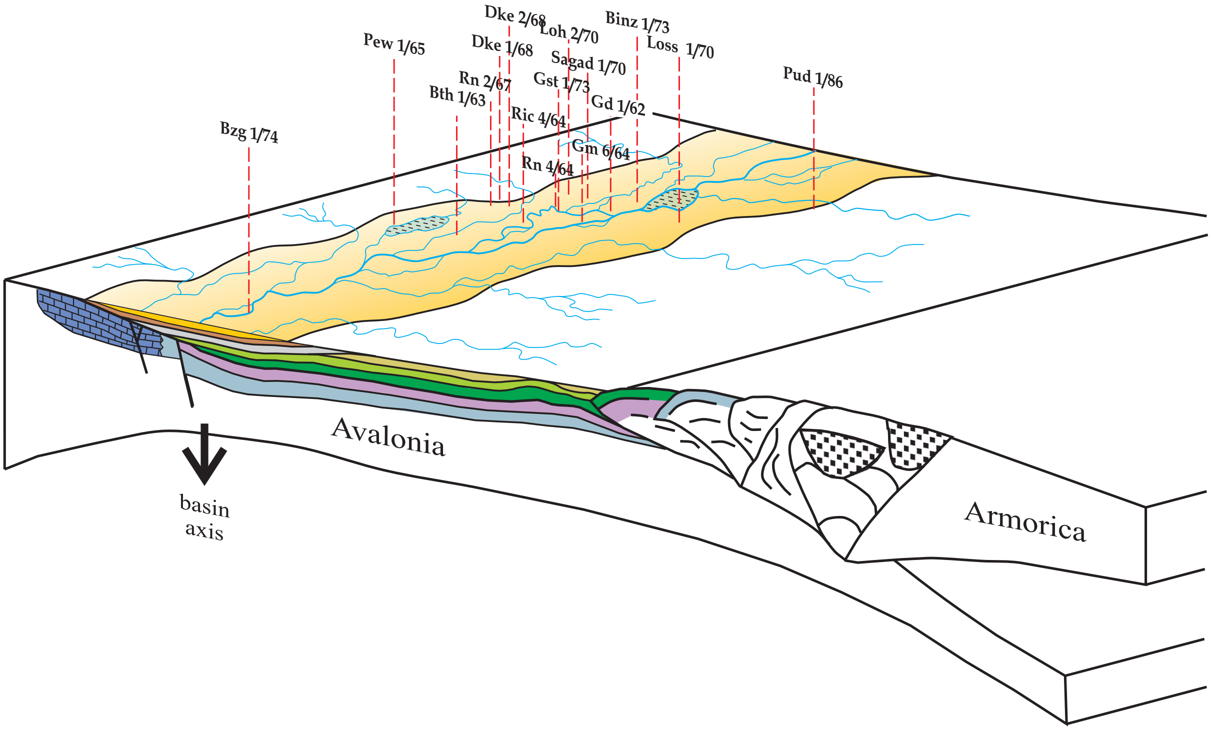

Figure 9.11: Cartoon of the tectono-sedimentary reconstruction for the Westphalian C-D. Tectonic information on the Variscan orogenic front after Oncken (1997). The thickness of Carboniferous strata is not to scale. For well abbreviations compare Tab. 2.2.

On the other hand, a resumption of mostly acidic volcanic activity was noted for the latest Westphalian D. This activity might indicate the resumption of tectonic movements which carried over to the Stephanian and "Post-Variscan" evolution of the area.

9.4 Stephanian and "Post-Variscan"

The sedimentary succession of the Stephanian and its basinwide distribution (Fig. 9.12) suggests a significant change in basin style since sedimentation in Stephanian times was, in contrast to the underlying Westphalian D, restricted to four separate "subbasins".

These comprise a liner region in the former area of foreland basin sedimentation (Fig. 9.12 area I) and three more restricted areas further to the south (Fig. 9.12 areas II-IV). In the areas II-IV to the south the Stephanian succession unconformably overlies the Namurian. Due to sparse borehole evidence little information can be provided on the spatial extent of the Stephanian sediments in the area to the south where the Stephanian would appear to be confined to relatively small areas. For example, in the Flechtingen Block (*i.e.* area III), the area of the Peckensen 1/70 well (*i.e.* area II) and further to the east where the Angermünde 1/68 and Oranienburg 1/68 wells recorded Stephanian sediments (*i.e.* area IV).

An alluvial depositional environment was recorded in area I and in the areas II-IV. In area I, a change from a mostly floodplain/braided river-dominated environment to alluvial fans and fluvial-to playa sedimentation has been suggested. A deposition of alluvial fans suggests an increase in relief which is required for the processes involved in alluvial fan deposition (*c.f.* Collinson, 1996). This presumed increase in relief and the creation of new accommodation space in the spatially confined areas to the south (areas II-IV in Fig. 9.12) may suggest that this creation of new accommodation space was, possibly, related to intracratonic, fault bounded extensional movements. These proposed extensional movements were probably related to the onset of wrench tectonic activity in late Carboniferous times (Timmerman, 2003). However, the lack of seismic data precludes definitive identifications of fault systems that may have been responsible for the suggested extensional movements. The observed changes in basin and sedimentation style suggest that the subsidence imposed through the VOF might have ceased at the end of the Westphalian. Subsequently, increased tectonic activity and increased volcanic activity have both been noted from the sedimentary record.

These changes in basin and sedimentation style are interpreted as the beginning of the "Post-Variscan" period of the so-called "Permo-Carboniferous" transition when western and central Europe was dominated by crustal reequilibration after the Variscan Orogeny (Timmerman, 2003). As the influence of the Variscan Orogeny waned, the

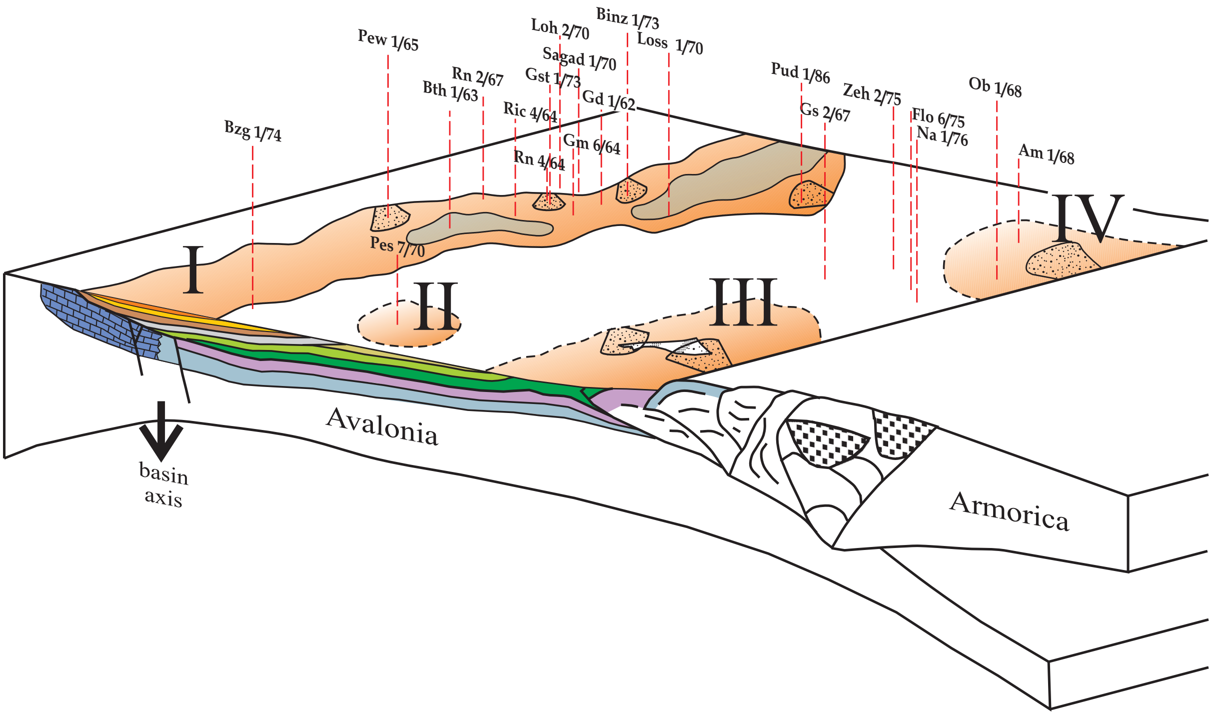

Figure 9.12: Cartoon of the tectono-sedimentary reconstruction for the Stephanian. Tectonic information on the Variscan orogenic front after Oncken (1997). The thickness of the Carboniferous strata is not to scale. For the well abbreviations compare Tab. 2.2.

area of NE Germany changed from that of a peripheral foreland basin governed by compressional movements to that of a intracontinental successor basin (Krawczyk et al. 1999) that was largely dominated by extensional activity and strike-slip movements (Ziegler 1990). The beginning of the Permian is marked by a phase of extensive felsic- to intermediate magmatism. These volcanic rocks form continuous layers up to 2000 m thick that may have covered an area of ca. 180.000 km^2 in total (Plein 1995, Benek et al. 1996).

9.5 Structural evolution of the NE German Variscan foreland basin

The Variscan history of the NE Germany began with the subduction of the Rheno-Hercynian Basin under the Mid German Crystalline High in the late Devonian (Ziegler, 1990) forming the Variscan orogenic front (VOF) and therefore initiating a nearly 60 Ma record (from late Devonian to late Westphalian) of convergent processes that were related to the subduction and collision of Avalonian crust beneath Armorican crust (Ricken et al. 2000).

The evolution of the peripheral foreland basin of NE Germany took place during the final phase of the Variscan Orogenic cycle (*i.e.* continent-continent collision) since the basin development was initiated during closure of the Rheno-Hercynian Ocean. Accordingly, this particular peripheral foreland basin evolved from the Rheno-Hercynian Basin as a successor basin which involved the transition from an early trench - fore-arc setting (*i.e.* remnant ocean basin) to a peripheral foreland basin setting during the Viséan. The NE German VFB developed exclusively on Avalonian crust including the thinned Rheno-Hercynian continental margin - with its carbonate platform sedimentation - to the north and the adjacent ocean remnants of the Rheno-Hercynian Basin to the south (see Fig. 2.5 and 9.3).

The main sedimentological trend in an evolving peripheral foreland basin is the progressive shallowing of the basin and coarsening of the sediments (Ricci-Lucci, 1986; Sinclair and Allen, 1992; Zoetemeijer, 1993; Sinclair, 1997). This trend was also observed in the sedimentary record of the NE German VFB, *i.e.* deep-marine deposits from the Viséan to the Namurian B-C in the foredeep and shallow-marine to subsequently continental sedimentation on the northern basin margin. Moreover, a continuous northward shift of the foreland basin axis and a progressive narrowing of the basin is suggested by the spatial evolution of the depositional environments. The continuous northward shift of the basin axis was deduced from isopach- and strata distribution maps (see Fig. 9.8).

As described in Section 2.1, the rheological properties of the lithosphere on which a foreland basin will develop have a significant amount of influence on its evolution. Important variables of the underlying crust include its thickness and age. These two variables determine the thermal properties, buoyancy and flexural strength of the crust and the variations strongly influence the palaeogeographical evolution of the basin (Stockmal et al. 1986; Stockmal and Beaumont, 1987). Basin evolution above old lithosphere will lead to the formation of a foreland basin that is initially relatively deep, but tends to deepen more slowly under the influence of the emplaced load: the resultant basin tends to be relatively wide because of the greater rigidity of the old basement (Miall, 1995). Foreland basins that form above young, relatively warm, buoyant and weak lithosphere with relatively low flexural rigidity tend to be narrow and deep. Young crust has a low flexural strength, and the foreland basin increases rapidly in depth. Flexural bending of relatively young crust produces uplift on its distal margin; the so-called forebulge.

However, the tectono-sedimentary reconstruction of the NE German VFB could not identify any area that could be interpreted as an area of forebulge uplift. Because the forebulge is an elevated feature, it is generally considered to be a zone of non-deposition or erosion. The succession of the NE German VFB included periods of non-deposition and erosion, especially on its distal margin. However, the development of a forebulge structure also implies the development of an according backbulge area. This area of relatively low subsidence rates (compared to the foredeep) is located between the forebulge and the stable craton. Such a backbulge area was also not identified within the studied basin. The non-existence of a forebulge structure is interpreted as, possibly, an effect of the rheological properties of the Avalonian lithosphere. The NE German VFB developed on relatively old continental lithosphere since Avalonia is a Gondwana-derived continental fragment of Precambrian age which was involved in the Caledonian and Variscan orogeny. On the basis of these considerations it is likely to presume that the studied basin did not develop a forebulge due to the age and history of the Avalonian lithosphere.

In general, the Variscan history of the NE German VFB can be explained by the structure and evolution of the VOF to the south together with more localised tectonics in the Rügen area. McCann (1999) suggested that the NE German VFB is a pseudocomposite basin with the advancing Variscan orogenic front to the south and presumed strike-slip movements along the Teisseyere-Tornquist Zone (TTZ) to the north. According to this, the tectonic events along the TTZ must have affected the basin geometry and sedimentary infill of the region in some way. On the one hand, this study could confirm localised tectonic effects on the northern basin margin but on the other hand, the study could neither approve nor disprove that these tectonic movements are linked to the TTZ since no distinct influence of the TTZ could be assigned to a basin event.

Franke et al. (1996) have argued, based on an observed stratigraphic break between the Namurian B and Westphalian A along the basins margin, that the final stages of Variscan deformation in eastern Germany were late Namurian in age. However, this study showed evidence of tectonic influence (*i.e.* first-order control) on the sedimentary record and the distribution of sedimentary environments and strata that were younger than Namurian. This would suggest that the effects of Variscan shortening, while, perhaps largely completed in the region during the Namurian, continued to be felt for a considerable time throughout the Westphalian. This study could confirm that the Stephanian evolution of the area introduced the "Post-Variscan" period. This included the change from a peripheral foreland basin setting - heralded by compressional movements - to an intracontinental successor basin (Krawczyk et al. 1999) that was dominated by extensional activity and strike-slip movements (Ziegler 1990). This successor basin is the NE German Basin. Therefore, the NE German VFB is regarded as the precursor of the NE German Basin.

Chapter 10

Conclusions

– The evolution of the peripheral foreland basin of NE Germany took place during the final phase of the Variscan Orogenic cycle. It evolved from the Rheno-Hercynian Basin as a successor basin. This involved the transition from a remnant ocean basin setting to a peripheral foreland basin setting during the Viséan.

– The final Variscan orogenic phase is marked by the break-up of the carbonate platform on the northern basin margin during the Asbian.

– The relief between the remains of the carbonate platform to the north and the foredeep area to the south was balanced during the Namurian A. This lead to a change in basin style, from sedimentation into prograding sub-basins to a basinwide distribution, *i.e.* the transition from the Rheno-Hercynian zone to the Variscan foreland zone *sensu* Hartley and Otava (2001).

– A post-tectonic rebound initiated uplift and erosion on the northern margin in the latest Namurian.

– No eustatic control on the sedimentation of the northern basins margin was noted throughout the Namurian and Westphalian A.

– A decrease of marine influences was observed during the Westphalian A-B. Subsequently, a cessation of marine influences was observed for the Westphalian C; the area of foreland basin sedimentation was decoupled from marine influences of the westward located ocean.

– The Westphalian D is characterised by a progressive shallowing of the basin and an overall coarsening of the sediments. This shallowing is interpreted due to the decrease of subsidence which may correspond to the cessation of Variscan shortening.

– The main sedimentological trend in an evolving foreland basin - the progressive shallowing of the basin and coarsening of the sediment - was also observed in the sedimentary record of the NE German foreland basin. Moreover, a continuous northward shift of the basin axis and a progressive narrowing of the basin during the Westphalian is suggested by the spatial evolution of the depositional environments. This shift of the basin axis is accompanied by an uplift and erosion in the southern basin area (*i.e.* former foredeep area) during the Westphalian B.

– The Stephanian evolution of the area introduced the "Post-Variscan" period. This included the change from a peripheral foreland basin to the intracontinental NE German Basin. The NE German Basin is one of approximately 70 intramontane basins that were combined to the Central European Basin. Therefore, the NE German Variscan foreland basin is regarded as the precursor of the NE German Basin.

– The tectono-sedimentary reconstruction of the basin could not identify any area that could be interpreted as an area of forebulge uplift. The nonexistence of a forebulge structure is interpreted as an effect of the rheological properties of the Avalonian lithosphere on which the basin is located. Avalonia is a Gondwana-derived continental fragment of Precambrian age which was involved in the Caledonian and Variscan orogeny. Therefore, it is likely to presume that the studied basin did not develop a forebulge due to the considerable age and tectonic history of the Avalonian lithosphere.

– The Variscan history of this Variscan foreland basin can be explained by the structure and evolution of the VOF to the south together with more localised tectonics in the Rügen area. McCann (1999) suggested that the NE German Variscan foreland basin is a pseudocomposite basin with the advancing Variscan orogenic front to the south and presumed strike-slip movements along the Teisseyere-Tornquist Zone (TTZ) to the north. According to this, the tectonic events along the TTZ must have affected the basin's geometry and sedimentary infill of the region in some way. On the one hand, this study could confirm localised tectonic effects on the northern basin margin but on the other hand, the study could neither approve nor disprove that these tectonic movements are linked to the TTZ since no distinct influence of the TTZ could be assigned to a basin event.

Acknowledgement

I would like to express my deep and sincere appreciation to my supervisor Prof. Dr. Tom McCann (University of Bonn) for offering me the opportunity to carry out this study, for his guidance, helpful advice and supervision.

Many thanks to Prof. Dr. Andreas Schäfer for agreeing to be my second examiner and to Prof. Dr. Armin Skowronek and priv. Doz. Stefan Herrgarten who complete the board of examiners.

I gratefully acknowledge the EEG-Erdgas Erdöl GmbH for access to the research wells, unpublished well reports and for permission to present the results. Dr. Jürgen Kopp (LGRB), Joachim Iffland (LUNG) and Dr. Bodo Ehling (GLA Sachsen-Anhalt) are thanked for their logistical support during the use of the core-stores.

This research was carried out with the financial support of the German Research Council (DFG). It was part of the Priority Program (SPP 1135) "Dynamik sedimentärer Systeme unter wechselnden Spannungsregimen am Beispiel des zentraleuropäischen Beckensystems" (Dynamics of sedimentary basins in alternating stressfields: The Central European Basin). Many thanks to all participants of the "Basin-Dynamics"-group that formed in the course of this Priority Program; our workshops and discussions were very helpful. Special thanks to Dipl. geol. Marion Geissler (TU Freiberg) for many discussions and helpful comments on my work.

Many thanks to Dirk Zorn from the LGRB archives for his literature research on the unpublished well reports. The discussions with Dr. Norbert Hoffmann (BGR-Berlin) on the spatial extend of the "Kohlenkalk"-platform was crucial for my considerations; I very much benefited from his work. Also, the discussion with Dr. Jürgen Kopp (LGRB) contributed to this study. Further, this study has benefited from scientific discussions with Prof. Dr. Andreas Schäfer, Prof. Dr. Nico Froitzheim (answers to the "Geological Question of the Day!"), Dr. Sven-Oliver Franz, Dr. Mario Manchego, Dipl. Geol. Mathias König, Dipl. Geol. Mathias Böhm (all University of Bonn), Prof. Dr. Werner Ricken, Dipl. Geol. Hans-Axel Kemna (both University of Cologne), Dr. Oliver Swientek (NAM, Shell-Exxon), Dr. Guido Port (IES, Aachen), Dr. med. Thomas Kaiser (DieM-Institute, Cologne) and Martin Behrens (Europaschule Bornheim); I would like to thank you all for your support. Thanks to Dr. Michael Pullmann for his LaTeX-support. Many thanks to the administrators who kept the network "running" and to Tania Beilfuss who helped me with some graphical problems. Many thanks to my student assistant Matthias Böhm who helped me with the photographs and during several visits of core-stores. Yessica Yeti and Guido Kirsten, thank you very much for your hospitality during my Berlin visits. I also enjoyed the company of my colleagues of the Geological Institute; especially the coffee break with Dirk, Klaus and Torsten. Several people helped me with proof-reading of the manuscript; thank you all.

Moreover, many thank to the folks who "just" gave me a good time or supported me during the last two and a half years: Basti, David, Hansa, Daniel, Guido, Matze (not only for your hospitality), Martin, Holger, Schelzig, Josie, Thomas, Linus, Silvia Royal, Erika, Egbert, Tobi, Luca, Südkurve, the First Football Club of Cologne, the German National Football Team, the Slovenian National Football Team, Slovenija, The Beatles, Elvis Aaron Presley, the Miles Davis Quintet, Sonny Rollins and of course my parents. Last but not least, very special thanks to Katrin.

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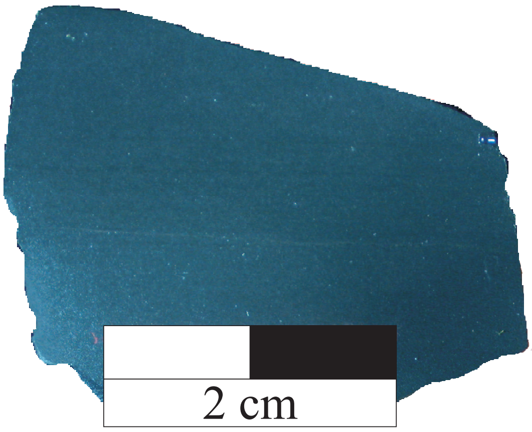

Figure 1: The photo depicts a massive mudstone (M,h) from the Peckensen 7/70 well (core barrel 4472.3 - 4477.8 m). It was assigned to a hemipelagite shale facies.

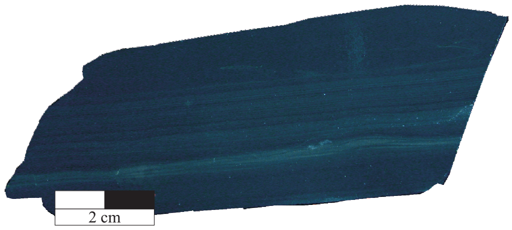

Figure 2: A parallel laminated mudstone (M,p) from the hemipelagite shale facies of the Peckensen 7/70 well (core barrel 4515.2 - 4521.0 m).

Figure 3: This photo shows a strongly bioturbated mudstone (M,h) from the Gingst 1/73 well (core barrel from 3454.4 - 3464.4). The sample represents a mudstone facies that was assigned to a shallow-marine depositional environment; *i.e.* a well oxygenated shelf environment.

Figure 4: This sample shows a well bioturbated, massive to weakly parallel laminated mudstone (M, h-p). The sample was taken from the Loissin Formation of the Parchim 1/68 well (core barrel 6887.5 - 6896.5 m). This mudstone was interpreted as a lagoonal tidal-flat deposit.

Figure 5: This photo depicts a sand/mud interbedded facies with flaser to lenticular bedding (M/Sf, l). It was taken from the Parchim 1/68 well (Loissin Formation: core barrel 6849.7 - 6858.7 m) and assigned to a lagoonal tidal-flat environment. Note the convolute bedding of some of the fine-grained sandstone interbeds.

Figure 6: This sample shows a hemipelagite shale facies with event-beds (M/Sf(m),h). It was taken from the Zehdenick 2/75 well (core barrel 5180.7 - 5185.5 m).

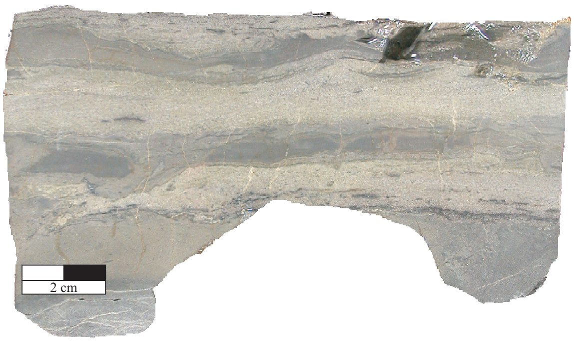

Figure 7: This sample shows a mud/sand interbedded facies with wavy parallel to flaser bedding (M/Sf,p-l). It was taken from the Gingst 1/73 well (Hiddensee Formation: core barrel 3376.1 - 3379.1 m) and assigned to a non-deltaic, coastal depositional environment.

Figure 8: This parallel bedded, fine-grained sandstone (Sf,p) was taken from the Loissin 1/81 well (Mönchgut Formation: core barrel 3302.4 - 3308.3 m). It was assigned to an alluvial depositional environment.

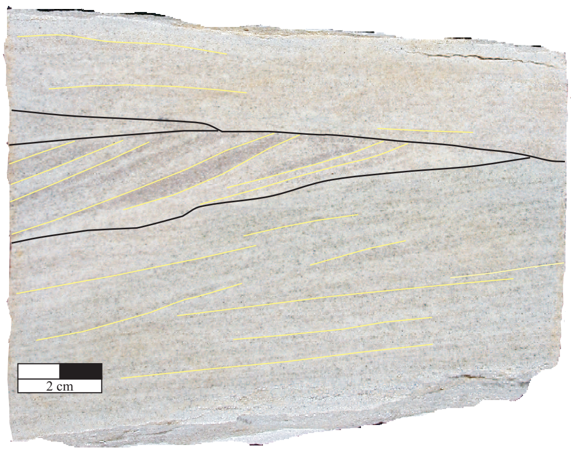

Figure 9: This sample shows a parallel cross-bedded sandstone with small-scale cross-bedding (Sf,r). It was taken from the Gingst 1/73 well (Lower Jasmund Formation: core barrel 3094.0 - 3103.5 m). The black lines mark crossets and the yellow lines the bedding. This sandstone was assigned to a fluvial channel subenvironment.

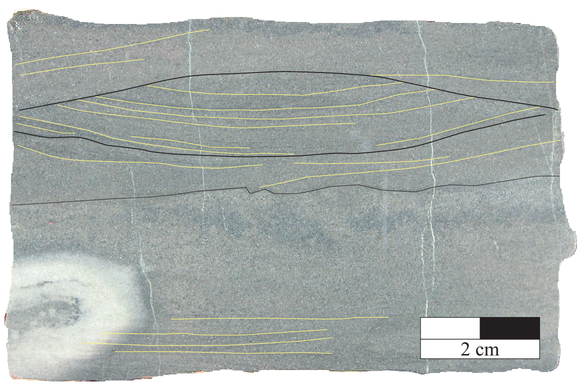

Figure 10: This photo depicts a hummocky-cross stratified sandstone (Sf,r) that was assigned to a coastal depositional environment that was influenced by wave-dominated currents. The sample was taken from the Gingst 1/73 well (Hiddensee Formation: core barrel 3376.1 - 3379.1 m).

Figure 11: This ripple cross-laminated sandstone (Sf,r) was assigned to a fluvial channel subenvironment. The cross bedding is small-scale. The sample was taken from the Loissin 1/70 well (Upper Jasmund Formation: core barrel 4061 -4070 m).

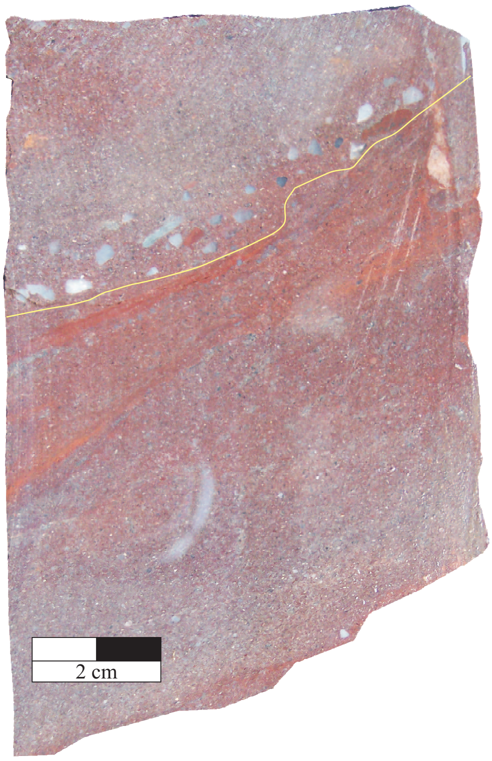

Figure 12: This sample was assigned to the medium-grained turbidite facies and depicts two stacked sandstone beds. The contact between these sandstone beds is marked by an erosive micro-conglomerate (yellow line) which corresponds to the T_a-interval. The sample was taken from the Flatow 6/75 well (core barrel 4392.8 - 4402.6 m).

Figure 13: The photo shows the erosive contact of a basal turbidite bed (Sf-m,h) to the underlying shale (M,h). The erosive sandstone bed corresponds to the T_a-interval of the medium-grained turbidite facies; note the normally graded bedding. The sample was taken from the Oranienburg 1/68 well (core barrel 4900.8 - 4910.0 m).

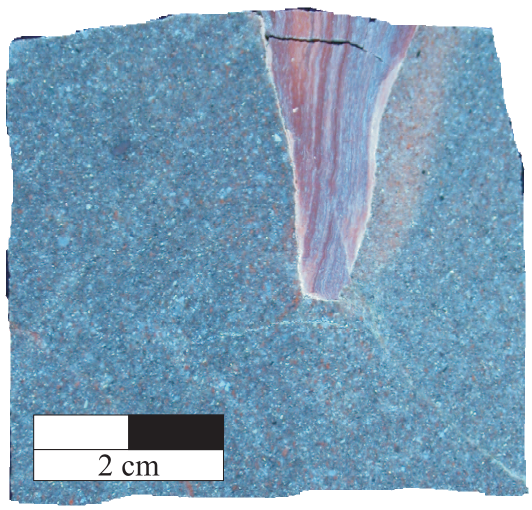

Figure 14: This weakly sorted sandstone (Sm(Sf),h) was taken from the Zehdenick 2/75 well (core barrel 4675.0 - 4683.0 m) and corresponds to the T_a-interval of the medium-grained turbidite facies; note the intraformational, muddy rip-up clast.

Figure 15: The contact between these two sandstone beds is marked by a flame structure which is outlined by the black line. This particular load structure may occurred because of unequal loading and liquefaction. The underlying muddy sandstone layer has moved up in the form of a flame into the overlying sand layer. Note the graded bedding of the overlying sandstone bed; it corresponds to the T_a-interval of the medium-grained turbidite facies. The underlying sandstone bed shows a weakly planar bedding and may, therefore, correspond to the T_b-interval of the medium-grained turbidite facies. The sample was taken from the Flatow 1/76 well (core barrel 4380.0 - 4392.8 m).

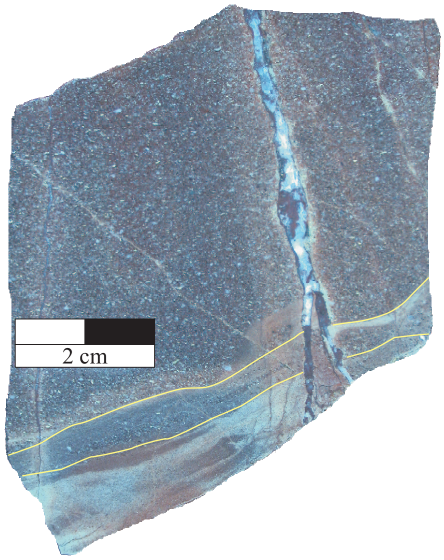

Figure 16: This photo depicts two stacked, medium-grained turbidites. The lower sequence is exceptionally thin but nevertheless characterised by a normally-graded bedding, *i.e.* the transition from the T_a- interval to the T_d-interval. The underlying mudstone corresponds to a T_d-interval of a relatively bigger turbiditic sequence. This sample was taken from the Eilsleben 8/76 well (core barrel 1342.8 - 1347.3 m).

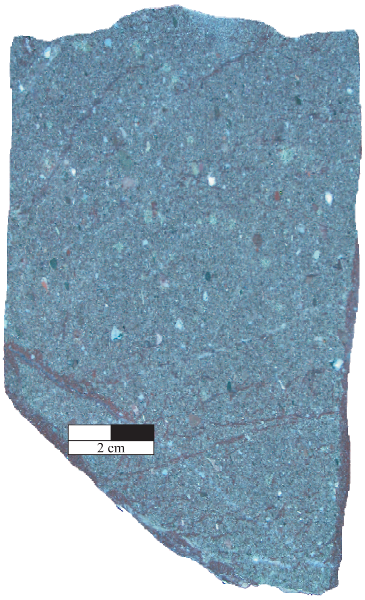

Figure 17: This sample shows a weakly sorted, massive and structureless sandstone (Sf-c,h) that is characterised by a considerable amount of fine-grained gravel. It was taken from the lower part of the Dreileben 3/70 well (core barrel 977.1 - 980.5 m) and interpreted as a deep-marine deposit. For the environmental discussion of massive sandstones in deep-marine environments compare with Chapter 8.11 and 8.10.

Figure 18: This photo shows a planar cross-bedded (medium-scale), fine-grained sandstone (Sf,r) with abundant pyrite concretions. Note the intraformational mud clasts. The sample was taken from the Eldena 1/74 well (core barrel 5089.6 - 5096.9 m) and assigned to a coastal depositional environment.

Figure 19: This sample was taken from the lagoonal tidal-flat facies association of the Parchim 1/68 well (Loissin Formation: core barrel 6887.5 - 6896.5 m). It shows a soilified sandstone bed (Sf,s) that was pedoturbated by the activities of rootlets. These rootlets are traced by the preserved organic matter and reach into the underlying laminated mudstone (M,p).

Figure 20: The photo depicts a soilified, sandy mudstone (M(Sf),s) that is characterised by an intense grey-brown colour and a disturbed primary bedding due to the activities of rootlets. Note the remains of the upright, big root that is located in the middle of the sample. This sample was taken from the Gingst 1/73 well (Lower Jasmund Formation: core barrel 3004.0 - 3015.5 m).

Figure 21: The photo depicts a soilified mudstone (M,s) that is characterised by a disturbed primary bedding due to the activities of rootlets and an intense grey-brown colour. This sample was taken from the Gingst 1/73 well (Upper Jasmund Formation: core barrel 2902.3 - 2912.3 m).

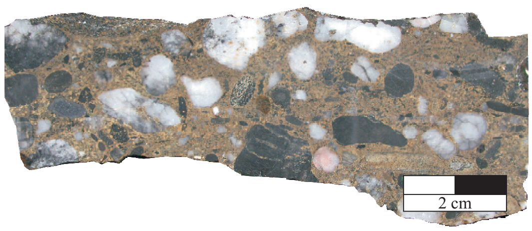

Figure 22: This is a matrix supported conglomerate (G,h) with rounded to well rounded siliciclastic clasts. The matrix comprises fine to coarse-grained sand with a carbonate fraction. It was taken from the Gingst 1/73 well (Gingst Formation: core barrel 3425.7 - 3434.7 m).

Figure 23: This photo depicts an overlying matrix supported conglomerate and an underlying, weakly sorted, massive sandstone. The conglomerate contains siliciclastic clasts. Note the intense red colouring of the sediment. The sample was taken from the Gingst 1/73 well (Mönchgut Formation: core barrel 1981.0 - 1986.1 m).