1. Introduction

1.1. Location and h istory

The Thuringian Syncline comprises a depression on the central and northwestern of the eastern part of Germany belonging to the Free State of Thuringian (Freistaat Thüringen), situated between the Harz Mountain on the north and the Thuringian Forrest on the south about 65 km, in north-south direction and ranging from Hainich to Finne areas from west to east comprising about 80 km with an approximate surface of 4000 square kilometer (km^2).

The studied area is located on the northwest side of the Thuringian Syncline about 45 km long and 68 km wide, between the coordinates 5,652,000 and 5,692,000 North and 4,370,800 and 4,433,300 East, using the system “Universal Transverse Mercator (UTM)” in Zone 01N (180 W to 174 W) and Geodetic Datum WGS 1984. The study covers an area of 2,757 square kilometres (km^2) (figure 1.1) with a total of two hundred fifty wells, comprising the fields “Allmenhausen, Behringen, Kirchheilingen, Eichsfeld, Fahner Höhe, Langensalza, Mühlhausen, Rockensußra, and Holzsußra” (figure 1.2 and enclousure-1 and table 1.1).

The history of hydrocarbon exploration of the Thuringian Syncline in East Germany begins in 1929 in the Volkenroda potassium salt mine 20 km NW of Erfurt (figure 1.1). From 1930 to 1938 petroleum and natural gas were extracted from the Zechstein Group (Z). These reservoirs were discovered in the joints of the main anhydrite (Hauptanhydrite) and the basal anhydrite (Basal-anhydrite). According to Karnin et al (1990) until the year 1996, the Thuringian Basin had an oil production of 51.000 tons. In the years 1931 and 1935 the fields in the Mühlhausen and Langensalza area were discovered. No fields were either discovered or explored during the decades 30`s and 40`s. In the 1950s decade, the German Democratic Republic (GDR) resumed the exploration in the Kirchheilingen and Allmenhausen fields. The first well in Kirchheilingen area was drilled in 1958 and in the Allmenhausen area in the year 1960. During the 60s until 1970 the exploration continued in the Behringen, Krahnberg, Holzthaleben, Rockensußra, Holzsußra and Mehrstedt fields (table 1.1). During this period, new oil and gas reservoirs were discovered in the Zechstein 2 carbonate (Ca2) and a minor quantity in the Buntsandstein Group. Excepting few explorations during the 70s, no more activities in the Thuringian Syncline had been done in that time. However the new geological studies and new technologies used in the

Brandenburg and Mecklenburg areas allowed the resumption of the exploration in the Thuringian Syncline during the early 90´s.

Figure .1.1. Location map of the oil and gas fields in the German Democratic Republic (from, Karnin et al 1990)

Field	**Year**	**Oil/Gas**	**Density (g/cm^3)**	**CH_4-%**	**Cumulative production 12/96**	**Observations**
Volkenroda	1930	Oil	0.848		82.350 t	extract by foreign companies in the potassium salt mine
Mühlhausen	1932	Gas		48.8	1.434.914.300 m^3	CO_2 2,1%
Langensalza	1935	Gas		56.5	239.306.400 m^3	CO_2 0,45%
Kirchheilingen ZS	1958	Gas		60	58.772.000 m^3	since 1968 UGS
Kirchheilingen SW	1958	Oill/Gas	0.78	60	282.412.800 m^3 28.787 t	

Table 1.1. Data on the oil and gas fields in the Thuringian Syncline (from Karnin et al, 1990)

Field	Year	Oil/Gas	Density (g/cm^3)	CH_4-%	accumulative production 12/96	Observations
Allmenhausen	1960	Gas		69	238.780.000 m^3	
Fahner Höhe	1960	Gas		18-24	48.006.100 m^3	CO_2 18,2%
Behringen	1962	Gas		51.7	2.723.818.700 m^3	CO_2 8,22%
Krahnberg	1963	Gas		28.6	-	CO_2 51,3% H_2S 0,15%
Holzthaleben	1969	Oil	0.84		1.400 t	abandoned in 1971
Rockensußra	1964	Oill/Gas	0.82	68.8	17.036.000 m^3 992 t	abandoned in 1984
Holzsußra	1970	Gas		65.5	2.247.000 m^3	abandoned in 1972
Mehrstedt	1970	Oill/Gas	0.84	66.5	521.000 m^3 2.591 t	abandoned in 1988

Table 1.2. Data on the oil and gas fields in the Thuringian Syncline (from Karnin et al, 1998)

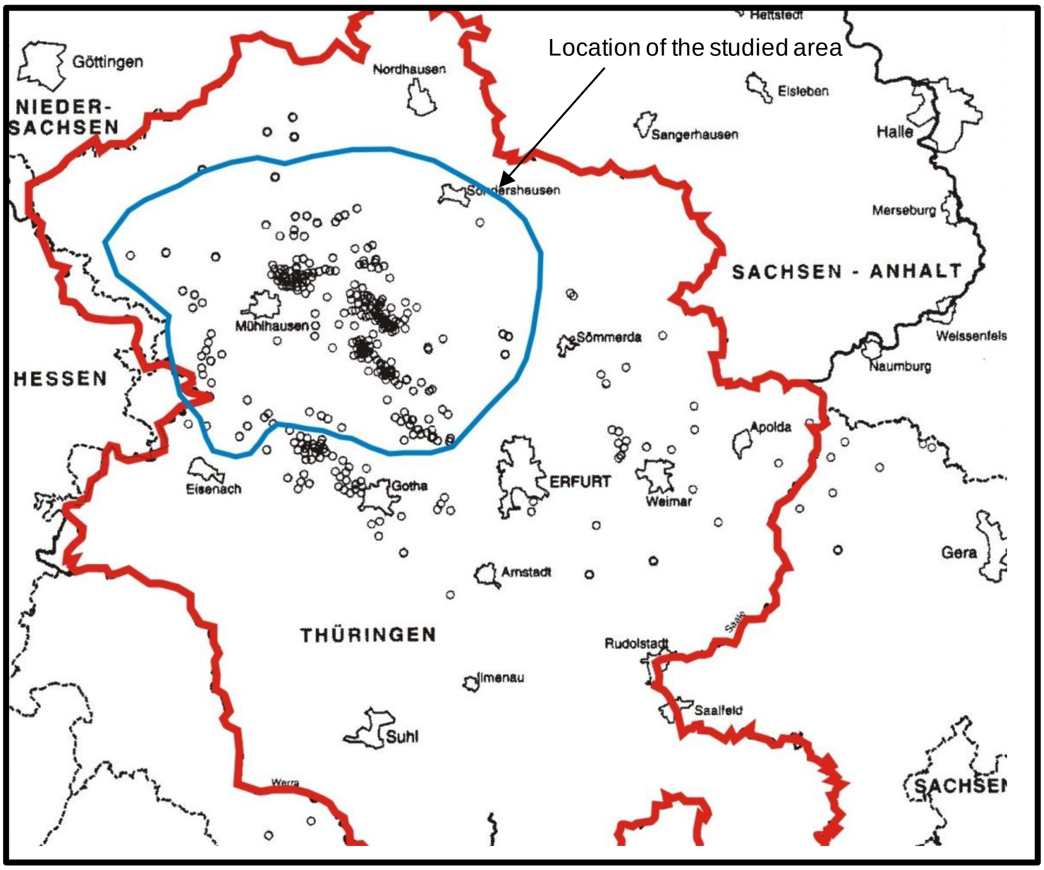


Figure 1.2.Well location map of the study area, belonging to the Thuringian Syncline (from Karnin et al, 1998)

1.2. Main objective

Over the years numerous studies have been done throughout the Thuringian Syncline mainly based on well logs correlation, the most of them are published by the "Thüringer

Landesanstalt für Unwelt und Geologie". In some cases, the stratigraphic subdivisions of the Buntsandstein Group were identified and others only the main subgroups were correlated. In the say way 2D structural interpretations of the different horizon of the Zechstein and Buntsandstein Groups as well as lithological descriptions of the well core and samples were done but without lithofacies identifications.

The project aims at the integration of sedimentological, structural and morphotectonic investigations resulting in a reservoir characterization of a hydrocarbon-bearing part of the Thuringian Syncline. Based on industry data as well logs, well core, geological maps, topographic maps information and previous publication, a 3D sedimentological-stratigraphic-structural model in the Middle Buntsandstein Subgroup is generated with the propose of integration all these studies. Based on this data is discussed the sediments distribution (fluvial, lacustrine and eolian sediment) or structural features that controlled the syncline as well as the thickness distribution in studied area.

The integration of stratigraphic sedimentological interpretation and structural characteristic leads to an integral 3D model of the evolution of the Thuringian Syncline, during Triassic time, especially in the Lower Triassic. The stratigraphic-sedimentological model is made in the Middle Buntsandstein Subgroup (Volpriehausen, Detfurth, Hardegsen and Solling Formations) and the structural model is created from the top of Zechstein Group in the Permian to the stratigraphic column of the Lower Triassic; at the top Middle Buntsandstein Subgroup.

1.3. Scope of work

The main objective of this study consists of generating a 3D Geological Model in the hydrocarbon province of the northwestern Thuringian Syncline, located in the eastern part of Germany. The next topics have been made:

- Checking and making detailed stratigraphic correlation for each formation in the Middle Buntsandstein Subgroup;
- Determinate sedimentation cycles and regional unconformities for the main lithostratigraphic units in the Middle Buntsandstein Subgroup;
- Generating electrofacies distribution maps showing depositional environments and lateral heterogeneities of sedimentological facies;

- Creating paleogeographic and isopach maps: gross, total net sand, net to gross in the Middle Buntsandstein Subgroup;
- Building structural cross sections from Permian, Zechstein Group to Triassic: Buntsandstein, Muschelkalk and Keuper;
- Making structural maps with the integration of the stratigraphic correlation;
- Creating a 3D structural model from top Zechstein to top Solling Formation;
- Building a sedimentological model for each formation in the Middle Buntsandstein Subgroup
- 3D stratigraphic-sedimentological and structural model (Geological Modelling) using the reservoir modelling tool Irap RMS 2009 software.

Field work around the area has been done to compare field data with well data making sedimentary facies analyses and lithostratigraphic study.

1.4. Data available

The data available at the start of the present study were the followings:

- Cutting information (lithology description), and well cores (several meters of rock)
- Wireline logs; Gamma Ray, Spontaneous Potential, resistivity, deviation surveys, well coordinates and ground level information.
- Geological and topographical maps taken by the Geological Service of Thuringian State (Thüringer Landesanstalt für Umwelt und Geologie)
- Structural maps of the top Middle Buntsandstein Subgroup (Schlegelmilch, 1972) and the top Lower Muschelkalk Subgroup (Vum Son, R. Jasgsch, 1963) obtained by the Geological Service of the Thuringian State
- Numerous reports and publications

The wells used in this study are located in the fields and areas: Altengottern, Allmenhausen, Fahner Höhe, Hainich-Berka, Hainich-Mihla, Heinleite, Holzsußra, Holzthaleben, Kirchheilingen, Krahnberg, Keula (Krs. Sonderhausen), Küllstedt, Langensalza, Mühlhausen, Rockensußra, Straußfurt, Tennstedt, Obermehler and Wiegleben.

2. Strategy and Methods

This study was elaborated mainly by compilation of Thuringian Regional Geology published literature and its surrounding areas and also by collecting and revising not only the wire-line logs (SP, GR Resistivity, deviated survey etc), and sample description but also well coordinates and structural data and maps. All of this information was received in paper and converted into digital format. The structural contour maps were drawn and processed as vector graphic and the well log data into “LAS” and “TXT” format by using ArcGis 9 software (geographic information system) to generate a base map with all available wells. The whole digital information was loaded into the KINGDOM 8.2 and IRAP RMS 2009 software.

The stratigraphic subdivision of the Lower Triassic Buntsandstein Group in the northwestern Thuringian Syncline has been mainly recognized in the wire-line logs and lithological data based on the lithostratigraphic units proposed by Boigk (1959, 1961) and Trusheim (1963) for the Northwest German Lowlands.

A consistent stratigraphic model for the Middle Buntsandstein Subgroup (Lower Triassic) in the northwestern Thuringian Syncline determined the subdivision of the geological formations: Volpriehausen, Detfurth, Hardegsen and Solling Formation. Detailed stratigraphic correlations were made in different directions in order to visualize the continuity of sand bodies and facies heterogeneity, stratigraphic changes, unconformities, boundaries and thickness distribution.

For the cyclicity study of the Middle Buntsandstein Subgroup, the gamma ray logs were used, although in occasions also; the spontaneous potentials to identify log patterns as peaks, breaks and trends by comprising fining upward cycles related to variability in precipitation (alternation of dry and wet periods).

Well cores have been analyzed for sedimentological analysis by making lithological description and determining sedimentary structures, reservoir characteristics, lithofacies identification, sedimentation cycles, sedimentary environment interpretation and unconformities additionally, outcrop studies for comparison purposes (lithofacies and paleocurrent interpretation).

The electrofacies distribution map of each geological formation in the Middle Buntsandstein Subgroup (sm) was created and associated to the sedimentary facies identified in cores. The integration of facies interpretation together with thickness maps allowed to create a consistent paleogeographic model.

Main geological structures such as faults, anticlines, synclines have been taken from the structural contour maps and surface studies tied to stratigraphic correlation generating structural maps (in depth) of the top of each formation defining and (re)interpreting folds, faults. Structural cross-sections based on well control allowed the spatial distribution understanding of the Buntsandstein Group.

A 3D structural model is developed Based on all compiled data, therefore an interpretation and integration of sedimentological-stratigraphic-structural analysis reservoir modelling have been done to create a 3D Geological Modelling of the Buntsandstein Subgroup in the northwestern Thuringian Syncline.

3 Tectonic and sedimentary setting of the Permo-Triassic in Central Europe

3.1 Permo-Triassic

3.1.1 Permian

The tectonic setting during the Permian and Triassic reflects a reorganization of the plate boundaries which was strongly influenced by the Variscan Orogeny and the consolidation of the supercontinent Pangea (1990). The collision between Gondwana and Laurussia combined with the Silurian-Devonian Caledonian orogeny created a thickened crust in northwestern Europe (Ziegler, 1990).

The subsidence in the Northern Sea area in Permian times created two main depocenters; the Northern and Southern Basins, separated by the Mid-North Sea Ringkøbing-Fyn highs (figure 3.1). The Northern Permian Basin and the western part of the Southern Permian Basin overlie the Variscan Mountain Belt developed in Late Carboniferous Time, while the eastern part of the Southern Permian Basin covers the Precambrian Baltic Shield and East European Craton (Maystrenko et al, 2008).

The Southern Permian Basin is composed of three (3) main sub-basins: the Anglo-Dutch Basin, the North German Basin and the Polish Trough (figure 3.2). All were produced by lithosphere thermal contraction (Ziegler 1990) and sedimentary load.

During the Late Carboniferous and Early Permian mainly dextral movements between Laurussia and Gondwana occurred, provoking oblique rift tectonics in the North German Basin (Ziegler, 1990) also affected by extensive igneous activity.

The Lower Permian comprises the Rotliegend Volcanics, which are mainly composed of thick andesitic and felsic rocks, occurring in the whole Southern Permian Basin being the product of numerous volcanic pulses. These Rotliegend Volcanics represent an important geological event coinciding with the formation of main graben system and subsidence centre. The volcanics of the Rotliegend Group are found in eastern Germany and can reach thickness until 3000 m (Hoffmann et al., 1997).

Sedimentation started during the early Permian Rotliegend Group (Rotliegend Sediments); these sediments overlie a system of thick volcanic rock, well recognised in northern Germany and Poland. Glennie et al (2003) indicate that the ages of Rotliegend

Volcanics coincide with the time of the Rotliegend deposition suggesting contemporaneous volcanic activity. The main depocenter in the Southern Permian Basin is the WNW-ESE trending North German Basin (figure 3.3). The accumulated sediments comprise continental silicaclastics and evaporites deposited under arid to semi-arid climate formed in eolian and playa lake environments as evidenced by the presence of halite. The Rotliegend sediments can reach a thickness of more than 1500 m but are highly variable in different areas (Coward, 1995).

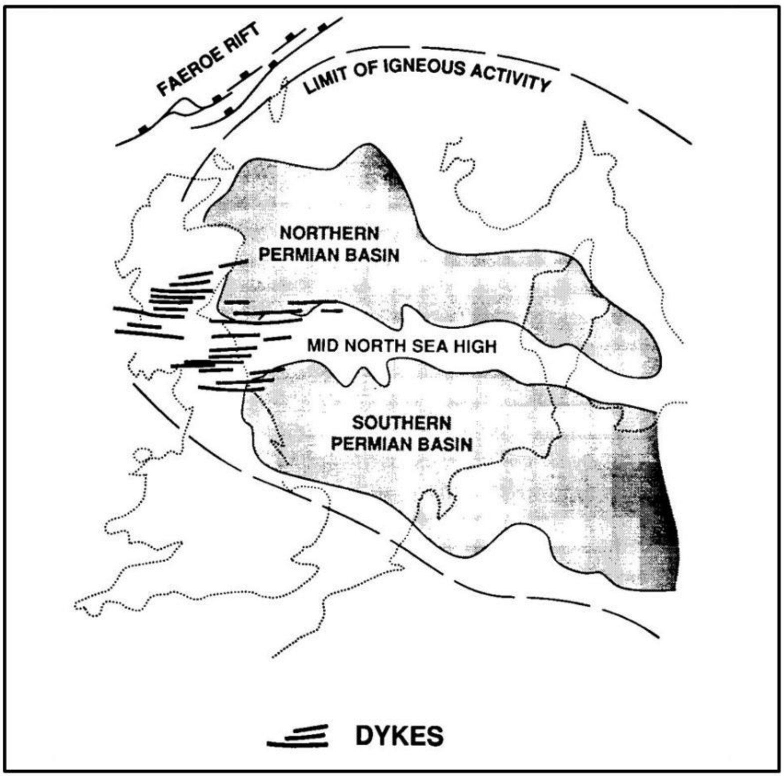


Figure 3.1 Map showing the two (2) main areas of subsidence during the late Permian (from Coward, 1995).

In the Late Permian, a transgression took place in the Northern and Southern Permian Basins as a result of rift reactivation. It initiated the deposition of Zechstein Group that followed the Rotliegend sediments. These deposits represent successions of carbonates, claystones and evaporites arranged in cycles, reflecting glacio-eustatic sea level fluctuations. The sedimentation and the thickness pattern of the first Zechstein cycle were mainly controlled by syndepositional extensional tectonic along the southern margin with west-north and north-north-east oriented lineaments (Ziegler, 1999).

The subsidence patterns during Zechstein are not easy to reconstruct in the Northern and Southern Permian Basin as a result of salt movement (diapirism) (Ziegler, 1999), but also leaching and erosion in areas where uplift took place during Mesozoic rifting phases

(Stollhofen et al, 2008). These events of post-Permian salt movement and the erosion could generate the variability of thicknesses in the Northern and Southern Permian Basin. During the Late Permian a second phase of tectonic movement took place, creating large disconformities in the Zechstein.

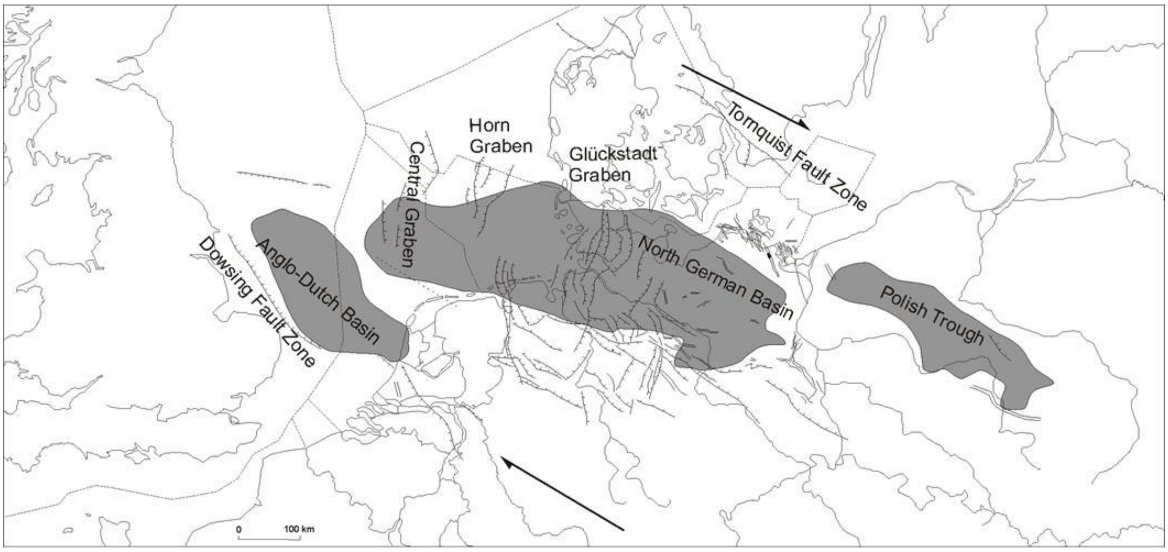


Figure 3.2 Map of subdivision of the Southern Permian Basin, which comprises the Anglo-Dutch and the North German Basins and the Polish Trough (outline during the Rotliegend Sediments) and the Late Triassic fault pattern (from Geluk, 2005).

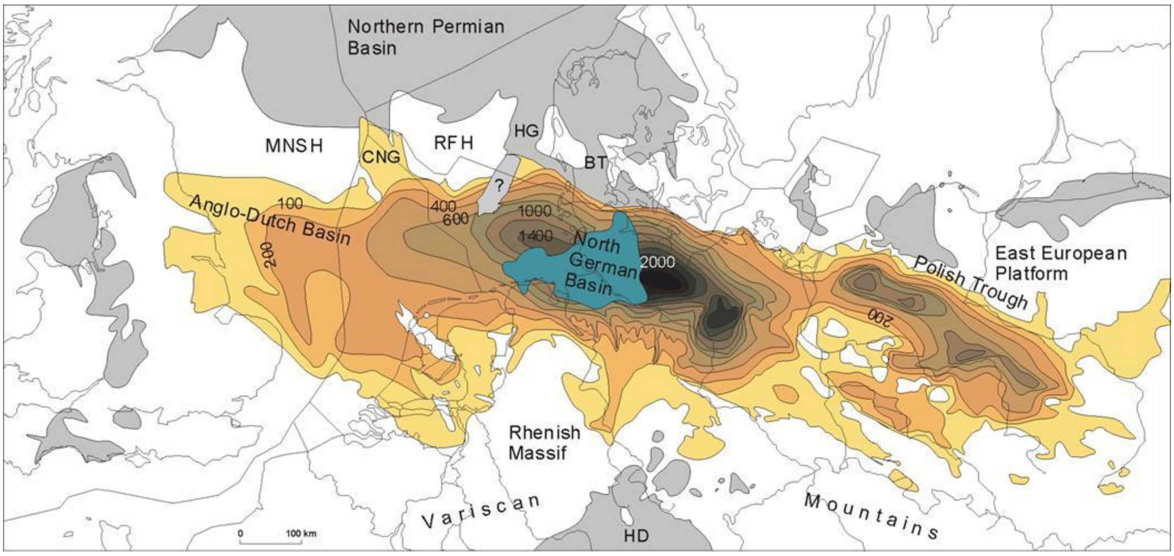


Figure 3.3 Isopach map of the Rotliegend Sediments in the Southern Permian Basin, these deposits can reach up thickness of 2000 m. The bluish area shows where the original thickness cannot be determined due to post-depositional movement of Rotliegend salt and erosion (from Geluk, 2005).

3.1.2 Triassic

The Southern Permian Basin as well as the Germanic Basin during Triassic times was affected by pulses extensional tectonics product of the break-up of Pangea, provoking a regional subsidence which started during the Lower Buntsandstein and Solling deposition and rifting in the Middle Buntsandstein and Middle Keuper deposition (Ziegler, 1999).

The tectonic evolution of the Germanic Basin was mainly controlled by two main systems: the reactivated Variscan structures composed of the Teisseyre-Tornquist Line, the Cracow-Odra-Hamburg Fault Belt, the Elbe Fault and the Saxo-Thuringian Lineament, situated in the eastern and southern parts of the basin. While the other system is composed of the North Sea rifting belt developed in the northwestern part of the basin (Feist-Burkhardt et al, 2008).

The Triassic Germanic Basin was located on the northern margin of the westward expanding Tethys Ocean overlie the Zechstein transgression composed of continental clastic deposits of eolian-fluvial, lacustrine, paralic and shallow marine environment (Feist-Burkhardt et al, 2008). The entire basin extends for more than 1500 km from the British Isles in the west to Poland in the east (Feist-Burkhardt et al, 2008). The complete Buntsandstein sequence is between 500 and 1200 m thick, but can reach up to 4000 m in graben structures. The Thuringian Basin[1] is part of the Mesozoic German Basin located between the west of Rhenish Massif and the east and southeast of the Bohemian Massif (figure 3.4). The main source of this Lower Triassic deposits are delivered by both Massifs and followed by marine carbonate deposited (Middle Triassic times) in northern extension of the Tethys Ocean.

In the Lower Buntsandstein Subgroup a regional subsidence started in the whole Southern Permian Basin due to thermal relaxation of the lithosphere and synsedimentary fault movements occurred during the deposition of Lower Buntsandstein sequence. These processes of synsedimentary fault control are mainly evidenced in the Glückstadt and Horn Grabens, both located in northwestern Germany. The grabens were formed under NW-SE extensional regime. Geluk (2005) suggested that thickness of the Lower Buntsandstein Subgroup remains fairly constant around 300 m, only varying notably in the Central, Horn and Glückstadt Grabens, like in the Polish Trough, showed a differential subsidence reaching up 400 m (figure 3.5).

During the deposition of the Middle Buntsandstein in the Southern Permian Basin took place two cross-cutting fault systems: one NNE-SSW trending and the other WNW-ESE trending (figure 3.6), which comprise a synsedimentary fault control with dextral

[1] In Triassic time, no separation existed between the north and south German Basin. The Thuringian Basin was part of this basin system, but not a basin in its own rights. Some authors therefore prefer the term “Thuringian Syncline”, but retain the established name “Thuringian Basin” in chapters 3 and 8.

transtensional movements of reactivated Variscan structures. The structural lineaments converge in the North German Basin (Geluk, 2005).

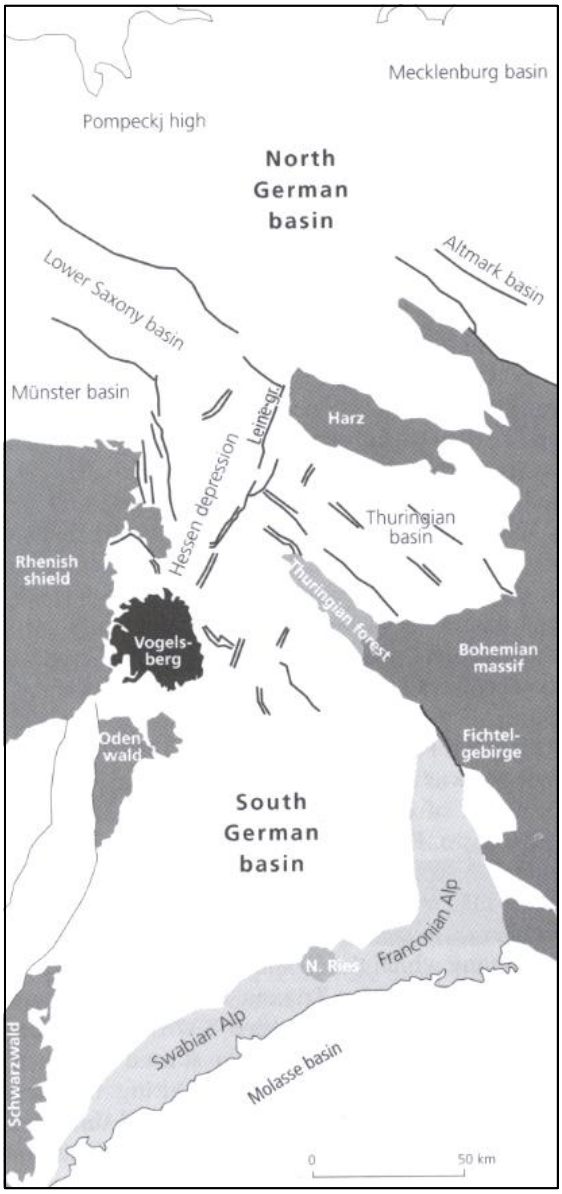


Figure 3.4 Location of the North, South German and Thuringian Basins* (from Demoulin, 2005).

Thickness differences due to differential subsidence across the basins are notable in the Middle Buntsandstein sequence (figure 3.6). In the Glückstadt and Horn grabens it can reach thicknesses of 2000 and 3500 m, respectively, and in the Polish Trough more than 1000 m. In other areas like the Central Graben the thickness decreases to 500 in the Eichsfeld-Altmark area to 130 m and in the Thuringian Basin in 140 m. Geluk et al (1997) affirm the changes of the thickness in the Middle Buntsandstein Subgroup are a product of a regional subsidence in the grabens, furthermore indicating the development of new subsidence axes, uplift on the borders and erosion along NNE-SSW and WNW-ESE trending faults. This tectonic activity caused the deposition of the Volpriehausen, Detfurth, Hardegsen and Solling Formation. During the deposition of Hardegsen Formation occurred a phase of extensional tectonics, associated with the break-up of Pangea and evidenced by isolated graben separated by transform faults (Ziegler, 1990).

The Solling Formation overlies the Hardegsen Unconformity (H-unconformity). This erosion surface cuts into the Lower and Middle Buntsandstein and even pre-Triassic rocks (figure 3.7). Geluk (2005) suggests the Solling Formation marks a break with the underlying units in terms of the basin geometry; the subsidence in the Northern German Basin was limited and in the Polish Trough the subsidence stopped as well as in Thuringian Syncline.

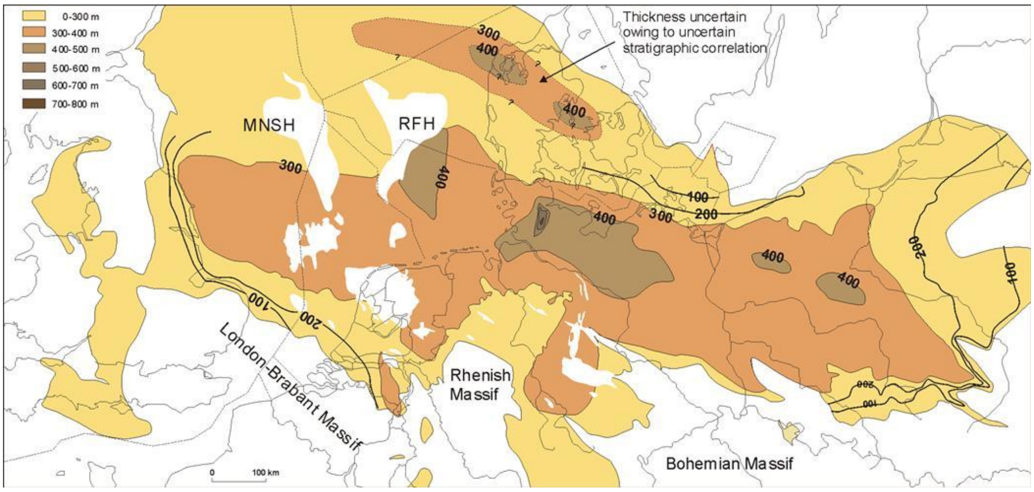


Figure 3.5 Isopach map of the Lower Buntsandstein Subgroup at the beginning of differential subsidence in the Glückstadt Graben. The map shows the thickness of the Southern Permian Basins area, between 200 and 400 m (from Geluk, 2005).

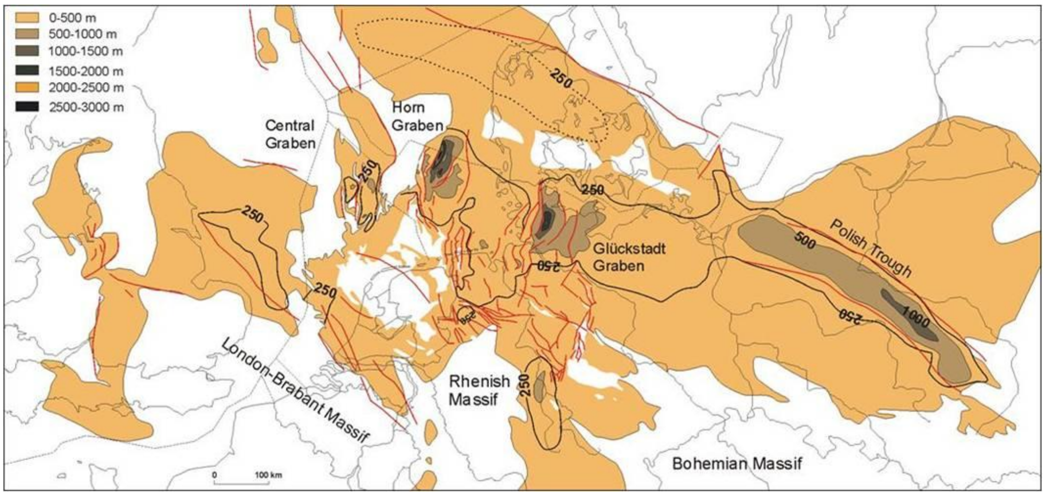


Figure 3.6 Isopach map of the Middle Buntsandstein Subgroup The map shows the strong subsidence of the Horn and Glückstadt Grabens and the Polish Trough (from Geluk, 2005).

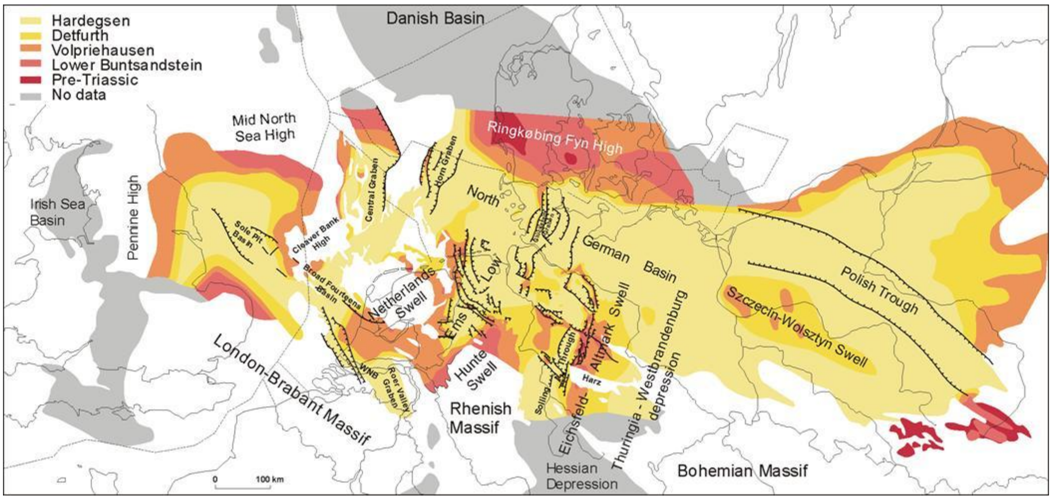


Figure 3.7 Subcrop map of the Hardegsen Unconformity. The Solling Formation was deposited over the Lower and Middle Buntsandstein and even on pre-Triassic rocks, product of strong tectonic movement (Geluk, 2005).

The deposition of the Upper Buntsandstein Subgroup (Röt Formation) in the Southern Permian and the South Germanic Basins are characterized by marine conditions resulting from transgression, which came from the Tethys Ocean trough the Silesian-Moravian Gate entered the German Basin and migrated into Thuringian and Württemberg along the Saxo-Thuringian subsidence centre (Feist-Burkhardt et al, 2008).

The tectonic activity was restricted in the Lower Röt sequence; which is composed of evaporitic facies. The subsidence was focussed on NNE-SSW trending troughs initiated during the Hardegsen sedimentation. The thickness of the Röt Formation in the Central, Horn and Glückstadt Grabens can exceed 300 m (Geluk, 1999b) (figure 3.8). This indicates a strong and rapid subsidence.

The upper part of the Röt Formation is composed of fined grained clastic of constant thickness, deposited in brackish-water lagoon. In the south-western offshore of the Netherlands, the formation decrease in 50 m, while in the Thuringian Basin, the Röt thicknesses display variation from 100 to 190 m. This lesser variability of thickness in the Upper Röt sequence indicates that the differential movement stopped during this period.

Geluk (2005) suggests that the change to clastic deposition in southern Germany could be the product of an increase in humidity, but in the Netherlands, northwestern Germany and Poland the environment was rather dry.

A regional regression took place in the western parts of the Southern Permian Basin during the period of the Röt deposition with the evaporitic facies grading into clastic deposits but not in eastern Poland, where carbonates sedimentation continued (Ziegler, 1990).

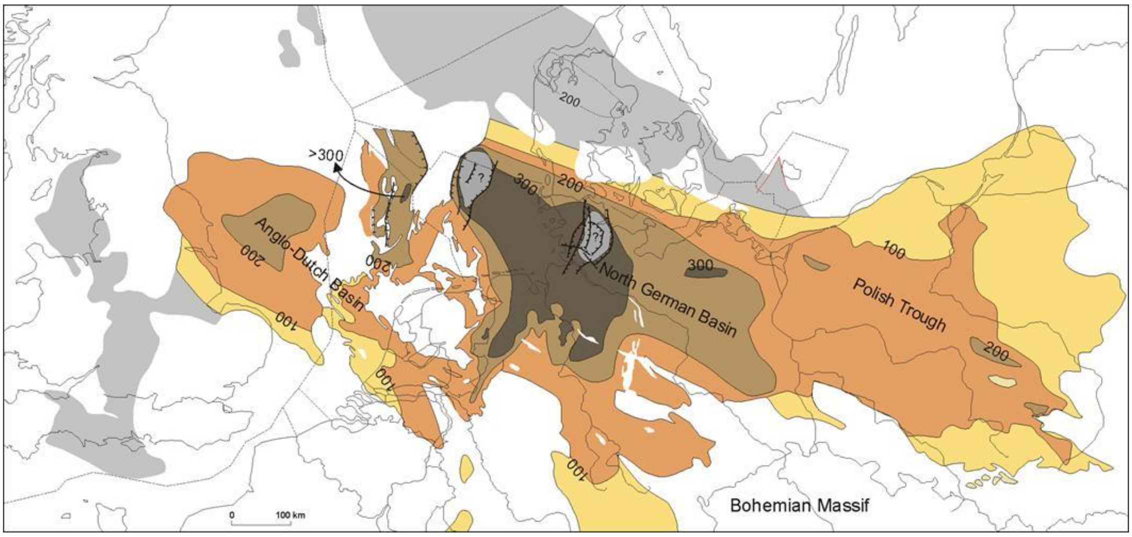


Figure 3.8 Isopach map of the Upper Buntsandstein (Röt Formation) the main subsidence patterns are located in Central, Horn and Glückstadt Graben with thickness of 300 m (Geluk, 2005).

The Muschelkalk Group represents a marine interval during the Middle Triassic comprises in the lower part (Lower Muschelkalk Subgroup) carbonatic deposits (grey limestones, dolomites and marlstones).

The Middle Muschelkalk Subgroup is dominated by evaporitic cycles, consisting of dolomites, anhydrites, halites and intercalated dolomitic claystone beds, while the upper part mainly consists of carbonates.

The Upper Muschelkalk Subgroup is composed of alternation of carbonatic deposits (limestones and marlstones) and claystone beds; it represents a transgressive period but with regressive cycles in the German Basin. The Upper Muschelkalk deposits comprises the most extensive event through the German Triassic (Stollhofen et al, 2008) and the top of Upper Muschelkalk Subgroup is characterized by content of clastic sediments product of the uplift in eastern and western areas. The thickness of the Muschelkalk Group in northern Germany ranges from 300 to 500 m, in Poland 450 m, in the southern North Sea about 400 m (figure 3.9) and in the Thuringian Basin from 200-250 m (Seidel, 2003).

Ziegler (1990) suggests that this thickness variation indicates continued differential subsidence of the major structural elements that had cut sequences since at least Middle Buntsandstein times. The main area of subsidence extended from North Germany into the Hessian Depression (figure 3.9). The Muschelkalk sequence presents a notable palegeographic change marked by a marine ingression from the Tethys Ocean into the western part of the Southern Permian Basin.

In some areas of the Southern Permian Basin semi arid conditions prevailed, as a result of limited access to sea water, at the same time there was an increase of extensional tectonics and subsidence in the Central, Horn and Glückstadt Grabens, reactivating numerous Variscan faults (Carboniferous Period) as in the Westdorf Graben in northwestern Germany and triggering subsidence associated to faulting in the NNE-SSW striking Hessian Depression (Geluk, 2005).

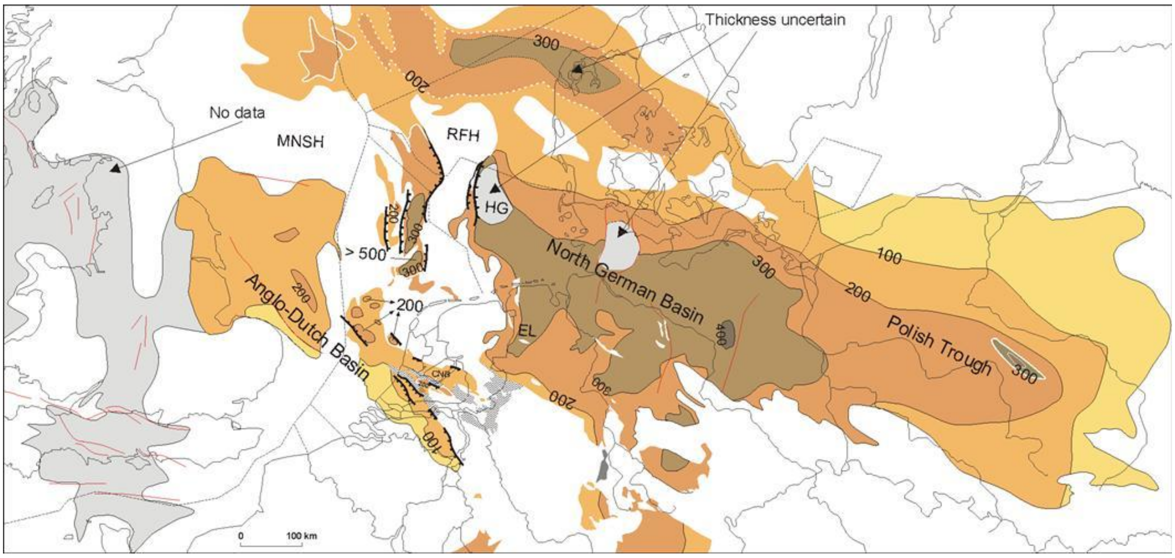


Figure 3.9 Isopach map of the Muschelkalk Group in the Southern Permian Basin showing thickness between 100 and 400 m. The main areas of subsidence area took place in the North German Basin (Geluk, 2005).

The complete Keuper Group in the Polish Trough and in northern Germany can reach a thickness of 2000 m, while in the Thuringian Basin decreases in 470 m (Seidel, 1995). This sedimentation occurred under climatic conditions between arid and humid. The Keuper Group was affected by extensional tectonic and induced salt movements occurred during the Late Triassic.

The deposition of the Lower Keuper Subgroup was controlled by sea level fluctuations and changes in precipitation. Fluvial and deltaic-estuarine systems were displayed from Fennoscandia along the southwestern basin margin in humid periods of level sea conditions. Marine ingressions reached the North German Basin through the Burgundy Gate, the Hessian Depression and the East Carpathian Gate with evidence of carbonatic deposits and fossiliferous fine grained sediments. The upper part of the Lower Keuper

Subgroup is marked by a regressive phase and erosional processes through the German Basins (figure 3.10).

The Lower Keuper deposits through the Southern Permian Basin shows uniform thicknesses between 80 and 125 m, while the Glückstadt Graben has 600 m of accumulated sediment (Geluk, 2005). It suggests a period of relative low tectonic activity. Three (3) main extensional structures in NNE-SSW trending are recognized during the deposition of the Keuper Group: the Horn-Ems Low, the Glückstadt Graben and the Gifhorn rift zone. The Glückstadt Graben comprises a synsedimentary subsidence with a sediments accumulation of reaching 5800 m (Stollhofen et al, 2008).

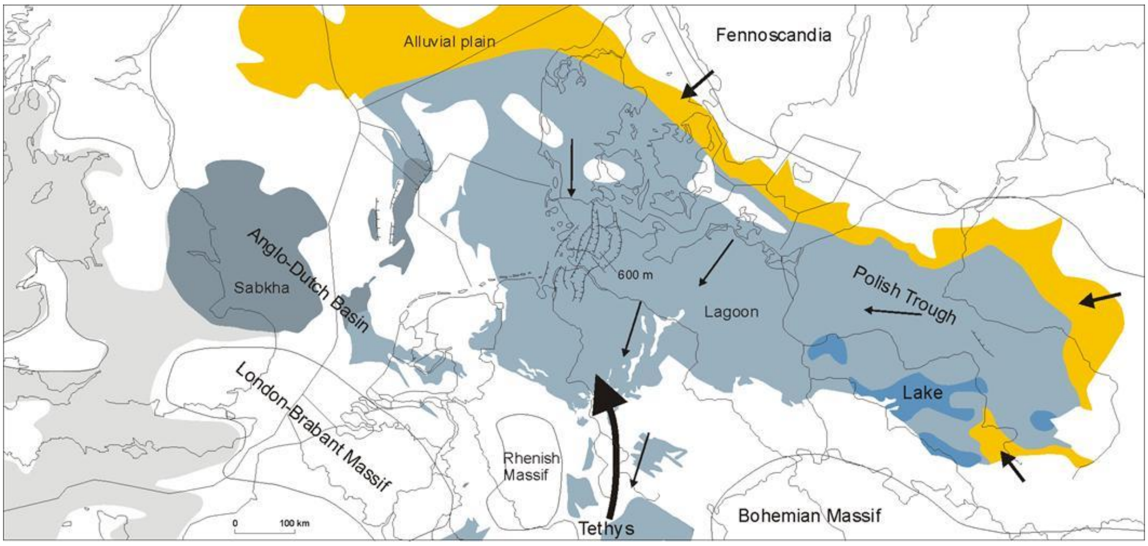


Figure 3.10 Distribution and facies map of the Lower Keuper (Late Ladinian) showing fluvial and deltaic-estuarine systems distributed from the Fennoscandia along the southwestern basin and marine ingression via the Burgundy Gate/Hessian Depression (from Geluk, 2005).

The lower part of the Middle Keuper Subgroup (the Lower Gipskeuper) coincides with a climate change toward arid conditions causing evaporitic deposits. An increase in subsidence produced by the strong rift pulses of the Early Kimmerian phase occurred during this period in the Glückstadt Graben. The thickness in this area can reach 5000 m and in other grabens 1000 to 1500 m. Geluk (1999b) affirms that in areas not affected by graben subsidence, the Lower Gipskeuper varies from 50 to 300 m. only in the Glückstadt Graben is mentioned 600 m.

Over the Lower Gipskeuper deposits follow the Schilfsandstein sediments deposited in the Northern German Basin in a fluvial-deltaic system under semi-arid climatic conditions. The subsidence during the Schilfsandstein sedimentation was relatively low but the humidity was high. The thickness along the Southern Permian Basin keeps relative constant, it varies from 50 to 150 m.

On the contrary to the Lower Gipskeuper and the Schilfsandstein deposits, extensional tectonic events occurred during the Upper Gipskeuper deposition, creating a notable subsidence in the external parts of the Glückstadt Graben and in other grabens embracing thicknesses over 4500 m. While in some areas of northwestern Germany the thickness reduces till 1000 m (figure 3.11). These deposits are composed of saline deposits (halite) and siltstones deposited in mudflat-playa system.

According to Geluk (2005), salts bodies were reduced during the deposition of the Upper Gipskeuper sediments compared with the Lower Gipskeuper deposition, only those in the Central, Horn and Glückstadt Grabens are notable.

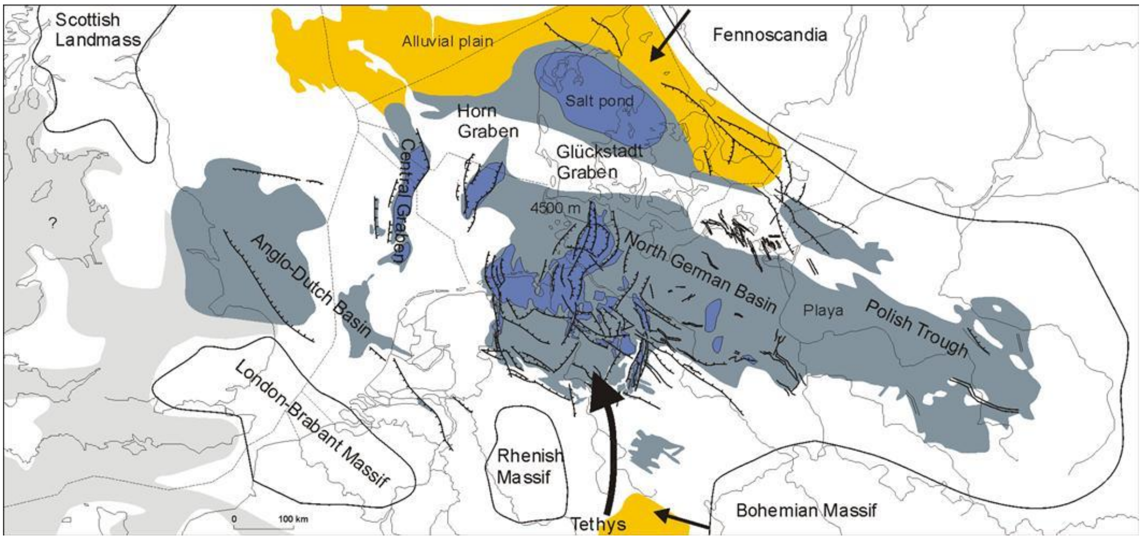


Figure 3.11 Distribution and facies map of the Upper Gipskeuper showing saline deposits in the North German Basin also the strong subsidence in the external parts of Glückstadt Graben where the thickness reach up 4500 m (from Geluk, 2005)

The Steinmergelkeuper comprises the upper part of the Middle Keuper. It represents post rift sedimentation with thicknesses almost uniform along the entire Southern Permian Basin from 50, 200 and 400 m in the southern Netherlands, the Central and the Glückstadt Graben, respectively (Geluk, 2005). These deposits are associated to a playa environment with some marine influence in southern Germany. This marine sedimentation is documented by carbonate intercalations.

The Upper Steinmergelkeuper is overlain by the Rhaetic Keuper. These sequences mark the transition from an epicontinental system to marine conditions. The thicknesses in the

North German Basin vary between 100 and 300 m and in the south of Glückstadt Graben reach till 600 m (Geluk, 2005). The Rhaetic Keuper deposits represent a notable connection with open sea situated toward the west between the Pennines High and the London Brabant Massif. Ziegler (1990) suggests that the Tethys Sea was connected with the Southern Permian Basin.

A deltaic system can be observed in some areas of southern Germany several sandstone units delivered by the Fennoscandia and the Bohemian Massif. According to Geluk (2005) the Rhaetic Keuper has a thickness between 20 and 100 m, while in the southern part of the Glückstadt Graben it reaches up 600 m.

4 Stratigraphy and sedimentation of the Buntsandstein Group in the German Basins

4.1 Geological framework

After the Variscan Orogeny and widespread extension in Early Permian (Rotliengend) time, the intracontinental Central European evolves. The transition between the Late Permian and the Triassic is marked by a reorganization of plate boundaries indicating the Mesozoic break up (Ziegler, 1990) und suggesting the Central European Basin started to during the Permian-Triassic times.

The boundary between the Zechstein and Buntsandstein is considered as conformable and characterized by high influx of sand defining the base of the Buntsandstein (Stollhofen et al, 2008).

The Zechstein Group is marked by a transgression representing the first marine ingression after the dominantly continental deposits of the Rotliegend Group which consists of succession hypersaline and sabkha sediments (evaporation cycles); composed of Werra (Z1), Staßfurt (Z2), Leine (Z3) and Aller (Z4) Folge. The Zechstein Group reaches thicknesses between 1000 and 1500 m through the Permian Basins and notably influenced the internal structure of the Germanic Triassic Basin, where the sedimentary patterns are extensively affected by Permian salt movements.

The Buntsandstein Group represents deposits formed during the Induan period to Early Anisian (Early Triassic) in intracratonic basin and characterized by a marginal position in the southeastern part of the Germanic Basin. It presents a notable variety of alternation of sediments, deposited in an area of epicontinental basin and mainly composed of fluvial-lacustrine, eolian, paralic, calcareous and evaporitic deposits with a predominate direction NW-SE. According to Geluk et al (1997), the thickness of the whole Buntsandstein Group displays from 500 to 1000 m and can reach up to 4000 m in the Glückstadt Graben, situated in northwestern Germany. This variation of thickness in the Triassic sediments indicates differential subsidence. The presence of the thin oolite beds in the Lower and Middle Buntsandstein Subgroups in some areas of Germany is evidence of a brackish water environment (playa deposits). The Buntsandstein Group succession into basin axes suggests deposition during thermal subsidence after an early rifting episode (Ziegler 1990).

The facies in the Lower and Middle Buntsandstein Subgroups fluctuate between fluvial-aeolian sandstones and floodplain- lacustrine deposits. The lithostratigraphic subdivision of the clastic and unfosiliferous deposits presents an asymmetric cyclic grain size pattern which is identifiable across the whole basins (Boigk 1959).

The thickness of Middle Buntsandstein Subgroup in the Eichsfeld Swell area was notably reduced, where the Detfurth and Hardegsen Formation are missing (Trusheim 1961), while increases to the east and to centre of Thuringian Syncline. These patterns suggest that the thickness differential could be produced by effects of rate subsidence. The paleotectonic elements present a NNE-SSW direction and do not coincide with the tectonic axis of Thuringian Syncline.

The Lower Buntsandstein sediments rest over the Zechstein Group in the Thuringian Syncline which is associated to sandstones, prograding from the southeast into the basin. In the southern and southeastern Thuringian Syncline, the Lower Buntsandstein facies are characterized by channel sandstones, floodplain deposits and eolian intercalations.

The Calvörde and Bernburg Formations have two main fining upward cycles composed of red brown siltstones, and intercalations of sandstones. In the centre of the Thuringian Syncline, the Lower Buntsandstein deposits contain oolitic limestone horizons (Puff 1995).

The Middle Buntsandstein Subgroup has been influenced from fluvial-eolian to lacustrine environments with transport direction from south to north and from south to NNE comprising megacycles defined by Boigk (1956) and observed in the wirelines logs recognized by Boigk (1959) and Trusheim (1963).

The Volpriehausen and Detfurth Formations are defined as fining-upward cycles with sandy deposits of braided rivers, the floodplain-channel ratio increases to the top of both formations.

The Hardegsen Formation is mainly composed of siltstones with sandstone intercalation in minor scale; in areas close to the Thuringian Syncline as the Eichsfeld Altmark swell this formation is missing.

The Solling Formation presents fluvial deposits over a regional unconformity and climatic change to more precipitation, which is indicated by plant fossils, calcareous material at the base of sandstone channels, this unit was defined by Boigk (1961).

The Röt Formation (Upper Buntsandstein) is characterized for being the first marine ingression into the German Basins during the Triassic dominated by evaporitic deposits grading to claystones and siltstones facies comprising shallow marine to sabkha mudplain environment.

The Buntsandstein Group of the German Basins has been subdivided by different authors, e.q. Hoppe (1959), Hoppe (1974), Radzinski (1967), Radzinski (1995) and Puff (1995) in the three (3) main subgroups (table 4.1): the Lower, Middle and Upper Buntsandstein.

Period	Epoch	Group	Formation
Triassic	Middle	Upper Buntsandstein (so)	Roter Röt Fm (soPUGPO+M)
			Grauer Röt Fm (soSA+PUM)
	Early	Middle Buntsandstein (sm)	Solling Fm (smS)
			Hardegsen Fm (smH)
			Detfurth Fm (smD)
			Volpriehausen Fm (smV)
		Lower Buntsandstein (su)	Bernburg Fm (suB)
			Calvörde Fm (suC)

Table 4.1 Stratigraphic subdivisions of the Buntsandstein Group in the German Basins

4.2 The Lower Buntsandstein Subgroup (su)

The Lower Buntsandstein Subgroup represents the first fining upward cycle above the Zechstein Group sequence mainly composed of fine-grained and red-brown clayey siltstones, with intercalation of sandstones and oolitic beds formed in brackish water environment which increases towards the top of the subgroup. It presents an average thickness between 200 and 400 m in the German Basins. Based on lithologic difference, the Lower Buntsandstein has been subdivided in Calvörde (suC) and Bernburg (suB) Formations and can be correlated across the Germanic Basin.

According to Geluk et al (1998), the Lower Buntsandstein Subgroup presents a sedimentation marked by cyclic and climatic changes, generating two main sequences with facies and thickness that indicate uniform and slow subsidence and delivery of sediment and water from the south.

4.3 Middle Buntsandstein Subgroup

The Middle Buntsandstein Subgroup in the German Basins has an average thickness from 140 to 3500 m. It mainly consists of intercalation sandstones, claystones and siltstones. The Middle Buntsandstein is subdivided into four (4) mains formations, representing tectono-stratigraphic units: the Volpriehausen (smV), Detfurth (smD), Hardegsen (smH) and Solling (smS) Formation (table 3.1). Each formation is characterized by a fining upward cycles with basal sandstone, grading into siltstones and claystones towards the top.

4.3.1 Volpriehausen Formation (smV)

The Volpriehausen Formation begins mainly over clayey succession of the lower Buntsandstein. It comprises compact basal coarse grained sandstone followed by an alternation of clay-siltstone and thin sandstones. Trusheim (1961) suggests a regional low relief angular unconformity in northern Germany found at the base of the Volpriehausen denominated the “V-unconformity”. This erosion cuts the Bernburg Formation in different subcycles in the Hunte and Eichsfeld-Altmark Swell areas, where the thickness of Bernburg succession decreases. The total thickness of the Volpriehausen Formation can vary between 90 and 120 m consisting of well developed fining upward cycles. According to Geluk et al (1999) the Volpriehausen Formation has been deposited during the first two series of four rifting pulses. The basal sandstone is mainly dominated by fluvial systems. The uppermost Volpriehausen comprises the “Volpriehausen-Wechselfolge” (clay siltstone) and the “Aviculaschichten (thin sandstones and claystone), respectively. The Upper Volpriehausen Formation is marked by bivalves and chonchostracans, mainly composed by clay-siltstone deposit with thin sandstones toward the top of the succession (Kozur & Seidel, 1983b.). The upper part of Volpriehausen Formation (the *“Avicula-Schichten”* Member) is composed of a succession of fining-upward cycles of lacustrine and eolian deposits which were deposited in almost the entire Thuringian Syncline, keeping a relative constant thickness.

4.3.2 Detfurth Formation (smD)

The Detfurth Formation is characterized by basal coarse grained sandstones (the “Detfurth Sandstein”) comprising fining-upward cycles. The base of Detfurth Formation presents a notable unconformity in the southern and western offshore areas of the Netherlands, but in the German Basins is less prominent. Röhling (1991) states, that the Detfurth Formation overlies unconformable on different subcycles of the “Volpriehausen Aviculaschichten” or the “Volpriehausen Wechselfolge”.

The Upper Detfurth (the “Detfurth-Wechselfolge”) represents fining-upward cycles mainly composed of claystones and dominated by lacustrine environment. The “Detfurth-Wechselfolge” is marked by the presence of bivalves and chonchostracans. The thickness of the whole Detfurth Formation in the Germanic Basin can fluctuate between 40 and 70 m.

4.3.3 Hardegsen Formation (smH)

The Hardegsen Formation comprises a rhythmic arrangement of five fining-upward cycles of material from coarse grained to fine grained. According to Röhling (1991) each cycle comprises four subcycles. The lithology is composed by alternation of reddish brown or grey sandstones and red siltstones which is dominated by fluvial system. Radzinski et al (2001) stated that the thickness of Hardegsen can have a notable variation through the German basins, influenced by the pre-Solling erosion. Geluk (2005) indicates that the Hardegsen Formation does not represent an independent sequence but rather belongs to a unique Detfurth-Hardegsen sequence.

4.3.4 Solling Formation (smS)

The Solling Formation rests uncomfortably on the H-unconformity over different formations of the Buntsandstein Group or even the Zechstein Group along the Germanic Basin, displaying variable thickness from 5 to 140 m, while the Thuringian Syncline only reaches up a maximum of 30 m (Puff et al in Seidel, 2003). The Solling Formation is defined as fluvial and eolian deposits but in some areas toward the top is characterized by a marine ingression.

Röhling (1986) states that the Solling Formation comprises different facies developments in different paleogeographic units comprising regional facies changes, this formation has been mainly subdivided in a coarse grained basal sandstone denominated Solling Basissandstein mainly characterized by low gamma-ray peaks and variable thicknesses throughout the German Basins. In areas as the Weser Trough is found a lower unit denominated the “Horizont der Grauen Tone” composed of reddish brown claystone and notable high gamma ray peaks (Rettig 1996), which overlies the Basis Solling (Rettig, 1996).

The Solling Basissandstein is followed by the “Tonige Zwischen-Schichten” composed of fine grained sandstone with clayish interlayer and colour variation of yellowish grey, reddish brown and violet grey in Reinhardswald, southern Bramwald located in Hessen and Lower Saxony respectively. In the Eichsfeld-Altmark Swell, this unit is denominated The “Holunger Wechselfolge” composed of carbonatic grey fined grained sandstones; with thicknesses oscillating between 0.5 and 4 m in the well Holungen-1 observed by Gaertner 1961 (in Rettig 1996). The “Holunger Wechselfolge” in the western Eichsfeld-Altmark Swell is missing or partially eroded, product of the stratigraphic erosive surface (the intra Solling unconformity) (table 4.2).

The upper part of the Solling Formation comprises fine grained sandstone with shale intercalation labelled with grey and light reddish brown colour denominates “the Chirotherien Sandstone”, also called “the Thüringer Chirotheriensandstein” in the eastern Thuringian area. The Chirotherien Sandstone rests directly on the Basis Solling in local areas product of the intra-Solling unconformity. In the Finne area located in the northern Thuringian Syncline, only the “Chirotherien Sandstone” is present (Radzinski et al 1997).

	Gaertner (1961/63		NW- Thuringian (TLG-25234/11)	N- Hessen (Lukas & Wenzel 1991)	Hannover-Eichsfeld (Herrmann & Hofrichter 1963b)	Ritter (1996) W-Schwelle boundary	Central Schwelle
Röt Formation							
Solling Formation	Chirotherien Sandstone	Upper bank	Thüringer Chirotherien Sandstone	Thüringer Chirotherien Sandstone	Chirotherien Sandstone	Thüringer Chirotherien Sandstone	
		Tonige Grenzschichten (Solling Claystones)	Tonige Grenzschichten (Solling Claystones)	Tonige Grenzschichten (Solling Claystones)	Basis Solling	S- unconformity Basis Solling	Holunger Wechselfolge Basis Solling
		Lower bank	Basis Solling	Solling Sandstone		*(Comprises from smS1 to sm S3)	Comprising sm S1
H- unconformity							

Table 4.2 Subdivision of the Solling Formation in Eichsfeld-Altmark Swell and other nearby areas proposed by different authors (Rettig 1996)

4.4 The Upper Buntsandstein Subgroup

The Upper Buntsandstein begins with a basal anhydrite. It mainly consists of evaporites and claystones, subdivided in Salinarröt and Röt Formation and reaches up to 300 m of thickness. This transition from Solling to Röt Formation is interpreted as an increment of marine influence attributed to a transgressive surface. The Salinarröt Formation consists of massive halite and anhydrite layer and the Röt Formation comprises fine grained clastic; silty claystones with intercalated carbonates overlie on the evaporitic deposits.

5. Stratigraphy and sedimentation in the northwestern Thuringian Syncline

5.1. Data base, working method and concepts

The data base used for the stratigraphic correlation and the facies study in the Northwestern Thuringian Syncline were the electric logs, basically composed of spontaneous potential (SP), gamma ray (GR), and resistivity log of 134 wells. 13 well boreholes of them show deviation survey (table 5.1). This information was received on paper and digitized and converted in digital format "*las* and *txt*" (appendix 1). The deviated wells do not present notable change, the inclination angle keeps almost vertical, there is not a notable difference between the measured depth (MD) and the true vertical depth (TVD) (figure 5.1).

Wells	Deviation Survey
All 32	X
FH 09	X
FH 11	X
FH 17	X
Kch 12	X
Kch 29	X
Kch 81	X
Kch 83	X
Küd 2	X
La 22	X
La 24	X
Mh 25	X
Mh 30	X

Table 5.1 Well logs with deviation survey in the study area constituted of 13 boreholes.

The spontaneous potential log (SP)

The spontaneous potential (SP) measures the potential, the difference in electromotive force in millivolts (mV), also the difference in salinity between the drilling mud and the fluid (formation water) in the pores of the rock. The measurement of this log can only be made in open holes filled with conductive mud.

The readings of the spontaneous potential logs are interpreted as negative to the left and positive to the right. Under normal circumstances where the fluid in the rock is older than the drilling mud, the deflection of the curves is high to the left side of scale (negative measure), giving information about porous rock (sandstones) and if the reading is positive (toward the right); It presents a non porous rock like shales, limestones or evaporites. A poorly defined or without reflection occurs the salinity of the mud is similar to the water formation as there is no good interpretation of the kind of rock.

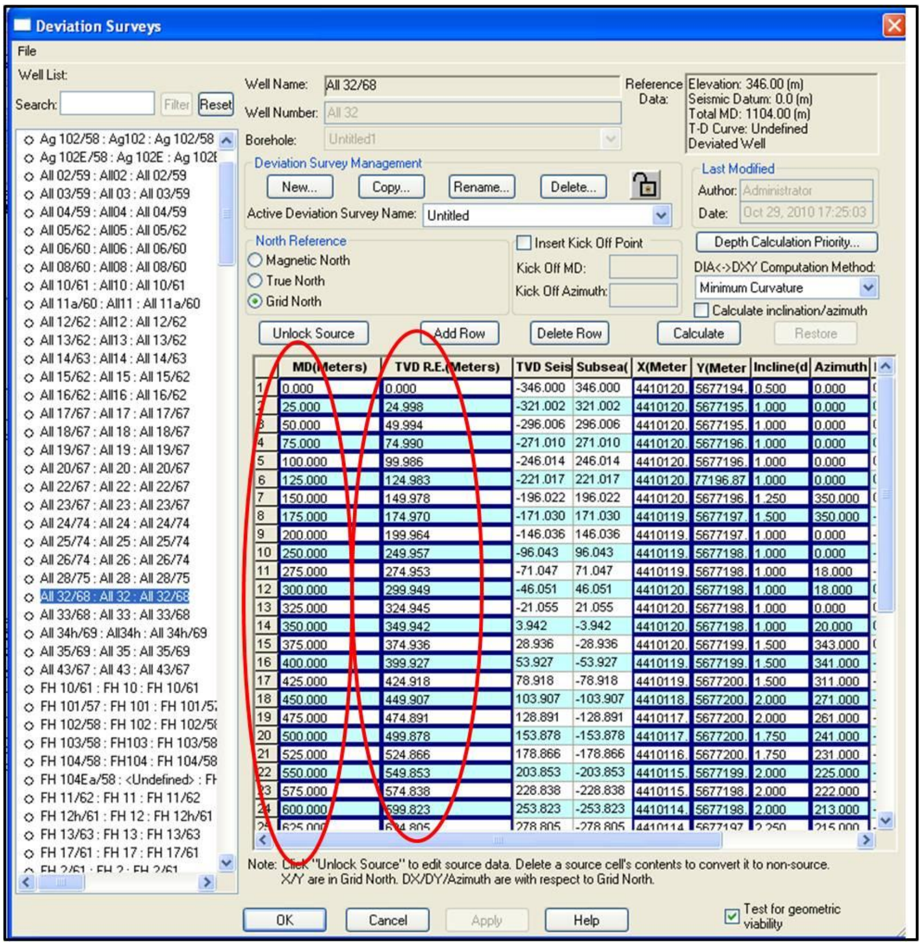


Figure 5.1 Deviation survey of the well Allmenhausen-33. There is no notable difference between measured depth (MD) and true vertical depth (TVD).

Radioactivity Log

There are basically two types of radioactivity log: the gamma ray (GR) and the neutron log (figure 5.2):

The gamma-ray (GR) log is used to measure the natural radioactivity of formations, which is very important to identify lithology in a borehole. This curve can differentiate argillaceous and non argillaceous rock mainly for identification of shales and other sedimentary rocks as sandstone, limestone or dolomite. The main radioactive element in the rocks is potassium (K), which is present in illitic clays, feldspars, mica, and glauconite. The gamma ray log also can be used to identify other radioactive elements like uranium and thorium. This log is normally measured in API (American Petroleum Institute) and CPS (counters per second[2]) units normally plotted on a scale from 0 to 100. However if the sandstones have numerous feldspars this curve is not useful due to it has higher values than usual gamma readings. The gamma ray logs can be affected by the diameter of the borehole and the properties of the fluids. The conventional nomenclature of the gamma log is presented on the left hand column in similar manner or together with the spontaneous potential log (figure 5.2).

The neutron log measures the amount of hydrogen in the fluids, essentiality correlative with the porosity and the fluids in the pore space of the rock (oil, gas, water and mud filtrate). However the neutron log cannot differentiate the content of them due to the fluids have similar percentages of hydrogen nuclei. The neutron log is shown to the right of the depth scale recorded normally in API, LPUs and SPUs units and is recommendable to be used together with the gamma-ray log (figure 5.2).

Resistivity log

The three main ways of measuring the electrical resistivity in the formations are: the normal, the lateral and the induction logs.

The measured resistivity (*R*) is proportional to the fluid (water) resistivity (Rw) and inversely proportional to the product of the porosity fraction and the water saturation. The electrical resistivity of formations can vary notably, in the porous rock saturated with gas, oil or fresh water, the measurement shows high resistivity and when the porous rock is saturated with salty water or brine, the log shows low resistivity.

When the run of the resistivity log is simultaneously made with the spontaneous potential (SP) log the interpretation of the lithology and the nature of the pores fluid can be done better. The unit used in the resistivity run is the Ohm-meter (Ω-m).

The stratigraphic correlation in this project is principally based in the available electric logs; they allowed to make a lithology interpretation, determination of stratigraphic horizons, as well as electrofacies definition and lateral changes.

[2] The radioactivity of rocks is normally measured in API, but there is not a direct calibration from CPS to API units. To avoid confusions and errors in the gamma ray logs, the data used in this work is plotted in CPS units.

For the lithologic and facies description; the cores of wells Fahner Höhe-13 and Rockensußra-2 were used, as well as cutting descriptions of the majority of wells taken from the "Thüringer Landesanstalt für Umwelt und Geologie". Excursions to the eastern and northeastern margins of the Thuringian Syncline were made, additionally diverse studies about the Thuringian Syncline were used such as Boigk (1956, 1959), Seidel (1995), Gaupp (1998), Voigt & Gaupp (2000) etc.

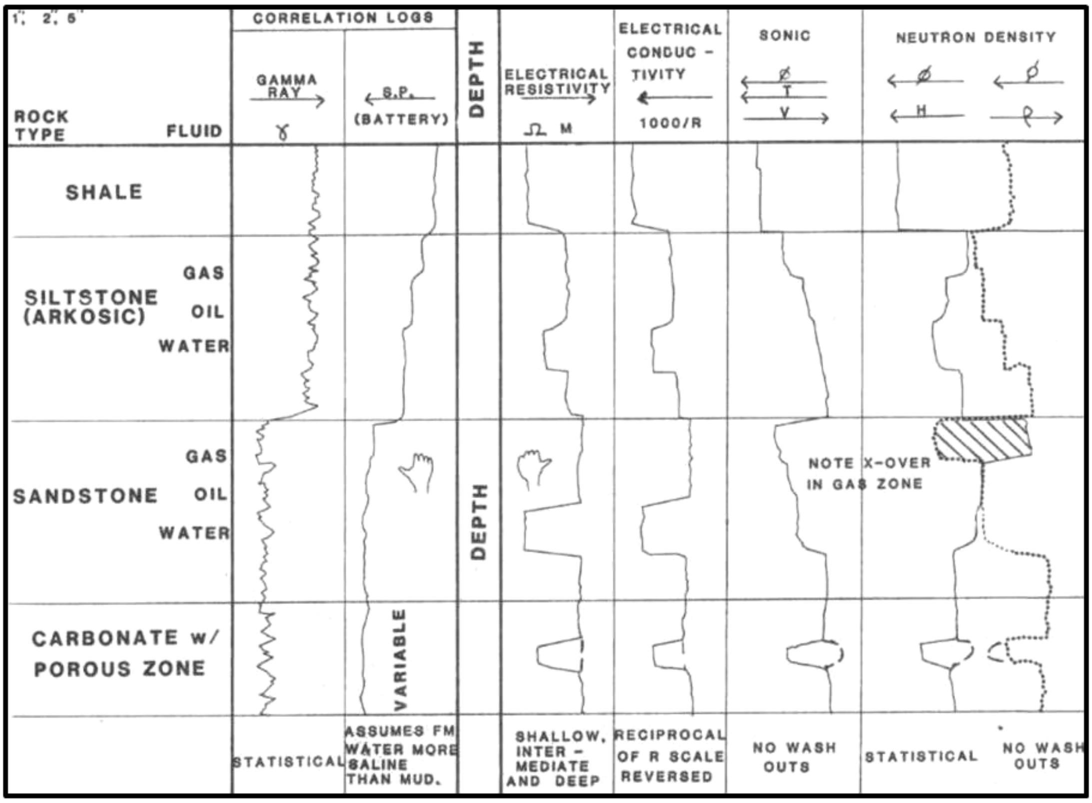


Figure 5.2 Spontaneous potential radioactivity and resistivity logs showing the correlation in different rock types (from Laudon, 1996)

5.2. Lithostratigraphic correlation of the Middle Buntsandstein Subgroup

The lithostratigraphic correlation of the Middle Buntsandstein Subgroup (sm) through the studied area has been defined in detail, using the concept and the lithostratigraphic subdivision defined by authors like Boigk (1951), Boigk (1965), Radzinski (1967), Röhling (1991), Seidel (1995), Radzinski and Seidel (1997), and Roman (2004). The Middle Buntsandstein Subgroup is divided into four megacycles; Volpriehausen (smV), Hardegsen (smH), Detfurth (smD) and Solling (smS) Formation, with each cycle is composed of fining upward sequences with a coarser grained basal sandstone and fined grained sandstones towards the top, Röhling (1991) states that the Middle Buntsandstein sequence, except for the Hardegsen Formation are characterized by basal unconformities.

The lower boundary of the Middle Buntsandstein Subgroup is the base of Volpriehausen Formation, above the Bernburg Formation (the Upper Folge of the Lower Buntsandstein Subgroup) and the upper boundary below the base of the Salinarröt Formation (Upper Buntsandstein Subgroup) can be clearly identified and indentified on each well log of the studied area.

The upper part of the Lower Buntsandstein Subgroup (Bernburg Formation) shows a curve deflection of the gamma ray with low pick or tendency to the right, reflecting shale intercalations and thin sandstones, while at the base of the Volpriehausen Formation, the well log decreases showing the curve with a notable pick to the left, which indicates sequences composed of compact sandstone and minor content of shale (figure 5.5).

The Lower-Middle Buntsandstein boundary is well defined through the Thuringian Syncline, which is visibly exposed in the valley of the Unstrut River near Wangen in the northeastern margin. Gaupp et al (1998) described the top Bernburg Formation as a sequence of fine grained white sandstones with some oolitic limestones interpreted as beach deposits of a shallow playa lake or a marginal sea.

The transition from Bernburg to Volpriehausen Formation is marked by red laminated claystones with intercalated thin sandstones representing a possible coarsing upward sequence at the upper part of the Bernburg Formation. The basal Volpriehausen is composed of medium grained reddish green fluvial-eolian sandstones with intercalated thin clay beds.

Trusheim (1961) states a regional unconformity at the base of Volpriehausen through the Germanic Basin mainly observed on the northern margin and in the Hessian Depression. In the outcrops near Wangen in the Northern Thuringian Syncline no erosive surface in the boundary between the Bernburg and Volpriehausen Formation has been observed (figure 5.3).

Röhling (1999) suggested a new lithostratigraphic unit in the lowermost Middle Buntsandstein in the North German Lowlands area denominated the “Quickborn Sandstone”. This unit rests unconformably (the V-unconformity) upon the Bernburg

Formation and is followed by the coarser grained basal sandstone of the Volpriehausen Formation displaying thicknesses between 15 and 50 m. Röhling (1999) states that the “Quickborn Unit” is truncated by the Volpriehausen unconformity. The gamma ray log of the “Quickborn Sandstone” is defined by a notable decrease in the radiation comprising a lithology of reddish brown sandstones and subordinate siltstone layers. Therefore this V-unconformity at the base of the Volpriehausen sequences is recognized by Röhling and Seidel (2008) in the Eichsfeld Altmark Swell stating that the thickness of the Bernburg Formation are notable reduced along this area.

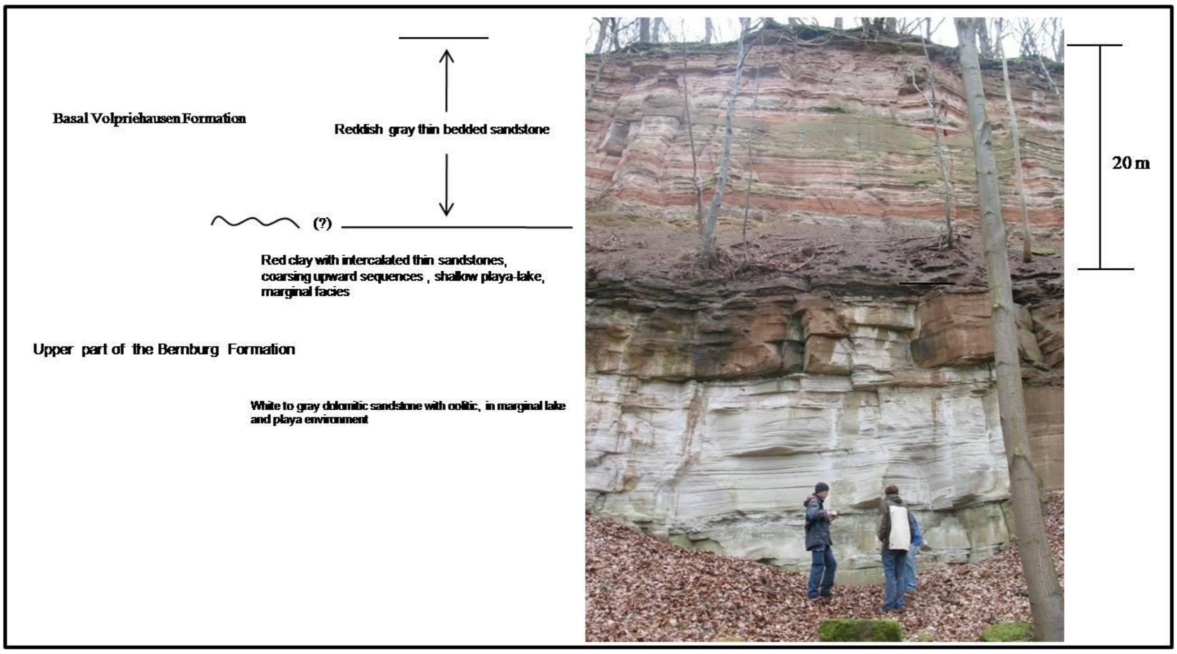


Figure 5.3 Outcrop in the area of Wangen showing the boundary between the Lower Buntsandstein (Bernburg Formation) and the basal Volpriehausen Formation. The top of the Bernburg Formation is composed of red laminated claystones and thin sandstones and the Volpriehausen base exposes medium grained reddish sandstones with some desiccation cracks.

The boundary between Volpriehausen and Detfurth Formation is clearly to differentiate in the gamma ray log. The upper part of the Volpriehausen Formation is notably marked by high radiation of gamma rays which indicates a higher content of shale and siltstones (figure 5.5). While the base of Detfurth Formation is characterized by a decrease of gamma log radiation suggesting the beginning of a new cycle, composed of basal sandstones well correlated through the Germanic Basin.

The boundary between the Hardegsen and Solling Formations is more difficult to identify; the lower boundary of Solling is marked by the so called H-unconformity which indicates that the Solling can rest on Hardegsen cycles or on pre-Hardegsen successions. The

Solling base mainly consists of thin basal sandstone identified as the "Solling Basissandstein" composed of coarse grained sandstone and characterized by decrease of radiation in the gamma-ray log.

For the definition of the upper boundary of the Middle Buntsandstein the base of the Röt Formation was established, which is marked by grey massive anhydrite bed (Basis-anhydrit) reported in the information of cutting descriptions received from the "Thüringer Landesanstalt für Umwelt und Geologie". In the same way the gamma ray curve shows a tendency to the left side with notable blocky shape, indicating very low radiation. This characteristic at the boundary between the Middle Buntsandstein and the Upper Buntsandstein has been used to establish the top of the Solling Formation as stratigraphical which is clearly identified in all wells.

Eight (8) stratigraphic cross-sections for the Middle Buntsandstein Subgroup were established in detail, using a horizontal scale (in equal distance) to 1: 5000 (m) and vertically scaled to 1:1500 (m). The cross-sections were oriented in west-east (W-E), northwest-southeast (NW-SE) and northeast-southwest (NE-SE) direction (figure 5.4). They were built up to visualize the stratigraphy, the continuity of sand bodies and facies heterogeneity. The log Kirchheilingen-32 was defined as the type log, which shows all lithostratigraphic units and the sequences studied in this work (figure 5.6).

The complete succession of the Middle Buntsandstein Subgroup in the study area displays an average thickness of 173 m. The maximum thickness reaches 223 m located in the western and the southwestern area (figure 5.7). It can be observed in the well logs, Straußfurt-2 and Straußfurt-3. The thickness is reduced in the centre and western area to 132 m in the wells Küllstedt-1 and Küllstedt-2 located in Eichsfeld Swell area.

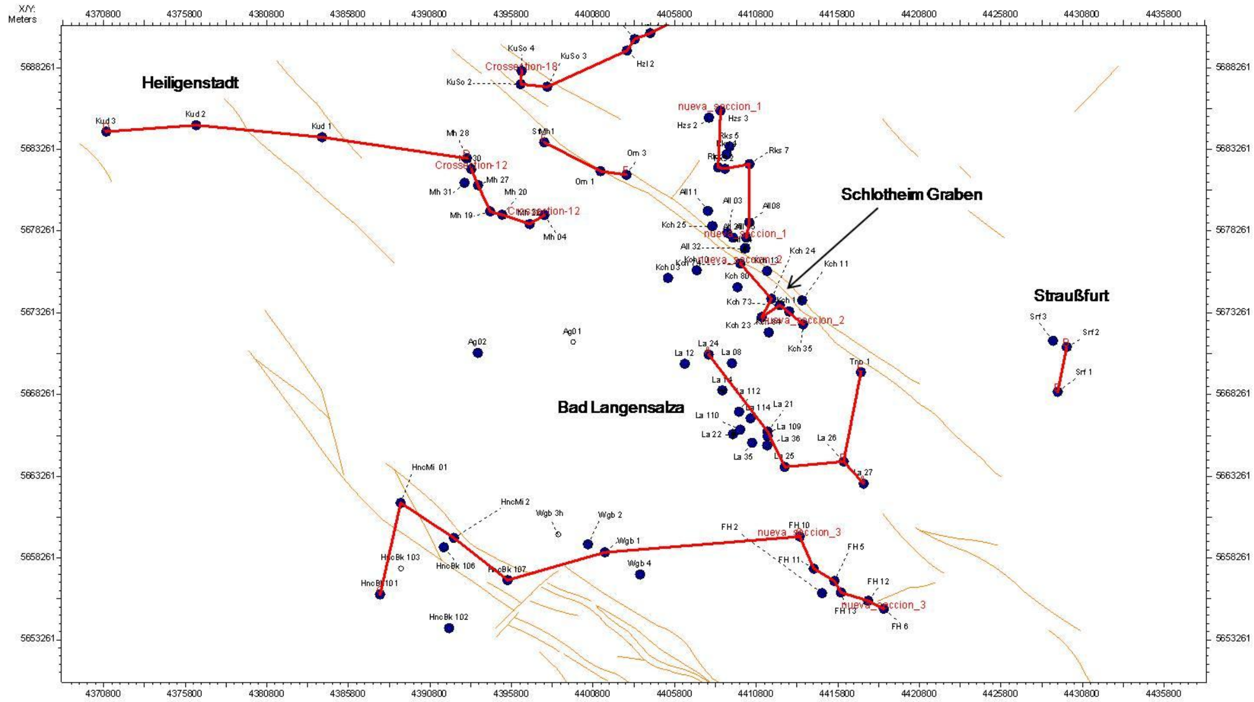


Figure 5.4 Location map of the stratigraphic cross-sections in the studied area. The sections were created in N-S, NW-SE and NE-SE direction.

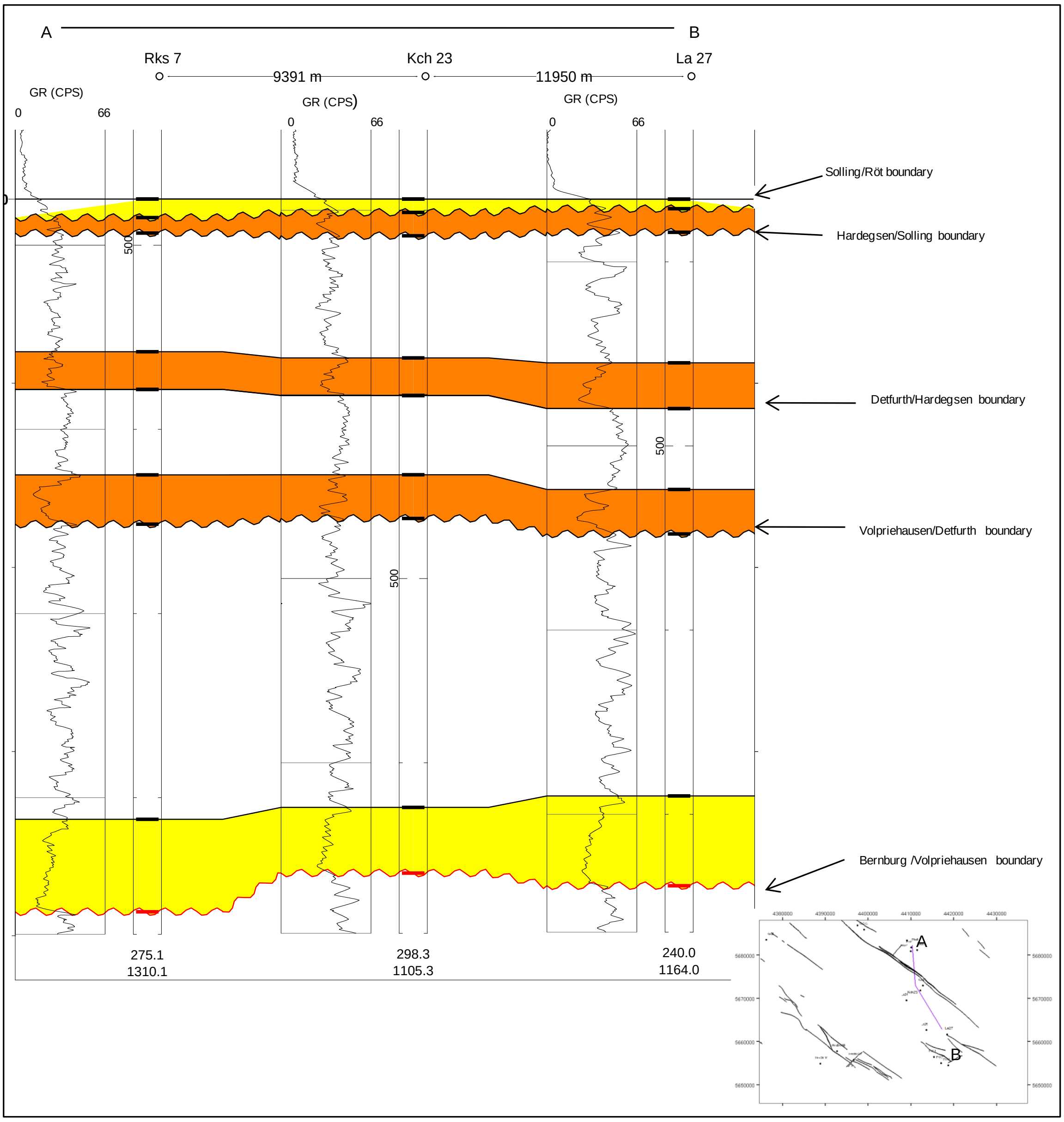


Figure 5.5 Definition of the boundary in the Middle Buntsandstein Subgroup: Bernburg/Volpriehausen, Volpriehausen/Detfurth, Detfurth/Hardegsen, Hardegsen/Solling and Solling/Röt. The stratigraphic cross-section embraces the Rockensußra, Kirchheilingen and Langensalza areas showing the change of radiation in the gamma ray logs at the boundaries of each formation. These log patterns are correlated throughout the study area.

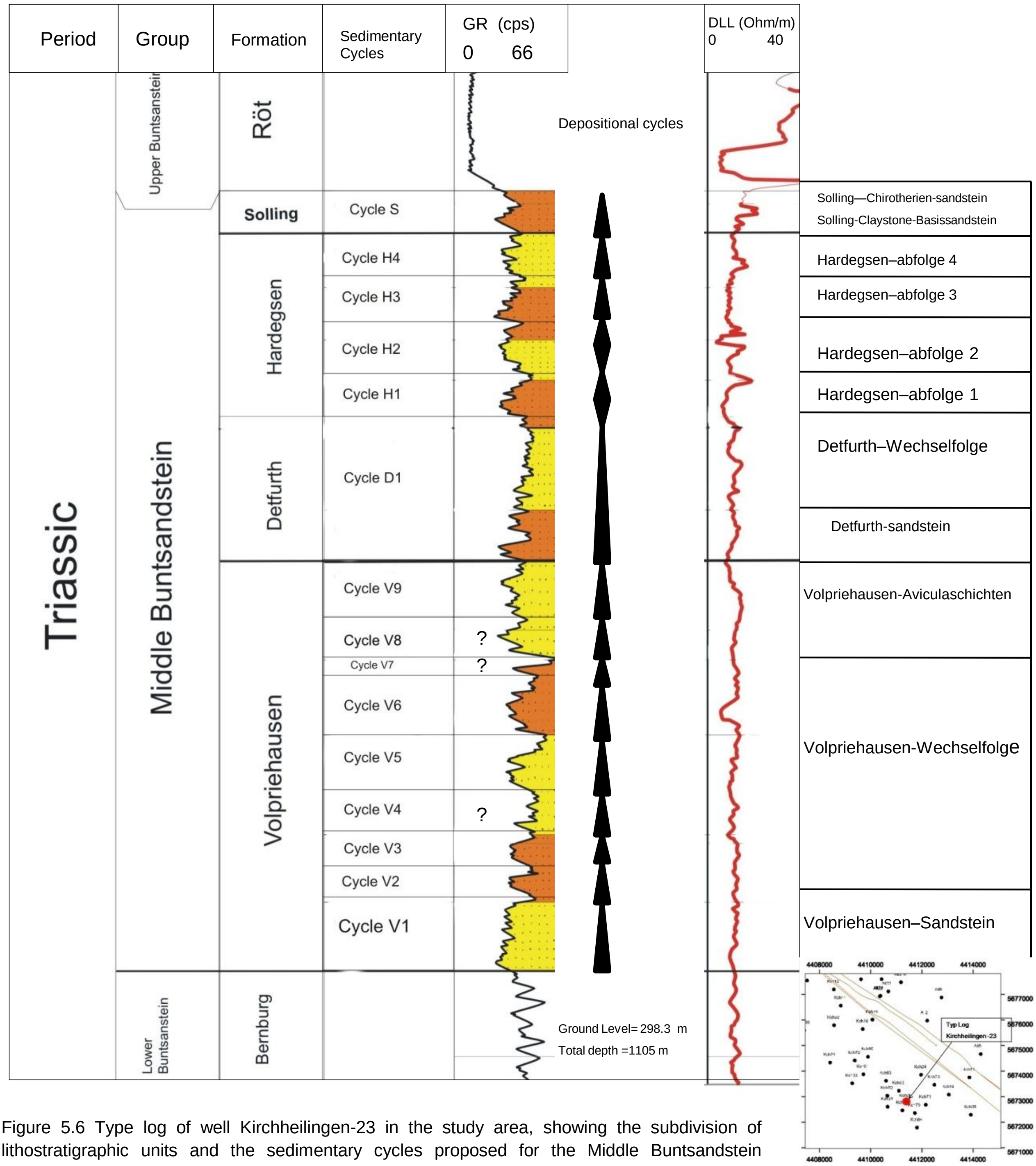


Figure 5.6 Type log of well Kirchheilingen-23 in the study area, showing the subdivision of lithostratigraphic units and the sedimentary cycles proposed for the Middle Buntsandstein Subgroup; the Volpriehausen, Detfurth, Hardegsen and Solling Formation.

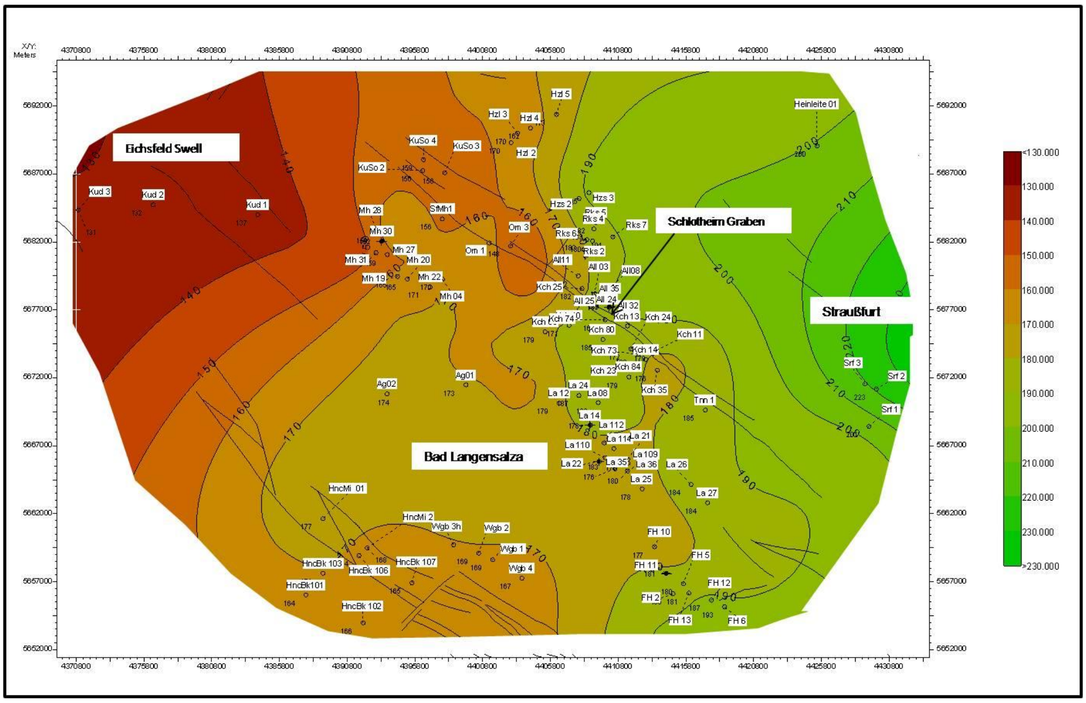


Figure 5.7 Isopach map of the Middle Buntsandstein (sm). Thicknesses are between 130 and 230 m. The contour interval is 10 m.

5.2.1 Volpriehausen Formation (smV)

The complete stratigraphic succession of the Volpriehausen Formation can be found in the whole Thuringian Syncline and is clearly recognizable in the gamma ray and the spontaneous potential logs; it rests on a discordant surface and is correlated in all wells. Over the Bernburg Formation the gamma ray log shows blocky characteristics (low radiation) keeping a relative homogenous lateral distribution (figure 5.8 and from enclosure 2 to enclosure 8).

The Volpriehausen begins with a succession of medium grained reddish sandstones, poorly sorted and well rounded, with some silty greyish sandstone intercalations characterized by low radiation in the gamma ray log and deflection to the left in the SP log. This succession is identified as the Volpriehausen-Sandstein and clearly observable in the well-core Fahner Höhe-13 and Rockensußra-2. The base of Volpriehausen Formation is followed by a succession of reddish and greyish medium to fine-grained sandstones with intercalations of shale, siltstone and argillaceous sandstones defined as the “Volpriehausen-Wechselfolge”. The top of the formation comprises compact thin sandstones with an alternation of shaly sandstones and sandstones with mudclasts. Seidel (1995) attributed this unit as “Volpriehausen-Aviculaschichten”.

The Volpriehausen Formation (smV) has an average thickness of 100 m. The maximum thickness displays between 120 and 125 m, located in the northwestern and western area, in the Eichsfeld Swell. The wells with the biggest thickness are Küllstedt-1 and Küllstedt-3. The minimum thicknesses are found in northeastern and the central area in the wells Keula-Sonderhausen-2, Keula-Sonderhausen-4 and Holzthaleben-2 with 76 m.

Radzinski (1966, 1967a) defined for the Volpriehausen Formation six (6) main sedimentation cycles in the southern Harzvorland, while Roman (2004) suggested for the Volpriehausen Formation four (4) main sedimentation cycles in northeastern Germany and central and southwestern Poland. In this study three (3) lithostratigraphic units were correlated within the Volpriehausen Formation: the "Volpriehausen Sandstein", the "Volpriehausen-Wechselfolge" and the "Volpriehausen Avicula-Schichten" constituting between eight (8) and nine (9) main sedimentation cycles (cycle V1-V9) (figure 5.5). Two additional sedimentary cycles (V0-V11) in the wells Küllstedt-1, Küllstedt-2 and Küllstedt-3 have been observed.

The sedimentation cycle V1 comprises the Volpriehausen-Sandstein mainly composed of medium grained sandstones. The gamma ray in the majority of the well log is characterized by low radiation showing a blocky characteristic. The cycles V2 and V3 representing the base of the "Volpriehausen-Wechselfolge" which consists of little fining upward successions correlated in all log wells through the study area. These cycles are dominated by red and grey silty sandstones with shale intercalations. The cycle V4 comprises fining upward successions of notable claystone intercalations which is not observed in all wells as in the well Allmenhausen-35.

The cycle V5 represents the middle part of the Volpriehausen-Wechselfolge showing a fining upward cycle dominated by red and brown silty sandstones with greyish green shale observed in the well cores Fahner Höhe-13 and Rokensußra-2.

The upper part of Volpriehausen-Wechselfolge is defined by the cycles V6 (a small cycle) and V7, which comprises fining upward successions although these two cycles are not clearly differenced in some well logs. The majority of the gamma ray logs like Kch-23 and All-04 show an interval with high radiation mainly towards the top of successions. It implicates more clayish material. This sequence is relative well correlated in many wells (figure 5.9).

The Volpriehausen-Aviculaschichten comprises the last two sedimentation cycles of the Volpriehausen Formation, defined as the cycle V8 and V9. These cycles show different lateral changes and the fining upward sequences in several GR log are not clearly identifiable.

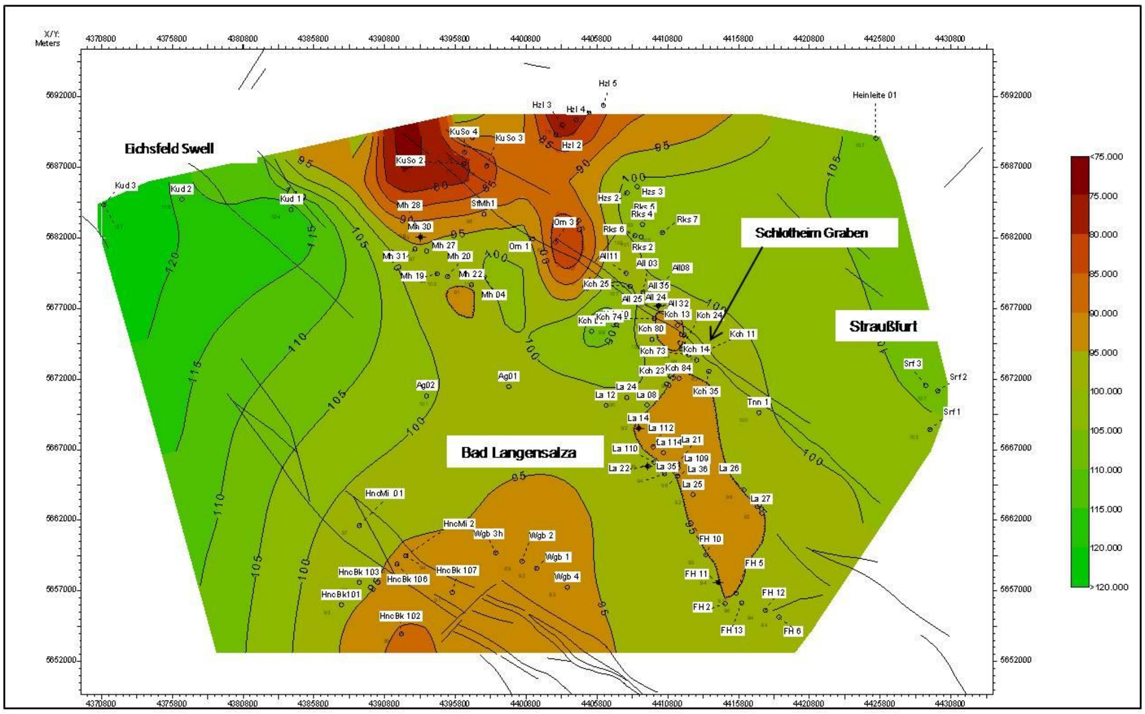


Figure 5.8 Isopach map of the Volpriehausen Formation (smV), the maximal thickness reaches 120 m in the central, northeastern and western area, while the thickness decreases to the north and south in the wells Keula-Sonderhausen-2, Keula-Sonderhausen-4 and Holzthaleben-2 and the wells Hainich-Berka with 76 m. The contour interval is 5 m.

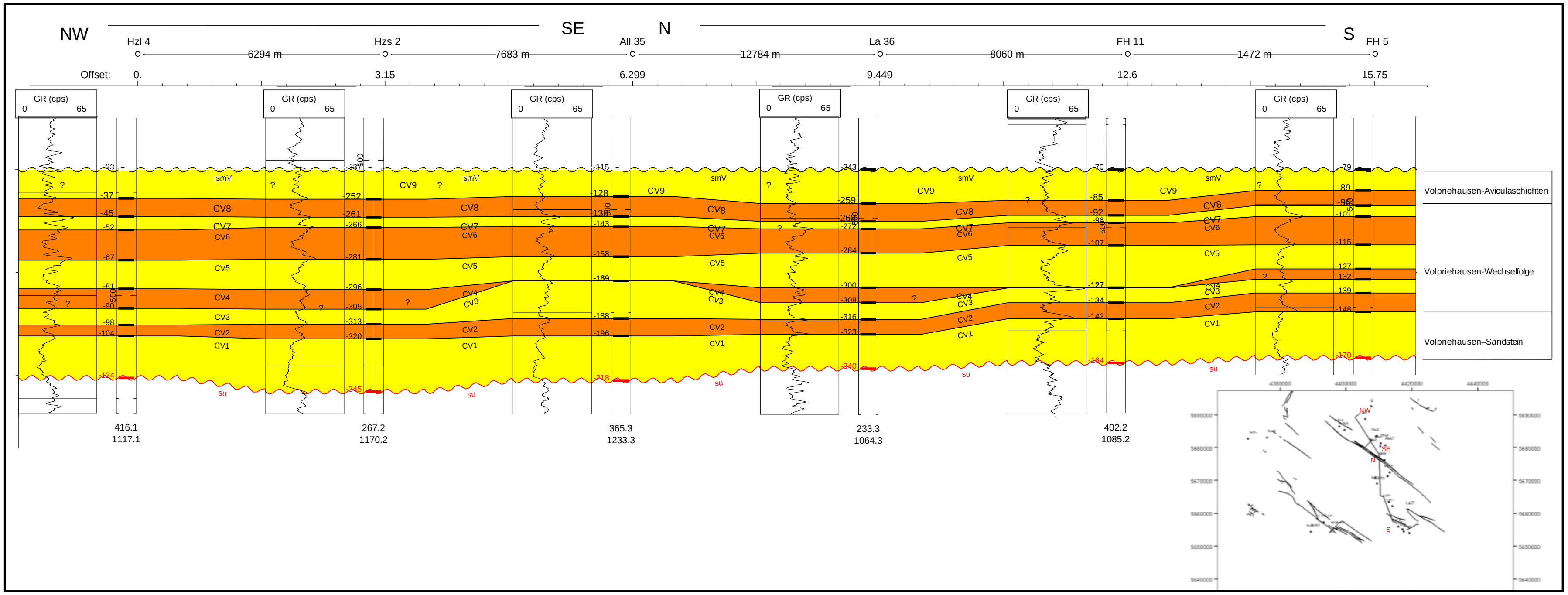


Figure 5.9 Stratigraphic cross-section in NW-SE direction throughout the studied area. The section shows the stratigraphic units and the sedimentation cycles in the Volpriehausen Formation; Volpriehausen Sandstein (CV1), Volpriehausen-Wechselfolge (CV2, CV3, CV4, CV5, CV6 and CV7), and Volpriehausen–Aviculaschichten (CV8 and CV9), the cycle CV4 is not present in some areas such as the well Allmenhausen-35. The cycles CV8 and CV9 are not clearly differentiated in some cases.

5.2.2 Detfurth Formation (smD)

The lower boundary of the Detfurth Formation can be identified relatively well in almost the whole studied area except in the Eichsfeld Swell where the formation is not present. The base of Detfurth is formed by the “Detfurth-Sandstein”. This unit is characterized by compact sandstones from medium to fine grain size resting unconformably on the Volpriehausen or Bernburg Formations. The well core Fh-13 shows an alternation of red and reddish brown sandstones, from moderate to well sorted grains with intercalations of claystones and shale. This lamination is evident in the majority of well logs where the radiation of the gamma ray curves shows high peaks. The top of the formation, denominated as the Detfurth-Wechselfolge is clearly identified in the well core Fahner Höhe-13. It comprises reddish brown fine grained sandstones with constant intercalations of siltstones. The gamma ray curve peaks show a notable tendency to the right.

The Detfurth Formation has an average thickness of about 21 m and the thickness distribution tends to reduce in the eastern area, observed in the wells Mh-19 and Mh-25 with a thickness of 10 m (figure 5.10). In the Eichsfeld Swell (NW Thuringian), the complete succession of the Detfurth Formation is absent. The well logs Küllstedt-1, Küllstedt-2 and Küllstedt-3 indicate complete erosion of the Detfurth Formation. Röhling and Seidel (2008) mentioned the absence of the Detfurth Formation in the stone quarry located in the Lengenfeld area in the east of Thuringian State. The thickness increases in northwestern, western and southwestern study area, reaching a maximum of 45 m (figure 5.10). The wells, Fahner Höhe-9, Fahner Höhe-12, Allmenhausen-6 and Wiegleben-2 contain the biggest thicknesses of the formation.

A sedimentation cycle in the Detfurth Formation has been defined; comprising the “Detfurth Sandstein” and “Detfurth Wechselfolge”. The lower part of the cycle forms the “Detfurth Sandstein”, which is characterized by the basal sandstone, well correlated in the whole studied area; also the gamma ray log shows a notable decrease in radiation curve with a notable tendency to the left (figure 5.5, figure 5.11 and from enclosure 1 to enclosure 6).

The upper part of the cycle comprises the “Detfurth-Wechselfolge,” observed in the majority of the gamma ray logs showing a fining upward succession. This is evident in the core of the well Fahner Höhe-13, which is composed of compact sandstones at base of the Detfurth-Wechselfolge and more siltstone intercalations towards the top of the cycle.

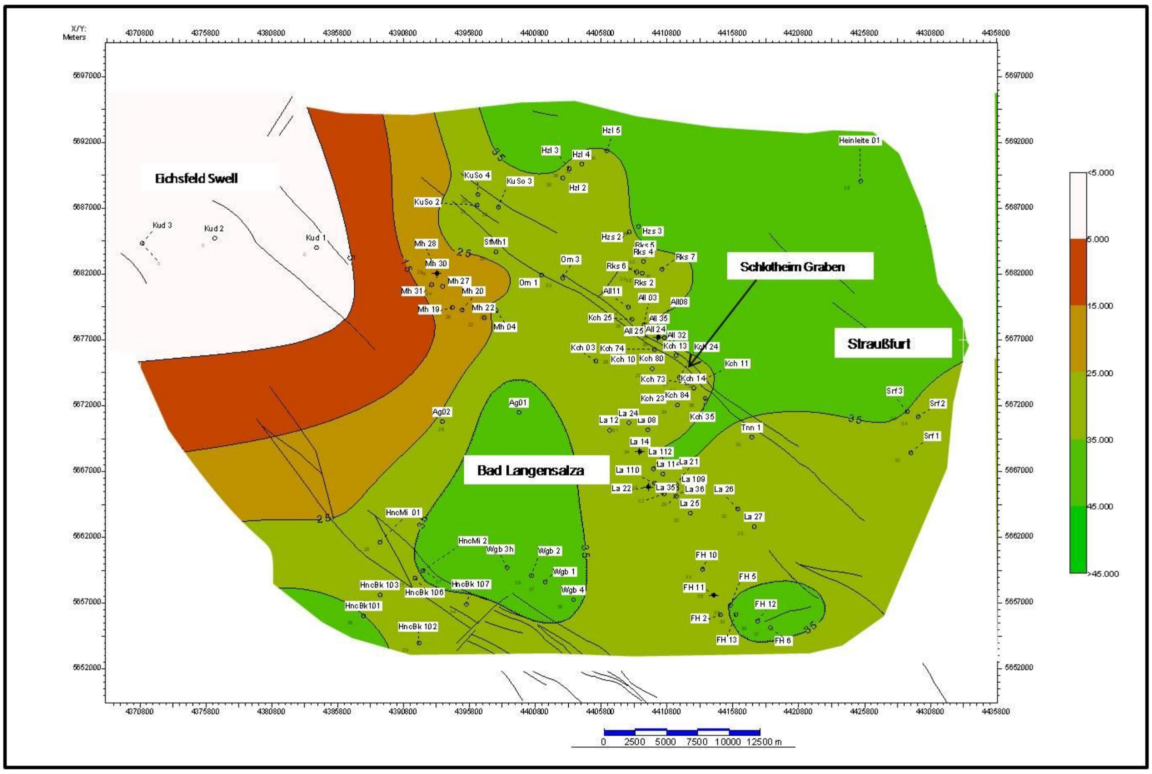
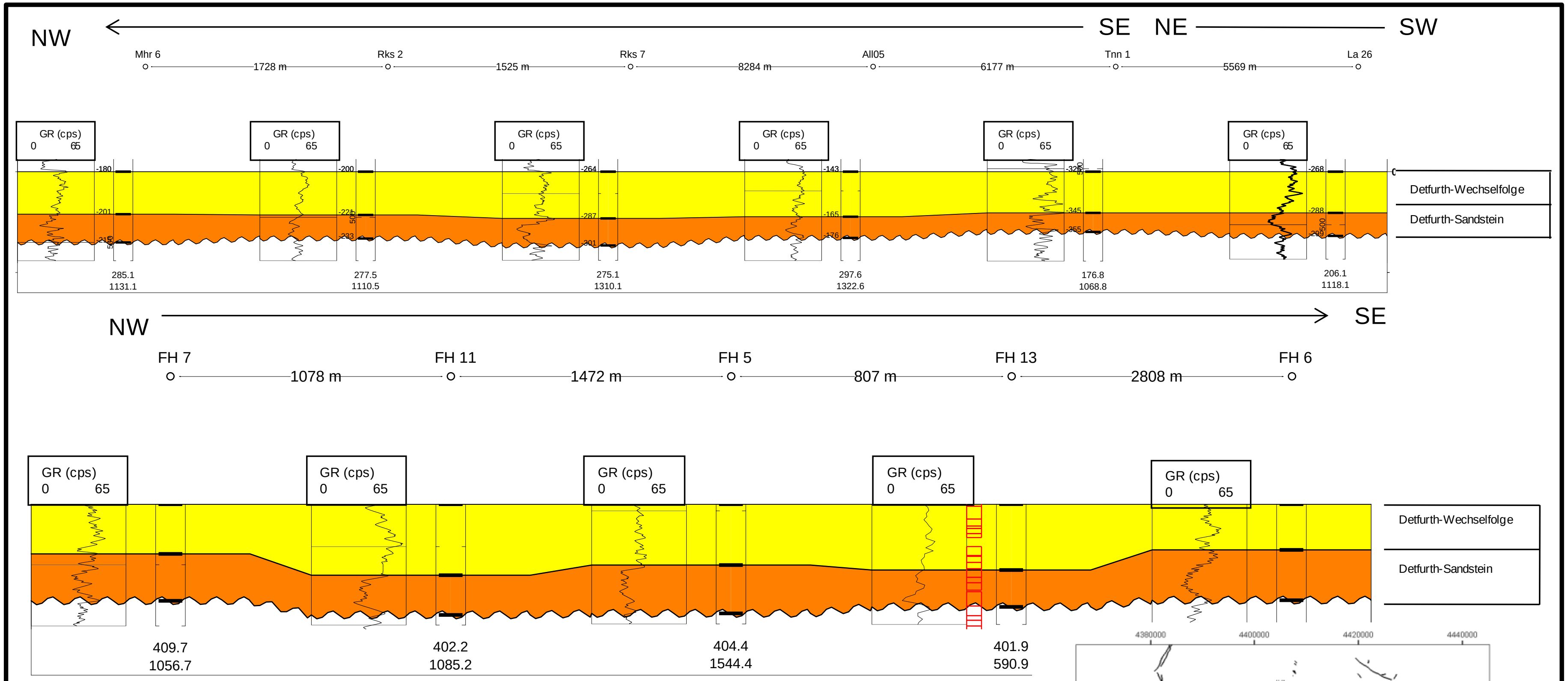


Figure 5.10 Isopach map of the Detfurth Formation in the studied area, the thickness distribution is reduced along the Eichsfeld Swell located in the northwestern study area, while the thickness increases 40 m in the southern and northeastern area.



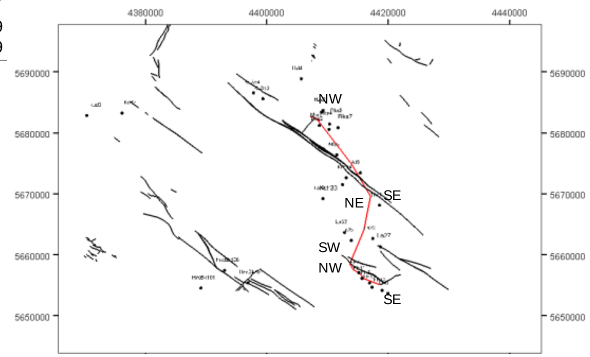


Figure 5.11 Log correlations in direction NW-SE and N-SW of the Detfurth Formation through the Rockensußra, Kirchheilingen, Allmenhausen and Fahner Höhe areas, the stratigraphic sections show the Detfurth Sandstein and Detfurth Wechselfolge. The distribution of the sequences is well correlated through the studied area.

5.2.3 Hardegsen Formation (smH)

The lower boundary comprises a succession from medium to coarse grained sandstone above the argillaceous sandstones of the "Detfurth Wechselfolge". The base of Hardegsen Formation in the majority of the logs presents a gamma-ray curve marked by a considerable decrease of radiation, showing discrete fining upward cycles and in some cases stacked successions. The Hardegsen Formation is basically composed of alternation of greyish sandstone and reddish silty sandstone, as shown in the well Fh-13 (figure 5.12). The Hardegsen Formation was subdivided, according to the classification proposed by Radzinski (1967) in the southeastern Harzvorland into four (4) lithostratigraphic units: Hardegsen-Abfolge 1, Hardegsen-Abfolge 2, Hardegsen-Abfolge 3 and Hardegsen-Abfolge 4 and in the same way in four (4) sedimentation cycles denominated H1, H2, H3 and H4 mainly constituted of fining upward successions. The upper boundary is marked by an erosional unconformity, the H-Unconformity at the base of the Solling Formation, which was established by Trusheim (1961) in southern Lower Saxony.

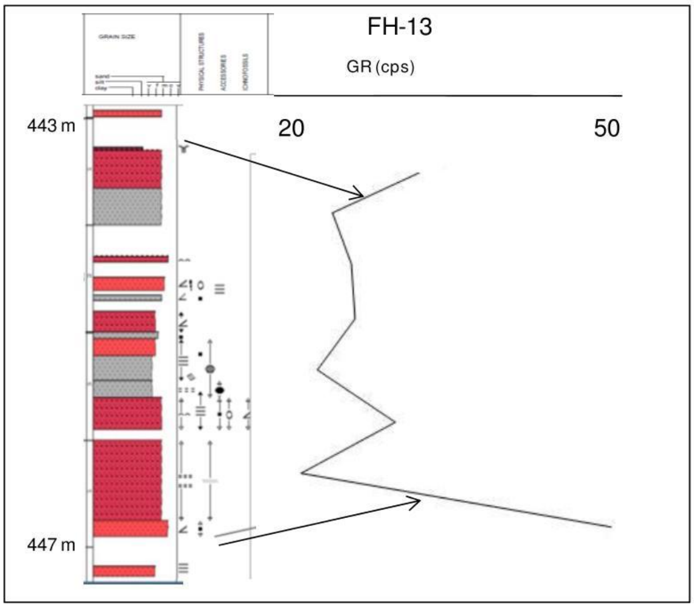


Figure 5.12 Lithological descriptions in the well Fahner Höhe-13, showing the lower Hardegsen Formation after from Schnee 2006). The sequence is indentified as the first sedimentation cycle (H1) above the "Detfurth-Wechselfolge". It consists of an alternation of greyish sandstones from medium to coarse grained and reddish silty sandstones (see legend in the enclosure 17).

This H-unconformity is present in the western area. It can be observed through the log correlation with erosion cutting the complete Hardegsen succession. This formation has an average thickness of 40 m. The maximal thickness is located in the Straußfurt area (figure 5.13) reaching 70 m, evidenced in the wells Srf-1 and Srf-2. In the Mühlhausen area the thickness decreases between 22 and 25 m, observed in the wells Mh 27 and Mh-

28 and the Keula-Sonderhausen area in 11 m which is evidenced in the well Kuso-5. In the central and southern area, the complete succession of the Hardegsen Formation can be observed in the wells the Straußfurt, Fahner Höhe, and Kirchheilingen and Langensalza show clearly the four cycles.

The log correlation through the study area in northwest-southeast direction shows the thickness changes and the evidence of the H-unconformity: the wells Obermehler-1 and Obermehler-2 located in the central area, the thickness of the Hardegsen Formation decreases to 20 m with the cycles H3 and H4 completely absent or partially eroded (figure 5.14). The H-unconformity is clearer in the northwestern area there in the wells Keula-Sonderhausen (Kuso-2, 3 and 4), Wattesattel-1, the cycles H3 and H4 are absent and the H2 thickness decreases (figure 5.14). On the Eichsfeld-Altmark-Swell the H-unconformity is more evident where the complete Hardegsen and Detfurth Formations are missing (figure 5.14). In some well logs in the study area, the Hardegsen Formations is present but does not display the four (4) cycles which evidence the H-unconformity. The stratigraphic cross-section in west-east direction verifies clearly the erosion at base of the Solling Formation (figure 5.15). The subcrop map suggests that Hardegsen Unconformity is more prominent in the western area, where the Solling Formation rests uncomfortably on the Volpriehausen Formation (figure 5.16).

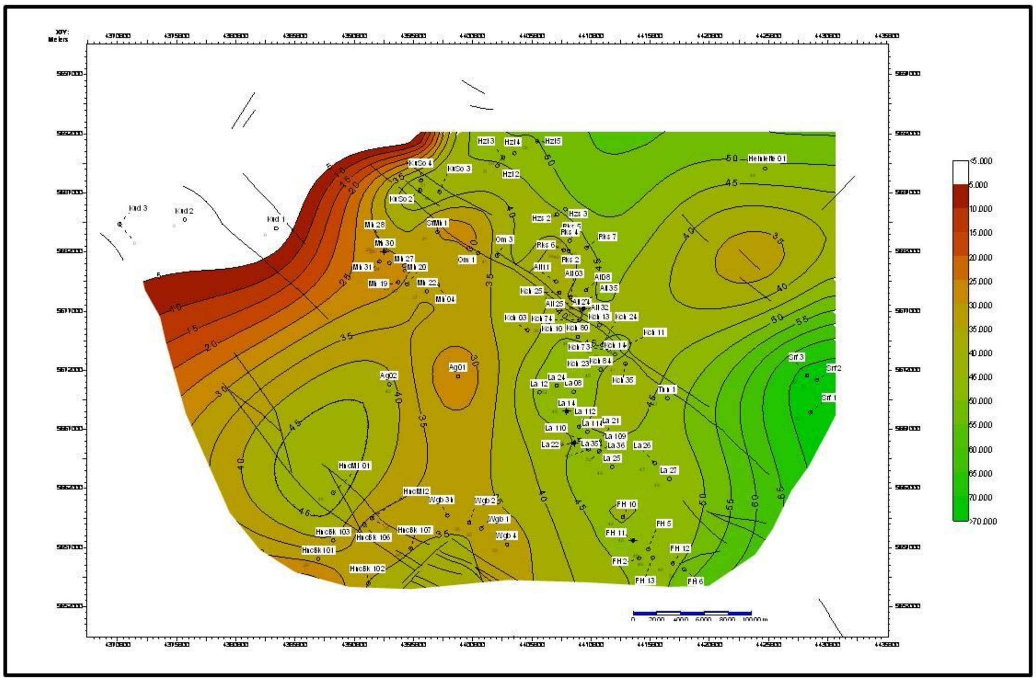
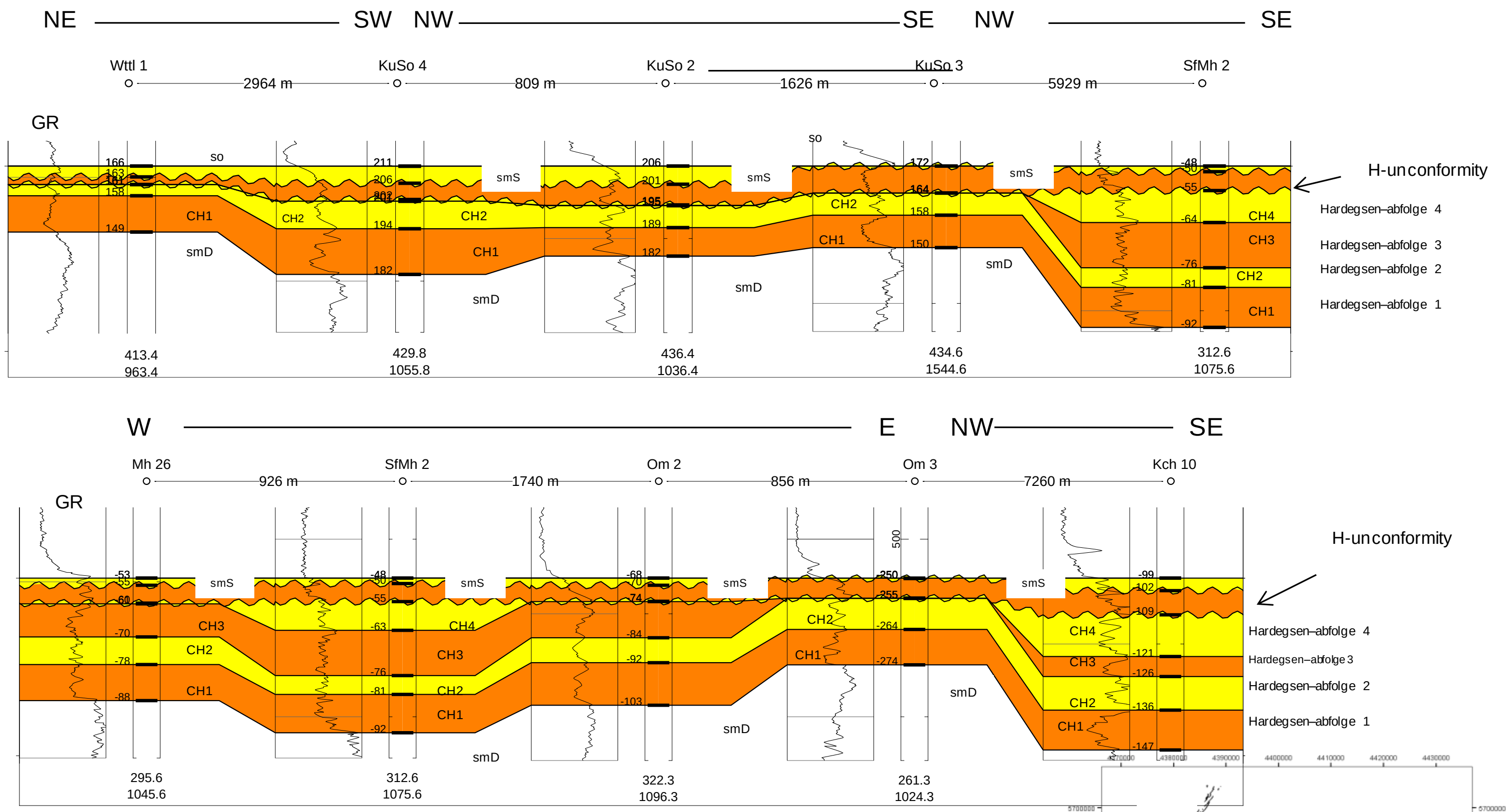


Figure 5.13 Isopach map of Hardegsen Formation, the thickness in the northeastern and eastern area reaches 70 m. In the northwestern area, the thickness decreases in 10 m.



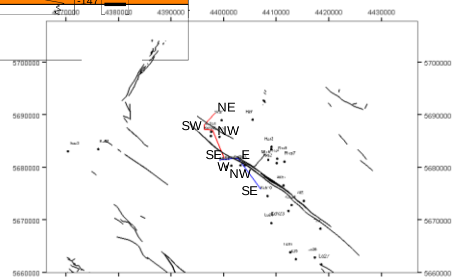


Figure 5.14 Stratigraphic correlation in northwest-southwest direction from well Wattesattel-1 to Kirchheilingen-10, the log correlation shows the Hardegsen Formation. The H-unconformity is more notable in the northwestern area; where the cycles CH4 and CH3 are absent.

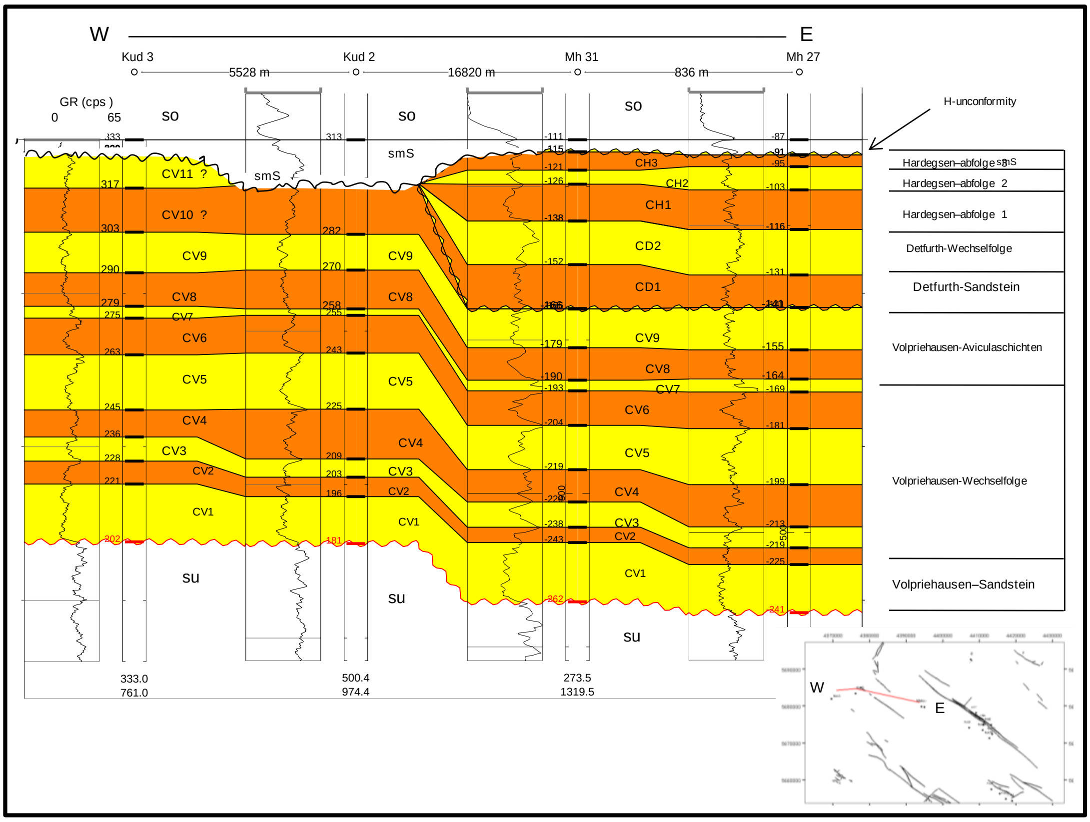


Figure 5.15 Log correlation in west-east direction, the H-unconformity is more notable in the western area, in the Eichsfeld Swell the Detfurth and Hardegsen Formations are absent as is shown in the wells Küllstedt-3 and Küllstedt-2.

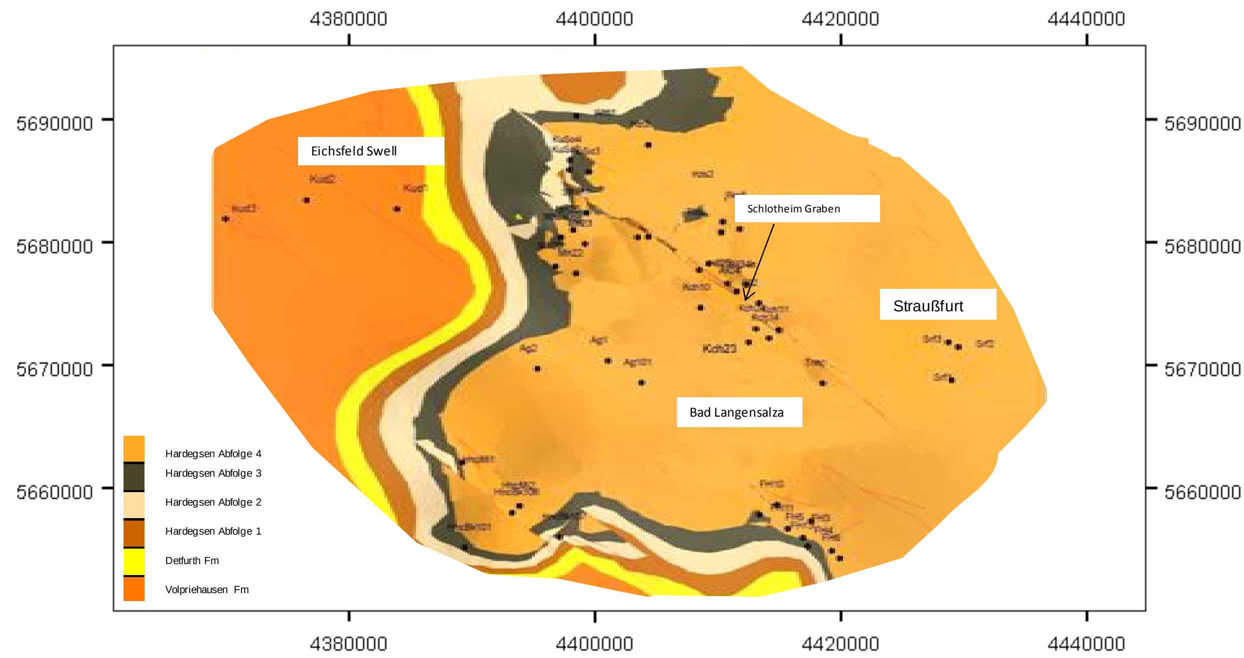


Figure 5.16 Subcrop map at the base of the Solling Formation illustrating the significant erosion; the H-unconformity, the tectonic erosion is more prominent in the Eichsfeld Swell where the base of the Solling Formation rests directly the Volpriehausen Formation. In the northeastern and southeastern area the H-unconformity is not present. The Subcrop map is created by using the well data information from Volpriehausen to Hardegsen Formation (H1, H2, H3 and H4) and created by the RMS 9.2 software.

5.2.4 Solling Formation (smS)

The Solling Formation rests directly on the H-unconformity and was defined and subdivided for the first time by Boigk (1957). The Solling Formation comprises a complex of different facies in different paleogeographic units (Röhling, 1991) and begins with the "Solling Basissandstein". This basal sandstone can be clearly correlated in the whole studied area and is mainly composed of red and brown rippled sandstones. The fines to medium grained sandstones are observed in the well cores of Fahner Höhe-13 and Rockensußra-2. The curves of the well logs are characterized by a considerable decrease of radiation in the gamma ray log.

Over the basal sandstone lies a unit that is recognized as the Solling claystones, also known as the "Tonige Zwischenschichten", where the radiation in the gamma ray log presents high peaks. This succession is mainly composed of brown claystones with intercalated red sandstones. At the top of the Solling Formation the "Chirotherien Sandstein" is found but is missing in some areas of this study. The "Thüringer Chirotherien Sandstein" is characterized by a succession of green compact sandstone with some bands of grey sandstone. This succession rests unconformably on the Solling claystones and is absent in some part of the area as show in the stratigraphic correlation (figure 5.18).

Rettig (1996) and Rettig et al (1998) recognized an intra-Solling unconformity in the middle part of this formation in the Eichsfeld-Altmark region. These authors suggest that the "Thüringer Chirotherien-Sandstein" overlies directly the Solling-Basissandstein. In the well Küllsted-1 the "Solling Basissandstein" can be found, as well as the "Holunger-Wechselfolge" (the "Tonige Zwischenschichten" equivalent) and the "Thüringer Chirotherien-Sandstein" sequences, however the intra–Solling erosion was identified (table 4.2). In the Mühlhausen area, the Intra-Solling Unconformity is recognized where the Upper Buntsandstein Subgroup rests directly on the "Solling-Basissandstein", while in the Rockensußra area the unconformity is not observed as shown in the well log Rockensußra-2 where the complete Solling Formation is present (figure 5.19).

The whole Solling Formation has an average thickness of 7 m; the maximal thickness comprises 14 m, located in the northeastern and northwestern area and can be observed in the wells Küllsted-1, Küllsted-2, Hainich-Berka-2 and Keula-Sondershausen-5, while the minimum thicknesses are found in centre of the area (figure 5.20), observed in the wells Allmenhausen-20, Allmenhausen-22 and Langensalza-36 in 3.4 m.

The Solling Formation in the studied area has been defined as one sedimentation cycle between the H-unconformity and the Röt Formation; however it is not easy to define. The Solling Formation embraces the base Solling (the “Basissandstein”) until the top of Solling claystones (“Tonige Zwischenschichten”). The upper part of the Solling Formation is denominated the “Chirotherien-Sandstein”, only present in some areas. This cycle is mainly composed of fluvial facies and in some cases marine sedimentation towards the top of the Solling Formation (the “Chirotherien-Sandstein”) as is observed in the well Rockensußra-2 (Lang, 2001).

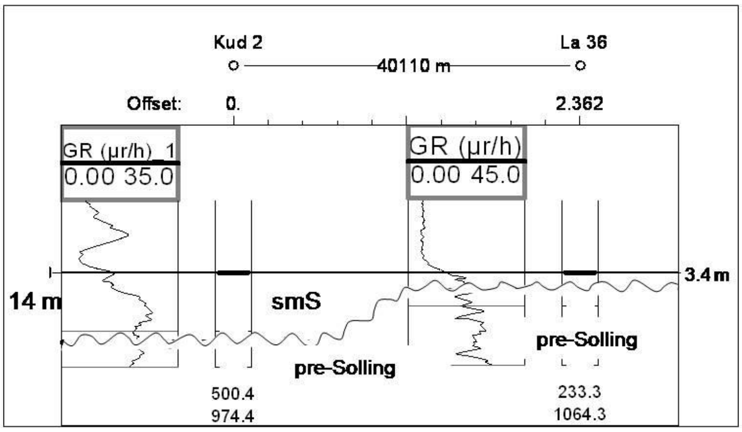


Figure 5.17 Log section of the Solling Formation showing the wells Küllstedt-2 and Langensalza-36 with the maximal and minimum thickness through the studied area.

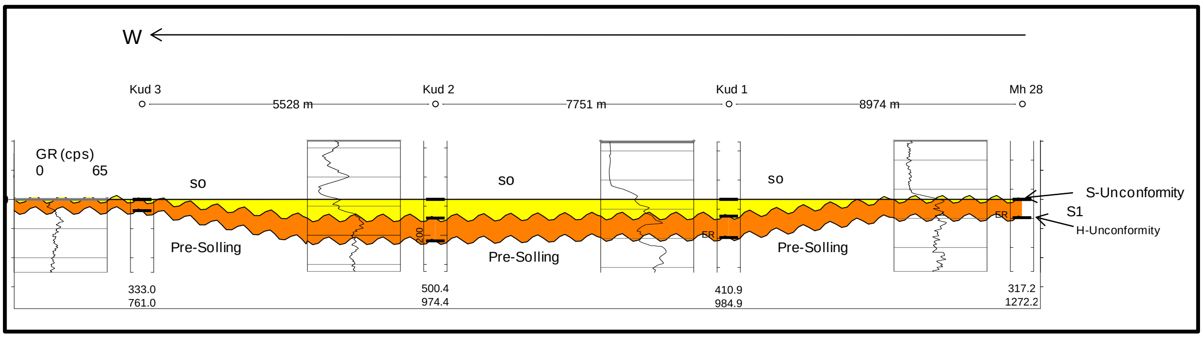


Figure 5.18 Log correlations in W-E direction embracing the wells Küllstedt-1 and Küllstedt-2, showing the Solling Formation. The Holunger-Wechselfolge the “Tonige Zwischenschichten” and the Thüringer Chirotherien-Sandstein are present, however the unconformity is identified in the Eichsfeld area by Rettig (1996). In the well log Mühlhausen-28 the intra Solling unconformity is more evident; the Upper Solling Formation lies directly on the Thüringer Chirotherien-Sandstein.

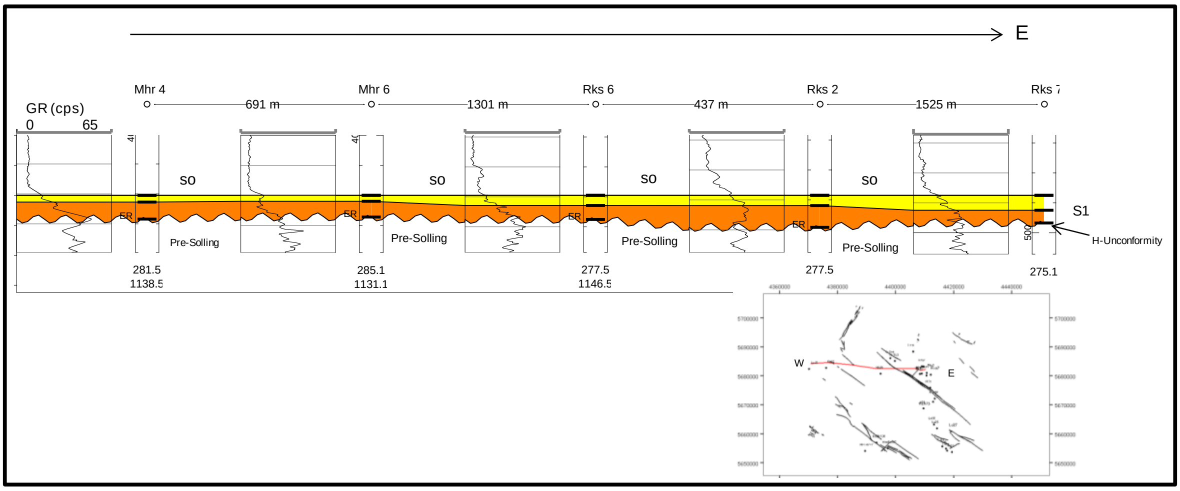


Figure 5.19 Log correlation in west-east direction located in the Mehrstedt and Rockensußra area showing the Solling Formation; the Basissandstein, Holunger-Wechselfolge (the "Tonige Zwischenschichten" equivalent). The wells Mhr-4, Mhr-6 and Rks-6 do not present the "Tonige Zwischenschichten".

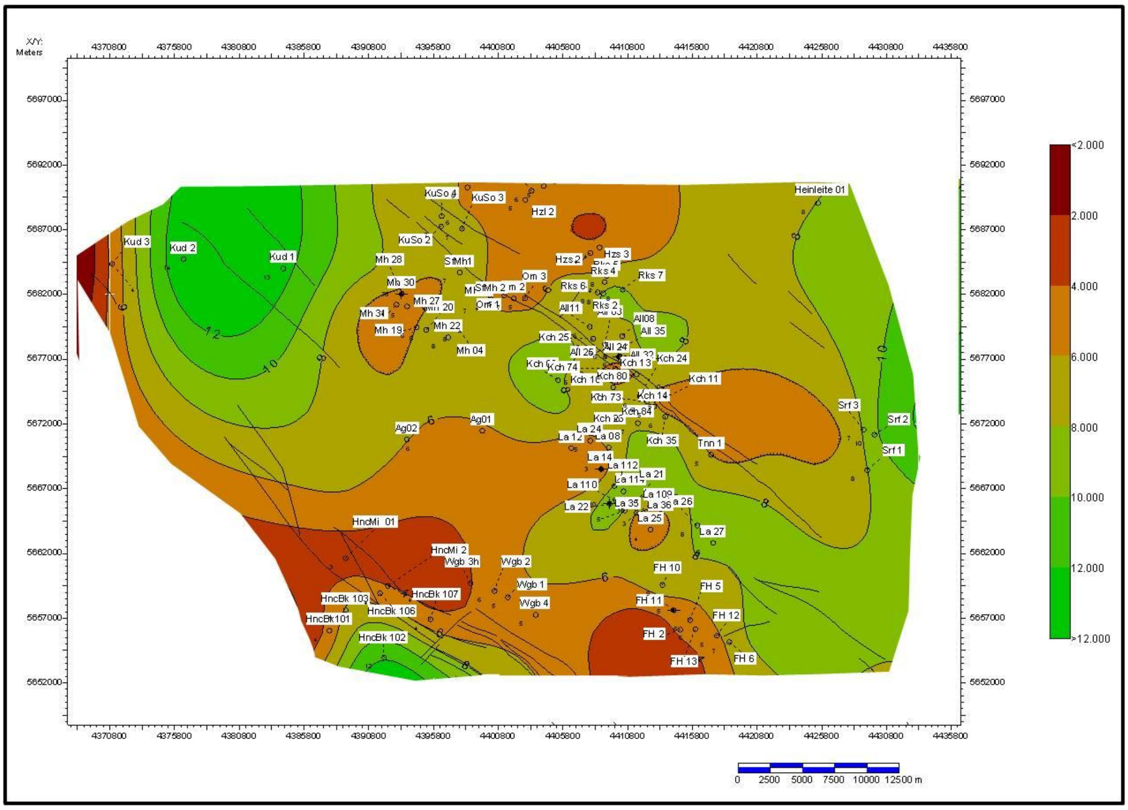


Figure 5.20 Isopach map of the Solling Formation, the maximal thickness comprises 14 m, located in the northeastern and northwestern area and the minimum thickness can be found in central and southern area with 3 m.

6 Facies and depositional environment of the Middle Buntsandstein Subgroup

The study of the lithofacies and the depositional environment in the Middle Buntsandstein was made using the available well cores; the Fahner Höhe-13 and Rockensußra-2, inside the study area. This interpretation has been done for each formation of the Middle Buntsandstein Subgroup: the Volpriehausen, the Detfurth, the Hardegsen and the Solling Formation in addition to these well cores, gamma ray logs from wells were used.

The vertical facies succession of the Middle Buntsandstein comprises horizons that are mainly formed by a complex fluvial-eolian-lacustrine interaction. This facies association exhibit vertical and lateral changes of both facies through the studied area.

The fluvial deposits mainly show cyclic composition limited at the base by an erosional surface and with thick clayey sediments at the top. These sequences are dominated by sheetflood facies, fluvial channel and floodplain deposits, while the eolian sequences mainly comprise intercalations of dune and sand plain facies (figure 6.1 and figure 6.2).

Detailed lithofacies descriptions were done for each sedimentation cycle. The eolian and fluvial deposits are mainly recognized in the cores.

The formations are predominately composed of sand bodies, deposited by eolian facies that show partially middle and high angles of inclination representing foresets together with occurrences of stacked dune sand sequences and intercalation of sand plain deposits. These eolian deposits present intercalation of thin silty clayey lacustrine sediments.

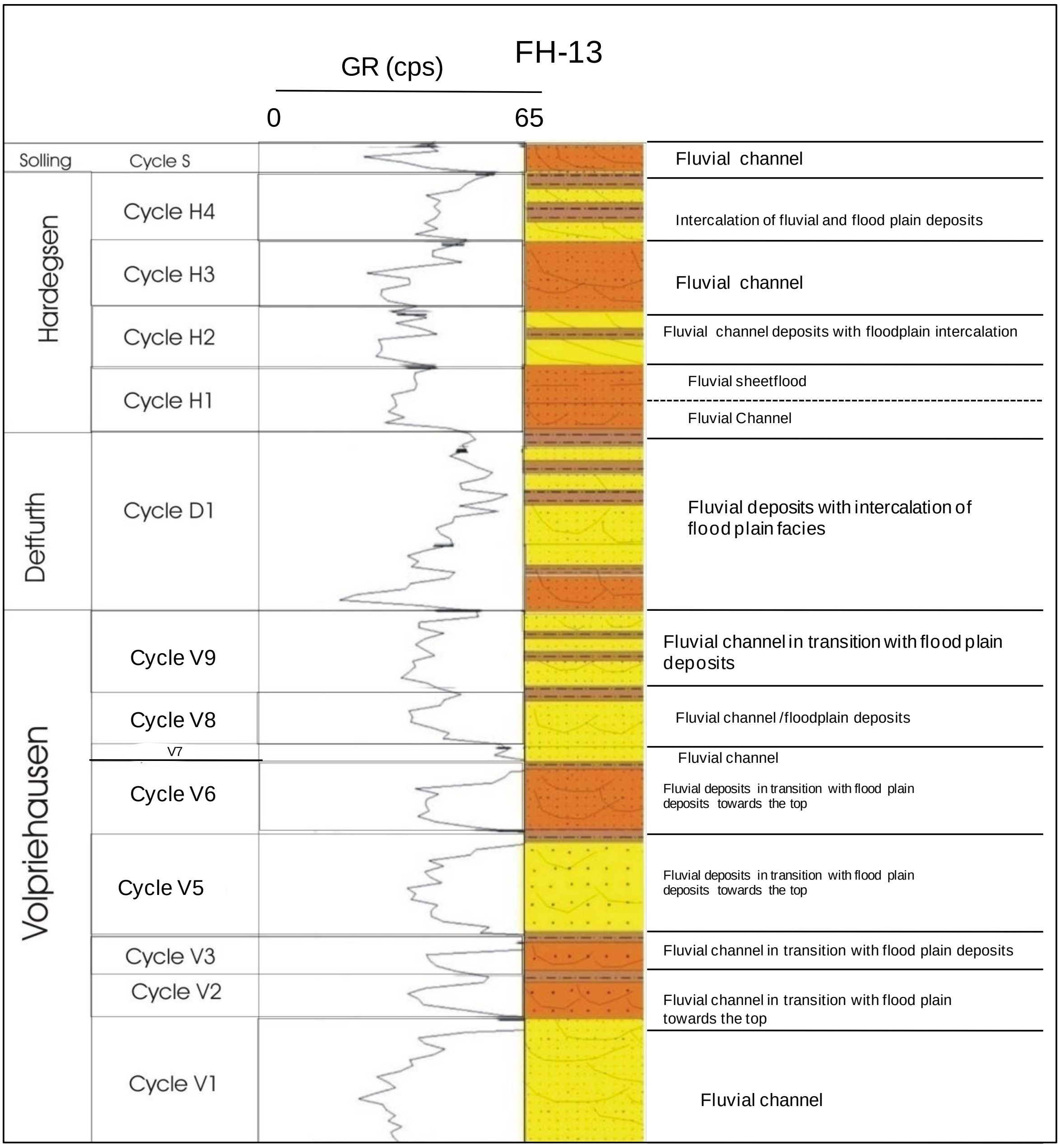


Figure 6.1 Vertical profile of the well core Fahner Höhe-13, showing the lithofacies association and depositional environments interpreted for the Middle Buntsandstein Subgroup mainly associated to fluvial facies.

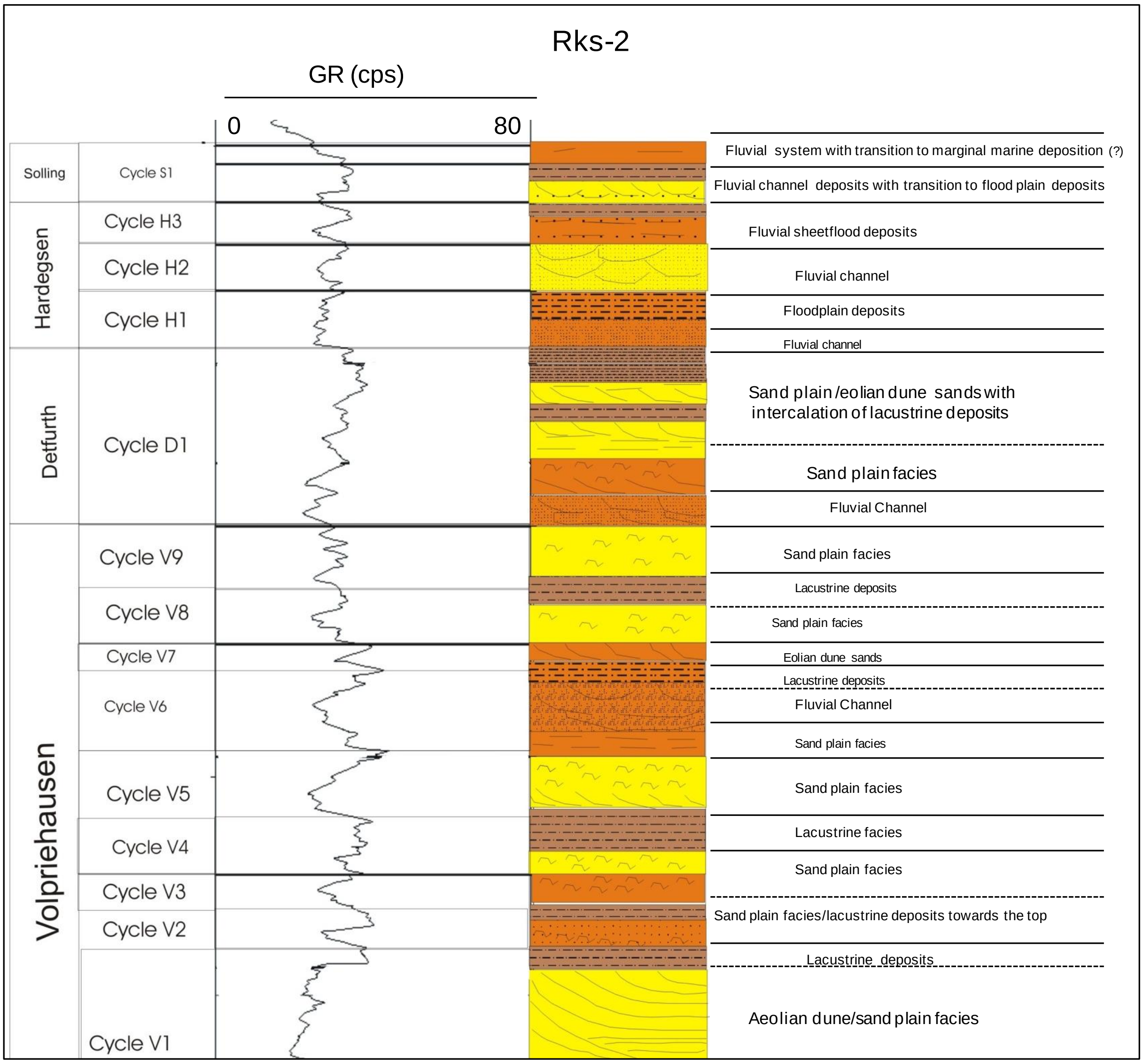


Figure 6.2 Vertical profile and gamma-ray log for eolian and fluvial facies of the Middle Buntsandstein Subgroup in the well core Rks-2.

6.1 Lithofacies a ssociation and facies analysis

Lithofacies interpretation of the Middle Buntsandstein Subgroup for the well cores Fahner Höhe-13 and Rockensußra-2 were done using the lithofacies classification taken from Miall, 1996 and compared with other facies interpretations in areas near this study area used by Gaupp et al (1998) and Roman (2004). The Middle Buntsandstein intervals of the well cores Fahner Höhe-13 and Rockensußra-2 have an approximate thickness up to 114 m and 180 m respectively and ten (10) lithofacies have been identified.

Lithof acies c lassific ation

Planar cross bedded sand (Sp)

This lithofacies are composed of very fine-to very coarse-grained sand, moderately sorted, thick sets, Large-scale planar tabular cross stratified, high angle (>20°).

Ripple cross laminated sand (Sr)

The Lithofacies comprise very fine to coarse grained sand, fine-to medium-grained sandstones are more common, poorly to well sorted, 1-6 cm thick sets, and ripples of all types (2D and 3D).

Horizontal bedded sand (Sh)

The horizontal bedded lithofacies presents very fine-to medium-grained sand, coarse grains with pebbles are present but are not common, moderately sorted, containing dispersed mudstone intraclasts.

Low angle cross bedded Sand (Sl)

The low angle cross stratification lithofacies is normally associated to the lithofacies Sh. It presents low angle cross bedding minor than 10° inclination, containing mudstone intraclasts.

Trough crossbedding (St)

Composed of very fine-to very coarse-grained sandstones, maybe pebbly, trough stratified sets or solitary, well sorted and well rounded thick cross-strata sets. Large scale cross-stratification, the foresets are composed of grain flow deposits grading down dip into wind ripple lamination. Migration of sinuous crested dunes within channels (eolian vs. aquatic).

Massive sand (Sm)

The massive or faint lamination lithofacies constitute fine-to coarse-grained sand, moderately sorted, without evident structures, containing some mudstone intraclasts.

Siltstone and mudstone (Fm)

This lithofacies is composed of massive claystones and siltstones with desiccation cracks and some bioturbation and bedded with sand layers.

Laminated siltstone (Fl),

Fine lamination to finely bedded of silt, clay or mud, and small ripples, few bioturbation.

Gypsum, laminated (Xl)

The lithofacies is characterized by finely laminated gypsum.

Gypsum, anhydrite nodular (Xn)

It comprises nodules of anhydrite, chicken wire structure.

6.2 Eolian and f luvial association

The facies of the Middle Buntsandstein Subgroup in the northwestern Thuringian Syncline mainly comprise eolian-fluvial-lacustrine interaction. According to Voigt & Gaupp (2000), the Basal Volpriehausen Formation is located in the Valley of the river Unstrut consists of eolian sandstones with some intervals of clays. This Volpriehausen Sandstone is composed of middle-to coarse-grained sandstones, from poorly to moderately sorted and well rounded. The colour of the rocks varies between reddish brown and greenish gray especially towards the top of the sequences. In the outcrops located in the Quarry west close to the Village of Wangen the base of Volpriehausen can be observed unconfined wavy lamination, little sandlenses with horizontal lamination (Sh) and low angle cross-beds (<15°), as well as desiccation cracks. Voigt & Gaupp (2000) suggest that these sedimentary characteristics indicate an eolian origin and could represent the relicts of dune bodies. Within some intervals isolated small ripples and rarely crossbedding are found.

The well cores Fahner Höhe-13 and Rokensußra-2 in the Volpriehausen and Detfurth Formations comprise stacked successions of eolian dune facies in vertical transition with sand plains, fluvial and lacustrine deposits showing fining upward grain size characteristics and exhibiting blocky and smooth serrate cylinder character in the gamma ray log.

The sedimentary facies of the Volpriehausen, Detfurth, Hardegsen and Solling Formations in the well Fahner Höhe-13 have been defined as fluvial deposits in vertical transition with eolian facies, while in the well core Rockensußra-2 the Hardegsen and the Solling were only dominated by fluvial and floodplain deposits.

Gaupp et al (1998) suggest that the top of the Hardegsen Formation (equivalent to the cycles CH4) located in the northeastern margin of the Thuringian Syncline at the quarry west of Nebra is composed of thin floodplain or a possible terminal fan deposits with evidences of bioturbation and chonchostracans. In the same way these authors observed that thin red brown sandy channel fills with lateral accretion. The floodplain deposits contain thin sand sheets, which could be interpreted as crevasse splay deposits.

The outcrops located at the quarry terrace west of Nebra that show the base of the Solling Formation are composed of coarse grained, pebbly sandstones associated with planar cross stratified sandstone which are interpreted as large channel cutting floodplain deposits (Voigt et al, 2000). In the area of Neue Welt/Schönburg and Leißling, the outcrops located between southern Saxony-Anhalt and eastern Thuringia, Roman (2004) describes the Hardegsen Formation as fine reddish and yellowish brown rocks composed of fine to middle grained sandstones with some intercalations of greenish gray siltstone which are mainly associated to planar cross stratified and trough cross stratified sets and in minor amount horizontal bedding belonging to a braided river system.

According to Roman (2004), the sedimentation cycles of the Hardegsen Formation in the well core Halle-Süd-1 situated in the southern part of Saxony-Anhalt (Sachsen-Anhalt) State comprises mainly massive fine grained sandstone that contain abundant carbonate nodules and marked bioturbation, suggesting a transition from a braided to a meandering fluvial system, associated to the Playa margin deposits (Playa-Sees) towards the top of the cycle. The base of the Solling Formation observed in the same well core by Roman (2004) is dominated by middle-to coarse-grained sandstones with notable cross bedding associated to stacked channels of a fluvial system.

6.2.1 Volpriehausen Formation

Sedimentation cycle CV1

Well Core Rockensußra -2

The Basissandstein (Sedimentation cycle SV1) of the well Rockensußra-2 belongs to the interval between 591.50 and 613.50 m. The base of the CV1 is clear defined resting on a sequence of greyish brown silty sediments belonging to the top Bernburg Formation. The sedimentation cycle exhibits a blocky characteristic in gamma ray log and is mainly composed of medium-to coarse-grained light reddish brown sandstones poorly to moderately sorted. The base of this cycle constitutes bimodal horizontal lamination with some white bands which are associated to sand plain deposits and are overlain by thin sets of bimodal, horizontal lamination and fine to medium grained sandstones with low angle and tabular cross stratification. The dip angles increase from the base to the top of sand sheets (from 8° to 20°). The thickness of this unit does not exceed 30 cm.

Towards the top of cycle SV1 the grain sizes vary from very fine-to medium-grained, composed of reddish brown sandstones inter-layered with greenish grey sandstones with fine to coarse grains and sorting from moderately to well sorted grading to argillaceous sandstone. The sequences show alternation of cross stratified (from 5° to 20°) sand and horizontal-laminated sand with subordinate features of massive and ripples cross lamination (figure 6.3).

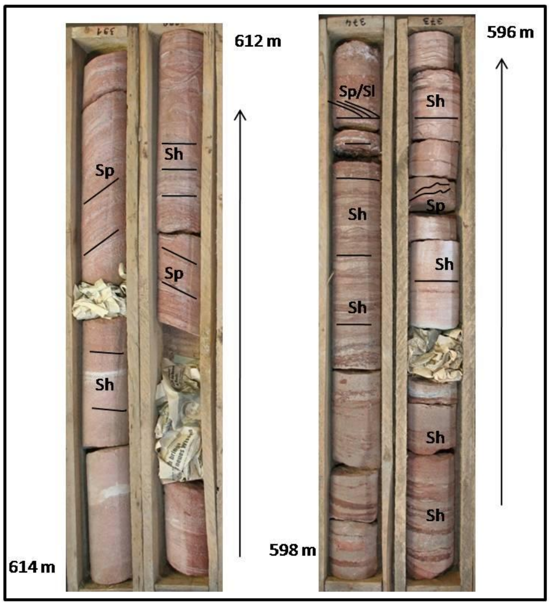


Figure 6.3 Core photograph of the Rockensußra-2 in the intervals 612–614 m and 596-598 m comprising the sedimentation cycle CV1 (Basissandstein-Volpriehausen), the base begins with sand plain deposits, showing horizontal lamination (Sh) in transition to eolian dune facies sand (cross stratified from 5° to 20°)

Well core Fahner Höhe -13

The first sedimentation cycle CV1 in the base of the Volpriehausen Formation comprises the Volpriehausen Basissandstein embracing thicknesses between 558 and 589 m. The base of this cycle is limited by an erosional surface and blocky character in gamma ray log. The cycle is composed of reddish brown bimodal laminated sandstones with some intercalation of greenish gray sandstones with intraclasts composed of clay and silt. The grain size varies from fine-to medium, from moderately to well sorted and partly bimodal, towards the top of CV1 can be found some low angles (about 5°) and planar cross stratified sandstone increasing the greenish grey sandstones, that are fine to medium grained with some argillaceous sandstones intercalation defining the top of depositional cycle. The lithofacies features observed in this sedimentation cycles suggest a fluvial channel system (figure 6.4).

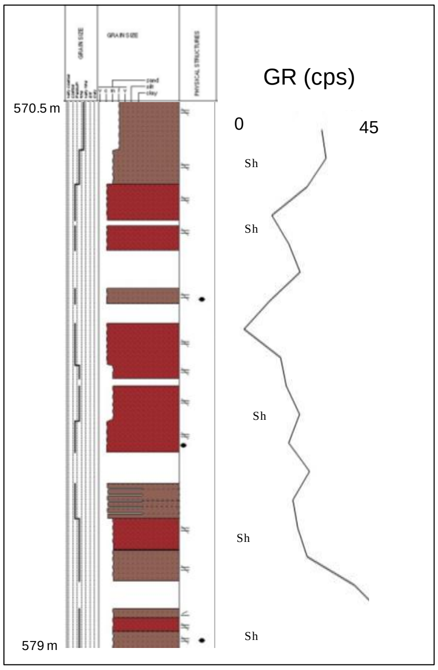


Figure 6.4 Lithofacies description of the Cycle CV1 at the base of Volpriehausen Formation in the well core Fahner Höhe-13. The sediments are composed of reddish brown sandstones (after Schnee, 2006). The lithofacies association comprises horizontal lamination (Sh). The sandstones are moderately-to well-sorted with some mudclasts at the base. This cycle is interpreted as fluvial channel deposits (.see legend in the enclosure 17)

Sedimentation cycle CV2 , CV3

Well Core Rockensußra -2

The cycles CV2 and CV3 of Rockensußra-2 comprise the interval between 567.4 and 591 m showing blocky gamma ray log. Each cycle is mainly composed of very fine and fine grained sandstones at the base with notable alternation of bedded siltstone in almost the whole sequence. Some intervals have medium-to coarse-grained sandstones with mudclasts, clay drapes and desiccation cracks. The lithofacies association comprises horizontal lamination and minor amounts cross stratified sets with isolated trough cross bedded sandstones, which suggests the alternation of sand plain facies in transition to lacustrine deposits. The colour of sandstones toward the top varies from light reddish brown to greenish gray and the grain size oscillates between fine to medium and from moderately to well sorted. The sandstones at the top mainly contain horizontal lamination characterized by intercalations of thin silty clayey lacustrine sediments showing fining upward sequences.

Well Core Fahner H öhe-13

These cycles are found between the intervals 544 and 558 m; the facies comprise fining upward depositional sequences. The base begins with reddish brown sediments; finely laminated composed of very fine-to medium-grained sandstones and moderately well sorted but passes gradationally to lithofacies as laminated silts and some cases massive. In some intervals the greenish grey sandstone is more common. Towards the top subordinate low angle cross beds (10°) and tabular cross stratified sandstones are observed like other sedimentary structures; clasts (>2 cm) and cement patches and increasing the amount of claystone forming fining upward cycles. This interval comprises fluvial facies with intercalations of thin silty clayey floodplain deposits.

Sedimentation cycle CV4

Well Core Rockensußra -2

This cycle CV4 is found between the intervals 567.40 and 557.70 m. The base consists of low angle cross beds and planar cross stratified sandstones in alternation with subordinate horizontal lamination, while towards the top the sequence is composed of reddish brown siltstone facies. The sandstones constitute fine grain size and are well sorted and well rounded. This cycle has been interpreted as sand plain deposits at the base in transition to lacustrine facies toward the top of the cyclothems. The facies interactions suggest fluctuation between a dry and sub aquatic conditions. The cycle CV4 in the well Fahner-Höhe-13 is not present.

Sedimentation cycle CV5

Well Core Rockensußra -2

This cycle is composed of light reddish brown sediments, well sorted with alternations of low angle cross bed and planar cross stratified sandstones with packages between 0.5 and 1 cm thick, embracing the intervals between 554.30 and 567.40 m with a blocky pattern in the gamma ray log. The cycle presents subordinated through cross stratified and ripples cross lamination sets of 5 mm composed of fine to medium grained sandstones, good sorting and partly bimodal. This succession has been interpreted as sand plain facies with some subaqueous dunes interbedded.

Well Core Fahner Höhe -13

The sedimentation cycle CV5 comprises the interval between 524 and 544 m exhibiting a blocky pattern but becoming finer upward. This cycle is mainly composed of very fine-to medium-grained reddish sandstones, well sorted with erosive base. The massive siltstone is observed toward the top of the cyclothems. In some intervals the colours of the sandstones varies from greenish gray sandstones with laminated siltstone in some intervals. The lithofacies association presents predominantly horizontal lamination and fine silty lamination toward the top. This lithofacies association suggests fluvial sand facies interbedded with some floodplain silts.

Sedimentation cycle s CV6, and CV7

Well Core Rockensußra -2

The sedimentation cycles CV6 and CV7 in the well core Rockensußra-2 comprise the intervals between 523.30 and 554.30 m. The sediments of the lithofacies association are composed of very fine-to coarse-grained sandstones. These cycles exhibit relative blocky character. The rocks are mainly characterized by horizontal lamination, ripple, cross lamination and subordinate trough cross stratified sets increasing at the top of CV7. These sandstones are generally from poorly to moderately sorted and exhibit in some intervals of weak bimodal grain size distribution, the colour of the rock is normally light reddish brown but varies to darker or to greenish grey and intraclasts greater than 2 mm, furthermore is observed at the top of CV6, reddish brown fine siltstone lamination and massive with thickness of 7 cm. The sandstones of cycle CV7 display large scale cross stratification features with set thicknesses of 0.5 m thick. In the upper part the dip of the foresets increases gradually.

The cycle CV6 exhibits at the base sand plain facies with residual deposits of eolian dunes and the massive and laminated mudstone suggest sedimentation of suspended load from water bodies (lacustrine deposits). The cycle CV7 is characterized by deposits of eolian dunes.

Well Core Fahner Höhe-13

The cycles CV6 and CV7 of the well Fh-13 are found between the interval 508.60 and 524.40 m, composed of fine and medium-grained sandstones, from moderately to well sorted, showing a variety of colours between reddish brown to greenish brown. The lithofacies is characterized by tabular cross stratified sandstones organized in 0.5 to 1 m thick sets. Which contains also clasts (3 mm), mud cracks and some load casts are notable. Towards the top of the cyclothems few intervals comprise horizontal bedding with notable intraclasts grain. The cycles are mainly associated to fluvial system composed of stacked erosive channel sets.

Sedimentation cycles CV8 and CV9

Well Core Rockensußra-2

The sediments in the base of the cycles CV8 and CV9 comprise very fine-to medium-grained sandstones varying from reddish brown to light reddish brown colours. The rocks are characterized by horizontal lamination and subordinate planar cross stratified sandstones, towards the top of CV8 the presence of massive and laminated mudstones is common, while at the top of CV9 the horizontal lamination increases and low angle cross beds ($<10°$) become abundant but are interbedded with laminated mudstone, mainly on the boundary with the Detfurth Formation.

The sandstone mainly varies from moderately to well sorted, present mudclasts, desiccation cracks and clay laminae in almost the whole interval of both cycles from 510 to 523.50 m. this succession is interpreted as sand plain facies in transition to lacustrine deposits.

Well Core Fahner H öhe-13

The cycles CV8 and CV9 are mainly composed of fine-to medium-grained reddish brown sandstones displaying horizontal lamination in its majority. Clasts of clay are observed in the whole sequence. Each cycle is bound at the base with an erosional surface and toward the top increases the fine-to very fine grained light reddish grey sandstones interbedded with red siltstones associated to horizontal lamination and low angle cross stratification (<5°), although with high angle crossbedding sands subordinate. These cycles have been interpreted as fluvial deposits in transition to flood plain deposits (figure 6.5).

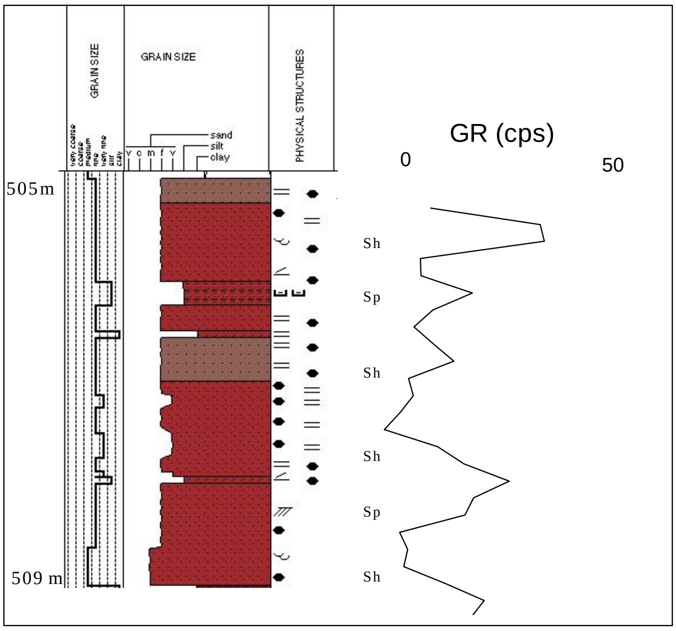


Figure 6.5 Lithofacies description of the cycle CV8 in the well core Fahner Höhe-13 mainly composed of reddish brown sandstones from fine to medium grained with some interval of massive siltstone (after Schnee, 2006). The grains are moderated well sorted with notable intraclasts at the base. The cycle is composed of high angle crossbedding and horizontal bedded sand suggesting fluvial channel deposits (see legend in the enclosure 17).

6.2.2 Detfurth Formation

Sedimentation cycle CD1

Well core Rockensußra -2

The Detfurth Formation comprises an only fining upward cycle observed in the majority of the gamma–ray log through the studied area. The well core Rockensußra-2 comprises the interval embraces 477.40 and 510.30. The base of this formation begins with a fine to medium grained dark reddish brown sandstones with high percentages of clay detrital. The grains are from moderately to well sorted, showing some intervals of low angle cross beds (<10°), the planar cross stratified with angle of fore-sets between 10° and 20° also are present identified as fluvial channel deposits.

The colour of the rock towards the middle of the cycle respect to the base varies to light reddish brown and some grey bands sandstones, which are composed of horizontally laminated units from moderately to well sorted with rare contents of clasts. This cycle comprises sand plain facies. The interval from 502 m become again to dark reddish brown with some greenish grey sandstones and fine lamination silts intercalation. The grain size of sandstone is occasionally coarse. The interval from 490 to 477.40 is more clayish with horizontal lamination associated to sand plain facies in transition with lacustrine deposits.

The upper part of this cycle comprises the intervals between 477.40 and 498 m. The lithofacies association at base is composed of horizontally laminated and crudely flat bedded (relative massive) sandstones associated with bimodal low angle cross stratified planar of distinct grain size variations; from fine to medium grained, well sorted and notably alternated, like laminated and massive silt. Some intervals present thin ripples cross laminated sets with siltstone intercalation. The top of this cycle has numerous mudclasts and clay drapes and the lithology is more argillaceous and notable light reddish brown and grey bands. The Detfurth Formation of the well core Rks-2 has been interpreted as sand plain facies with isolated bodies of eolian dune sands and the thin laminated silt indicates lacustrine influence (figure 6.6).

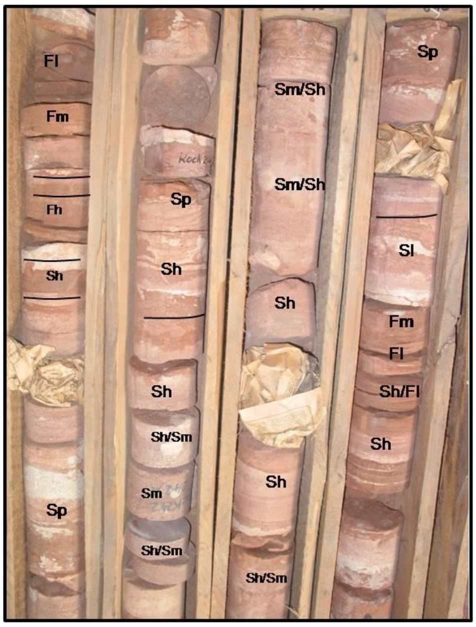


Figure 6.6 Core photograph of the Rockensußra-2, between 480 and 484 m showing the upper part of the sedimentation cycle (the Detfurth Formation). The main lithofacies are the horizontal lamination and low angle cross stratified; the cycle comprises sand plains facies deposits with intercalation of thin silty clayey lacustrine sediments. The isolated cross bedded sets suggest residual deposits of eolian dunes.

Well core Fahner Höhe -13

This cycle CD1 comprise the interval between 451.2 and 484.30 m comprising smooth serrate cylinder gamma ray log. The lower part the Detfurth Formation mainly composed of fine grained dark reddish brown sandstones and intercalations of dark reddish brown siltstones with thickness of 10 cm, showing weak lamination from moderately sorted to well rounded grains. The intercalation of siltstone presents characteristic features as fine lamination, small ripples and massive structures.

The sandstone units comprise at the base; horizontal lamination and low angle crossbedding (<5°), with intercalation of lithofacies as planar cross and trough bedding sets, also clasts (>2 mm) which are evidenced also as clay drapes, mud cracks and bleached layers.

The upper part of the cycle is composed of reddish brown and sandstone of very fine to fine grained within intervals of medium grained. The colour of sandstones in some intervals varies from light reddish brown to greenish grey presenting trough cross bedding sets in thickness of 10 cm. high angle cross bedding are observed but in minor amount. The grains are moderately well sorted and sub-rounded and poorly sorted with mudclasts, some bioturbation also as anhydritic patches. Towards the top the horizontal beddings are more frequent and the presence of the reddish brown siltstone increases, showing clearly a fining upward sequence. The observed lithofacies suggest fluvial facies with notable transition to flood plain deposits towards the top (figure 6.7).

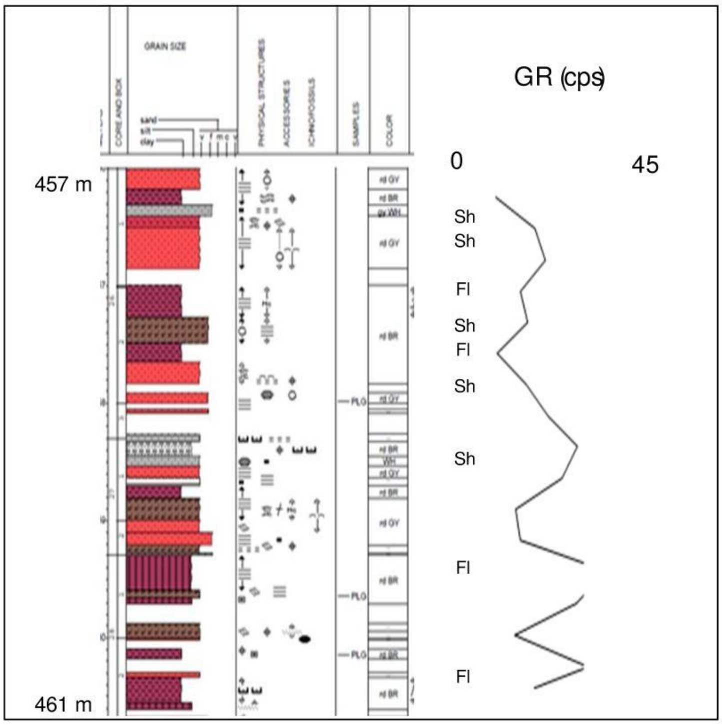


Figure 6.7 Lithofacies description (Fh-13) at the upper part of Detfurth Formation (cycle CD).The cycle shows Sh and Fl facies comprising fluvial facies in transition to floodplain deposits (after Schnee, 2006. see legend in the enclosure 17).

6.2.3 Hardegsen Formation

Well core Rockensußra -2

The determination of the boundary between the top of Hardegsen and the base of Solling in well core Rockensußra-2 is not clearly identifiable; the top of Hardegsen has been established through the regional stratigraphic correlation, using this information was approximately set the boundary.

According to stratigraphic correlation done in this work the H-unconformity is observed in the well Rockensußra-2 where only the cycles CH1 and CH2 and the lower part of CH3 are present, but the upper of the CH3 and the whole CH4 was eroded. However the unconformity was not clearly observed in the well core but with was determined making the regional cross section through the study area (figure 6.8).

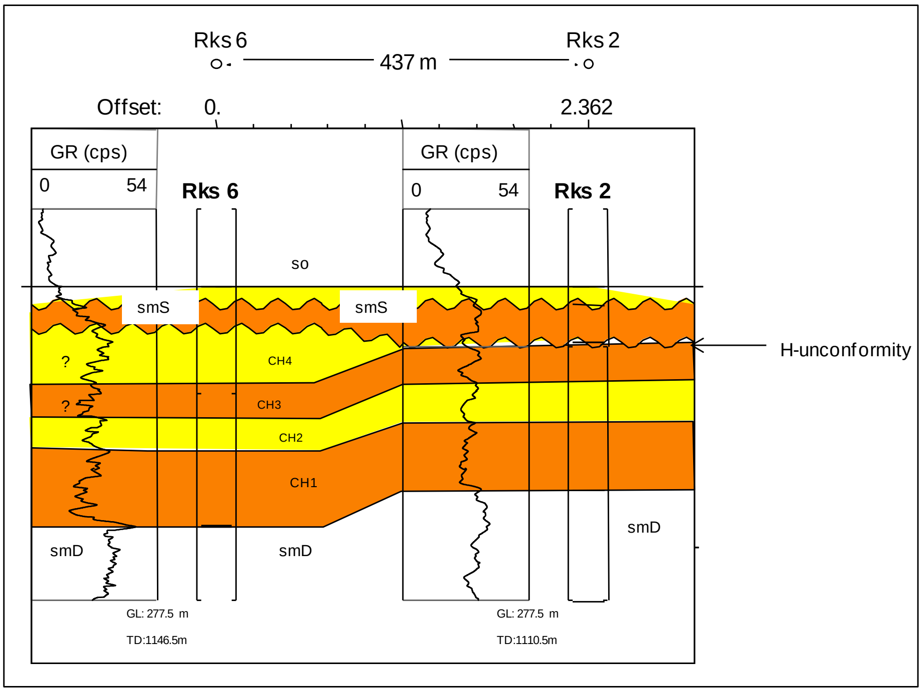


Figure 6.8 Stratigraphic cross-sections showing the H-Unconformity in the well Rockensußra-2, however the erosion is not easily recognisable in the well core.

Sedimentation cycle CH1

The first sedimentation cycle deposited in Hardegsen Formation for the well Rks-2 is found between 466 and 477.40 m. The base of this cycle comprises fine-to medium-grained sandstones from moderately well to well sorted is overlain by the more argillaceous part of the Detfurth Formation). The rocks present light reddish brown appearances and some greenish grey bands. The sedimentary features are composed of horizontal lamination, crudely stratified (relative massive) with like intervals of tabular and trough cross stratified sandstones. Some argillaceous mudclasts are present along the sequences. At the middle part of CH1, the colour of rocks varies from light to dark reddish brown. Towards the top of the cycle, the colour of the sandstones are again light reddish brown with grain size of moderately to well sorted, and the lithofacies association mainly comprises planar cross stratified (high angle) and truncate trough cross stratified sets. Thin intervals present fine lamination of siltstone, also the presence of mudclasts and white stains is notable. This cycle CH1 is composed of fluvial facies association and the thin siltstone suggests transition to flood plain deposits.

Well core Fahner Höhe -13

The cycle CH1 in the well Fh-13 embraces the intervals from 440 to 451.20 m. The base of this cycle is composed of medium to coarse grained reddish brown sandstones and some intervals of reddish grey colour. The sandstones generally present horizontal cross bedding, low angle and high angle cross bedding with some ripples or thin silts lamination in some intervals and mud lenses. The sandstones at the top of the cycle have greenish grey colour, with thickness of 20 cm. In the same way the grain size varies from fine to medium. The intraclasts are common on the top of the cyclothems with grains size about 2 cm. The sedimentary features recognized in this cycle indicate fluvial and fluvial sheetflood system (figure 6.9).

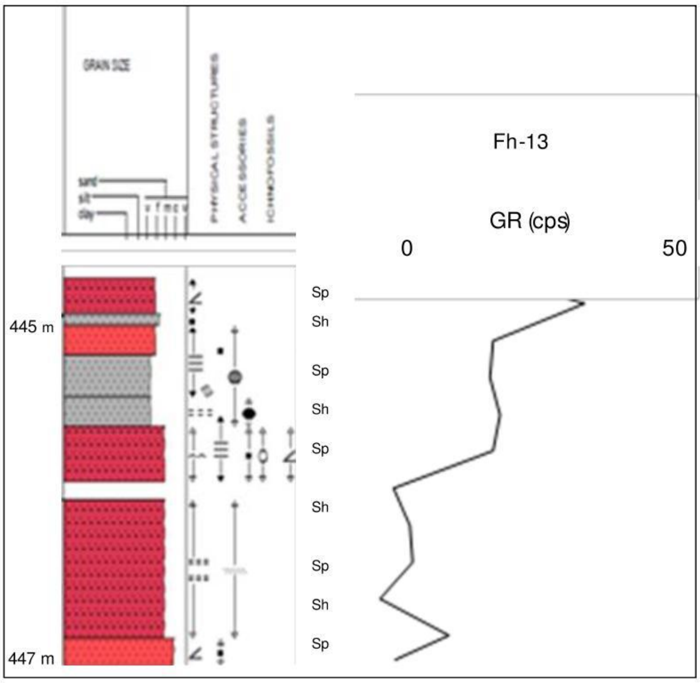


Figure 6.9 Lithofacies description at the upper part of sedimentary cycle CH1 in the well core Fh-13 composed mainly of sandstones from medium to coarse grained and well sorted (After Schnee, 2006). The main lithofacies are the horizontal lamination (Sh) and high angle crossbedding (sp) associated to fluvial channel sands (see legend in the enclosure 17).

Sedimentation cycle CH2

Well core Rockensußra -2

The cycle CH2 embraces the intervals between 457.30 and 466 m. The base is composed of medium to fine grained light reddish brown sandstones, which are well sorted and exhibit a weak bimodal size of the grains. This unit is mainly associated at the base with planar cross stratified sandstones and occasion trough cross stratified interpreted as fluvial channel units. Some intervals appear as reddish brown silts intercalation, which may suggest certain lacustrine influence (figure 6.10).

Towards the top of cycle CH2, the sandstones are horizontal laminated and low angle cross stratification but in occasion massive. The rocks are predominantly light reddish brown with some thin grey bands and laminated to bedded silt, forming fining upward cycle. The grain size is generally composed of medium grained from poorly to well sorted, also are observed detrital clays as mudclasts, clay drapes and desiccation cracks. These deposits in the upper CH2 mainly comprise fluvial channel.

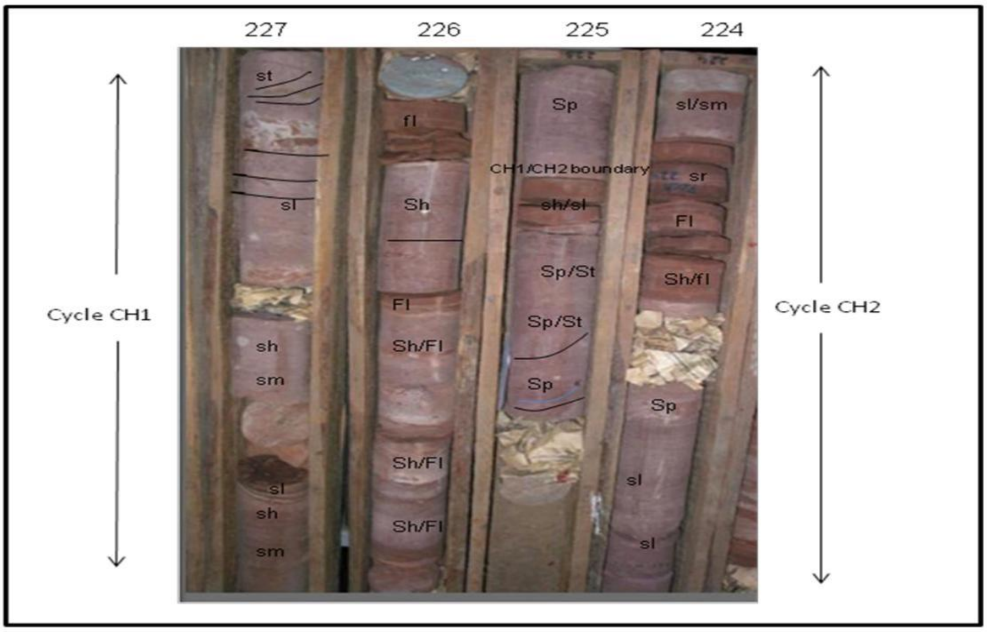


Figure 6.10 Core photograph of the Rockensußra-2, showing the boundary of CH1/CH2 in the Hardegsen Formation Characterized by fluvial facies some intercalation of thin silty clayey lacustrine sediments.

Well core Fahner Höhe -13

The cycle CH2 in the well Fh-13 comprises the intervals between 430.7 and 440.4 m. The sandstone shows wedge shape geometry and upward gradation from low angle to high angle cross bedding. Few interbedded claystones-siltstones are present in the succession. The colour of the rocks is basically reddish brown but some thin band of greenish grey can be observed. The sandstones present variation between fine and medium grained. They are moderately well sorted displaying weak bimodal lamination. This lithofacies association comprises fluvial system channel.

Sedimentation cycle CH3

Well core Rockensußra -2

The CH3 comprises the last interpreted cycle of the Hardegsen Formation under the H-unconformity; the lower part of the cycle CH3 is only present comprising the interval between 449.21 and 457.30 m. This succession is composed of light brown to dark reddish brown sandstone with some greenish grey bands. Numerous intraclasts (≥ 2 mm) have been observed. The sandstones are moderately to well sorted showing bimodal lamination, and comprising fine to medium-grained. Towards the top are observed thin silty clayey intervals. The dominantly horizontal lamination and the subordinate very low angle cross stratified (<° 5), suggests low energy, gradually decelerating suspension currents in shallow depths associated to fluvial sheetflood deposits.

Well core Fahner Höhe -13

The cycle CH3 embraces the interval from 418 to 430.3 m of the well Fh-13 numerous intervals through the core were no recovered. The lithofacies association is characterized by fine and medium-grained sandstones with reddish brown appearances. The deposits constitute stacked erosive channel sets. There is also notable the presence of intraclasts composed of grains between 2 and 3 cm. The sandstones have high angle crossbedding and some massive bodies, alternating in occasion with massive siltstone and small ripples. According to lithofacies observed the cycle CH3 is associated to a fluvial channel system.

Sedimentation cycle CH4

Well core Fahner Höhe -13

The uppermost cycle of the Hardegsen Formation embraces the intervals between 405.60 and 418 m. The grain size varies from fine to coarse, representing a fining upward cycle. The sandstones are moderately sorted and the sedimentary features are characterized of low angles cross beds, increasing the angle towards the top of the cyclothems. The sequence presents intercalation of thin silty-clayey sediments. This lithofacies association suggests fluvial channel facies in transition with flood plain deposits (figure 6.11).

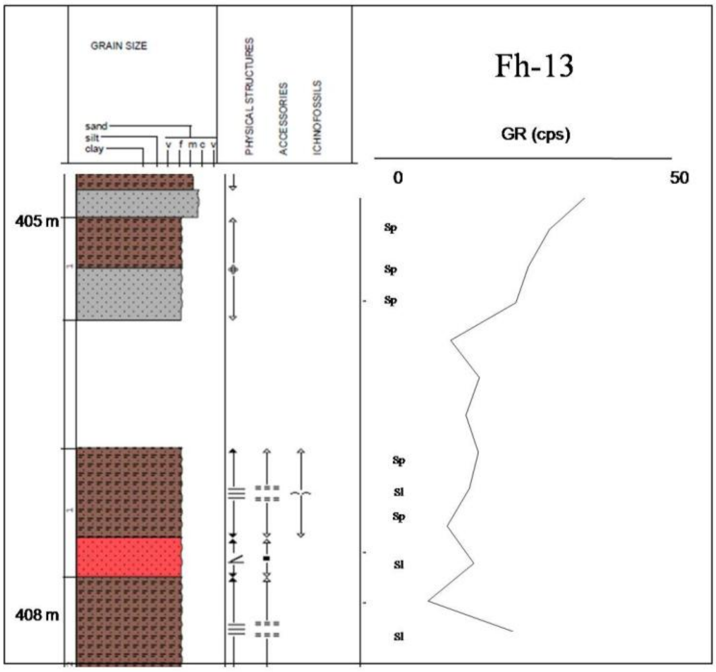


Figure 6.11 Lithofacies description of the cycle CH4 in the well Fh-13 composed of greenish grey, light and reddish brown sandstones with intercalation of silty-clayey sediments (after Schnee, 2006). The cycle has been interpreted as fluvial channel system in clear transition to floodplain deposits (see legend in the enclosure 17).

6.2.4 Solling Formation

Sedimentation cycle S

Well core Rockensußra -2

Sedimentation cycle S is composed of the “Solling Basissandstein”, the “Tonige Zwischenschichten” and the “Thüringer Chirotherien-Sandstein” comprising the Interval between 438.50 and 449.20 m.

The top of Hardegsen and the base of Solling are difficult to define. According to Lang (2001) the top of Hardegsen (cycle CH3 in this work) of the well core Rks-2 comprises a fining upward sequence from dark brown fine grained sandstones to fine silty clayey lamination (figure 6.12). The base of the Solling Formation begins with medium grained sandstones and reddish brown appearances.

The lower part of the Solling Formation embraces the “Basissandstein” and the “Tonige Zwischenschichten“, indicating a well developed fining upward sequence. The “Solling Basissandstein” is mainly composed of dark reddish brown sandstones with presence of green and gray stains. Modal grain size varies from fine to medium. The sandstones are generally moderately well sorted and the intraclasts of clay are common in this sequence. The lithofacies predominantly at base are associated to tabular cross stratified of high angle. In occasion is observed massive to crudely flat bedded indicating high flow regime (figure 6.12). Towards the top of the “Solling Basissandstein”, the sandstone is composed of fine to medium-grained and the colour varies to light reddish brown and with some grey bands. The lithofacies showing horizontal lamination or low angle cross stratified (<5°), which suggests possibly low energy deposition.

The Solling claystones (“Tonige Zwischenschichten”) in the well core Rockensußra-2 has an approximate thickness of 4.5 m exhibiting heterolitic sequences with fine grained light reddish brown sandstones and irregularly bedded silts. The observed intraclasts have a diameter between 1 and 2 mm, also are present numerous roseate and green carbonate concretions (0.5 and 1 mm). In some thin intervals of this sequence the percentage of claystones-siltstones dominates over the percentage of sands. It suggests loads at low energy deposition. Towards the top the amount of relatively rounded intraclasts increases. The sequence of the cycle S is dominated by braided river systems in transition to flood plain deposits (figure 6.12).

The upper part of the Solling Formation comprises the “Chirotherien-Sandstein” between 438.50 and 441.90 m mainly composed of medium to coarse-grained sandstones with green and dark green appearances. The sedimentary structures are not clearly identified. In some intervals are observed a possible low angles cross a beds and massive beds but generally the structures have been destroyed. The sandstones have clasts well sorted and well rounded. Some intervals present siltstone laminations, anhydritic concretions, gip mineral and well rounded clasts.
Lang (2001) suggest that towards the top of the Solling Chirotherien, is notable the presence of anhydrite. This sequence is dominated by fluvial system with transition to marginal marine deposition.

Figure 6.12 Core photograph of fluvial sheetflood deposits, showing horizontal bedding with occasional low angle crossbedding (<5°) composed of dark brown fine grained sandstones and thin lamination of claystones at the top of Hardegsen Formation (CH3), while the base of the Solling Formation ("Solling Basissandstein") comprises light brown sandstones of middle grains, dominated by braided river systems. The boundary between both formations has not been clearly identified; the base Solling was established through the stratigraphic correlation and the definition proposed by Lang (2001).

Well core Fahner Höhe -13

In the well Fahner Höhe-13, only the lowermost part is present; the "Solling Basissandstein", embracing the intervals between 400 and 405.60 m, the core was not completely recovered. The lithofacies association of the well core evidences that the base of the Solling Formation consists of medium-grained reddish brown argillaceous sandstones with greenish grey bands alternation overlain by a finer sand unit. The sandstone is commonly composed of mudstone clasts and grains varying from moderately to well sorted and grading towards the top to reddish siltstone. The high angle cross-bedding is present in the whole cycle, with subordinate horizontal lamination and massive sandstones. The well Fh-13 in the Solling Formation mainly consists of fluvial channel deposits in transition to floodplain facies (figure 6.13).

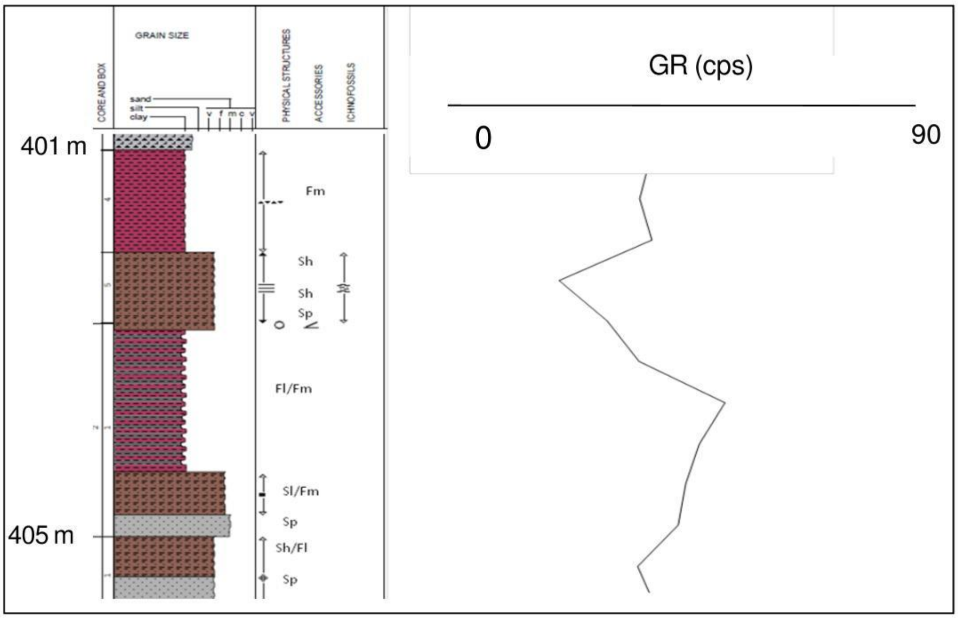


Figure 6.13 Lithofacies description in the Solling Formation (the “Solling Basissandstein”) for the well core Fahner Höhe-13. The sequence consists of greenish grey, light and reddish brown sandstones with intercalation of reddish brown and grey siltstone. The sedimentary features mainly comprises planar cross stratified (Sp), horizontal lamination (Sh), low angle cross stratified (Sl), massive silt (Fm) and finely bedded (Fl). The sequence has been interpreted as fluvial deposits in transition to floodplain deposits (see legend in the enclosure 17).

6.3 Electrofacies study

This electrofacies study consists in the recognition of the characteristics and the behaviour of the gamma ray and spontaneous potential in the wells defining log types. This interpretation has been integrated with lithofacies and sedimentary environments recognized in the well cores Fahner Höhe-13 and Rockensußra-2.

The differentiation of the logs pattern in the Middle Buntsandstein Subgroup is not easy to make, for this reason the net sand, net to gross maps have been calculated to get a better overview of electrofacies distribution through the study area. This allowed to establish the percentage of clayey-silty sediments in the sandstones.

This facies interpretation was developed for each formation of the Middle Buntsandstein: Volpriehausen, Detfurth, Hardegsen and Solling Formation. The log shapes of 133 wells have been studied through the studied area, composed in their majority of gamma ray, and some spontaneous potential logs, these electrofacies mainly comprise shape characteristics which are shown in the figure 6.14.

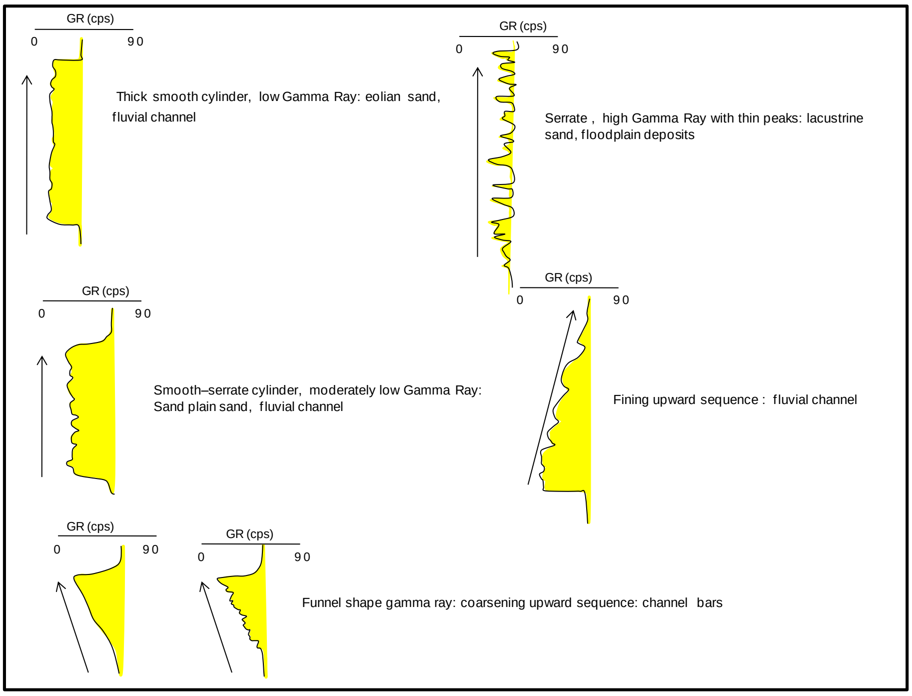


Figure 6.14 Facies interpretation of the Middle Buntsandstein Subgroup using the log shapes. These log characteristics are based on the facies types proposed by Miall (1996).

6.3.1 Log patterns in eolian facies

Eolian and sand plain facies have been recognized in the Volpriehausen and Detfurth formation with traces of fluvial deposits at the base of Detfurth. The gamma ray and spontaneous potential logs present moderately low intensity of the curves; the log patterns observed in the majority of logs are composed of smooth cylinder and smooth-serrate cylinder patterns.

Well log Rockensußra -2

Volpriehausen Formation

The well log Rockensußra-2 at the Volpriehausen base (cycle CV1) displays thick smooth cylinder shape with values oscillating from 15 to 20 cps. It shows more predominance of eolian dune and sand plain facies (according to core description done in the chapter 5). The top of Volpriehausen (CV2, CV3, CV4, CV6, CV7, VC8 and CV9) in the wells core suggested fine and medium grained sandstones with notable alternation of bedded siltstone or fining upward cycles and the log shapes comprise notable serrate cylinder patterns with interactions of low and high values (34 and 50 cps) in horizontal scale from 0 to 65 cps units. This pattern indicates high amount of clay suggesting lacustrine and floodplain deposits. This characteristic of the gamma curves varies according with the alternating of sand plain and eolian dune facies.

Detfurth Formation

The log values in the Lower Detfurth oscillate between 39 and 45 cps composed of light reddish brown and some grey bands sandstones constituted of smooth serrate cylinder shapes and relatively low gamma ray value. The lithofacies in Rockensußra-2 comprise fine to medium grained sandstones characterized by horizontal lamination and subordinate planar cross stratified interpreted as fluvial-eolian interaction on a sandflat.

The GR curve in the upper part of the Detfurth Formation presents the same thick smooth serrate cylinder pattern with moderately low values between 42 and 46 cps, with lithofacies association composed of horizontally laminated and crudely flat bedded sandstones associated with angle cross stratified planar and silty intercalation. The

Detfurth lithofacies are mainly composed of sand plain facies in transition to lacustrine deposits.

6.3.2 Log patterns in fluvial facies

The whole Middle Buntsandstein in the Fahner Höhe-13 is mainly composed of fluvial depositional regimes, while in the well core Rockensußra-2, these facies were only observed the Hardegsen and Solling Formations. The logs exhibit patterns basically composed of bell shaped peaks, smooth serrate-cylinder and fining upward cycles with moderately low values and in occasion increasing in high peaks.

Well Log Fahner Höhe-13

Volpriehausen Formation

The base of the Volpriehausen Formation begins with CV1 (“Volpriehausen–Sandstein”) which consists of gamma ray log with cylindrical shape and smooth serrate cylinder forms. This curve shows low peaks and some intervals of relative high radioactivity in the gamma ray log (tendency to the right), composed of values between 28 and 36 cps, in a horizontal scale varying from 0 to 90 cps.

The cycles CV2, CV3, CV4 CV5, CV6, CV7 (Volpriehausen-Wechselfolge) and the CV8 CV9 (Volpriehausen-Aviculaschichten) are composed of very fine to medium grained sandstones, moderately well sorted and passes gradationally to lithofacies as laminated silts and in some cases massive, which comprise fining upward sequences. The gamma log shows smooth-serrate cylinder curves mainly characterized by low peaks. These values oscillate between 57 and 90 cps. The lithofacies description suggested fluvial channel in transition to floodplain deposits.

Detfurth Formation

The Detfurth Sandstein presents a cycle composed of low gamma ray radiation with values varying from 40 to 60 cps and thick cylinder shape. The gamma ray curve in the upper part of Detfurth Formation (The Detfurth Wechselfolge) varies from 59 to 79 cps which keeps more serrate cylinder characteristics representing sandstone and silts alternation.

Hardegsen Formation

The lower part of the Hardegsen Formation (CH1 and CH2) is mainly composed of fine grained dark reddish brown sandstones, with intercalations of dark reddish brown siltstones with horizontal lamination and low angle crossbedding suggesting fluvial facies with notable transition to flood plain deposits. The CH1 and CH2 comprise log characteristic of smooth cylinder form iterating with intervals of serrate cylinder shape. The values of the gammy ray log oscillate from 51 to 59 cps.

The cycle CH3 is characterized of fine to medium grained sandstones with reddish brown appearances comprising stacked and fining upward cycles of high angle crossbedding and some massive sand bodies and showing a gamma ray log with serrated cylinder tendency. The curve in the cycle CH4 is characterized by low gamma ray between 51 and 72 cps, in a horizontal scale from 0 to 100 cps. The well core description suggested fluvial channel deposits.

Solling Formation

The “Solling Basissandstein” consists of fine-to medium-grained argillaceous sandstones and some greenish grey bands. This sequence is characterized by a notable decrease of gamma ray radiation showing a very low and relatively constant reading. This curve log exhibits cylinder log pattern interpreted as fluvial channel deposits. The uppermost Solling Formation is not present in this well.

Well Log Rockensu ßra-2

Hardegsen Formation

The cycle CH1 is mainly composed of medium to coarse grained sandstones showing horizontal bedding, low angle and high angle cross bedding but with some ripples or thin silts lamination in some intervals. The cycle CH1 presents notable serrate cylinder form of gamma ray with values oscillating from 37 to 45 cps.

The cycles CH2 and CH3 are associated with planar cross stratified sandstones and occasion trough cross stratified and horizontal lamination, while towards the top is present low angle cross stratified (<° 5). The logs in both cycles show thick smooth serrate cylinder shape with low gamma ray radiation between 32 and 40 cps. The top of the sequences is marked by an abrupt change of the log shape; this cycle CH3 according with the facies observed in the well core consists of fluvial sheetflood deposits.

Solling Formation

The base of the Solling Formation consists of fine-to medium-grained argillaceous sandstones beginning with an erosive surface, showing fining upward shape with values of gamma ray from 32 to 42 cps. This log shape represents a sequence of fluvial channel.

The upper part of the cycle is composed of medium to coarse grained sandstones with possible low angles cross stratified and massive lithofacies, and some intervals are destroyed. The Log exhibits a funnel cylinder shape showing gamma ray variability from 32 to 38 cps units with sequences interpreted as fluvial channel with marine influence toward the top.

6.3.3 Distribution of characteristic log facies in the Middle Buntsandstein Subgroup

The facies interpretation in the Middle Buntsandstein sequences using the log is not easy to identify, if a sequence comprises shaly sand, due to the curve patterns are similar in almost all of the well logs. For this reason for obtaining the percentage of sand accumulation in each formation, net sand maps have been constructed.

The Isochore map indicates the graphic representations of the vertical thickness of the reservoir rock or the geological formation, which in this case is defined by two stratigraphic horizons and used to determine rock volume that can be saturated with hydrocarbons (Laudon, 1996). An Isochore map allow to obtain the distribution of geological units in three dimensions. The creation of the Isopach maps requires that the structure and stratigraphic levels are honoured rigorously, using the fault planes and structure contour map and faulted well information.
The net sand Isopach (thickness) map comprises the total interval of sandstone that could be saturated with oil or gas (Laudon, 1996). That is calculated in meters and indicates the sand accumulation in a total thickness, which is based on the gamma ray and spontaneous potential logs. This map normally is combined and integrated with paleogeographic maps.

The thickness of the net sand in each well log was established using a cut off according to the horizontal scale of normalized gamma ray and spontaneous potential. The core description of wells Fh-13 and Rks-2 were upscaled to a length scale relatively equivalent to the resolution of the gamma ray logs. The Net to Gross (N/G) curved is based a distribution of sands and clays and using the same cut-off values for the net sand in all well logs. These values were plotted for each stratigraphic unit (smV, smD, smH and smS) showing the distribution of sands and shale-sand alternation through the studied area.

For the construction of the net-to-gross maps a 65 % cut off rate was established if the amount of sand is greater than this percentage, the interval is considered as sandy facies, represented in yellow areas. But if the amount of sand is less than 65 %, it can be interpreted as shale-sand alternation which is represented in brown (figure 6.15). All of these maps have been calculated and created with the Kingdom 8.2 software.

6.3.3.1 Electrofacies facies interpretation in the Volpriehausen Formation

The well log Kirchheilingen-61 comprises a net-to-gross relation of 54 % exhibiting log with a relatively serrate shape and high gamma ray peaks, while the Mühlhausen-19 displays a net-to-gross value of 0.76 % and log with cylinder shape (figure 6.15). The sand distribution of the Volpriehausen Formation through the studied area is rather homogeneous; the net-to-gross map contains a high sand distribution of 88 % and shale-sand alternation of 12 %. The reduction of sand thickness is located in central and northwestern area (figure 6.16). The Volpriehausen Formation in the Northwestern Thuringia Synclinal represents the thickest sequence of the Middle Buntsandstein Subgroup.

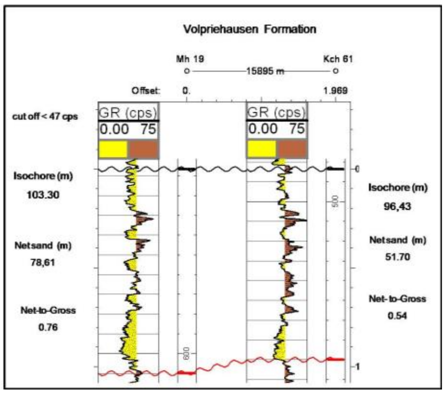


Figure 6.15 Determination of net-to gross values in the Volpriehausen Formation for the well logs Mühlhausen-19 and Kirchheilingen-61 and establishing a cut off of 47 cps.

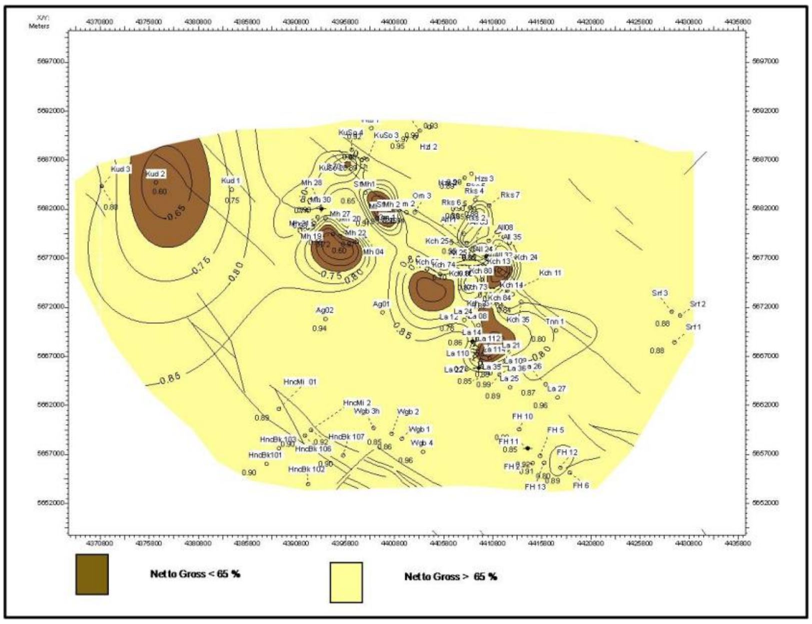


Figure 6.16 Net-to-gross map of the Volpriehausen Formation showing high distribution of sand through the studied area. The shale-sand alternation distribution is mainly located in the central and northwestern area.

6.3.3.2 Electro facies interpretation in the Detfurth Formation

The electrofacies map in the Detfurth suggests a sand and shale-sand distribution of 60 % and 40 % respectively. The well log Mühlhausen-19 comprises net sand Isochore of 13.6 m in a complete thickness of 27 m, which represents a net-to-gross value of 0.49 using a cut off of 45 cps (figure 6.17). The well Mühlhausen-27 has a net sand value of 19.50 m and an Isochore value of 25 creating a net-to-gross of 0.78. The shale-sand distribution is located in the northwestern-southwestern and southwestern-southeastern area, while the sand distribution is mainly situated in central and northern area with northeast-southwest orientation (figure 6.18).

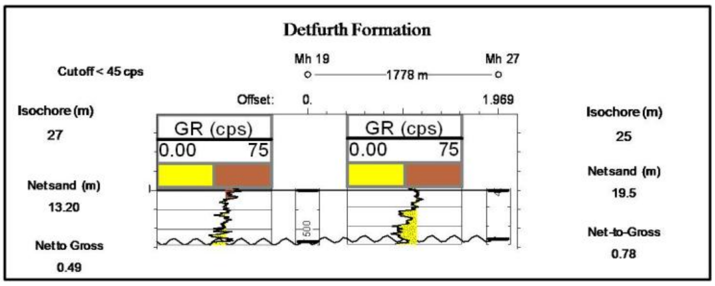


Figure 6.17 Determination of net-to-gross values for the Detfurth Formation in the well logs Mühlhausen-19 and Mühlhausen-27 with values of 0.49 and 0.78 respectively.

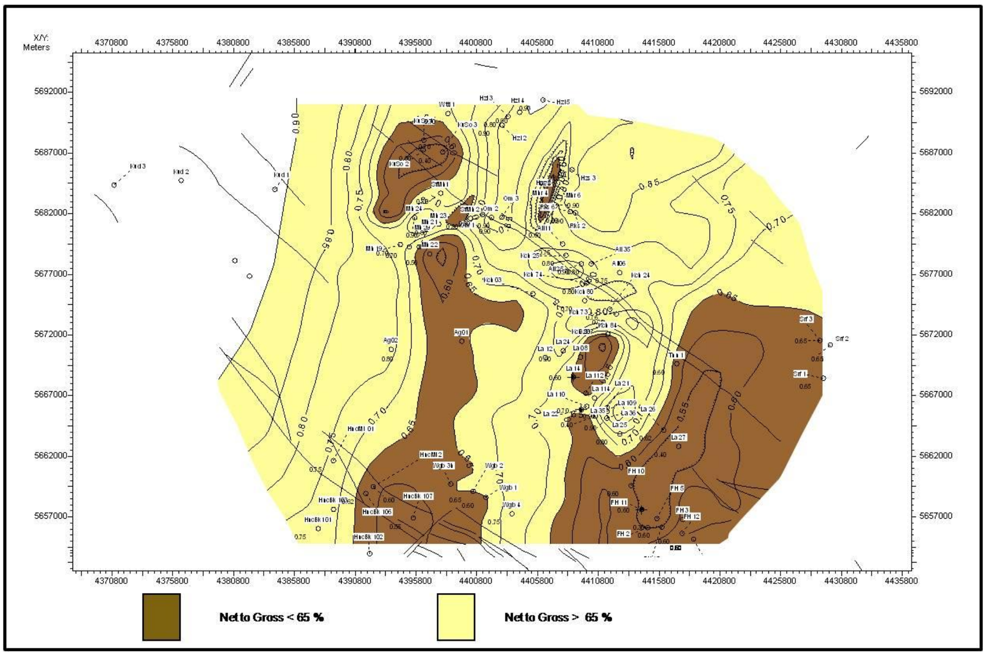


Figure 6.18 Net to gross map of the Detfurth Formation, the shale sand alternation mainly presents northeast-southwest orientation.

6.3.3.3 Electro facies interpretation in the Hardegsen Formation

The sand and shale-sand distribution of the Hardegsen Formation comprises 80 and 20 % through the studied area; the well Allmenhausen-32 displays a net-to-gross value of 0.50 with net sand in 22 m and an isopach data of 44 m. The well Kirchheilingen-11 presents a net-to-gross value about 0.85 with a net sand of 40 m in a complete thickness of 47 m (figure 6.19). The shale-sand distribution presents northeast-southwest orientation (figure 6.20).

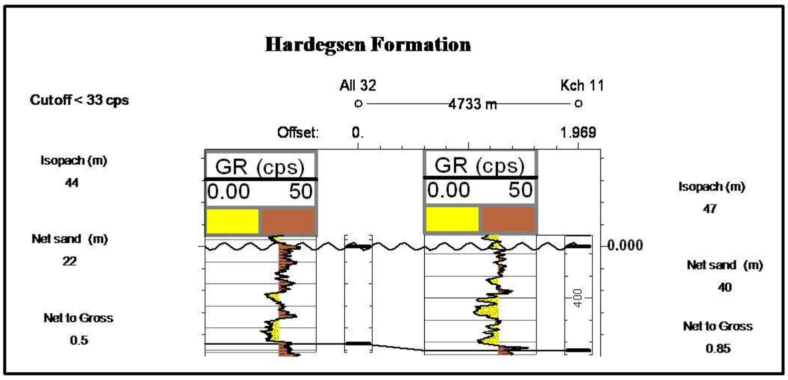


Figure 6.19 Determination of net-to-gross in the Hardegsen Formation for the well logs Allmenhausen-32 and Kircheilingen-11, presenting values of 0.5 and 0.85 respectively.

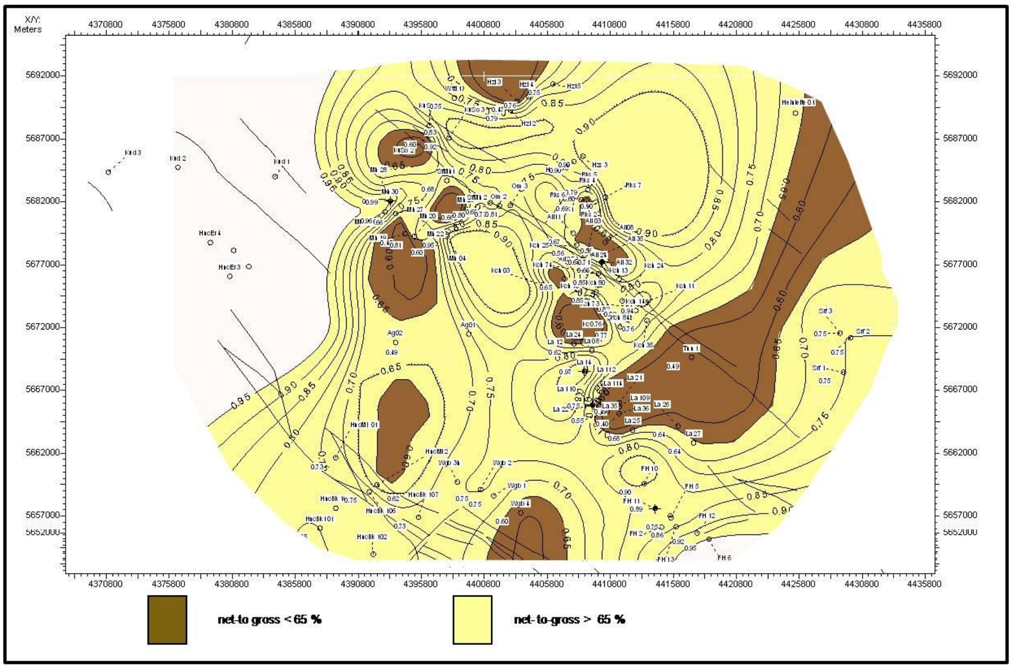


Figure 6.20 Net to gross map of the Hardegsen Formation, the shale-sand alternation distribution is located in the northeastern and southern area presenting a northeast-southwest tendency.

6.3.3.4 Electro facies Interpretation in the Solling Formation

The Solling Formation comprises a 67 % and 33 % of sand and shale-sand alternation observed through the studied area, the well log Mühlhausen-20 is composed of a net-to-gross value about 0.45 % in a complete thickness of 7.2 m and net sand Isochore of 3.3 m. The well log Allmenhausen-03 comprises a net-to-gross in 0.90 for a thickness of 9.2 m with a net sand value of 8.3 m (figure 6.21).The shale-sand alternations are distributed in the whole area as well as sand facies. The net-to-gross map suggests that the shale-sand alternation presents a northeast-southwest orientation (figure 6.22).

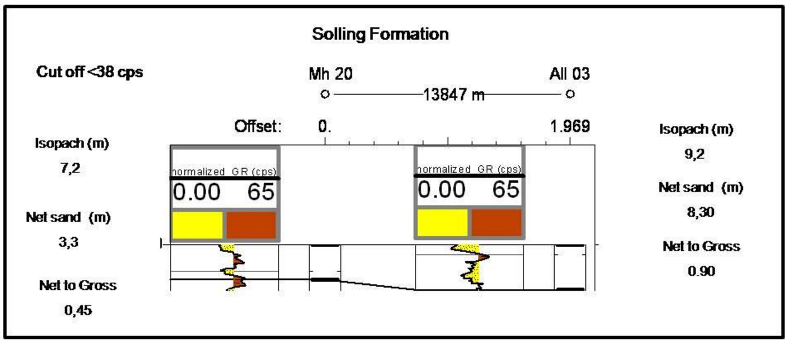


Figure 6.21 Determination of net-to-gross values in the Solling Formation for the well logs Allmenhausen-34 and Allmenhausen-24 presenting values of 0.45 and 0.90.

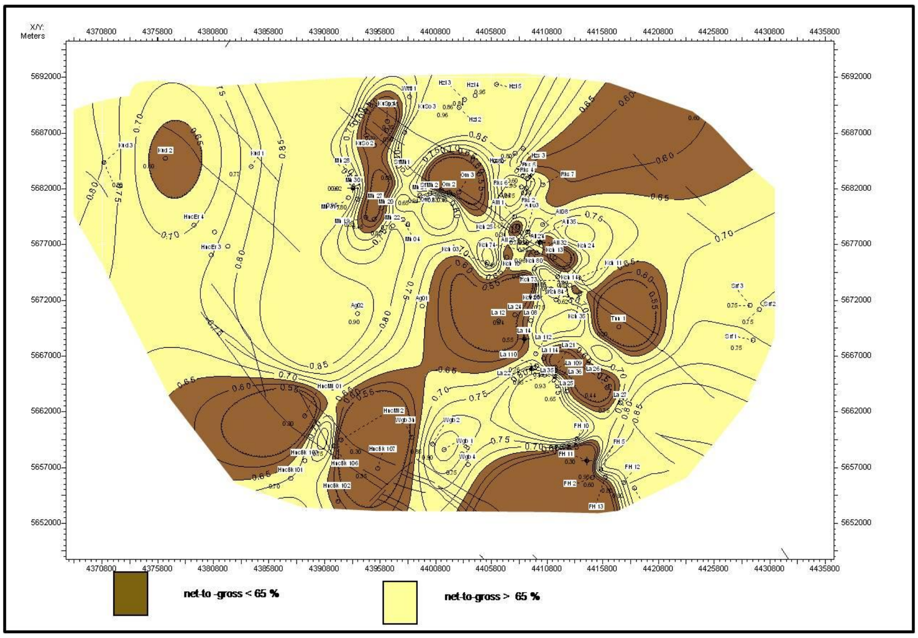


Figure 6.22 Net-to-gross map of the Solling Formation, showing sand and shale-sands distribution through the study area. The shale-sand alternation presents mainly a northeast-southwest orientation.

7. Cyclicity of the Middle Buntsandstein Subgroup

Sequence stratigraphy was defined in passive margin settings (Van Wagoner et al. 1990) but has been applied by various authors in continental basins (e.g. Aigner et al. 1992, Bachmann et al. 2008). The sediments of the Lower and Middle Buntsandstein Subgroups were deposited during Triassic times in continental environment of a large intracratonic basin, comprising cyclicity patterns associated to climatic variations (Milankovitch climate cycles) and does not depend of sea-level fluctuations in the sense of the sequence stratigraphy, except for the Röt Formation which presents marine influence. The Thuringian Syncline occupies a marginal position in the southeastern part of the Germanic Basin comprising tectonically controlled areas of relatively slow subsidence, which is evidenced in the uniform thickness.

The sediments of the Middle Buntsandstein Subgroup consist of eolian, fluvial, floodplain and lacustrine deposits (e.g. Boigk 1956. 1964, Trusheim. 1963 and Hoppe. 1976a, 1976b). Towards the top of the Solling Formation, a transition to marginal marine deposits occurred. This subgroup through the Germanic Basin mainly consists of red sandstones, shales and anhydrite sediments. Roman (2004) suggested for the Thuringian West Brandenburg Depression, marine incursions during the deposition of the Volpriehausen and Detfurth Formations.

The deposition of the Middle Buntsandstein Subgroup throughout the studied area constitutes a reorganization of the pattern subsidence, representing tectonic-stratigraphic units showing higher order sequences of fining upwards cycles implying genetic small cycles. Szurlies (2003) states that the high resolution of the Middle Buntsandstein Subgroup in the Central European Basin represent climatic fluctuation of alternation drier and wetter periods with a periodicity of about 100 ka related to Milankovitch eccentricity cycles.

The Buntsandstein Group are bounded by regional unconformities (basal unconformities), evidenced in different areas of the German basins and the Netherlands as has been described by numerous authors; Trusheim (1961), Brünning (1986), Aigner et al, (1992), Geluk et al (1997), Geluk (2005) etc.

Aigner & Bachmann (1992) defined the entire German Triassic as a second order transgression-regression cycle caused by changes in basin subsidence and eustatic sea level created by third order depositional cycle, system tracts and parasequences.

Geluk & Röhling (1997) and Geluk (2005) established that the Lower Triassic “Buntsandstein” in the Netherlands and northwestern Germany comprises sequences of tectonostratigraphic origin bounded by regional unconformities, which can be correlated over large area. Geluk (2005) explained that the Buntsandstein Group is composed of parasequences, bearing a distinct hierarchical Milankovitch signature.

Bachmann et al (2008) interpreted the Buntsandstein Group in the Central European Basin System as part of two different depositional cycles made up of transgressive phase, peak transgression (maximum flooding interval) and regressive phase.

Based on gamma ray logs and lithostratigraphic analysis Szurlies (2007) divided the complete Buntsandstein into about 60 sedimentary cycles correctable throughout Central Germany. This author proposes that this sedimentary succession is probably due to solar induced short eccentricity cycles; also state that the Middle Buntsandstein Subgroup is composed of 14 to 29 fining upward cycles

The Buntsandstein cyclicity throughout the northwestern Thuringian Syncline are laterally correlated from well to well using gamma ray logging and in some cases spontaneous potential based in high resolution lithostratigraphic characteristic and the well cores of Rks-2 and Fh-13. The Middle Buntsandstein Subgroup comprises in the studied area thickness between 130 and 220 m, which consists of about fifteen small fining upward cycles implying recognition on the well logs of patterns such as breaks, peaks and trends (figure 7.1). The cyclicity can be recognized and correlated throughout the northwestern Thuringian Syncline. The lithostratigraphic subdivision uses the trends; basal sandstones and towards the top clayey sediments (Boigk, 1959 and Hoppe, 1959). Wells located in the Schlotheimer Graben and others areas comprise relatively the same number of cycles keeping uniform thickness. The low radiation in the GR logs indicates sandy lithology at the base and the higher values displays more shaly content towards the top of each cycle.

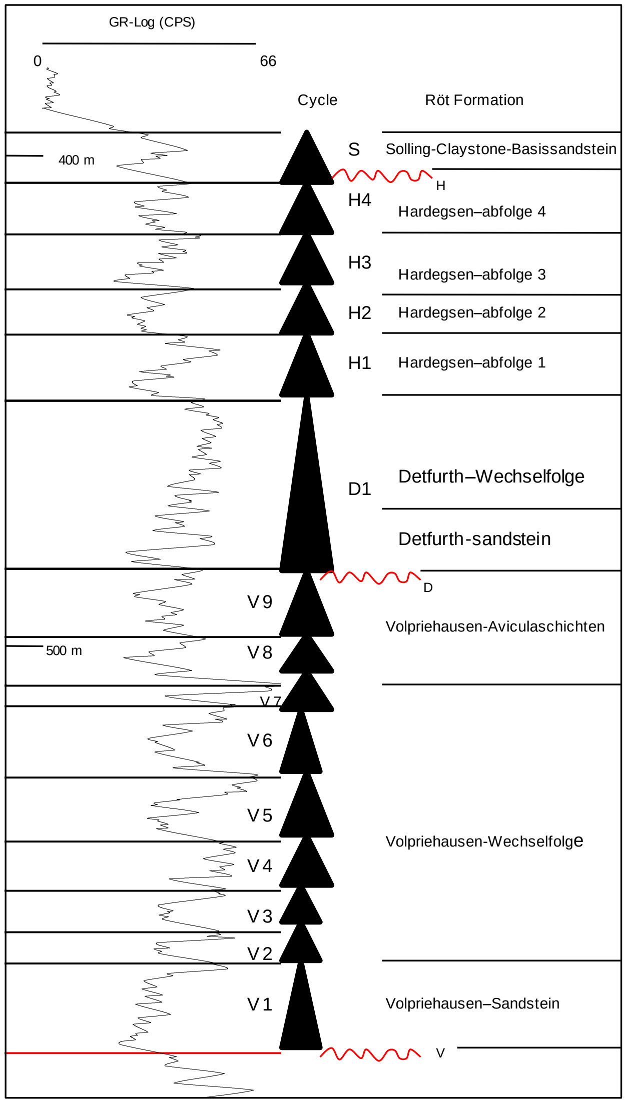


Figure 7.1 Cyclic stratigraphy of the Middle Buntsandstein Subgroup in the well log Kircheilingen-23 comprising fifteen fining upward cycles.

Tectonic events occurred during the deposits of the Middle Buntsandstein Subgroup and induced important unconformities at the base of the Volpriehausen, Detfurth and Solling Formation (Trusheim 1961 and 1963), but these unconformities that separate these formations are not visible or in some cases are completely absent. The Volpriehausen unconformity is mainly recognisable in the Germanic Basin and in the Polish Sub-Basin, while the H-unconformity is pronounced in the Hunte and Eichsfeld-Altmark Swells but also in Poland (Roman, 2004). The complete thickness of Middle Buntsandstein Subgroup in the Central Hunte Swell has been eroded (Trusheim, 1961).

7.1 Cyclicity of the Volpriehausen Formation

The Volpriehausen Formation comprises the “Volpriehausen Sandstein”, “Volpriehausen-Wechselfolge” and the “Volpriehausen-Aviculaschichten” deposited in the entire northwestern Thuringian Synclinal slightly reduced in the northern and southern studied area with thickness between 70 and 120 m. The Volpriehausen Formation comprises nine fining upward cycles identified from bottom to top as V1, V2, V3 V4, V5, V6, V7, V8 and V9 cycles. Szurlies (2007) suggested that the Volpriehausen Formation in Central Germany consisted of 5 to 10 fining upward cycles ranging from about 10 to 20 m in thickness. In Central Germany, the Volpriehausen succession displaying a complete thickness between 150 and 200 m. the well log Solling-5 located in the southern part of the Hessian Depression is subdivided in ten cycles and the well log Bockenem-A100 in nine cycles. While In the well log Königslutter-Z1 located in the Eichsfeld Altmark Swell, only five cycles have been preserved (Szurlies, 2007) with Solling Formation resting upon the lower and middle part of the Volpriehausen Formation, as product of uplift and erosion after Hardegsen deposition (H-unconformity). In the well logs Küllstedt 2 and Küllstedt 3, the complete Volpriehausen Formation is present comprising 10 and 11 fining upward cycles respectively.

At the base of the Volpriehausen Formation is recognized a regional angular unconformity which was recognized by Trusheim 1961 in the Northwest German onshore and offshore areas, but in the studied area is not clearly observed. The basal Volpriehausen Formation, also called “Volpriehausen-Sandstein Member (smVS)” is mainly characterized by medium grained sandstones with smooth cylinder and/or blocky character in gammy ray and spontaneous potential logs and comprises the cycle V1. This stacking pattern is defined as fluvial–eolian system observed in the well cores Fahner Höhe-13 and Rockensußra-2. Szurlies (2007) divided the “Volpriehausen-Sandstein” in two fining upward cycles throughout the Central Germany.

The basal Volpriehausen is followed by The Volpriehausen-Wechselfolge Member (smVW) consisting of six fining-upward cycles from V2 to V7 and composed of red sandstones with shale alternation. These cycles are characterized by low peaks in the gamma ray log which is characteristic in the whole studied area. This cyclicity comprises eolian-fluvial interaction observed in the well cores. The well Rks-2 is more common lacustrine siltstone and claystone in the “Wechselfolge Volpriehausen Member”.

The Hunte Swell and the Hessian Depression mainly comprise four cycles (from V3 to V6) in the "Wechselfolge Volpriehausen". Geluk & Röhling (1997) stated that this succession is composed of fined grained sediments with notable high gamma ray reading, representing lacustrine deposits.

The "Volpriehausen-Aviculaschichten Member" display a basal part composed of sandy sediments and grading upward with silty-clayey intercalation, characteristic observed in the majority of the well logs displaying two fining upward cycles V8 and V9) which were deposited in the entire northwestern Thuringian Syncline keeping uniform thickness. Szurlies (2004) suggested that the "Volpriehausen Aviculaschichten Member" in the Hessian Depression consists of three fining upward cycles (from V7 to V9 cycles).

According to Geluk (2005) the Volpriehausen Formation in the Netherlands and northwestern Germany areas became part of tectonic uplift pulses and erosion before deposition of the Detfurth and Hardegsen Formations.

7.2 Cyclicity of the Detfurth Formation

The lower boundary of this formation is formed by the base of the Detfurth-Sandstein, deposited on an angular unconformity (D-unconformity sensu Trusheim, 1961), which is not too prominent in the Germanic Basin as in the southern and western offshore areas of the Netherlands (Geluk et al., 1996). In the Eichsfeld Altmark Swell area the Detfurth Formation is missing.

The base Detfurth "Detfurth Sandstone (smDS)" consists of medium-grained sandstones, belonging to a fluvial-eolian system clearly observed in the well cores Rks-2 and Fh-13. The Detfurth Sandstein is followed by Detfurth-Wechselfolge (smDW)". The complete Detfurth Formation has been defined as one fining upward cycle denominated D1, which presents in the upper part increase of shales, keeping constant thickness throughout the studied area (between 19 and 45 m). Unconformities between the Detfurth and Hardegsen Formation in the northwestern Thuringian Syncline are present (Röhling & Seidel, 2008). Szurlies (2007) subdivided the Hardegsen Formation into four cycles in the central Germany area comprising thickness between 50 and 70 m. Aigner et al (1992) and Geluk & Röhling (1994) suggest that the Detfurth and the Hardegsen Formations in the Netherlands like in northwestern Germany represent one mega-sequence, referred to as “2nd–Order Cycles”, which comprise the whole Detfurth and Hardegsen Formations. The Detfurth deposits represent periods of short tectonic pulses through the Germanic Basin.

7.3 Cyclicity of the Hardegsen Formation

The Hardegsen Formation is composed of four fining upward cycles (H1, H2, H3 and H4) and rests conformably on the Detfurth Formation throughout the studied area as well as in entire the Germanic Basin. The gamma ray log in this interval is characterized by notable decrease of radiation. The thickness of the Hardegsen Formation is strongly marked by the pre-Solling erosion displaying notable variations (from 15 to 70 m) in the northwestern Thuringian Syncline. In some areas like the Rockensußra the lower cycles CH1 and CH2 are present while the upper cycles CH3 and CH4 were eroded. In the Eichsfeld Altmark Swell, the complete Hardegsen is missing evidenced uplift and erosion after the Hardegsen deposition and with strong movement. This tectonic event occurred prior to the Solling deposition resting directly on the Volpriehausen Formation. The Hardegsen Formation observed in the wells Fh-13 and Rks-2 mainly comprises brown sandstones with interbedded clayey silty sediments reflecting fluvial-floodplain interactions.

According to Wycisk (1984); the maximum thickness of the Hardegsen Formation in the Hessian Depression reaches up to 120 m consisting of 10 to 12 fining upward cycles. This cyclicity was also observed by Szurlies (2007) on the well logs Solling-5, Dokumenta-6/77 and Beberbeck-6 located in the northern part of the Hessian Depression. While in the well logs Brüggen-Z1 and Königslutter-Z1 situated in the Hunte and the Eichsfeld Altmark Swells respectively, the whole Hardegsen Formation has been eroded.

According to Trusheim (1963) on the western flank of the Hunte Swell, the Hardegsen Formation is completely absent. Röhling (1991) stated that the complete Hardegsen Formation has been observed in the well log Sagermeer Z12 situated in a graben on the western flank of Hunte Swell and in others areas of northwestern Germany, this succession can reach more than 200 m thickness.

7.4 Cyclicity of the Solling Formation

The base of the Solling Formation constitutes the cycle boundary which marks a significant uplift and erosion creating the most important unconformity of the Triassic; the Hardegsen unconformity (H-unconformity). This erosion comprises a regional irregular surface embracing the Netherlands and the Germanic Basin as in the Hunte Swell where the erosion reaches over 200 m (Trusheim 1963) and can cut the Lower Buntsandstein and even the Zechstein Group (figure 7.2).

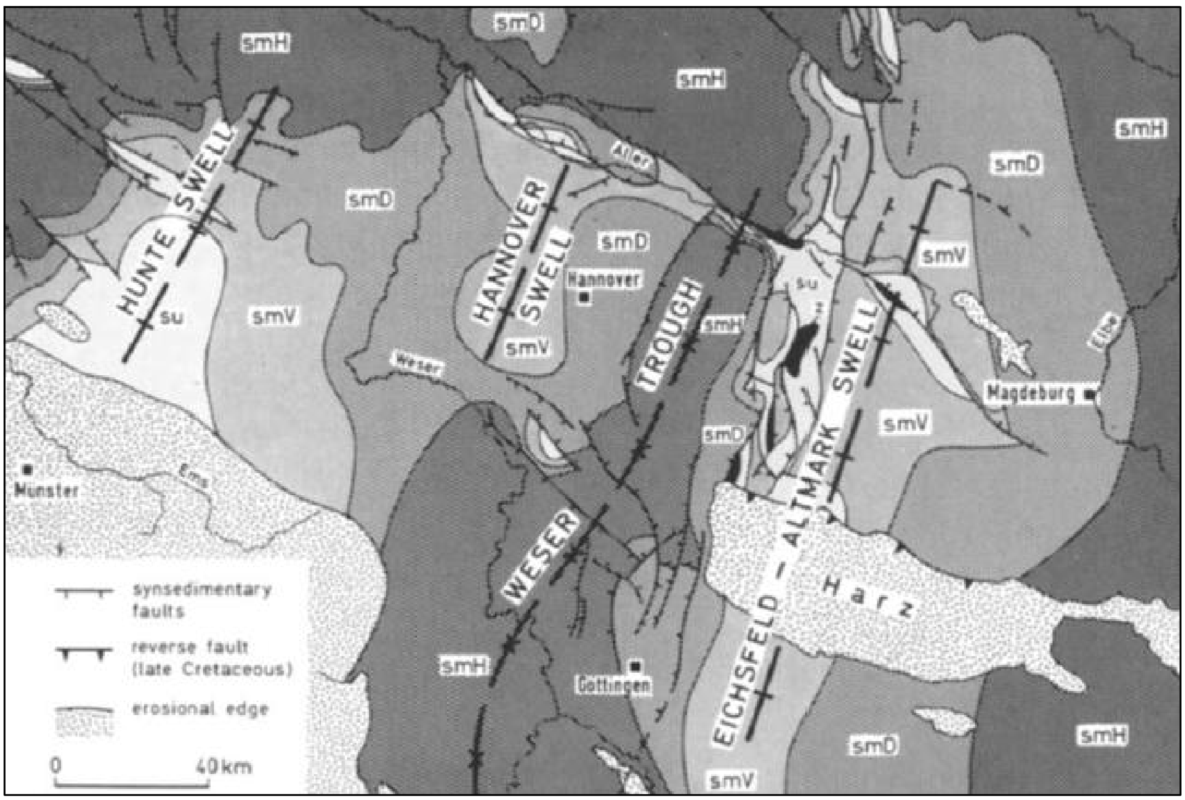


Figure 7.2 Subcrop map of the German Triassic, showing the erosion (the H-Unconformity) at the base Solling Formation, the erosion can cuts, the Hardegsen, the Detfurth Volpriehausen Formations, the Lower Buntsandstein Subgroup and even the Zechstein Group (from Aigner et al 1992).

The Solling Formation present lateral changes throughout the Germanic Basin; however the sedimentary cycles are complicate to difference throughout the study are. Puff et al (1967) defined two cycles in the Thuringian Syncline. In Central Germany four cycles have been identified by Geluk & Röhling (1997) and Szurlies (2007) with thickness between 80 and 120 m. Röhling (1991) mentions that the Solling Formation is characterized by different facies development in the different paleogeographic units.

The H-unconformity is overlain by medium-grained fluvial sandstones throughout the northwestern Thuringian Syncline, denominated “the Solling Basissandstein”. This basal sandstone is attributed by Boigk (1961) and characterized by low gammy ray radiation. Over this unit rests a middle unit recognized as the Solling claystones “the Tonige Zwischenschichten” indicating high gamma ray radiation deposited in floodplain and lacustrine environments, which is identified an intra Solling unconformity in some areas of this study.

The upper part of the Solling Formation (Thüringer Chirotherien Sandstein) comprises fluvial sandstones in transition to marine deposits in some areas, with deposits of halite and gypsum clearly observed in the Middle/Upper Buntsandstein (Röt Formation) boundary. The well core Rks-2 clearly evidences this playa environment with marine ingressions (Lang, 2001). The complete succession of the Solling Formation throughout the northwestern Thuringian Syncline comprises thickness between 3 and 14 m.

At the base of the Upper Buntsandstein (Röt Formation) presents an irregular unconformity is developed in northern Germany where part of the Solling Formation has been eroded (Wolburg, 1968). According to Richter-Bernburg (1974), the erosion in the Röt Formation can cut even the upper part of the Hardegsen Formation in southwestern Germany (in the Saarland, Pfälzerwald and Schwarzwald areas). This erosion is not evidenced in the northwestern Thuringian Syncline. The presences of evaporitic facies in the Upper Buntsandstein sequence are interpreted as a playa environment with marine ingression from east to west (Ziegler 1990). The Röt Formation in the well core Rks-2 comprises a succession of silty, grey anhydritic shales and dark gray sandstones.

8 Tectono -sedimentary evolution of the northwestern Thuringian Basin *

8.1 Database, data preparation and structural modelling workflow

The structural model for this study is based on information and data from the “Thüringer Landesanstalt für Umwelt und Geologie, 2003”. The data base includes structural maps of the top Middle Buntsandstein Subgroup (Schlegelmilch, 1972) and the top Lower Muschelkalk Subgroup (Vum Son, R.J 1963) and the Geological map of Thuringian State (Seidel et al, 2002) taken from the “Thüringer Landesanstalt für Umwelt und Geologie”, all on 1:200,000 scale. At the levels of the three stratigraphic horizons mentioned were digitized in the software ArcGis, creating a data system in coordinates X, Y and the true vertical depth (TVD), the value Z.

A 3D structural model was developed using the RMS 2009, this 3D modelling has been constructed through the northwestern Thuringian Basin between the coordinates 5,653,261 and 5,688,261 north and 4,370,800 and 4,435,800 east and 2000 m along the vertical.

8.1.1 Fault Modelling

The majority of the faults used for the 3D model building were taken from the structural map information. Others were reinterpreted (in the Schlotheimer Graben) according to structural trends and evidences observed in the log wells. The faults present limited surfaces (denominated horizontal and vertical extension for the RMS 2009 software), cut by lithostratigraphic surfaces (horizon tops) and the topographic contours.

Several faults are cut by the well logs and information as throw of faults, missing and repeated sections were loaded in the fault modelling. A gridding algorithm (general algorithm) was used with a grid increment of 100 and a smoothing factor was considered in some surfaces were 60 % and for the others were not required this adjust.

The control of the shape and extension (vertically and horizontally) in the faults are made using the convex hull parameter to determine the surface. The faults in occasions are cut each others, therefore have been defined truncations with a process automatic, but in some cases required manual edition.

8.1.2 Horizon modelling

The horizon modelling was created through all stratigraphic surfaces (horizon tops) which has been tightly connected to fault modelling for executing the 3D structural modelling. The H-Unconformity and topographic contours (surface information) were considered for the model run, they are used as unconformity surface truncating the lower horizons. The 3D structural modelling contains the Zechstein Group however the lower boundary of the model does not include the base of the Zechstein (Z1) and the variability of thickness pattern or tectonics erosion in the Zechstein Group has not been examined, only the top horizon was correlated. The model includes six layers from the top Zechstein Group to the top Lower (su) and top Middle Buntsandstein Subgroups (smV, smD, smH, smS) also creating structural maps of all tops (enclosure 12 to enclosure 16).

In the study area 153 faults have been identified and recognized (figure 8.1, figure 8.2 and figure 8.3):

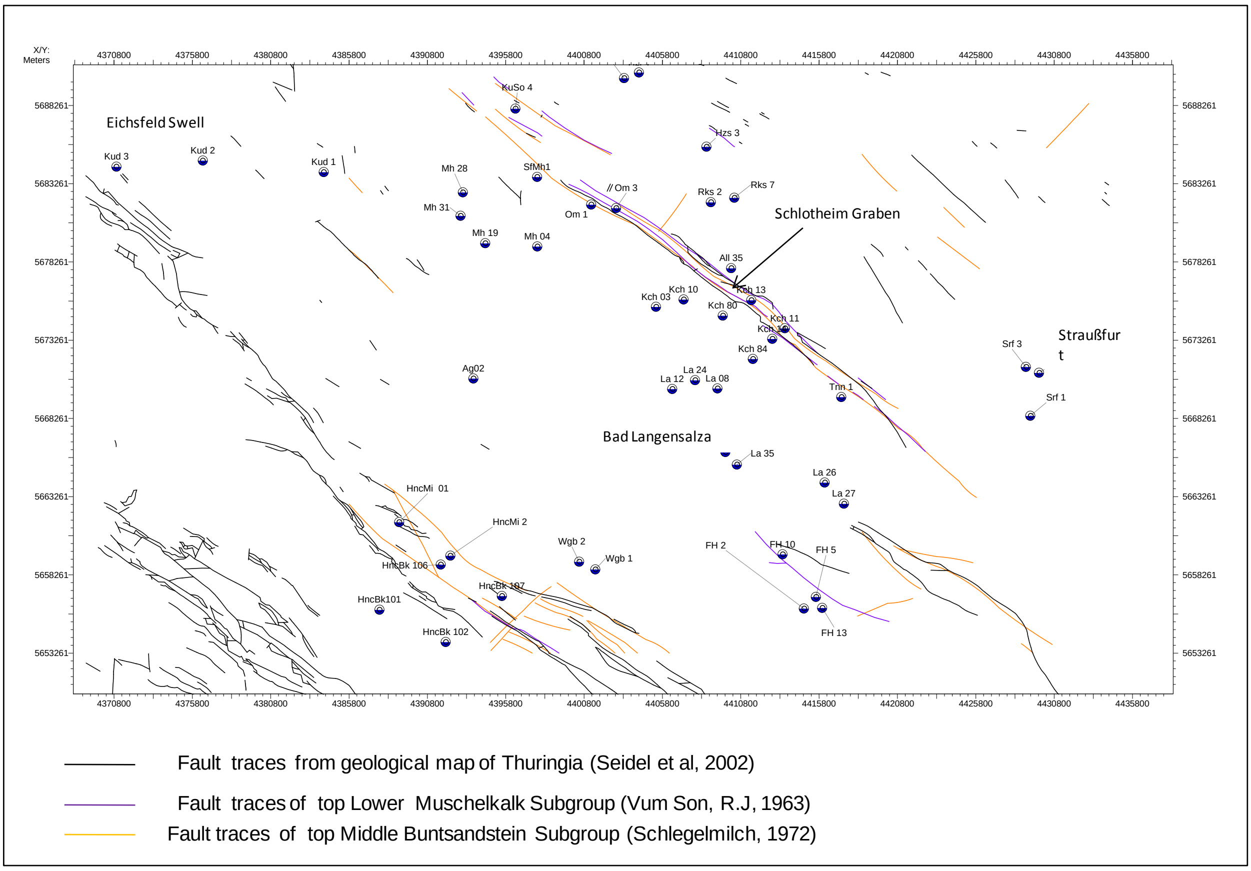


Figure 8.1 Base map showing the fault traces at the top Middle Buntsandstein and top Lower Muschelkalk Subgroups as well as surfaces faults.

The recognition of faults are based in the geometry of the structure contours and wells evidence as depth and amount of missing or repeated section and previous interpretation, 145 of them were interpreted as normal faults and 8 as inverse faults (Appendix 2 and 3).

The structural cross sections in the Schlotheimer Graben are the results of our interpretation and this digital information was loaded into the program and using as hard data for the 3D-model.

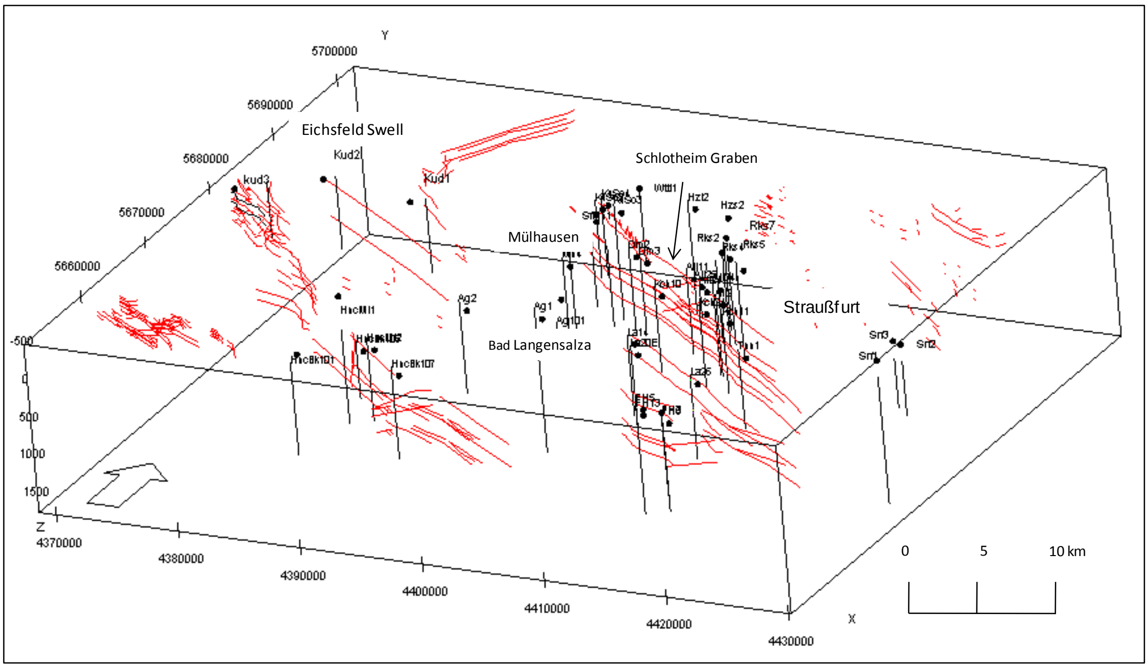


Figure 8.2 Depth mid lines in of the all faults system (153 faults) in the studied area, these represent the fault traces at depths of 200 and -300 m and several fault traces at -455 and -765 m (vertical exaggeration 6:1).

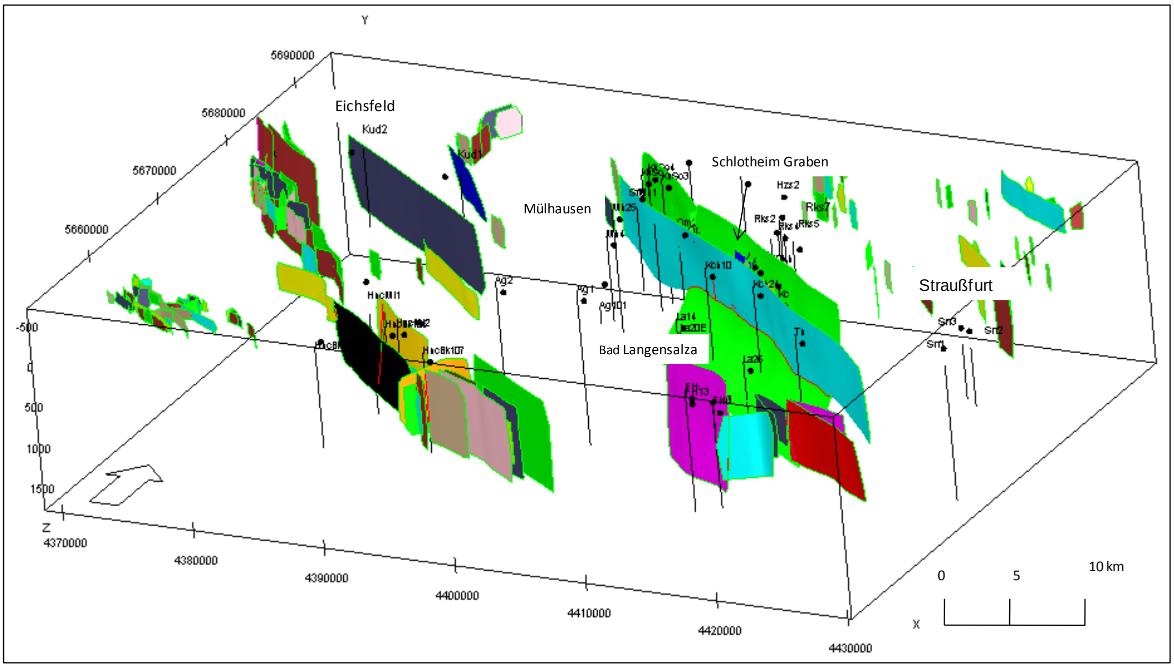


Figure 8.3 Fault model created through the trace faults interpreted and the faulted well observed. A system of NW-SE trending faults predominates in the study area (Vertical exaggeration 6:1).

8.2 Results

The study area, like the complete Thuringian Basin is mainly dominated by trending WNW-ESE structures in the Late Permian and Triassic time (figure 8.18). The main structural system in the study area is denominated the Schlotheim Graben but other areas of this study present some structural and tectonics characteristics, which are described in this chapter. The sedimentary thickness of the Zechstein Group has not been considered in the model, but in some wells close to the Schlotheimer Graben, the stratigraphic correlation of the Zechstein subdivision were done for building the structural cross-section. Although the variability of thickness pattern or tectonically induced erosion in the Zechstein has not been examined in detail, no evidence of Permian Salt movements (diapirism) has been recognized.

In the northwestern Thuringian Basin as well as the Southern Permian Basin, regional subsidence occurred during the Lower Buntsandstein deposition. However in the study area, it was not as strong as for example in the Glückstadt Graben. The Lower Buntsandstein thickness in the northwestern Thuringian Basin keeps constant between 300 and 380 m, indicating uniform subsidence. According to Geluk (2005), at the end of the Lower Buntsandstein deposition a structural reorganization occurred reactivating a Variscan bidirectional system of NNE-SSW and WNW-ESE trending faults. This event displays strong local subsidence.

Ziegler (1990) states that the isopach maps of the Middle Buntsandstein Subgroup suggest the development of new subsidence axes. These subsidence patterns are clearly evidenced in the Central, Horn and Glückstadt Grabens and the Polish Trough which contain very notable thicknesses (figure 3.6). By contrast, in the studied area the thickness difference between the Schlotheimer Graben and areas around it is not very notable, varying between 150 and 200 m. This indicates that the subsidence was not as strong and more uniform in the northwestern Thuringian Basin (figure 5.7).

The Upper Buntsandstein Subgroup was affected by the regional subsidence mainly in the North German Basin but in the studied area it was limited, the thickness keeps constant in almost the whole Southern Permian Basin, the differential movements ceased during the Röt deposition because the thickness variations are not too prominent (Geluk, 2005).

The Structural Model is mainly characterized by NW-SE trending faults, indicating that the subsidence mainly took place in the Schlotheimer Graben, which is the main structure in the study area with probably NE-SW extensional regime. In the Eichsfeld Altmark Swell; the Detfurth and Hardegsen Formations were not preserved, it was caused by uplifted during the Middle Buntsandstein deposition, like a tectonic erosion (the H-Unconformity) at the same time (figure 5.16).

8.2.1 Schlotheimer Graben

The Schlotheimer Graben located in the centre of the studied area trends WNW-ESE (figure 8.8 and figure 8.18) and is mainly associated to subsidence patterns evidencing extensional faults during the Lower Buntsandstein. However the subsidence was not so strong or kept a constant sedimentation rate. There is not a notable difference of thickness in the Lower and Middle Buntsandstein deposition (280-380 and 140-230 m, respectively) between the graben and other areas of the studied area, as in the northwestern Europe where the thickness presents a uniform sedimentation rate over large areas. The tectonism in the Thuringian Basin did not play an important role during the Late Permian to the formation of salts structures.

The subsidence was limited during the Solling deposition in the Thuringian Basin indicated by low thicknesses between 3 and 30 m in the entire basin. The Solling sequence represents a change of the basin geometry respect the lower formations. Although the Upper Buntsandstein Subgroup and the Muschelkalk and Keuper Group were not included in the 3D model but the top formations were used to create the structural cross section, which can be inferred that during the deposition of these units took place a period of low tectonic activity, considering that the thickness keeps uniform in the northwestern Thuringian Basin.

The Schlotheimer Graben is situated northeast of Kirchheilingen and Mühlhausen areas and south-west of Allmenhausen area. The central area of the graben is bounded by two notable anticlines, located in the Allmenhausen and Kirchheilingen areas, respectively. Both structures present axial planes striking NW (305°) and limbs with gentle north-east and south-west dipping from 3 to 5° (figure 8.8). The anticline in the south west of the graben is evidenced in the majority of the wells located in the Kirchheilingen area, while the other anticline is verified in the wells; Allmenhausen-25, Allmenhausen-32 and Allmenhausen-35, where the true vertical depths of the horizon tops are shallower than in other areas.

The Schlotheimer Graben belongs to an extensional system 29 km long and 0.7-1.2 km wide. Three structural sections in NE-SW direction have been built to show its structural characteristics (figure 8.6, 8.7). This system comprises three main faults striking N55W: F1, F2 and F3 and two minor faults; FA and FB with similar orientation. Some wells intercepted these faults, showing a notable reduction of thickness (table 8.1 and 8.2, figure 8.5 and enclosure 11). The fault F1 dissected Late Permian in the Zechstein Group and continued to Middle Triassic; the Keuper Group.

In the structural cross-section in NE-SW direction suggested by Grumbt (1964); the fault F2 dissected the sequences from Zechstein to Keuper group keeping a high dip and cut by the F1 (figure 8.4). In this work the fault F1 presents in the Zechstein deposits a notable low angle dip advancing to southwest, dipping 35°, while the F2 only dissect the Triassic (figure 8.6 and 8.7). This fault is evidenced in some wells (Appendix 4).

The uplift of the Zechstein deposits observed in the Schlotheimer Graben (figure 8.7) is clearly evidenced by Grumbt (1964) in the well Kirchheilingen-16. In this work has been observed this gentle uplift of the Zechstein in the wells Kirchheilingen 45 and 46. In the Lower Buntsandstein Subgroup, the Fault F1 dip can reach up 75° to southwest and average throw of 35 to 280 m. The F1 is cut by some wellbores (table 8.1, figure 8.5, 8.6 and 8.7).

The F3 is a synthetic fault associated to F1, dipping 55° to south-west, a thrown from 25 to 150 m dissecting the Buntsandstein, the Muschelkalk and the Keuper Group (figure 8.6 and 8.7). This normal fault F3 is evidenced in different wells which are indicated by intervals of missing strata (table 8.2). The fault F2 comprises an antithetic fault associated to F1, dipping to north-east and with stratigraphic throws from 20 to 100 m

	Well Name	Horizon	True vertical depth subsea (m)	Missing section (m)
	All 17	so	-54.6	110
	All 20	mo	48	90
	Kch 5	su	-322	150
Fault-1 (F1)	Kch 47	su	-327	130
	Kch 46	su	-452.5	40
	Kch 45	su	-393.2	220
	Kch 49	su	-269	280
	Kch 16	smH	-174.4	50
	All 23	so	91.5	55
	Om 3	su	-401	170
	Kch 11	so	-83	56
	Kch 12	z	-570.46	140

Table 8.1 Wellbores cutting the fault F1 and indicating the missing section in different horizons through the Schlotheimer Graben.

Fault-3 (F3)	Well Name	Horizon	True vertical depth subsea (m)	Missing section (m)
	All 17	smS	-19	50
	Kch 5	smV	-247.6	150
	Kch 45	su	-393.2	220
	Kch 49	smV	-260	280
	All 23	mu	130.5	25

Table 8.2 Wellbores cutting the normal fault F3 and indicating the missing section in different horizons through the Schlotheimer Graben.

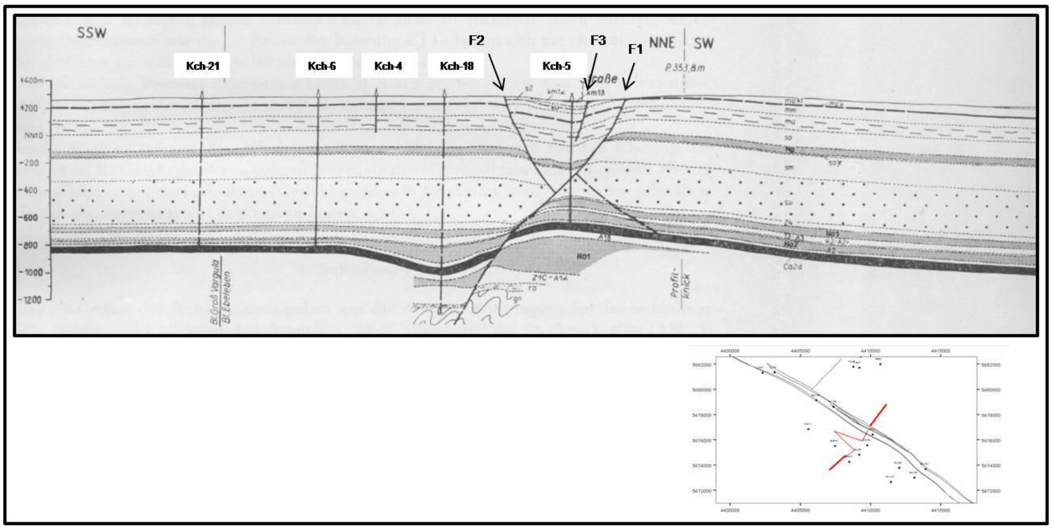


Figure 8.4.Structural cross-section in SE-NW direction showing the geometry in the Schlotheimer Graben proposed by Grumbt (1964). The main fault F1 dissects the Zechstein Group, and the F3 does not dissect the Middle Buntsandstein in this model.

The secondary faults FA and FB have the same direction as the main system and south-eastern dip and with displacement of 20 m (figure 8.6). The well log Allmenhausen-20 cuts the fault FA in a depth of 220 m in the Upper Muschelkalk Horizon and the fault FB in Middle Muschelkalk Horizon in 110 m and with a missing section of 20 m. They represent antithetic faults associated to the F3. The fault FB dissects from the Lower Buntsandstein to Middle Keuper and the fault FA from Upper Muschelkalk to Middle Keuper. The fault F4 belongs to same fault system, showing a N45W strike, steep dip cutting the all sequences.

A normal fault F10 in 045NE direction and perpendicular to the F1 is located in the northeastern part of the Schlotheimer Graben with north western dip (figure 8.8) which is observed in the structural map of the top Middle Buntsandstein done by Schlegelmilch (1972).

In the northeast of the studied area and close to Heinleite and Sonderhausen areas are located ten faults taken from the maps before mentioned and labelled: F26, F27, F28, F76, F87, F89, F120, F130, F132 und F135 showing a NW (305°) strike, dipping to south-west and average throw of 25 m. The faults F26, F27 and F28 dissect from Zechstein to the top Solling Formation.

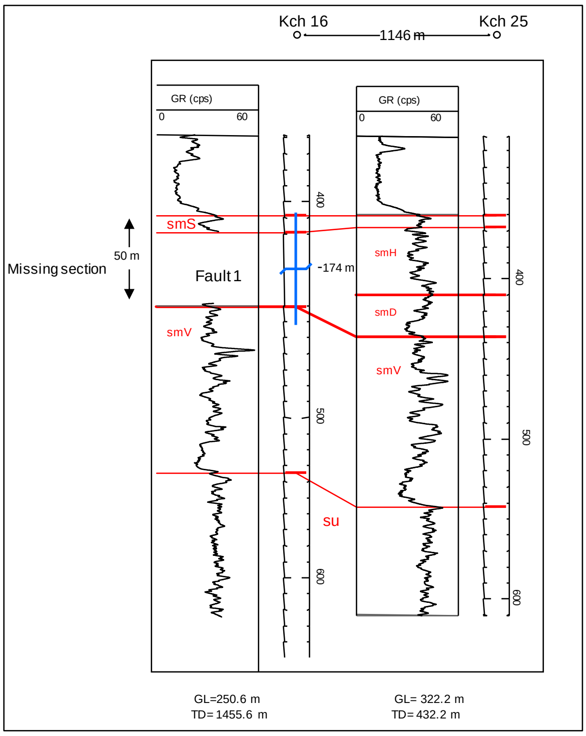


Figure 8.5 Comparison between a faulted well and a well with a complete Middle Buntsandstein sequence located in the Schlotheimer Graben area. The normal fault F1 is cut by the well Kirchheilingen-16. The Solling and Hardegsen horizons are absent; the missing section observed in the well is about 50 m.

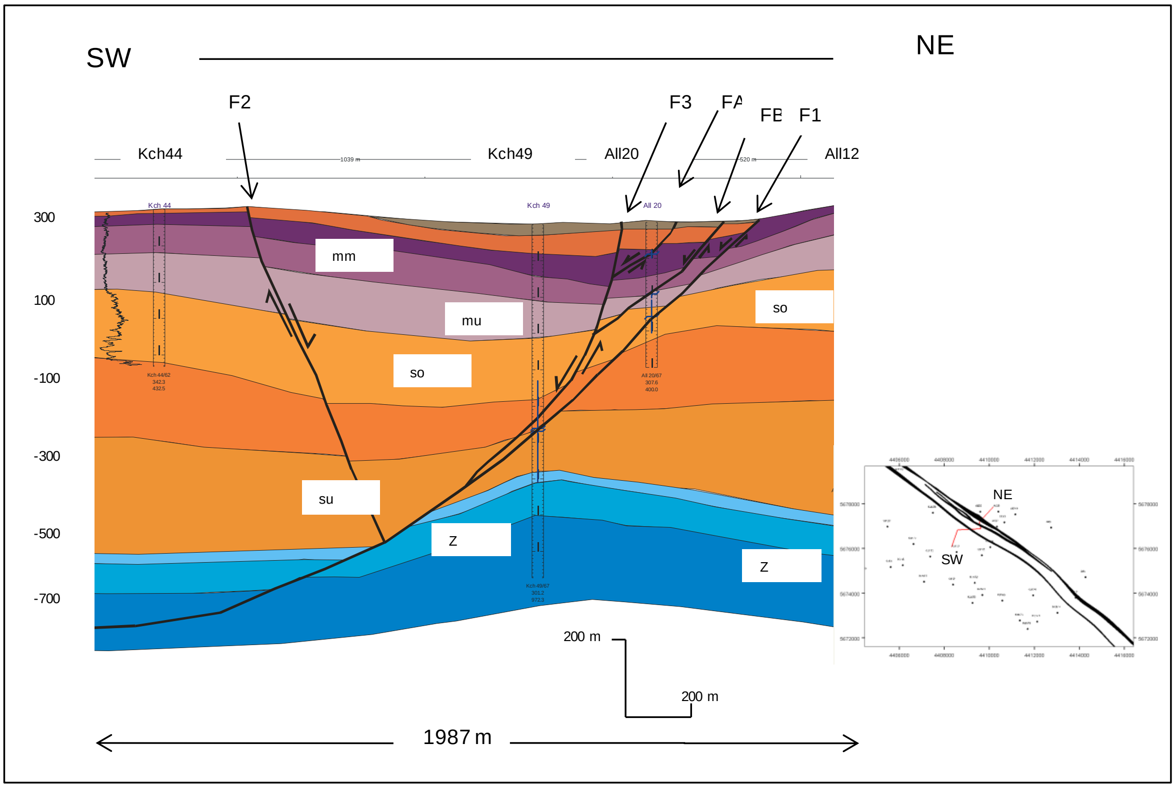


Figure 8.6.Structural cross-section in SE-NW direction illustrating the geometry of the Schlotheimer Graben. The faults FA and FB have the same direction as the main fault system dipping to south east and throw of 20 m.

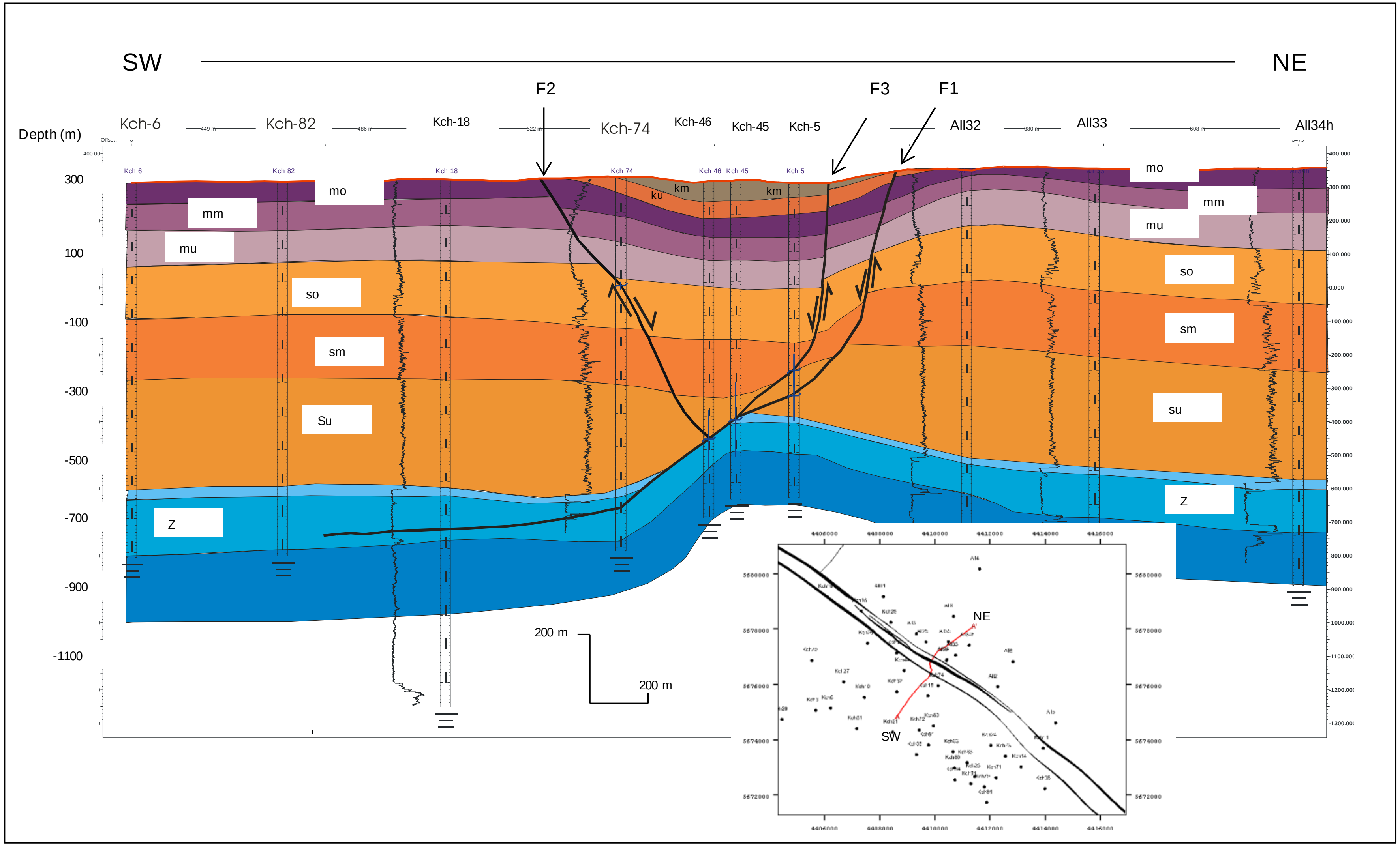


Fig 8.7 Structural cross-section in SE-NW direction illustrating the geometry of the Schlotheimer Graben, showing sequences from Late Permian; Zechstein to Triassic; Buntsandstein (su, sm, so), Muschelkalk and Keuper Groups. The main fault system is composed of faults F1, F2 and F3 with 120° (SE) strike The fault F1 presents a low dip through the Zech stein. The F3 comprises a synthetic fault associated to F1. The sequences keep constant thickness along the Triassic period.

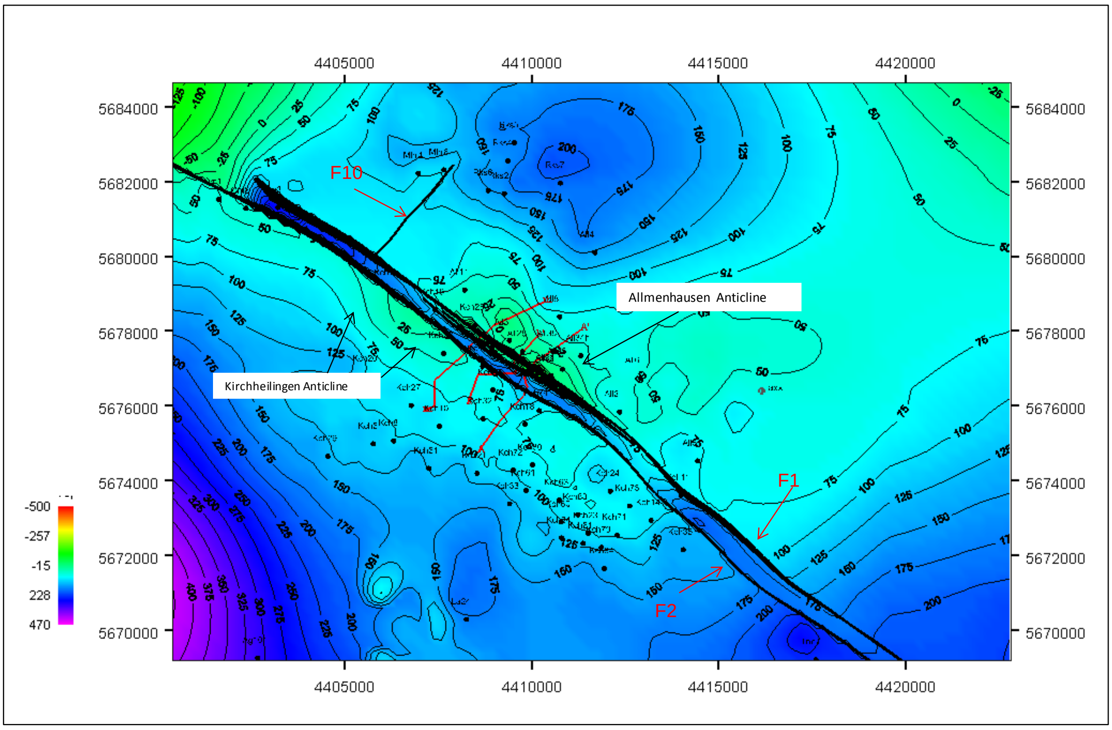


Figure 8.8 Structural map of the top Solling Formation in the Schlotheimer Graben, showing the faults system F1, F2 and F3 and the Allmenhausen and Kirchheilingen Anticlines trending 55 (NW). According to structural map of the top Middle Buntsandstein proposed by Schlegelmilch (1972) a normal fault F10 in 45 (NE) direction perpendiculars to the fault F1 located in the northwestern area.

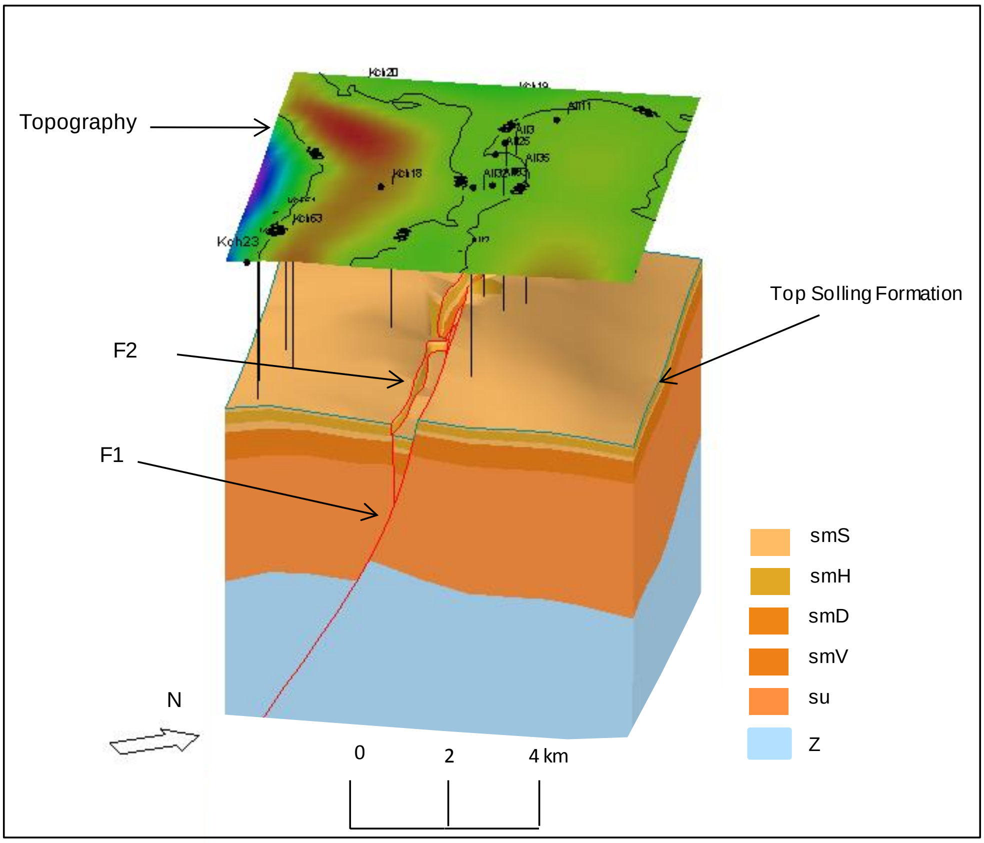


Figure 8.9 3D model (vertical exaggeration 6: 1) of the Schlotheimer Graben, between Kirchheilingen and Allmenhausen areas, the figure shows the fault system F1 and F2 dissecting the sequences from Zechstein to top Middle Buntsandstein Subgroup. The sedimentation rate was uniform during the Lower Triassic; there is not a notable change of the thickness.

8.2.2 Fahner Höhe a rea

The Fahner Höhe area comprises a gentle syncline with an ENE-WSW trending axial surface and an anticline of similar orientation comprising surface of 20 and 21 km^2 respectively. These structures are cut by system of NW(330°) and NW(315°) trending normal faults, labelled F22, F23, F24, F32 and F112 dipping to northeast (figure 8.10). The fault F31 with the same orientation has been interpreted as a reverse fault, evidenced in the well log Fahner-Höhe-3, where the sequence of the Middle and Upper Buntsandstein are repeated on this well log (figure 8.11). This reverse fault presents a throw between 100-150 m.

Another 70°(NE) trending fault, F25 is located in the south-eastern area and perpendicular to the inverse fault F31, these structures are composed of axial planes in NW-SE trending and folds with dip about 10 ° to north-east located close to the faults F31 and F32 (figure 8.10). All faults located in the Fahner Höhe area cut the complete sequences from Zechstein to top Solling Formation.

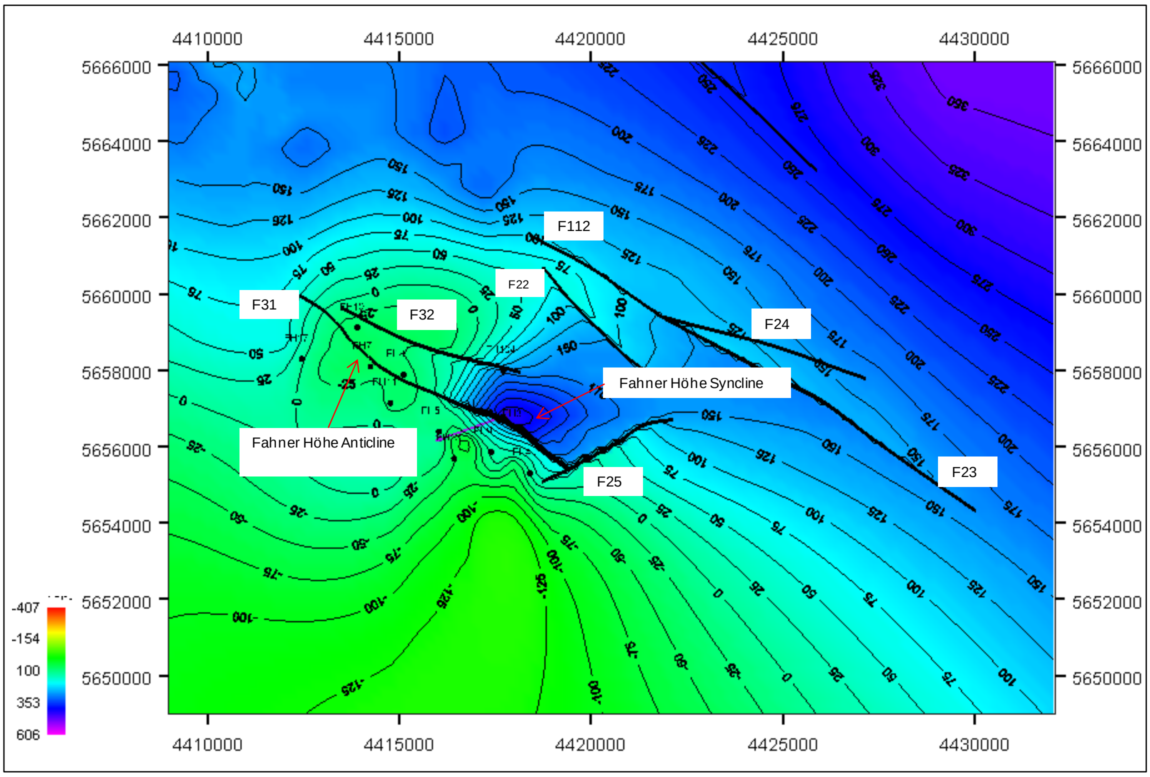


Figure 8.10 Structural map of the top Solling Formation in the Fahner Höhe area, with directional orientation, NW(330°) and NW(315°) trending faults F22, F23, F24, F25, F31, F32 and F112. The fault system has been interpreted as normal except for the fault F31 which represents a reverse fault. An anticline and syncline structure with an ENE-WSW trending axial surface is located in the area.

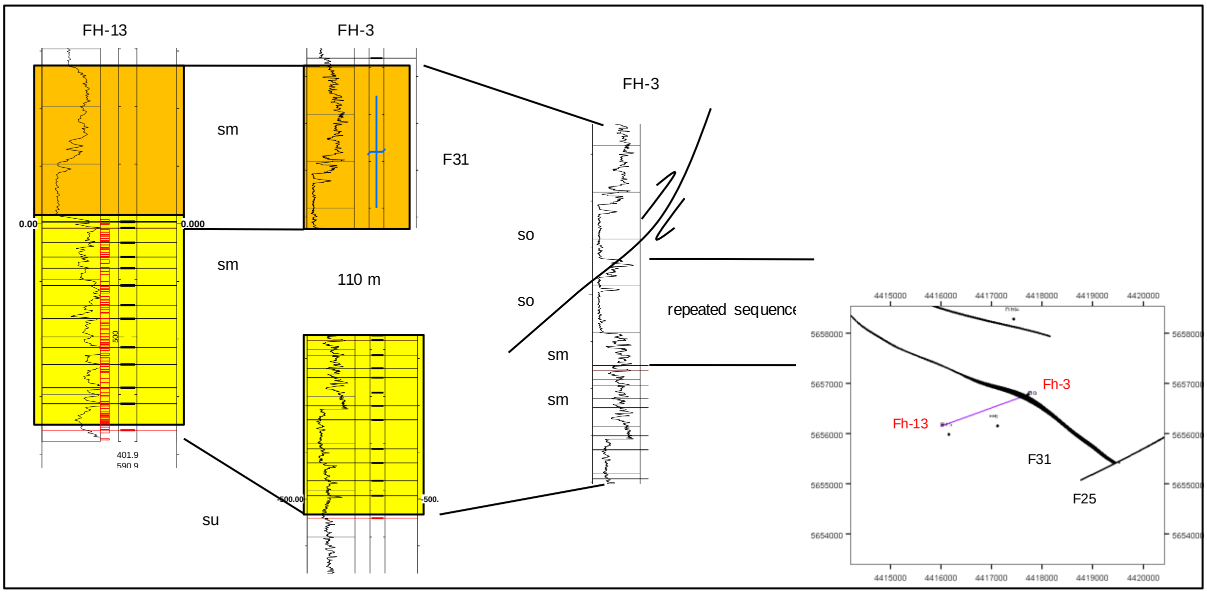


Figure 8.11 Well logs illustrating a reverse fault (F31) cut by the well Fahner Hohe-3, comparing with an unfaulted well (FH-13). The well Fh-3 shows repeated sequence of 110 m in the Middle and Upper Buntsandstein.

8.2.3 Mühlhausen, Langensalza and Rockensußra area

A notable Synclinal with an approximately surface of 190 km^2 is located between the south-east of Mühlhausen and the north-west of Langensalza area; it presents axial plane trending in NW-SE and limbs with gentle north-east and south-west dipping about 5° (figure 8.12). No faults are identified in the structure, but the synclinal is evidenced in the wells Altengottern-1 and Altengottern-2 where the true vertical depths of the horizon tops are deeper compared with the wells in the Mühlhausen and Langensalza areas.

Another synclinal situated in the north of the Allmenhausen Anticline in the Rockensußra area with axial plane trending NW-SE and limbs dipping 2° to north-east and south-west respectively, no fault is identified in the area, the well Rokenßura-2 located in the synclinal shows a true vertical depth deeper than the other wells around the area. This structure presents an approximately surface of 12 km^2 (figure 8.13).

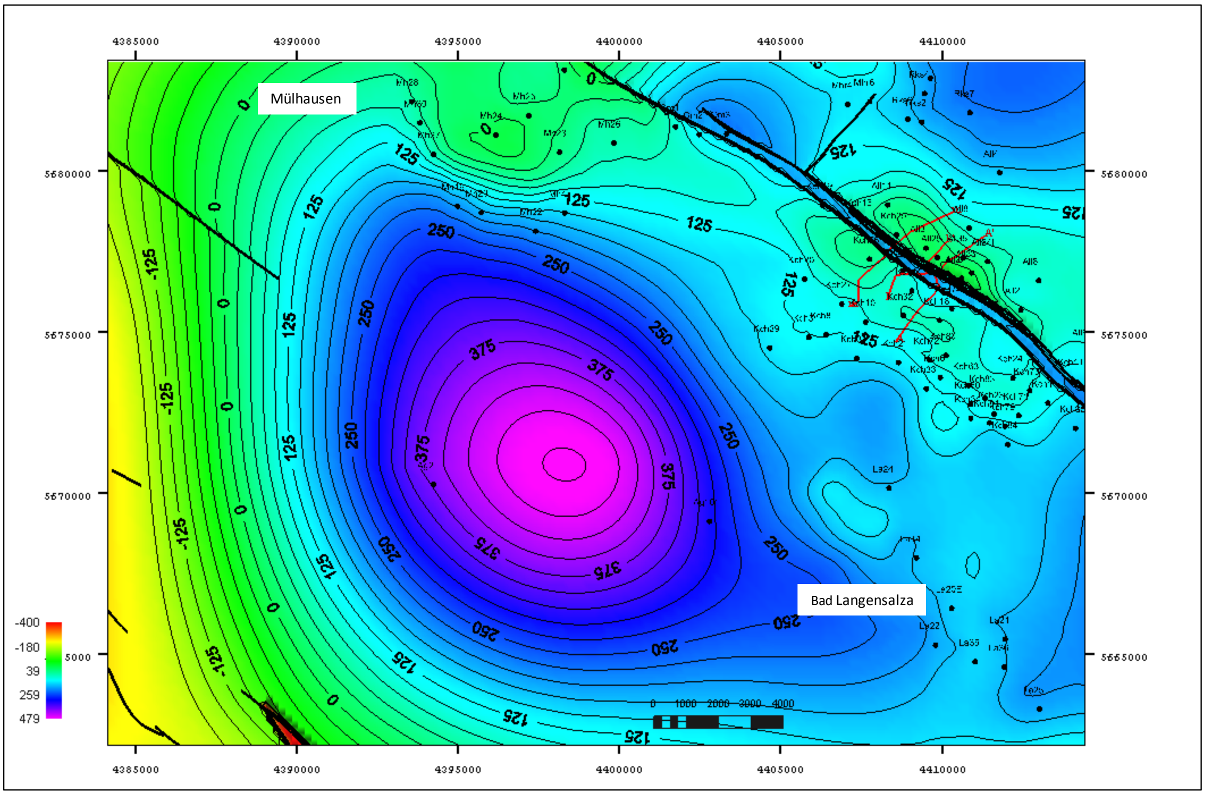


Figure 8.12 Syncline structure of the top Solling Formation located between the Mühlhausen and Bad Langensalza area with axial plane trending NW-SE and limbs dipping 5° to north-east and south-west respectively.

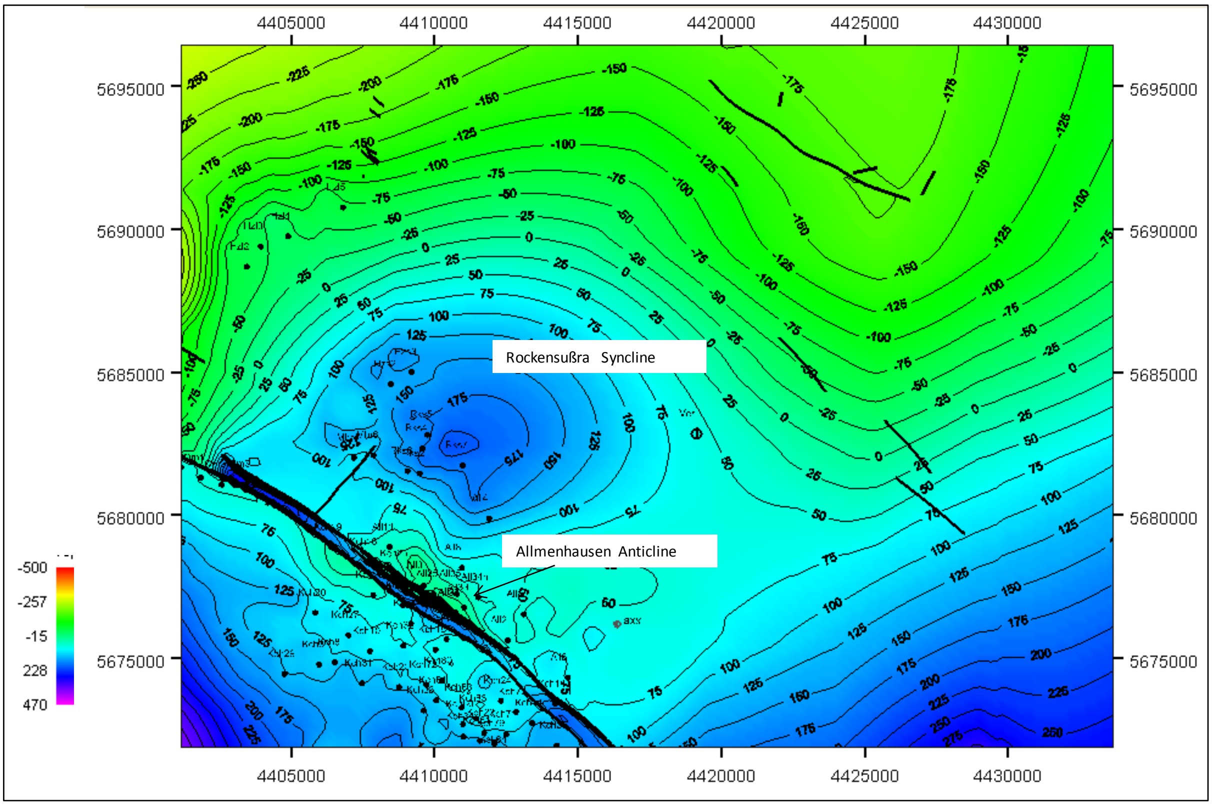


Figure 8.13 Syncline structure of the top Solling Formation located in the north of Allmenhausen Anticline with axial plane trending NW-SE and limbs dipping 2° to north-east and south-west respectively.

8.2.4 The Eichsfeld Swell and the Berka vor dem Hainich area

In the Eichsfeld Swell and the Berka vor dem Hainich areas an important uplift occurred, with a system of NW-SE trending normal faults similar to the Schlotheimer Graben system located in northwestern and southeastern area (figure 8.14, 8.15 and 8.18).

The phase of transtensional tectonics occurred in the Berka vor dem Hainich area is composed of normal faults identified as F5, F6, F7 and F13 also the fault F5, which was reactivated to reverse. The fault system dips to the northeast and southwest with an offset between 100 and 150 m. No evidence of the tectonic erosion (H-Unconformity) has been observed in the Berka vor dem Hainich area.

A system of NW-SE trending faults is found in the south of Berka vor dem Hainich area, It belongs to group of normal faults, labelled F12, F14, F15, F16, F17, F18, F20 and F21, dipping to southwest and perpendicular to this system is located another normal fault labelled F8.

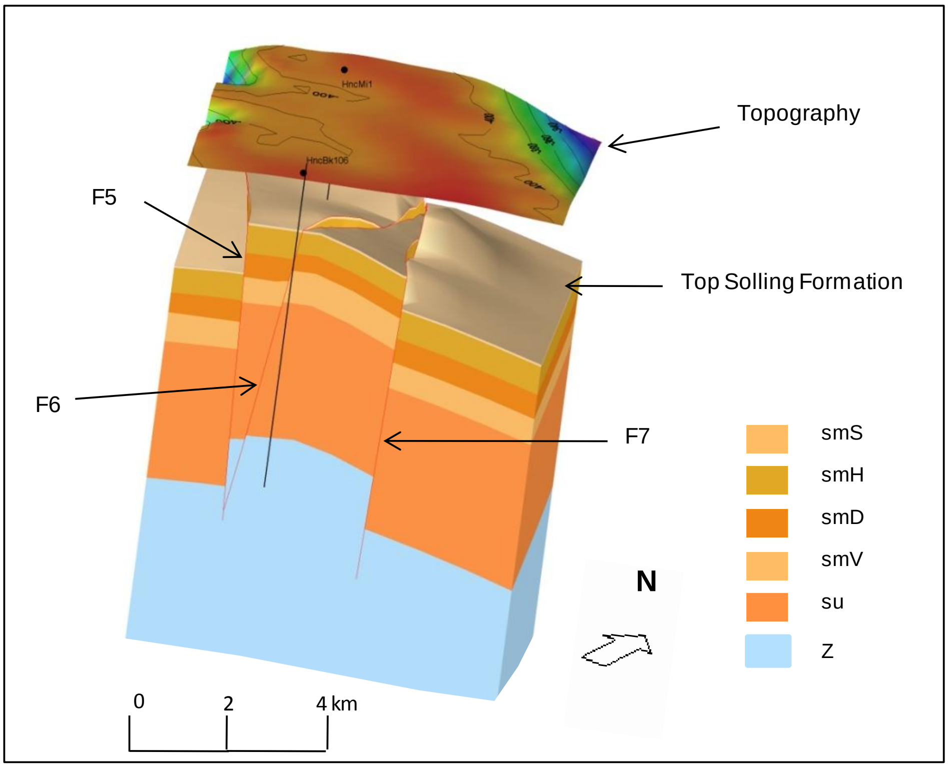


Figure 8.14 3D-structural model (vertical exaggeration 6:1) located in the Berka vor dem Hainich Area, showing the main fault system comprises the faults F5, F6 and F7. In this area is notable the uplift along the faults with a throw between 100 and 150 m cutting the sequences from Zechstein to top Solling Formation, The sedimentation rate was uniform during the Lower and Middle Triassic deposition; there is no notable change of thickness.

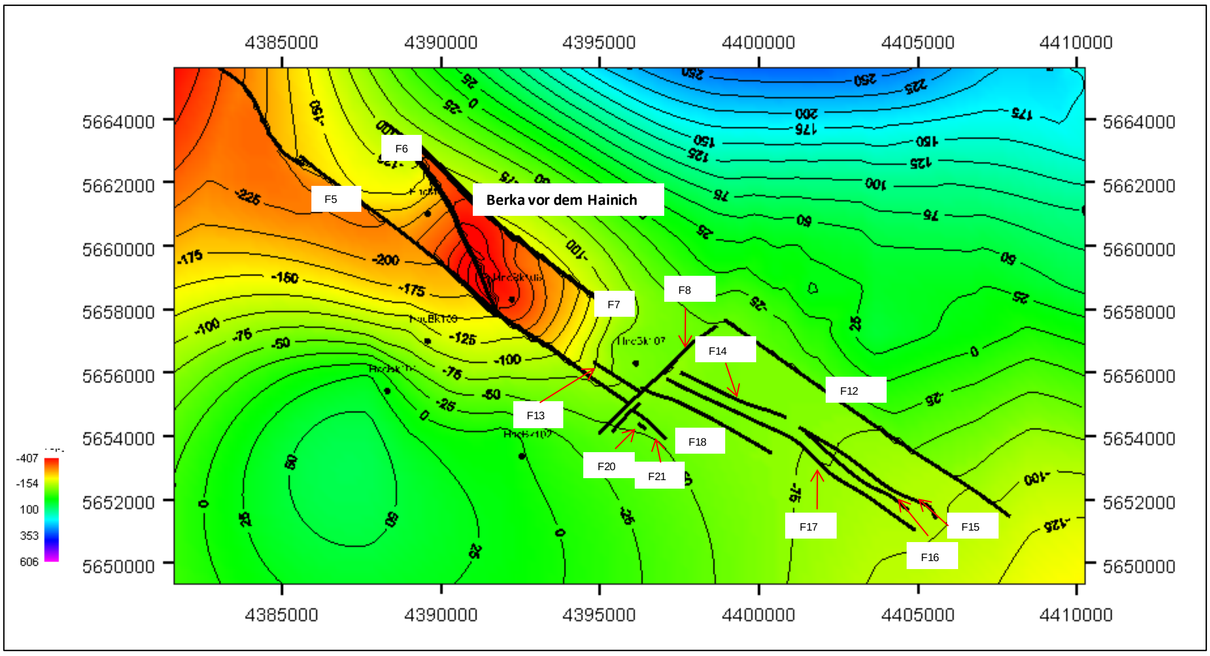


Figure 8.15 Structural map of the top Solling Formation, showing the Berka vor dem Hainich area, composed of the faults identified as F5, F6, F7 and F13 trend NW-SE, but the fault F6 was reactivated to reverse.

The Uplift of the Eichsfeld Swell probably occurred after the deposition of Hardegsen Formation, as the tectonically induced erosion (H-Unconformity); evidenced with the Solling Formation resting over the Volpriehausen Formation, where the Detfurth and Hardegsen sequences have been eroded during the uplift (figure 5.16, 8.16 and enclosure 14). The well logs Kullsted-1, Kullsted-2 and Kullsted-3 evidence this unconformity. Ziegler (1990) states that the sedimentation in that period was temporarily interrupted at the onset of the Hardegsen depositation sub cycle.

According to Geluk (2005) the Hardegsen unconformity was caused by highly differentiated subsidence belonging to a process of extensional tectonics during the Triassic. The Eichsfeld Swell comprises NW-SE trending faults; F29, F30, F34, F35, F36, F37, F38, F39, and F45 (figure 8.17), dipping north-eastern and south-western and with average throw between 120 and 150 m.

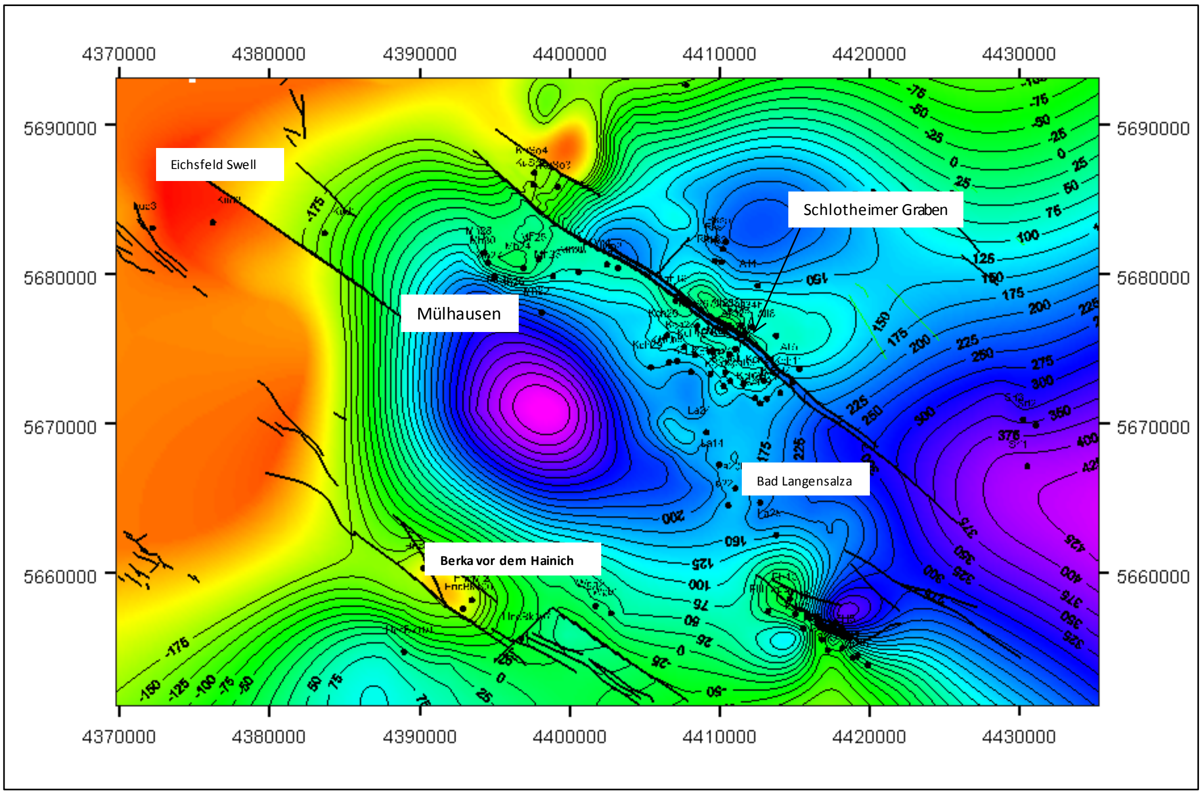


Figure 8.16 Structural map of the top Hardegsen Formation, In the Eichsfeld area the Hardegsen Formation has been eroded during the uplift.

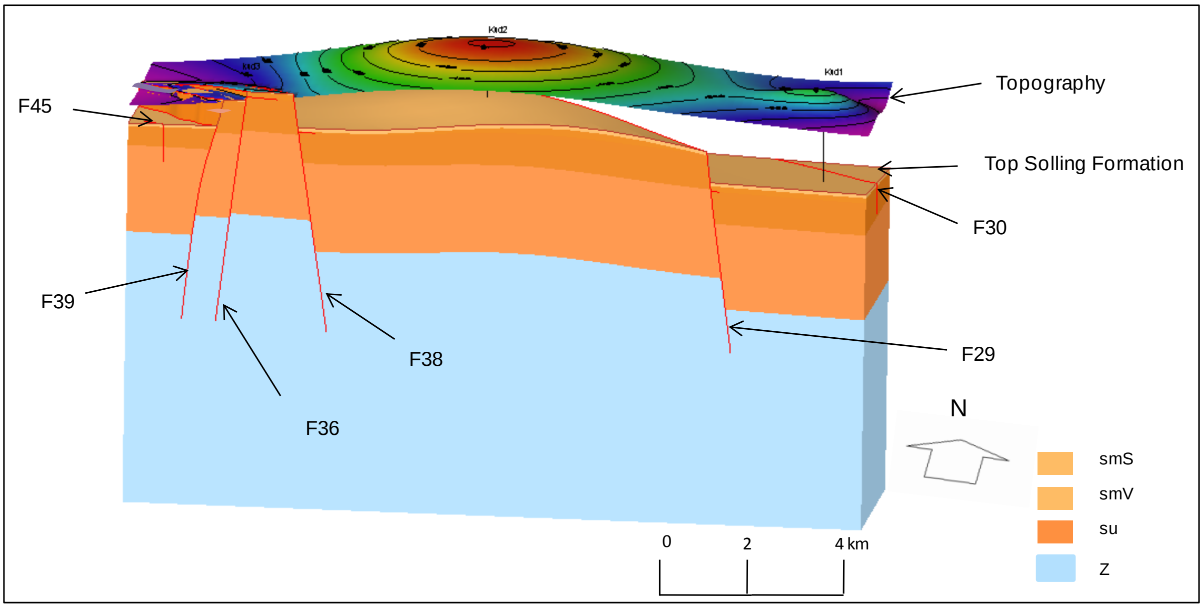


Figure 8.17 .3-D structural Model (vertical exaggeration 6:1) of the Eichsfeld area, in this area uplift took place, along NW-SE trending normal faults, which cut into the Zechstein Subgroup. This fault system is composed by faults F34, F35, F36, F37 and F38, F39 and F45 with a vertical offset between 120 and 150 m. The fault F29 represents a synsedimentary fault showing to the east that Muschelkalk and Keuper were deposited.

8.2.5 Southwes tern study area

A Series of 28 normal faults with NW-SE trend and dipping to northeast are located in the southwestern area and to the west of the Berka vor dem Hainich Area; they have been taken from the Geological map of Thuringian (Thüringer Landesanstalt für Umwelt and Geologie, 2003). There is no well control or well information in this area. A secondary fault system (6 normal faults) is found in this area with NE-SW and W-E trending. The offset of the faults is between 10 and 20 m and are not present in the Buntsandstein sequences only cutting from Muschelkalk to Keuper Group.

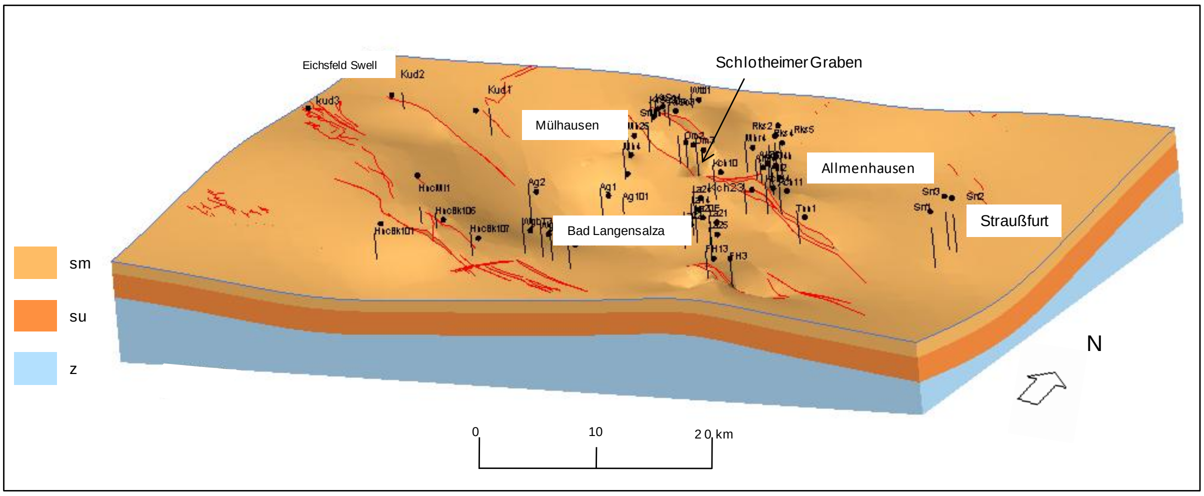


Figure 8.18 3D-Structural Model proposed in the northwestern Thuringian Basin of the sequences from the top Zechstein to top Solling Formation characterized by directional system of NW-SE trending faults.

9 Interpretation and integration of sedimentologica l-stratigraphic -structural data (facies modelling) in the Middle Buntsandstein Subgroup

The facies modelling has been created for each formation of the Middle Buntsandstein Subgroup (smV, smD, smH and smS). This model consisted in creating 3D parameter of facies distribution using a geological grid. The facies modelling is based on the well data, the electrofacies study and the facies analysis in the well cores Rockensußra-2 and Fahner Höhe-13. The faults interpretation and the 3D structural model have been integrated in the depositional modelling.

9.1 Geological 3D grid

An appropriate geological 3D model has been designed and built in the area using the horizons top for designing the formations of the Middle Buntsandstein Subgroup. The "RMS 2009" software creates between two horizons a subgrid denominated zone, which represents a stratigraphic volume. In the case of this project the grid is defined by four zones; the horizon tops of the Lower Buntsandstein Subgroup (su), Volpriehausen (smV), Detfurth (smD), Hardegsen (smH) and Solling Formation (smS) (figure 9.1).

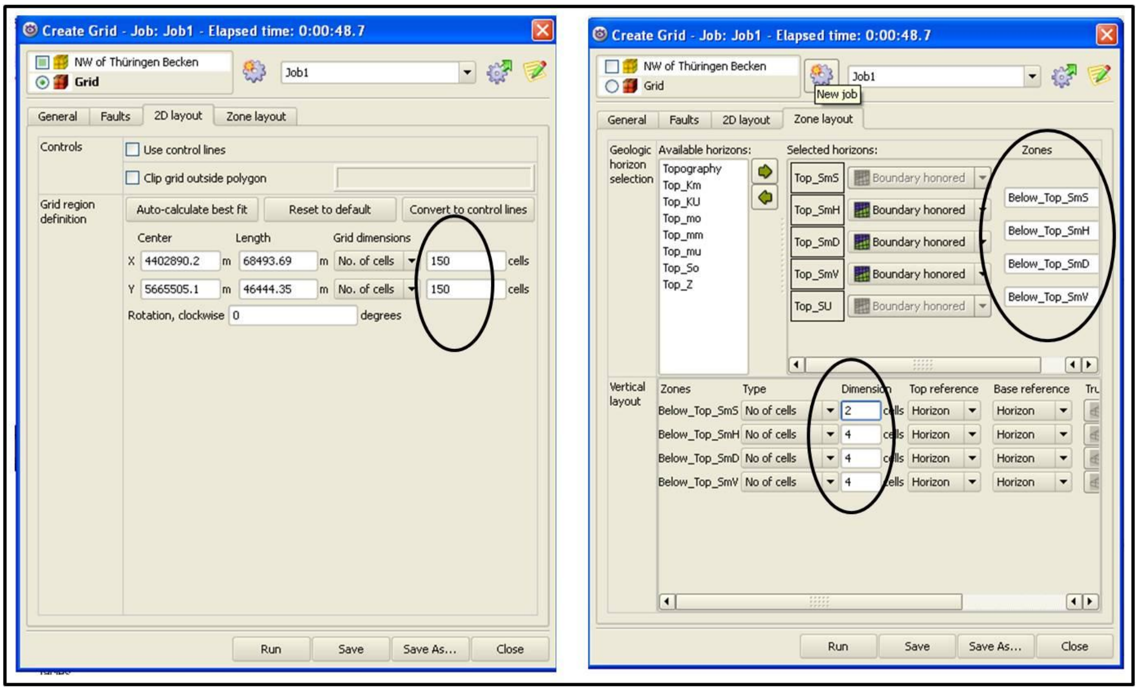


Figure 9.1 Building a geological 3D grid in the study area for the Middle Buntsandstein Subgroup, the horizontal resolution of the grid is composed of 150 cells. The vertical resolution is defined of five horizons which created four zones. The whole zones are composed of 11 vertical cells.

The defined zones are vertically composed of 14 cells: Zone smV: 4, Zone smD: 4, zone smH: 4 and zone smS: respectively and the definition of the horizontal resolution (2D layout; x, y) is determined by 150 x 150 cells (figure 9.1). The lateral extension of the zone must be the same for all selected horizons. The faults system is used and adjusted for creating the 3D geomodel; the grid is visualized in the figures 9.2 and 9.3 showing the stratigraphy of the Middle Buntsandstein Subgroup.

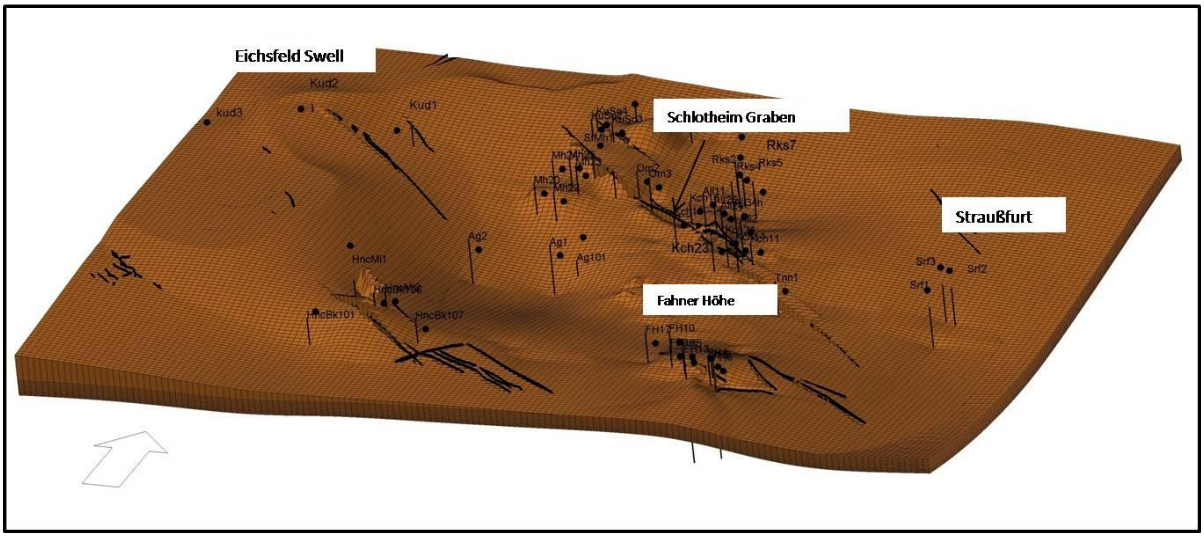


Figure 9.2 visualization of 3D grid for the Middle Buntsandstein Subgroup in the study area which comprises four zones (top smS, smH, smD and smV). The grid is designed with horizontal resolution of 150 x 150 cells. The vertical exaggeration of the grid is 6:1

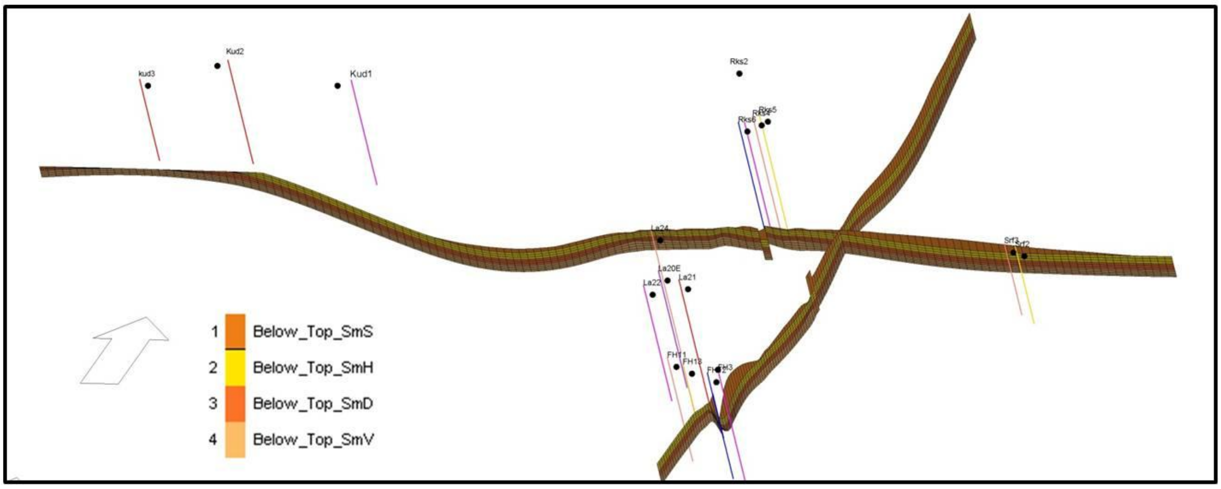


Figure 9.3 visualization of the cross section in the grid for the Middle Buntsandstein Subgroup, displaying the four zones (top smS, smH, smD and smV), in west-east and north-south direction. The vertical exaggeration is 6:1

9.2 Deposition al model

The Middle Buntsandstein Subgroup of the northwestern Thuringian Syncline is mainly characterized by interaction between eolian and fluvial sedimentation with general transport of paleocurrent toward north-northeast (Puff & Langbein, 1995) (figure 9.4 and figure 9.5). The differentiation between fluvial and eolian facies is mainly based on sedimentological characteristics like sorting, geometry, sedimentary structures, lithologic and bounding surfaces in outcrops and cores. In the case of this work; gamma ray log information was used for the facies interpretation additionally, the well cores Fahner-höhe-13 and Rockensußra-2 were examined. However, in the studied area is not easy to make eolian-fluvial discrimination or identify the lateral and vertical variability of these facies associations only using the gamma ray logging, due to similar characteristics of the logs in eolian and fluvial facies.

Comparison of facies indentified in the core Rks-2 suggested that the facies associations of the Volpriehausen and the Detfurth Formation mainly at the basal units are dominated by eolian elements composed of sand plain facies (with low angle lamination) and cross stratified dune sands mainly at the basal units elements in transition to thin silty clayey lacustrine facies (figure 9.6). These eolian deposits are coexisting with several intervals of fluvial sediments. The fluvial facies is mainly characterized by braided channels (trough cross bedding) with lateral transition to floodplain deposits. The Volpriehausen Formation in the Well Rks-2 present percentage of eolian, fluvial and clays sediments in 79, 18 and 3 % respectively, while the Hardegsen Formation comprises 53, 12 and 35 % of eolian, floodplain and fluvial sediments (figure 6.1 and 6.2).

The well core Fh-13 in the Volpriehausen and Detfurth intervals are mainly composed of fluvial channel system exhibiting vertical transition to floodplain deposits. Eolian facies were not recognized in this core (figure 6.1).

The Hardegsen Formation exhibits braided fluvial patterns passing lateral and vertical to floodplain deposits (figure 9.4 and figure 9.6). This sequence is mainly composed of a combination of channel belts dominated by sandy bedload.

The Solling Formation comprises sandy braided river system with low sinuosity or straight in transition with muddy deposits (figure 9.5 and figure 9.6). The base of this formation overlies a regional unconformity (H-Unconformity) which is mainly composed of medium grained sandstones. Lang (2001) suggested that towards the top of the Solling Formation a transition to marine deposition occurred which is observed in the well core Rockensußra-2.

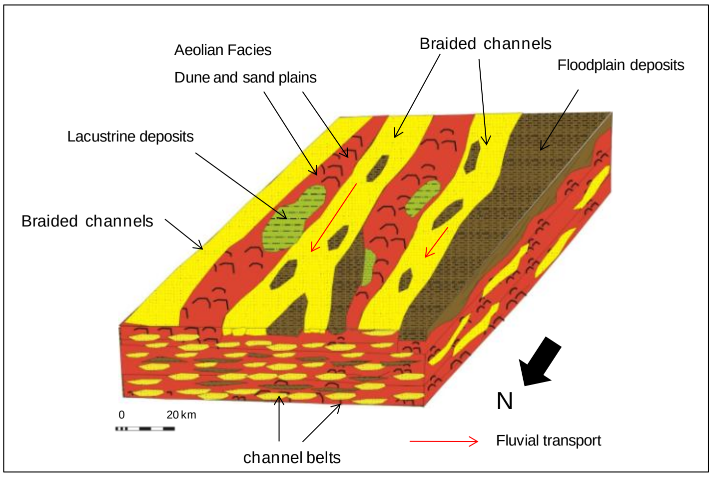


Figure 9.4 Schematic block diagrams for the facies associations of Volpriehausen and Detfurth Formations illustrating braided channel transport intertonguing with eolian sediments and in transition with floodplain and lacustrine deposits.

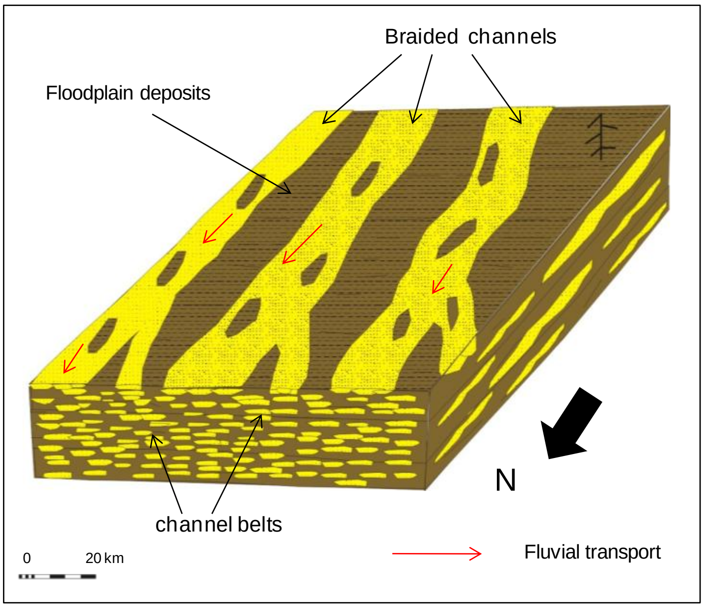


Figure 9.5 Schematic block diagrams for the facies associations of Hardegsen and Solling Formations, mainly composed of fluvial deposits with low sinuosity or straight in transition with floodplain facies. The channel deposits comprise a combination of channel belts.

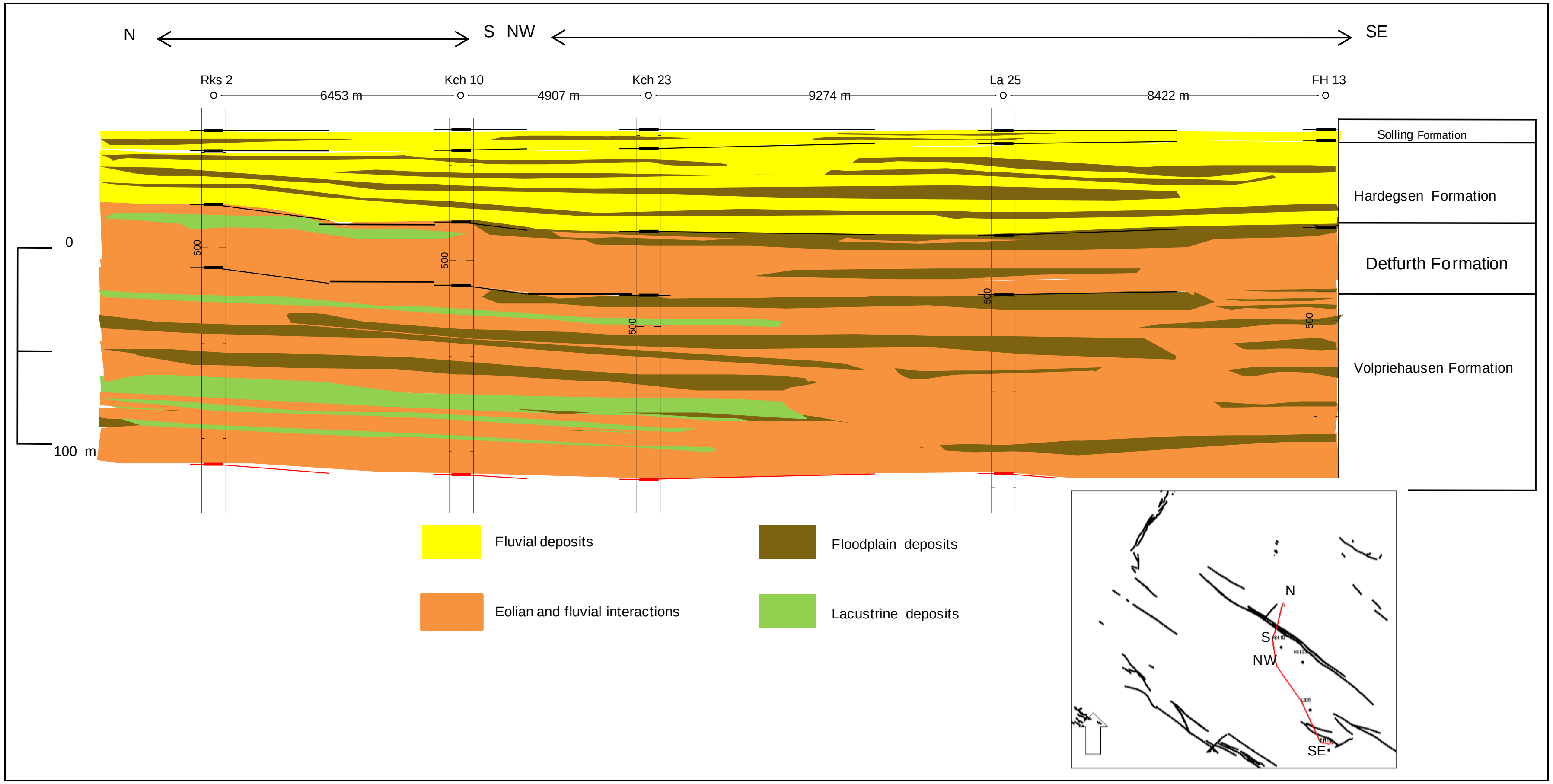


Figure 9.6 Lithostratigraphic facies in cored and non cored wells of the Middle Buntsandstein Subgroup characterized by intertonguing of fluvial and eolian facies in the Volpriehausen and Detfurth Formations, while in the Hardegsen and the Solling Formations comprise fluvial deposits in transition to floodplain facies

For the simulation of the depositional models with the RMS 2009 software all of the available gamma ray logs from the study area were imported for modelling. The well data must be scaled up to the grid resolution before to execute the interpolation. Each facies has been coded with a value embracing the intervals where it has been observed through the well core (figure 9:7 and figure 9.8). The facies modelling has been made creating parameter in terms of geometry (shapes, facies distribution), dimensions (width, length, thickness; sinuosity), orientation, proportions (frequencies), also honouring the stratigraphic characteristics and the facies description.

The simulation represents a spatial facies distribution controlled by well data but make extrapolation in areas where there is no well control. In the case of the Volpriehausen and Detfurth Formations is not possible to separate eolian and fluvial facies only using log interpretation.

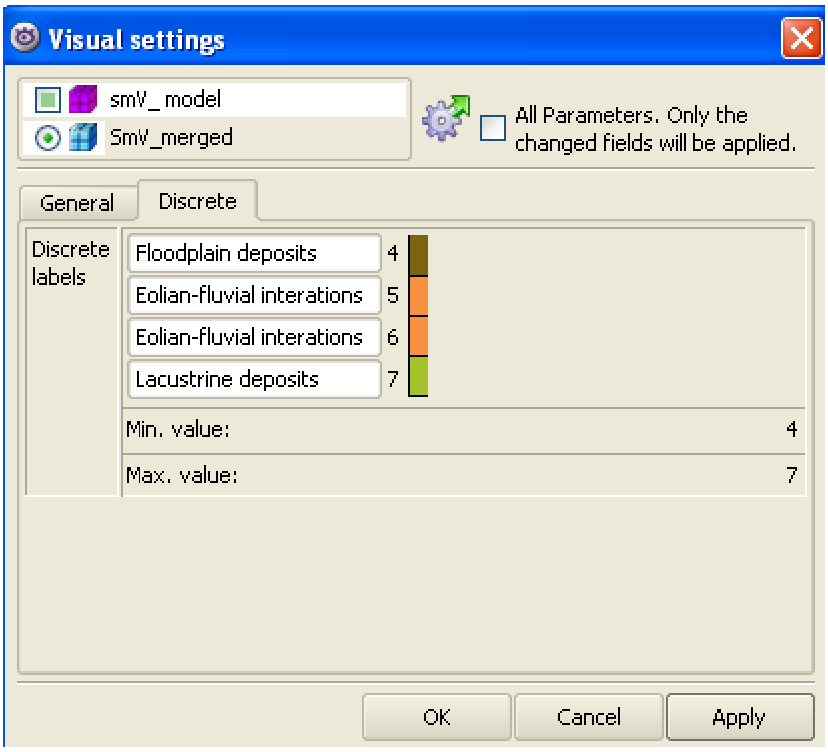


Figure 9.7 Visual settings showing the assigned code to recognized facies in the study area

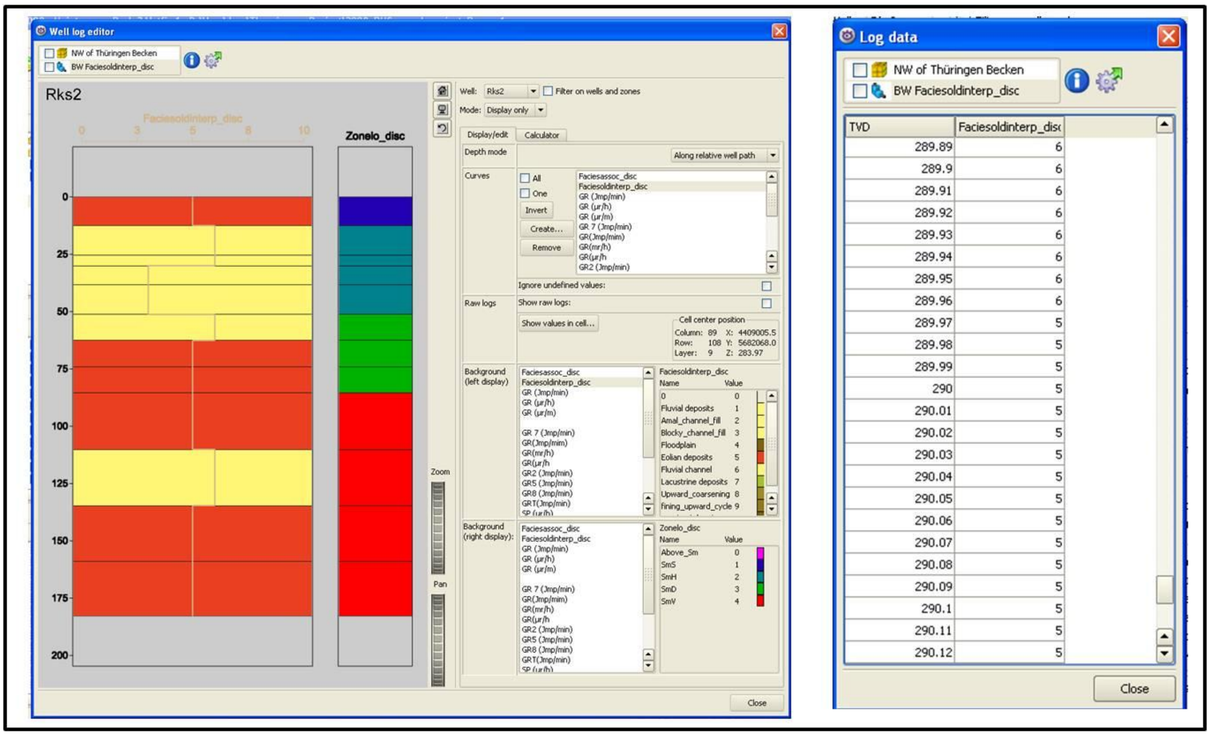


Figure 9.8 Well log editor showing the facies and the assigned code in the Middle Buntsandstein Subgroup.

The facies modelling and paleogeographic map obtained in the studied area using the RMS 2009 software, does not show a facies discrimination between fluvial and eolian sediments in the case of the Volpriehausen and Detfurth Formations, which is also observed in the outcrops. This facies differentiation in occasions is not easy to separate mainly in fluvial deposits with eolian re-deposition. These facies differentiation in the modelling are the product of a statistical method which is mainly based on the well logs information and the definition of shapes, dimensions and locations of channel belt sandstones bodies are complicate to define realistically.

9.2.1 Depositiona l model of the Volpriehausen Formation

The facies modelling of the Volpriehausen Formation presents eolian and fluvial deposits in lateral and vertical interaction (figure 9.9 and figure 9.10) and thickness between 65 and 125 m (table 9.1). The facies model of eolian-fluvial intertonguing in the Volpriehausen Formation comprises about 70 % throughout the study area. The Volpriehausen Formation in the well core Rockensußra-2 is composed of sand plain deposits with some intercalations of cross stratified dune sands showing several intervals with fluvial associations (figure 6.2). The majority of the well logs are correlated in large areas over 1500 km^2, which suggests that the eolian-fluvial facies are laterally extensive and were periodically deposited and between wells as much as 11 km apart (figure 9.10 and 9.11). The eolian deposits in the well core Rockensußra-2 comprise are sand plain and dune facies (figure 6.3) in transition of silty clayey lacustrine deposits.

Fluvial associations have been recognized in the well core Fahner-Höhe-13. They comprise a sandy braided system representing channel belts with low sinuosity or straight with thickness between 4 and 31 m (table 9.1). These fluvial deposits consist of stacked erosive channel (cross bedded sandstones) sets separated by floodplain deposits and eolian facies (figure 9.6). The well core Fahner Höhe-13 is mainly composed of low angle cross bedded sandstones and toward the top of the cycles the floodplain-channel ratio increases constituting silty sediments. According to Röhling & Seidel 2008, the outcrops of Volpriehausen Formation situated in the Neuendorf area (the Eichsfeld Altmark Swell) comprise fluvial facies. The lithostratigraphic description made by theses authors for the well Küllstedt-2 is characterized by fining upward cycles of fine medium grained brown and reddish brown sandstones with interbedded reddish brown siltstones, which suggests vertical transition to floodplain deposits.

Formation	Thickness (m)	Paleocurrent directions	Facies Interpretation
Solling	3-15	to N and NW	Fluvial facies composed by a single channel belt, floodplain deposits. Possible transition to marginal marine deposits toward the top (?)
Hardegsen	21-73	to N and NW	Fluvial deposits with low sinuosity or straight composed of different channel belts in transition to floodplain deposits.
Detfurth	15-45	to N and NW	Eolian sand plain deposits with dune sand intercalation, lateral transition to lacustrine deposits -Braided channel with low sinuosity, lateral transition to floodplain
Volpriehausen	65-125	to N and NW	Eolian facies (dune and sand plain) with transition to lacustrine deposits. Fluvial facies comprising a combination of channel belts with floodplain deposits to the top the cyclothems.

Table 9.1 Summary of facies association and thickness in the Middle Buntsandstein of the northwestern Thuringian Basin

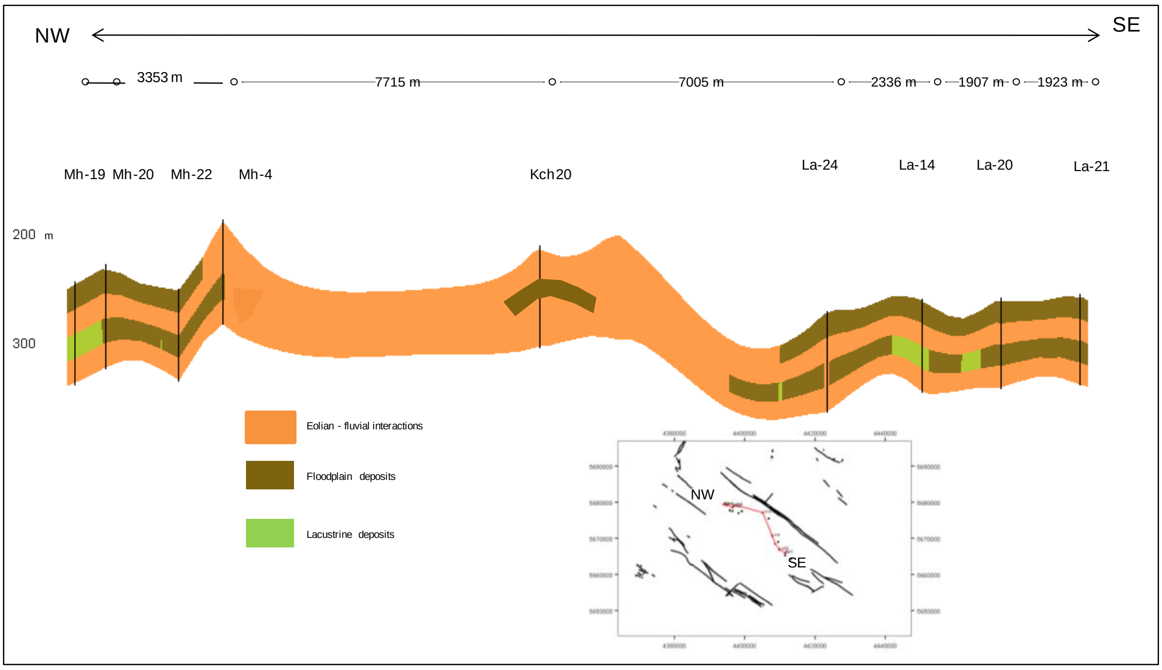


Figure 9.9 Facies cross-section of the Volpriehausen Formation using the RMS 2009 software in northwest-southeast direction. The section shows eolian-fluvial interactions in transition with floodplain-lacustrine deposits (vertical exaggeration 25:1). Notice that this a 2D section of the 3D model. Location of facies boundaries is influenced by wells outside the cross-section.

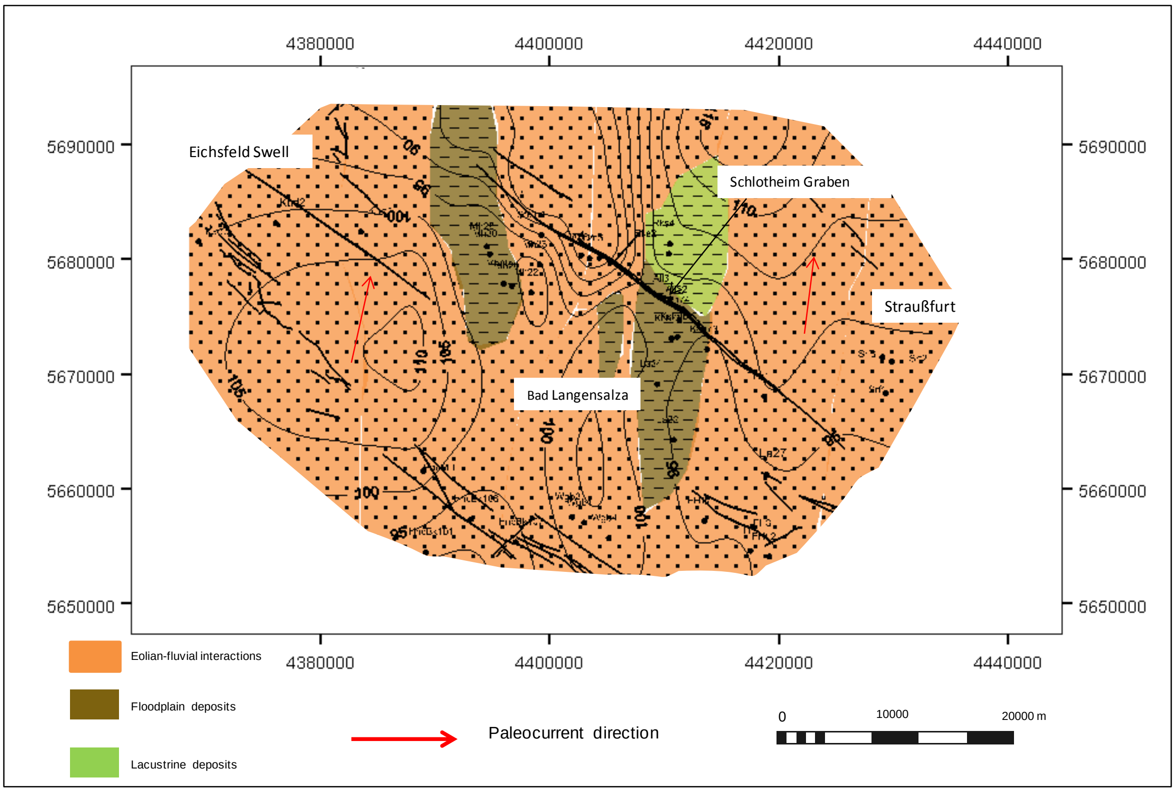


Figure 9.10 Schematic palaeography of the Volpriehausen Formation based on the facies and electrofacies indentified in the wells through the study area. The diagram shows eolian-fluvial interactions in lateral transition with muddy deposits. The fluvial transport is mainly from SSW to NNE direction.

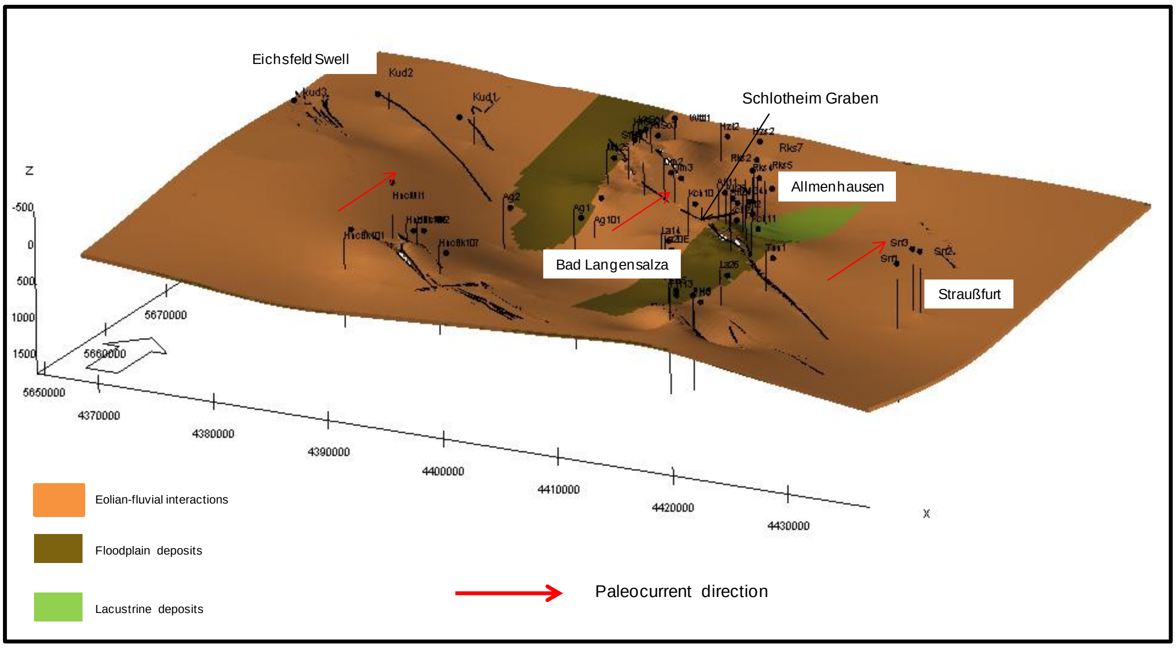


Figure 9.11 Depositional model of the Volpriehausen Formation in the studied area created with the RMS 9000 software, characterized by aeolian-fluvial interactions. Floodplain and lacustrine deposits have been recognized (vertical exaggeration 6:1)

9.2.2 Depositional model of the Detfurth Formation

Eolian-fluvial interactions also have been recognized the Detfurth Formation embracing a 60 % through the studied area (figure 9.12 and figure 9.13). The well core Rockensußra-2 mainly comprises sand plain facies with some isolated dune bodies and interbedded with silty clayey sandstones of lacustrine origin (figure 6.2 and figure 6.6). The Detfurth Formation is not present in the Eichsfeld area as a product of the regional erosion (H-unconformity).

The eolian facies are in lateral and vertical transition with fluvial deposits throughout the studied area (figure 9.12 and 9.13). The fluvial facies observed in the well Fahner Höhe-13 comprises stacked, massive, fining upward cycles of fine to medium grained sandstones. The fluvial deposits comprise channel belts of thickness between 10 and 12 m with floodplain deposits intercalation (figure 9.12). According to Puff et al (1995) the fluvial sedimentation in the Thuringian Syncline presents transport from south to north and northeast (figure 9.13 and figure 9.14). The eolian-fluvial interactions of the Detfurth Formation can be correlated between wells in large distance about 11 km presenting thickness from 15 to 45 m (table 9.1). The floodplain deposits constitute facies in lateral and vertical transition with the braided system.

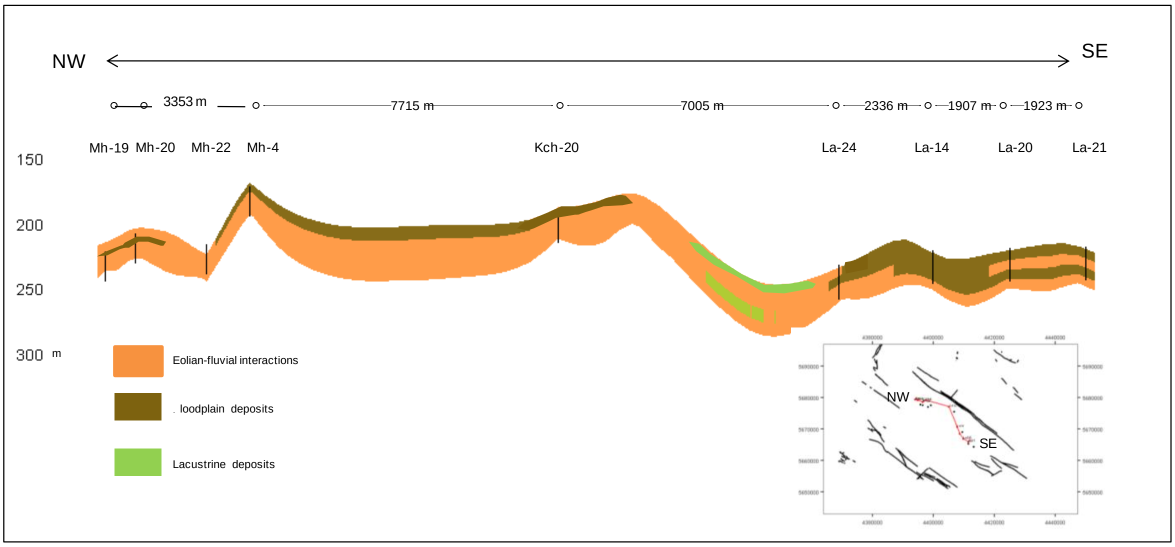


Figure 9.12 Facies cross-section in NW-SE direction of the Detfurth Formation in the study area. The section exhibits eolian-fluvial interactions in transition toward the top to flood plain deposits. The facies can be correlated in large distance between wells (vertical exaggeration 25:1). Notice that this a 2D section of the 3D model. Location of facies boundaries is influenced by wells outside the cross-section.

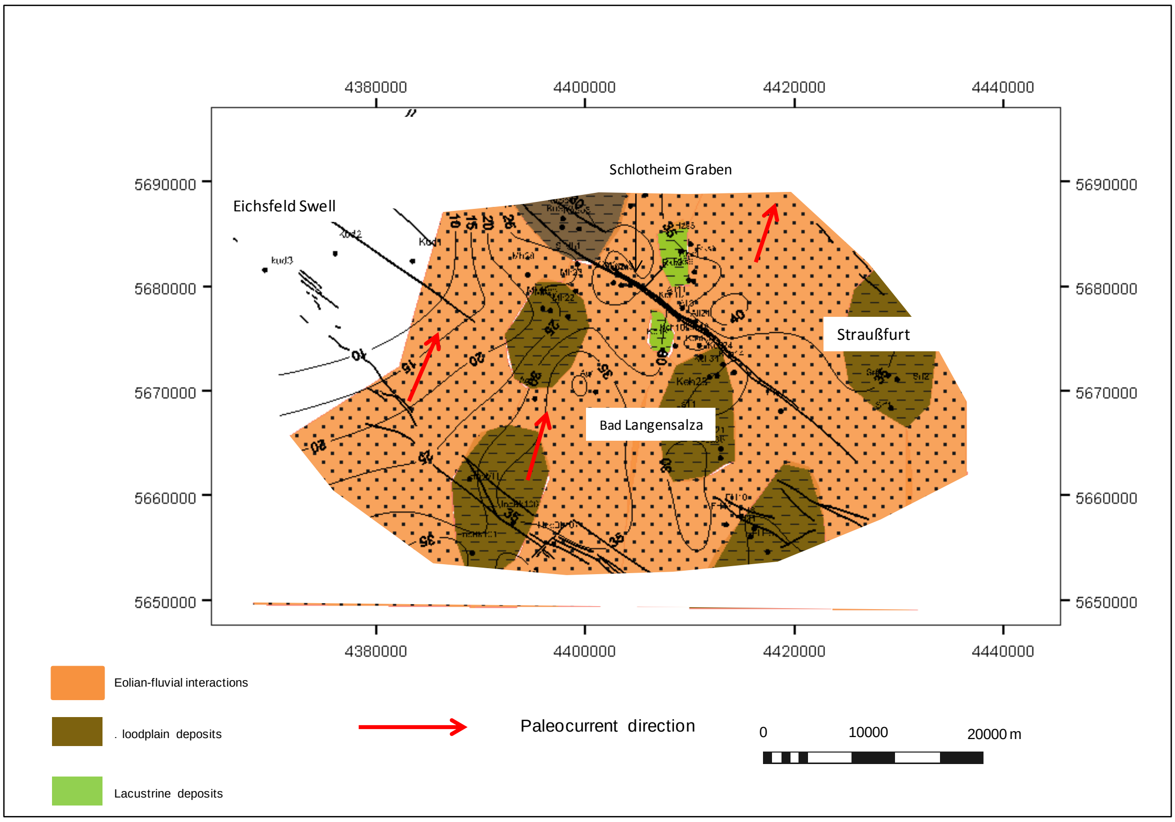


Figure 9.13 Schematic palaeography illustrating the facies distribution of the Detfurth Formation in the study area. The figure shows eolian-fluvial interactions in lateral transition to lacustrine and floodplain deposits.

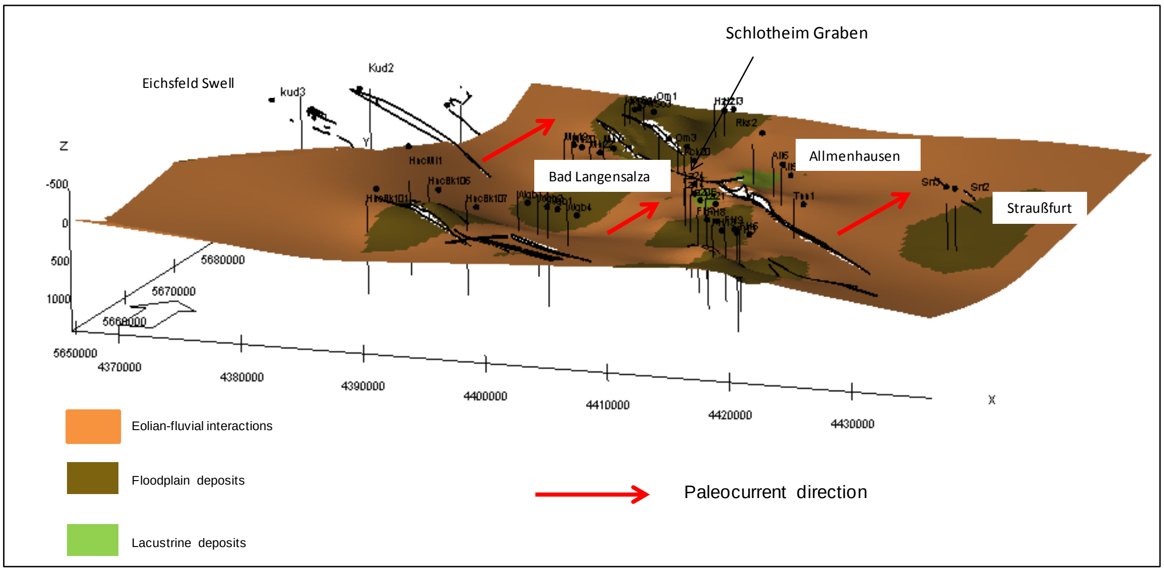


Figure 9.14 depositional model of the Detfurth Formation mainly composed of eolian-fluvial interactions in lateral transition to floodplain and lacustrine deposits (vertical exaggeration 6:1).

9.2.3 Depositional model of the Hardegsen Formation

Fluvial associations encountered in the northwestern Thuringia Syncline through the Hardegsen Formation embracing about 70 % of the studied area. This depositional system is composed of stacked erosive channel (cross-bedded sandstones) sets and fluvial sheetflood deposits, presenting low sinuosity comprising thickness between 21 and 70 m. The main sedimentological characteristics observed in the wells core Fahner Höhe-13 and Rokensußra-2 are low angle cross beds and tabular cross stratified sandstones. The estimated paleocurrent suggests from south to north and northeast orientations and the main channel. The fluvial system observed in the depositional model may not represent a single channel but is the result of lateral and vertical amalgamation of multiple channel belts elements (migration) (figure 9.15, 9.16 and 9.17). The thickness of each channel belt can vary between 11 and 14 m and are well correlated in a section of 4.3 km long across the study area. Towards the top of the Hardegsen Formation are frequently observed floodplain deposits (figure 9.15) which are eroded by the overlying Solling sandstone. The floodplain facies comprises notable silty sandstones and has lateral extensive geometry. In the Eichsfeld Swell, area the Hardegsen Formation is not present. No eolian deposits in the Hardegsen Formation have been observed.

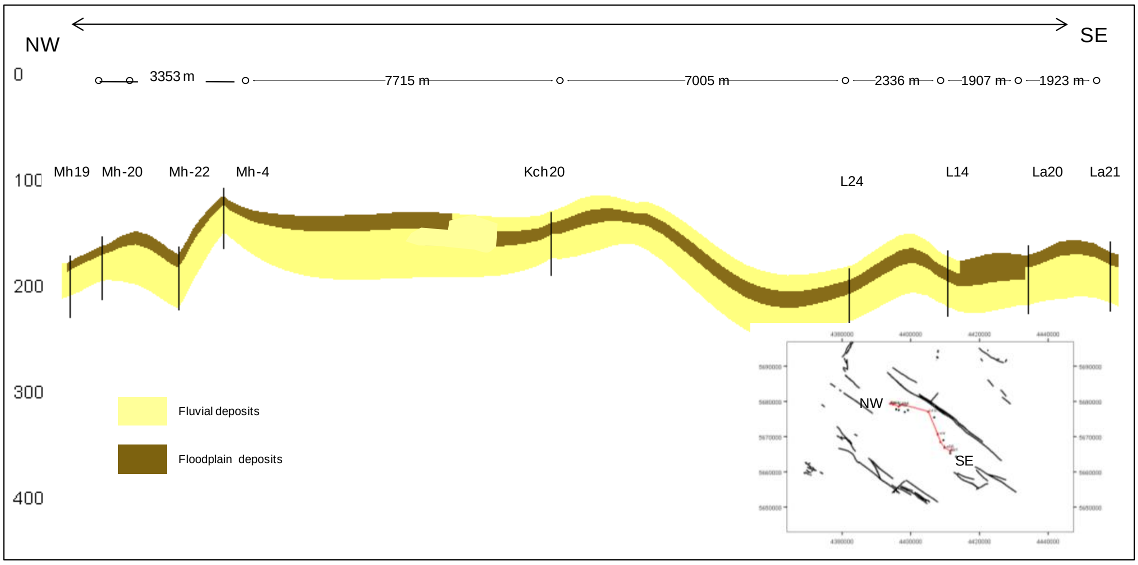


Figure 9.15 Facies cross-section in NW-SE direction of the Hardegsen Formation showing fluvial association in lateral and vertical transition with floodplain deposits. The channels can be correlated in large distance between wells (vertical exaggeration 25:1).

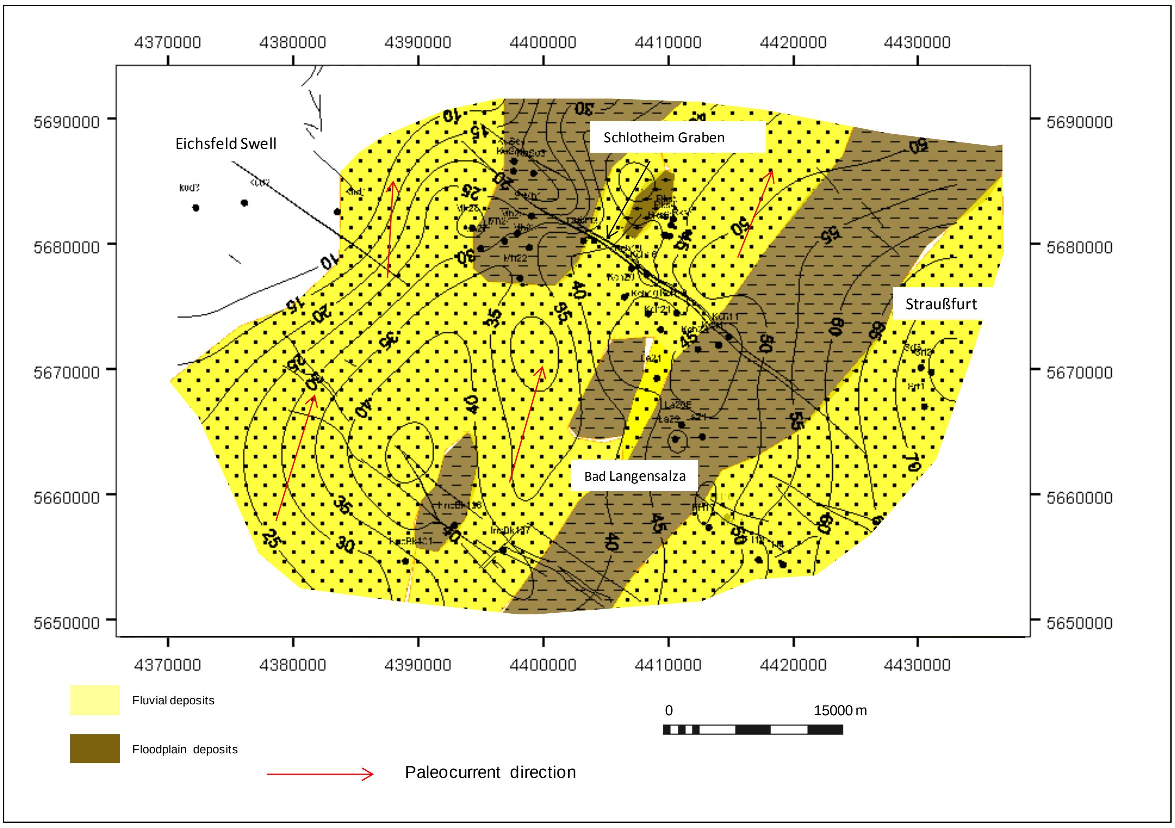


Figure 9.16 Palaeography map of the Hardegsen Formation illustrating a fluvial system with deposition direction from south to north and northeast and lateral extension of floodplain deposits. The widths of fluvial deposits is the result of migrating channel belts

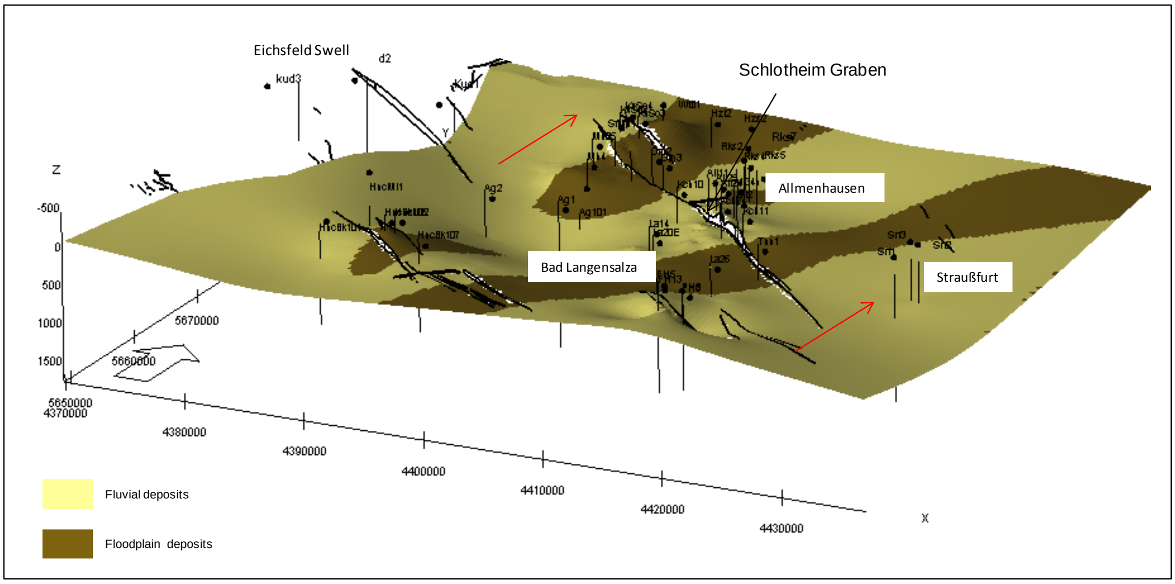


Figure 9.17 depositional model of the Hardegsen Formation constitute fluvial process and floodplain deposits. The braided channel presents a system with general transport toward N and NE: The fluvial system is composed of migrating channel belts. The Hardegsen Formation in the Eichsfeld area has been eroded.

9.2.4 Depositional model of the Solling Formation

The Solling Formation in study area is dominated by sandy fluvial deposits; the base of these channels is composed of fine to medium grained sandstones with low angle bedding and planar cross stratified beds. These lithofacies associations were observed in the wells core Fahner Höhe-13 and Rockensußra-2: The interpreted channels cut into floodplain deposits (figure 9.18). This fluvial system presents thicknesses between 3 and 11 m composed of a vertical single channel belt but with possible lateral amalgamation. The channels are characterized by moderate braiding, with sedimentation direction toward north and northeast (figure 9.19 and 9.20). Point bar deposits have not been identified in the area. Some well logs show coarsing upward cycles interpreted as channel bar with dimensions of 7 km long and 3 km width. The Floodplain associations are found in lateral transition mainly composed of siltstone and mudstones truncating the remnant fluvial bodies. The top Solling Formation of the well Rockensußra-2 is characterized by siltstone laminations and anhydrit concretions.

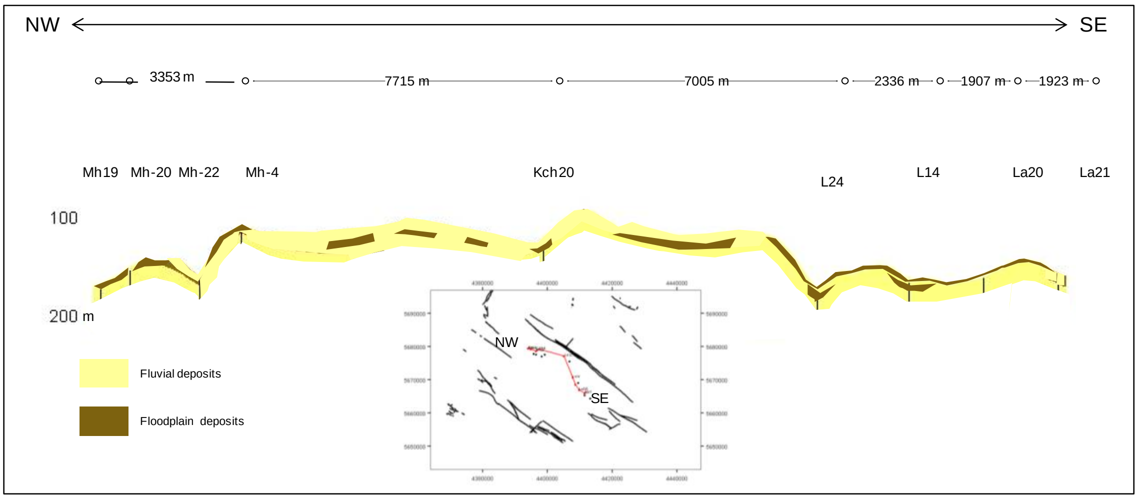


Figure 9.18 Facies cross-section of the Solling Formation. This stratigraphic cross section in NW-SE direction shows fluvial association composed of migrating channel belts with lateral extension of floodplain deposits (vertical exaggeration 25:1).

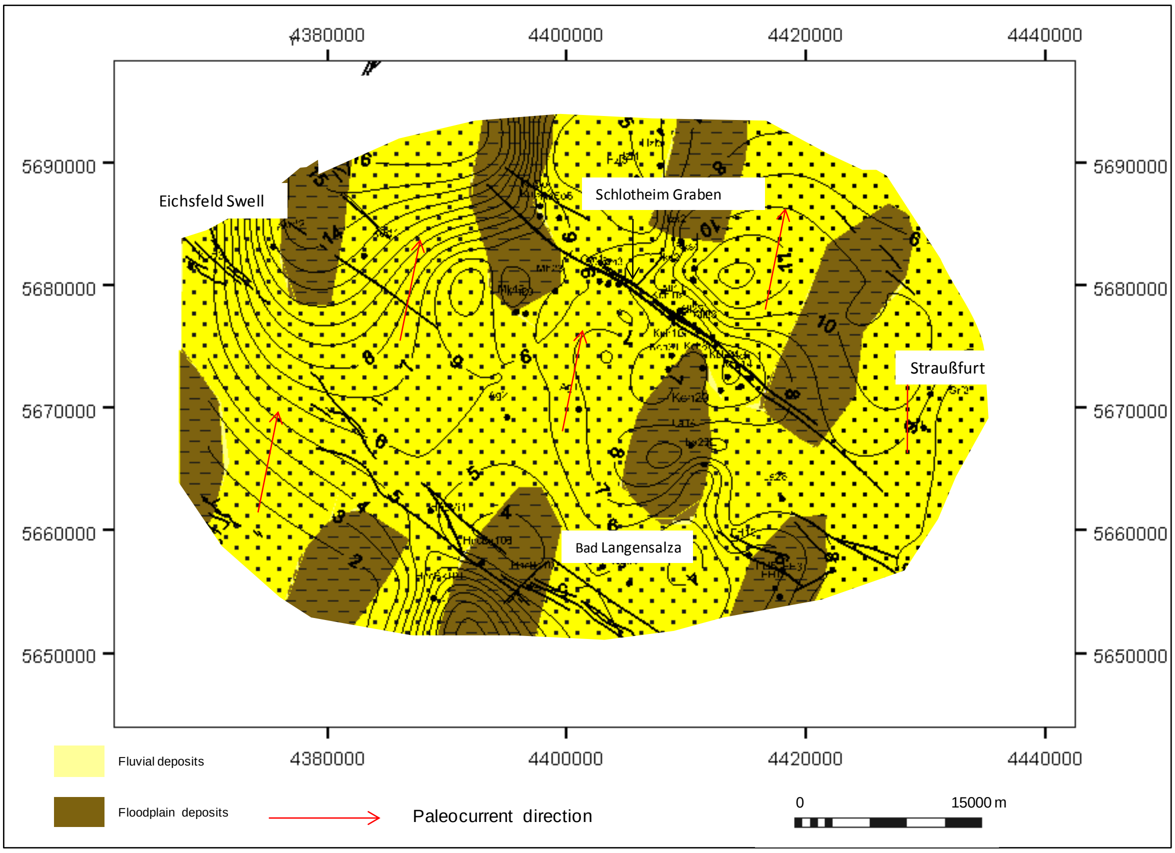


Figure 9.19 Palaeographic map of the Solling Formation illustrating fluvial channels with deposition direction from south to north and northeast and lateral extension of floodplain deposits.

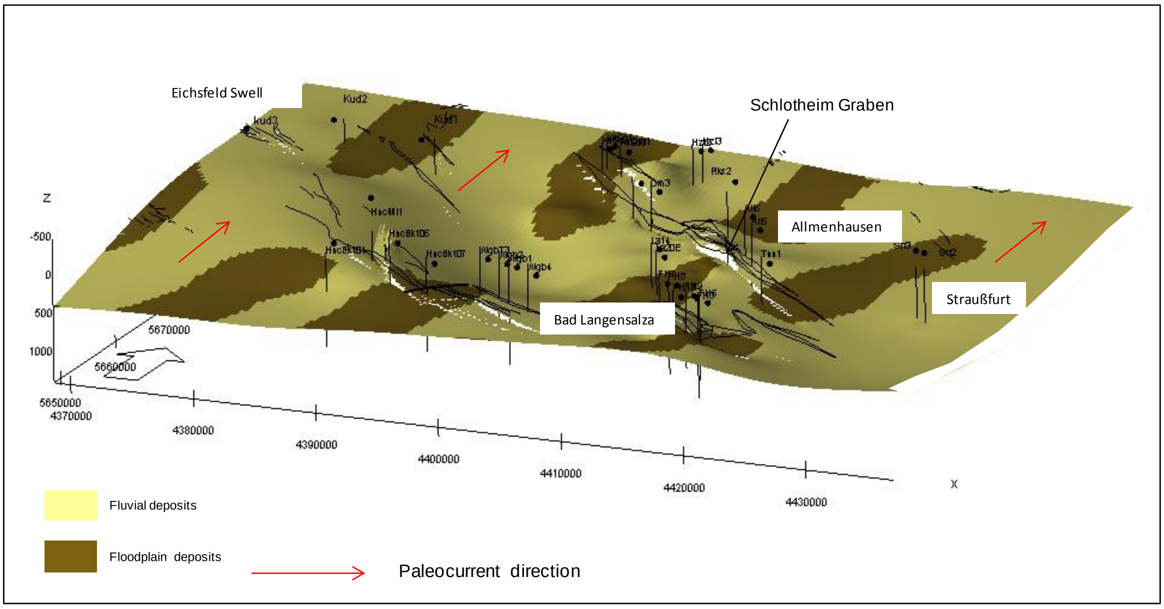


Figure 9.20 depositional model of the Solling Formation constituted of fluvial deposits and floodplain process. The channels have general transport toward N and NE (vertical exaggeration 6:1).

10. Conclusions

- The Middle Buntsandstein Subgroup in the Northwestern Thuringian Syncline comprises four stratigraphic units: the Volpriehausen, Detfurth, Hardegsen and Solling Formations, recognized and well correlated on the wire logs throughout the studied area, with boundaries between formations clearly defined by the transition from clay-dominated to sand-dominated deposition. This is similar to large parts of the Germanic Basin.
- The sediments which comprise the northwestern Thuringian Syncline and the South German Basin are supplied from the south. The Bohemian Massif served as the main source of clastic sediments during Early Triassic time (Lower and Middle Buntsandstein deposition).
- Based on logs and lithostratigraphic study, the Middle Buntsandstein Subgroup mainly consists of fifteen to seventeen fining upward cycles forming a high resolution lithostratigraphic framework: nine in the Volpriehausen Formation, one in the Detfurth Formation, four in the Hardegsen Formation and one in the Solling Formation. The cyclicity patterns can be interpreted as base level cycles which are related to Milankovitch climate fluctuations between wet and dry periods with an estimated duration of 100 ka (100,000 years), following the suggestion of Geluk & Röhling (1997) for the Netherlands and northwestern Germany.
- The subsidence patterns during the Buntsandstein deposition in the studied area were controlled by short-lived tectonic pulses identified in the Netherlands and the northwest German Basin by Geluk & Röhling (1997); these occur prior to Volpriehausen, Detfurth, Solling and intra-Solling deposition as evidenced by regional unconformities, but mainly before the Solling depositions which was the strongest provoking uplifted and erosion evidenced by the H-Unconformity.
- A structural reorganization occurred at the end of the Lower Buntsandstein deposition in the Southern Permian Basin (Kozur 1999, from Geluk, 2005). In the northwestern Thuringian Syncline NNE-SSW tensional and transtensional stresses reactivated NW-SE trending faults. Unlike other areas of the German Basin, only few faults of NNE directions are presents in the studied area, which indicates that the WNW-ESE extensional-transtensional regime in the north German Basins did not play an important role in the northwestern Thuringian Syncline.

- The study area is characterized by about 150 faults mainly trending NW-SE, which most of them were identified as normal and only some as inverse. Some of these faults were determined from the well logs.
- The Schlotheim Graben system comprises three main normal faults striking NW (305°) with stratigraphic throws from 20 to 280 m as well as two minor faults with similar trend and displacement around 20 m. these extensional stress are the result of regional subsidence during the Early Triassic throughout the entire Southern Permian Basin.
- In the northwestern Thuringian Syncline, the lowly differentiated thickness of the Buntsandstein indicates uniform subsidence, but the apparently decreased thickness of the Lower and Middle Buntsandstein beneath the Schlotheim Graben suggests that the normal faulting began during the Buntsandstein deposition. Additionally, the subsidence was limited during the deposition of the Solling Formation in the entire Thuringian Syncline indicated by low thicknesses between 3 and 30 m.
- The phase of transtensional tectonics is mainly evident in the Berka vor dem Hainich area and the Eichsfeld Swell. The axes of the uplifted areas show an orientation; NW-SE trend occurred after the deposition of the Hardegsen Formation as well as the tectonically induced erosion. The strongest movement occurred in the Eichsfeld Swell where the Solling Formation rests upon the Volpriehausen Formation comprising across the H-unconformity, indicating erosion of about 60 m. In others areas of the Northwestern Thuringian Syncline the Solling Formation truncates different depositional cycles of the Hardegsen Formation.
- The Middle Buntsandstein Subgroup in the northwestern Thuringian Syncline mainly consists of continental clastic deposits of eolian-fluvial-lacustrine interaction; and controlled by tectonic activity and climatic variations reflecting alternating arid and humid periods. Sediment transport is mainly to the NNE.
- The Volpriehausen and Detfurth Formations are characterized by successions of eolian-fluvial sediments interacting in lateral and vertical transition with lacustrine and flood plain deposits.
- The Hardegsen and the Solling Formations constitute fluvial systems in vertical and lateral transition with floodplain deposits. Towards the top of the “Solling

Chirotherien", in the Rockensußra area the presence of anhydrite is notable, which suggests a transition to marginal marine deposition (Lang, 2001).

- The depositional model of the Hardegsen Formation mainly comprises fluvial deposits of stacked erosive channel sets, presenting low sinuosity. Each channel belt comprises thickness between 11 and 14 m in lateral transition to floodplain deposits.
- The Solling Formation is dominated by sandy fluvial deposits presenting thicknesses between 3 and 11 m characterized by a single channel belt in lateral migration with sedimentation direction towards the north-northeast. Therefore flood plain associations are found in lateral transition.

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List of f igures and tables

List of Tables

Well Name	Digital Log	Well Name	Digital Log	Well Name	Digital Log
Ag02	GR	Kch 11	GR9	La 109	GR9
All 02	GR	Kch 12	GR2	La 110	GR10
All 03	GR	Kch 13	GR9)	La 112	GR6
All 04	GR	Kch 14	GR9	La 114	GR7
All 05	GR	Kch 19	GR10	La 22	GR4
All 06	GR7	Kch 20	GR6	La 24	GR9
All 08	GR2	Kch 21	GR7	La 25	GR
All 11	GR	Kch 23	GR8	La 26	GR
All 24	GR	Kch 24	GR	La 27	GR
All 25	GR	Kch 25	GR9	La 35	GR
All 32	GR	Kch 26	GR5	La 36	GR
All 33	GR	Kch 27	GR5	Mh 04	GR7
All 35	GR	Kch 29	GRT	Mh 19	GR9
All34h	GR	Kch 31	GR9	Mh 20	GR9
FH 02	GR	Kch 32	GR9	Mh 22	GR10
FH 03	GR	Kch 33	GR5	Mh 23	GR2
FH 05	GR	Kch 34	GR6	Mh 24	GR3
FH 06	GR	Kch 35	GR2	Mh 25	GR9
FH 07	GR9	Kch 44	GR	Mh 26	GR
FH 08	GR9	Kch 60	GR	Mh 27	GR
FH 09	GR	Kch 61	GR	Mh 28	GR
FH 10	GR	Kch 63	GR	Mh 30	GR9
FH 101	GR	Kch 71	GR	Mh 31	GR
FH 11	GR	Kch 72	GR	Mhr 04	GR
FH 12	GR	Kch 73	GR	Mhr 06	GR
FH 13	GR	Kch 74	GR	Om 1	GR9
FH 17	GR	Kch 79	GR	Om 2	GR
HncBk 101	GR	Kch 80	GR	Om 3	GR
HncBk 102	GR9	Kch 81	GR	Rks 2	GR
HncBk 106	GR	Kch 83	GR	Rks 4	GR
HncBk 107	GR	Kch 84	GR	Rks 5	GR
HncMi 1	GR9	Küd 1	GR	Rks 6	GR
HncMi 2	GR	Küd 2	GR	Rks 7	GR
Hzl 2	GR	Küd 3	GR	Sfmh 1	GR9
Hzl 3	GR	KuSo 2	GR2	Sfmh 2	GR9
Hzl 4	GR	KuSo 3	GR	Srf 1	GR9
Hzl 5	GR	KuSo 4	GR2	Srf 2	GR
Hzs 2	GR	La 07	SP	Srf 3	GR
Hzs 3	GR	La 08	GR	Tnn 1	GR
Kch 03	GR	La 12	GR	Wgb 1	GR
Kch 10	GR9	La 14	GR9	Wgb 2	GR
Kch 12	GR2	La 20	GR9	Wgb 4	GR
Kch 16	GR9	La 21	GR5	Wgb T3	GR
Kch 18	GR5	La 106	SP1 mv	Wttl 1	GR
Kch 08	GR9	La 108	GR2		

Appendix 1 Data table of available log information (spontaneous potential and gamma ray curves) used for the stratigraphic cross-section. There are 132 well with gamma ray logs and 2 logs with spontaneous potential.

Fault Name	Displacement	Fault Name	Displacement	Fault Name	Displacement	Fault Name	Displacement
F1	Normal	F22	Normal	F44	Normal	F65	Normal
F2	Normal	F23	Normal	F45	Normal	F66	Normal
F3	Normal	F24	Normal	F46	Normal	F67	Normal
F4	Normal	F25	Normal	F47	Normal	F68	Normal
F5	Reverse	F26	Normal	F48	Normal	F69	Normal
F6	Reverse	F27	Normal	F49	Normal	F70	Normal
F7	Reverse	F28	Normal	F50	Normal	F71	Normal
F8	Normal	F29	Normal	F51	Normal	F72	Normal
F9	Normal	F30	Normal	F52	Normal	F73	Normal
F10	Normal	F31	Reverse	F53	Normal	F74	Normal
F11	Normal	F32	Normal	F54	Normal	F75	Normal
F12	Normal	F34	Reverse	F55	Normal	F76	Normal
F13	Normal	F35	Reverse	F56	Normal	F77	Normal
F14	Normal	F36	Reverse	F57	Normal	F78	Normal
F15	Normal	F37	Normal	F58	Normal	F79	Normal
F16	Normal	F38	Reverse	F59	Normal	F80	Normal
F17	Normal	F39	Normal	F60	Normal	F81	Normal
F18	Normal	F40	Normal	F61	Normal	F82	Normal
F19	Normal	F41	Normal	F62	Normal	F83	Normal
F20	Normal	F42	Normal	F63	Normal	F84	Normal
F21	Normal	F43	Normal	F64	Normal	F85	Normal

Appendix 2 Table of faults and the used nomenclature in the study area

Fault Name	Displacement	Fault Name	Displacement	Fault Name	Displacement	Fault Name	Displacement
F86	Normal	F107	Normal	F128	Normal	F149	Normal
F87	Normal	F108	Normal	F129	Normal	F150	Normal
F88	Normal	F109	Normal	F130	Normal	F151	Normal
F89	Normal	F110	Normal	F131	Normal	FA	Normal
F90	Normal	F111	Normal	F132	Normal	FB	Normal
F91	Normal	F112	Normal	F133	Normal		
F92	Normal	F113	Normal	F134	Normal		
F93	Normal	F114	Normal	F135	Normal		
F94	Normal	F115	Normal	F136	Normal		
F95	Normal	F116	Normal	F137	Normal		
F96	Normal	F117	Normal	F138	Normal		
F97	Normal	F118	Normal	F139	Normal		
F98	Normal	F119	Normal	F140	Normal		
F99	Normal	F120	Normal	F141	Normal		
F100	Normal	F121	Normal	F142	Normal		
F101	Normal	F122	Normal	F143	Normal		
F102	Normal	F123	Normal	F144	Normal		
F103	Normal	F124	Normal	F145	Normal		
F104	Normal	F125	Normal	F146	Normal		
F105	Normal	F126	Normal	F147	Normal		
F106	Normal	F127	Normal	F148	Normal		

Appendix 3 Table of faults and the used nomenclature in the study area

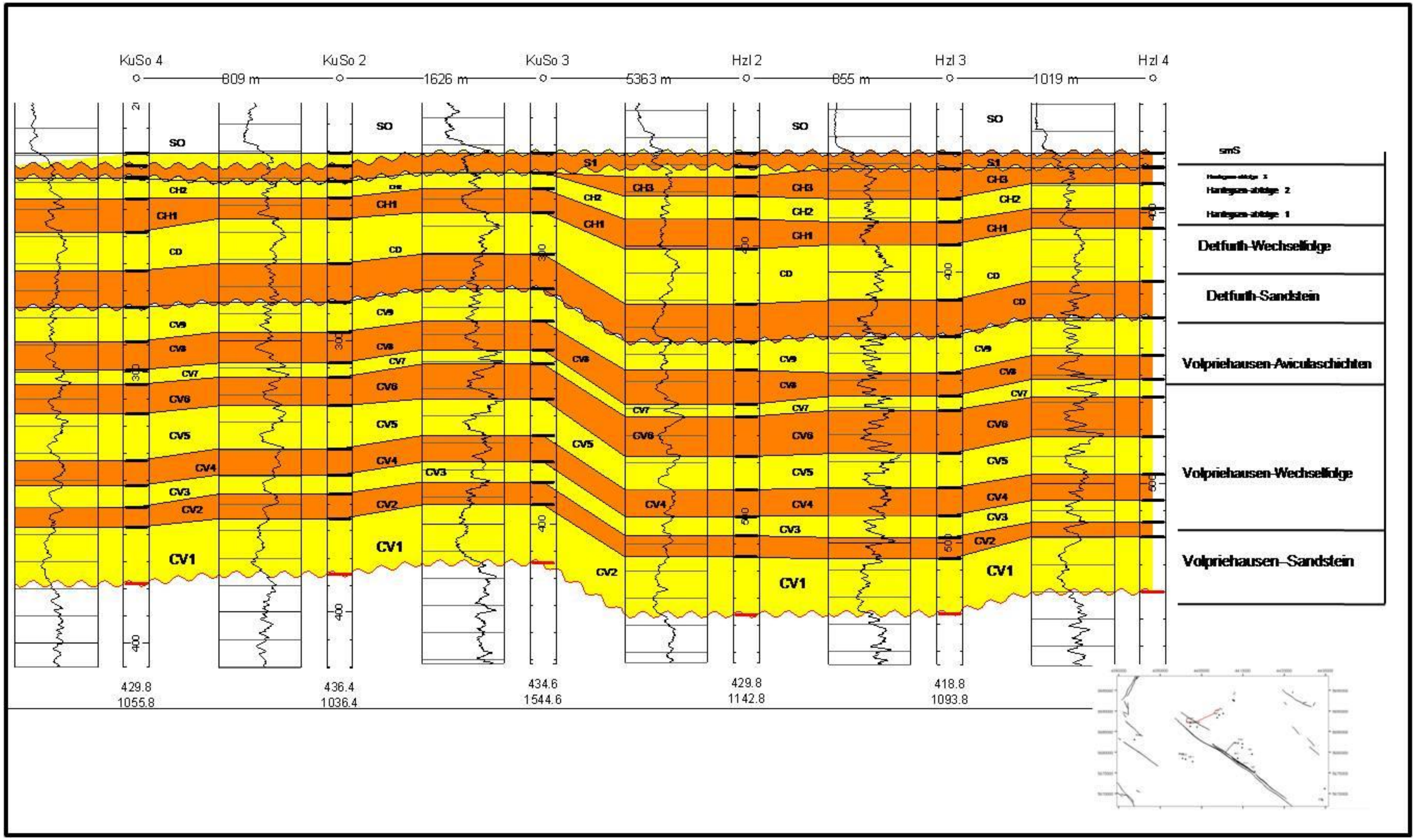
Fault 2 (F2)	Well Name	Horizon	True vertical depth (m)	Missing section (m)
	Kch 47	smH	-237	85
	Kch 46	su	-452.5	40
	Kch 12	smS	-155.04	100
	Kch 74	smS	6	20

Fault A (FA)	Well Name	Horizon	True vertical depth (m)	Missing section (m)
	All 20	mo	219.6	20

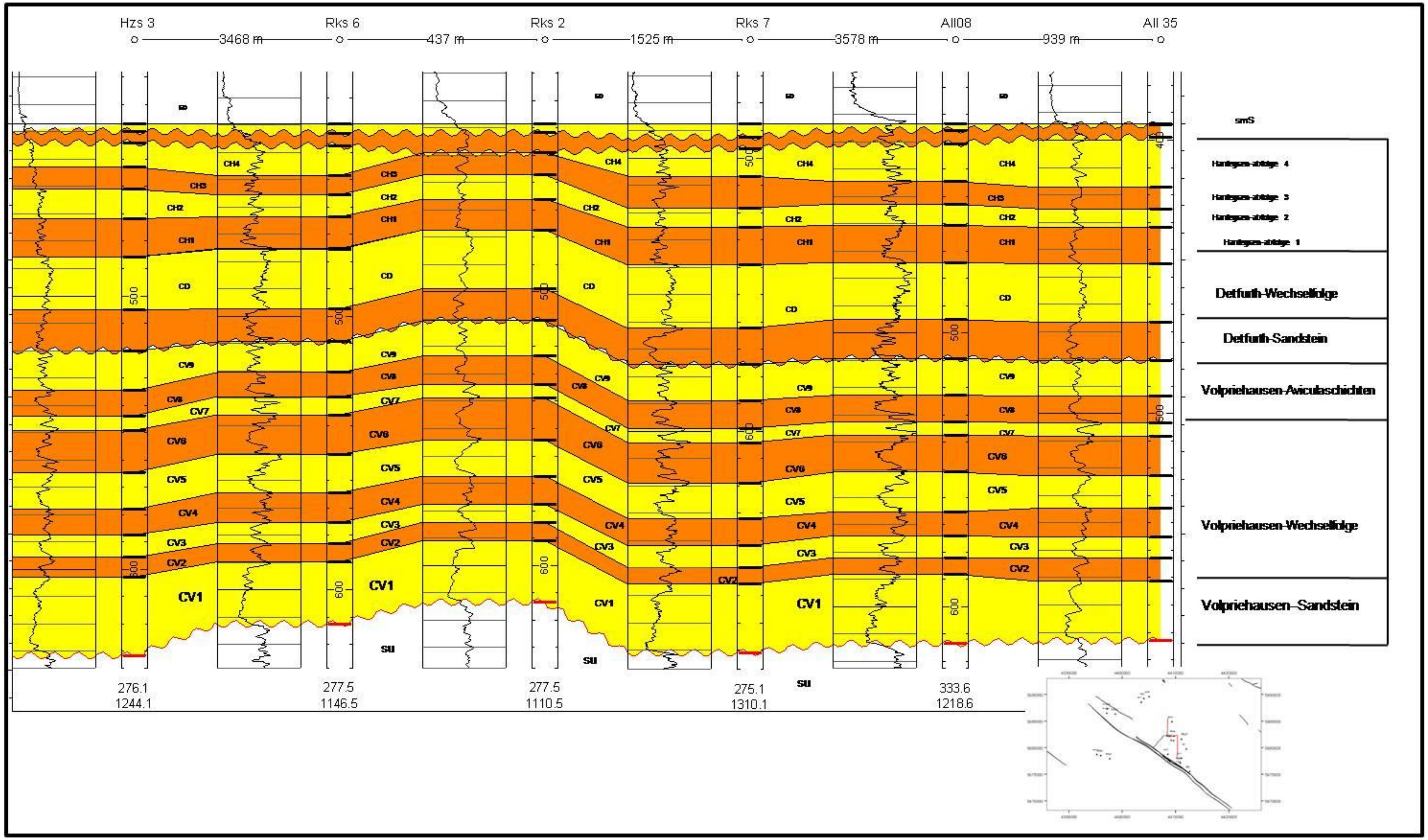
Fault B (FB)	Well Name	Horizon	True vertical depth (m)	Missing section (m)
	All 20	mm	109.6	20

Appendix 4 Wellbores cutting the faults F2, FA and FB indicating the missing section in different horizons through the Schlotheimer Graben

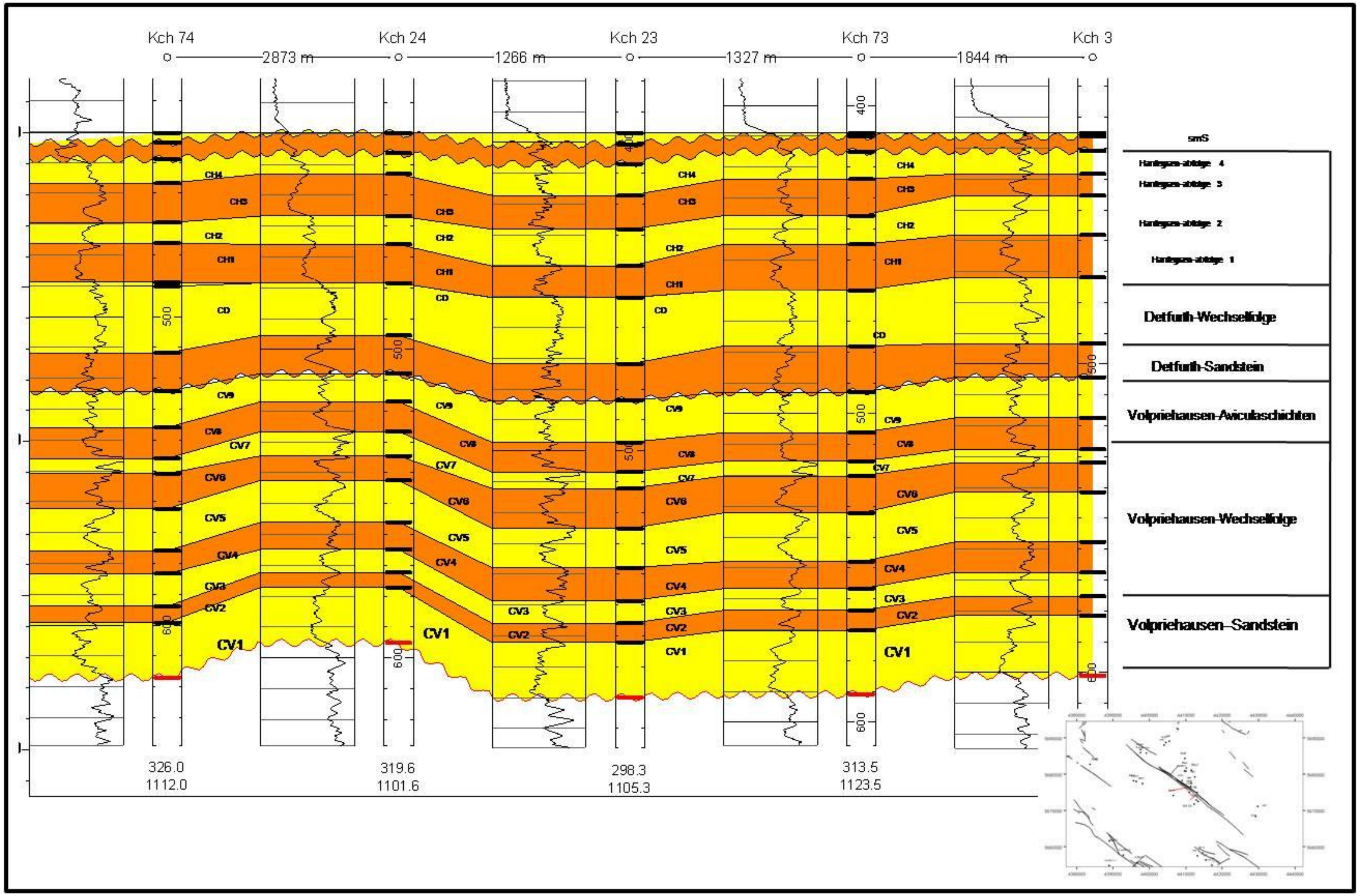
Enclosure. 1



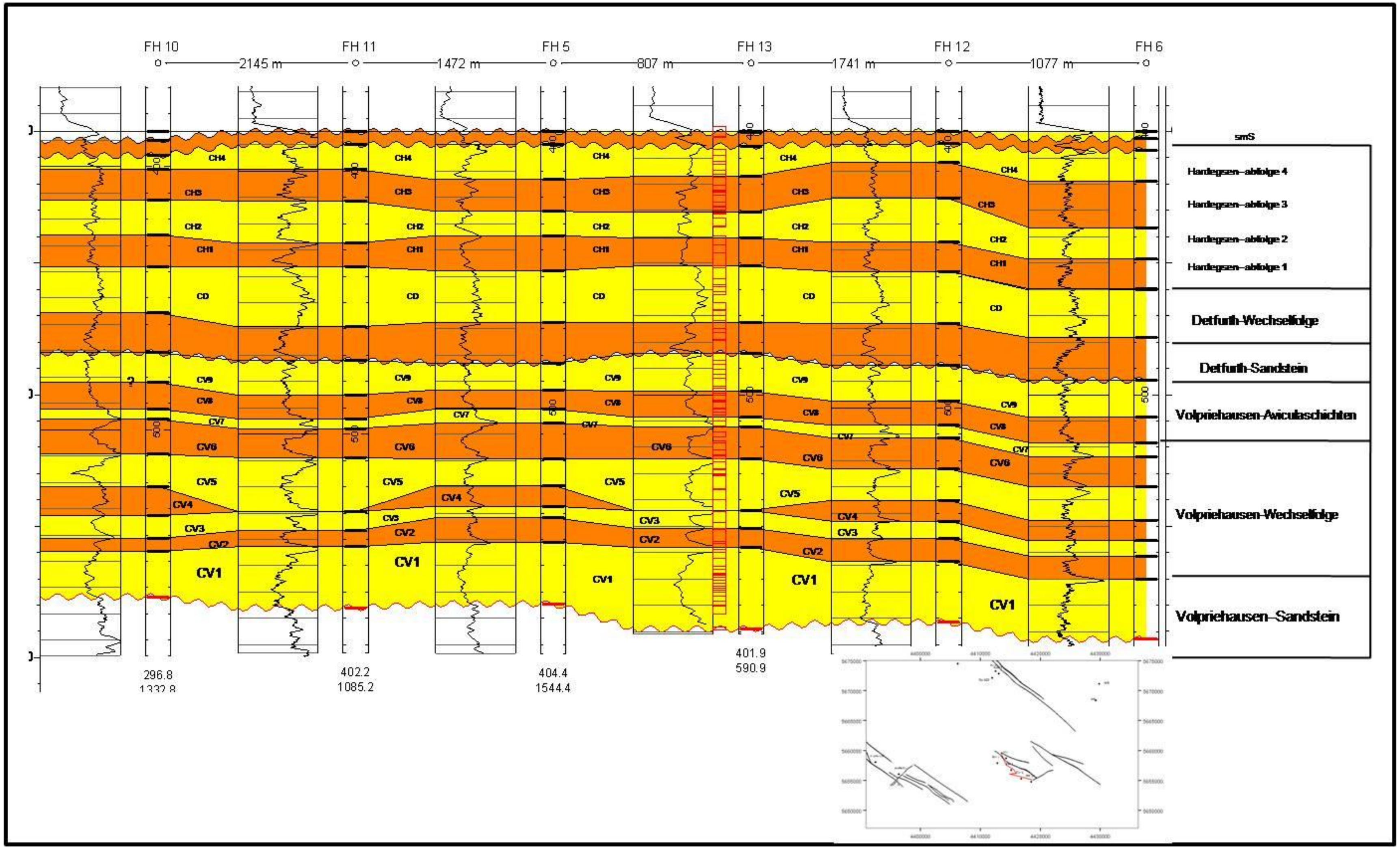
Enclosure 2 Stratigraphic cross-section in W-E direction located in the northern study area showing the complete Middle Buntsandstein



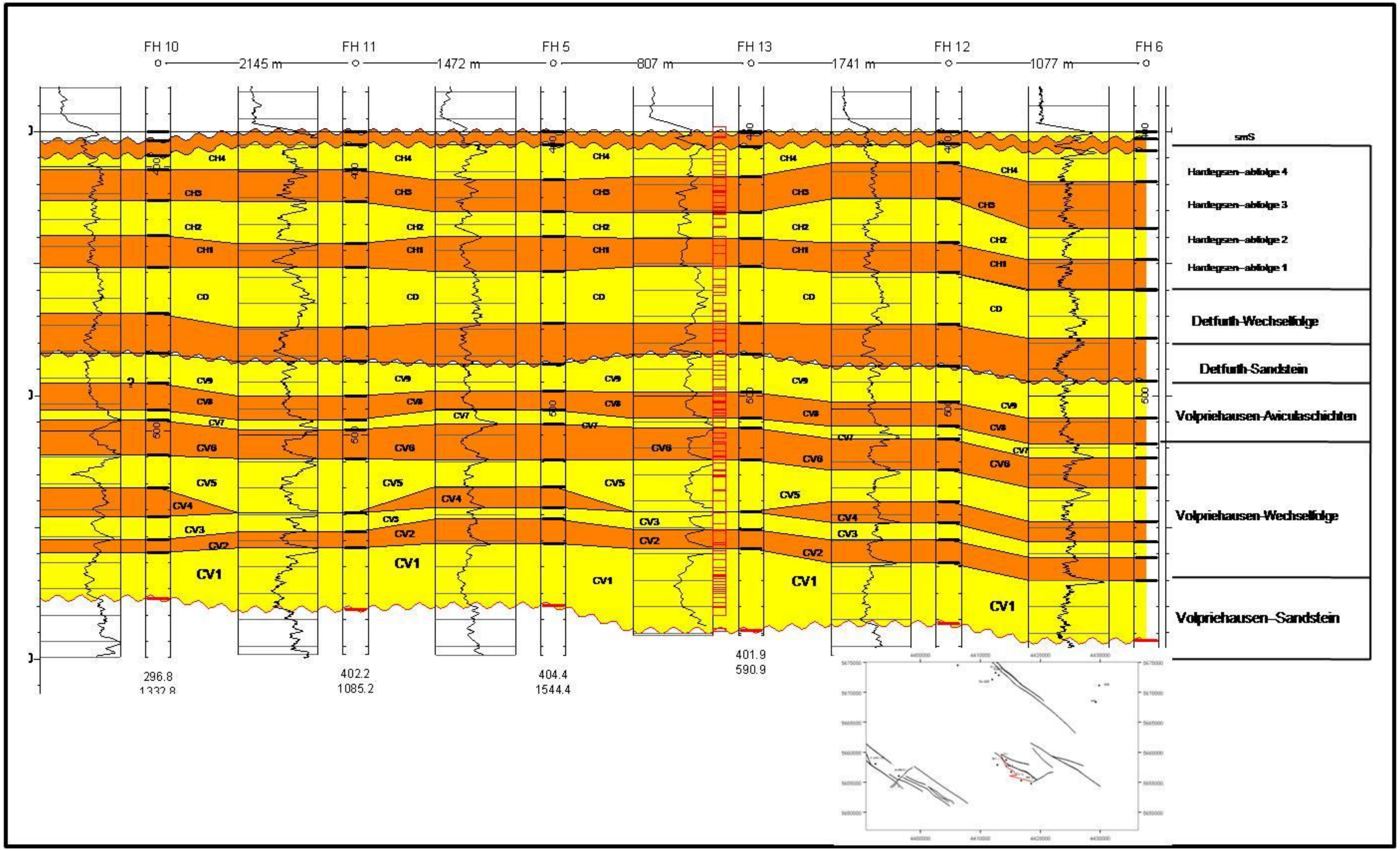
Enclosure 3 Stratigraphic cross-section in W-E direction located in the northern study area showing the complete Middle Buntsandstein



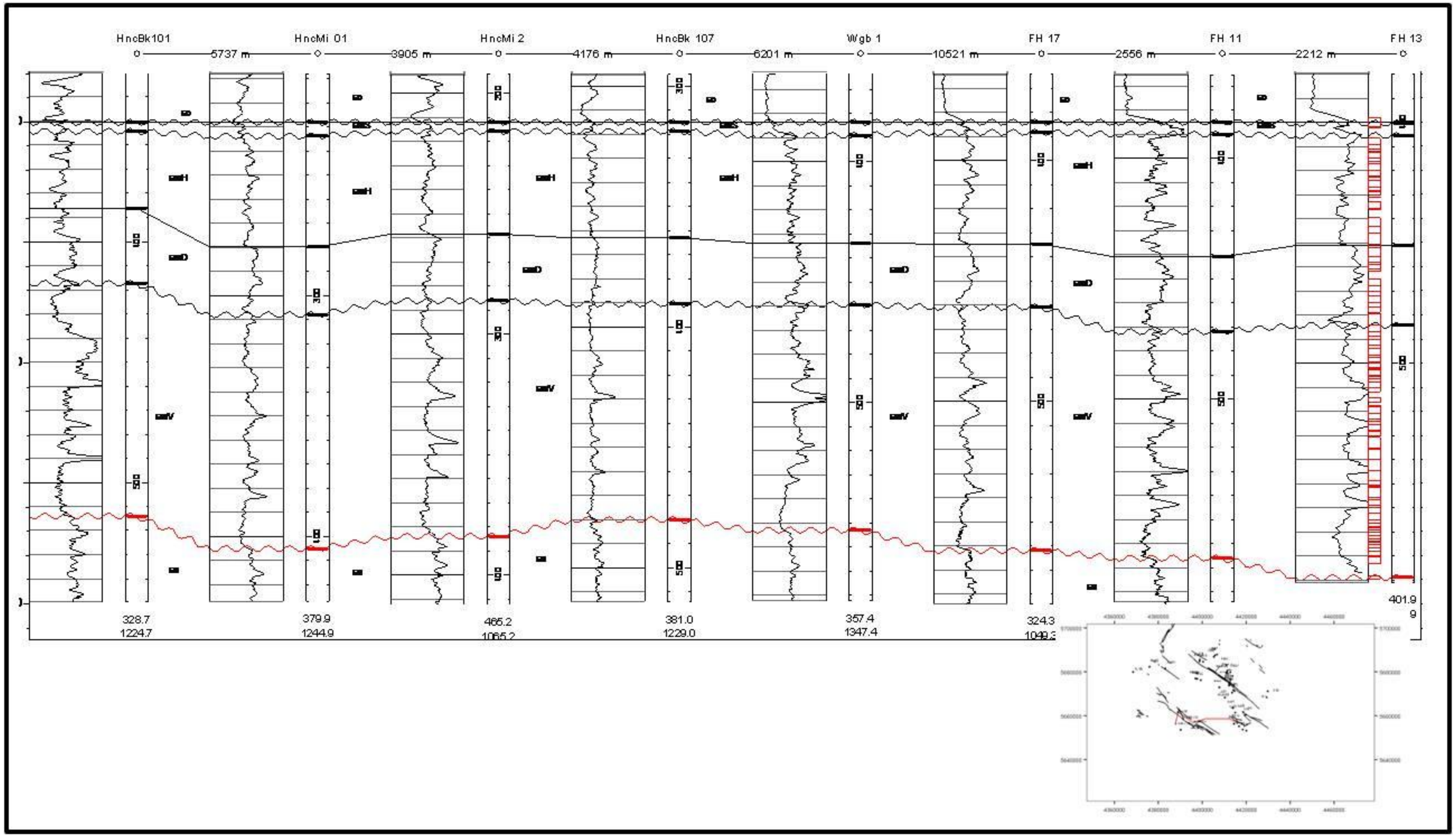
Enclosure 4 Stratigraphic cross-section in W-E direction located in the northern study area showing the complete Middle Buntsandstein



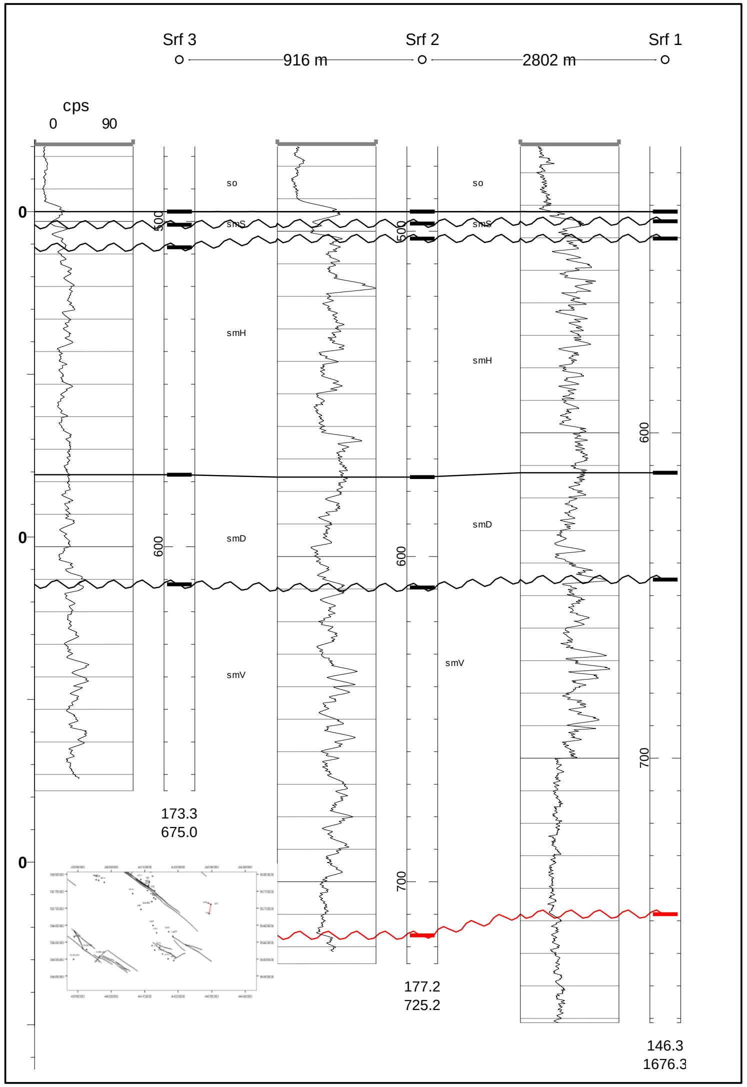
Enclosure 5 Stratigraphic cross-section in W-E direction located in the northern study area showing the complete Middle Buntsandstein



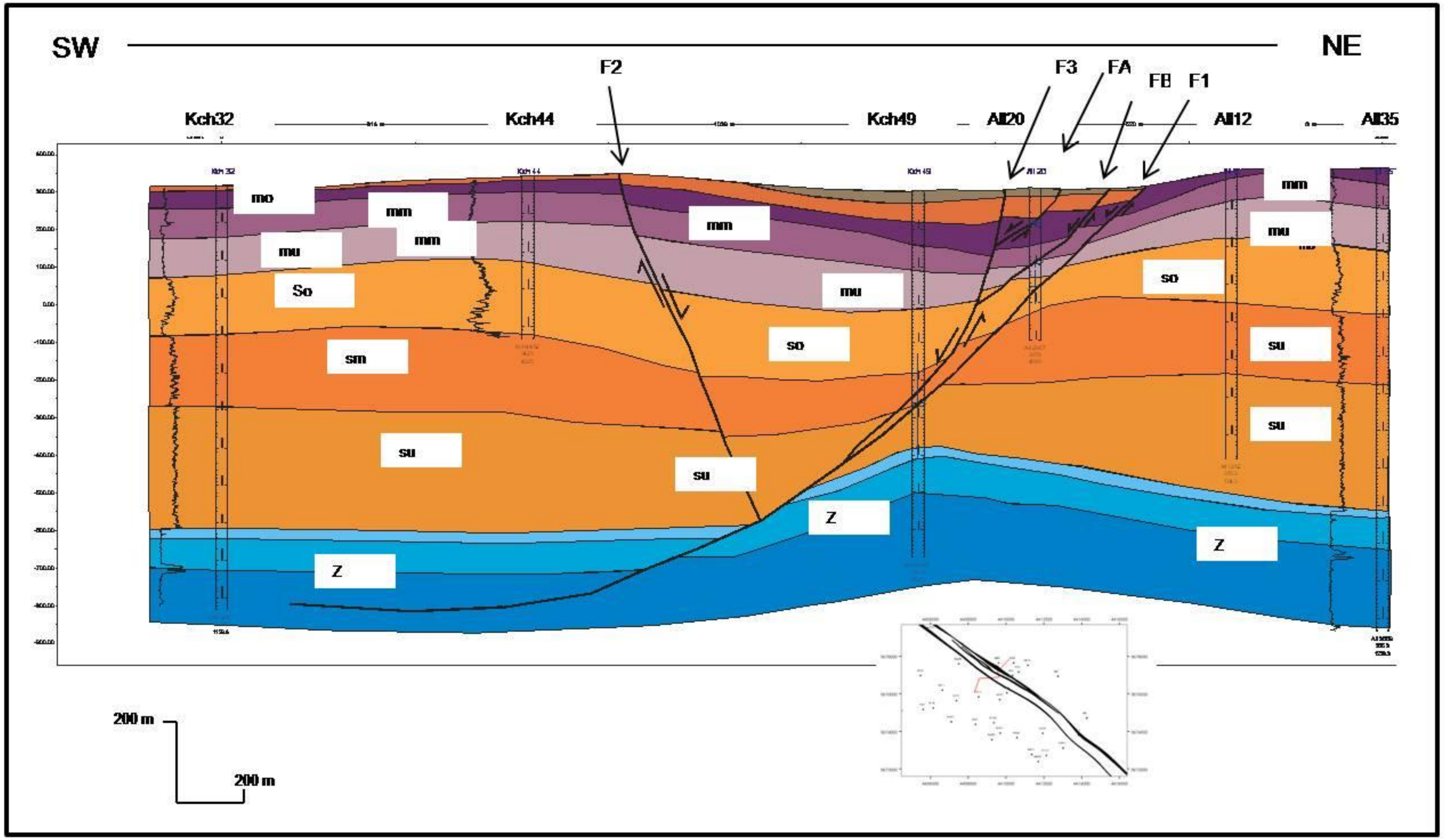
Enclosure 6 Stratigraphic cross-section in W-E direction located in the northern study area showing the complete Middle Buntsandstein



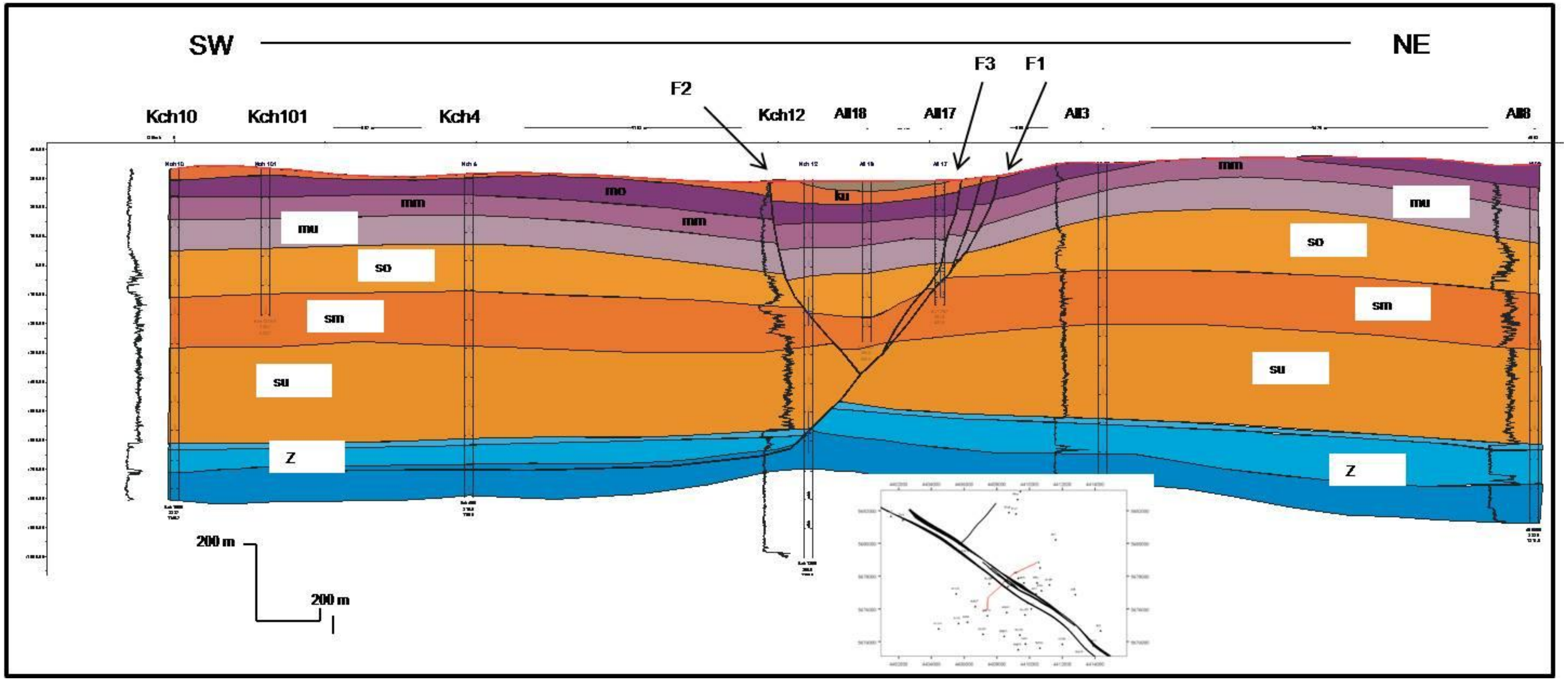
Enclosure 7 Stratigraphic cross-section in W-E direction located in the northern study area showing the complete Middle Buntsandstein



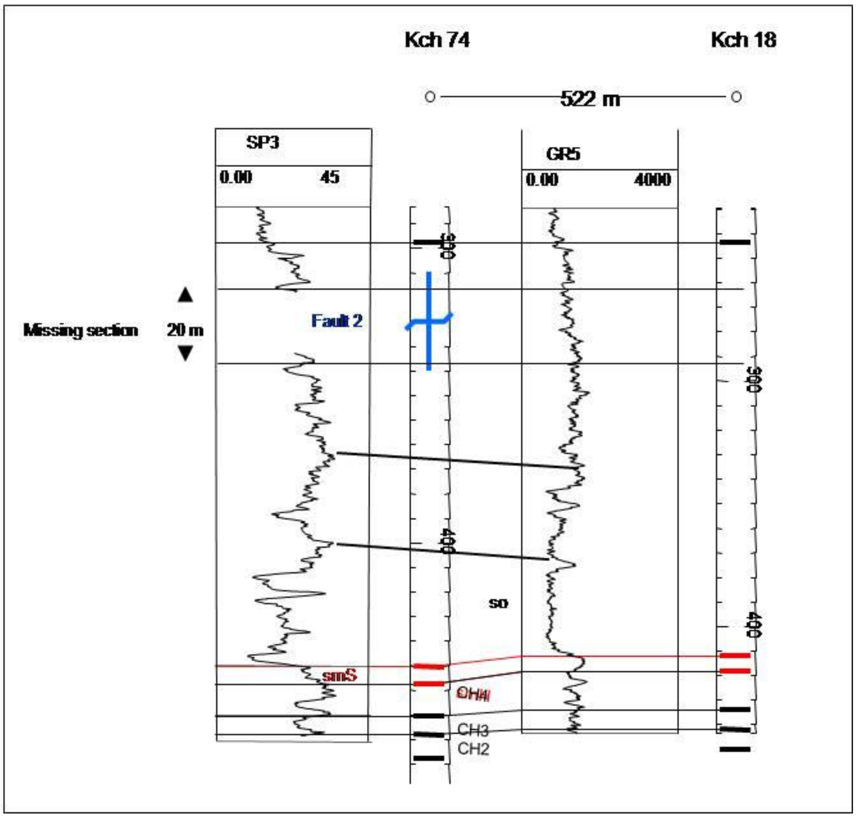
Enclosure 8 Stratigraphic cross-section in W-E direction located in the northern study area showing the complete Middle Buntsandstein



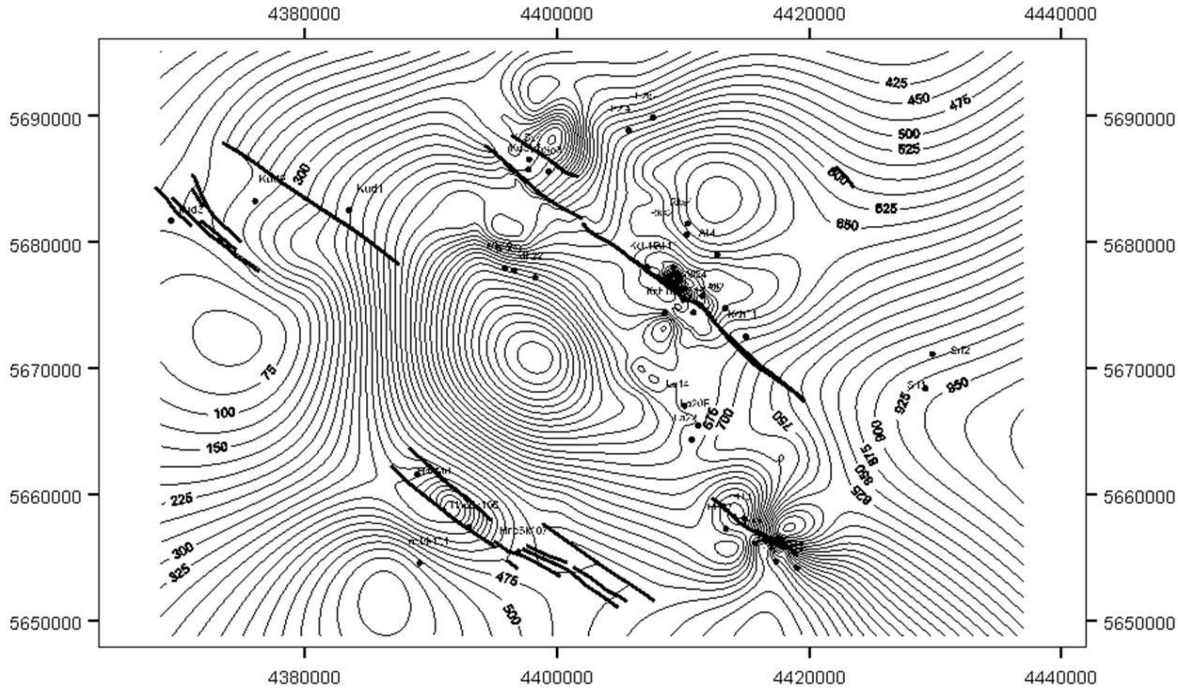
Enclosure 9 Structural cross-section in SE-NW direction illustrating the geometry of the Schlotheimer Graben



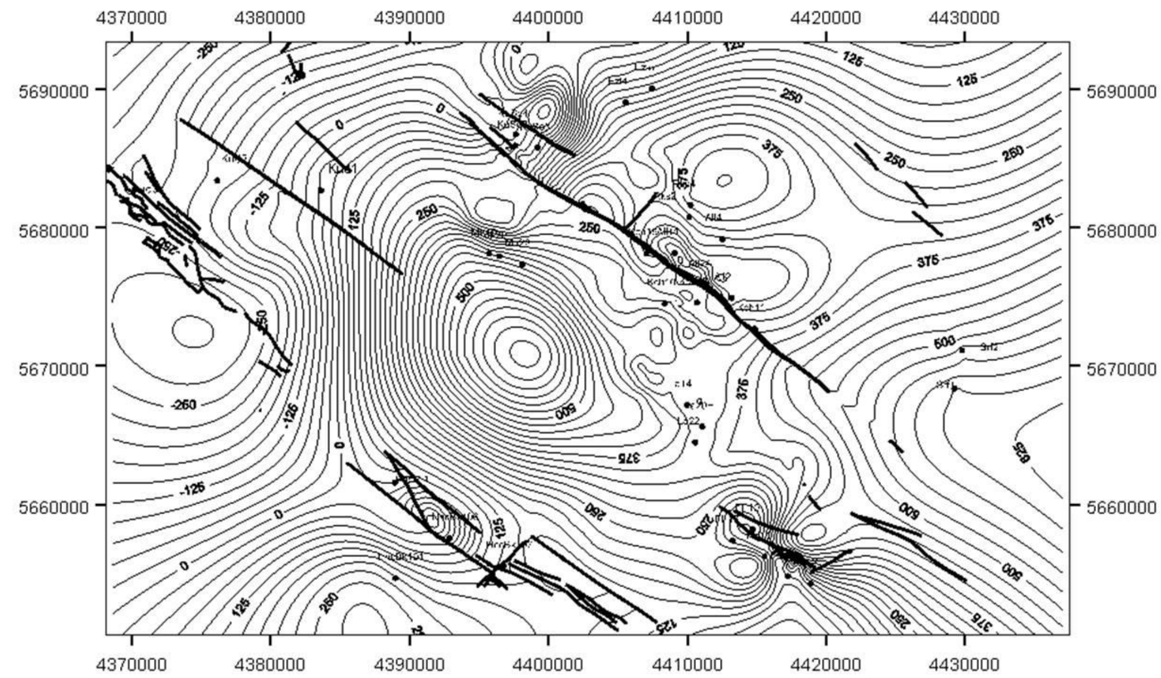
Enclosure 10 Structural cross-section in SE-NW direction, illustrating the geometry of the Schlotheimer Graben



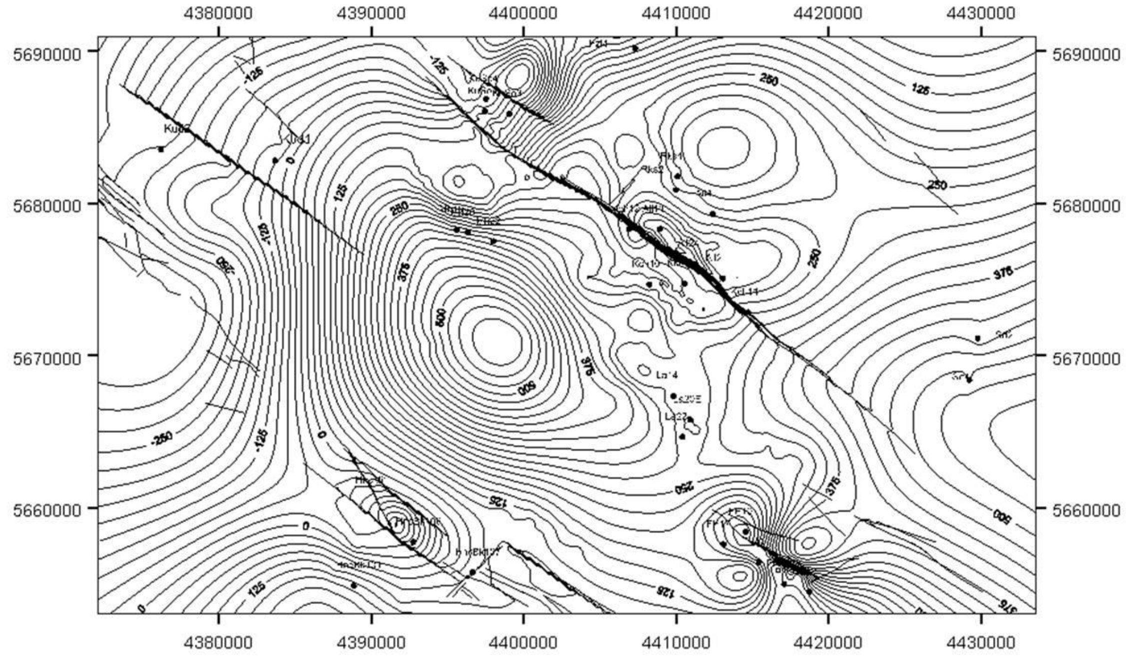
Enclosure 11 Comparison between a faulted well (f2) and a well with a complete Upper Buntsandstein sequence located in the Schlotheimer Graben area.



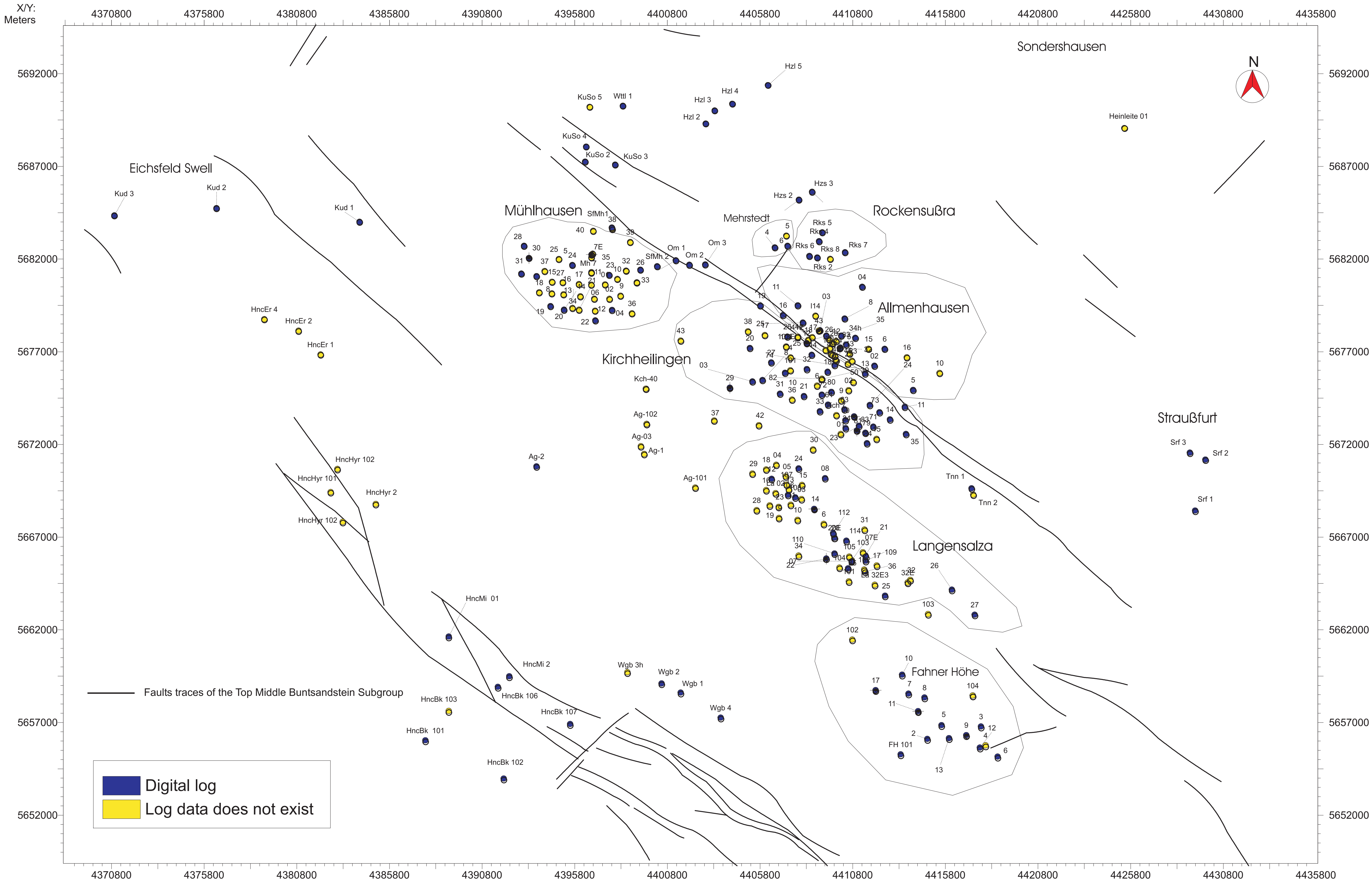
Enclosure 12 Structural map of Top Zechstein Formation in the northwestern Thuringian Syncline



Enclosure 13 Structural map of the Top Lower Buntsandstein Formation in the northwestern Thuringian Syncline



Enclosure 14 Structural map of the top Volpriehausen Formation in the northwestern Thuringian Syncline



Enclosure 1: Well location map

Seismic Micro-Technology, Inc.

Northwestern Thuringian Syncline

Scale = 1:200.000

0 2000 4000 6000 8000 10000 m