Bundesanstalt für
Geowissenschaften
und Rohstoffe

Final Disposal of Radioactive Wastes

in deep geological formations of Germany

Investigation and evaluation of

Argillaceous rock formations

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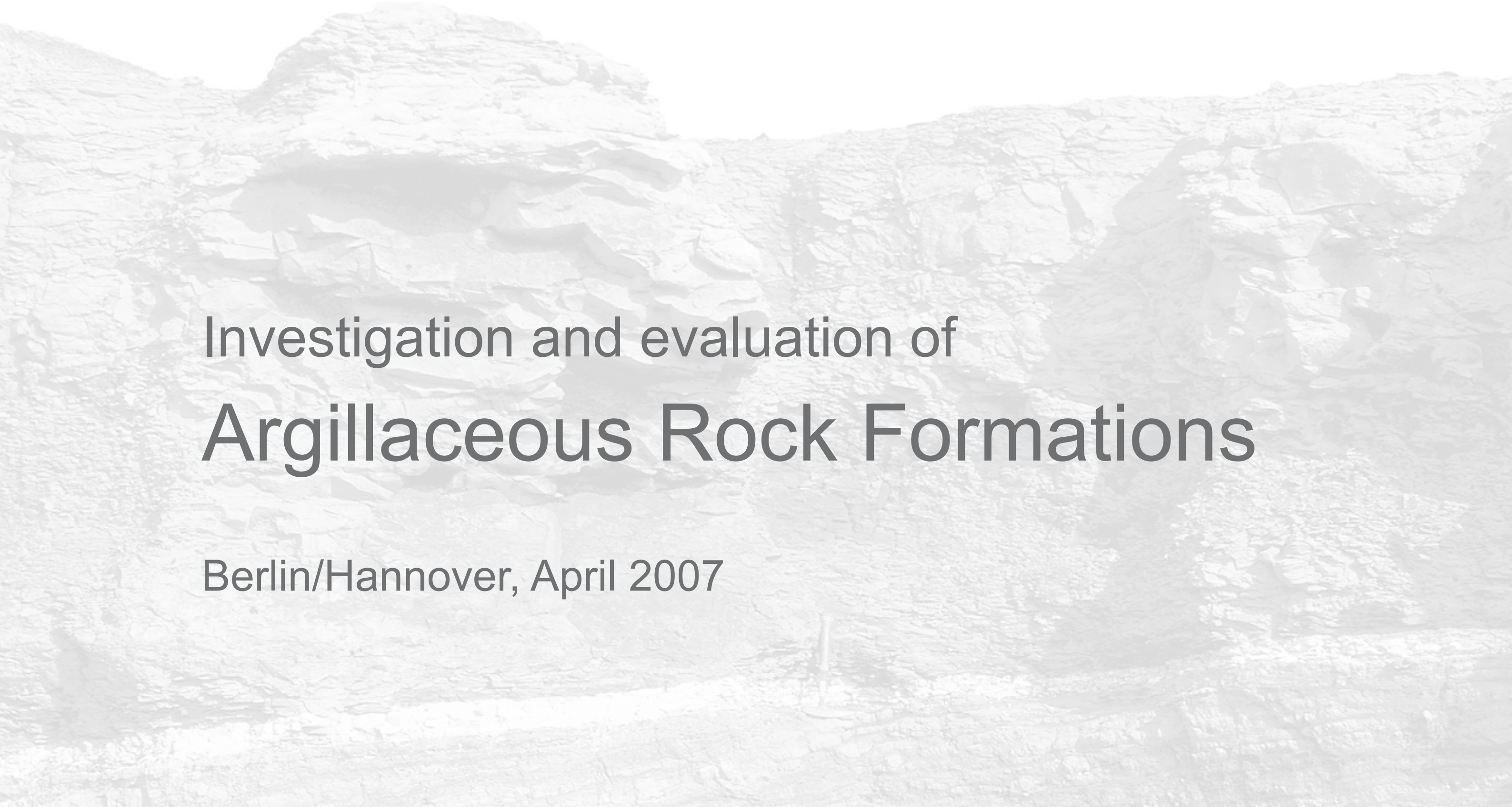

Investigation and evaluation of
Argillaceous Rock Formations

Berlin/Hannover, April 2007

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1 Foreword and study objectives

Around thirty per cent of the electricity consumed in Germany is generated by nuclear power stations. In addition to the safe operation of the power stations, another important prerequisite for the use of nuclear power is proper disposal of the high-level radioactive waste generated by power generation. The Federal German Government is accountable for the final disposal of high-level radioactive waste in accordance with the "Act on the Peaceful Utilization of Atomic Energy and the Protection against its Hazards" (Atomic Energy Act).

The German disposal concept envisages the concentration and isolation of high-level radioactive waste in deep underground geological formations. The safe long-term disposal of the waste in a repository and its isolation from the biosphere are guaranteed by a multi-barrier system consisting of a geological and a technical barrier. The geology of the host rock is a crucial factor because a favourable overall geological setting with a suitable host and barrier rock playing the main part in the total barrier system pursuant to the German repository concept, is a vital prerequisite for selecting a suitable nuclear repository location. Because of the different nuclear repository concepts investigated internationally, a range of different host rocks have also been studied to assess their suitability for the final disposal of high-level radioactive waste. Argillaceous rocks play an important role in different countries due to the respective national geology. This was why the Federal Institute for Geosciences and Natural Resources (BGR) was engaged in 2003 by the Federal Ministry of Economics and Technology (BMWi) to elaborate a study investigating and evaluating argillaceous rock formations for the final disposal of strong heat-generating, high-level radioactive waste in Germany.

BGR used its many years of experience to publish catalogues in 1994 on the salt and crystalline rock formations in Germany. These findings are still largely up to date and valid:

- Final disposal in deep geological formations in Germany of high-level radioactive waste generating significant amounts of heat – investigation and evaluation of regions in non-salt formations (BRÄUER et al. 1994);
- Final disposal in deep geological formations in Germany of high-level radioactive waste generating significant amounts of heat – investigation and evaluation of salt formations (KOCKEL und KRULL, 1994).

The investigation of argillaceous rocks which complements the previous studies was based on the host-rock-independent exclusion criteria and minimum requirements elaborated in 2002 by the Committee on a Site Selection Procedure for Repository Sites (AkEnd). This was supplemented by internationally recognised host-rock-dependent selection criteria for argillaceous rocks. Other criteria considered essential from a geo-scientific point of view for the regional selection of argillaceous rock formations in Germany were also incorporated in the evaluation.

The aim of this study is to identify partial areas in Germany with argillaceous rock formations considered potentially suitable as host rocks for a nuclear repository according to the current state-of-the-art. To achieve this, it was necessary to develop a method oriented to the available data to allow argillaceous rock formations to be evaluated across the whole of Germany. The elaboration incorporated all of the available data from maps, archives and boreholes. No field studies were carried out as part of this investigation.

AkEnd has already reported on the first results of the ongoing evaluation of argillaceous rocks potentially suitable for nuclear repositories for high-level radioactive waste (1999-2002). Interim results from the investigations carried out as part of this study were presented in 2003 at the 12. Jahrestagung der Gesellschaft für Geowissenschaften (GGW) ; and in 2005 at the workshop on „Gegenüberstellung von Endlagerkonzepten in Salz- und Tongestein (GEIST)" workshop; in four interim reports (HOTH et al. 2005); as well as in an overall report on the "Investigation and evaluation of regions with potentially suitable host rocks" (BGR 2006). The knowledge base on argillaceous rock formations in Germany has since been enlarged.

The authors of this study wish to express their thanks to the Geological Surveys in the German states, and the companies involved, for their support in preparing this report, and in particular for providing data and making data available for review.

2 Properties of argillaceous rock formations and their significance for a nuclear repository

Argillaceous rocks have favourable barrier properties primarily because of their generally very low permeability and the associated low hydraulic conductivity coefficient (see e.g. Katsube and Connell 1998; Bryant 2003). Other favourable properties are their typical plasticity, their chemical buffering properties, and their retention capacities for contaminants and radionuclides. These properties make them suitable for various engineering applications (landfill barriers and covers, isolation and preservation material) and therefore also make them appear suitable as barriers and host rocks for the final disposal of high-level radioactive waste if certain criteria are fulfilled (see Chapter 3.6.2). Argillaceous rocks therefore have the potential to fulfil the specifications laid down for host rocks, as well as acting as natural geological barriers. This is why unconsolidated clays (e.g. Boom Clay in Belgium) are currently being investigated in several countries dependent on the natural geological conditions, this is also the case for consolidated argillaceous rocks (e.g. Opalinus Clay in Switzerland, Callovian-Oxfordian argillaceous rocks in France) (NEA 2004).

Clay is a clastic sediment, and unlike sand (grain size: 2.000 mm to 0.063 mm) and silt (grain size: 0.063 mm to 0.002 mm) is defined by a very low medium grain size of less than 0.002 mm (Heling 1988). A different definition is used in the USA in particular where the grain size boundary between clays and silts is defined as 0.004 mm. Clays primarily consist of mixtures of different clay minerals. The properties of clay are determined by the ratio of these different clay minerals and the proportion of other minerals - the variation in these percentages accounts for the enormous range of different clay types. Figure 2.1 shows as an example two possible classification schemes for clastic sedimentary rocks. Whilst Figure 2.1(a) is a purely material classification scheme along the lines of Pettijohn et al. (1973), Figure 2.1(b) from Dott (1964) takes into consideration the material composition as well as the grain size. The differences between these diagrams demonstrate the difficulty in classifying fine grained solid rocks with high proportions of phyllosilicates. This explains the large number of different terms for the groups of siltstones and claystones in the international literature (e.g. mudstone, shale, claystone, siltstone, pelite, pelitic rocks, argillaceous rocks) which are sometimes used as synonyms with no clear definitions.

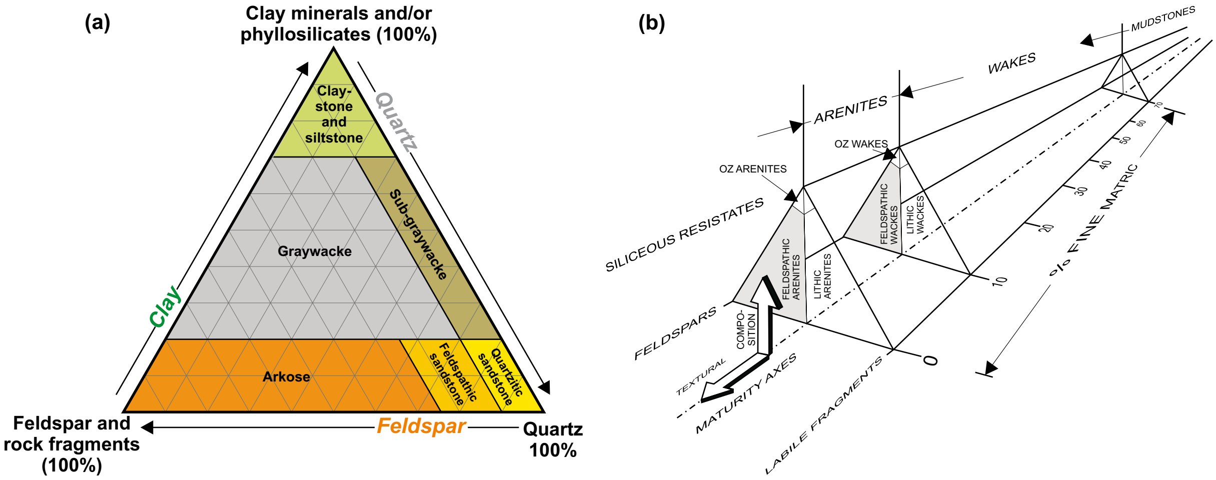


Figure 2.1: Classification schemes for clastic rocks (a) after Pettijohn et al. (1973) and (b) after Dott (1964)

The favourable barrier properties of clays and claystones are primarily attributable to the fine to extremely fine grained texture of these rocks and the high proportion of phyllosilicates and clay minerals. The latter can be easily split orthogonal to the c-axis of the crystals. This is due to their lamella shape and the formation of fine-grained mixtures when subjected to mechanical stress. The properties of clays and claystones, and thus the enormous diversity, not only reflect the grain sizes, but also the proportions of the various clay minerals (e.g. kaolin, illite, montmorillonite/smectite, chlorite, vermiculite), as well as the proportion of other minerals, organic carbon, water content, and the degree of consolidation and diagenesis (see e.g. Aplin et al. 1999).

Another classification problem is where to set the boundary between unconsolidated and consolidated rocks, and thus the assessment of the degree of diagenesis or consolidation. When clay formations are buried, the increasing temperatures and pressures give rise to compaction and mineralogical reactions which significantly change the mineralogical, chemical and petrophysical properties. For instance, the minerals consisting of interlaminated halite and smectite, or pure montmorillonite, which are stable at relatively low temperatures, are partially or completely converted to illite by the effect of increasing temperatures and the reduction in the proportion of swelling layers. These alterations give rise to changes in the structure (degree of orientation, grain sizes) which determine the petrophysical properties. Figure 2.2 shows the relationship between porosity and burial depth for various clays and claystones. At shallow levels, simple mechanical compaction (see diagram showing change in rock particles) is defined by very marked porosity/depth gradients.

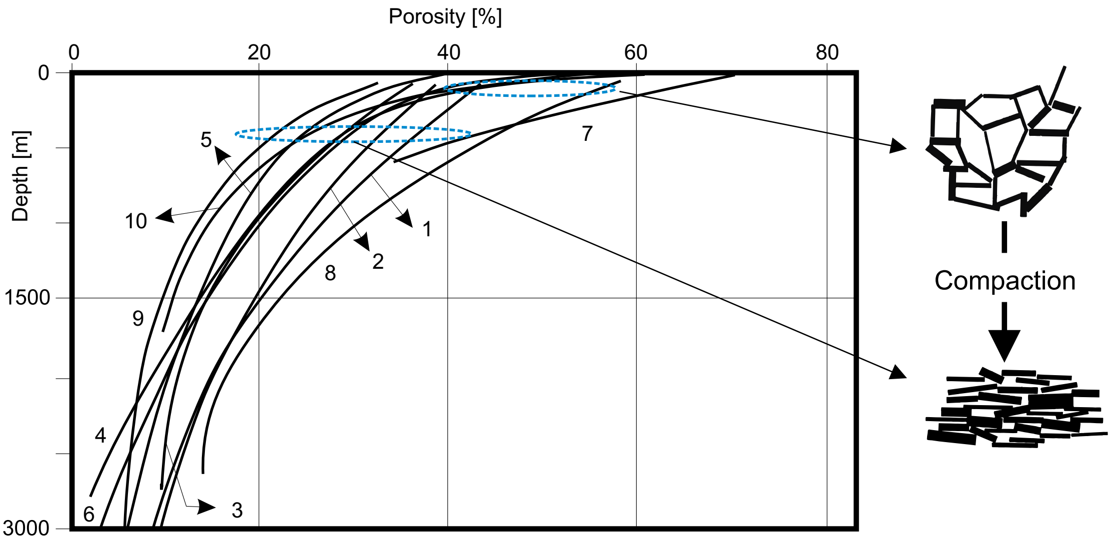


Figure 2.2: Porosities dependent on burial depth of clays and argillaceous rocks. Plots from: 1, 2, 3 Osipov et al. (2004); Engelhardt (1973); 5, 6 Addis & Jones (1985); 7 Hamilton (1976); 8 Magara (1968) (published in Füchtbauer 1988); 9 Proshlykov (1960) (published in Füchtbauer 1988); 10 Meade (1966) (published in Füchtbauer 1988)

In addition to the pressure and temperature parameters primarily reflecting the degree of burial, the diagenetic alteration of clays is also affected by chemical and other physical parameters, as well as time. As clearly shown in Figure 2.2, it is therefore not possible to precisely differentiate between clay, claystone and argillaceous rocks purely on the basis of depth. Although it can be assumed that Mesozoic argillaceous deposits will probably be present in the form of consolidated claystones at depths greater than 300 m, this does not apply to Tertiary clays. Within a transition zone at least, these rocks tend to be clays and at best only very slightly consolidated claystones.

The sedimentary facies and the degree of diagenesis are therefore extremely important factors in assessing the suitability of clays and claystones for a range of applications. Aplin et al. (1999) emphasise in their summary description of the transport and other physical properties of mudstones (comprising according to definition claystones, clayey marls and siltstones), that despite their very widespread occurrence, these rocks have so far not been as thoroughly investigated as other rock types. The main deficits are considered to be as follows:

- Accessibility of petrophysical data for geologically and geochemically well defined rocks;
- One and two-phase flow in claystones;

- Correlation between chemical and mechanical properties;
- Spatial analysis of claystone and siltstone sequences as well as the geophysical exploration methods.

Up until 2000, argillaceous rocks in Germany had not been looked at in detail to assess their suitability as host rocks for the final disposal of high-level radioactive waste. German experience in this field was primarily gained as part of the site investigation of the Konrad Mine (hydraulic investigations), and participation in international field and underground experiments.

Rock formations are defined as argillaceous rock formations in the following study if they primarily consist of argillaceous rocks but also contain other rocks, e.g. sandstones or carbonates. Argillaceous rock formations are therefore not exclusively defined by their argillaceous rocks.

3 Methodology

3.1 Database

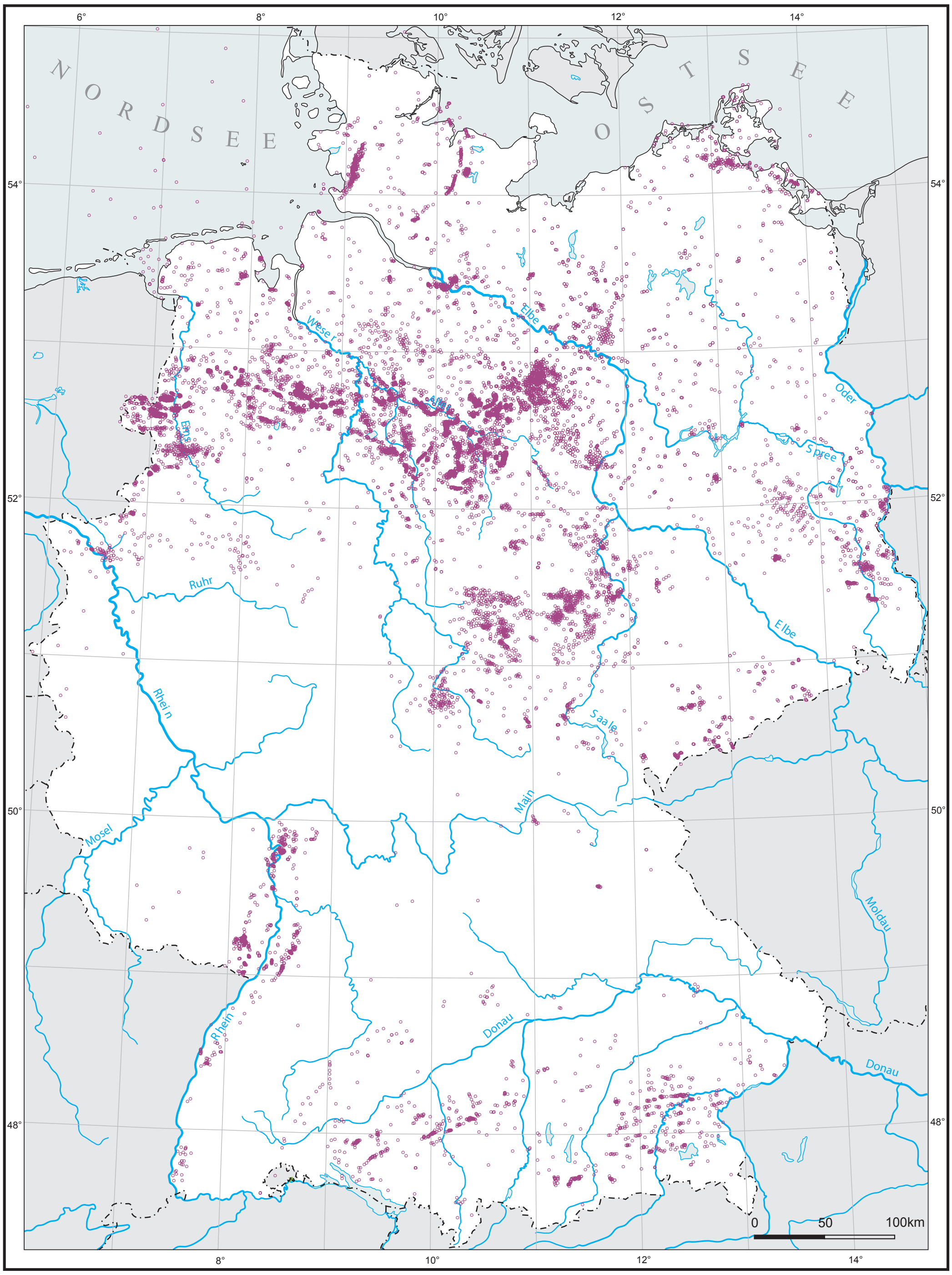
The data sets listed below form the basis for regional characterisation and delimitation of argillaceous rock formations worthy of further investigation in Germany. They also form the basis for the development of the methodology and the means of testing potentially more detailed investigation methods. These data sets were supplemented by comprehensive literature researches and reference reviews so that each of the regions could be investigated using databases which were as comparable as possible.

The argillaceous rock formations located at depth in Germany were investigated on the basis of boreholes drilled for the exploration or production of oil, gas, salt, ores or other natural resources, and to a lesser extent boreholes drilled for research and mapping purposes, as well as the evaluations of these boreholes (see Figure 3.1). The borehole data is stored in existing databases by the Federal Institute for Geosciences and Natural Resources (BGR), the State Authority of Mining, Energy and Geology of Niedersachsen (LBEG), as well as other state Geological Surveys. Private sector legislation does mean, however, that access to this data is restricted. The databases used include:

- The LBEG oil and gas exploration database (see e.g. Brauner & Koschyk 2000, Brauner 2003);
- The mapping borehole data and findings database;
- The BGR borehole database held by the Department “Utilization of Deep Geological Formations“.

The oil and gas data contain the well information of oil and gas wells drilled in Germany by private companies. This data is managed for LBEG by the Hydrocarbons Geology Department which administers a database system (see e.g. Brauner & Koschyk 2000; Brauner 2003). The well locations are shown in Figure 3.1.

The borehole database of the “Use of deep underground formations” Department is also held in a relational database system and contains the basic well data in addition to stratigraphic and lithological data. Information is also available for some of the wells on the geochemistry and other special data (well logs, reservoir tests, maturity data from the BGR database) covering the interesting sections penetrated by the wells.



○ Deep boreholes

Figure 3.1: Well locations (approx. 25,000) penetrating the depth zone relevant for nuclear repository sites in Germany (> 300 m)

Agreements were reached with the companies involved on the use of the geological and geophysical data for the regional evaluation of argillaceous rock formations. These agreements all stipulate that the data can be used for the regional evaluation but that no detailed data should be forwarded to third parties. This final report therefore contains no detailed information with respect to the data covered by these agreements.

Any gaps identified in the available digital datasets were closed by acquiring the relevant data during the implementation of this project. This primarily involved detailed information on the argillaceous rock formations focused on by this study as well as other deep boreholes drilled for different exploration purposes (e.g. geothermal, ore exploration). This involves the use of archives at BGR in Hannover and Berlin, LBEG, and other state Geological Surveys. The well data were supplemented by important seismic lines which provide an important basis for identifying and characterising faults and their continuation at depth. In addition to the direct well information, use was also made of unpublished reports issued by the state Geological Surveys, a range of well reports (e.g. KÄMPFE 1994; HOTH et al. 1993), already published information, and diverse already prepared compilation reports. The latter particularly include the Geotectonic Atlas of Northwest Germany available in analogue form (BALDSCHUHN et al. 1996) and digital form (KOCKEL 1999), as well as the Geotectonic Atlas of North Germany currently still being prepared by the "Utilization of Deep Geological Formations" Division in Berlin, and particularly the north-east German Chapter, as well as regional geological and geophysical atlases (e.g. JARITZ 1969, ZGI 1970, 1978; GEOPHYSIK LEIPZIG 1989).

We would also like to acknowledge here the work of the „Arbeitsgruppe Deponien" of the state Geological Surveys (AG Deponie 1997) which made compilation data available on the distribution of potential argillaceous barrier rocks in shallow zones as part of its landfill site analysis. By incorporating the experience gained by all of the states in Germany, this study provides a good insight into the presence of argillaceous rock formations in the various regions.

To support implementation of the AkEnd exclusion criteria, additional publications on the following subjects were also taken into consideration and used in digital form for the geo-evaluation steps:

- Large-scale vertical movements
- Seismic and volcanic activity (including the earthquake zone map and underground geological classification for Baden-Württemberg)

- Temperature field at 1000 m depth
- Digital topographic models.

Digital processing, conversion and analysis of the data were implemented using ArcGIS software (Environmental Systems Research Institute, ESRI, GeODin (FUGRO Consult GmbH), ISPOO3 (CCI of ATOS ORIGIN GmbH, former SATTLEGGER GmbH, GeoFrame, Oilfield Services der Schlumberger GmbH), CORRELATOR (OLEA and SAMPSON 2002) and PetroMod 1d (Integrated Exploration Systems, IES).

3.2 Barrier properties of argillaceous rocks

3.2.1 Determining the clay percentage on the basis of petrographic properties

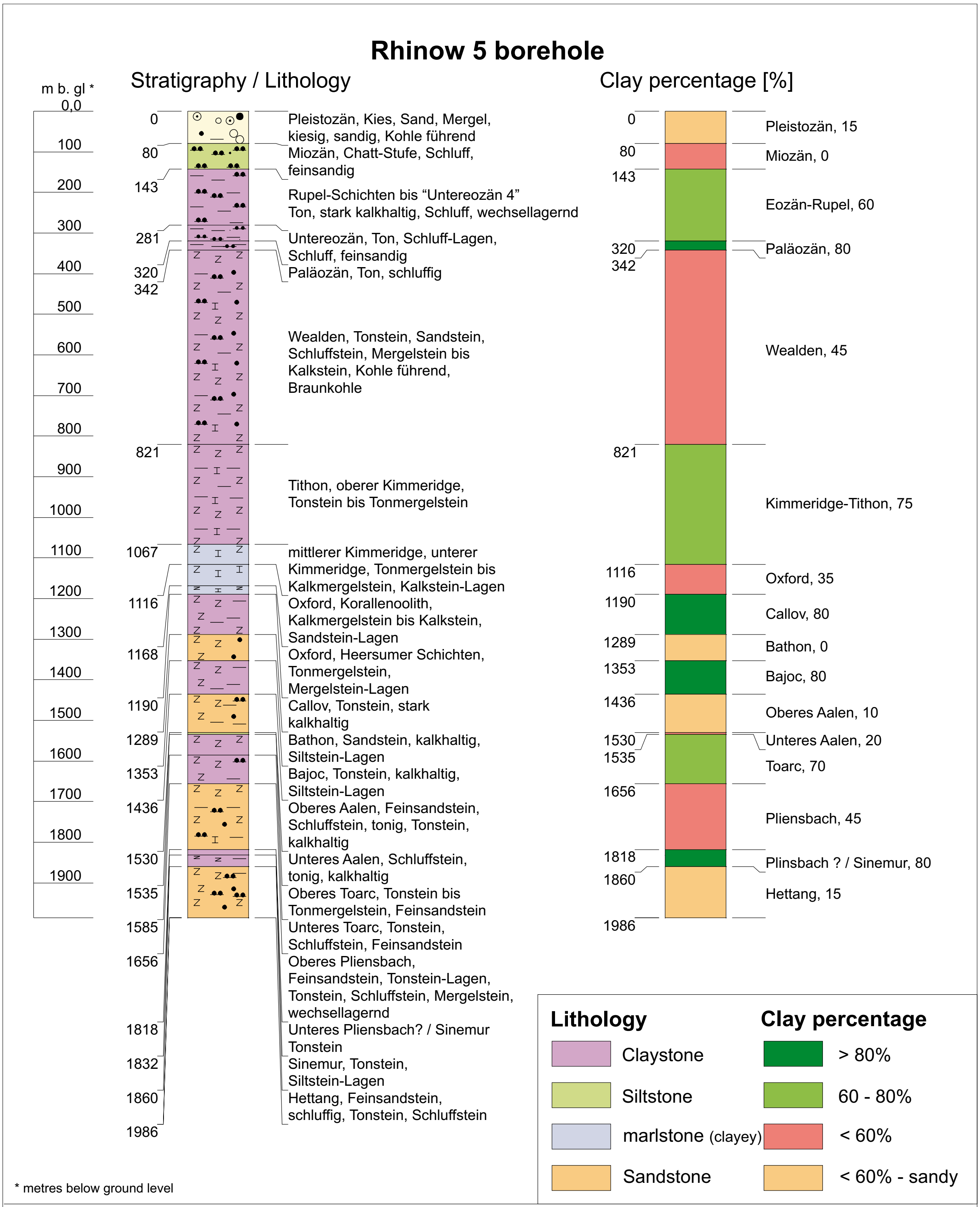
Because of their hydraulic barrier properties, clays and argillaceous rocks control the transport of fluids in both the shallow and deep parts of sedimentary basins. They usually act as aquiclude and therefore form the boundaries of deep (often saline) ground-water storeys, as well as fresh water aquifers important for drinking water abstraction and the biosphere. In North Germany, the Oligocene clays in particular form barriers preventing the upward movement of brine from deep underground formations. Claystones are very important in hydrocarbon deposits because they act as the seals for oil and gas deposits. They also affect the formation of over pressurised zones which developed during the burial of sedimentary sequences.

Because argillaceous rock formations are often heterogeneous, and can be differentiated according to their mineralogical composition and the degree of claystone diagenesis (see Chapter 2), there are also considerable differences in the effective barrier properties of argillaceous rock formations. Substances dissolved in pore water can be transported by advection or diffusion in argillaceous rocks. Advective transport is only possible in interlinked pore or fracture networks. The hydraulic conductivity coefficient (k_f) defines the rock and fluid specific hydraulic transmissivity or permeability of the rock associated with the pore and fracture structure.

Interlinked fracture structures in argillaceous rocks are primarily caused by special geotectonic processes. For instance, they can occur in the vicinity of major normal fault systems, pressure release fractures as a result of strong tectonic uplift, or weathering processes, not to mention exposure to strong thermal effects. Fracture structures of this kind are almost exclusively restricted to strongly diagenetically affected and consolidated argillaceous rocks. The dominant transport process in rocks with hydraulic conductivity coefficients of $k_f < 10^{-12}$ m/s is diffusion. This is described by the diffusion coefficient. It can be measured by testing rock samples in the laboratory, or determined on the basis of natural tracer logs. Data of this kind only exist for very intensely investigated locations (see e.g. Nagra 2002).

As discussed in Chapter 3.1, the regional evaluation conducted as part of this study is not only based on single well and laboratory investigations, but also largely on older archive data and compilations. Special analysis of the permeability of argillaceous rock formations or argillaceous rocks is rare because most of the wells were drilled for the exploration or production of oil and/or gas. An indicator was therefore required which could be derived on the one hand from simple well data, and further verified on the basis of more detailed data, and which could be used on the other hand to compare argillaceous rock formations and estimate the hydraulic conductivity coefficient (k_f).

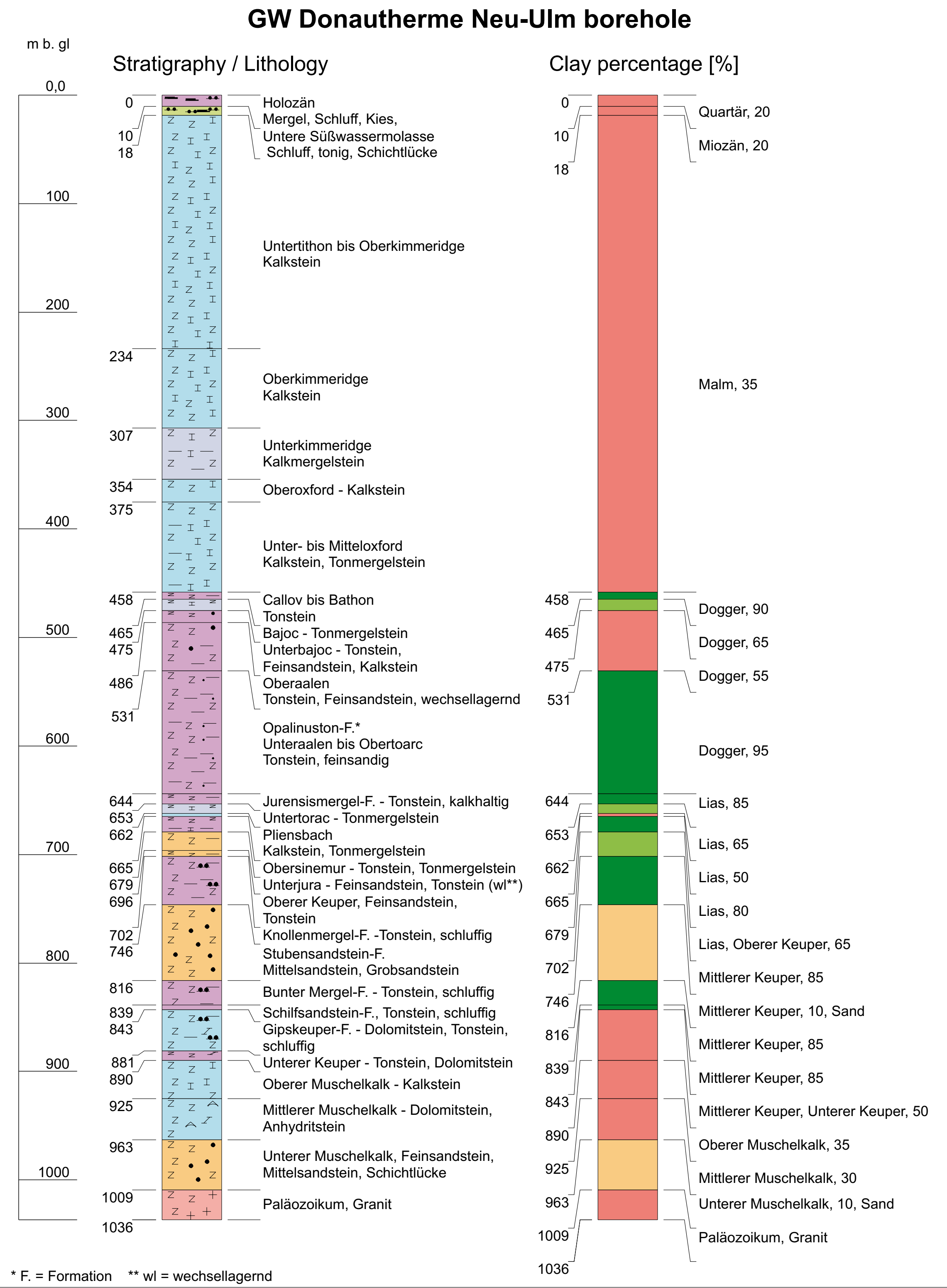
Various studies highlight the general correlation between the proportion of clay or clay minerals in a rock and its permeability (see e.g. Reuter 1995; Bryant 2003; Osipov et al. 2004). This means that a rough estimate of the proportions of clay can be made on the basis of the petrographic descriptions of the strata records (see Figures 3.2 and 3.3). These estimates can be further verified by interpreting the bohrehole measurements (cf. Chapter 3.3.2). To standardise the estimates of the clay content from the strata records, clay percentages were defined for the various lithotypes on the basis of the average composition. The definitions in Table 3.1 were made on the basis of sedimentary petrological aspects (cf. Füchtbauer 1988).



Rhinow 5 borehole: lithology and clay percentage (Quaternary to Jurassic)

Height at surface location: 41 m	Easting: 4526670
Depth scale: 1:15000	Northing: 5842992

Figure 3.2: Estimate of the clay/claystone percentage in the Rhinow 5 well (from Hoth et al. 2005)



Geothermal well Donautherme - Neu-Ulm: lithology and clay percentage

Height at surface location: 70 m	easting: 4350930
Depth scale: 1:5500	northing: 5362735

Figure 3.3: Estimate of clay/claystone percentage in the Donautherme Neu-Ulm well (lithology after FRANZ et al. 2001)

Table 3.1: Key for estimating the clay percentage in potentially interesting argillaceous rocks (claystones to argillaceous marlstones)

Lithology	Composition	Clay percentage [%]
Clay/claystone	clay	100
Clay/claystone with minor interbeds[1]		80 (-90)
Clay/claystone, silty or sandy or calcareous[2]	clay, silt or sand or carbonate	85 (-95)
Marley claystone	clay, carbonate	80
Evaporitic clay	evaporite	70
Argillaceous marlstone	clay, carbonate	65

[1] e.g. sandstone beds, anhydrite and dolomite beds, lignite
[2] present in low or minor quantities

A key was also developed (Table 3.2) in case the strata record did not report the different lithological proportions. This ensures that the clay percentages of beds with different lithologies are estimated uniformly, and takes into consideration the succession and the number of lithologies given for each bed. It is assumed here that the most dominant lithology is listed first and that the subsequent lithologies are present in the bed in lower proportions.

If the stratigraphic/lithological logs reveal the presence of interbedded layers of highly permeable rock, e.g. sandstone or limestone, these were dealt with separately. This argillaceous rock formation evaluation procedure takes into consideration the presence of highly permeable interbeds, particularly sandstones. The estimates of the clay percentages in Figure 3.2 and 3.3 based on petrographic properties are shown from typical examples of a North German and a South German well.

3.2.2 Relationship between clay percentage and field hydraulic conductivity

Although most studies have highlighted the general relationship between clay percentage and permeability, no systematic analysis has been carried out on the relationship between the clay percentage of argillaceous rocks and their permeability.

Table 3.2: Key to determining the clay percentage in interbedded sequences or when several lithologies are listed without detailing their specific proportions

Beds with a range of lithologies and interbeds	Clay percentage [%]
Clay, sand, silt, limestone	40
Silt, **clay**, sand, limestone	25
Sand, silt, **clay**, limestone	20
Sand, silt, limestone, **clay**	15
Clay, sand, silt, limestone, anhydrite	30
Silt, **clay**, sand, limestone, anhydrite	20
Sand, silt, **clay**, limestone, anhydrite	20
Sand, silt, limestone, **clay**, anhydrite	15
Sand, silt, limestone, anhydrite, **clay**	15
Clay, silt (interbedded)	60
Silt, **clay** (interbedded)	40
Clay, silt, sand (interbedded)	40 (-50)
Silt, **clay**, sand (interbedded)	30
Sand, silt, **clay** (interbedded)	(20-) 30

This is due on the one hand to the difficulty in measuring the very low permeabilities of claystones. The second main reason is the wide range of fine clastic sedimentary rocks which are partially classified as “claystones”: (Yang & Aplin 1998; Dewhurst 1999). Tavenas et al. (1993) showed that there is a complex relationship between the two parameters which depends on several, in some cases, poorly determinable parameters. According to their investigations, the k_f of clays ranges from 1000 pm/s to 2000 pm/s (1 pm/s = $1x10^{-12}$ m/s) when the clay percentage (fraction < 2µm) reduces from 80 % to 60 %. Clays with 60 % to 80 % or > 80 % clay percentages analysed by Bryant (2003) had hardly any differences in permeabilities, which were all extremely low with k_f below 20 pm/s (at porosities of around 40 %). Dewhurst et al. (1999), however, showed that the permeabilities in argillaceous rocks with 65 % or 30 % clay percentages varied by more than one order of magnitude (0.1 pm/s and 50 pm/s). Models calculated by Yang and Aplin (1998) show differences in permeabilities in claystones with clay percentages of 35 % to 40 %, 50 % to 55 % and 75 % and more, varying by more than two orders of magnitude. Low permeabilities were measured in claystones with high clay percentages in a number of sedimentary basins in North America (Katsube et al. 1991; Katsube and Connell 1998; Katsube et al. 1998).

With respect to estimating the suitability of argillaceous rocks for the final disposal of high-level radioactive waste, the study assumes that formations with clay percentages exceeding 80 % have a very high probability of fulfilling the minimum requirements for field hydraulic conductivity ($k_f < 100$ pm/s) (cf. Chapter 3.6.2). These formations consist of clays, claystones or marly claystones and only have minor coarser clastic or calcareous con-stituents. Appel & Habler (2001, 2002) compiled the available test data and showed that at depths of 300 to 1500 m, these rock types had average hydraulic conductivity coefficients of 0.95 pm/s ranging from 0.0055 pm/s to 2.05 pm/s.

Formations with clay percentages of 60 % to 80 %, largely consisting of argillaceous marlstones, marly claystones and/or claystones with coarser clastic or calcareous constituents, can also partially fulfil the minimum criterion for field hydraulic conductivity in some cases. In addition to the aforementioned papers, this is also shown by the studies conducted by Appel & Habler (2001, 2002). They show that marlstones with a clay percentage of 50 % have average hydraulic conductivity coefficients of 30.7 pm/s at depths between 300 m to 1500 m. It is important to note here though that marlstones have very variable carbonate and clay contents and that the marlstones analysed by Appel & Habler (2001, 2002) were probably thin homogeneous marlstones. It should also be noted that formations with clay percentages between 60 % and 80 % can contain considerable proportions of coarser clastic and calcareous constituents which may also be interbedded with the claystones. The permeabilities of these formations can therefore vary enormously and also have high field hydraulic conductivities. It is therefore much more difficult to classify such claystones in terms of the specified low field hydraulic conductivities.

Formations with estimated clay percentages of less than 60 % are not considered worthy of further investigation because of their inhomogeneous and coarser clastic compositions and the associated high probability of having inadequate field hydraulic conductivity coefficients ($k_f > 100$ pm/s).

The relationships derived here between clay percentage and field hydraulic conductivity were verified on the basis of data from 84 in situ hydraulic tests conducted in primarily argillaceous and clay-bearing rock formations. The permeability tests were carried out in eleven wells in North Germany and Switzerland.

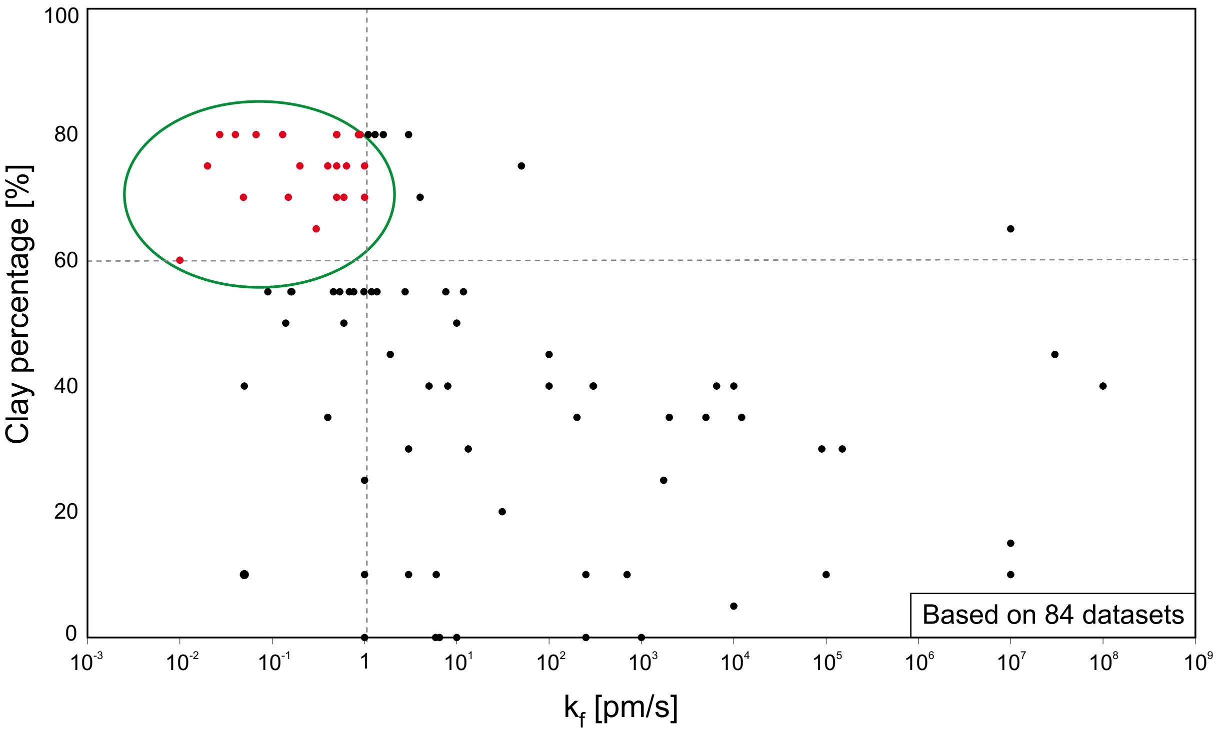


Figure 3.4: Field hydraulic conductivity of rock formations (depths 100 m to 1500 m) versus estimated clay percentage. The red dots highlight that the field hydraulic conductivity for clay percentages exceeding 60 % is mostly ≤ 1 pm/s (pm/s ^= 1x 10^{-12} m/s).

The test zones were between 3 m and 128 m long at depths of 100 m to 1394 m (mostly 400 m to 1000 m). Almost all of the zones were in Mesozoic formations. Five tests were carried out in Tertiary or Rotliegendes formations.

The clay percentages of the tested formations were estimated using the keys in Table 3.1 and Table 3.2. The analysis revealed that formations with a clay percentage ≥ 80 % had average permeabilities of 0.85 pm/s (3 pm/s to 0.027 pm/s) (Table 3.3 and Figure 3.4). Fifteen formations with a clay percentage of 60 % to 80 % had an average field hydraulic conductivity of 4 pm/s /(50 pm/s to 0.01 pm/s).

Verification using the in situ hydraulically tested argillaceous rock formations largely confirms that clay percentages ≥ 80 % correlate with a field hydraulic conductivity of k_f ≤1 pm/s; and that clay percentages of 60 % to 80 % usually correlate with field hydraulic conductivities of k_f ≤100 pm/s. However, these relationships only apply if the sequences do not contain any sandstone or carbonate beds with thicknesses exceeding a few metres and defined by high hydraulic transmissivities.

Table 3.3: Hydraulic tests in argillaceous rock formations in wells in North Germany and Switzerland. The lithology is coded using the geological symbol key (PREUSS et al. 1991; DOMINIK et al. 2003). The lithologies are described in NLFB (1986): Dolgen; Matter (1988): Riniken; NAGRA (1992); MOE et al. (1990); MATTER et al. (1988): Schafisheim; NAGRA (2001): Benken; GERARDI (1986): Konrad 101/1984

Well name	Depth top [m]	Depth base [m]	kf [pm/s][1]	Lithology	Clay [%]	Gamma Ray Log [gAPI][2]
Clay percentage > 80 % (estimated from lithological well description)						
Konrad 101/1984	428	449	3,000	^t,u4,s,^s(lag)	>80	85
Konrad 101/1984	776	880	0,900	^t,s,u,^mt,^s(lag)	>80	90
Dolgen VI	102	111	1,100	^t,u,k,s2,^k(lag),^mt	>80	100–130
Dolgen VI	119	129	0,860	^t,u,k,s2,^k(lag),^mt	>80	100
Dolgen VI	140	150	1,300	^t,u,k,s2,^k(lag),^mt	>80	125
TB Riniken	398	430	0,040	^t,u2,^s(lag),^mt(lag)	>80	85
SB Schafisheim	1001	1029	0,500	^t,u,^s(lag)	>80	95
SB Schafisheim	1052	1080	0,500	^t,u,^t,u,^s(lag),"py"	>80	95
SB Benken	566	597	0,067	^t,k,u,s,^u(lag),^mt,^s(lag),^k	>80	90
SB Benken	600	603	0,027	^t,k,u,s,^u(lag),^mt,^s(lag),^k	>80	95
SB Benken	605	624	1,600	^t,k,u,s,^u(lag),^mt,^s(lag),^k	>80	95
SB Benken	624	656	0,130	^t,k,u,s,^u(lag),^mt,^s(lag),^k	>80	70–85
Clay percentage 60 % to 80 % (estimated from lithological well description)						
Konrad 101/1984	241	292	1,000	^mt,^t,u2,s2,k2	70	30–55[3,4]
Konrad 101/1984	302	427	0,500	^t,u,s,^mt,u,^s	75	70
Konrad 101/1984	480	608	1,000	^t,^mt,^s(lag),^mk	75	65–90[4]
Konrad 101/1984	919	1002	0,400	^t,u,^s(lag),^mt,^mk	75	100
Remlingen 6	279	329	0,150	^t,k,d,"ah","y"	70	40[3]
Remlingen 6	330	380	4,000	^t,k,d,"ah","y"	70	40[3]
Remlingen 6	687	698	50,000	^t,k,ah,^mt	75	40[3]
TB Riniken	339	400	0,020	^t+^mt,^s(lag),^k(lag),"py"	75	80
TB Riniken	433	490	0,600	^t,s2,^s(lag),^mt,^mk,^k,^md	70	80–85
SB Schafisheim	961	988	0,010	^mt,s^t,^mk,^k,^ms,^m	60	55–90[4]
SB Schafisheim	989	1017	0,500	^t,u,^s(lag),^ms,^mt,^k	70	65–95[4]
SB Schafisheim	1029	1057	0,200	^k(lag),^s(lag)	75	95
SB Schafisheim	1080	1108	0,300	^t,k,^k(lag),^u,^md,^k	65	50–95[4]
SB Benken	549	565	0,640	^t,^u(lag),^s(lag),^mt,^k	75	100
SB Benken	657	698	0,049	^t,^s(lag),^mt,^k(lag)	70	–

[1] 1pm/s = 10^{-12} m/s (pm/s: Pikometer pro Sekunde)

[2] gAPI: Gamma-API-Einheiten (siehe dazu Kapitel 3.3.1)

[3] Messwert des Gamma Ray Log fraglich

[4] im Testintervall inhomogene Gesteinsfolge

It is important to emphasise again that the clay percentage cannot be used to derive field hydraulic conductivity directly. Clay percentage is only a tool supporting the regional evaluation of German argillaceous rock formations as reported in this study.

3.3 Geophysical methods for characterising argillaceous rock formations

3.3.1 Borehole logging methods

In addition to lithological logs, many of the deep boreholes have also been surveyed by electric logging tools in the depth zone of interest for nuclear repositories. These electric logs can be used to interpret the lithological and mineralogical conditions in the wells and to determine parameters of interest in repository evaluation (e.g. clay content, porosity) using additional reliable data. The following methods were used in selected areas and provide detailed results – depending on the number of well logs available – on the lithology and characterisation of the argillaceous rocks in the specific wells. The well logs from different wells can be correlated to interpret the spatial distribution of the claystone horizons (see Chapter 3.4.1). Seismic data tied to the wells can also be used for this purpose (see Chapter 3.4.2). These correlations provide information on how homogeneously the claystones are distributed and how the various parameters (clay content, porosity) continue or change laterally. The geophysical methods discussed in the following therefore support the methods described in Chapter 3.2 to provide complex and detailed characterisation of the argillaceous rocks in specific areas.

Table 3.4 summarises the various standard well logging methods. Detailed descriptions of well log analysis are available in the literature (e.g. SCHÖN & FRICKE 1999; DOVETON 1994; BOYER & MARI 1997; THEYS 1999).

However, because most of the wells were drilled as part of oil and gas exploration and production programmes, and mainly drilled in the 50s and 80s, the well logs available for most of the wells are only suitable for approximate lithological interpretation of the sequence penetrated by the boreholes. They usually only consist of the following logs:

- Caliper Log (CALI)
- Gamma Ray Log (GR) or Self-Potential Logs in older wells (SP)
- Resistivity Logs (ILD or LLD).

Table 3.4: Well logging methods (cf. Ellis 1987; Schön & Fricke 1999)

Technique	Measurement parameter	Example	Interpretation result
Passive electrical and electromagnetic methods			
Self-potential log	potential difference between the reference electrode and the well electrode	SP Log	Lithology in sand and clay sequences
Active electrical and electromagnetic methods			
Resistivity log	resistance (current input and galvanic voltage scanner)	Resistivity Log, Microlog, Induction Log, Electromagnetic Propagation Tool	Lithology, porosity and saturation interpretation
Inductive field transmission			
Electromagnetic wave propagation			Dielectric Conductivity
Passive radioactive methods			
Gamma log	Natural gamma radiation - integral - spectral	Gamma Ray Log Spectral Gamma Ray Log	Lithology and clay content
Active radioactive methods			
Gamma-Gamma Log	Gamma radiation using - Compton effect - Photo effect	γ-γ Density Log P_e Log	Density, porosity Lithology
Neutron log	Neutron radiation using - interaction - temporal decay - activation	n-n Log, n-γ Log Pulsed n-Log, n- γ Spectroscopy, n-Activation	Lithology Neutron porosity Clay content Porosity
Acoustic methods			
Transmission Refraction	- Refracted or guided waves on the borehole wall	Acoustic Log	Porosity, reservoir properties, fracturing, mechanical petrophysical properties
	- Waves travelling along the casing/cementation	Cement Bond Log	
Reflection	- Waves reflected by the borehole wall/casing	Borehole Televiewer Acoustic Borehole Televiewer	Fracturing, inhomogeneities borehole orientation
Properties, parameters and movement of borehole fluids			
	Temperature, conductivity	Temperature Log, Mud Log, Salinity Log	Change in temperature
	Vertical movement	Impeller Flow Meter Heat-Pulse Flow Meter	Production rate, hydraulic parameters
Gravimetric logs			
	Vertical changes in density	Borehole Gravimeter	Formation density, block density
Methods for determining geometrical parameters			
	Diameter, borehole position	Caliper Log Borehole Deviation Log	Technical condition of the well bore, lithology

The logs required to determine the porosity or the detailed lithological parameters of claystones were only available in the more recent wells, or were only logged in the sections of the well which penetrated the reservoir rock, but were not run in the claystone sections. The following additional logs are required as a minimum in the claystone zones to be able to determine the material parameters of claystone formations:

- Acoustic Log (DT)
- Density Log (RHOB)
- Neutron Porosity Log (NPHI)
- Photo-Electric Factor Log (PEF).

Caliper Log (CALI)

Caliper Logs measure the diameter of the well bore. They provide information on the well bore geometry as used to calculate the caliper corrections. Caliper Logs were primarily used in this study to qualitatively estimate the quality of the other logs. When the Caliper Log identifies parts of the well bore which are significantly out of gauge, it can be assumed that the logs subsequently recorded across these zones will provide qualitatively poor results because there is no contact between the tool and the rock in these zones.

Gamma Ray Log (GR) or Self-Potential Log (SP)

Gamma Ray Logs record the natural radioactivity of the rock. The logs report the total integral measurement according to the API standard scale (API = American Petroleum Institute). In sedimentary rocks, the normal relationship is for the radioactivity to be higher in rocks containing clay minerals than in rocks without clay minerals. Gamma Ray Logs can therefore be used to interpret the clay content of a rock. This is also possible in principle with a Self-Potential Log. However, Gamma Ray Logs usually provide better results and should therefore be used in preference to a Self-Potential Log where possible.

Sonic Log (DT), Density Log (RHOB) and Neutron Porosity Log (NPHI)

Sonic Logs, Density Logs and Neutron Porosity Logs are used to measure porosity. The porosity can be estimated from the Sonic Log using the WYLLIE equation (3.3) or (3.4) (WYLLIE et al. 1958), or the RAYMER-HUNT-GARDENER equation (3.5) (RAYMER et al. 1980).

Density is a function of matrix density, porosity and density of the fluid occupying the pore spaces. The density log can therefore be used to determine the porosity if the matrix density of the rock and the fluid which occupies the pore space is known.

The Neutron Porosity Log measures the concentration of hydrogen in the formation. This means that in rocks without clay, the log measures the amount of filled pore space (e.g. with water or oil). If the log measures several different lithologies, it is necessary to correct for the different lithologies when evaluating the log results. The most commonly used Neutron Logs are Compensated Neutron Logs (CNL) or Sidewall Neutron Logs (SNP). The logging results can be directly converted into limestone, sandstone or dolomite porosity units.

Photoelectric Factor Log (P_e log or PEF)

The results of a P_e Log are determined by the average nuclear charge of the rock. This makes it possible to differentiate between rock types on the basis of their different elemental compositions. P_e Logs are frequently combined with γ-γ density logs (RHOB) in the Schlumberger “Lithodensity Log”.

3.3.2 Determining the clay content

The clay content can be determined from the Gamma Ray Log or if necessary from the Self-Potential Log. Because clays have higher natural radioactivity than carbonates or sandstones, this property can be used to determine the clay content of a formation. With the exception of the special conditions discussed below, clastic rock sequences follow the following rule: the higher the radioactivity the more clay-rich the rock. The clay content (V_{sh}) can be determined directly from the Gamma Ray Log results using the gamma ray index:

$$I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \qquad (3.1)$$

Where:

I_{GR} = gamma ray index
GR_{log} = Gamma Ray Log results
GR_{min} = gamma ray value for sandstones
GR_{max} = gamma ray value for claystones.

Care must be taken if the following situations apply:

- Th-rich and U-rich minerals can occur in sedimentary rocks and give rise to corresponding high gamma activity in the rocks not attributable to the clay content.
- The same applies to sandstones and siltstones with high concentrations of potash feldspar.
- Organic constituents can also occur in higher concentrations in coarse clastic rocks under certain circumstances and lead to its enrichment in uranium.
- The potash content of clays increases as a result of diagenetic reactions corresponding to increasing burial/temperature.

The Self-Potential Log can be used to verify the clay concentration and should always be used if no Gamma Ray Log was run. However, the interpretation of the Self-Potential Log results is not as reliable as the interpretation of Gamma Ray Log results in zones with thick mud cake where the membrane-active clay particles in the mud cake give rise to a membrane potential which distorts or diminishes the diffusion potential in the permeable zone. A clay line (maximum) and a sand line (minimum) have to be determined first to determine the clay concentration V_{sh} from the Self-Potential Logs. However, the clay line often changes gradually with depth or across faults, which makes it difficult to determine V_{sh} (cf. e.g. SCHÖN & FRICKE 1999). Determination of the self-potential index is carried out analogous to (3.1):

$$I_{SP} = \frac{SP_{log} - SP_{min}}{SP_{max} - SP_{min}}, \tag{3.2}$$

Where:

I_{SP} = self-potential index
SP_{log} = results of the Self-Potential Log
SP_{min} = self potential value of the sand line
SP_{max} = self potential value of the clay line.

3.3.3 Porosity determination

Porosity can be determined from three log types (Sonic Log, Density Log, Neutron Porosity Log). Although none of the methods measures the pore volume directly, porosity can be determined from the logs if the mineralogy of the rock matrix is known and the characteristic petrophysical parameters of the minerals are also known. Most of the analysis carried out by the oil and gas industry are based on reservoir rocks which are usually only a few tens of metres thick and often have very clearly defined rock matrix values. However, these values can fluctuate significantly in claystones, as well as change with depth as a result of compaction and diverse chemical diagenetic processes. Models used to define reservoir rocks can therefore not be directly extrapolated to claystones. One attempt is made in the following to apply various correction techniques to the standard methods for reservoir analysis and to thus use these models to define claystones. To analyse claystones in detail, however, it is necessary to tie these models to the specific petrophysical parameters of the claystones measured in the laboratory by analysing core samples (see e.g. Table 3.5).

Sonic Log

The Sonic Log measures the interval travel time (Δt) of a compression wave as it spreads in the formation along the well axis. This travel time is the reciprocal of the velocity of the compression wave in the formation. Because Δt is dependent on the lithology and porosity, sonic porosity can be determined if the matrix travel time of the formation is known. The WYLLIE equation (Wyllie et al. 1958) can be used to estimate the porosity from the Sonic Log:

$$\Delta t = \Phi_S \Delta t_f + (1 - \Phi_S)\Delta t_{ma}, \tag{3.3}$$

where

Δt = travel time determined from the Sonic Log
Δt_f = travel time of fluids
Φ_s = the sonic porosity
Δt_{ma} = the travel time of the rock matrix.

Φ_s is derived from (3.3) as follows:

$$\Phi_S = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}. \tag{3.4}$$

Raymer, Hunt and Gardener propose another way of calculating porosity (Raymer et al. 1980):

$$\Phi_{S,RHG} = \frac{5}{8} \cdot \frac{\Delta t - \Delta t_{ma}}{\Delta t}. \tag{3.5}$$

Porosity is derived from the Sonic Log after making corrections for the influence of compaction in unconsolidated sediments, the presence of hydrocarbons, and the effect of argillaceous materials.

The sonic porosity in argillaceous rocks appears higher than it actually is because of the longer travel times in clays and claystones. The proper correction factor can only be applied when the proportion of clay (V_{sh}) in the formation is already known. This can be determined from e.g. the Gamma Ray Log (Chapter 3.3.2). The influence of argillaceous materials can therefore be taken into consideration by making the following corrections (Dresser Atlas 1974):

$$\Phi_{S,korr} = \left(\frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \cdot \frac{100}{\Delta t_{sh}} \right) - V_{sh} \cdot \left(\frac{\Delta t_{sh} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \right) \tag{3.6}$$

Or after Dewan (1983)

$$\Phi_{S,korr} = \Phi_S - V_{sh} \cdot \Phi_{S,sh}, \tag{3.7}$$

Where:

$\Phi_{S,corr}$ = the clay-corrected sonic porosity
$\Phi_{S,sh}$ = the sonic porosity of claystones
V_{sh} = the volume percentage of clay
Δt_{sh} = the travel time for argillaceous rocks.

Density Log

Formation density (ρ_b) is the function of matrix density, porosity and the density of the pore fluid (water, mineralised water, hydrocarbons). The matrix density of the formation and the type of fluid filling the pore space must be known to calculate the density porosity (Φ_D). The following equation can be used to estimate the density porosity (Φ_D) from the Density Log (RHOB):

$$\rho_b = \Phi_D \cdot \rho_f + (1 - \Phi_D)\rho_{ma}, \tag{3.8}$$

Where:

ρ_b is the density from the RHOB Log,
ρ_f the density of the fluid
Φ_D the density porosity,
ρ_{ma} the density of the rock matrix.

Φ_D gives:

$$\Phi_D = \frac{\rho_b - \rho_{ma}}{\rho_f - \rho_{ma}}. \tag{3.9}$$

The Density Log operates using the Compton effect. The photo effect is another way of measuring a γ-γ Log. This uses a low energy source (energy range around 40 keV to 120 keV) to measure the absorption coefficient P_e (PEF Log) (cf. also Schön & Fricke 1999).

P_e Logs are often combined with γ-γ Density Logs in e.g. the Schlumberger Lithodensity Tool. The PEF Log can thus be used to determine the lithology and therefore for the simple classification of argillaceous rocks.

Analogous to the travel time corrections (Sonic Log), calculation of the porosity from the density log requires prior correction for the presence of hydrocarbons and heavy metals, and the influence of argillaceous materials.

Neutron Porosity Log

The principle behind the Neutron Porosity Log is the collision of neutrons with hydrogen nuclei. This intensity is measured to determine the hydrogen concentration. A second step is measuring the porosity: the “hydrogen density” for water is calculated as follows:

$$\rho_{H_2O} \cdot 2H/(2H + O) = 2 \cdot 1/(2 \cdot 1 + 16) = 1/9. \tag{3.10}$$

The hydrogen index for water can be used as a reference level and is generally set at 1.

Modern logging methods detect porosity directly. The Sidewall Neutron Log (SNP) contains a transmitter and a receiver pressed against the wall of the borehole. The SNP Log is relatively insensitive to lithological effects but is sensitive to well bore irregularities, which can therefore cause a problem during logging. A better method is the Compensated Neutron Log (CNL) which uses a tool containing a transmitter and two receivers and is therefore relatively insensitive to well bore irregularities. Both of these tools can record porosity as limestone, sandstone or dolomite porosity.

The neutron porosity in clays varies according to the minerals, composition and residual water. This means that the hydrogen content of the minerals is also recorded by the detector. Typical values for claystone porosities are 30 % to 40 %.

The neutron porosity appears higher than the actual formation porosity in the presence of clay because of the water held in the clay structure. DEWAN (1983) proposed the following equation to correct for this effect:

$$\Phi_{\mathrm{N,korr}} = \Phi_{\mathrm{N}} - V_{\mathrm{sh}} \cdot \Phi_{\mathrm{N,sh}}, \tag{3.11}$$

Where:

Φ_N neutron porosity
$\Phi_{N,corr}$ the clay-corrected neutron porosity value
$\Phi_{N,sh}$ the neutron porosity of clays.

According to SCHLUMBERGER (1975) the following correction can be applied if a Density Log and a Neutron Porosity Log are available:

$$\Phi_{\mathrm{N,korr}} = \Phi_{\mathrm{N}} - \left[\left(\frac{\Phi_{\mathrm{N,sh}}}{0,45} \right) \cdot 0,03 \cdot V_{\mathrm{sh}} \right]; \tag{3.12}$$

$$\Phi_{\mathrm{D,korr}} = \Phi_{\mathrm{D}} - \left[\left(\frac{\Phi_{\mathrm{N,sh}}}{0,45} \right) \cdot 0,13 \cdot V_{\mathrm{sh}} \right]. \tag{3.13}$$

Table 3.5: Typical rock matrix values for calculating porosity
(cf. e.g. Schlumberger 1971; Doveton 1994; Asquith & Krygowski 2004)

Lithology	Δt_{ma} bzw. Δt_f (Wyllie) [µs/m]	Δt_{ma} bzw. Δt_f (RHG) [µs/m]	ρ_{ma} bzw. ρ_f [g/cm³]	P_e [barns/e]	U [barns/cm³]	Φ_{SNP} [%]	Φ_{CNL} [%]
Sandstone	168…182	184	2,64	1,81	4,79	-1	-2
Limestone	156	161	2,71	5,08	13,77	0	-1
Dolomite	143	144	2,88	3,14	9,00	2	1
Anhydrite	164		2,96	5,05	14,95	-1	-2
Salt (halite)	219		2,04	4,65	9,45	-2	-3
Baryte			4,50	267	1070	-1	-2
Montmorillonite			2,12	2,04	7,28	40	44
Illite			2,65	3,55	10,97	20	30
Kaolinite			2,44	1,84	6,14	34	37
Fresh water			1,00	0,36	0,40		
Salt water	620		1,15	0,81	0,96		
Oil	607		0,85	0,12	0,11		

The corrected neutron density porosity ($\Phi_{ND,corr}$) can be determined from the corrected porosities, $\Phi_{D,corr}$, $\Phi_{N,corr}$ according to Dewan (1993):

$$\Phi_{ND,korr} = \sqrt{\frac{\Phi^2_{N,korr} + \Phi^2_{D,korr}}{2}}. \tag{3.14}$$

Table 3.5 gives the matrix values for various types of rock formations. These values form the theoretical basis for determining porosity from the relevant log types. As discussed above, though, detailed determination requires laboratory core analysis.

3.3.4 Determining the lithological composition

The classification or mutual delimitation of different rock types can be carried out using cross-plots. The following log pairs are usually used for this purpose:

- Neutron Porosity Log (NPHI) – Density Log (RHOB)
- Neutron Porosity Log (NPHI) – Sonic Log (DTI)
- Photoelectric Factor (PEF) – Density Log (RHOB)
- Sonic Log (DT) – Density Log (RHOB).

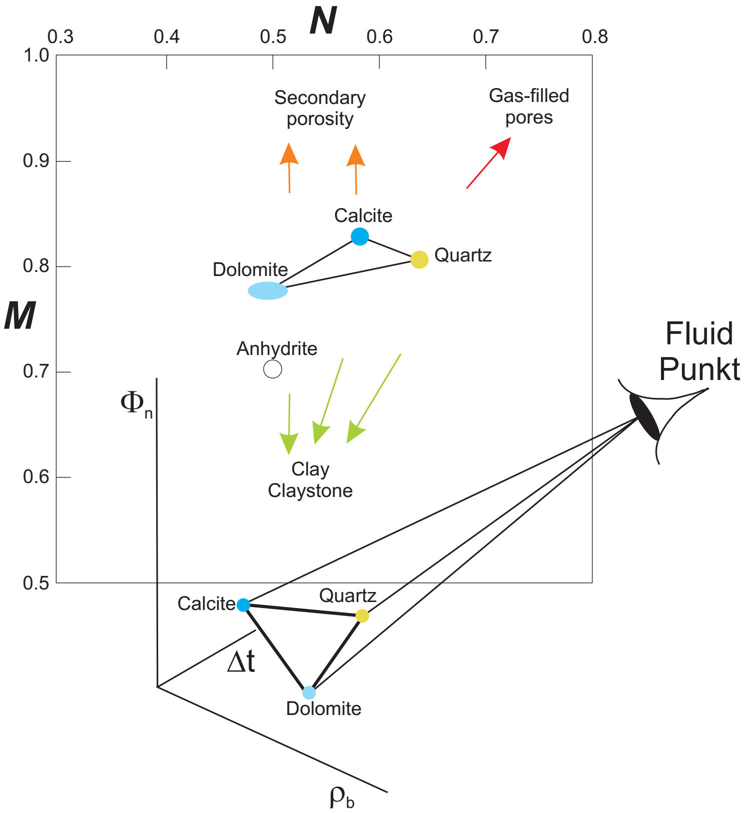


Figure 3.5: The ***M-N***-plot shown as a conic projection of the data in the Neutron-Density-Sonic Log space observed from the fluid point (DOVETON, 1993)

These cross-plots can be used to lithologically discriminate between the main rock types. Cross-plots and detailed descriptions in SCHLUMBERGER (1991), DOVETON (1993), ASQUITH & KRYGOWSKI (2004). SCHLUMBERGER (1991) recommends a neutron porosity-density cross-plot to identify clay minerals.

The M-N-plot

The ***M-N***-plot was proposed by BURKE et al. (1969) and used in particular to estimate the composition of rocks (Figure 3.5). It is used to convert the three porosity logs (RHOB, DT and NPHI) to two dimensions. The variables ***M*** and ***N*** combine the three porosity logs in a form which eliminates the volume of pore water by way of a conical projection of the data from the three porosity logs. This gives a porosity-independent plot to determine the lithology. ***M*** is set for the metric system as:

$$\boldsymbol{M} = \frac{\Delta t_f - \Delta t}{\rho_b - \rho_f} \cdot 0,003. \tag{3.15}$$

M is therefore a relatively porosity-independent parameter. The following equation applies to ***N***:

$$\boldsymbol{N} = \frac{\Phi_{\mathrm{N,f}} - \Phi_{\mathrm{N}}}{\rho_{\mathrm{b}} - \rho_{\mathrm{f}}}, \qquad (3.16)$$

Where:

$\Phi_{N,f}$ is the neutron porosity of the fluid (usually 1.0)
Φ_{N} the measured neutron porosity from the NPHI Log.

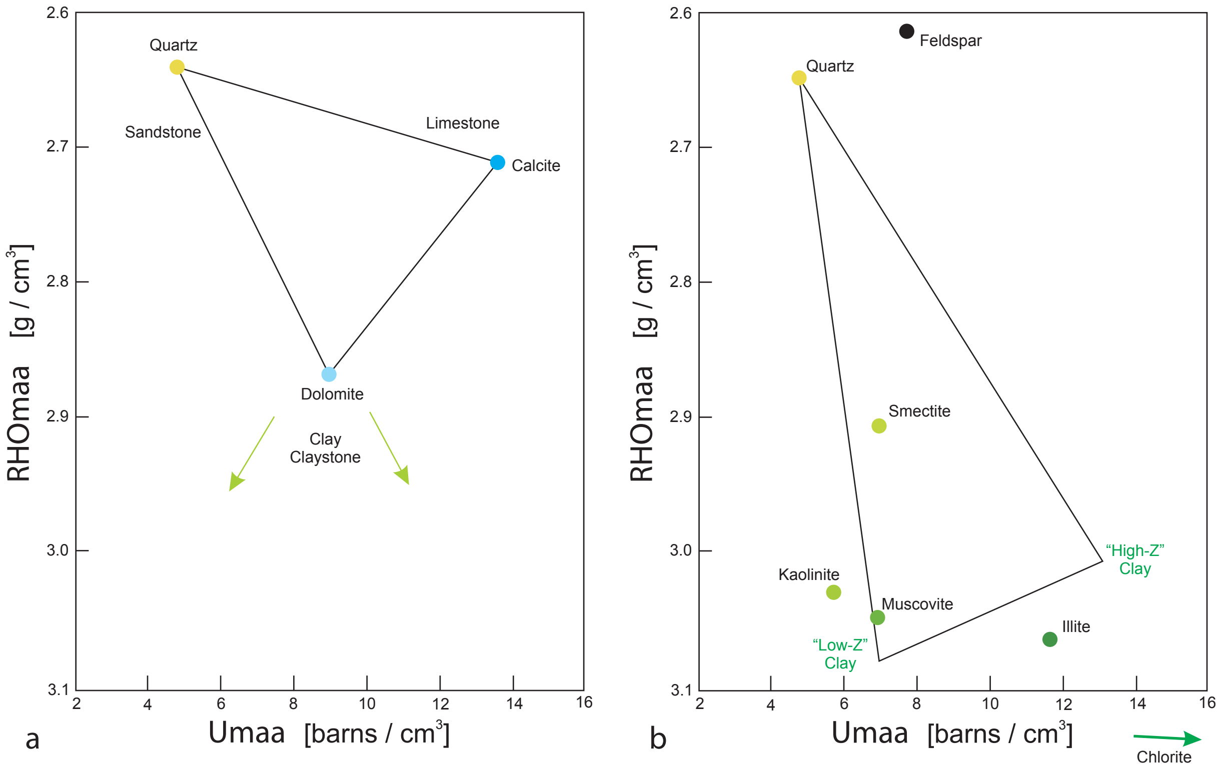


Figure 3.6: The ***RHOmaa-Umaa plot*** (a) for the three main minerals quartz, calcite and dolomite; and (b) showing the position of the claystones and the maximum values High-Z clay and Low-Z clay (from DOVETON 1994)

RHOmaa-Umaa plot

The ***RHOmaa-Umaa*** plot is used to simultaneously evaluate the P_e Log, the Neutron Porosity Log and the Density Log. In an analogous way to the ***M-N-***plot, the problem is converted to a two-dimensional diagram. ***RHOmaa*** represents the apparent matrix density and ***Umaa*** the apparent volume-related photoelectric absorption. The Pe Log is very sensitive here to the mineralogical composition of the formation. Figure 3.6 shows a ***RHOmaa-Umaa*** plot including the average values for quartz, calcite, dolomite and the various clay minerals.

The first step in determining the parameters ***RHOmaa*** and ***Umaa*** is to convert the photoelectric index Pe to the volume-related parameter U. The conversion involves multiplication with the electron density ρ_e:

$$\mathrm{U} = \mathrm{P_e} \cdot \rho_\mathrm{e} = \frac{\mathrm{P_e}(\rho_\mathrm{b} + 0,1883)}{1,07} \tag{3.17}$$

or approximately

$$\mathrm{U} = \mathrm{P_e} \cdot \rho_\mathrm{b}, \tag{3.18}$$

where U is the volume-related photoelectric factor. Density P_e and U are properties of the formation matrix and the pore fluid. The apparent density (***RHOmaa***) and the photoelectric absorption of the matrix (***Umaa***) can be estimated by eliminating the values for the pore fluids. This first requires determination of the true porosity Φt which is read off or calculated from the neutron porosity/density cross-plot. ***RHOmaa*** and ***Umaa*** can then be calculated as follows:

$$\rho_\mathrm{b} = \Phi_\mathrm{t} \cdot \rho_\mathrm{f} + (1 - \Phi_\mathrm{t}) \cdot \textbf{\textit{RHOmaa}} \tag{3.19}$$

or

$$\textbf{\textit{RHOmaa}} = \frac{(\rho_\mathrm{b} - \Phi_\mathrm{t} \cdot \rho_\mathrm{f})}{(1 - \Phi_\mathrm{t})} \tag{3.20}$$

and

$$\mathrm{U} = \Phi_\mathrm{t}\mathrm{U_f} + (1 - \Phi_\mathrm{t}) \cdot \textbf{\textit{Umaa}} \tag{3.21}$$

or

$$\textit{Umaa} = \frac{(U - \Phi_t U_f)}{(1 - \Phi_t)}. \qquad (3.22)$$

Depending on the type of fluid, the density of the fluid rho_f is defined as one or larger than one. 0.5 barns/cm^3 is generally used as the fluid value for photoelectric absorption U_f.

3.3.5 Determining the mineralogical composition

Selective or spectral Gamma Ray Logs can be used to estimate the mineralogical composition of claystones. The log results are shown after special processing as U, Th and K concentrations. This requires special calibration (spectral stripping) of the tools. Selective logging involves separate measurement of the pulses in the windows for the typical energies of K, U and Th radiation, and registration in a separate channel as pulse rates (GRS-K, GRS-U, GRS-Th). Spectral logging involves recording the whole spectrum with a 256-channel tool.

Because clay minerals often have characteristic potassium concentrations or thorium/potassium ratios, it is possible to differentiate claystones with different compositions on this basis (cf. also Schlumberger 1981; DOVETON 1994; ASQUITH & KRIGOWWSKY 2004).

No spectral or selective Gamma Ray Logs were available at the depth of interest in the previous test areas.

3.4 Correlation of well logs and seismic data

3.4.1 Well logs

Two important criteria for assessing the potential suitability of claystone formations for the final disposal of high-level radioactive waste are the ability to define their three-dimensional extent and the associated assessment of their homogeneity. This can only be done by correlating the well logs in specific regions. The CORRELATOR software package (OLEA & SAMPSON 2002) was used for this purpose: it is an interactive expert system for well log correlation and was specially further developed for this particular task. Well logs are correlated by analysing the similarities between two log types: one is used to determine the clay percentage, whilst the other is used to determine changes in its special petrophysical parameters (e.g. resistivity, acoustic impedance). The clay concentration can be defined using the Self-Potential Log (SP), or better still a Gamma Ray Log (GR). Correlation involves comparing interval A in well X with an interval of the same length in well Y. Well Y is analysed to identify intervals which have maximum similarity in terms of clay content and the two selected petrophysical parameters. CORRELATOR works with a weighted correlation coefficient $w_{1,2,3,4}$(i;k;n) to enable it to use the information from both logs. The correlation coefficient is defined as the product of the standardised shale-similarity coefficient $\alpha_{1,3}$(i;k;n) and the Pearson correlation coefficient $r_{2,4}$(i;k;n).

$$w_{1,2,3,4}(i,k;n) = \alpha_{1,3}(i,k;n) \cdot r_{2,4}(i,k;n), \tag{3.23}$$

where i is the index at depth z_i which lies at the centre of the interval in the reference well. k is the offset between the mid point of the comparative interval (measured in sampled intervals). (2n+1) is the number of values in an interval.

λ_1 and λ_2 are the shale logs in two wells located in the same sample interval. If λ_1(j) is the value of log λ_1 at depth z_j, the standardised shale-similarity coefficient is calculated as follows:

$$\alpha_{1,3}(i,k;n) = 1 - \frac{1}{2n+1} \sum_{j=1-n}^{i+n} \left| \frac{\lambda_l(j) - \lambda_{\text{shale},1}}{\lambda_{\text{min},1} - \lambda_{\text{shale},1}} - \frac{\lambda_3(j+k) - \lambda_{\text{shale},3}}{\lambda_{\text{min},3} - \lambda_{\text{shale},3}} \right|, \tag{3.24}$$

where:

$\lambda_{\text{Shale},1}$ is the hypothetical value for pure clay
$\lambda_{\text{min},l}$ the minimum value of log l.

Values for the standardised shale-similarity coefficient range between 0 and 1.

The Pearson correlation coefficient can then be calculated as follows:

$$r_{2,4}(i,k;n) = \frac{\text{cov}_{2,4}(i,k;n)}{s_2(i,n) \cdot s_4(i,k;n)}, \tag{3.25}$$

where S_2(i;n) is the standard deviation for (2n+1) logging interval with mid point z_i in log λ_2. S_4(i;n) is the standard deviation for the same interval length at midpoint z_{i+k} in log λ_4. $\text{cov}_{2,4}$(i;k;n) is the covariance between the same intervals in s_2(i;n) and s_4(i;k;n). (OLEA 2003).

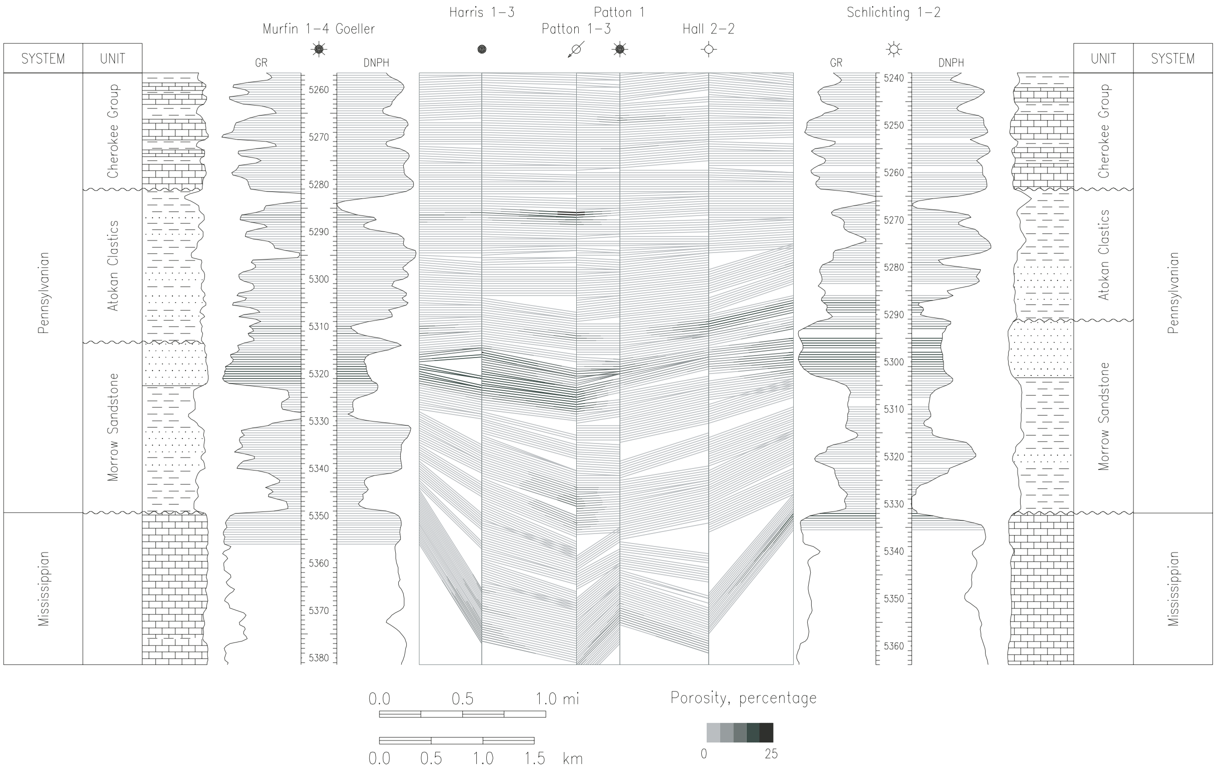


Figure 3.7: Well correlation diagram (oilfield in Kansas). Three different rock types shown: sandstone, carbonate and claystone (Figure after Olea 2003)

Figure 3.7 shows an example of a correlation between the well logs in six wells in an oil field. The figure shows the identified correlations as well as the variation in porosity. The latter was determined in this example using the data from the Density Log as well as from a Neutron Porosity Log. The porosity was estimated from the logging data of these two logs using the following correction:

$$\Phi = \Phi_{ND,korr} - V_{sh} \cdot \Phi_{sh}, \qquad (3.26)$$

where:

$\Phi_{ND,corr}$ is approximately half of the total of the density porosity
V_{sh} is the clay content
Φ_{sh} is the average porosity for typical claystones.

Tests in different regions with different logs reveal that CORRELATOR is a good tool for the detailed characterisation of clays and claystones in terms of their regional extent and homogeneity. It is particularly important when dealing with very complex geology that all of the fixed stratigraphic data is taken into consideration, and ring correlations are carried out between the wells to exclude mathematically correct but geologically inappropriate correlations.

3.4.2 Seismic data

Geophysical and geological analyses of the well data provide information and interpretations of the section penetrated by the well and the immediate surroundings. This means that well logs basically only provide one-dimensional information on the selected parameters. To extrapolate this information two-dimensionally and three-dimensionally requires two-dimensional cross-sections along lines or three-dimensional seismic surveys. The choice of 2D or 3D seismic depends on the parameters which need to be determined. Correlation between wells can be done using seismic data.

Seismic surveys depend on the generation of waves and detection of impedance contrasts, i.e. the identification of horizons at impedance boundaries (acoustic impedance, the product of velocity and density). These impedance differences can be recognised in the wave field of the seismogram after data processing and can be interpreted in terms of lithology and stratigraphy. Interpretation of the overall geological situation involves tying the 2D or 3D methods to the 1D methods (well results).

Different lithological parameters can be measured with relatively high degrees of accuracy at specific depths in a well. The travel time is detected by the seismic surveys and converted to depth using the relevant velocity model. Borehole results have to be tied to the seismic data to geologically identify the seismic events and convert the measured travel times to depth. This is done using various 2D and 3D methods which are not described here in any more detail. Detailed descriptions on these methods can be found in e.g. YILMAZ (1987), BENDER (1985), MILITZER & WEBER (1987), LA FRENIER & DUNKELBERG (1997).

Seismic data in the form of stack sections or time migrated sections was available for this study. The main reflectors in the seismic lines are picked and tied to the stratigraphy identified in wells to interpret the reflections geologically. The main tools for this purpose are core analysis and cuttings analysis, well velocity surveys (WVS), vertical seismic profiling (VSP) and Sonic Logs. These logs are used to convert lithology and depths at each horizon into two-way travel times (TWT) so that they can be correlated with the seismic data. The borehole logs are also used to determine the velocities at the well locations, and this data is used to calculate the velocity model. Figure 3.8 shows how seismic data is interpreted.

The interpreted stacked sections and the velocity correlation are used to produce depth maps (isobath maps). The relevant methods are described in detail in e.g. SATTLEGGER (1984, 1985, 1988); LA FRENIER & DUNKELBERG (1997).

These investigations generate a database (grid points) for selected clay formation horizons. This in turn forms the basis for structural mapping, the construction of cross-sections, and 3D pictures of the structural setting. Together with the results from the well log interpretations, these investigations enable the overall geology to be estimated and the suitability of the rock as a barrier and/or host rock to be assessed.

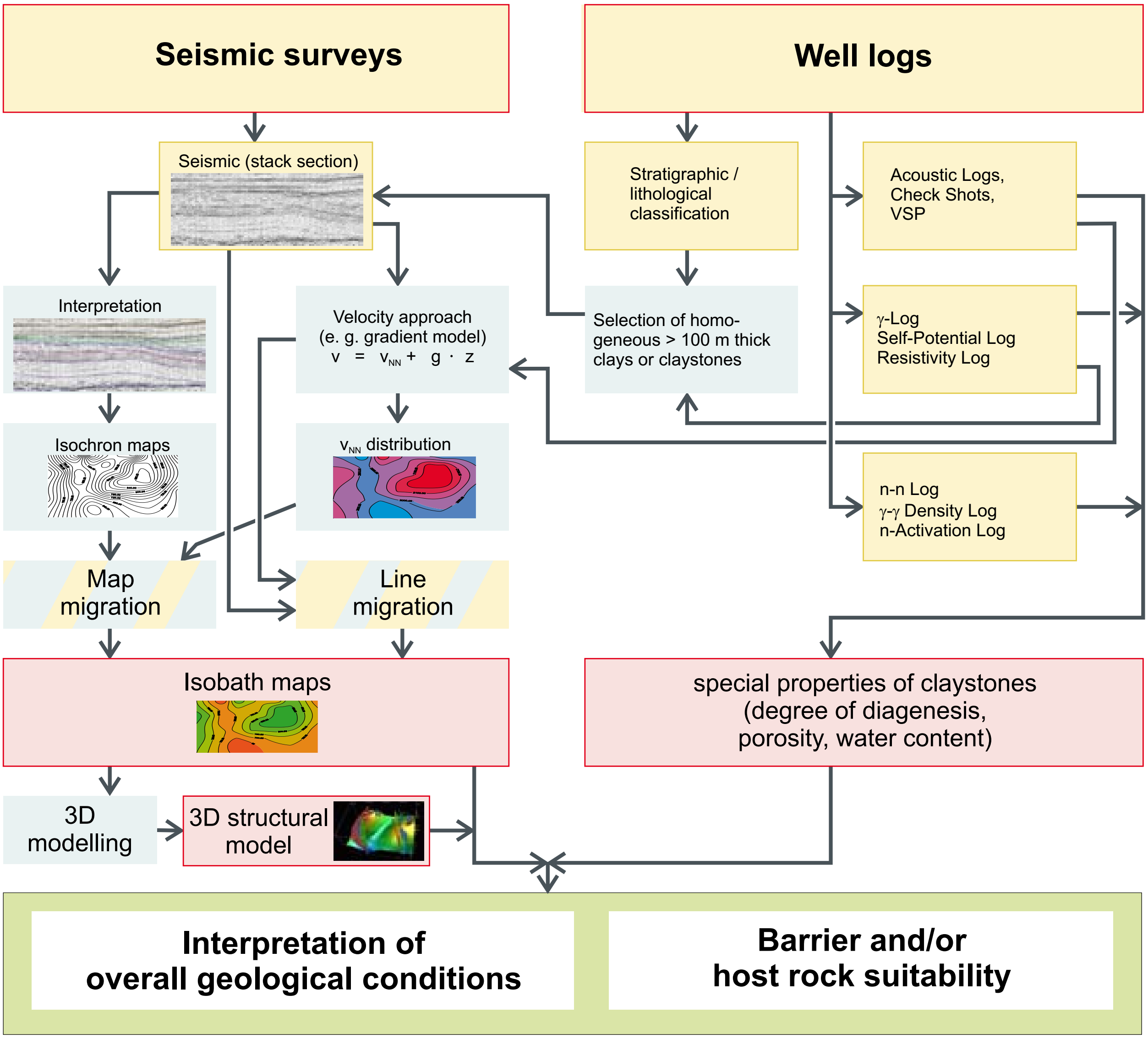


Figure 3.8: Diagram showing interpretation of seismic data and well logs

3.5 Estimating the maximum temperature exposure

As discussed in Chapter 2, information on the degree of diagenesis of clays and argillaceous rocks is very important for assessing the suitability of host rocks. The summary in OSIPOV et al. (2004) highlights the following facts in this context using as examples the sealing rocks above oil and gas fields:

- The properties of clays below depths of 400 m to 600 m make them highly suitable for sealing off hydrocarbons and thus forming the seals for oil and gas reservoirs.
- The good barrier properties are retained in argillaceous rocks exposed to average diagenetic stress levels.
- Under higher diagenetic stress conditions, some claystones tend to form microfractures and microfissures (dependent on facies and the proportion of phyllosilicates).

Density and Sonic Logs can be used to estimate the degree of diagenesis of claystones (Yang & Aplin 1998). Analysis of the depth trends of these logs makes it possible to compare the degree of diagenesis of various claystone sequences, as well as to identify claystones which were formerly at greater burial depths, and claystones affected by abnormal pressure conditions (MAGARA 1976; REISER 1991; HEASLER AND KHARITONOVA 1996). Interpretations can be verified by additional rheological/geochemical and petrophysical analysis of rock samples.

The temperature resistance of the clays and argillaceous rocks is directly associated with the degree of diagenesis. The rock lying directly adjacent to the repository cavities must not be affected by any mineral alterations at temperatures of up to 100 °C which deleteriously affect the barrier properties of the effective enclosing rock so that it fails to comply with the specifications (AkEnd 2002). An important indicator for estimating the possible temperature-related changes to petrological properties is therefore the maximum temperature stress to which clays and claystones were exposed during burial and their overall geological history. Figure 3.9 summarises the various indicators which can be used to roughly estimate the degree of diagenesis and the maximum temperature exposure. However, these indicators are only available from a few wells and are therefore untenable for regional evaluation.

The exception to this paucity of data is the data available on the maturity of organic matter. The organic particles which are very frequent constituents of claystones are defined by different original chemical compositions and are classified into maceral groups (vitrinite, exinite, inertinite). The average degree of reflectance r [%] of vitrinite is determined microscopically and using statistical techniques, and corresponds to the degree of carbonification and therefore the level of maturity of the rock (see Figure 3.9). The vitrinite reflectance depends on the degree of aromatisation and ring condensation of the carbon and the bedding parallel orientation and stacking of the aromatic crystallites (Koch & Schellschmidt 2001). It increases dependent on the maximum temperature to which the vitrinite was exposed – in addition to the temperature, time is or can also be an important influencing factor (Barker 1983; Quigley & Mackenzie 1988; Sweeney & Burnham 1990; Koch & Schellschmidt 2001).

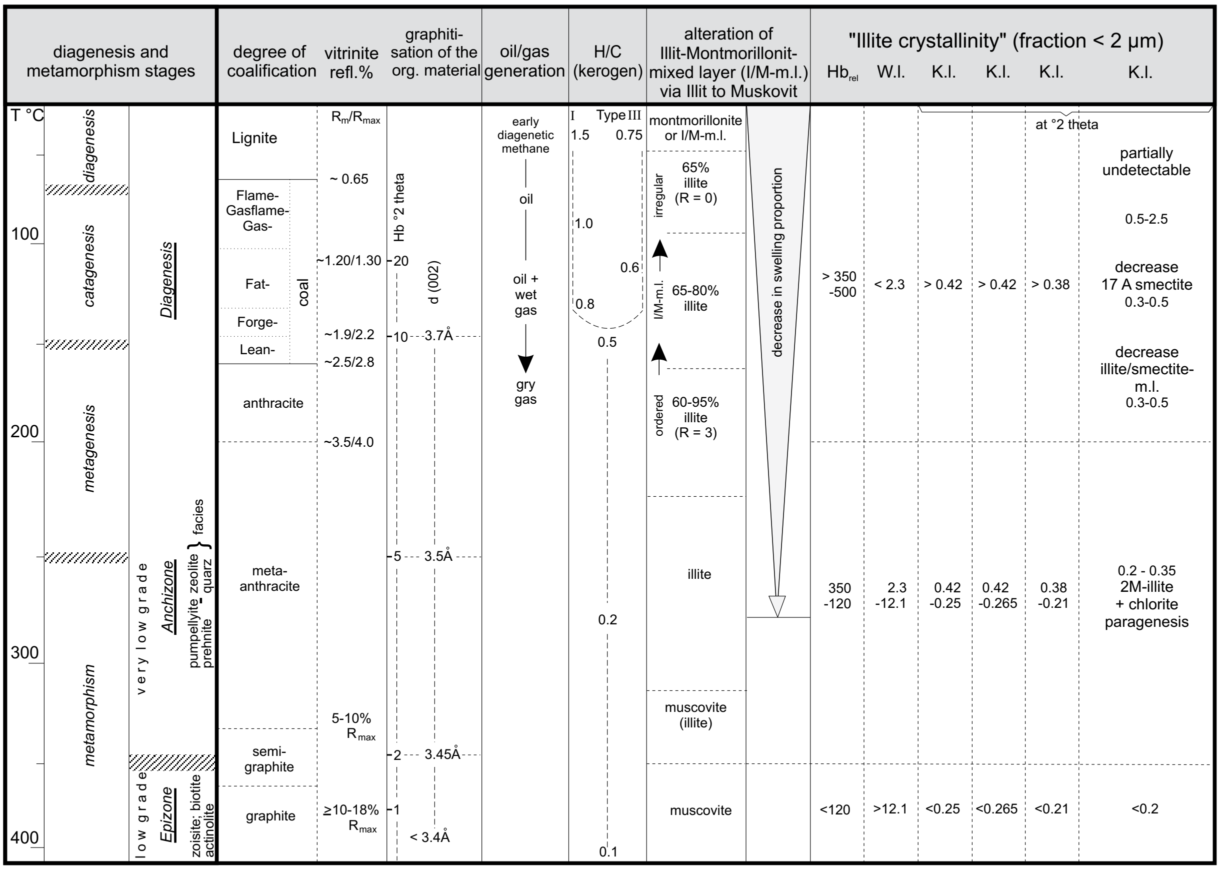


Figure 3.9: Means of estimating the maximum temperature exposure of claystones during burial diagenesis (Heroux et al. 1979; Stach 1987; Teichmüller 1987; Weaver 1984; Kübler 1984; Krumm et al. 1988; Hoth 1997)

Vitrinite reflectance data is available from the depth relevant for the location of nuclear repositories, particularly from numerous oil and gas wells. This data can be used to make a comparison of the degree of diagenesis. The study also tested the extent to which this data can be used to estimate the maximum temperature exposure undergone by the clays and claystones during burial and their geological history. This involved modelling the temperature and burial history with the PetroMod 1D numerical basin simulation program, and comparing the results with the empirical models published by KOCH & SCHELLSCHMIDT (2001) and BARKER & PAWLEWICZ (1994). The results show that even simple models can be used to roughly estimate the maximum temperature exposure of claystones.

3.6 Selection criteria

The aim of this study was to identify partial areas with argillaceous rock formations considered worthy of further examination because of their potential suitability as host rocks for the final disposal of high-level radioactive waste in Germany. A partial area suitable for further examination is defined as an area with a geological host rock formation potentially suitable for the construction of a nuclear repository (argillaceous rocks in this case) and a favourable overall geological setting. The brief of this study was not to identify specific nuclear repository sites.

The identification and selection of partial areas worthy of further examination as conducted in this study is based on a range of categories of criteria and specifications discussed in the following chapters.

3.6.1 Requirements for a nuclear repository site

Generally applicable basic specifications have been internationally defined for nuclear repository sites. They are primarily based on the general specifications elaborated by the International Atomic Energy Agency (IAEA) (IAEA 1993, 1994). The Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (NAGRA – National Cooperative for the Disposal of Radioactive Waste) used the IAEA specifications to formulate a Swiss concept for the construction of a nuclear repository in argillaceous rocks including the following priority specifications (NAGRA 2002):

- Long-term geological stability (e.g. tectonically stable geological area)
- Favourable host rock properties (e.g. geotechnical properties)
- Adequate extension of host rock

- The absence of any disturbances (e.g. no risk of human interference)
- Ruggedness with respect to disturbances (e.g. in the case of competing use)
- Explorability (e.g. simple geological structure, homogeneous rock)
- Predictability (e.g. extensive stable geotectonic environment).

The French nuclear repository concept for argillaceous rocks also specifies almost identical criteria for a site (DSIN 1991).

The first step involved the geoscientifically justified and safety-oriented delimitation of partial areas worthy of further investigation selected on the basis of these internationally recognised specifications, and also taking into consideration the exclusion criteria and minimum requirements defined by AkEnd - as described in the following chapter (Chapter 3.6.2).

More regions were excluded from further investigation in a second step by applying host-rock-dependent criteria for argillaceous rocks and incorporating the findings on the special regional geological conditions in Germany (Chapter 3.6.3). Chapter 4.2 contains a list of the results and a discussion of the relevant areas.

3.6.2 Exclusion criteria and minimum requirements

As already discussed in Chapter 1, geological barriers are of crucial importance for the final disposal of high-level radioactive waste in deep geological formations in Germany. The main priority for a nuclear repository site must therefore be the fulfilment of all safety-relevant geoscientific criteria.

In accordance with AkEnd recommendations, the first step in the identification of areas in argillaceous rock formations in this study involved the application of the following geoscientific and host-rock-independent exclusion criteria:

- Large-area vertical movements: The repository area must not show large-area uplifts of more than one millimetre per year on average during the predictable period.
- Active fault zones: There must not be any active fault zones in the repository area.
- Seismic activity: In the repository area, the seismic activities to be expected must not exceed Earthquake Zone 1 according to DIN 4149.

- Volcanic activity: In the repository area, there must neither be any quaternary nor any expected future volcanism.

AkEnd formulated additional safety-relevant minimum requirements to identify areas with geological structures which may satisfy the criteria defined for depth and adequate isolation. Non-fulfilment of the following criteria leads to the exclusion of more partial areas:

- The isolating rock zone must consist of rock types to which a field hydraulic conductivity of less than 10^{-10} m/s can be assigned.
- The thickness of the isolating rock zone must be at least 100 m.
- The depth of the top of the required isolating rock zone must be at least 300 m.
- The repository mine must lie no deeper than 1,500 m (see also Chapter 3.6.3).
- The isolating rock zone must have an areal extension that permits the realisation of a repository (e. g. approximately 3 km² in salt or 10 km² in clay or granite).
- Neither the isolating rock zone nor the host rock must be at risk from rock burst.
- There must be no findings or data which give rise to doubts whether the geoscientifc minimum requirements regarding field hydraulic conductivity, thickness and extent of the isolating rock zone can be fulfilled over a period of time in the order of magnitude of one million years.

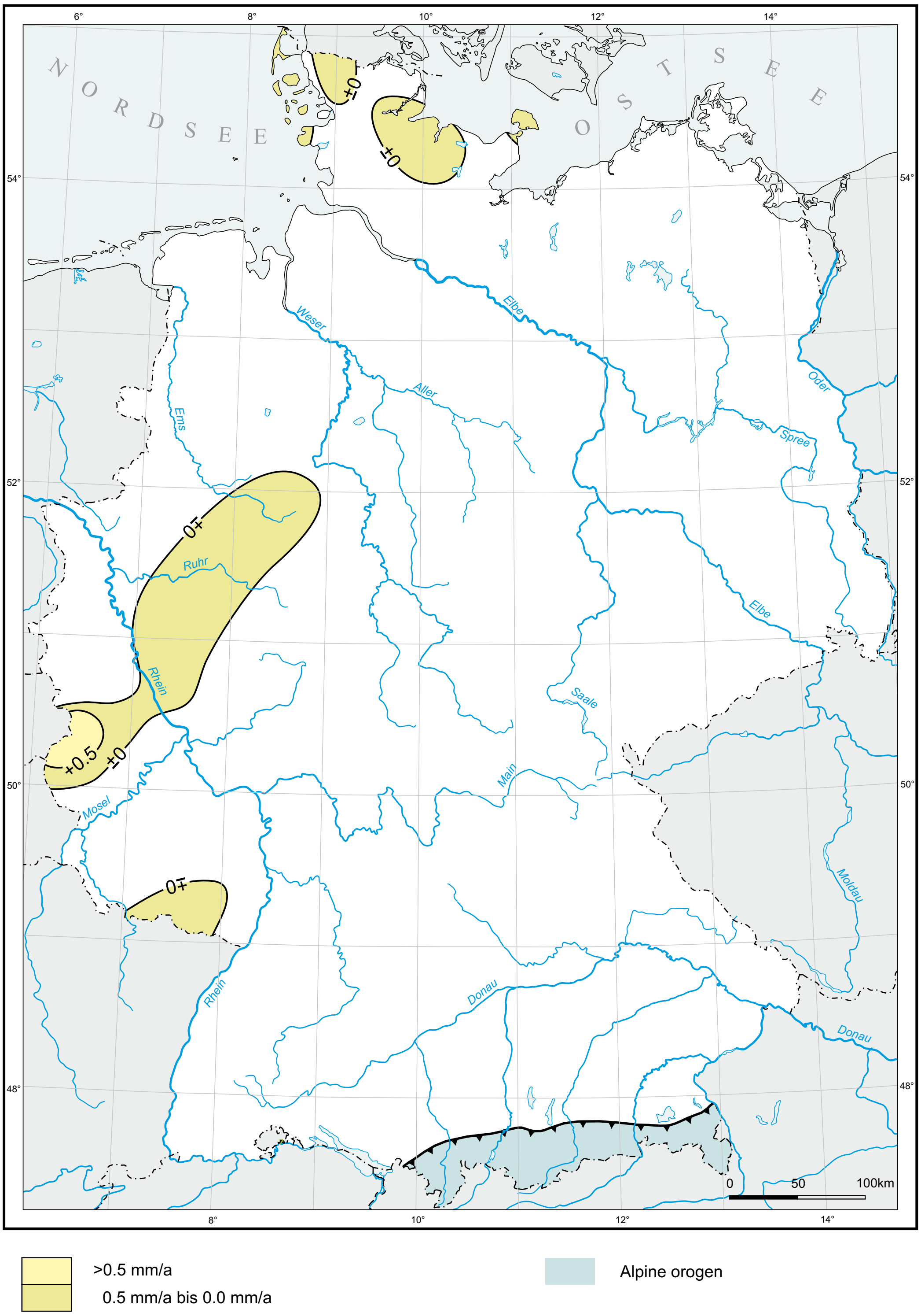


Figure 3.10: Vertical crustal movement (uplift) in Germany after FRISCHBUTTER & SCHWAB (2001)

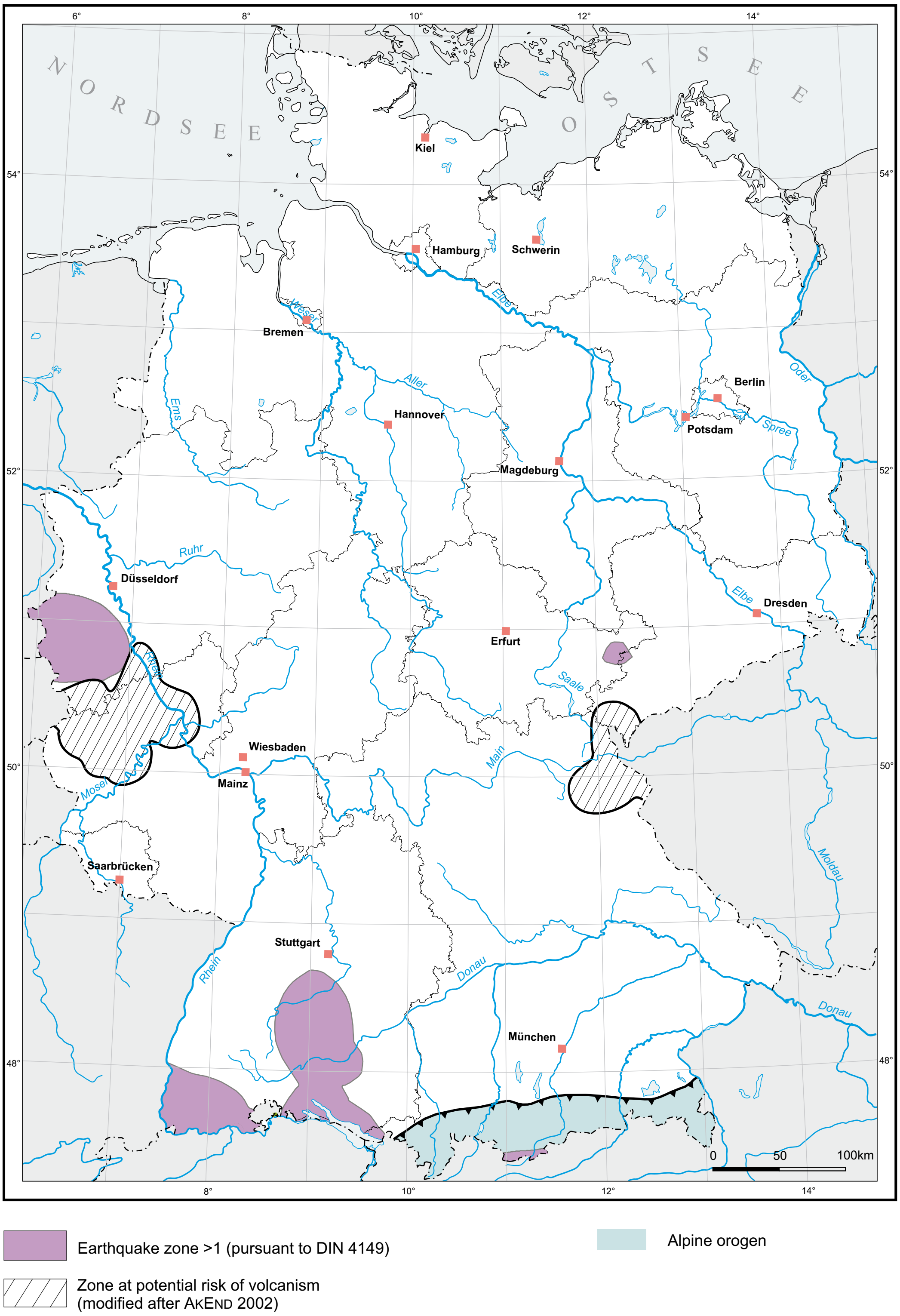


Figure 3.11: Exclusion criteria: Earthquake zone > 1, and potential risk of volcanism

The application of these exclusion criteria and minimum requirements in the selection process for areas with argillaceous rock formations in Germany results in the identified partial areas with potential suitability for the final disposal of high-level radioactive waste, as shown in the separate maps (see Chapter 4.1 and 4.2).

3.6.3 Host-rock-specific selection criteria for argillaceous rocks

Argillaceous rock formations have proven their long-term effectiveness as geological barriers where they form tight seals, e.g. above hydrocarbon reservoirs. The favourable properties of argillaceous rocks relevant for final disposal are primarily their very low permeability and their high sorption capacity.

However, the expense involved in constructing and running a nuclear repository, the safety during the operating phase, and the ability to seal up the nuclear repository during and after emplacement of the high-level radioactive waste, also strongly depend on the rock mechanical properties of the host rock. Although a great deal is known in Germany about the rock mechanics of evaporites, much less is known about argillaceous rocks.

Argillaceous rocks exhibit a wide range of rock-mechanical properties, with a spectrum from plastic clays, transitional types, and strongly consolidated and partially fractured claystones. This range of types can be associated with considerable differences in deformation behaviour, temperature sensitivity and formation stability. For these reasons, the evaluation process for international nuclear repository concepts considering clay formations as host rocks also includes rock-mechanical properties in the host-rock-dependent selection criteria for argillaceous rocks. One of the main criteria in this context is the maximum depth of the nuclear repository in the argillaceous rock formation.

The concept for final disposal in deep geological formations generally assumes that the formation will exhibit adequate strength for the construction and maintenance of underground tunnels. The depth of the nuclear repository has a considerable influence here on the stability of the emplacement tunnels and therefore also for the mining construction factors and mining engineering feasibility. The stability of tunnels in argillaceous rocks can only be guaranteed by additional supporting techniques. However, cement-based rock support methods are undesirable for reasons including the long-term safety aspects (altering the natural geochemical conditions) (NAGRA 2002). The depth of a nuclear repository in argillaceous rocks must therefore not only be selected to ensure that it is a safe and secure distance from the biosphere, it must also be at a depth that completely satisfies rock-mechanical criteria to avoid undesirable long-term effects.

BGR already proposed a nuclear repository depth of maximum 1000 m in argillaceous rocks back in 1977 in a study on potential nuclear repository host rock formations in Germany (BGR 1977). This specification was adopted in 1979 as a recommendation in a study for the EU member states at the time, and has now gained world-wide recognition (EU 1979). The French concept in Jurassic claystones also specifies an emplacement depth between 200 m and 1000 m (ANDRA 2001). IAEA's general guidelines also specify a depth of "several hundred metres" for nuclear repository tunnels (IAEA 2003). Calculations by Jobmann et al. (2006) on the technical safety aspects for the layout of a nuclear repository in claystone also reveal that for thermal and mechanical reasons: "absolute preference should be given to claystone formations at the shallowest possible depth". The Swiss nuclear repository concept for the Opalinus Clay also specifies a maximum depth of approx. 900 m (NAGRA 2002).

International experts are therefore unanimous that very difficult rock-mechanical conditions can be expected in argillaceous rock formations deeper than 1000 m. Such depths involve enormous expense in tunnelling and operating a nuclear repository (BfS 2006). For all of these reasons, this study defines a maximum possible depth of 1000 m as a limiting factor for argillaceous rock formations.

In addition to mining engineering aspects, and therefore rock-mechanical aspects in defining the maximum depth of a nuclear repository mine, consideration must also be given to the temperature at the emplacement level. The maximum temperature of the rock should not exceed 50 °C because claystones have much poorer thermal conduction capacities than salt. This means that heat will be transported much more poorly out of a nuclear repository mine constructed in claystone. Jung et al. (2002) reported temperatures averaging 40 °C to 50 °C at depths of 1000 m in North Germany. Much higher temperatures exist in large parts of the South German Block and the Oberrheingraben (cf. Figure 3.12).

In addition to mining engineering problems, the rock-mechanical properties of argillaceous rocks are also one of the most crucial factors in assessing long-term safety. AkEnd (2002) also pointed out the importance of the long-term rock-mechanical behaviour of the host rocks in the weighing criteria formulated for potential nuclear repository regions. The rheological behaviour of claystones also plays an important role in assessing the mechanical stability of underground workings in the Swiss nuclear repository concept (NAGRA 2002). Time-dependent deformation processes have to be taken into consideration, particularly in the case of clays with plastic properties.

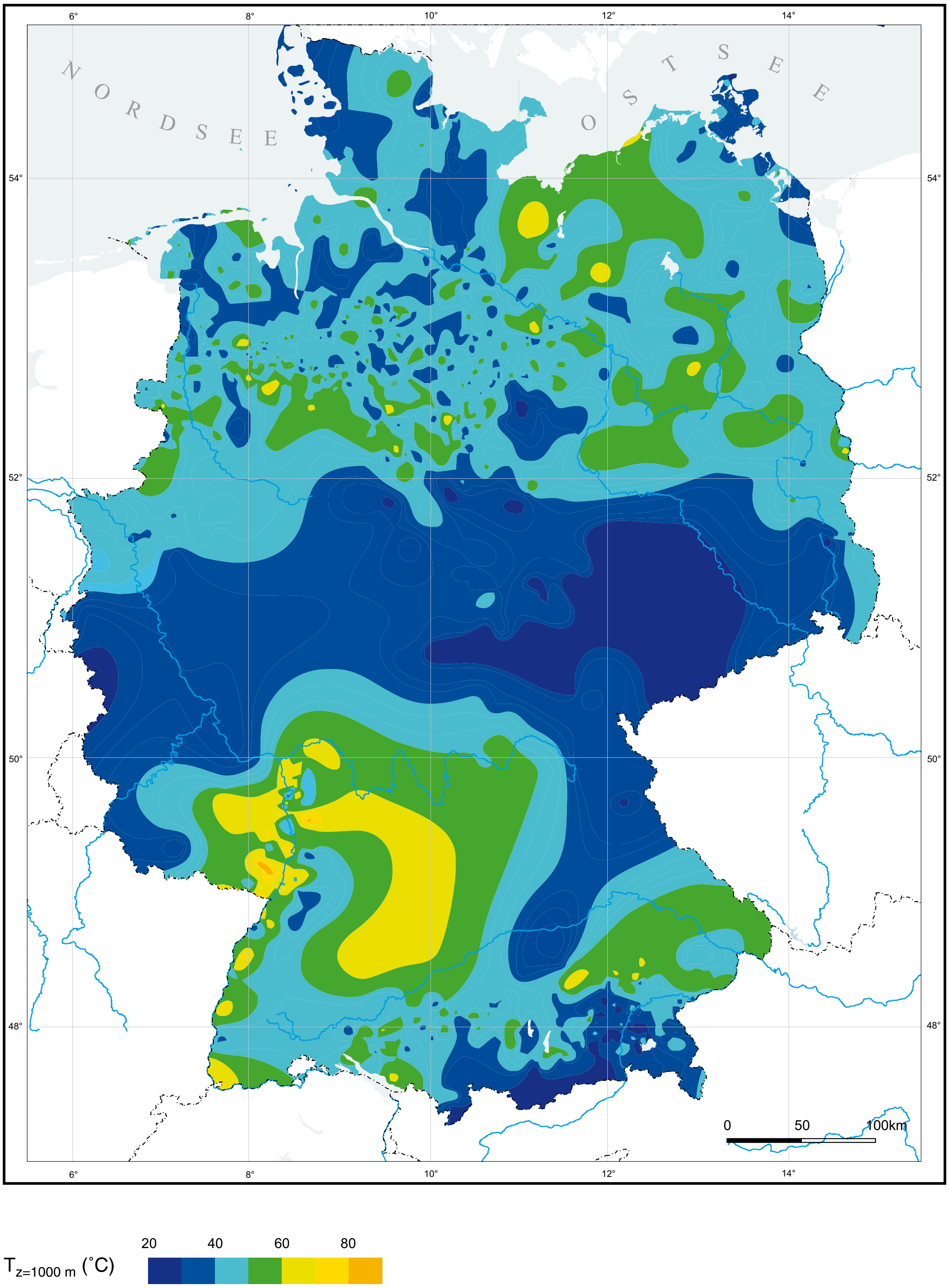


Figure 3.12: Temperature distribution at 1000 m depth after Jung et al. (2002)

Laboratory tests so far mainly provide information on the short-term material behaviour of clays (LUX 2002). Extrapolation of these results to long time periods has proved extremely difficult, particularly when also taking into consideration the thermal effects of heat-generating waste after emplacement. Given the very small amount of information available compared to salt as a host rock, a good characterisation of clays is only possible on a site-specific basis and at unproportionately high expense.

Against the background of the unfavourable material properties of unconsolidated clay in Germany, this study dropped from further investigation the mostly plastic Tertiary argillaceous rock formations occurring at the relevant depths for nuclear repositories in Germany.

4 Results

4.1 Argillaceous rock formations in Germany

The geological development of Germany outside of the Alpine zone gave rise to a clear tripartite division of the rock formations. The oldest units are formed by folded and foliated formations in which the original sedimentary and igneous rocks have been altered to metamorphic rocks by high temperatures and pressures. The weakly to highly metamorphosed rocks have been penetrated in varying degrees by younger plutonic rocks. These igneous rocks together with the metamorphic rocks form the basement in Germany. The basement rocks are primarily of Precambrian (> 550 million years) to Carboniferous (295 million years) age. The younger igneous rocks are mostly Permian, but sometimes younger.

The parts of the basement with only very weakly metamorphosed sedimentary rocks contain no claystones because these were altered to at least clay slate by the high pressure and temperature conditions. Because of their foliation and the presence of fractures, these clay slates often have very much higher field hydraulic conductivites than specified ($k_f < 10^{-10}$ m/s). There is therefore inadequate evidence to prove that larger zones exist (min 10 km^2) where clay slate fulfils the specified criteria for low field hydraulic conductivity. Thick extensive claystone strata are also not present in regions where crystalline basement either outcrops at the surface or lies at very shallow depths (see Figure 4.1). Thicker clays in these regions are highly localised and usually consist of weathering products (e.g. kaolin deposits in Sachsen).

The basement is discordantly overlain by the consisting of only slightly deformed and non-metamorphic strata. In Southern and Central Germany where the basement is of Variscan age (ranging from approx. 330 million years to 305 million years old), the overburden already begins in parts with deposits of Lower Carboniferous age, and with extensive deposits of at least Upper Carboniferous and Rotliegendes sediments. Along the north-east German coast beneath Rügen, Usedom and the mainland, where deep boreholes have penetrated Caledonian basement (420 million years old), the overburden already begins in the Middle Devonian, whilst below the Baltic Sea to the north-east of Rügen, the overburden starts with Cambrian deposits overlying the crystalline basement rocks of the Baltic Shield, as proven in boreholes. From this base comprising sediments of a range of ages, the overburden extends up to the youngest Tertiary deposits (approx. 1.8 million years).

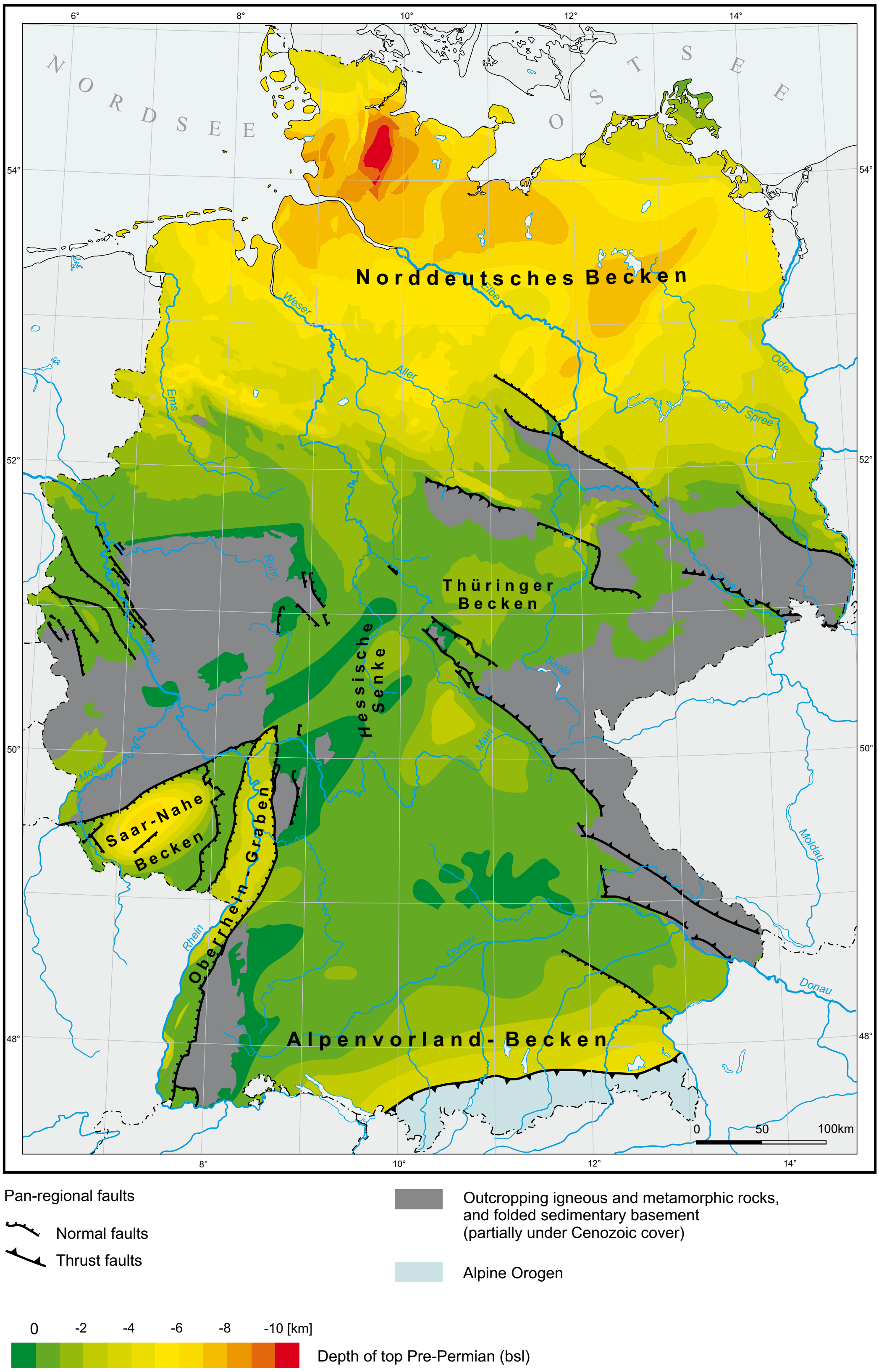


Figure 4.1: Depth of base sedimentary overburden in Germany (sedimentary basin locations)

The youngest geological units or rock formations are formed by unconsolidated Quaternary sediments primarily found in the North German Plain and in the Alpine Foreland. Because of their shallow depth alone, Quaternary clay deposits have very unfavourable properties for the final deposal of high-level radioactive waste, and are therefore not considered further in this report.

The geological development of Germany, the distribution of different rock formations, and the subsurface structure are discussed in several papers including those of Walter (1995), Bachmann & Müller (1996), Stratigraphische Kommission Deutschland (1997), Henningsen & Katzung (2006), Menning & Hendrich (2005).

Figure 4.1 shows the depth of Top Pre-Permian (in part the base of thick younger overburden deposits above rocks of Carboniferous and older age > 300 million years old). Figure 4.1 shows the regions in Germany where the igneous and metamorphic basement crops out at the surface or lies at very shallow depths below thin Cenozoic cover rocks. This figure also shows the regional distribution of thick overburden deposits. The latter are concentrated in areas which underwent subsidence over the course of geological time and therefore accumulated thick sequences of sedimentary rocks (sedimentary basins, grabens). Sedimentation is even continuing today in some cases. The two most important zones in Germany in this context are the Norddeutsches Becken and Alpenvorlandbecken (Nordalpines Molassebecken). Figure 4.2 shows the geology of the southern part of the Norddeutsches Becken. This shows argillaceous rock formations of Cretaceous and Jurassic age at relevant depths for nuclear repositories. The cross-section from the Schwäbische Alb in the Molassebecken (Figure 4.3) shows the thick Tertiary fill above the Jurassic in the Molassebecken.

Thick clays and claystones worthy of further investigation in the search for nuclear repository sites are almost exclusively found within the sedimentary basins shown in Figure 4.1 because of their geological development. Clays and claystones occur in almost all stratigraphic units with strong variations in thickness, areal extent, homogeneity and composition.

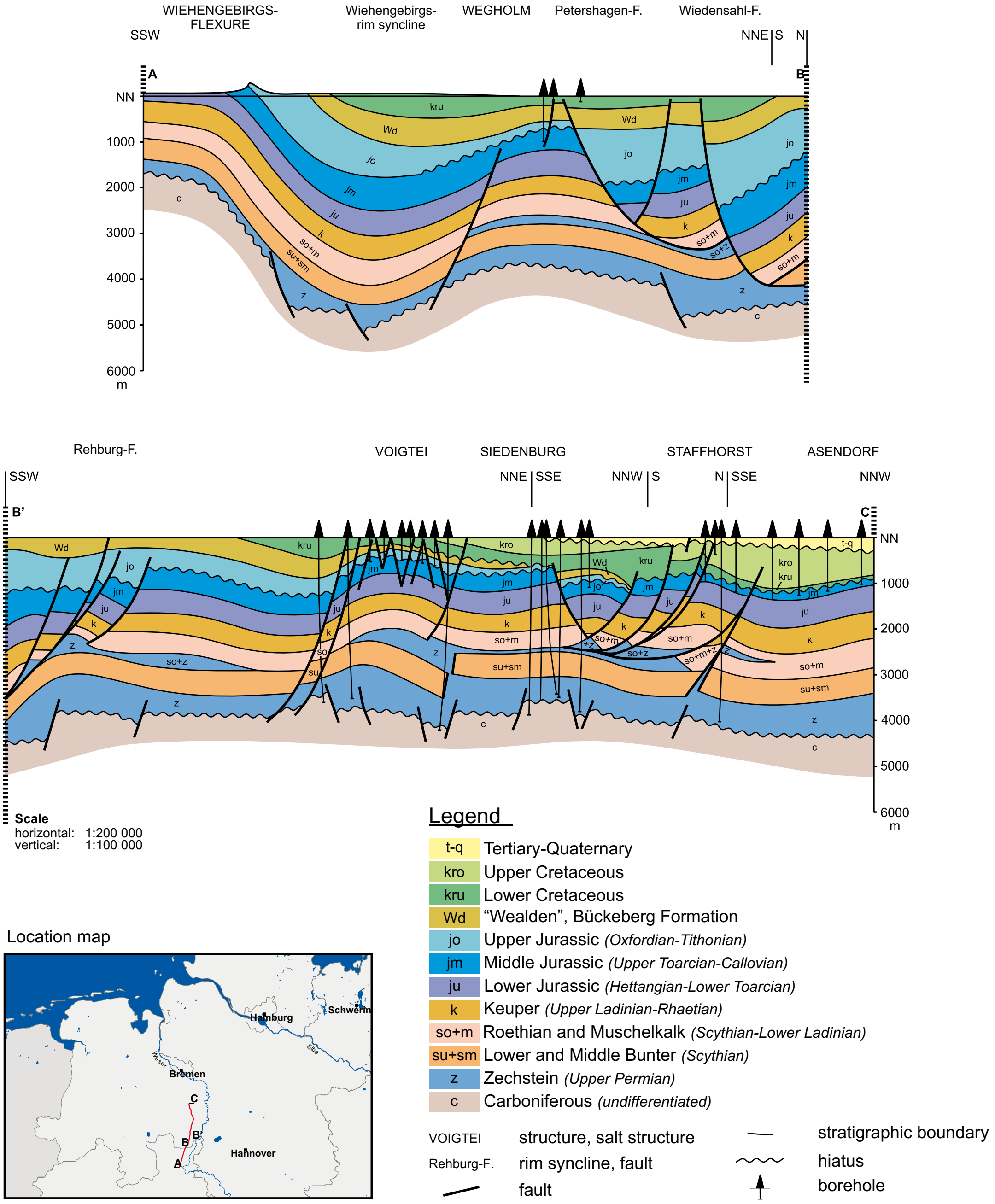


Figure 4.2: Cross-section through the southern part of the Norddeutsches Becken (section after BALDSCHUHN et al. 2001, modified)

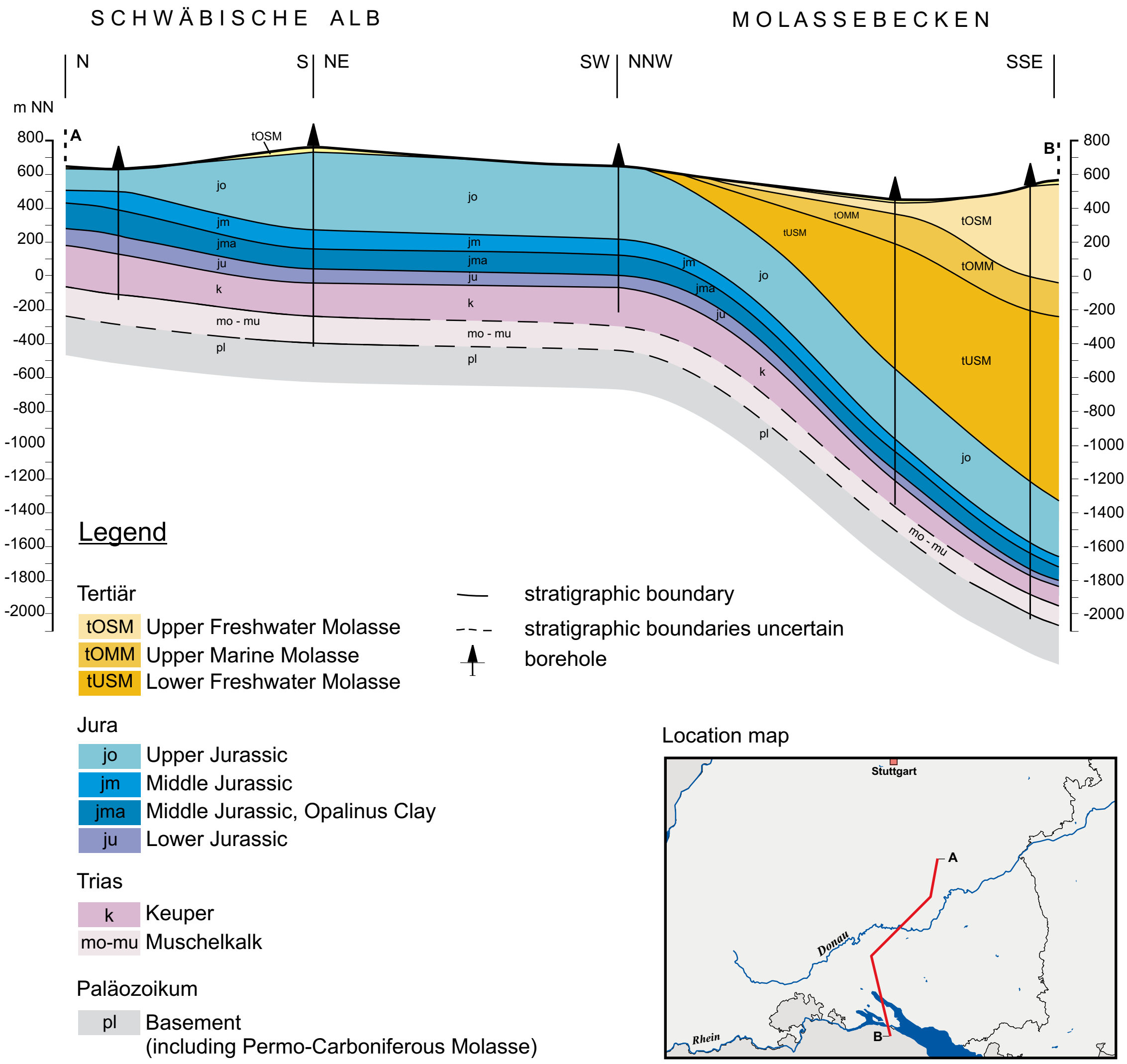


Figure 4.3: Cross-section through the Schwäbische Alb – Molassebecken

The distribution of potential argillaceous barrier rocks has been studied at shallow depths primarily as part of landfill site investigations (AG Deponien 1997). The results presented in this report, when combined with the experience acquired by all federal German states, provides a good insight into the occurrence of argillaceous rock formations at shallow depths in the various regions. As already discussed in Chapter 3.1, the analysis of deeper sedimentary sequences in Germany is based on boreholes primarily drilled in the course of oil, gas, salt, ore or other natural resource exploration and/or production activities, as well as to a lesser extent research and mapping boreholes. Additional information can be derived from reflection seismic and other geophysical surveys tied to the well results. From the compilations and publications available to date on deep geology in Germany (see e.g. ZGI 1970, Kämpfe 1984, Lemcke 1988; Geophysik Leipzig 1989, Geyer & Gwinner 1991, Katzung & Ehmke 1993, Hoth et al. 1993, Seidel 1995, Freudenberger & Schwerd 1996, Bandlova 1997, Baldschuhn 2001, Katzung 2004, Menning & Hendrich 2005), one can conclude that clay/claystone formations fulfilling the basic specifications with regard to depth and thickness discussed in Chapter 3.6.2 occur in the following regions and stratigraphic sections (Figure 4.4).

1. Jurassic clays/claystones: primarily in the Niedersachsen-Becken, in parts of Sachsen-Anhalt and Mecklenburg-Vorpommern, in the Süddeutsches Molassebecken as well as in the Schwäbische/Fränkische Alb.

2. Lower Cretaceous clays/claystones (primarily Valanginian to Albian): primarily in Niedersachsen and parts of Sachsen-Anhalt, Mecklenburg-Vorpommern and Brandenburg. Upper Cretaceous clays/claystones occurring highly localised in South Germany.

3. The Tertiary clays/claystones: primarily in Schleswig-Holstein and parts of Mecklenburg-Vorpommern, Brandenburg and Niedersachsen (Upper Palaeocene to Miocene), as well as in the Süddeutsches Molassebecken and Oberrheingraben (Eocene to Miocene).

The investigations carried out to date concentrated on these rock formations because they fulfil the basic specifications according to the geological information currently available. More highly localised argillaceous formations in other stratigraphic units (Triassic, Permo-Carboniferous) do not fulfil most of the minimum requirements defined in Chapter 3.6.2 because they either lie at excessive depths within the basins or do not achieve the necessary thickness when they lie at the margins of the basins. Although there are local exceptions, they are not considered further here because of the difficulty in mapping their spatial distribution.

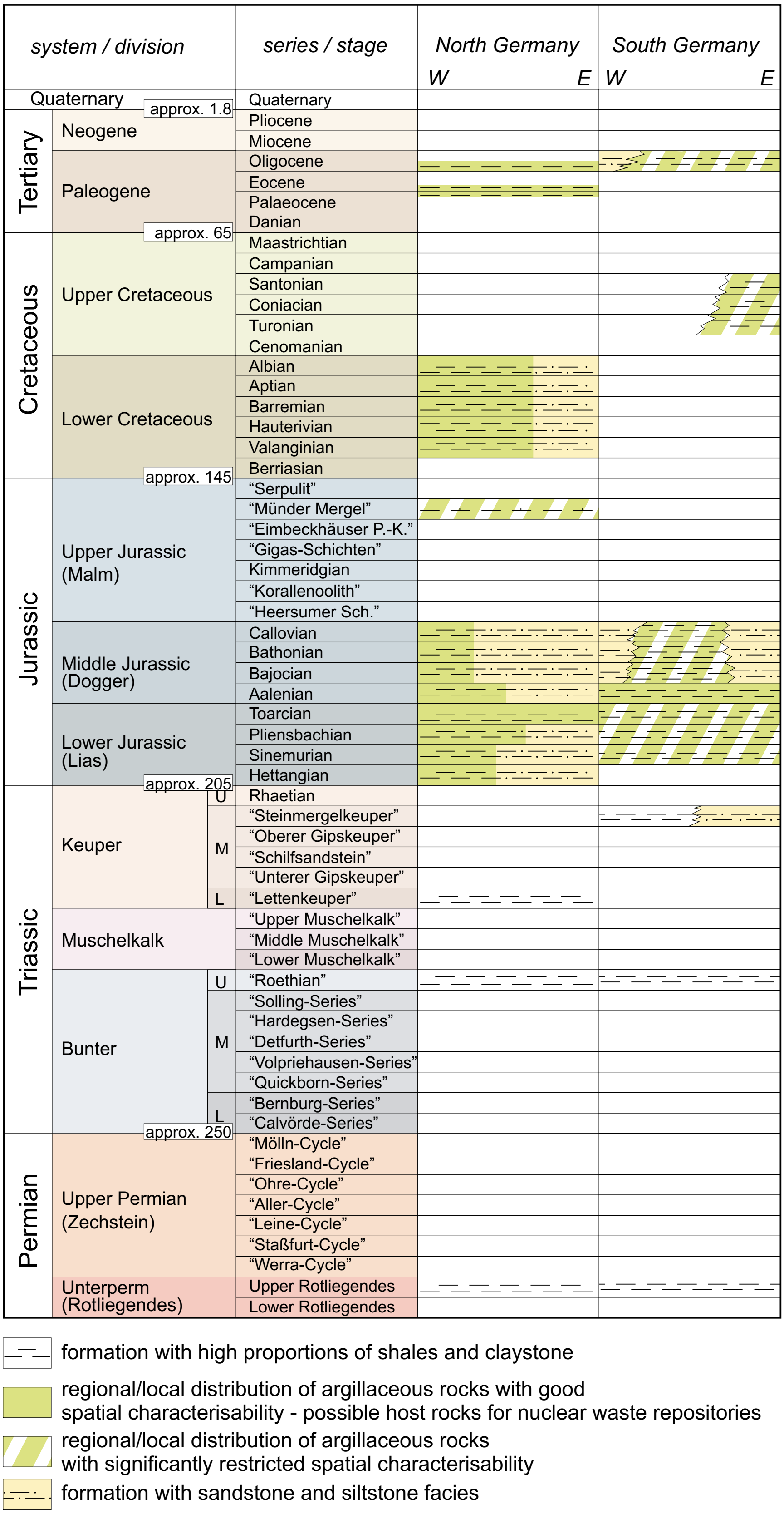


Figure 4.4: Stratigraphic position of argillaceous rock formations in Germany

The following must be observed when evaluating the thicknesses relevant for final disposal: the Opalinus Clay formation consists almost completely of claystones. In contrary, the argillaceous rock formations within the marine Lower Cretaceous for instance, consist of several argillaceous rock strata of varying thickness with interbedded sediments including sandstones and siltstones. The whole of the Opalinus Clay formation is therefore specified as host rock. In the case of the marine Lower Cretaceous or Lower and Middle Jurassic sediments in North Germany, specific claystone strata in the formations with thicknesses of at least 100 m need to be considered separately and correlated with one another.

4.1.1 Jurassic argillaceous rock formations

Figure 4.5 shows the general distribution of Jurassic clays and claystones in Germany. Thick claystones occur in North Germany within the Lower and Middle Jurassic. Because of the global expansion of the marine environment at the Triassic/Jurassic boundary, deposition in the Norddeutsches Becken at this time was almost completely marine. As the Lower Jurassic proceeded, the depositional conditions changed with cyclic marine transgressions and regressions. The Lower Jurassic sediments in the Norddeutsches Becken generally consist of more sandy facies in the east and more argillaceous facies in the west (also known as basin facies) (Brand & Hoffmann 1963). The arenaceous sediments were primarily sourced from the north-east and south-east.

The marine conditions prevailed from the Lower Jurassic into the Middle Jurassic. The Middle Jurassic also contains argillaceous deposits several hundreds of metres thick. However, these claystone sequences were more frequently interbedded with sandstones than was the case in the Lower Jurassic. According to Boigk (1991), the shallow marine and the coastal sands sourced from the east were deposited right up to the western margin of the Gifhorn and East Holstein Troughs. Sand was also brought in from a delta lying to the north which laid down tongue-like sand deposits extending almost as far as the Rhine Block.

The most important potential barrier rocks in South Germany were described in AG Deponien (1997). The study looked at the following claystone-bearing sequences in the Jurassic in the states of Baden-Württemberg and Bayern:

Lower Jurassic: Baden-Württemberg / Lias β (Lower and Upper β Clays)

Lower Jurassic: Bayern / Lias δ and ε (Amaltheen Clay and Posidonia Shale)

Middle Jurassic: Baden-Württemberg and Bayern / Dogger α (Opalinus Clay).

The Lower Jurassic claystones in South Germany do not fulfil the minimum criteria for thickness (≥ 100 m) and are therefore not looked at any further. This means that the only Jurassic claystones considered worthy of further investigation are the claystones of the Dogger α (Opalinus Clay). The Opalinus Clay was deposited in a shallow epicontinental sea which had existed since the Lower Jurassic (Ziegler 1982). The nearest land masses were the Vindelitian Land in the east, and the Alemannian Land located in the region of the present Aar-Gotthard Massif. The Alemmanian Land was probably also partially flooded during the Aalenian at least. A carbonate platform existed in the west whose eastern margin ran to the southwest from the Alsace to Burgundy (Ohmert & Rolf 1994). The Opalinus Clay in the Molassebecken stretches from southern Baden-Württemberg eastwards well into Bayern where the boundary (south-eastern boundary against the Vindelitian Land) runs slightly east of a line running through Coburg, Amberg, Regensburg and München (Meyer & Schmidt-Kahler 1996).

The Opalinus Clay is also present in the southern part of the Oberrheingraben. Most of the graben fill itself consists of thick Tertiary sedimentary packages which are also underlain by argillaceous sedimentary series of Jurassic age from the south up to the level of Heidelberg. The tectonic structure of the around 300 km long and 35 km wide graben is defined in particular by the active graben boundary faults to the east and west of the Rhine and the numerous en echelon faults within the graben. Because of the strongly tectonised structure of the region it can be assumed that the argillaceous rocks are partially broken up by rupture and fracture zones, and that the synsedimentary effects of these tectonic units will create series which are very lithologically inhomogeneous, with barrier functions which are difficult to define spatially. All of the argillaceous rock formations in the Oberrheingraben are considered unworthy of further investigation because of the unfavourable tectonic conditions described above and partial exclusion as an earthquake zone > 1 (cf. also LGRGB 2005).

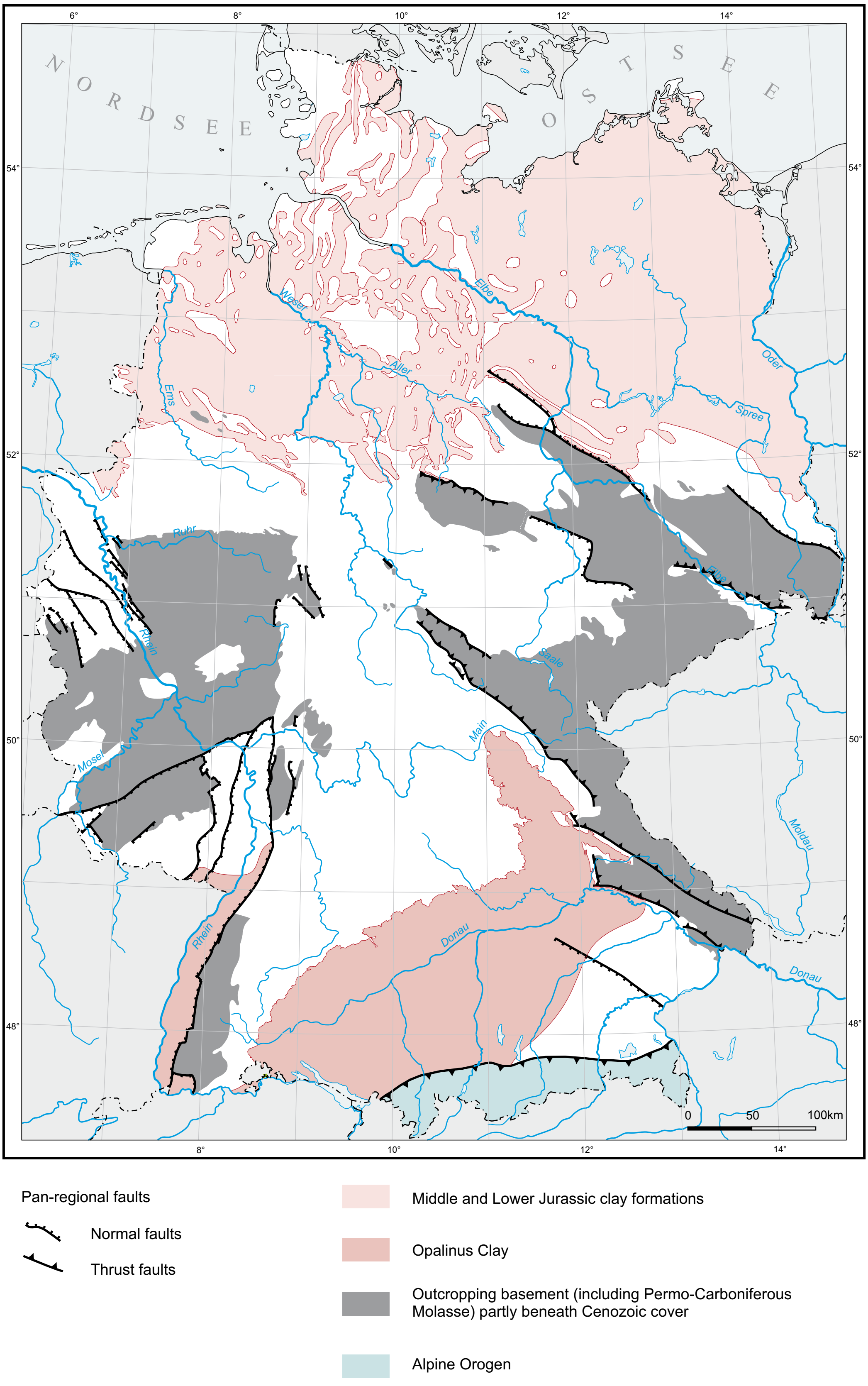


Figure 4.5: Schematic distribution of Jurassic clay formations

4.1.2 Cretaceous argillaceous rock formations

Figure 4.6 shows the general distribution of Cretaceous clay formations in Germany. The argillaceous sediments of this stratigraphic period are largely found in North Germany. Unlike the situation in the Upper Jurassic, there was almost no connection at all to the open ocean during the Berriasian (Wealden). Sapropelic claystones deposited in the central part of the basin are typical of this sedimentary sequence. Sand was also transported into this basin from the continent to the south. At the proximal ends of the sedimentary fans, thick sandstone units interbed with silty-argillaceous sediments which grade into sapropelic claystones towards the centre of the basin. The end of the Wealden is marked by a few marine transgressions to produce interbedded brackish-limnic and marine sedimentary sequences (Boigk 1991). The whole of the Niedersachsen-Becken and even parts of the Pompekjian high were again covered by marine water during the Valanginian (Kemper 1973).

Most of the sediments deposited in the Lower Cretaceous marine facies in north-west Germany consist of dark-grey claystones, argillaceous marlstones and marlstones. Interbedded sandstones sourced from the Rhine Massif and the East-Holland Ridge mainly occur in the western and southern part of the Niedersachsen-Becken.

An extension of the Niedersachsen-Becken stretches to the north-east into south-west Mecklenburg and north-west Brandenburg as far to the east as Vorpommern and into the Niederlausitz. Wealden deposits in this part of the basin reach up to 900 m thick in parts (Diener 1968). Marine transgression did not occur here until the Upper Valanginian, and in some cases not until the Hauterivian. Continuous sequences of Hauterivian to Aptian sediments are only known in the western part of this depositional basin. The sediments in these areas are mainly argillaceous marlstones and claystones. The northern and eastern regions in Mecklenburg-Vorpommern and Brandenburg contain incomplete sedimentary sequences with a high proportion of sandstones.

Thicker argillaceous sediments occur in South Germany in the Upper Cretaceous of Bayern and particularly in the Wasserburger Basin and the Braunauer Trough. According to Unger & Meyer (1996) the Wasserburger Basin also contains sediments of Lower Cretaceous age. The thickness of Upper Cretaceous sediments in this basin exceeds 500 m, with up to 1000 m in the Braunauer Trough. These two basins began to develop from the Upper Cenomanian and experienced extensive subsidence in the Coniacian in particular. Poorly to moderately sandy argillaceous marls with fine-grained to medium-gained sandstone interbeds were deposited in the Santonian in particular. This type of sedimentation also continued in the Braunauer Trough in particular up until

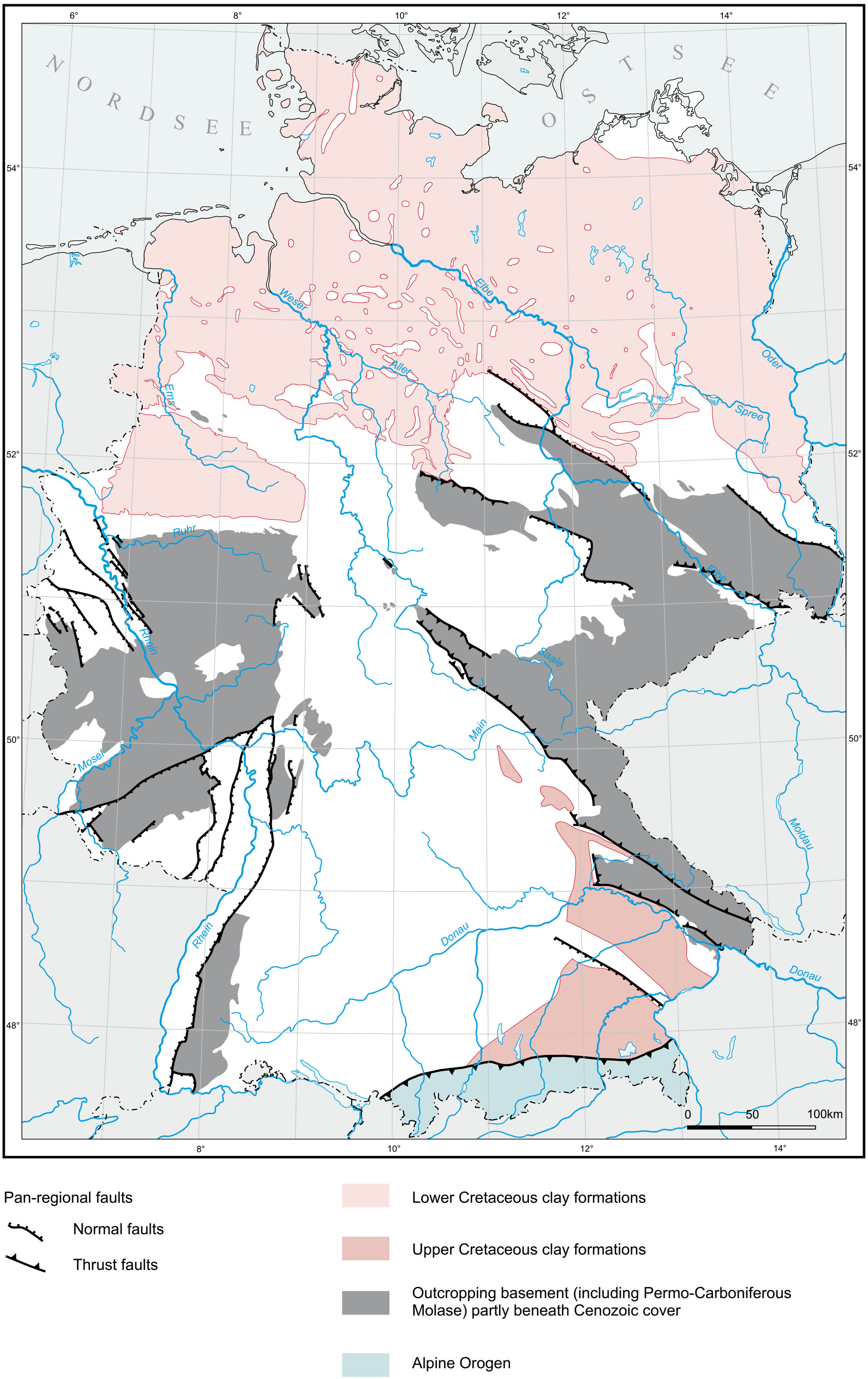


Figure 4.6: Schematic distribution of Cretaceous clay formations

the Campanian, depositing large thicknesses of sediments. The current understanding is that the Campanian sediments represent the last Upper Cretaceous deposits laid down in the Alpine Foreland Region.

A detailed evaluation of 16 wells (e.g. Endorf 2, Albaching 2, Ampfing 1, Thanndorf 1, Birnbach 1, Parkstetten 1) drilled in the Wasserburger Basin and the Braunauer Trough, which all penetrated the Upper Cretaceous, revealed the presence of argillaceous marls and argillaceous marlstones with thicknesses > 100 m in both basins. However, these sedimentary sequences contain sandstone interbeds of varying thickness in some of the wells. The clay/claystone proportion of these sequences estimated from geological and well logs is mostly only 65 %. Although such rock sequences can under certain circumstances satisfy the specifications defined in Chapter 3.2.1 for very low field hydraulic conductivity ($k_f > 10^{-10}$ m/s), the fact that this clay/claystone proportion is accompanied by very strong facies variability, leads to the conclusion that the basic specifications would probably not be fulfilled. Moreover, the Upper Cretaceous argillaceous marl in the Wasserburger Basin lies at depths exceeding 1500 m. The Upper Cretaceous deposits in Bayern are therefore not considered to be suitable host rocks for nuclear repositories for the reasons discussed above.

4.1.3 Tertiary clay/claystone formations

Thick Tertiary argillaceous sediments are present in the North German Basin, the Oberrheingraben and the Alpenvorlandbecken. Figure 4.7 shows that the largest area in the country with Tertiary clays and claystones is North Germany. The Tertiary in this area began with a basin-wide regression so that marine sediments were not deposited again until the basin-wide transgression in the Upper Palaeocene and Eocene. Thick and widely distributed clays and claystones are present in North Germany in Upper Palaeocene, Eocene, Middle Oligocene and Middle Miocene sequences. The distribution of the boundary in the North German realm shown in Figure 4.7 corresponds with the argillaceous Upper Palaeocene and Eocene sediments. Figure 4.8 shows the depth of top Lower Eocene to Palaeocene which roughly corresponds to the top of these argillaceous rock formations. The red colours highlight areas with depths >1500 m bsl, green colours zones with depths between 250 m and 1500 m bsl. The white patches within the areal distribution are mostly areas defined by salt structures where there are no argillaceous sediments. The depth map of the top Lower Eocene to Palaeocene reveals that claystones in parts of Schleswig-Holstein and around Hamburg are too deep to meet the minimum requirements. Large parts of south Niedersachsen, Sachsen-Anhalt, Mecklenburg-Vorpommern are also excluded because the clay sediments here are shallower than the specified minimum depth of 300 m.

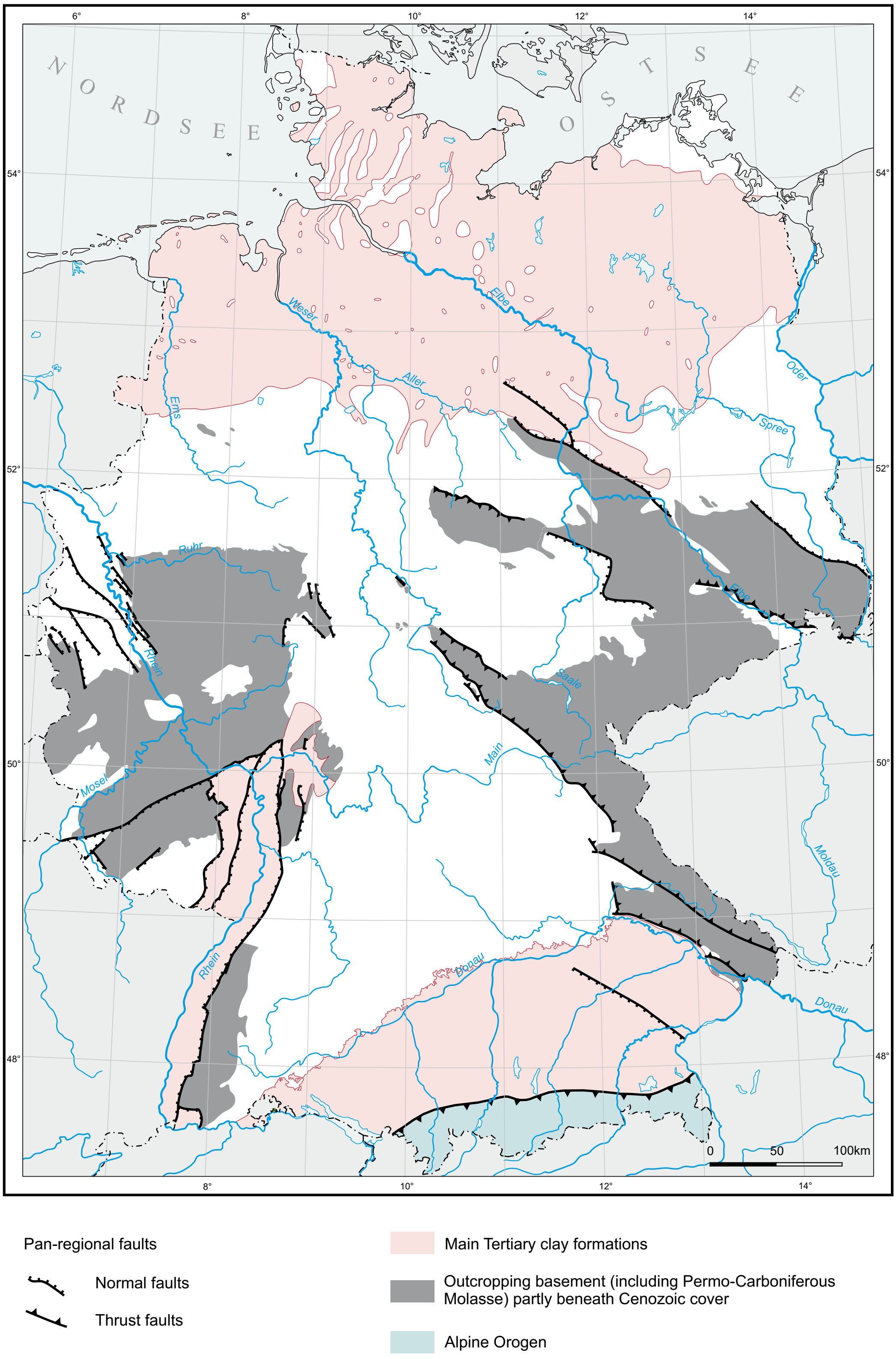


Figure 4.7: Schematic distribution of Tertiary clay formations

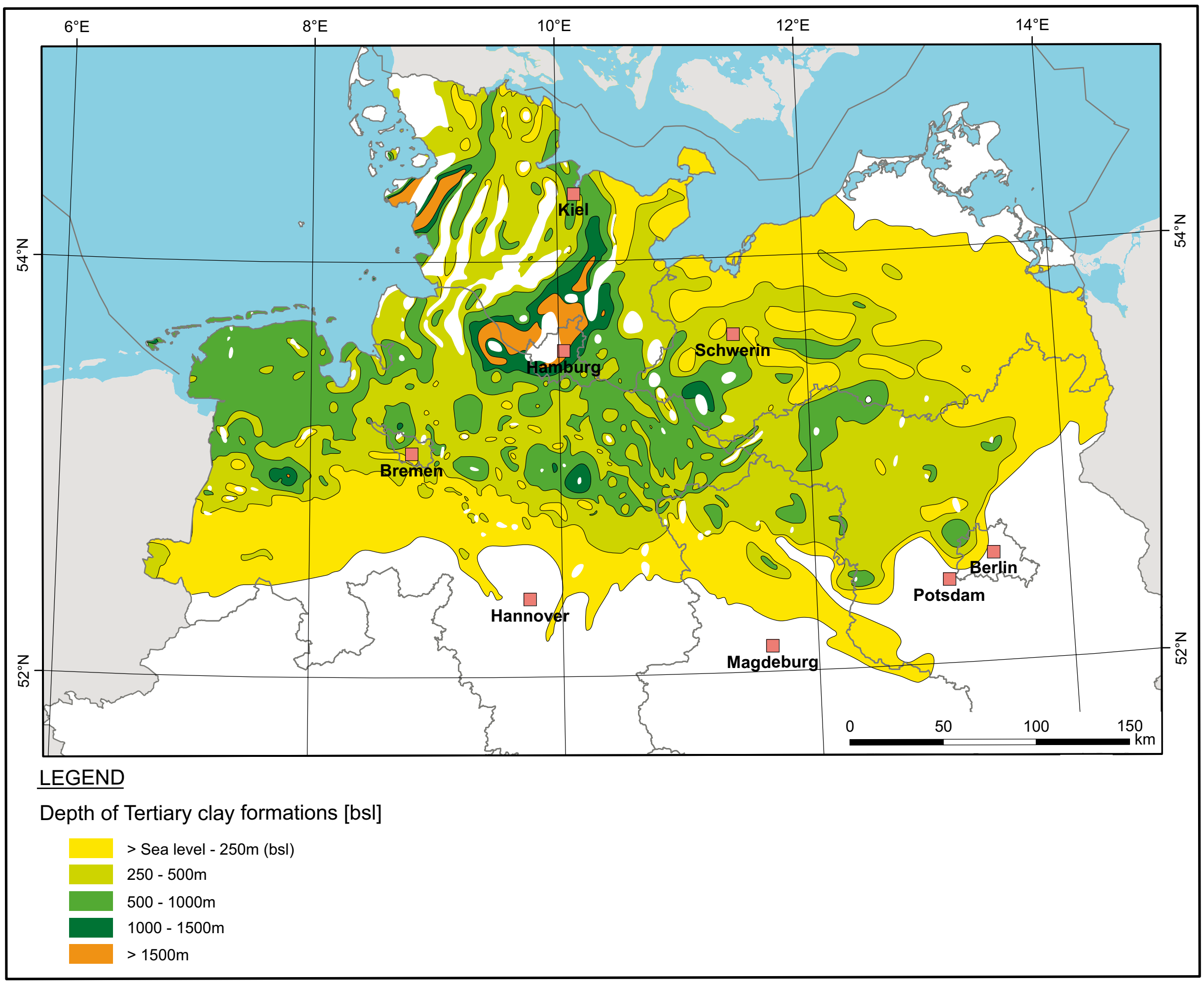


Figure 4.8: Depth of Tertiary clay formations (top Lower Eocene to Palaeocene)

Analysis of the thickness of the argillaceous sediments also reveals that the specified minimum thickness is also not fulfilled in the southern margins of the basin and in eastern North Germany (parts of Brandenburg and Mecklenburg-Vorpommern). However, particularly thick sequences are found especially in northern Niedersachsen and parts of Schleswig-Holstein.

It should be noted when assessing the host rock suitability of the Oligocene Rupelian Clay in North Germany that this is the most important barrier between the salt and the freshwater stock works and therefore lies directly adjacent to receptors.

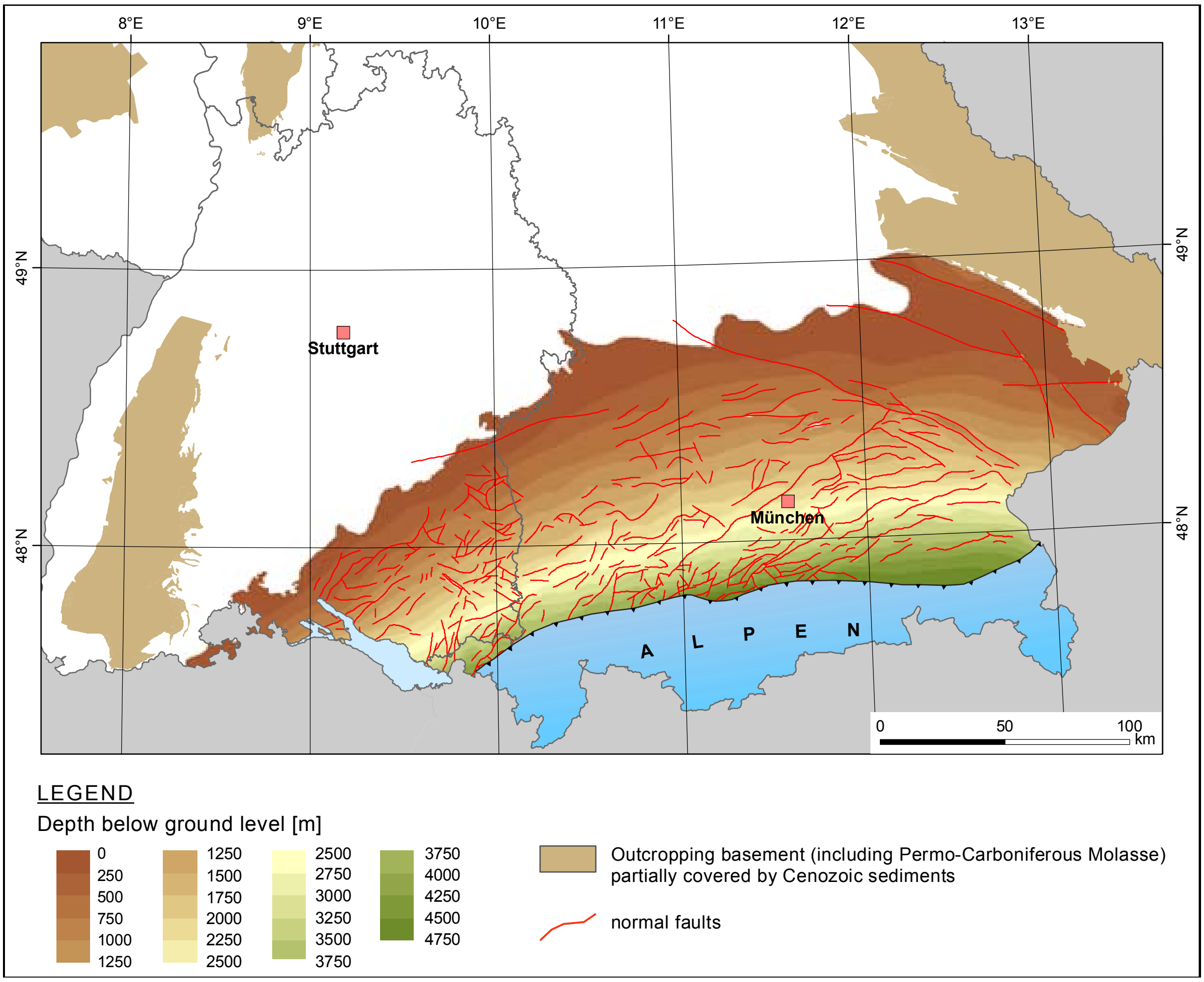


Figure 4.9: Depth to base Tertiary in the Alpenvorlandbecken

Another important area with Tertiary clays and claystones is the Oberrheingraben. The graben fill itself mainly consists of thick packages of Tertiary sediments. However, because of the unfavourable tectonic and lithological conditions described in Chapter 4.1, these clays/argillaceous rock formations are not considered further in this evaluation.

The Tertiary sequences in the Alpenvorlandbecken (Figure 4.9) are at their thinnest in the north, with a thickness of around 100 metres, but thicken towards the Alps to over 5000 m (see e.g. Geyer & Gwommer 1991; Freudenberger & Schwerd; Rohrmüller 2003; Drong 2003). Even greater thicknesses have been penetrated in wells drilled south of the boundary of the Alpine Thrust. The many wells drilled by the oil and gas industry prove that these sedimentary sequences not only consist of coarse clastic rocks (sandstones, conglomerates) but also thick fine-grained clastic rocks (claystones and siltstones) as well as finer calcareous sediments.

Schwerd et al. (1996) for instance provide a good summary of the total facies development in the Tertiary sediments. The Oligocene sediments were mainly deposited in marine environments and the sequence of the „untere Meeresmolasse” also includes argillaceous marl beds, particularly close to the Alpine margin. These sediments are overlain by the „untere Süßwassermolasse“ (Upper Oligocene) which also contains argillaceous marl beds although not as thick as in the underlying sequence. A hiatus exists between the „untere Süßwassermolasse“ and the „obere Meeresmolasse“ deposited in the Lower Miocene. Argillaceous and fine-grained sandy siltstones represent the fine-grained clastic rocks in this sedimentary sequence. The „obere Süßwassermolasse“ deposits were laid down from Middle to Upper Miocene after the marine regression. In addition to sandy sediments, this sequence also contains very calcareous marlstones, siltstones and claystones, which also contain lignite in parts.

The argillaceous rocks deposited under these variable sedimentary conditions form good hydrogeological barriers in some cases. However, the configuration of the sedimentary bodies is very complicated because of the highly variable depositional environments (fluviatile channels, flood plains, lacustrine and marine depositional environments) which existed in the Alpenvorlandbecken (see also NAGRA 2005). For this reason, properly mapping the claystones in accordance with the minimum requirements is considered to be very limited.

In conclusion, the clays and claystones of the Tertiary are of enormous importance as hydrogeological barriers. In addition to the restrictions already discussed with respect to fulfilment of the minimum requirements and their characterisability, other restrictions apply with respect to their suitability as host rocks. Because of the largely only minor to very minor degree of consolidation of Tertiary clay sediments, it can be assumed at least in the upper part of the designated zone of interest (between 300 m to around 500 m) that because of the age of the sediments and their exposure to only minor temperatures and compaction that these rocks are primarily still clays or at best rocks at the transition to claystones. Because of the associated unfavourable geomechanical properties of such rocks and their sensitivity towards significant increases in temperature (mineralogical reactions), considerable restrictions are placed on their potential suitability as host rocks in Germany. Claystones of Upper Palaeocene and Eocene age in North Germany, and claystones in the „untere Meeresmolasse“ and „untere Süßwassermolasse“ in South Germany, are therefore not considered worthy of further investigation.

4.2 Limitation of partial areas worthy of further investigation

After discussing the general distribution of clay and argillaceous rock formations, in the next step, the argillaceous rock formations classified as worthy of further investigation as potential host rocks from a geological point of view, were divided up further into the following regional stratigraphic units.

Lower Jurassic (Lias)	North Germany	Chapter 4.2.1
Middle Jurassic (Dogger)	North Germany/South Germany	Chapter 4.2.2/4.2.4
Lower Cretaceous	North Germany	Chapter 4.2.3.

The delimitation of regions with clay/claystone formations worthy of further investigation in the aforementioned rock formations or stratigraphic intervals involves a step-by-step evaluation looking at the exclusion criteria and minimum requirements (cf. Chapter 3.6.2 and 3.6.3).

It should also be noted that argillaceous rock formations below 1000 m depth are probably associated with very difficult rock-mechanical conditions which would make mining very expensive and the operation of a nuclear repository very difficult. In addition to these rock-mechanical aspects, the selection of a maximum depth for a nuclear repository mine also needs to take into consideration the temperature in the emplacement zones. The maximum depth for a nuclear repository mine is therefore defined as 1000 m taking these two aspects into consideration (cf. Chapter 3.6.3).

Other geological aspects which make adequate forecasting difficult, and complicate spatial characterisation, are the extremely steep bedding in the vicinity of salt structures, faults and narrow elongated structures. The latter significantly restrict the ability to construct emplacement tunnels, and therefore fail to comply with the specification for a favourable overall geological setting.

The criteria defined in Chapter 3.6 were applied step-by-step to select partial areas worthy of further investigation. How this procedure was put into practise will be demonstrated using the Lower Jurassic argillaceous rock formations in North Germany, and the Opalinus Clay formation in South Germany. The maps discussed in the following primarily concern stratigraphic and in some cases also geophysically distinguishable rock formations primarily consisting of argillaceous rocks. The thicknesses of the beds given in these maps are not therefore pure (100%) clay or claystone.

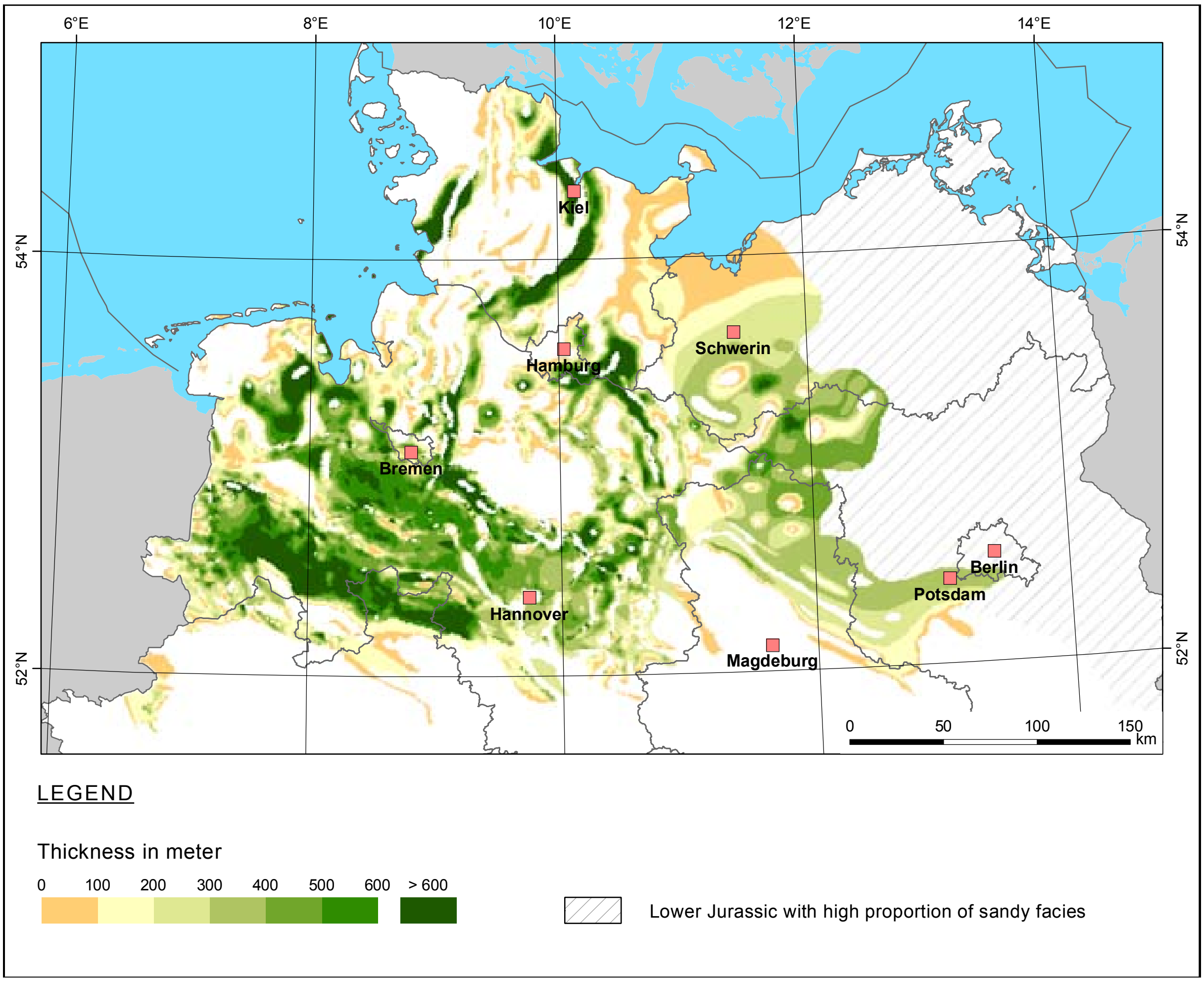


Figure 4.10: Thickness of Lower Jurassic in North Germany

4.2.1 North Germany – Lower Jurassic

The Lower Jurassic in North Germany is between 100 metres and maximum approx. 1500 metres thick (see Figure 4.10). The greatest thicknesses are in north-west Germany where they are concentrated in two roughly NW-SE striking and around 50 km wide zones in Niedersachsen (central north-west part of the Norddeutsches Becken and Niedersachsen-Becken), and Rhenohercynian aligned troughs or basins (NNE-SSW). The formation of the latter is associated at least in part with movement of the Permian evaporite sequence. The “Gifhorn-Hamburg Trog” is also characterised by significant thicknesses. The up to 1500 m thick rock sequences in this area which have been locally penetrated by wells primarily contain generally calcareous to marly, dark-coloured claystones.

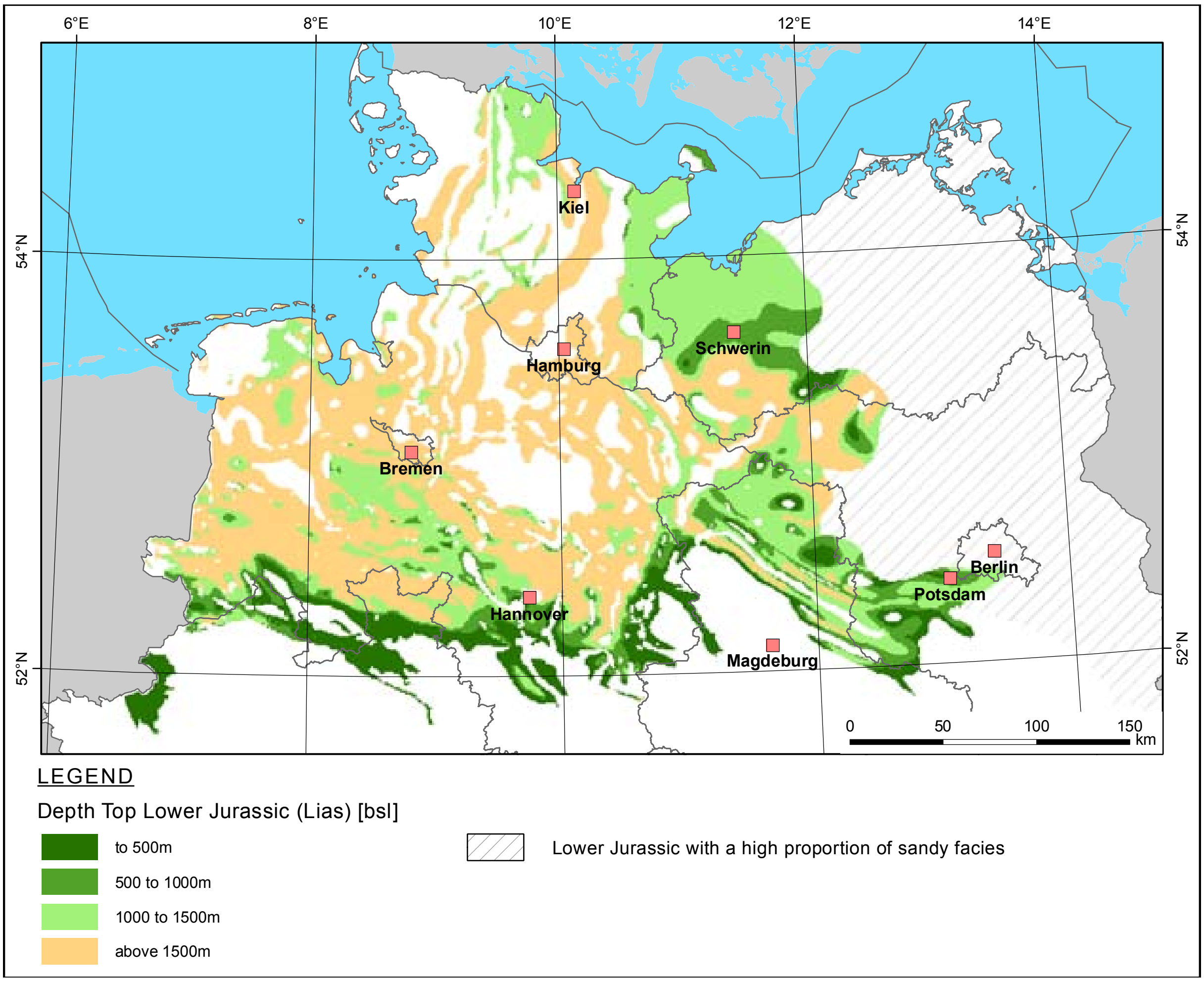


Figure 4.11: Depth Top Lower Jurassic in North Germany

Outside of these areas, much of the remainder of Niedersachsen and Schleswig-Holstein only have residual thicknesses of Lower Jurassic or no Lower Jurassic at all. The thickness in the eastern part of North Germany is mainly between 200 m to 400 m: greater thicknesses of up to 800 m in the east of the Norddeutsches Becken only occur in highly localised areas.

The Lower Jurassic deposits can generally be divided up into two main facies (BRAND & HOFFMANN 1963; KÖLBEL 1968; TESSIN et al. 1975). The basin facies is dominated by claystones and argillaceous marlstones, whilst the shallow water facies close to the coast primarily consists of coarse clastic sediments. The Posidonia Shale of Lower Toarcian age is the most important and economically most significant mapping horizon in the basin facies. The Posidonia Shale is an around 20 m to 40 m thick claystone to

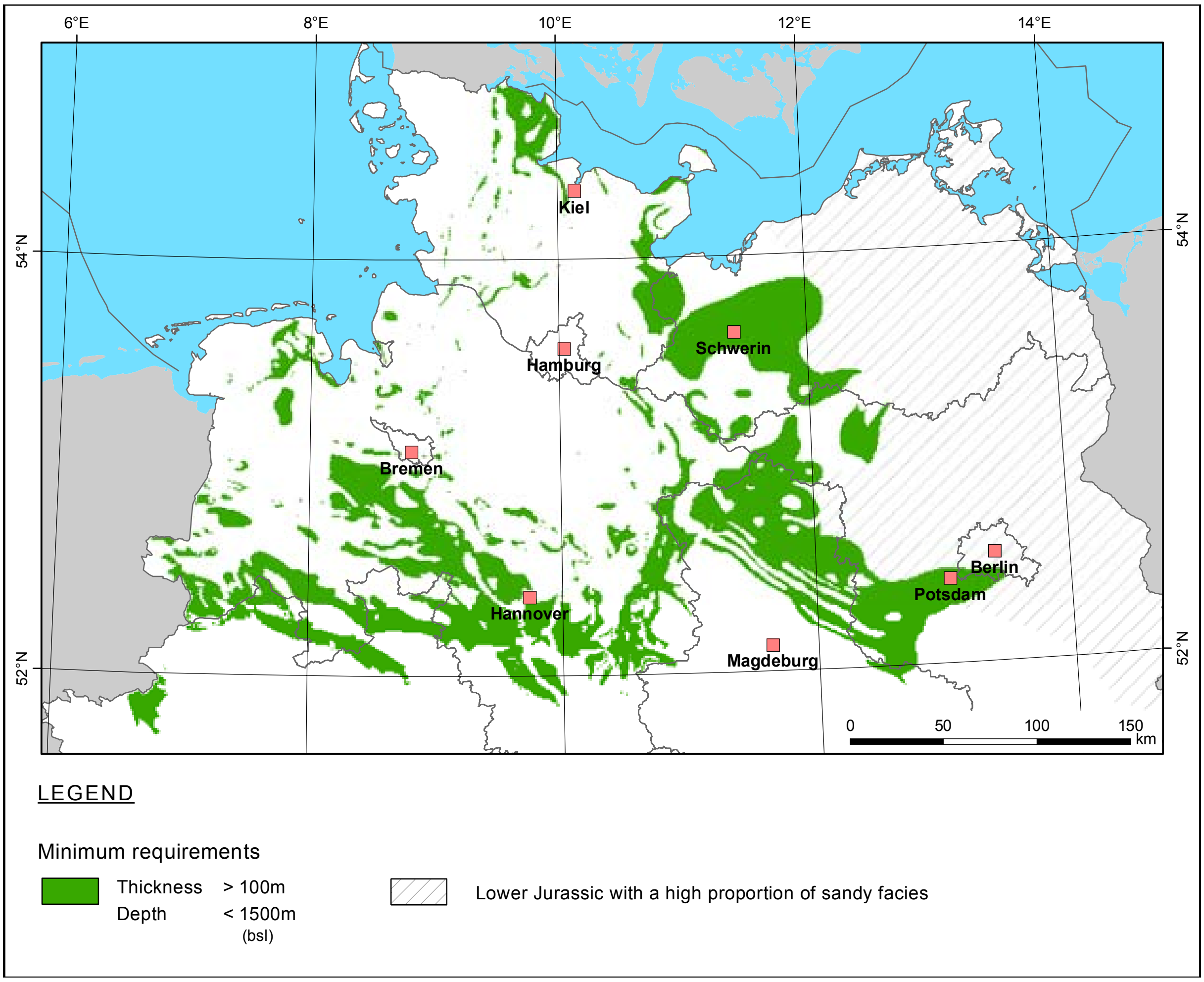


Figure 4.12: Lower Jurassic: application of AkEnd criteria “thickness and depth”

marlstone bed containing up to 15 % organic carbon. This horizon can be very easily identified by Gamma Ray Logs in wells because of its high natural radioactivity. And its different petrophysical properties compared to the surrounding rocks also make it an outstanding seismic marker. It is also an important oil source rock which accounts for some of the oilfields in north-west Germany (Binot et al. 1983; Kockel et al. 1994). The Posidonia Shale has also been confirmed in the eastern part of the Norddeutsches Becken in west Mecklenburg, in north-western Brandenburg and in the Altmark. The organic content decreases continuously to the east, and the Posidonia Shale is no longer present east of a line running approximately between Rostock and Brandenburg. According to the lithological/paleogeographic maps of the Lower Jurassic elaborated by Tessin et al. (1975), the boundary between the two facies described above corresponds roughly to the distribution boundary of the Posidonia Shale and its equivalents. Unlike

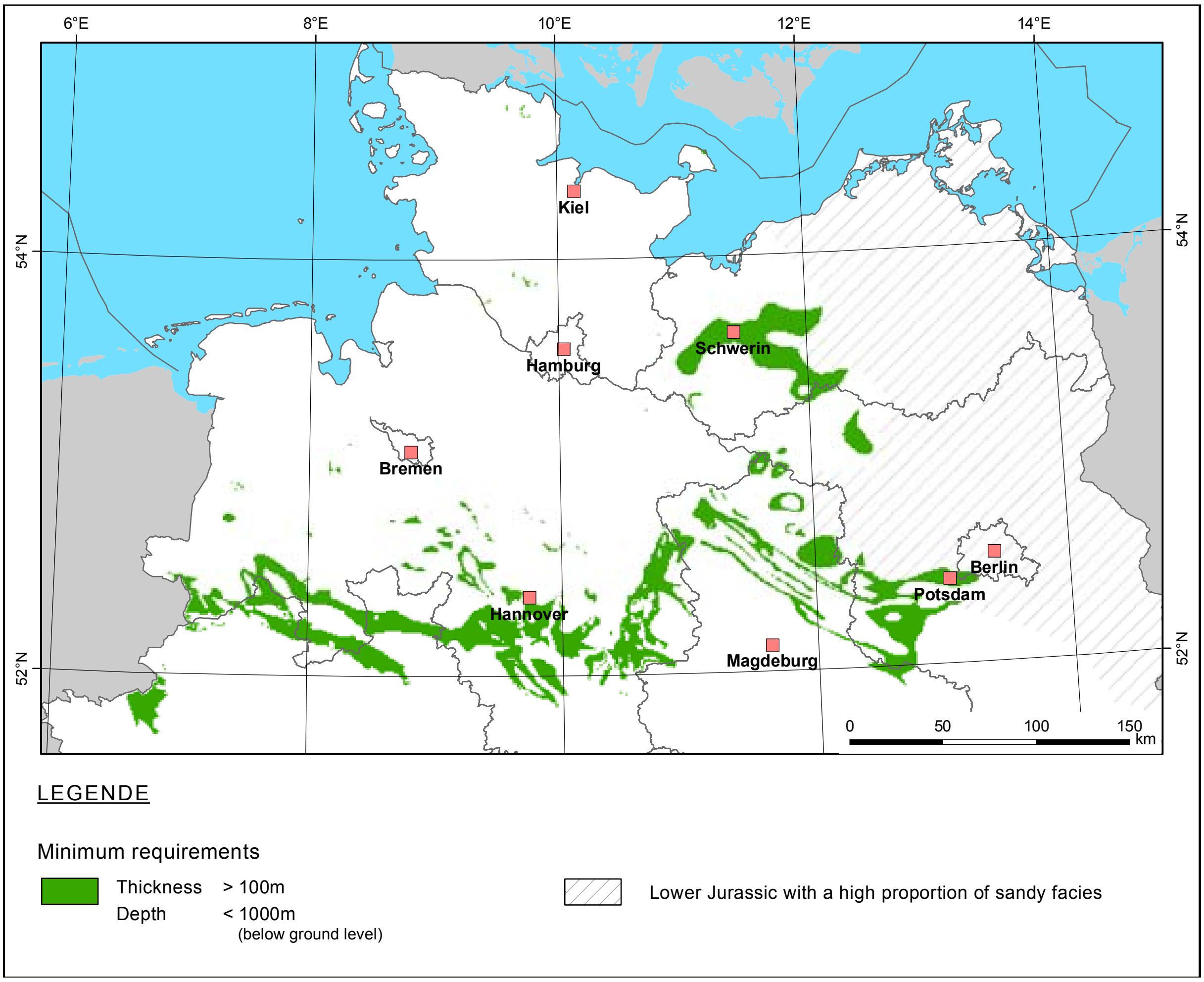


Figure 4.13: Lower Jurassic: Application of the host-rock specific criteria

the western (marine) facies zone, numerous sandstone horizons occur in the eastern areas. The arenaceous constituents were transported into the Norddeutsches Becken from the north-east and the south.

Evaluation of the wells using the method discussed in Chapter 3.2.1 (cf. Figure 3.2) revealed that the existing lithological/paleogeographic maps (ZGI 1978) are suitable for delimiting regions dominated by sandstones and siltstones with only subordinate claystones. It can therefore be assumed that because of the numerous thick sandstone interbeds in the eastern parts of Brandenburg and Mecklenburg-Vorpommern, there will be no argillaceous rock formations in these areas which fulfil the minimum specifications for homogeneous thickness (> 100 m), and the specified field hydraulic conductivity of $k_f < 10^{-10}$ m/s. The Lower Jurassic in these areas is therefore excluded from further investigation. To ensure that there is an adequate safety margin, the boundary was

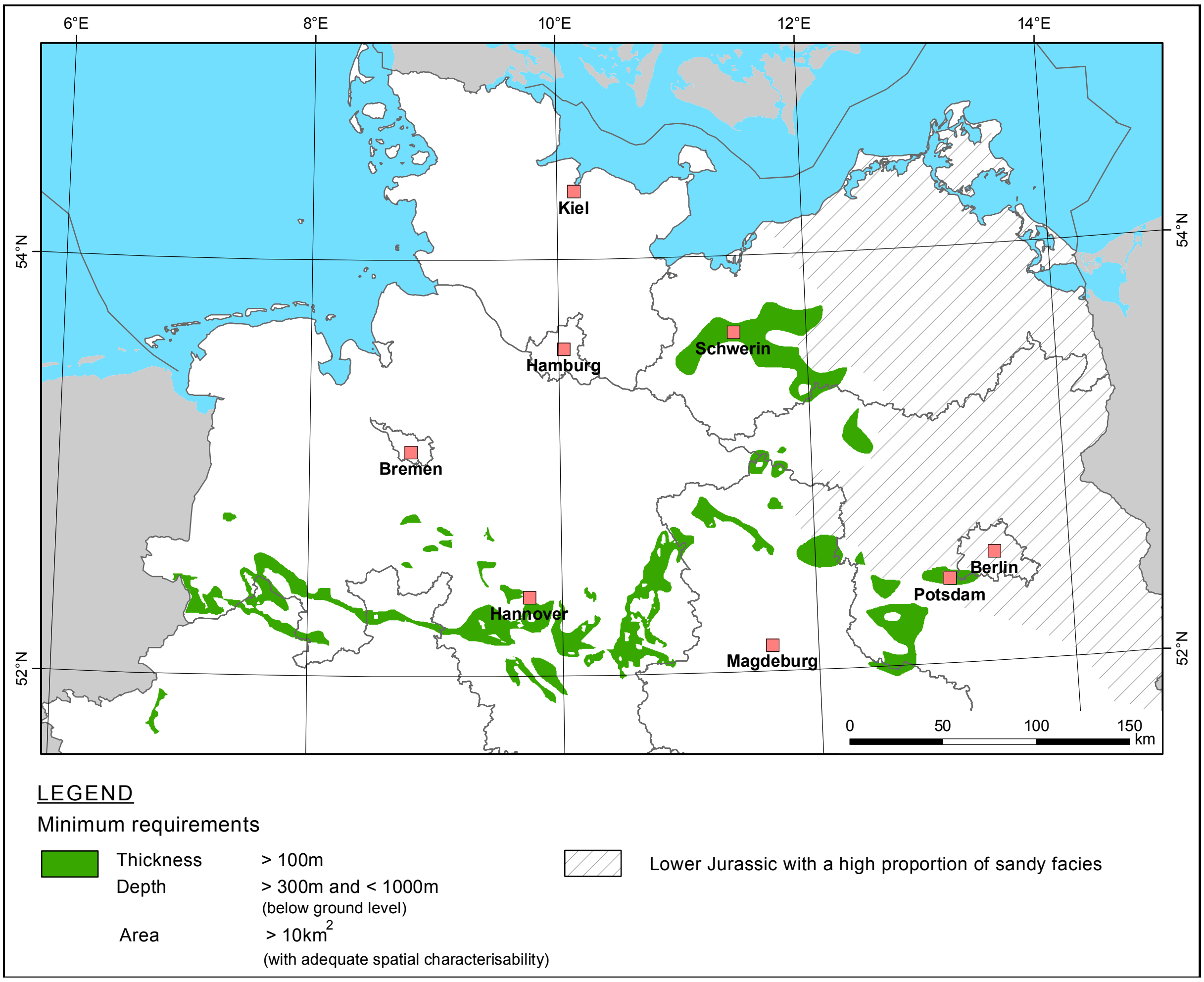


Figure 4.14: Lower Jurassic: Application of all selection criteria defined in Chapter 3.6

drawn analogous to the distribution of the Green Series of Toarcian age (name derived from the presence of green-grey argillaceous marlstones and sandstones). In Figures 4.10, 4.11, 4.12, 4.13 and 4.14 the hachured areas mark Lower Jurassic containing higher percentages of sandstone.

Figure 4.11 shows the depth of Top Lower Jurassic. Areas < 1500 m deep are shown in green. The diagram clearly shows that Lower Jurassic argillaceous rock formations in many regions in North Germany lie deeper than the specified maximum depth and are therefore unsuitable for the final disposal of high-level radioactive waste in a repository mine. The depth criterion alone significantly reduces the number of partial areas worthy of further investigation.

A further reduction in candidate areas is produced by combining the depth to top Lower Jurassic with the thickness data (Figure 4.12). Superimposing both diagrams highlights the remaining partial areas which fulfil the minimum safety-based requirements for thickness (100 m), rock types with low field hydraulic conductivity ($k_f < 10^{-10}$ m/s) and depth (max. 1500 m). The remaining partial areas are found in Niedersachsen, Mecklenburg-Vorpommern, Sachsen-Anhalt, Brandenburg as well as to a lesser extent in Schleswig-Holstein and Nordrhein-Westfalen.

The following aspects and criteria were then applied in the next delimitation stage:

- Minimum depth of 300 m to top of the effective rock isolation zone
- Maximum repository depth 1000 m
- Effective rock isolation zone must cover an area of at least 10 km^2 and be adequately spatially characterisable
- No steep bedding in the vicinity of salt structures or faults.

When all of these criteria are taken into consideration, this leaves behind those partial areas in North Germany shown in Figure 4.14 containing Lower Jurassic claystone host rocks worthy of further investigation in parts of Niedersachsen, Sachsen-Anhalt, Brandenburg and Mecklenburg-Vorpommern.

4.2.2 North Germany – Middle Jurassic

Unlike the Lower Jurassic argillaceous formations, depositional environments in the Middle Jurassic were much more heterogeneous (frequent lateral and vertical changes in lithofacies). The Middle Jurassic sequence therefore needs to be analysed in greater detail when evaluating claystones as potential host rocks for the final disposal of high-level radioactive waste.

The distribution of the Middle Jurassic in North Germany shown in Figure 4.15 is based on several sources: Schön et al. 1988; Diener et al. 1989, 1990; Diener & Wormbs 1990; Diener et al. 1992b, a, 1991; Wormbs 1989, Geophysik Leipzig 1989; Baldschuhn et al. 2001). Well data was used to verify the boundaries and correct them where required.

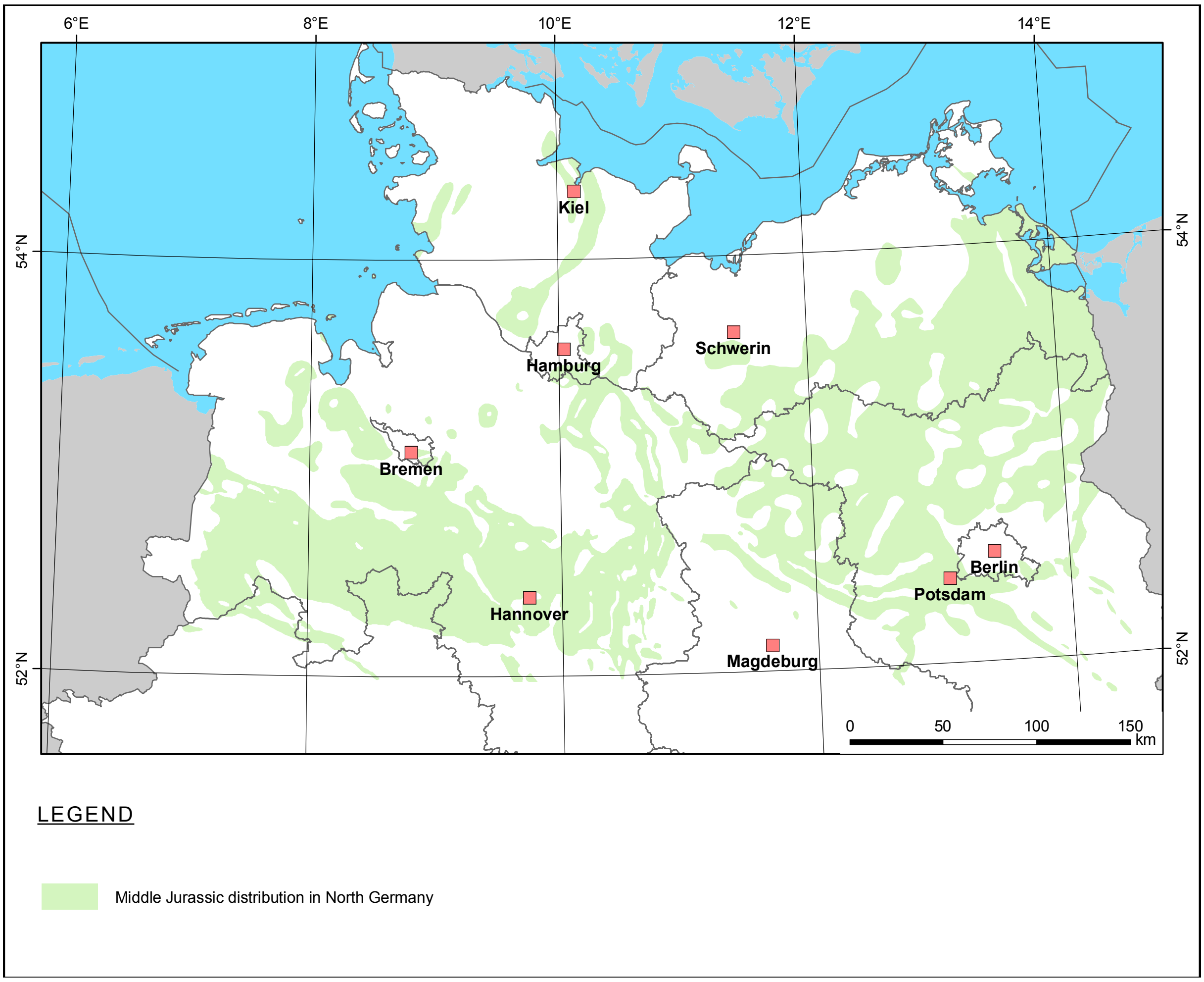


Figure: 4.15: Middle Jurassic distribution in North Germany

The investigations reveal that the thick argillaceous rock formations in north-west Germany are extensive, unlike north-east Germany where they tend to be localised or regional at best. The thickness of the Middle Jurassic varies between 10 m to more than 1000 m. Very large thicknesses occur in the eastern and western Glückstadt Graben, in the Braunschweig-Gifhorn Zone, as well as in primary and secondary rim synclines around some salt domes. The Middle Jurassic is locally also more than 800 m thick in southern Niedersachsen. Minor thicknesses (up to 100 m) mainly occur along the Middle Jurassic pinch-out. The eastern parts of Mecklenburg-Vorpommern and Brandenburg also have thin Middle Jurassic sequences (up to max. 220 m).

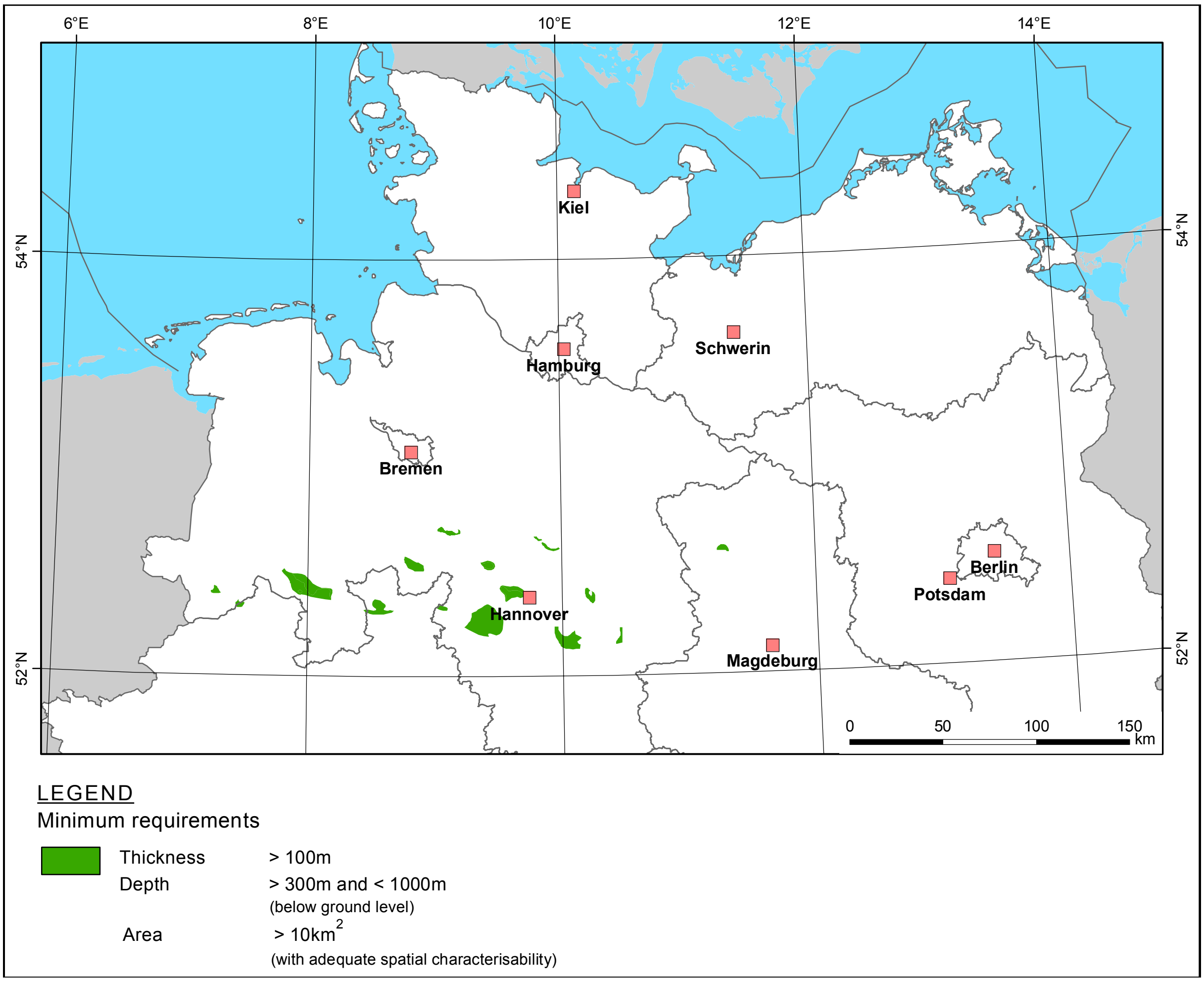


Figure 4.16: Middle Jurassic: Application of all selection criteria from Chapter 3.6

Well analysis revealed that argillaceous rock formations with thicknesses exceeding 100 m occur in various stages of the Middle Jurassic and are marked by strong differences in facies. Although claystones are the dominant lithology in the sedimentary sequence penetrated by wells, the numerous interbeds of siltstones, sandstones and limestones reduce the proportion of clay or claystones in the sequences to below 60 % in many regions. These regions are therefore not looked at further because the specified low field hydraulic conductivity is either not present or cannot be guaranteed over a wide enough area.

Top Middle Jurassic over large parts of north-west Germany lies at depths exceeding 400 m below ground level. The maximum depths (> 3000 m) occur in the eastern and western Glückstadt Graben. Top Middle Jurassic around the Niedersachsen Block often lies at depths between 300 m and 1400 m. Top Middle Jurassic in north-east Germany lies at depths between 500 m and 1500 m. Depths shallower than 300 m occur in the extreme south and south-east, i.e. the margins of the former sedimentary basins or zones associated with salt structures.

The same iterative procedure discussed in Chapter 4.2.1 is used to identify the partial areas where Middle Jurassic argillaceous rock formations fulfil the minimum geoscientific requirements (thickness, depth, distribution, permeability and/or clay percentage). The remaining areas of interest shown in Figure 4.16 are much more restricted than the Lower Jurassic partial areas. The remaining partial areas cover areas between 15 km^2 and 500 km^2 and are primarily located in southern Niedersachsen.

4.2.3 North Germany – Lower Cretaceous

The general distribution of Cretaceous argillaceous rock formations is shown in Figure 4.6. As already discussed in Chapter 4.1.2, the only sequences of interest for further evaluation are those regions with argillaceous Lower Cretaceous sediments. The Lower Cretaceous in North Germany can be divided up as a simplification into three large chronostratigraphic sections. The first is the transition from the youngest Jurassic sequences. These sediments were laid down in brackish and evaporitic facies (Münder Marl, Serpulite). The next sequences were strongly limnically influenced sandy-clayey sediment (Wealden) with some marine horizons. The second section begins with the Valanginian or Hauterivian. This section was marked by marine transgressions which deposited marine sediments. Therefore, during the Valanginian to Aptian, primarily marine argillaceous-marly sediments were deposited in central basin zones overlying the characteristic sandy-calcareous transgressive horizons. Sediments in the marginal basin zones are dominated by sandy lithologies occasionally containing iron ooids and detrital ore rocks. The third section of the Lower Cretaceous begins around the Middle Albian (increase in marly and calcareous sediments) and marks the transition to the Upper Cretaceous.

Because of this development, the Valanginian to Middle Albian sequence is generally called the marine Lower Cretaceous. The typically dark claystones in this Lower Cretaceous section also contain occasional interbeds of “foliated clay” (Barremian) and “fish shale” (Aptian). The central basin zones are surrounded by regions in which marginal facies were deposited (HISS et al. 2005). These marginal facies typically include hick sandstone interbeds (e.g. Bentheimer, Gildhäuser, Osning and Hils sandstones). These form important oil reservoirs particularly in the Emsland. The marine Lower Cretaceous claystones form the seals of the oil and gas fields to the east and west of the

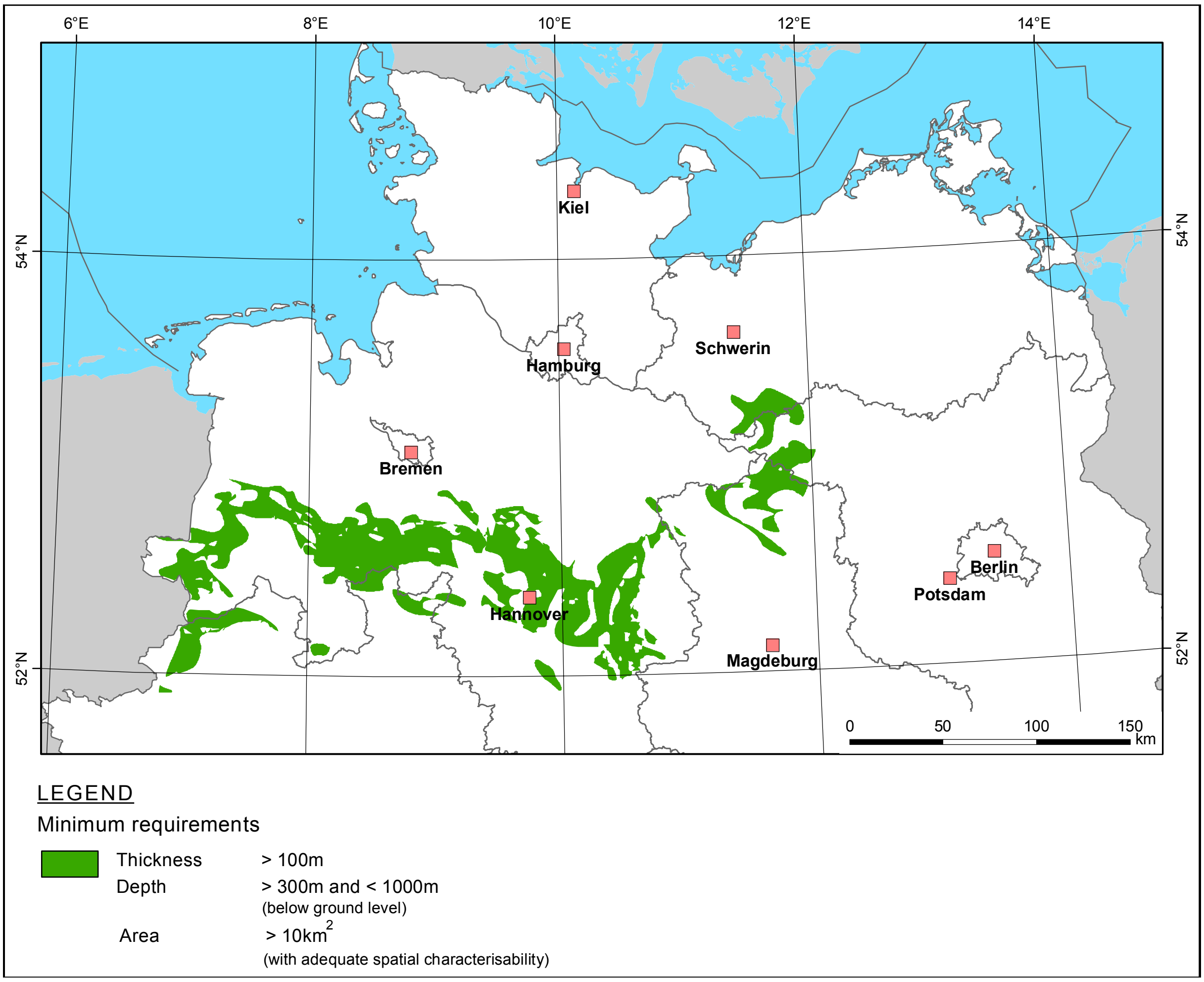


Figure 4.17: Lower Cretaceous: Application of all selection criteria from Chapter 3.6

river Weser and to the west of the river Ems. Detailed descriptions of the lithostratigraphy and lithology of the marine Lower Cretaceous are found in numerous publications (e.g. Diener 1967; Jaritz et al. 1967; Diener et al. 1970; Kemper 1973; Bartenstein 1977; Kemper 1983; Kemper & Weiss 1995; Elstner & Mutterlose 1996; Stratigraphische Kommission Deutschland 2000).

The maximum thickness of the total Lower Cretaceous sequence in the Niedersachsen-Becken exceeds 2000 m (Kemper 1979). The marine Lower Cretaceous also reaches significant thicknesses of several hundred metres and in part over 1000 m in the relevant regions in Niedersachsen.

The thickness of the marine Lower Cretaceous thins dramatically in the regions bordering the Niedersachsen-Becken to the east. Moreover, the northern and eastern regions of the eastern part of the Norddeutsches Becken have incomplete sequences and a very high proportion of sandstones. Sandstones up to more than 100 m thick are known from north-east Mecklenburg for instance. The presence of thick claystone formations in such regions is therefore impossible according to the data and compilations currently available. It must therefore be assumed that most of these areas will not have thicknesses of homogeneous claystone horizons exceeding 100 m because of the numerous sandstone interbeds.

No homogeneous claystone horizons with thicknesses ≥100 m will be present in most of Schleswig-Holstein and parts of north-west Niedersachsen. Other regions can be excluded because of the depth to top marine Lower Cretaceous. The only remaining partial areas with Lower Cretaceous claystones worthy of further investigation are shown in Figure 4.16.

4.2.4 South Germany – Middle Jurassic

As discussed in Chapter 4.1.1, the only argillaceous rock formation worthy of further analysis in South Germany is the Opalinus Clay Formation. The Opalinus Clay consists of dark-grey to black claystones, silt and sand lenses as well as calcareous concretions. The clays were deposited in a continuously subsiding stagnant water basin (Meyer & Schmidt-Kahler 1996; Allia 1996). Unlike the North Swiss Jura, where the Opalinus Clay is completely stratigraphically assigned to the Early Aalenian, there is no sharp boundary in South Germany at the transition to the Jurensis Marl (Upper Toarcian). According to Ohmert & Rolf (1994), claystones of the Opalinus Clay facies were already deposited in the late Toarcian. According to Gautschi (1997) and NAGRA (2005) the Opalinus Clay penetrated in wells in North Switzerland is a well consolidated, dark-grey, micaceous, silty claystone.

The mineralogical composition found in the Opalinus Clay penetrated by these wells is defined as follows (NAGRA 2005):

Illite: 9 % to 29 % and illite/smectite interbeds, 4 % to 12 %

Chlorite: 3 % to 10 % and kaolinite: 6 % to 20 %

Quartz: 15 % to 30 % and feldspars: 1 % to 7 %

Calcite: 6 % to 40 % and siderite: 2 % to 2 %

Pyrite: 1 % to 3 % and organic carbon: 0.5 % to 1.0 %.

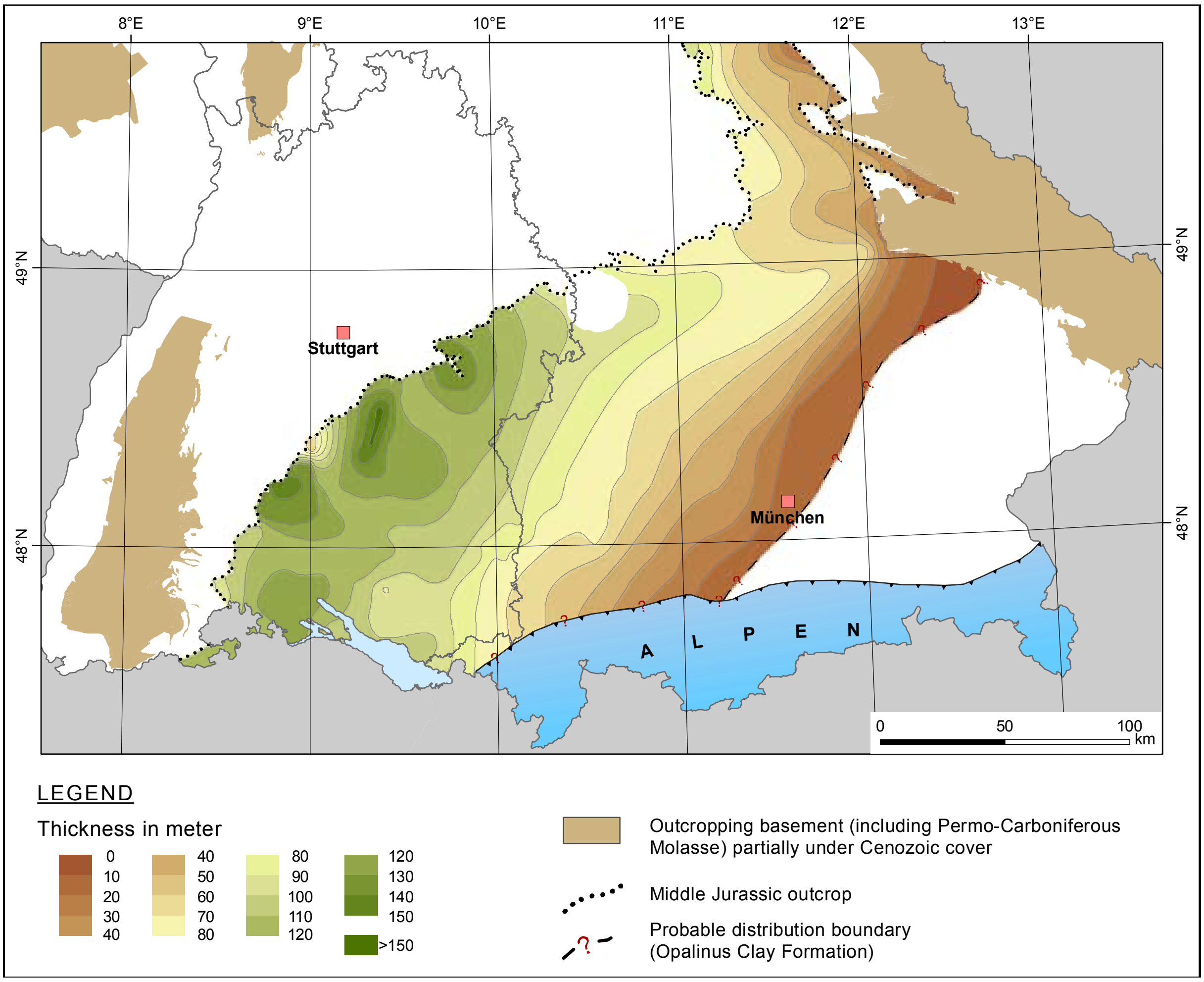


Figure 4.18: Thickness of the Opalinus Clay Formation in the Alpenvorlandbecken

There is very minor lateral variability in facies and lithology in North Switzerland and the adjacent regions of Baden-Württemberg. The rock is typically extremely homogeneous (NAGRA 2005; Lemcke 1988; Meyer & Schmidt-Kahler 1996; Allia 1996). The water content in zones without fractured and weathering zones varies between 4 % and around 20 % as reported in the available publications. In very special cases, traces of gas are reported in a few wells which penetrated very deeply buried Opalinus Clay (see also Lemke 1988).

Detailed studies by NAGRA (2002) revealed that the Opalinus Clay fulfils the minimum requirements for field hydraulic conductivity of $k_f < 10^{-10}$ m/s defined by AkEnd.

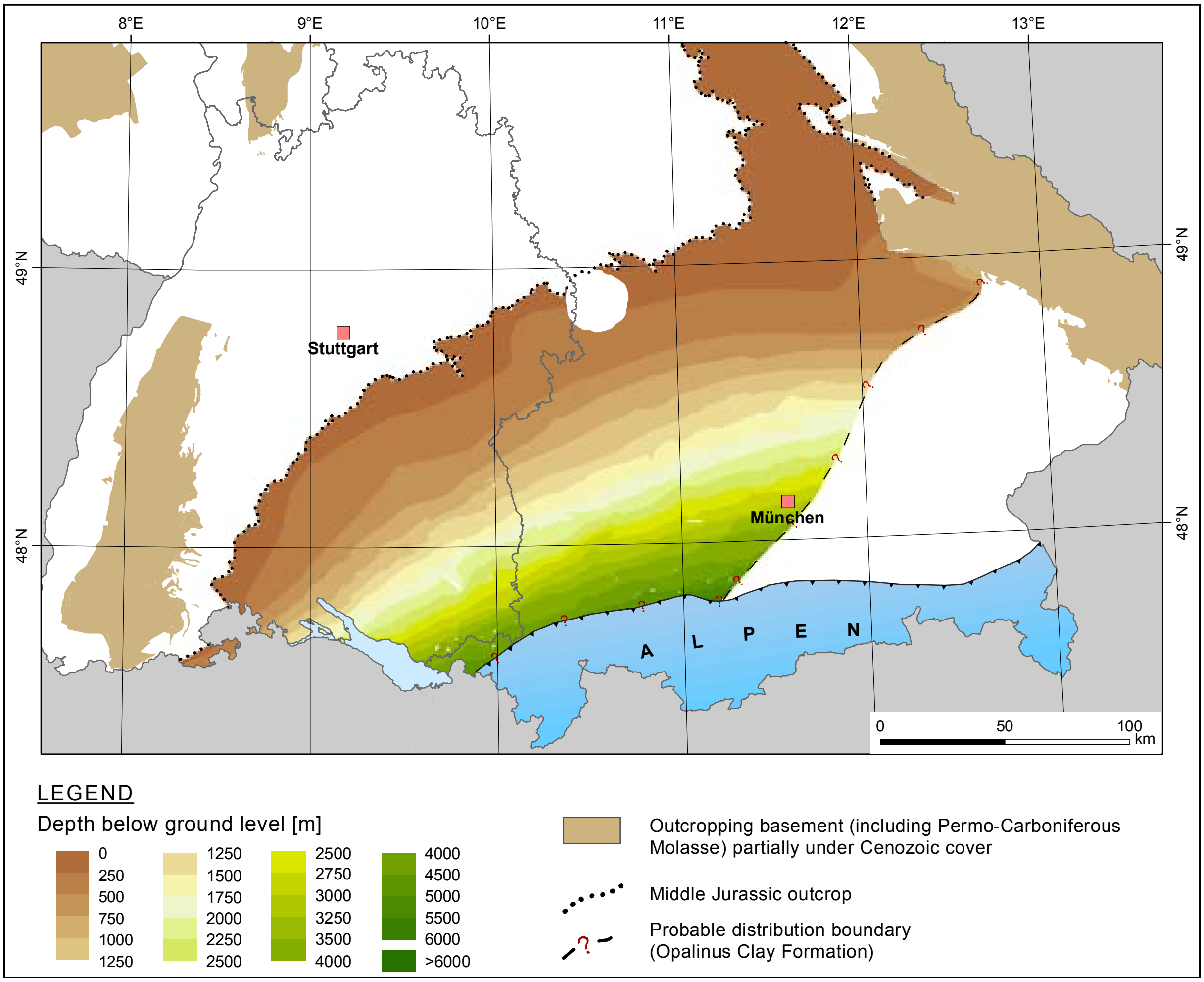


Figure 4.19: Depth of top Opalinus Clay Formation in the Alpenvorlandbecken

The northern and western pinch-out of the Opalinus Clay Formation, which is the oldest unit of the Middle Jurassic in the Swabian and Fränkische Alb, is very well documented in the geological maps of the area (see Figure 4.18). The Mesozoic sequences generally dip gently to the south where they are overlain by very thick Tertiary sedimentary sequences in the Molassebecken. The Middle Jurassic beds dip conformably with the other sequences down to depths of several thousand metres and were overthrust by the Alpine cover rocks which were thrust northwards. In some cases, the Middle Jurassic beds were dragged up during the uplift of the Alps. The claystones of the Opalinus Clay Formation do not extend as far as the Alps in the south-east of the area because they strike out along a southwest-northeast line (München-Landshut-Straubing).

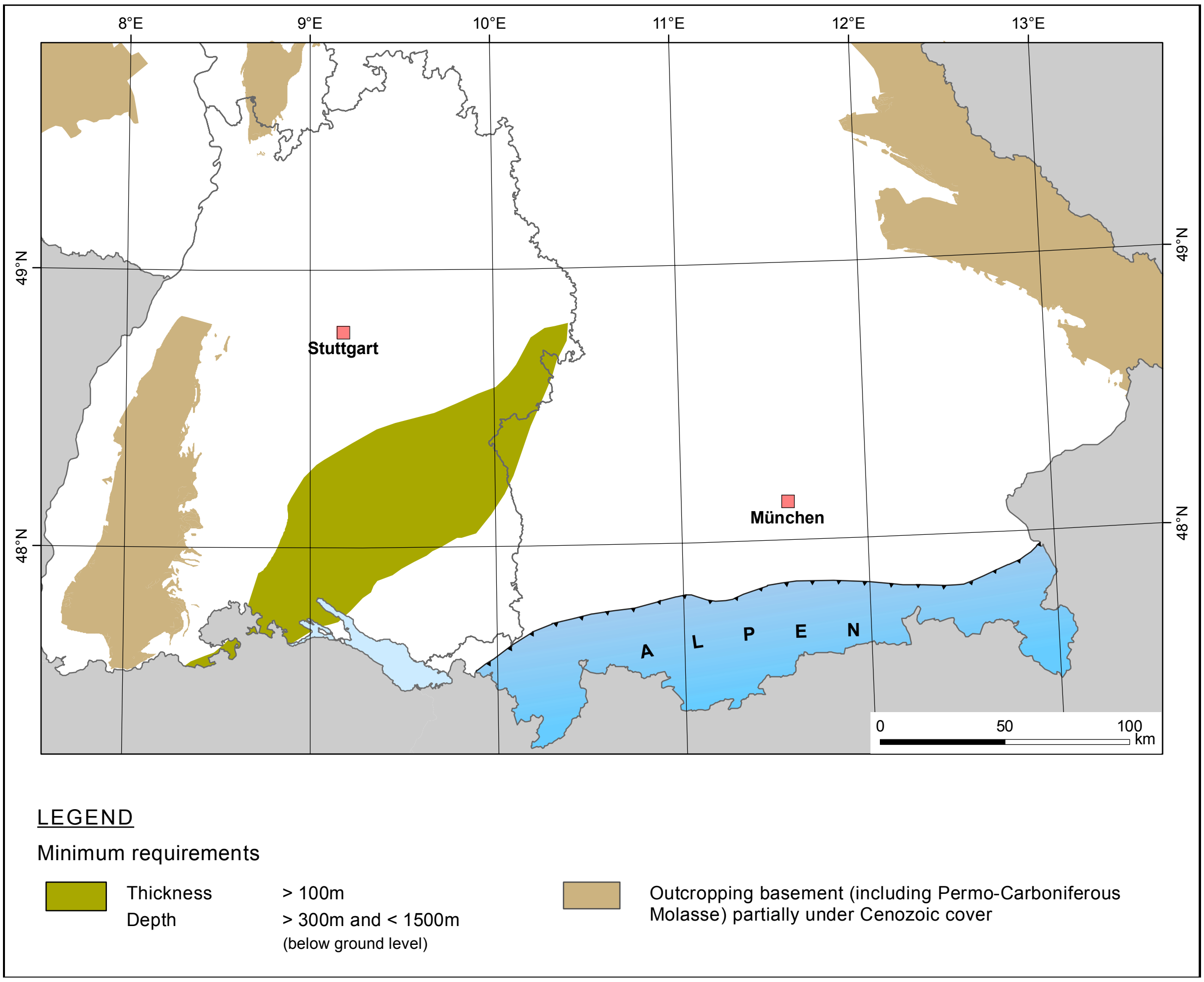


Figure 4.20: Opalinus Clay Formation: application of AkEnd criteria “Thickness and depth”

The thickness of the Opalinus Clay increases continuously to the north-west of this line and reaches its greatest thickness of 150 m in the Schwäbische Alb to the west of Ulm. It only reaches a maximum thickness of almost 100 m in the Fränkische Alb in the extreme north near Bamberg (Figure 4.18). The Opalinus Clay can therefore generally be classified as worthy of further investigation to the south of the northern margin of the Schwäbische Alb where it complies with the specified thicknesses and depth intervals. With the exception of a small partial area, the Opalinus Clay in Bayern is not worthy of further investigation because of its inadequate thickness.

Analogous to the other argillaceous rock formations, the thickness map (Figure 4.18) and depth map (Figure 4.19) of the Opalinus Clay Formation were superimposed. This highlights the partial areas fulfilling the minimum safety-related requirements for thickness (100 m), rock type with low permeability ($k_f < 10^{-10}$ m/s) and depth (1500 m) (Figure 4.20).

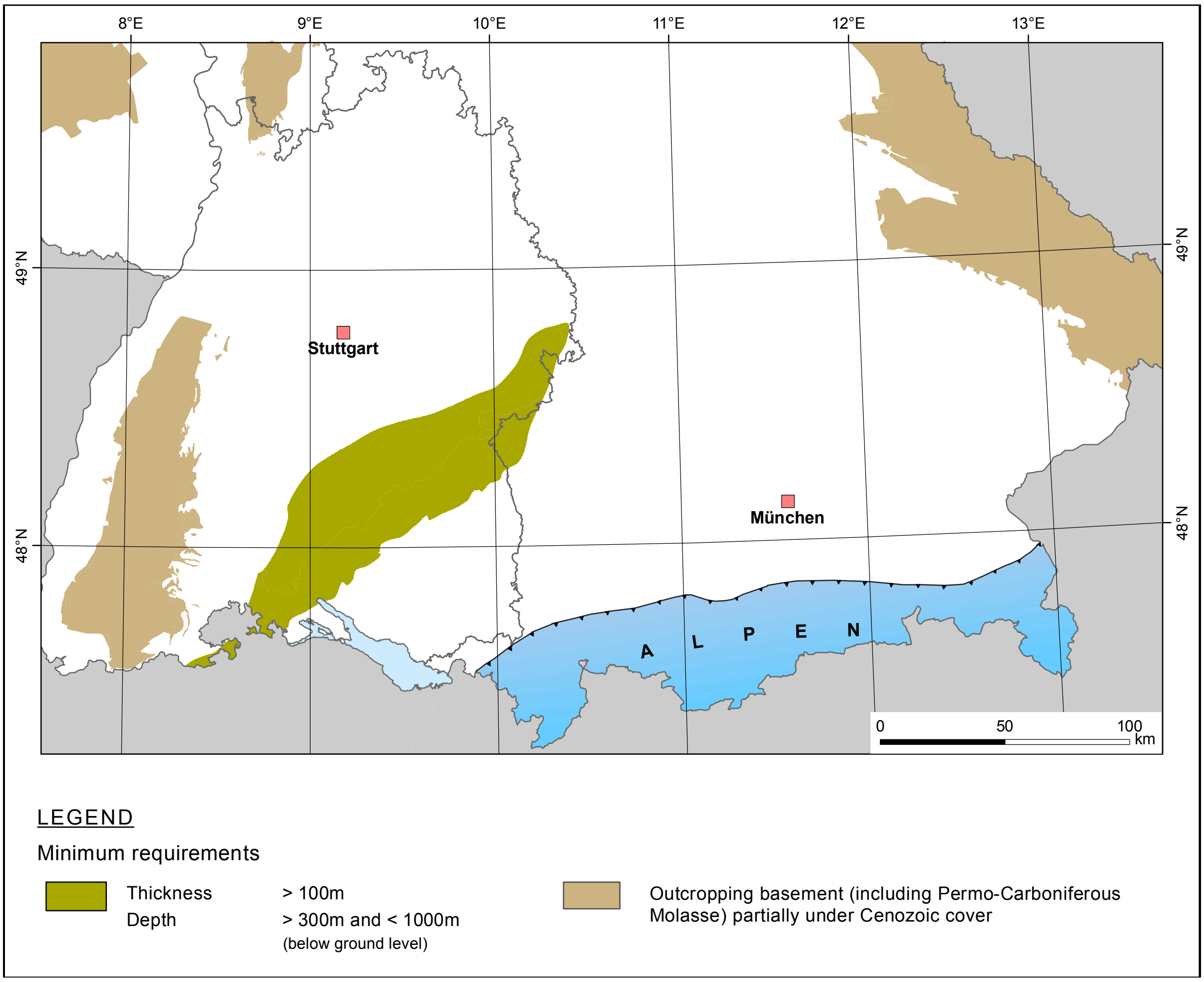


Figure 4.21: Opalinus Clay Formation: Application of host rock specific criteria

The same rock-mechanical and temperature-related restrictions applying to the regions in North Germany also apply to the Opalinus Clay Formation in South Germany (cf. Chapters 3.6.3 and 4.2.1). This means that any regions worthy of further investigation here are also those in which the Opalinus Clay Formation lies at the specified depth of between 300 m and 1000 m below ground level, and satisfies the minimum areal requirements (≥ 10 km^2) with adequate spatial characterisability. The partial area fulfilling these specifications occupies an approx. 40 km wide SW-NE striking band as shown in Figure 4.21.

Applying the other defined exclusion criteria after detailed analysis of the remaining claystone regions worthy of further analysis restricts the area even further.

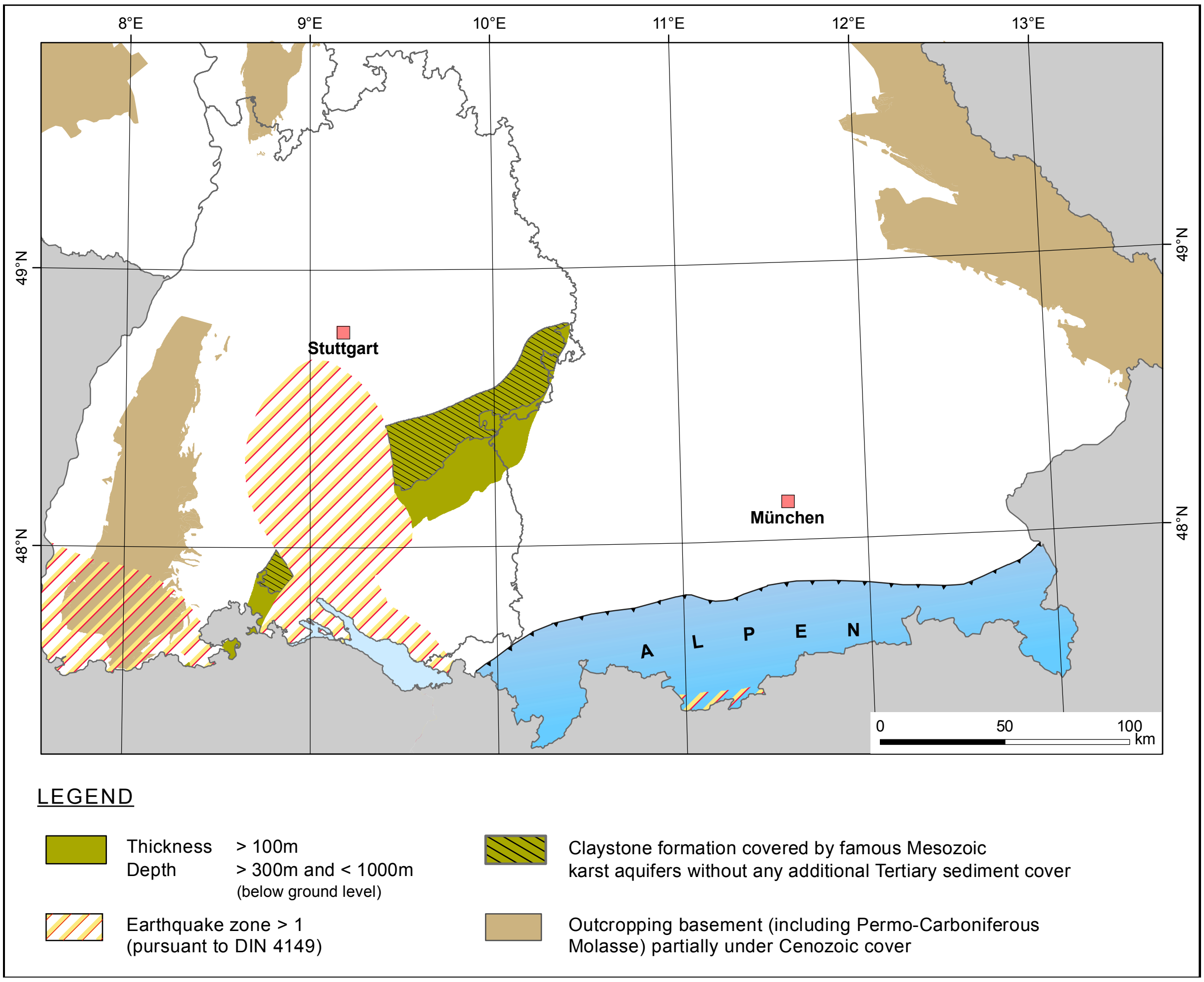


Figure 4.22: Opalinus Clay Formation: Application of all exclusion criteria defined in Chapter 3.6

Specifically, the western part of the Schwäbische Alb is another relatively very active seismic region in Germany in addition to the Oberrheingraben. The main zones are the area of the Hohenzollern Graben and its southern extension. According to the AkEnd exclusion criteria, areas lying within earthquake zones classified as higher than 1 are excluded from further examination. This criterion considerably reduces the remaining areas (see Figure 4.22). Additional special geological conditions also have to be taken into consideration: parts of the remaining regions are characterised by important karst aquifers, partially used for drinking water supplies. Figure 4.22 shows those zones where the karst aquifers are not covered by Tertiary sediments and therefore crop out at the surface or very close to the surface. Because of the special hydrogeological conditions, a further analysis of the suitability of the Opalinus Clay as a host rock involves special detailed investigations.

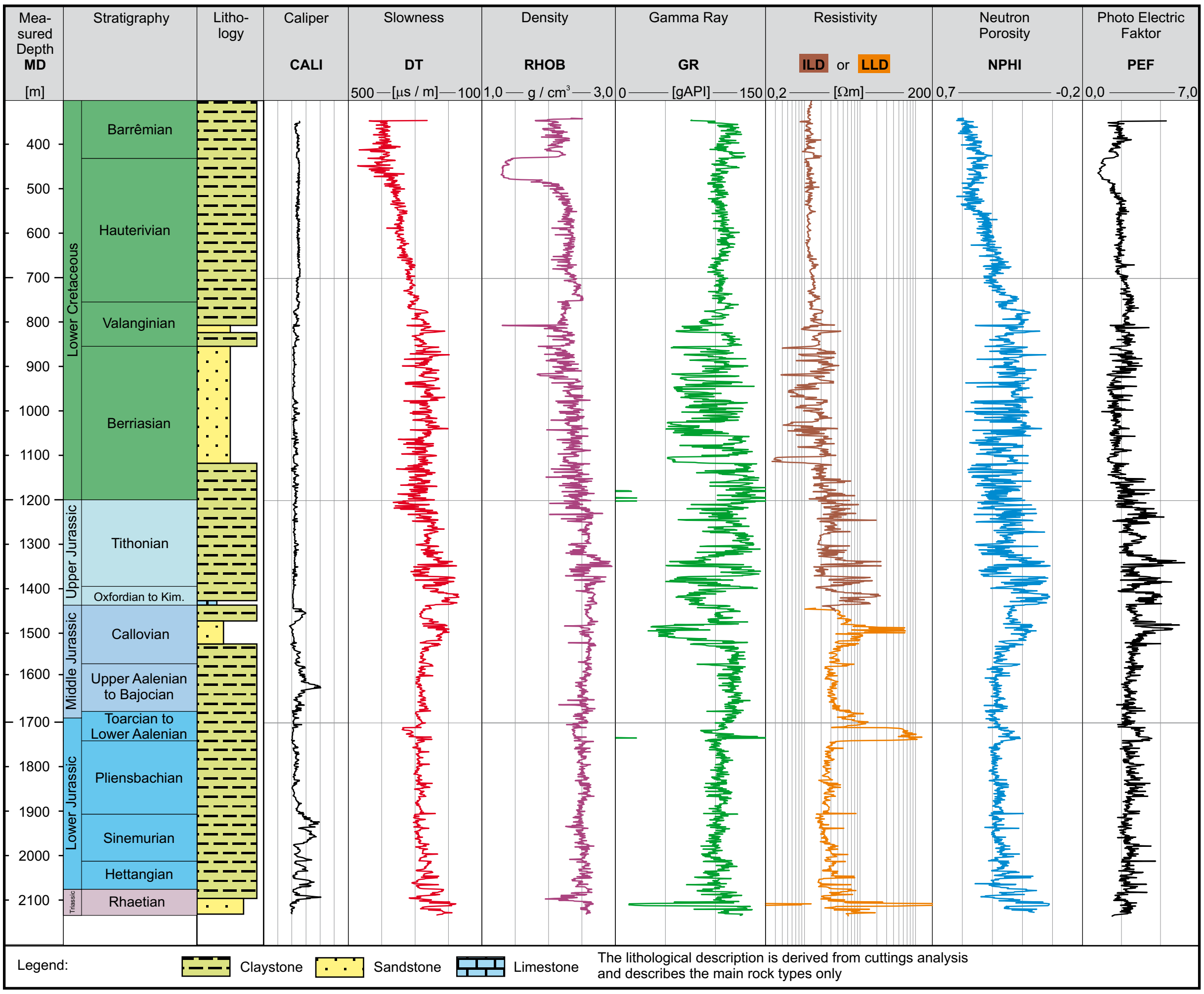


Figure 4.23: Well logs, stratigraphic and lithological descriptions from a North German well

4.3 Further characterisation of areas worthy of further investigation

Evaluation of well logs

Detailed analysis of partial areas and detailed characterisation of argillaceous rocks at a number of typical localities was carried out to verify the reliability of the data on which this study was based. The typical localities lay within the partial areas defined as worthy of further investigation in North and South Germany discussed in Chapters 4.1 and 4.2. The aim of the more detailed analysis was to determine whether extensive homogeneous argillaceous rocks with thicknesses of at least 100 m could be identified within the argillaceous rock formations in these partial areas. Another aim of this plausibility check was to show whether other restrictions could be defined when appropriate geophysical surveys were available. This is discussed in more detail in the following on the basis of an example.

Figure 4.23 shows the final well log of a deep borehole. The left-hand side of the diagram details the stratigraphy of the drilled sequence and the lithological interpretation of the original author. The lithological log shows that argillaceous rocks are present in the Lower Cretaceous and Jurassic and that their thickness considerably exceeds 100 m. Similar results were obtained from other wells in this partial area. The well logs available for the analysis are shown on the right-hand side of the diagram.

The logs available for the investigations at the relevant depth are a Caliper Log (CALI and BS), Sonic Log (DT), Density Log (RHOB), Gamma Ray Log (GR), two Resistivity Logs (ILD and LLD), Neutron Porosity Log (NPHI) and P_e Log (PEF).

The caliper deviation in per cent was calculated from the Caliper Log (CALI) and the bit size (BS). The equation used is as follows:

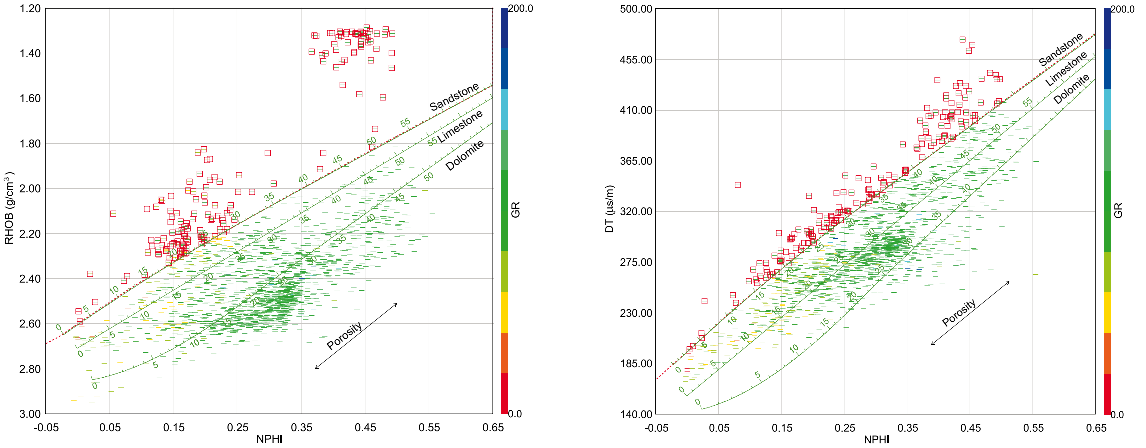
$$\Delta d_{\mathrm{DCAPC}} = \frac{d_{\mathrm{CALI}} - d_{\mathrm{BS}}}{d_{\mathrm{BS}}} \cdot 100\ \%, \qquad (4.1)$$

where:

Д d_{CAPC} is the caliper deviation in per cent, d_{CALI} the diameter of the well bore according to the caliper log, d_{BS} the bit size. Because of the minor caliper deviation throughout the analysed well section, one can assume good contact between the well bore and the other logging tools run in the well.

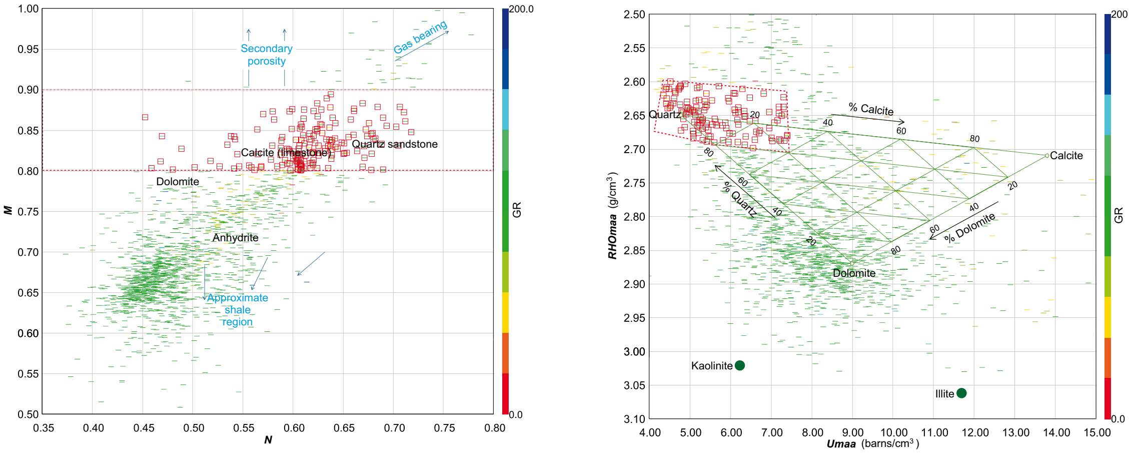
The first part of the well log interpretation involved a range of cross-plots. The following diagrams show the well known oil and gas industry cross-plots for the DT, RHOB and NPHI logs. This allows preliminary lithological classification.

Figures 4.24(a) and 4.25 show a cross-plot of formation density (RHOB) and neutron porosity (NPHI). The selected classification schemes were a porosity model for sandstone, limestone and dolomite, and a model for various claystone constituents (Figure 4.25). The Gamma Ray Log was also used for colour coding. Most of the values from the Gamma Ray Log lie in the 80 gAPI to 120 gAPI range. This confirms the results of the cuttings analysis which classified the lithology as mainly claystones to argillaceous marlstones. Figure 4.24(a) shows data points which have lower densities and therefore differ very significantly from the sandstone model (red highlights). These sections probably concern, in part at least, gas-bearing layers (claystones and sandstones).



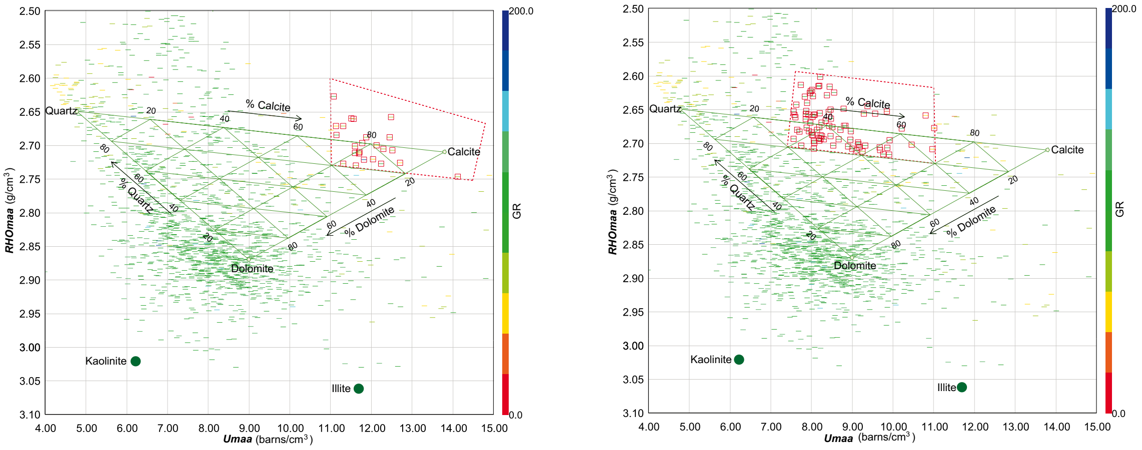
(a) Formationsdichtelog (RHOB) über Neutronenporositätslog (NPHI)

(b) Akustiklog (DT) über Neutronenporositätslog (NPHI)



(c) ***M-N***-Plot

(d) ***RHOmaa-Umaa***-Plot



(e) ***RHOmaa-Umaa***-Plot

(f) ***RHOmaa-Umaa***-Plot

Figure 4.24: Cross-plots from a North German well highlighting zones with special lithological-mineralogical compositions in each case. Classification according to SCHLUMBERGER models (1991)

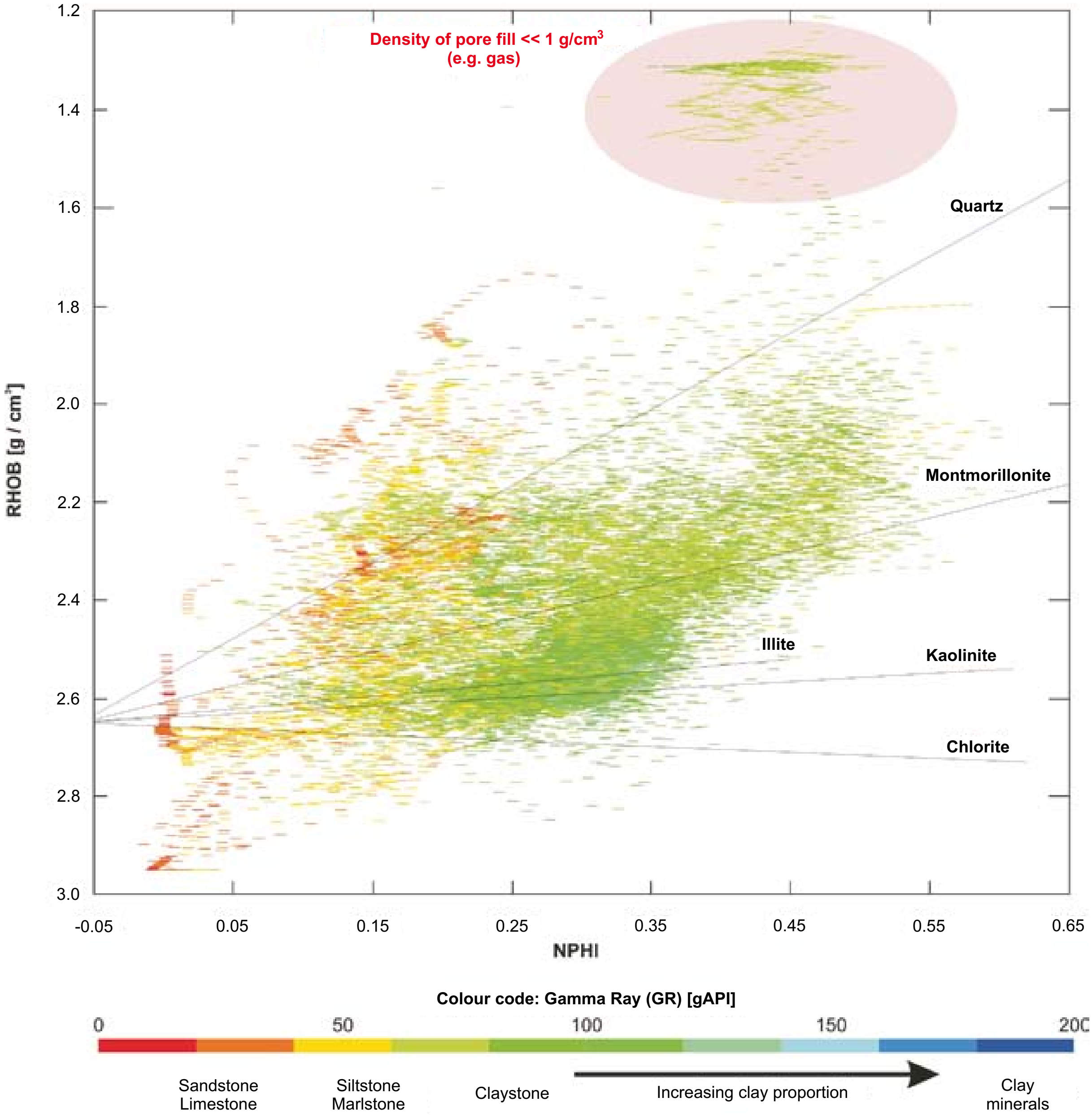


Figure 4.25: Cross-plot of Formation Density Log (RHOB) and Neutron Porosity Log (NPHI) of a North German well. Specification of claystone constituents according to SCHLUMBERGER (1991)

The lithological interpretation of the first author is generally in agreement with our analysis although the evaluation of the well logs allows much more detailed lithological-mineralogical differentiation of the deeper zones.

Because the well primarily penetrated argillaceous rock according to the cuttings samples and the Gamma Ray Logs, the cross-plot (Figure 4.25) can be used to differentiate between claystone constituents. This used the logs with the original logging separations (0.1 m) and a model for the various claystone constituents.

Many of the data points in the argillaceous rocks, defined by Gamma Ray Log values > 80 gAPI, have densities of 2.4 g/cm^3 to 2.6 g/cm^3. The corresponding neutron porosities of these rocks vary between 0.25 and 0.35. Logs with gamma ray values of ≥ 100 gAPI, which are relatively pure claystones, are also usually found in this range in the diagrams. Data points with much lower densities and higher neutron porosities which also have gamma ray values of > 80 gAPI indicate higher illite-montmorillonite or montmorillonite percentages. Higher proportions of these swelling clay minerals in the North German Cretaceous are described from many wells (see e.g. Brockamp 1976; Gaida et al. 1978; Eckhardt 1991). An increase in the proportion of these components from the Berriasian to the Albian, and further up into the Upper Cretaceous appears to be typical for many regions. Figure 4.25 generally indicates that the claystones penetrated by the well primarily consist of illite. Other clay mineral constituents in order of importance are interlayered illite-montmorillonite minerals and kaolinite.

Figure 4.24(b) is a cross-plot of the Sonic Log (DT) and the Neutron Porosity Log (NPHI). The porosity model overlay used here is again for sandstone, limestone and dolomite. The log values with high travel times (low formation velocities) highlighted in red reveal rocks with special properties which slow down the propagation velocity of sonic waves. This can be caused for instance by a very loose fabric (e.g. poorly compacted claystones with high proportions of swelling clay minerals, or sandstones with low levels of compaction and diagenesis), as well as gas-filled pores.

Although these zones cannot be unequivocally classified on the basis of a Sonic Log-Neutron Porosity Log cross-plot on its own, it is probable that these claystones have special properties (high proportion of swelling clay minerals or high proportion of organic matter).

Figure 4.24(c) shows the ***M-N***-plot, whilst Figures 4.24(d), 4.24(e) and 4.24(f) show the ***RHOmaa-Umaa*** plot. These plots can be used to define the mineralogical composition of the formation and incorporate the results of all porosity logs (RHOB, DT, NPHI). Zones with sandstones, limestones and calcareous marlstones are highlighted in the ***M-N***-plot in Figure 4.24(c).

The ***RHOmaa-Umaa*** plots in Figures 4.24(d), 4.24(e) and 4.24(f) highlight sandstones (< 25 % calcite), limestones (> 75 % calcite) and their transitional lithologies.

Previous experience underlines that it is not possible to define the lithology of a well section in detail by analysing only a few cross-plots (Figures 4.24(a), 4.25 and 4.24(b)). Simultaneous analysis of all three porosity parameters is required (DT, RHOB, NPHI).

The material composition of the rocks is estimated in Figure 4.26(a) on the basis of the ***RHOmaa-Umaa*** plots. The analysis shows that the section predominantly consists of claystones. Transitions to siltstones and marlstones are also clearly shown.

It is also generally possible to differentiate between the different claystone constituents. This will have to be verified by at least carrying out mineralogical-geochemical analysis of samples. The detailed lithological classification is derived from the complete analysis of the well logs (Figure 4.26(b)). The general lithological interpretation largely corresponds with the lithological interpretation of the original author. Analysis of the well logs, however, provides much higher resolution. Sandstone interbeds in the argillaceous rocks can be identified. In some cases these are very thin sandstones, and in others packages of such beds form thicker zones. Other interesting features in this well are horizons which appear to be gas-bearing.

Correlation between well logs and seismic data

In addition to the detailed characterisation of argillaceous rocks in wells, another very important aspect in the assessment of the barrier and host rock suitability of claystones is to be able to evaluate their homogeneity and the areal extension of homogeneous zones, to draw conclusions on their spatial characterisability. To look at this question, analysis was carried out in selected areas using the CORRELATOR software package (Olea & Sampson 2002) to investigate the correlation of well logs. Correlation between the wells in the area described in more detail here was conducted as follows:

- Use of the Gamma Ray Logs and Sonic Logs at depths for which these logs were available in the wells;
- Calculation of all correlations between the wells with varying correlation intervals (5 m to 30 m);
- Determining the clay percentage using the gamma ray index (see Chapter 3.3.2) for the horizons being correlated;
- Use of the Self-Potential Log for zones for which no Gamma Ray Logs were available. Calculating a synthetic Gamma Ray Log using a theoretical sand line and clay line; correlation between these synthetic logs.

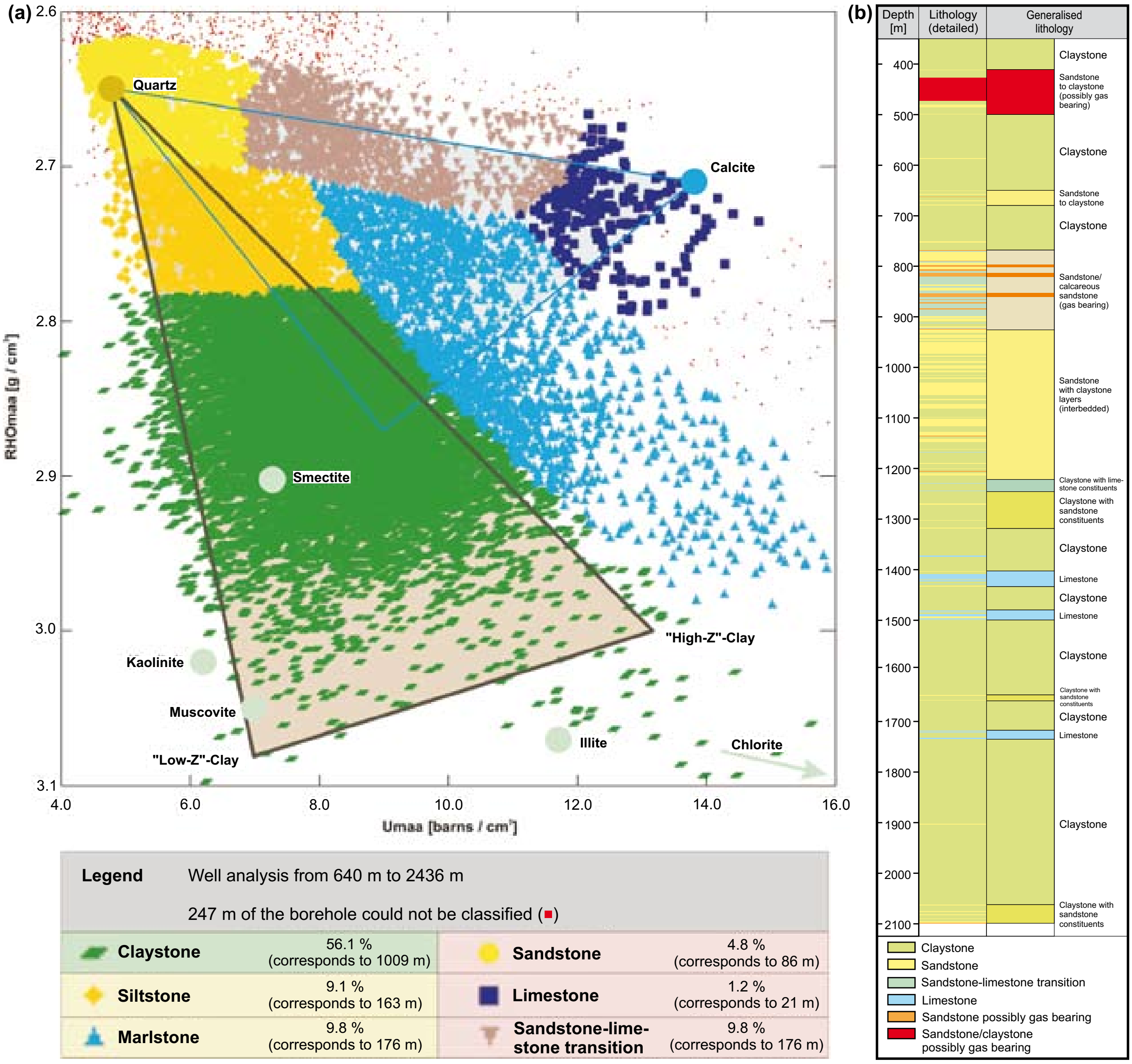


Figure 4.26: Classification of rock types in a North German well: (a) on the basis of the ***RHOmaa-Umaa*** plot; (b) on the basis of the porosity logs (RHOB, DT, NPHI), the P_e-Log and the Gamma Ray Logs. Presentation of the results according to the well logs (detailed and generalised)

An important result of these investigations is shown in Figure 4.27. This Figure shows the estimated clay or claystone percentage for the whole of the well derived from the Gamma Ray Log or Self-Potential Log.

To fill the gap in the upper parts of the wells where no Gamma Ray Log was run, a synthetic Gamma Ray Log was generated using the Self-Potential Log. The diagram shows that the thick claystones are relatively homogeneous and easily correlatable. Claystones towards the top have more marly horizons.

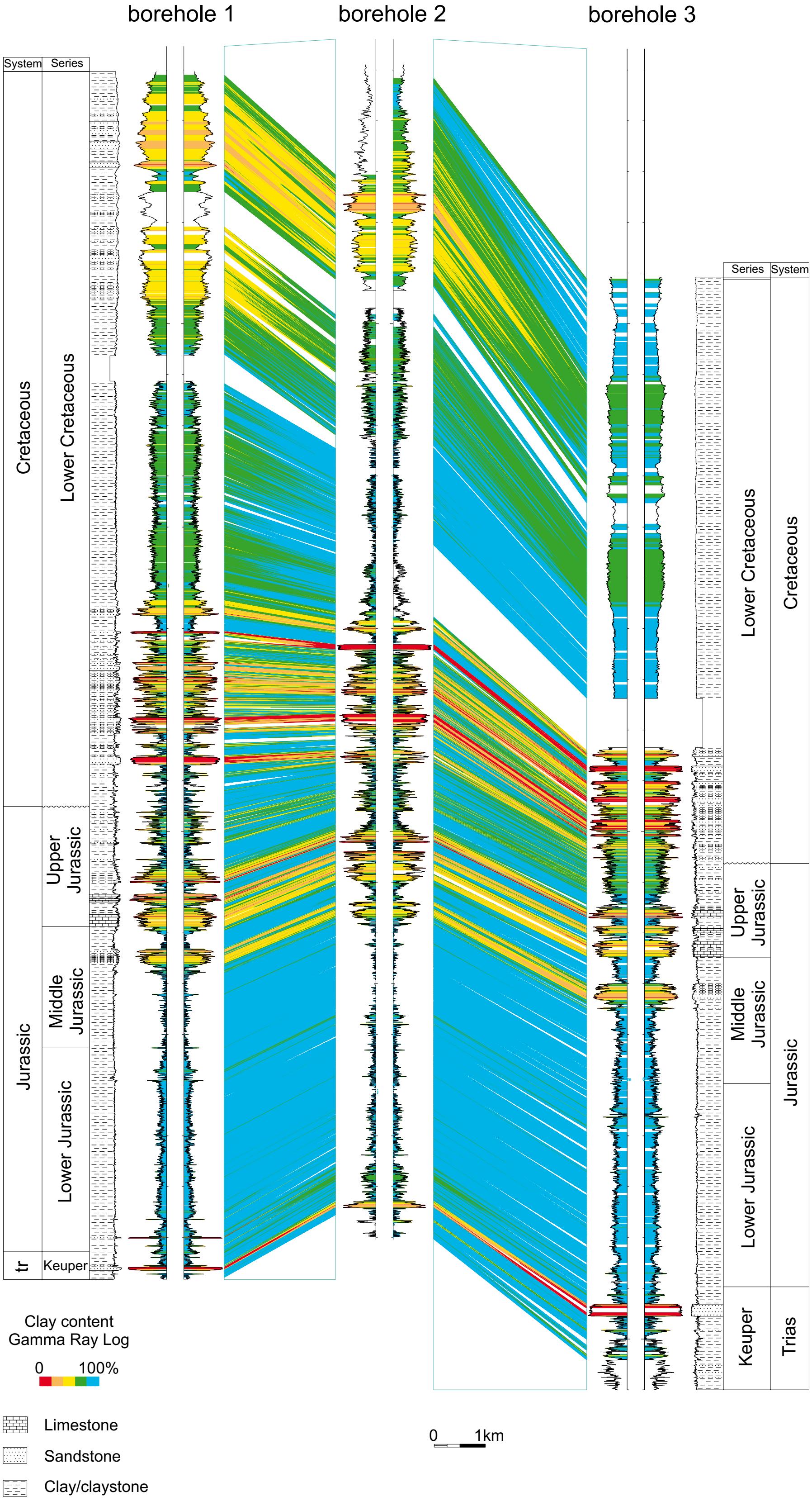


Figure 4.27: Well log correlation (Gamma Ray Log) between three North German wells with colour coded clay/claystone concentrations

As already shown when analysing other study areas, the selected method again proved very suitable here for estimating the homogeneity and spatial characterisability of thick claystones. This means that when wells with good quality logging suites are available, it is possible to tie these wells to the seismic data and thus to spatially define claystone formations.

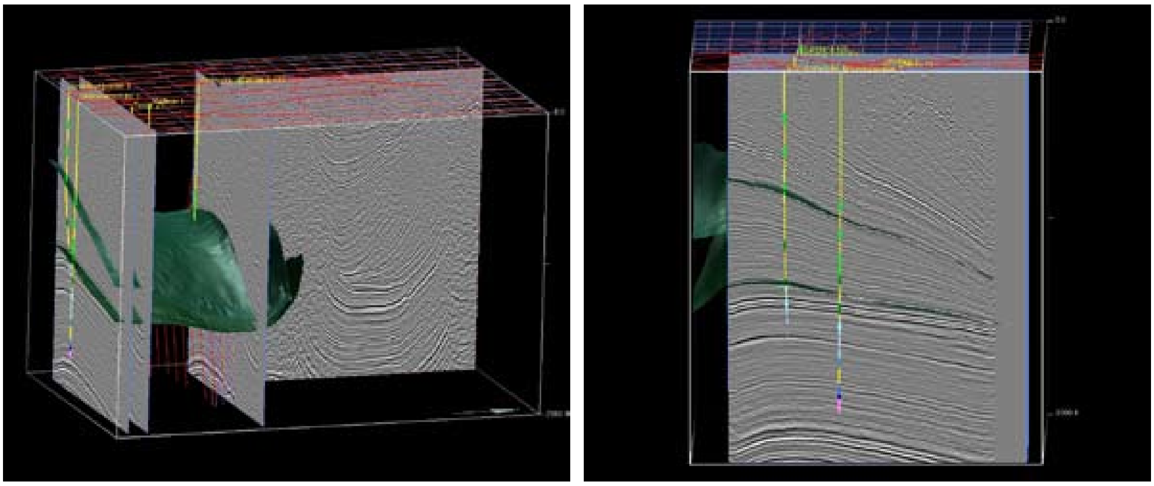
Interpretation of the seismic data focused on the following main questions:

- Continuation of characteristic reflection horizons;
- Identification of faults;
- Assessment of claystone structuration;
- Correlation of the seismic data with the well logs.

The following main reflection horizons can be picked in the whole area in the Lower Cretaceous to Jurassic section:

- Top Lower Cretaceous
- Intra Lower Albian
- Approx. Base Aptian;
- Approx. Base Barremian;
- Lower Hauterivian
- Wealden (Berriasian)/Tithonian boundary
- Intra Upper Jurassic (approx. Base Kimmeridgian);
- Intra Toarcian (approx. top very Corg-rich claystones/Posidonia Shale);
- Intra Rhaetian-Keuper.

Figure 4.28 shows seismic lines tied to wells highlighting the spatial distribution of the Wealden/Tithonian boundary horizon and Base Barremian. Tying the seismic to the well logs shows that several homogeneous claystone sections in the Lower Cretaceous and Jurassic can be picked over a wide area. The figure highlights the clear boundaries of claystone packages. The seismic interpretations in this example area made it generally possible to improve the mapping and areal delimitation of the homogeneous argillaceous rocks identified from the well logs. It also allowed more detailed analysis of the in



(a) Blickrichtung von E nach W (b) Blickrichtung von S nach N

Figure 4.28: Selected seismic sections in North Germany showing the picked horizons: Wealden/ Tithonian boundary (lower reflector), and Base Barremian (upper reflector).

fluence of halotectonism on the structure of the argillaceous rocks. Homogeneous and unfaulted argillaceous rocks are mainly found in the example area discussed here in areas with gentle dip. Claystone horizons close to salt structures generally have strong dips so they are also often severely faulted.

The detailed analysis of different areas proved that the selection of partial areas worthy of further investigation is generally plausible (see Chapters 4.1 and 4.2). Homogeneous and areally extensive argillaceous rocks of adequate thickness could be confirmed in almost all of the investigated partial areas. There are some exceptions: these primarily concerned the edges of the selected areas. The presence of 100 m thick homogeneous argillaceous rocks in these zones was shown to be doubtful by the detailed analysis primarily because of the presence of sandstone interbeds. One example is reported in Hoth et al. (2005), and another example concerns the Potsdam region. However, because detailed investigations of this type in the study were not carried out to the same extent in all of the selected partial areas, it is only possible to draw the conclusion that further regional restriction of the partial areas is a possibility. This cannot be taken into consideration in the maps in Chapter 4.4 because the criterion “correlatable homogeneous claystones confirmed on the basis of seismic and well logs” cannot be applied over large areas and throughout the country.

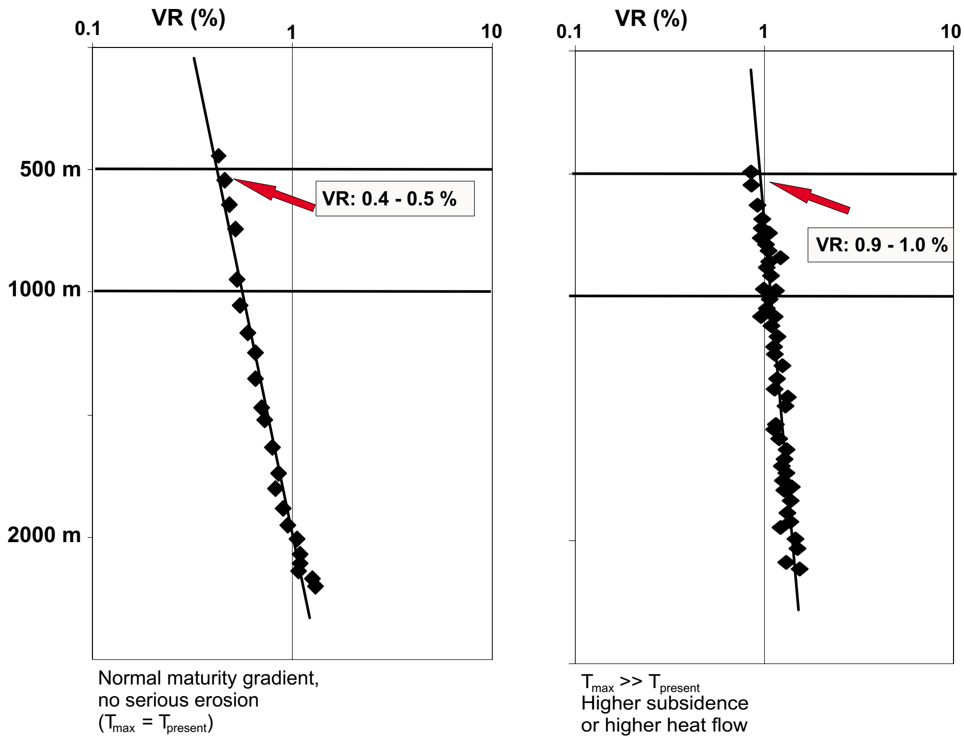


Figure 4.29: Maturity trend from wells in two North German partial areas

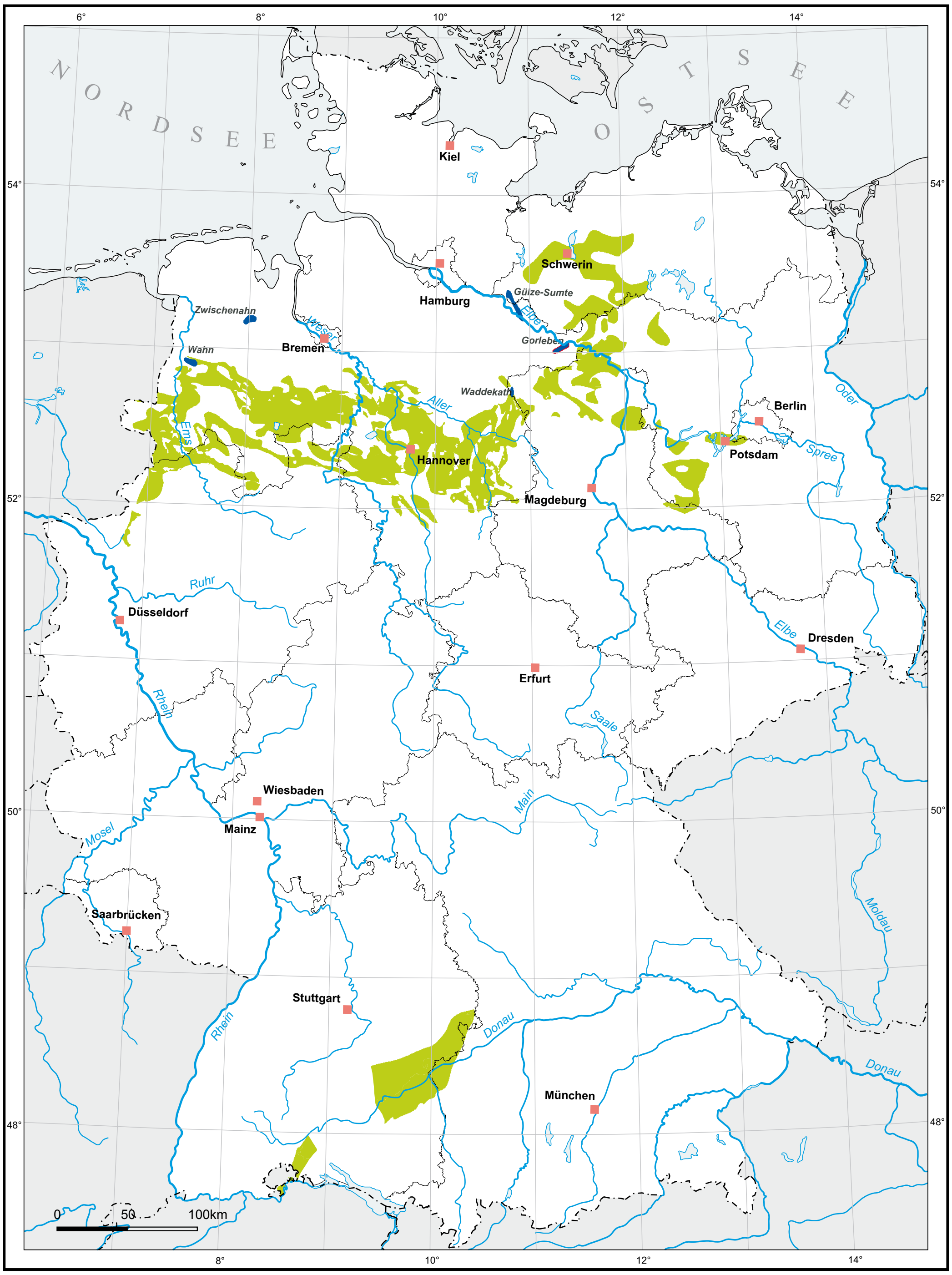
Estimating the degree of diagenesis

The importance of the degree of diagenesis of argillaceous rocks was discussed in Chapter 3.5. The example areas were also evaluated to see which data was available to estimate the degree of diagenesis. Research revealed that the only data for this purpose is almost exclusively vitrinite reflectance data. Much of this data is available in the BGR's digital maturity database. The degree of maturity of the argillaceous rocks for relevant depths can be estimated using this data and the information from the aforementioned archives. There were significant differences in the degree of maturity at a depth of 500 m: levels in North Germany vary between 0.25 % and 5.00 %. However, the very high values are limited to special regions in south-west Niedersachsen affected by major uplift or heating up of the rock by plutonic rocks in the geological past (BARTENSTEIN 1971; BUNTEBARTH & TEICHMÜLLER 1979; SENGLAUB et al. 2005). The estimated degree of maturity in the other regions in North Germany is estimated to lie between 0.5 % and 0.8 %. Exceptions with maturity levels up to 1.00 % are primarily found in the southern margins of the North German Basin. Figure 4.29 shows the available vitrinite reflectance values against depth from wells in two partial areas. A comparison between the two diagrams clearly shows the very strong differences in the degree of maturity at a depth of 500 m, which means that the claystones present at this depth have been exposed to very different temperatures during their geological history. If the simple empirical model referred to in Chapter 3.5 is used to estimate the maximum temperature exposure, most values lie between 30 °C and 70 °C with slightly higher temperatures in some localities. In those areas with very high degrees of maturity, it can be assumed that they were affected by very high maximum temperatures (100 °C to 200 °C) and that this will significantly diminish the barrier properties of the claystones (e.g. cause microfracturing for instance). Sonic Log interpretations can be used to qualify the estimates of the degree of diagenesis.

4.4 Overall estimation of the argillaceous rock formations worthy of further investigation in Germany

The following additional regional restrictions were taken into consideration in accordance with the criteria formulated in Chapter 3.6 to select partial areas with argillaceous rock formations worthy of further investigation as potential nuclear repository host rocks in Germany:

- All of the argillaceous rock formations in the Oberrheingraben have been classified as not worthy of further investigation because of partial exclusion by being located in an earthquake zone graded as higher than 1, and because of the tectonic and lithological conditions (complicated geological structures, strongly deformed bedding).
- Although the Tertiary clays in North Germany are important hydrogeological barriers, their suitability as host rocks is considered to be highly restricted because of their low level of consolidation compared to Lower Cretaceous and Jurassic claystones (see Chapters 3.6.3 and 4.1.3). They are therefore not taken into consideration as potential host rocks and therefore not shown in the map (Figure 4.30).



🟩 Claystone formations in Germany potentially suitable for further investigations

Figure 4.30: Partial areas with argillaceous rock formations in Germany worthy of further investigation

- Because of their significant lithological variability compared to the other argillaceous rock formations, the Tertiary clays and claystones of the Alpenvorlandbecken can only be investigated at disproportionately high expense in order to acquire data and interpretations of comparable quality. In addition, most of them have only undergone minor consolidation. They are therefore not investigated further in this study.
- Sub-areas of the Opalinus Clay Formation in South Germany are excluded because they lie in an earthquake zone graded as higher than 1.
- The potential use of the Opalinus Clay Formation as a host rock is restricted in part of its area of distribution in South Germany by the presence of a major exploited karst aquifer in the overlying rocks. This restriction covers at least those regions in which this aquifer is used for the abstraction of drinking water, thermal brines or for geothermal energy. Figure 4.22 also shows in particular the areas where there is no continuous Tertiary cover above the Malm karst and thus where it is exposed at the surface or lies at very shallow depths and is therefore still undergoing karstification today. The hydrogeology would need to be analysed in detail when looking further at the potential suitability of the Opalinus Clay. This would require the hydrogeological and petrophysical characterisation of an around 100 – 200 m thick sedimentary sequence between the Opalinus Clay and the Upper Jurassic, as well as three-dimensional groundwater modelling (see also Bertleff 1986; Frisch & Huber 2000; Clauser et al. 2001).
- Areas with extremely steep bedding in the vicinity of salt structures are classified as not worthy of further investigation because of their complicated structure, the difficulty in characterising them, and the disproportionately high expense which would be involved in investigating them in detail.
- Partial areas with narrow elongated shapes significantly restrict the construction of repository tunnels. The associated disproportionately high costs for detailed investigation also mean that these partial areas are classified as not worthy of further investigation.
- With regard to the degree of diagenesis and consolidation of the argillaceous rocks looked at in Germany, the existing studies indicate that argillaceous rocks with intermediate levels of diagenesis and consolidation are likely to be the most suitable host rocks for a nuclear repository for high-level radioactive waste. Compared to poorly consolidated claystones, they benefit from better

geomechanical properties for the construction of a nuclear repository. In addition, these argillaceous rocks have also been exposed to higher temperatures during their geological history than claystones which have undergone minor diagenesis. On the other hand, there is a risk that argillaceous rock formations which have undergone very high levels of diagenesis, may no longer have good barrier properties because of microfracturing.

The remaining partial areas with thick argillaceous rock formations are in the North German Cretaceous sequence and in the North and South German Jurassic sequences. These are shown in Figure 4.30. In addition to the hydrogeological restrictions in South Germany, additional weighing criteria can also be used to delimit the partial areas further as discussed in Chapter 4.5.

4.5 Other potential regional restrictions

In addition to the already discussed and applied criteria, there are other relevant aspects concerning argillaceous rock formations which restrict the regions worthy of further investigation from a geoscientific point of view. These include the following aspects.

- Competing use by, e.g. oil and gas production, gas storage, geothermal exploitation, and salt mining. Safety margins have to be defined even if these uses take place at other depths.
- There is a risk in areas affected by major uplift or strong thermal influences during their geohistory, that the argillaceous rocks may have undergone microfracturing. This can raise the hydraulic transmissivity and thus restrict their uses as host rocks.
- It is also likely that claystones with a higher proportion of organic carbon may contain raised levels of gas (carbon dioxide and/or hydrocarbons), and that this may also apply to the neighbouring rocks.
- The suitability of argillaceous rocks as host rocks can also be regionally or locally restricted with the presence of porous and permeable sandstone interbeds in the claystones, or the presence of such porous and permeable beds above or below the claystones.
- Tertiary volcanic rocks occur in one partial area (Hegau volcanic zone). The Opalinus Clay was penetrated by numerous volcanic vents in this area. In the vicinity of these volcanic pipes at least, it can be assumed that the Opalinus

Clay has lost its good barrier properties. The exploration and mapping of the properties of the Opalinus Clay in this region therefore involve disproportionately high costs because an adequate safety margin must be guaranteed around each volcanic body.

- Partial areas defined by faults with major throws affecting the argillaceous rocks (e.g. throws > 100 m in the case of 100 m thick argillaceous rocks) are associated with the risk that these faults have created hydraulic migration paths. They are also often part of wide fault zones involving several parallel faults and fracture zones.

5 Study limitations

The results of the investigation and evaluation of argillaceous rock formations in Germany is directly dependent on the quantity and quality of the available geoscientific data. Although gaps in the data could largely be filled by extrapolation in line with the methods described earlier, the study still has limitations with respect to the strength of its detailed conclusions and presentation possibilities. This is discussed in detail in the following:

General

- The study does not conclude by naming specific sites. It only provides a general overview of partial areas with argillaceous rock formations suitable for further investigation to assess their potential for the final disposal of radioactive waste in Germany.
- The evaluation undertaken in this study is based on the specifications defined for the German nuclear repository concept and the geology in Germany. It is not possible to derive from the study, and was never one of the objectives of the study, to pass judgement on the concepts pursued internationally based on country-specific geological conditions.
- The investigations and evaluations were based on the current understanding of German geology. This took into consideration data shortages and gaps in the data. The extrapolation of the investigation results to areas with lower data densities was only possible on the basis of geoscientifically justifiable indicators.
- The evaluation is only based on safety-oriented geoscientific criteria. Planning criteria such as protected areas or sociological criteria were not taken into con-

sideration.

- With respect to estimating the suitability of argillaceous rocks for the final disposal of radioactive waste, it was generally assumed that formations with clay contents exceeding 80 % would very likely fulfil the criteria specifying the minimum degree of low field hydraulic conductivity.

Database

- The amount of information on argillaceous rocks is restricted compared to other potential host rocks. Data on argillaceous rocks derived from surface outcrops is of little relevance for assessing their suitability as host rocks for a nuclear repository.
- References and archive material form the main database for the investigations. No field investigations were carried out for the purposes of this study. Details of approx. 25,000 wells were available as a data source. Only a minor amount of additional subsurface data was available to supplement the well data.
- The oil and gas exploration data often lack detailed descriptions of the lithology of the argillaceous rocks because they were not the main exploration objective.
- Concerning the estimates for regional uplift trends, only one general source was available (FRISCHBUTTER & SCHWAB 2001). Uncertainties in this interpretation, in the southern part of Germany in particular, were irrelevant for the more detailed analysis.

Presentation of the results

- The results of the study are shown in small scale base maps. The line of outcrop of the argillaceous rock formations shown in the diagrams are defined subject to the inaccuracies reflecting the data quality and quantity, and projected from their underground geological positions to the surface.
- The partial areas are mainly outlined by the lines of outcrop of the stratigraphic boundaries of the clay formations. Lithologically uniform homogeneous zones can only be specified on the basis of the location-specific geology (e.g. 3D-seismic, wells).

- Only post-Carboniferous argillaceous rock formations were taken into consideration stratigraphically. Older formations located at depths relevant for a nuclear repository have undergone extensive tectonism (e.g. Carboniferous in the Ruhr). Such formations were therefore not considered worthy of further investigation.

6 Conclusions

This study identifies and evaluates argillaceous rocks as potential nuclear repository host rocks in partial areas in Germany. The study is based on the available and utilisable data from maps, archive material and approx. 25,000 wells. No additional field or laboratory investigations were conducted.

The host rock independent exclusion criteria and minimum requirements recommended in 2002 by the Committee on a Site Selection Procedure for Repository Sites (Arbeitskreis Auswahlverfahren Endlagerstandorte AkEnd) were used to delimit the partial areas worthy of further investigation. With respect to the estimation of the suitability of argillaceous rocks for the final disposal of radioactive waste undertaken in the study, it was generally assumed that formations with a clay content exceeding 80 % would very likely fulfil the specified minimum low field hydraulic conductivity criterion. The minimum requirements were supplemented by internationally recognised host rock dependent selection criteria, and special weighing criteria applying to the situation existing in Germany.

The study did not result in the description of nuclear repository sites. The study does, however, identify thick and homogeneous claystones found in North Germany in Lower Cretaceous and Lower and Middle Jurassic rock formations which fulfil the host rock specifications. The rocks identified as worthy of further investigation in South Germany are more strongly regionally localised Middle Jurassic rocks. Tertiary clay formations were not looked at further in this study because of their unfavourable mechanical properties. The identified partial areas lie primarily in Niedersachsen, Mecklenburg-Vorpommern, Sachsen-Anhalt, Baden-Württemberg, and to a lesser extent also in Bayern, Brandenburg and North Rhine Westphalia. The report discusses other possible regional restrictions which are taken into consideration.

More detailed evaluation of the claystones in the shortlisted areas could only be conducted on the basis of an expensive investigation programme aimed at selecting locations for the final disposal of high-level radioactive waste.

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