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Master Thesis

Applicability of Ultra-Deep Vienna Basin Drilling Experience for Future Exploration Requirements

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Affidavit

(Eidesstattliche Erklärung)

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

Leoben, ________________ ______________________

Erich Strasser

Acknowledgement

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Kurzfassung

Nachdem die seichten Öl- und Gaslagerstätten bereits gefunden und produziert werden, ist die Ölbranche gezwungen, immer tiefer in die Erdkruste zu bohren. Die vier Übertiefbohrungen, welche tiefer als 6,000 m gebohrt werden, haben das dritte Stockwerk des Wiener Beckens erreichten und sind das Hauptthema in dieser Arbeit.

Ziel dieser Diplomarbeit ist es, die Erfahrungen der übertiefen Bohrungen aufzuzeigen und zu erläutern. Des Weiteren ist es von Interesse, welche Erfahrungen für zukünftige Projekte von Bedeutung sind.

Neben den bohrtechnischen Aspekten gilt es auch die Geologie und Struktur des Wiener Beckens zu verstehen und somit mögliche Hochdruckzonen zu erkennen. Die Herausforderungen von übertiefen, vertikalen Bohrungen werden erklärt, welche sich von horizontalen Bohrungen wesentlich unterscheiden können.

Das Bohrprinzip ist über die Jahre gleich geblieben, aber es sind viele Arbeitsmethoden verbessert oder sogar neue Geräte entwickelt worden. Auch diese Themen werden diskutiert.

Die Erfahrungen aus den späten 70er und frühen 80er Jahren sollen helfen, zukünftige Tiefbohrprojekte zu planen. Die gewonnenen Daten sollen die zu erwartenden Begebenheiten aufzeigen bzw. helfen, Fehler und kritische Situationen zu vermeiden.

Die ermittelten Erfahrungen werden verwendet, um einen Bohrplan für ein zukünftiges Bohrprojekt Zistersdorf Übertief 3 zu erstellen. Das Programm enthält alle notwendigen Daten, die für die Planung und Durchführung notwendig sind, um die Gaslagerstätte der Bohrung Zistersdorf Übertief 1a in einer Teufe von 7,544 m erneut zu erschließen.

Abstract

The shallower oil and gas reservoir have already been explored and produced. The oil business is forced to drill deeper into the earth's crust. The four ultra-deep wells which have a true vertical depth greater than 6,000 m, reached the third floor of the Vienna Basin and are the main subject of this thesis.

The objective of this thesis is to list and discuss the experiences made at the ultra-deep wells. Furthermore it is important which experiences are relevant for future projects.

Beside the drilling aspects it’s important to understand the geology and the structure of the Vienna Basin and so to identify high pressure zones. The challenges of ultra-deep vertical wells – which are significant different from horizontal wells – are discussed.

The main drilling principle has not change for years but many drilling techniques have been improved or newly developed. These subjects are discussed, too.

The experiences from the late 1970s and early 1980s should help to plan future ultra-deep drilling projects. The obtained data should demonstrate the expected incidents and help to avoid mistakes and critical situations.

The determined experiences are used to make an intent-to-drill for a future drilling project Zistersdorf Ultra-deep 3. The program has all necessary data for planning and completion to explore the gas formation of the previous Zistersdorf UT1a well in a depth of 7,544 m again.

1 Introduction

The industrial revolution of the 20th century and its demand for hydrocarbons made it necessary to increase the production rate of oil and gas. As the shallower reservoirs were already explored it was time to drill deeper into the earth's crust.

In Austria the deep exploration started in the 1960s by the OMV Aktiengesellschaft. The first well drilled to 6,000 meter was the 'Schönkirchen T32' with a final depth of 6,009 m in 1968. Three further wells were drilled to 6,000 m in the 1970s.

A potential for hydrocarbons was assumed in the deep 3rd floor of the Vienna Basin. The Autochthonous Mesozoic below the Alpine-Carpathian top was considered for exploration. In 1977 the first of 4 wells, which reached this zone in such great depths, had been spudded. After a gas kick at 'Zistersdorf Übertief 1a' at 7,544 m the well got lost due to wellbore instability in January 1980. An additional well 'Zistersdorf ÜT2' was drilled to 8,553 m to prove the potential gas reservoir but the well was dry. Close to the Zistersdorf wells a third one was drilled. 'Maustrenk ÜT1a' reached a depth of 6,563 m and has producing gas and oil for several months. The fourth well 'Aderklaa UT1a' which was even drilled into the Kristallin at a depth of 6,630 m was not hydrocarbon bearing.

For almost 25 years no well to such great depths was drilled in Austria. The increasing energy demand worldwide has indicated, that ultra-deep exploration could get economic again in the future.

The objective of this master thesis is to analyse the four ultra-deep projects to all intents and purposes, which lessons learned have been made and find out if / which experiences made from 1977 to 1986 are applicable for future exploration requirements in Austria. From these analyses a preliminary well design for a future ultra-deep drilling project a Zistersdorf is done. To gain insight in this complex subject this thesis covers also challenges in ultra-deep drilling, drilling technology and an overview of the geology of the Vienna Basin.

The main focus of this thesis are technical aspects, but also some economic considerations are covered in this work.

2 History in Deep Drilling

This chapter gives a detailed overview of the milestones in deep drilling and the deepest holes ever drilled.

2.1 Definitions

Like every business has the oil business its own terms and abbreviations. For a clear understanding some fundamentals which are used in this thesis are listed below.

2.1.1 Type of well

There are four different types of wells which declare the status of a field development:

- Wildcat well: A well drilled in an area not known to be an oil field.
- Exploration well: A well drilled in the initial phase of a petroleum operation to approve the existence of hydrocarbons.
- Appraisal well: Drilled after successful exploration to determine the size of the oil or gas field and to assess field characteristics.
- Production well: A well drilled primarily for producing oil or gas in the development phase.

2.1.2 Depth

It is very important to distinguish between MD – Measured Depth and TVD – True Vertical Depth:

- MD: Is the length of the hole or the length of pipe down to the drill bit. For inclined wells the MD is always longer than the TVD.
- TVD: Is the vertical distance from a point in the well to the surface. TVD is used for calculations like the bottom hole pressures (BHP) which is related to the hydrostatic head of drilling fluid in the wellbore.

This master thesis is only dealing with nearly vertical wells and no horizontal or inclined wells. If the terms ‘depth’ or ‘deep’ are used it always means true vertical depth.

2.1.3 Deep, Ultra-deep or Super-deep

For deep drilling there are three different terms for the depth [Reference 1 and 70]:

- Deep (Tief / T): TVD > 4,500 m / 15,000 ft
- Ultra-deep (Übertief / ÜT): TVD > 6,000 m / 20,000 ft
- Super-deep (Supertief): TVD > 7,500 m / 25,000 ft

2.2 Milestones of drilling in Austria

By the early 20th century the Austrian-Hungarian Empire was the third largest oil producer in the world. In 1909 was the peak oil production with 2.1 million tons. Only Russia and the United States produced more oil.

The first commercial oil discovery in Austria was made in 1934. The well 'Gösting 2' near Zistersdorf is 50 km north-east of Vienna and already used rotary-drilling technique.

After World War II the SMV (Soviet Mineral Oil Administration) was formed by the Russian occupying force and operated in the Vienna Basin. The discovery of the largest oil field in Europe – field Matzen – resulted in a sudden increase in production.

In 1955 the Austrian State Treaty was signed and all operations were transferred to the Austrian Republic. This included 34 medium-sized drilling rigs. To administrate all the operations the OMV (Österreichische Mineralölverwaltung) was founded in 1956 [2].

The first well drilled to a depth of 3,000 m was the well 'Palterndorf 1' in 1957 with 3008 m.

The 4,000 m mark was reached with 4,005 m at 'Schönfeld 1' in 1961. At this well the first IDECO SBS Super 7-11 drilling rig was in use.

The 'Baumgarten 7' well passed the 5,000 m in 1967. The wellbore reached a depth of 5397 m.

In the same year the first 6,000 m well was drilled by OMV. 'Schönkirchen T32' with 6,009 m was the first well of the ultra-deep exploration program and the gas field 'Schönkirchen Ultra Deep' was discovered [3].

2.3 Austria's deepest wells

An overview of the deepest wells (ultradeep and superdeep wells) in Austria is given in Table 1.

Well Name	Spud Date	End Date	Final Depth
Schönkirchen T32	22.11.1966	05.12.1967	6,009 m
Schönkirchen T90	20.05.1973	28.05.1975	6,122 m
Gänserndorf ÜT1	27.10.1975	15.12.1977	6,346 m
Berndorf 1	21.04.1978	06.06.1979	6,028 m
Prottes ÜT2	28.04.1981	14.08.1982	6,043 m
Zistersdorf ÜT1a	02.11.1977	26.01.1980	7,544 m
Zistersdorf ÜT2A	06.03.1981	31.05.1983	8,553 m
Maustrenk ÜT1a	14.09.1982	14.09.1984	6,563 m
Aderklaa UT1a	12.07.1982	23.01.1985	6,630 m

Table 1: Austria's deepest wells [3]

The four deepest wells reached the third floor of the Vienna Basin. They are the main subject of this thesis and are discussed in detail in Chapter 6.

2.4 World's deepest wells

Table 2 shows the five deepest wells ever drilled in the world.

Well Name	Depth	Year	Location
Zistersdorf ÜT2A	8,553 m / 28,061 ft	1981-83	Zistersdorf, Austria
KTB	9,101 m / 29,859 ft	1990-94	Windisch-Eschenbach, Germany
Baden 1	9,159 m / 30,050 ft	1970-72	Elk City, Oklahoma, USA
Bertha Rogers 1	9,583 m / 31,441 ft	1972-74	Burns Flat, Oklahoma, USA
Tiber well	10,685 m / 35,055 ft	2009	Keathley Canyon, Gulf of Mexico
Kola SG-3	12,262 m / 40,230 ft	1970-89	Kola Peninsula, Russia

Table 2: World's deepest wells [4 - 11, 67]

The wells 'KTB' and 'Kola SG-3' were drilled for scientific purposes. That means they were performed to gather information about the following topics:

- Earth's crust structure, composition and evolution
- Earthquake and volcanic activity
- Natural forces, climatic and environmental changes
- Evolution and extinction of species

The other three wells were spudded to find hydrocarbons. The Tiber well is an offshore well.

2.4.1 Zistersdorf Übertief 2A

This well is a subject of this thesis and is discussed in detail in Chapter 6.

2.4.2 Kontinentale Tiefbohrung (KTB)

In 1985 the Federal Republic of Germany gave the final approval for the continental deep drilling program – a non-commercial geoscientific research project to investigate the processes of the earth's deep continental crust. The project location is near Windisch-Eschenbach in the north-eastern part of Bavaria, southern Germany. It lies at two major tectonic units which are regarded as a zone formed by the closure of an ocean basin 320 million years ago.

At first a pilot hole was planned and drilled to collect a maximum of geoscientific data before drilling the main hole. It was spudded in September 1987 and after 400 logging runs and taking 3564 m cores it reached a final depth of 4,000.1 m in April 1989. Drilling, coring and logging techniques were tested to reduce the costs and improve the progress at the superdeep hole.

In October 1990 the superdeep hole was spudded 200 m next to the pilot hole. For this project the largest onshore rig UTB 1 with a height of 83 m and a maximum hook load of 8,000 kN (816 metric tons) was designed and constructed. Difficult drilling conditions as borehole stability and temperatures exceeding 250° C had to be passed. After 600 round trips and 266 logging runs the well reached a final depth of 9,101 m (29,859 ft) in October 1994 [5, 6].

2.4.3 Baden # 1-28

This well was drilled by the Lonestar Petroleum Company in the Anadarko Basin in west-central Oklahoma (U.S.). It was spudded near to Elk City in 1972. After two years drilling it reached a total depth of 9,159 m (30,050 ft) [7, 8].

2.4.4 Bertha Rogers # 1-27

After completion of well ‘Baden 1’ the Lonestar Petroleum Company spudded the wildcat well ‘Bertha Rogers #1’ in 1972. The well site was near to ‘Baden 1’, south of Burns Flat. The drilling operations were encountered by enormous temperatures and pressures (up to 25,000 psi or 1723 bar). At a depth of 9,583 m (31,441 ft) the bit drilled into a reservoir of molten sulphur. This happened in 1974 and this well is still the deepest wellbore in the world drilled for hydrocarbons. In total a number of 52 wells have been drilled in the United States below 25,000 ft or 7620 m [7, 8].

2.4.5 Kola SG-3

In 1962 the former Soviet Union established an ‘Interdepartmental Scientific Council’ on the investigation of the Earth’s crust. The target was to drill as deep as possible through the Baltic continental crust which has a total thickness of 35 km and 2.7 billion years old rocks at the bottom. The selected location is on the Kola Peninsula, 110 km northwest of the town Murmansk.

The drilling operation started in May 1970 with the Uralmesh-4E drilling rig. Later on they changed the rig to an Uralmesh-15,000 drilling series rig. Nine years later in June 1979 the well measured 9,584 m. In August 1984 the wellbore reached 12,066 m. After a drill pipe loss of 5,000 m in the well drilling was restarted from 7,000 m. Five years later in 1989 the well reached the record depth of 12,262 m (40,230 ft). The temperatures in this depth were higher than expected – 180° C instead of 100° C. Drilling deeper to the target of 15,000 m was not feasible due to the high temperatures and as a consequence drilling was stopped.

As in the KTB project long-term observations of fluid have been made in the well for several years. After the turn of the millennium the location was abandoned, the rig destroyed and nowadays there are only some ruins left [9 – 11].

2.4.6 Tiber well

In September 2009 the Tiber oil field was discovered. It is an offshore field in the Gulf of Mexico and was drilled under 1,260 m (4,130 ft) of water. The Tiber well reached a true vertical depth of 10,683 m (35,050 ft) and measured depth of 10,685 m (35,055 ft). It was drilled by the semi-submersible drilling rig 'Deepwater Horizon', which sank one year later after an explosion due to a blowout. Unfortunately there is no well data available. And as the requirements of deep-water drilling are different from onshore operations, the well is not a topic of this thesis [67].

3 Challenges in Ultra-Deep Drilling

Drilling operations always bring a lot of challenges to the responsible persons. In ERD (Extended Reach Drilling) where the horizontal displacement is at least twice the vertical depth there are different challenges than in ultra-deep drilling. Torque & Drag, Differential Sticking and Cuttings transport is a major problem in horizontal drilling.

In deep drilling two important criteria are the high pressure (HP) and the high temperature (HT). The original definition of a HP/HT well was introduced by the Department of Trade Industry (DTI) for the United Kingdom Continental Shelf (UKCS). It was defined for bottom hole temperatures higher than 149°C (300°F) and a pore pressure of a drilled formation greater than 689 bar (10,000 psi). A slightly different definition is used by the Norwegian Petroleum Directorate (NPD). It is a HP/HT well if the well is deeper than 4000 m true vertical and/or the temperature is higher than 150°C and/or the expected wellhead shut-in pressure is greater than 10,000 psi [12]. Also OMV is using this definition of the NPD. A HP/HT classification by Courtesy Baker is given in Table 3.

	Pressure	**Temperature**
HPHT	10,000 – 15,000 psi	300 – 350 °F
Ultra HPHT	15,000 – 20,000 psi	350 – 400 °F
Extreme HPHT	20,000 – 30,000 psi	400 – 500 °F

Table 3: HPHT classification by reservoir temperature/pressure [13]

3.1 Planning

The key to a project's success is a good planning. There are never ideal conditions to drill a well and a good preparation helps to reduce risks and incidents.

3.1.1 Casing Setting Depth

A challenge of the planning process is to find the optimal casing setting depth. The decision is depended of the mud weight window which is given by the formation pore pressure and the frac gradient of the different formations. The pore pressure in deep wells is not always hydrostatic and the prediction of abnormal pressure zones is very complex. A low clearance between pore pressure and fracture pressure makes it difficult to find a way to bottom. Depending on the formation type and properties the different pressure zones should be isolated by the casing sections. Long open hole sections increase the risks of wellbore instability and fracturing of a formation which results in mud losses and possible kick situations. The number of casing sections is limited by the spud diameter.

3.1.2 Mud Type

The mud types and their properties used for the different hole sections are dependent on the formations. A good filter cake against fluid losses is achieved and formation damage should be avoided. Difficult formations to handle are salt or clay. The rheology of the drilling fluid is a great issue in drilling deep wells. Due to the long way the fluid is pumped the viscosity and so the friction pressure losses should be as low as possible. On the other side it's very important to have enough yield strength to bring the cuttings bottom up.

3.2 Equipment

Deep drilling requires equipment and material that handle heavy loads and withstand high pressures and temperatures. Operations in extreme ranges need proven equipment and safe working to avoid incidents and complete the well.

3.2.1 Drilling Rig

For drilling an ultra-deep well a very heavy drilling rig is necessary to lift the heavy loads. The maximum allowable hook load is a limitation of a rig - the maximum load occurs at running casing. A high setback capacity is essential to store all the drill pipe stands in the mast. The height of the substructure is important for the size of the blow out preventer (BOP).

3.2.2 Drill String

High forces are acting on the drill string. Torque & Drag is not a big issue as for horizontal drilling whereas the torque is still high. The drill string has to withstand high loads (tensile strength), high pressures (burst resistance) and possible corrosive fluids.

3.2.3 Mud Pumps

Friction pressure losses along the pipes create very high stand pipe pressures. Powerful mud pumps are required for the circulation of the drilling fluid. High non-productive time should be taken into consideration for the number of mud pumps. A shut-down of the pumps may cause enormous well control problems.

3.2.4 Mud System

Deep wells start with larger diameters and a higher mud volume is in the well. This requires an equivalent tank system on the rig site. The capacity of the mud pits is important in case of fluid losses and mud change. Shale shakers, hydro cyclones and centrifuges should have the required capacities to clean the mud.

3.2.5 Well Control

Great depth and high reservoir pressures demand higher-rated well control equipment. Blow out preventers and x-mas trees up to 30,000 psi (2,068 bar) are essential. Well control equipment like BOP and choke manifold should be dimensioned in a safe range.

3.3 Formation Evaluation

The knowledge of formation properties is very important in drilling operations. Data which is not available has to be evaluated during or after each drilling section. Incorrect parameter and wrong decisions may cause enormous well problems.

3.3.1 Logging

Measurements while Drilling (MWD), Logging while Drilling (LWD) and Wireline logging are a big issue in formation evaluation. There are already tools which are pressure and temperature resistance for these great depths but their physical life is not as long as for common tools already used.

A high inclination for wireline tools in deviated wells is critical but in case of ultra-deep vertical wells there are other challenges. The drill pipe elongation is dependent on its own weight and the temperature. But the wireline has an elongation under tension and shrinkage under high temperatures. An appropriate depth correlation is necessary to exactly know to which depth the measured data belong to.

3.3.2 Cuttings

The analysis of the cuttings is essential to identify the different formations and their properties in the well. In deep wells the distance of cuttings transport is much longer and the cuttings have more time to mix up. Good mud properties increase the chance for less merged rock pieces. The sample intervals and the delay time of the cuttings to the surface have to be considered by the mud loggers.

3.3.3 Formation Tests

To determine the formation strength (frac pressure) the standard procedures like Leak-Off Test (LOT) and Formation Integrity Test (FIT) have to be performed. Due to the great TVD and hydrostatic pressure the tolerances in mud weight density get smaller. In abnormal pressure zones there is a very narrow mud weight window. So formation tests have to be done carefully. Long open hole sections should be avoided to reduce the risk of well control incidents.

3.3.4 Coring

An important way to get formation and reservoir properties is the gathering of cores and rock samples. Getting deeper into the earth's crust means a hotter environment, higher pressure and harder rock. This results in higher vibrations, dynamic loads and equipment wear/failure. And these conditions leads to less core recovery. The aim is to improve efficiency and reduce time and costs.

3.4 Drilling

Knowledge and experience is a very important factor for drilling superdeep holes. The following topics require a good planning and immediate decisions in case of troubles.

3.4.1 Wellbore stability

A good well path is very important in ultra-deep drilling. A long open hole section through different stress formations should be avoided to keep wellbore stability. Mud weight and Equivalent circulating density (ECD) should be in the required range to prevent a well collapse. Wellbore incidents may cause loss of expensive downhole equipment and result in high non-productive time.

3.4.2 Vertical well

The well trajectory is another challenge to manage. To drill a vertical well in such great depths is not as easy as it seems. Different formation dips deviates the bit and bends or dog legs are created. For long open holes such curves immediately result in increasing torque. To avoid sidetracking in deep wells inclination and steering tools are necessary to keep the well path as straight as possible.

3.4.3 Casing

The casing in deep wells has to withstand high pressures. Collapse and burst resistance have to be designed sufficiently for the different casing scenarios. The clearance between pipes and formation should not be too small to bring the casing down. Stable well conditions are required to run the casing with moderate speed into the well.

3.4.4 Cementing

The target of a cement job is to isolate the formations and sustain the casing. Due to high pressures and temperatures in the well the cement has different requirements than for lower sections. For a good cement bond there should be neither gas nor other formation fluids in the well. For long open hole sections challenging more-stage cementing jobs may necessary.

3.4.5 Well Control

Well control in ultra-deep wells is the most important subject for a success. Kick detection in such wells is much more difficult due to great mud volumes and long circulation times. The continuous monitoring of kick detection parameters is essential. Enough mud reserves have to be on the rig-site or rapidly available. Well control equipment up to 30,000 psi is required and the personal should be trained for kick situations.

4 Drilling Technology

In case of drilling technology there is one major question: ‘What has been changed from the late 1970s to now with regard to technology?’

4.1 Seismic

The seismic helps to find fault distribution and subsurface structures. It is an important tool to find anticlines or traps for possible reservoirs. The technology has been improved over the last decades. A 3D-seismic and a computer-based analysis is the standard method today.

4.2 Equipment

Many inventions and improvements have been made on drilling equipment. For deep drilling the requirements on a drilling rig are very high – loads and capacities of many heavy rigs do not meet the requirements for ultra-deep drilling. A table of the rig specifications of the used rigs for ultra-deep drilling in Austria is given in the appendix.

There are a lot of new tools which improve the work on a drilling rig. They may not change the drilling procedure itself but they help to reduce time and risk. Two of the most important tools on the rig floor are the Top Drive and the Iron Roughneck.

Another important development has been done on the drill string. As the wells get deeper or longer also the hook load increases. The good old steel pipes are still used on the rigs but the use of other materials like titanium or aluminium in combination with steel reduces weight. Already at the Kola well aluminium pipes were used beside steel pipes. Research on titanium and aluminium alloys and further development for HPHT applications have shown the potential for the oil industry [15].

4.3 Drilling mud

With increasing depth the drilling mud has to sustain higher temperatures and higher pressures. The mud has to complete several tasks like cuttings transport, fluid loss control, lubrication or shale stabilisation. Many improvements have been made since the 1970s on rheology. A water-based mud for high temperature applications up to 180°C has stable properties for drilling such deep wells today and the research goes on [16].

4.4 Casing

The casing material and sizes itself didn’t change so much. There are some new techniques to bring the pipes down to the planned depth. One important invention is the OverDrive or TorkDrive by Weatherford which enables circulation and rotation of the pipes during running casing. A low clearance or doglegs cause problems and pulling out the casing results in increase of time and money. Another technique is to drill with the casing itself. Drill pipes are replaced by the casing and the formations are almost isolated while drilling. This reduces casing and liner runs and the borehole is ready for cementing when TD is reached.

Many drilling problems like stuck pipe or a lost fish cause to drill a sidetrack. This means a reduction in casing diameter. For ultra-deep wells large top hole diameters are necessary to reach the desired depth. Sidetracking can’t be avoided but there is the possibility to reduce the casing sizes by solid expandable tubular. After the wellbore has been opened or drilled by an underreamer the casing is enlarged by mechanical expansion. As a field appraisal well has shown it is possible to set several liners back-to-back with the same inner diameter [17].

4.5 Data monitoring

The computer era has changed dramatically since the 1980s – so on the drilling sites. Many parameters are still measured mechanically or hydraulically but the data processing is much faster. Real-time monitoring or analysis helps the driller immediately to react. Every kind of data can be stored or monitored at any place. The drilling parameters can be seen as on the rig site as in the head office. This gives the opportunity for a faster indication of kicks or other drilling problems and to take action as soon as possible.

5 Geology of the Deep Vienna Basin

The Vienna Basin in the north-east of Lower Austria is the main exploration area for hydrocarbons in Austria. This basin consists of three floors but only four wells were drilled into the third floor in two different regions. This chapter gives a detailed overview of the development of the Vienna Basin and the structures of the two focused regions.

5.1 The Vienna Basin

5.1.1 Location

The Vienna Basin is a sedimentary basin between the Eastern Alps and the Western Carpathian Mountains. It is bounded from Uherské Hradiste in the north and Gloggnitz in the south.

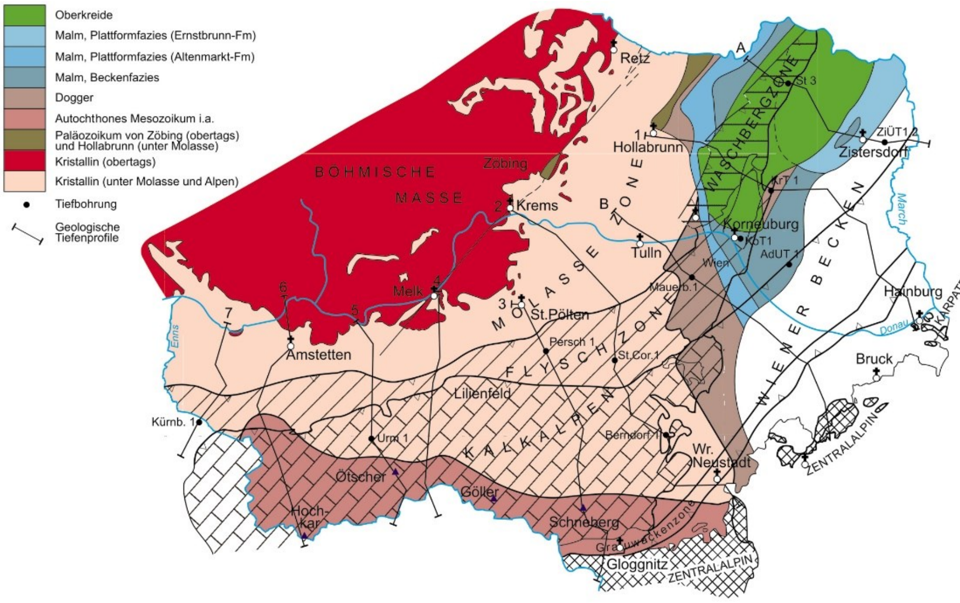


Figure 1: Vienna Basin / Wiener Becken [19]

The basin is 200 km long and has a maximum width of 50 km. It is spindle-shaped and lies parallel to the south-east flank of the Bohemian Massif (Figure 1). The Lower Austrian unit is separated by the rivers March and Thaya from the Slovakian and Moravian part. This again can be divided into a southern part below the Danube and a northern part which is named Marchfeld. The main focus is on this northern part where the four ultra-deep wells have been drilled.

5.1.2 History of Research

More than 200 years the basin has been researched. First investigations were above ground on geology and palaeontology. In the 1960s and 1970s the search for hydrocarbons got deeper into the earth's crust and explored the Alpine-Carpathian bedrock. In the 1980s the third or autochthonous floor was reached in depths up to 8.5 km. Further methods as geophysics (seismic) and gravimetry helped to understand this complex structure.

5.1.3 Faults and Tectonics

The Vienna Basin is a tectonically cauldron subsidence with some hundreds of faults. They follow a certain direction resulted from the pull-apart mechanism. The surfaces have an inclination between 50 and 60°. Along the faults the subsurface mountainsides have differences in vertical height up to 6 km which corresponds to the relief of the primary mountains before later erosion.

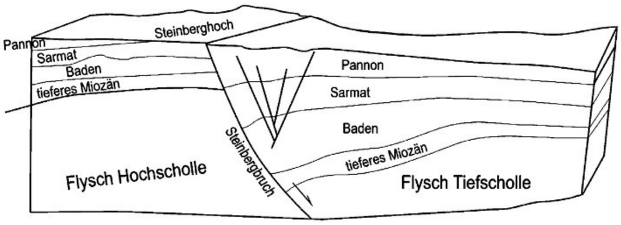


Figure 2: The Steinberg fault [19]

The Steinberg fault (Figure 2) has a length of 55 km from north to south-south-east. It reaches from Moravia (Czech Republic) to Hohenruppersdorf. Between the Badenian and the Pannonian an extreme synsedimentary settlement occurred which resulted in the biggest offset of 8,000 m (6,000 m vertical) at Zistersdorf – known as Zistersdorf depression today. Figure 18 and Figure 19 in the Appendix shows the Vienna Basin and its faults & underground structures today.

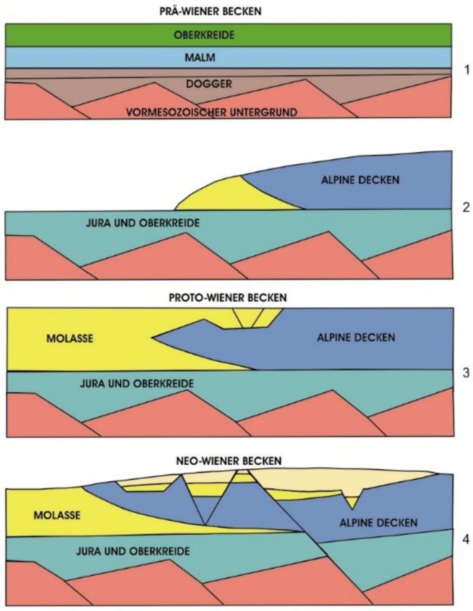
5.1.4 Historical development

The development of the Vienna Basin depends to its position next to the Bohemian Massif, the Alps and the Carpathians. In the late stage of the alpine-carpathian tectonics the north-south compression pushed parts of the crust wedge-shaped to the east. West and north-east of Vienna the movements stopped at the end of the Carpathian 17 million years ago, eastwards younger. The last drifts had taken place in the Pannonian 9 million years ago in Romania. This delay resulted in strain and lateral movements inside the thrust fault. Characteristics of a pull-apart mechanism are represented by a rhombic form, depocenters (high sedimentation in subsidence zones) and step faults.

The development of the basin happened in stages – Pre-, Proto- and Neo-Vienna Basin (Figure 3).

Pre-Vienna Basin

During Dogger the Bohemian Massif was overlayed by a rift basin, during Malm and Cretaceous by a passive marginal basin (Figure 3, Phase 1). Alpine-carpathian units from different basin types were shifted over the generated foreland basin in Eocene and Oligocene (Figure 3, Phase 2).



JURA:
- Riftbecken im Dogger
- Passivrandbecken vom obersten Dogger bis inklusive Oberkreide

PALÄOGEN:
- Überschiebung der alpin-karpatischen Decken über ältere Tertiärmolasse

TIEFERES NEOGEN:
- Molassesedimentation vor den noch überschiebenden Decken und am Rücken derselben ("piggy-back")
- erste Dehnung

HÖHERES NEOGEN:
- intensivierte Dehnung in einem ortsfesten Becken bei beendeter Deckenüberschiebung

Figure 3: Development of the Vienna Basin [19]

Proto-Vienna Basin

The Alpine-carpathian nappe shifted again over the foreland to the north-west – from the Eggenburgian to the end of the Carpathian. At the front movement and sedimentation interfere. The sediments overlayed the nappes and get carried (as piggy-back basins) at the back of tops (Figure 3, Phase 3). Due to the pull-apart effect normal faults occur. Sediments of the Badenian lay undisturbed and with constant thickness above (compare Figure 21, upper profile between Wilfersdorf 2 and Mistelbach U1). The main geographical extension of the Proto-Vienna Basin is in the northern part of today's basin.

Neo-Vienna Basin

Since the Badenian the Vienna Basin got its actual dimensions (Figure 3, Phase 4). The alpine nappes stopped and the basin got stationary. In the north-east they continued and strain & extension resulted in concentrated faults in the basin.

5.1.5 Sediments

The layer sediments range from early Miocene to the Ice age – a period of 20 million years. The variety of lithology ranges from coarse deposits of shores & river mouths to fine sediments of the inner basin and lime formation in shallow water. A variety of species was verified from shallow coasts up to tropic seas.

Sea level fluctuations and astronomic cycles effected different sequences of sedimentation. Tectonic elevation & subsidence changed the erosion conditions and the delivery of sediments. A compensation of a submarine relief was possible which is shown by the enormous differences in layer thickness at different subsidence conditions.

Higher zones in the basin formed areas with shallow water & lower thickness and surrounding zones as depressions with larger thickness. An extreme difference can be seen between the Steinberg high and the Zistersdorf depression.

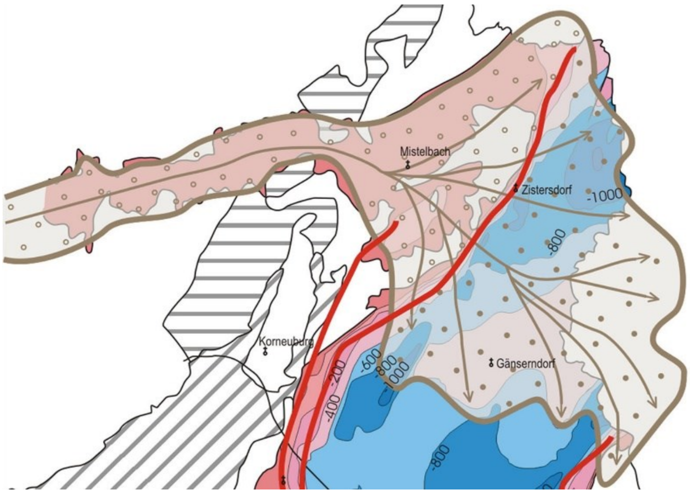


Figure 4: Base of Pannonian [19]

The main deposit of clastic material into the northern Vienna Basin happened over the Molasse. The pathway and delta of the 'Ur-Danube' is shown in Figure 4. A detailed overview of the sedimentation of the Vienna Basin is given in Figure 20 in Appendix A.2 [19].

5.2 Structure

For this thesis the structure of two regions are of interest - the Zistersdorf profile with well Zistersdorf ÜT1, Zistersdorf ÜT2 and Maustrenk ÜT1 and the Aderklaa profile with well Aderklaa UT1.

The deposits of the Vienna Basin are in autochthonous position (developed in situ) and in allochthonous position (moved from point of origin). The basin can be classified in three main floors. The first and factual Vienna Basin consists of sediments of the Neogene. The second floor is allochthonous from alpine-carpathian nappes and the deepest floor is the autochthonous Mesozoic.

5.2.1 Zistersdorf profile

A cross section at Zistersdorf with the three ultra-deep wells is shown in Figure 5. A more complex profile can be seen in Appendix A.2 (Figure 21).

First floor

The first floor – or Neogene - of the Vienna Basin is up to 6,000m thick. The Steinberg fault - which is the biggest fault of the Basin - generated a total different stratigraphy of the Maustrenk and Zistersdorf well. The Neogene at MauUET1 has a thickness of 490 m and at ZiUET1 a thickness of 4,885 m down to the Steinberg fault - and this with a linear distance between the wells of only 5 km. The first floor consists of terrigene sands & sandstones, clays & marly clays and fewer amounts of gravel and conglomerates.

Second floor

The second floor at MauUET1 can be separated in a Flysch and a Waschberg zone. The Flysch zone with a thickness of 4,290 m reaches from the Upper Cretaceous to the Eocene. The rock composition of this zone consists of diversified sequences of sandstone and marl turbidites. Below is the Waschberg zone with a thickness of 1,630 m. This zone is composed of allochthonous, palaeogenous sediments. There are coloured clayey-marly parts, grey / green with brown marls and fine clastic layers. In the lower Waschberg zone there are two formations embedded – a marlstone layer of 190 m and Malmian upper carbonates of 6 m thickness. A limited oil production from the carbonates at MauUET1 was done.

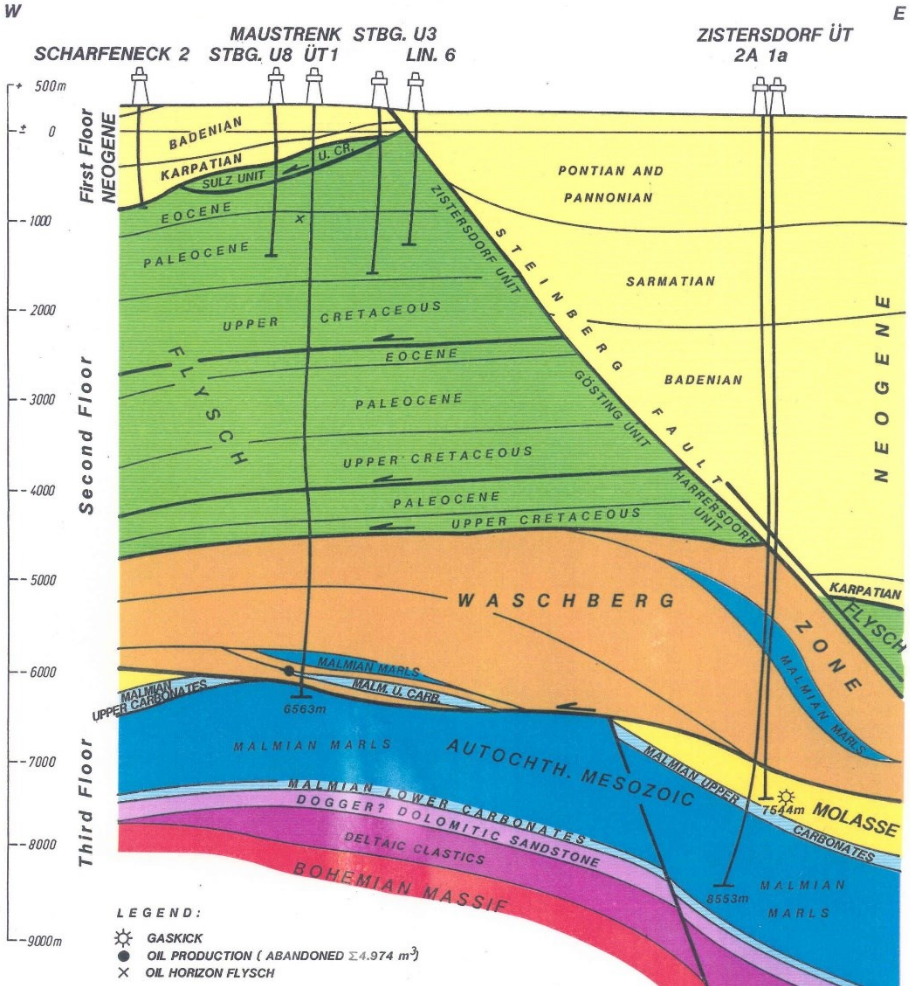


Figure 5: Cross-section Zistersdorf [20]

At the Zistersdorf wells there's no Flysch zone due to the Steinberg fault – a normal fault. The Waschberg zone at these wells has a thickness of 2,352 m with an embedded marlstone layer of 423 m at ZiUET1 and 400 m at ZiUET2.

Third floor

The third floor was reached at these three wells but was not drilled through. At Maustrenk 153 meters into the Autochthonous Mesozoic were drilled – final total depth 6,563 m. There are no Upper carbonates as they were already shifted as klippe into the Waschberg zone. And the Molasse exists only in allochthonous position.

At Zistersdorf ÜT1 the well was drilled 306 m into the Molasse. The kick at 7,544 m results probably from gaps, disruptions or a karst formation in the breccia basis of the Molasse. Deeper drilling at ZiUET2 showed the Malmian Upper Carbonates as grey lime below the Molasse with a thickness of 65 meters. The marl formation below is at least 922 m thick as this distance was drilled. The Malmian lower carbonates and Dogger formations have not yet been reached.

5.2.2 Aderklaa profile

A cross section at Aderklaa with the ultra-deep well is shown in Figure 6. In the Appendix is a large profile of the Aderklaa high (Figure 22).

First floor

The Neogene at Aderklaa has at thickness of 3,607 m and developed from sedimentation after the movement of the Alpine nappes stopped. At about 2,700 m there are the Aderklaa conglomerates with a thickness of 185 m.

Second floor

The next floor has a thickness of 1,825 m. In the upper half of the second floor at Aderklaa there are the Calcareous Alps (743 m) and below is the Flysch zone (1,082 m). The Calcareous Alps as its name already says consists mainly of limestone (very often dolomite). The Flysch zone can be divided into three beds – clayey-marly rocks from Eocene (Agsbach beds), a sandstone complex from Palaeocene (Hois beds) and Upper cretaceous rocks (Kaumberg beds).

The 618 m thick formation below belongs neither to the second nor to the third floor. The so named Helveticum from the Eocene has green-grey to grey pelites and less sandstone. It seems to belong to the Waschberg-Steinitzer Unit.

Third floor

At the top of the third floor is the Autochthonous Mesozoic. The Malmian marl with a thickness of 178 m is a dark marlstone. The 24 m thick limestone below is a mud-limestone. Directly below the Malm at 6,252 m is the Crystalline (Bohemian Massif) which is totally unweathered. Aderklaa UT1 is the only well which ever reached Bohemian Massif in such depths – 378 m were drilled into this formation. The rock of this basis was garnet-mica schist. The Molasse was sheared off and is so missing in this profile [20].

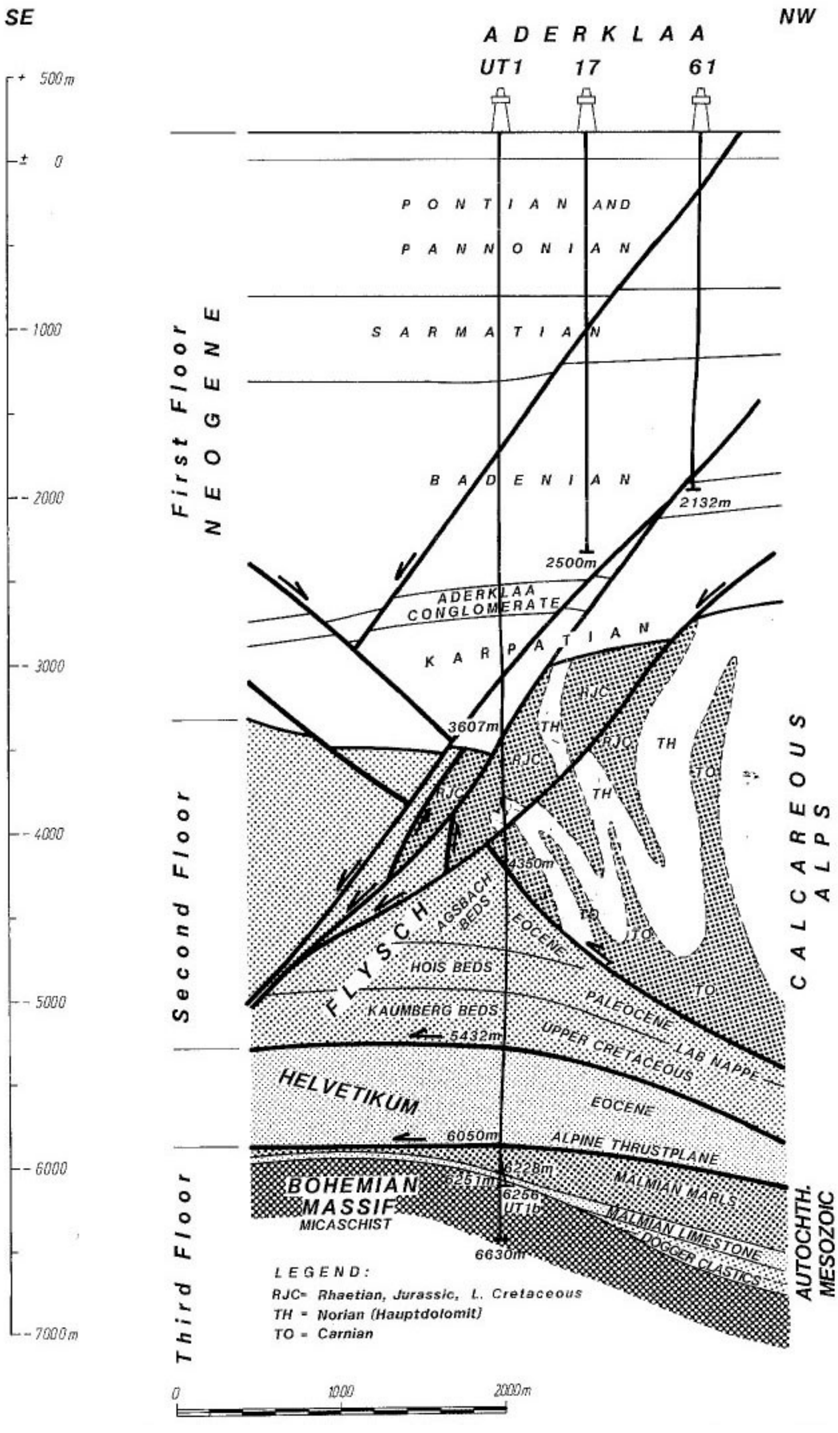


Figure 6: Cross-section Aderklaa [20]

6 Well Reports of the Ultra-deep Wells

This chapter gives the operations of each ultra-deep well including drilling, casing and cementing jobs. The wells are sorted by the main well respectively sidetracks and subdivided by drilling sections. Detailed data of the OMV rigs is given in Table 51 in the appendix. The data of the rigs used in Germany, USA and Russia is shown in Table 52. The available casing specifications are also given in the appendix (Table 54 and Table 55).

6.1 Zistersdorf ÜT1 / 1a

The object of drilling Zistersdorf ÜT1 was to investigate the Steinberg anticline in a deeper floor below the alpine-carpathian nappe in case of hydrocarbons. In the shallower formations (Neogene and Flysch) hydrocarbons within the anticline had already been proved. The assumptions of the Autochthonous Mesozoic as reservoir rock came from drilled Gresten beds & Malmian carbonates in the west and Malmian carbonates with riff complexes within the Waschberg zone in the east. Drilled palaeozoic carbonates at Nemcicky 1 in Slovakia showed an occurrence of HCs.

6.1.1 Zistersdorf ÜT1

The well was spudded on the 29th of October 1977 by the ÖMV (later OMV) two kilometres north-east of Zistersdorf (Table 4). A 24 1/2” standpipe to 28 m and a kelly hole were drilled for starting.

Section 1 – 23” bit and 18 5/8” casing

The top hole section was drilled by a 23 inch bit within one week to 511 m. Starting with a spud mud and a mud weight of ~ 1.12 SG no drilling problems occurred. Running an 18 5/8” casing to 509 m and following cementation (1.86 – 2.00 SG) to surface had finished this section.

Operation:	29.10.1977 – 26.06.1979	Coordinates:	N 48° 32’ 51”
Drilling:	02.11.1977 – 06.01.1979		E 16° 47’ 34”
		Sea level:	177.86 m
Final depth:	6,851 m	Drilling rig:	3127 – H 3000

Table 4: Well data Zistersdorf ÜT1 [24]

Section 2 – 17 1/2" bit and 13 3/8” casing

After 48 drilling days with a 17 1/2” bit the planned drilling depth was reached at 2,983 m – mud weight between 1.12 and 1.14 SG. A pin break of a drill collar caused a fishing job. The 2.29 m long fish (bit & stabilizer) was caught by a 12 3/4" overshot within one day. Several logging runs by Schlumberger and OMV were done. The 13 3/8” casing was run to 2,981 m and cemented (1.60 – 1.86 kg/l).

Section 3 – 12 1/4” bit and 9 5/8” casing

The next section started with a 12 1/4" bit and a mud weight 1.15 – 1.27 kg/l. The planned drilling depth was about 5,100 m. At 4,125 m and at 4,585 m a core was taken. After the second core the mud weight was increased due to an overpressure zone. At 4,598 m (57 drilling days) up to 100 % gas readings were seen. Within one week the mud weight was increased up to 1.62 SG while circulation the gas out of the well (3.1 m³ mud losses). After the well was balanced & doing two logging runs they decided to stop drilling because of the overpressure zone & long open hole section and set the casing earlier. The 9 5/8” casing was run to 4,592 m and cemented with a specific gravity of 1.60 to 1.90.

Section 4 – 8 1/2" bit and 7” casing

Before starting drilling the mud was changed to an oil mud with 1.52 SG and continuous weighted up. At 4,588 m an open hole test was done. At 4,679 m gas readings were recognized and the mud weight was increased up to 1.90 kg/l. After a second OHT still gas was measured and drilling mud was weighted up to 1.94 SG. Directly after the test during pull out of hole a fish was detected – 15.36 m of the BHA were lost. It took seven days to catch the missing parts by an overshot. During the third coring job the drill string got stuck. With an overpull of 225 t a drill pipe broke and 4,615 m of the string was lost in the hole. It took three days to get the fish to surface. After gas readings at 4,969 m another two Leak-off test were made at 4,984 and 5,069 m. At 5,318 m stuck again, the drill string broke due to 240 t overpull – two days fishing. Down from 5,627 m (2.24 SG) several gas readings were measured but no problems occurred. Drilling this section to 6,851 meters took in total 278 drilling days. Eighteen core jobs were done; the drill string got 11 times stuck and stood up five times.

The 7” liner was run down to 6,438 m when 80 t were lost on the hook. Only 314 m of casing were pulled out of hole. The rest (2,111 m) was lost in the hole. Fishing trials with pressure tests for probable disconnections were done for 34 days. The single disconnected pipes were fished successfully out of the well and a disconnected string of pipes (1,682 m) was left in the hole. In total nine V-150 couplings broke. Another 25 days the crew had to wait for new 7” pipes.

After running the 612 m casing into the hole the casing was connected to the fish – liner head at 4,412 m and casing shoe at 6,705 m. Several pressure tests for tightness later the pipes were cemented (2.23 SG). During pumping 22.9 m³ losses occurred and a squeeze cementation on the leader head was done. While drilling through the casing shoe and the cement many problems occurred. The drill string got stuck several times. In May a 37.31 m fish (5 7/8” bit and four 4 3/4” drill collar) was detected. After 27 days of unsuccessful fishing operation the decision to drill a sidetrack was made. A plug cementation (6,780 – 6,600 m) was necessary and a turbine began to drill the sidetrack from 6,724.5 to 6,730 m. The consequences of the casing couplings were six month of lost time.

6.1.2 Zistersdorf ÜT1a

The well 1a started on the 27th of June 1979 at a depth of 6,730 m - details in Table 5.

Operation:	27.06.1979 – 27.09.1980	Coordinates:	N 48° 32' 51"
Drilling:	27.06.1979 – 16.01.1980		E 16° 47' 34"
Sidetrack:	6,730 m	Sea level:	177.86 m
Final depth:	7,544 m	Drilling rig:	3127 – H 3000

Table 5: Well data Zistersdorf ÜT1a [24]

Section 5 – 5 27/32" bit

The sidetrack Zistersdorf ÜT1a was drilled by a 5 27/32" bit and a mud weight between 2.22 and 2.24 kg/l. During reaming at 6,757 m (TD 6,793 m) a pressure drop of 30 bar happened. A drill collar pin broke and the bit, one crossover and twelve 4 3/4" DCs were left in the well. The 126.4 m long fish was caught by an overshot within two days.

Nine days later the drill string again got stuck at 6,751 m (TD 6,820 m) – this time without circulation. An overload of the string up to 240 t and a pump pressure up to 250 bar didn't work. By shock vibration the drill string was released and a 10.23 m fish was left. After two weeks the fishing job by an overshot was successful. In total the string got six times stuck. On the 16th of January 1980 and 203 days drilling that sidetrack a drilling depth of 7,544 m was reached [24].

Kick

16.01.80: At 8:30 o'clock in the morning and at drilling depth of 7,544 m a pit level drop was indicated. The weight on bit was reduced to 1 t (1.1 m³ mud losses). At 8:50 drilling was stopped and the bit taken 9 m from bottom. A circulation with a rate of 480 l/m was ongoing (1.3 m³ losses). Pumping was stopped at 9:33 until 9:40 – 1.2 m³ influx. From 9:40 to 10:15 circulation with 400 l/min was done and the former pit volume of 68.2 m³ was reached. The pumps were stopped again at 10:15 for seven minutes (2.3 m³ influx). Another eight minutes circulation was enabled (1.8 m³ influx). At 10:30 the drilling fluid was circulated through the choke manifold (further influx). One hour later gas reached the wellhead. A pressure of maximum 400 bar was allowed to build up and through intermittent closing of the well the pressure was controlled. At 14:30 o'clock 10 m³ mud and loss controlling material was pumped into the well. During the night shift 55.6 m³ mud were pumped through the drill string – intermittent pressure control ongoing.

17.01.80: From 9:30 in the morning the gas was led over the discharge line to the flare stack and continuous flared. At 15:30 mud with lost controlling material was pumped into the well (51 m³ in total).

18.01.80 Flaring the gas was continued. From 7:30 to 16:30 the shut in casing pressure (SICP) was decreasing from 290 to 80 bar. The shut in drill pipe pressure (SIDPP) lied between 52 and 95 bar. During the afternoon gas was flared intermittent (SICP between 74 and 100 bar).

19.01.80 Every hour 1 m³ oil mud was pump into the drill string. During the night water was pumped into the annulus and after 25 m³ the gas from the annulus was flared until water came out again (SICP from 97 to 80 bar decreasing).

20.01.80 Mud was continuous pumped every hour. At 7:00 the SIDPP increased from 110 to 190 bar – pumping was stopped. At 12:30 the SICP was reduced from 102 to 65 bar by flaring. From 13:30 two and a half hours on 27.6 m³ water was pumped into the annulus (SICP 65 – 58 bar decreasing).

21.01.80 At 4:15 the SICP was released from 97 to 68 bar – gas was flared. The annulus pressure was kept between 100 and 40 bar. Water was pumped after each pressure release into the annulus until an increase of pressure.

22.01.80 The drill string was pressured up with 300 bar and was tight. The SICP was released from 100 bar until it was non-pressurized. As there was no pumping possible a wireline calliper was run and localised a bridge inside the 5” drill pipe at 935 m [25].

The next seven months several operations were done to save the well. A special high pressure snubbing unit from Otis from the USA was flown in. A 15,000 psi BOP stack, a 20,000 psi pumping equipment and a 2 1/16” combination macaroni string were necessary. After the bridge was drilled out a collapse of the 9 5/8” casing between 4,352 and 4,357 m was detected. As some of the macaroni couplings failed another string had to be flown in. As further couplings of the macaroni string failed and fishing didn’t bring any success the efforts were stopped [26].

Abandonment

On the 8th of August the first bridge plug was set at 4,915 m. The next day another one was set at 4,910 m. Five days later a 4 1/2" liner was run to protect the detected collapse. The liner depth was set from 4,909 m to 4,309 m with a 9 5/8” x 7” liner hanger at 4,297 m. Above a 7” tieback was run to surface and cemented. At 28th of September the disassembling of the rig started and on the 22nd of October the rig moved to Zistersdorf ÜT2 [23].

6.2 Zistersdorf ÜT2 / 2A / 2Aa

The well Zistersdorf ÜT2 was drilled to continue the exploration of the autochthonous sediments below the alpine-carpathian nappe at Zistersdorf ÜT1a. The existence of the formation and natural gas was proven in the first well. The aim was to make the gas accessible for production and furthermore to explore the Mesozoic and palaeozoic profile with potential gas formations [28].

6.2.1 Zistersdorf ÜT2

The well Zistersdorf ÜT2 is located 120 m north-west of ÜT1a and was spudded on the 27th of November 1980. To ensure drilling to the planned depth one casing size larger was chosen to start – a 32” standpipe to 26m. Table 6 shows the basic parameter of this well.

Section 1 – 17 1/2" x 24” x 29” bit and 24 1/2” casing

Section number 1 was drilled with a water-based mud and a mud weight between 1.12 and 1.14 kg/l. At first a 504 m well was drilled with a bit diameter of 17 1/2" inch in four days. Afterwards the borehole was opened with a 24” hole opener and then with a 29” hole opener to the required diameter (6 days hole opening). The 24 1/2” casing was run to 499 m but got disconnected at 385 m. It was possible to insert the upper casing into the coupling but no connection was achieved. The pipes were cemented (1.55 & 1.86 SG) by the usage of a wooden centralizer and a seal. During waiting time the wooden centralizer was pulled out of hole.

Operation:	22.10.1980 – 23.02.1981	Coordinates:	N 48° 32’ 53”
Drilling:	27.11.1980 – 25.01.1981		E 16° 47’ 29”
		Sea level:	178.88 m
Final depth:	1,910 m	Drilling rig:	3127 – H 3000

Table 6: Well data Zistersdorf ÜT2 [28]

Section 2 – 23” bit and 18 5/8” casing

During drilling out of the casing shoe the bit and one stabilizer were lost. Several fishing jobs with overshots were done for four days and the fish was brought to surface. The well was drilled to 1,910 m without further troubles (mud weight 1.13 -1.15 SG). The 18 5/8” casing was run to roughly 1,910 m and cemented to top. During the cementation the pump pressure was increasing rapidly which caused a pushing up of the casing. After cementing the pipe pressure was let off to bring the casing into the exact position again.

When the 17 1/2" bit was run into hole for drilling the casing shoe it stood up at 1,747 m. The casing was collapsed due to a high external pressure. Two weeks were tried to mill the casing but it had no success and so it was decided to start from top again [27].

6.2.2 Zistersdorf ÜT2A

The rig was disassembled and moved on the rig side 20 m to the east (Table 7). Again a 32” standpipe was drilled to 26 m for spudding. The well Zistersdorf ÜT2A started 97 days after ÜT2.

Section 1 – 23” x 29” bit and 24 1/2" casing

The first section was drilled by a 23” bit to 265 m and then opened to 29 inch (mud weight 1.13 SG). A 24 1/2" casing was run to 262 m and cemented to top.

Operation:	24.02.1981 – 21.11.1983	Coordinates:	N 48° 32’ 53”
Drilling:	04.03.1981 – 31.05.1983		E 16° 47’ 30”
		Sea level:	178.88 m
Final depth:	8,553 m	Drilling rig:	3127 – H 3000

Table 7: Well data Zistersdorf ÜT2A [29]

Section 2 – 23” bit and 18 5/8” casing

Without any problems the next section was drilled with a 23” bit to 1,675 m (mud weight 1.11 – 1.15 SG). Due to some bit changes the depth was reached after 34 days. An 18 5/8” casing was run to 1,673 m and cemented to top.

Section 3 – 17 1/2" bit and 14” casing

When the casing shoe was drilled a leak off test was done at 1,711 m. The mud weight laid between 1.14 and 1.22 kg/l and was weighted up to 1.44 kg/l beginning at ~ 4,200 m. After 112 drilling days and without any troubles the well reached a depth of 4,340 m. A 14” casing was run from 4,336 m to top and cemented with a slurry density of 1.50 and 1.90 SG.

Section 4 – 12 1/4" bit and 10 3/4" casing

Before the next section was started the mud was changed to an oil-based mud – in total 363 m³. When the casing shoe was drilled through a leak off test at 4,346 m was done by Halliburton. The mud weight was slightly weighted up 1.70 SG. From 4,377 to 4,685 m an 8 1/2" bit was used and afterwards opened up to 12 1/4 inch. The first gas readings came up at about 4,498 m which made it necessary to increase the mud weight to 2.21 SG. During hole opening a pin broke but the fish was caught within one day. At 5,648 m a pin break of a 9 5/8” spacer caused three days fishing. As there were some gas readings again the mud was weighted up to 2.24 kg/l.

The drilling lines were change from 12 to 14 due to the casing weight. The 10 3/4" liner was run to 5997 m – liner hanger at 4,142 m. With a slurry density of 2.27 SG the pipes were cemented. Twenty days later a 10 3/4” tie back to surface was run to 4,142 m and cemented (2.23 SG). After the BOP work the drilling lines were changed back to 12 lines. Five cores were taken in this section.

Section 5 – 8 3/4" bit and 7 5/8” casing

A leak off test by Halliburton was performed after drilling the casing shoe. At 6,500 m some pressure tests on the BOP were done. The 5” pipe rams were changed and the last pressure test with 1,000 bar was okay. The mud weight during drilling was between 2.23 and 2.25 SG. When the first gas readings in this section were detected the mud density was increased to 2.27 kg/l. A depth of 7,221 m was reached after 143 days on the 3rd of August - five cores were taken.

The 7 5/8” casing was run into the well but it stood up at 5,430 m. It was run to 5,451 m with circulation but mud losses of 10 m³ occurred. Running down to 5,464 m caused again 18 m³ losses. The casing was pulled out of hole where further 3 m³ of mud were lost. The following 16 days were necessary to clean the hole. Again the 7 5/8” casing was run to 7,220 m – this time without problems (liner hanger at 5,794 m). After pulling out of hole a 3.6 m fish were lost – a 3.2 m slick-joint and a 0.4 m crossover to the wiper plug. Four days later the slick-joint was brought to surface but the wiper plug was still in the hole. A 7” packer was run to 7,085 m and cemented with a slurry density of 2.31 SG. Three days later a 9 5/8” packer was set at 5,798 m and cemented. Milling and fishing jobs were done for the next two weeks – some aluminium junk was caught. Again the 5” casing with drill pipes were run to 6,344 m and every 1,000 m a pressure test was done.

Two leak off tests were done after drilling the casing shoe. Schlumberger perforated the interval 7,195 – 7,196.5 m and made some pressure tests (up to 304 bar). A 7” packer was set to 7,214 m and cemented. After drilling the cement from 7,150 to 7,185 m again Schlumberger perforated an interval (7,172 – 7,173.5 m). A 7” packer was set at 7,150 m and a pressure test was done. For cementing a 7” packer was set at 7,152 m and cemented. The cement and the packer were drilled and the junk brought to surface. Another 7” packer was set at 7,155 m and a squeeze cementation with 6.5 m³ and 630 bar was done. Further nine days were necessary to drill the cement and the rest of the packers and fish the junk.

The mud weight was reduced to 1.92 SG and then the oil mud was changed to a water-based mud (HT-XP20). After four days junk catching the circulation through the perforations was tested with 300 bar and the liner was tested with 430 bar (tight). A 7” packer was set at 7,213 m and after circulation it was cemented. The 5” casing liner was again run to 6,346 m and every 1,000 m a pressure & temperature test were done. The casing was pulled out again.

Section 6 – 6” bit and 5” casing

On the 24th of November drilling started again – mud density between 1.89 and 1.91 kg/l. At 7,290 m an influx of 1.5 m³ and gas readings up to 79 % occurred (MW 1.90 SG). The next day 2.8 m³ losses and 40 % gas were monitored. After circulation and POOH a 1.74 m fish (bit and bit stabilizer) was recognized. The box of the stabilizer broke and three days fishing operation with an overshot and a spiral grapple was successful. At 7,347 m during a coring job the pin of a crossover broke and an 11 m coring tool were left in the hole. Two days later the fish was on surface. At a depth of 7,575 m a logging run was performed by Schlumberger. As the tool got stuck at 5,808 m the wire was cut. The 12.6 m long fish was brought to surface three days later. At 7,883 m a logging tool from Schlumberger measured a bottom hole temperature of 211 °C. Again a pin of a drill collar broke and a 113.98 m fish (bit to 11th DC) was lost. On the third day the missing string was brought to surface. During a logging run at 8,256 m the wire broke due to pulling with overload but the fish was caught four days later. The mud weight was slightly increased in this section to 2.23 SG and nine cores were taken. After 189 days the final depth of 8,553 m was reached on the 31st of May 1983. Three weeks later the 5” casing liner was run to 7,623 m (liner hanger at 6,982 m) and cemented. The well was operated for testing and other purposes until the 21st of November 1983 [27, 29].

6.2.3 Zistersdorf ÜT2Aa

The target of the well Zistersdorf ÜT2Aa again was to explore the hydrocarbons of Zistersdorf ÜT1a. The formations drilled in ÜT2A had a low porosity and at ÜT1a there may be a stronger tectonic fissuring. The well was planned with a deviation at 6,020 m to east-southeast – the target of ÜT1a in 7,544 m should be 140 m in an azimuth of 123° in a depth of roughly 7,600 m. Table 8 shows the basic well data of Zistersdorf ÜT2Aa.

Operation:	24.05.1985 – 14.11.1986	Coordinates:	N 48° 32' 53"
Drilling:	07.04.1986 – 24.08.1986		E 16° 47' 30"
Sidetrack:	6,020 m	Sea level:	178.88 m
Final depth:	7,007 m	Drilling rig:	3127 – H 3000

Table 8: Well data Zistersdorf ÜT2Aa [31]

On the 24th of May 1985 the rig assembling started. Due to vacation replacement the rig was closed during summer for three months. The first two weeks in September the rig was assembled. From mid of September 1985 to end of March 1986 preparation work was done (drilling cement, milling, repair etc.). The well fluid was changed to an oil-based mud with a density of 2.25 kg/l. The sidetrack started on the 7th of April at a depth of 6,020 m [30 -31].

Section 7 – 9" bit

The sidetrack was drilled with a 9" bit and a mud weight between 2.25 and 2.26 SG. At 6,120 m mud losses occurred but no influx or gas were detected (in total 42.5 m³ in 6 days). The drill string got stuck several times at the sidetrack entrance. At 6,846 m again losses (33 m³) occurred but without consequences. At 7,006 m one cone of the bit was left in the hole. The cone was milled to the final depth of 7,007 m (in total 137 drilling days).

Abandonment

The string with the milling tool got stuck at 6,041 m and the string was clipped off – 506.85 m of the string were left in the borehole. During the fishing operation also the overshot was lost in the hole. The efforts were stopped at the 14th of November 1986 [27, 31].

6.3 Maustrenk ÜT1 / 1a

The well Maustrenk ÜT1 was intended to explore the autochthonous sediments of the Molasse and the Mesozoic below the Neogene and the Alpine-carpathian Flysch nappe. The existence of foreland sediments was already proven at Zistersdorf ÜT1. The accumulation of hydrocarbons along the Steinberg fault was an indication for a potential reservoir also southern of the Steinberg anticline [33].

6.3.1 Maustrenk ÜT1

On the 26th of August 1982 the rig was moved from Prottes ÜT2 to the rig site near Maustrenk and assembled (see Table 9). The initial mud type was a XP-20 KCl and had a density of 1.10 kg/l. The well was spudded on the 14th of September – starting with a 32” standpipe to a depth of 17 m.

Section 1 – 23” x 29” bit and 24 1/2" casing

The first section was drilled to 92 m with a 23 inch bit and opened afterwards to a 29 inch hole. A 24 1/2" casing was run to 90 m and cemented to top.

Operation:	26.08.1982 – 10.06.1984	Coordinates:	N 48° 33’ 06”
Drilling:	14.09.1982 – 20.04.1984		E 16° 43’ 21”
		Sea level:	295.02 m
Final depth:	6,285 m	Drilling rig:	3120 – H 2500

Table 9: Well data Maustrenk ÜT1 [33]

Section 2 – 23” bit and 18 5/8” casing

Nineteen days drilling without any troubles the well reached a depth of 733 m. An 18 5/8” casing down to ~ 733 m was cemented to top.

Section 3 – 17 1/2" bit and 13 3/8” casing

This section was drilled with a 17 1/2" bit and a mud weight between 1.10 and 1.35 SG. At 1,056 m a pin broke but the 2.04 m long fish was brought to surface within one day. At 1,250 meters 40 ‘Disken’ (inserts) of the bit were lost. Fishing with a junk basket didn’t bring any insert to surface. At several depths (1,352, 1,565 and 1,741 m) again a junk basket was in use but none of the inserts were recovered. Another pin break caused a 2.03 m long fish at 1,913 m. It was caught by an overshot on the same day. Due to the caving formations it was decided to set the casing – planned depth 3,000 m. After one week junk fishing & hole cleaning a 13 3/8” casing was run to ~ 1,913 m and cemented with slurry density of 1.86 kg/l.

Section 4 – 12 1/4" bit and 10” casing

Before drilling the mud type was change to Drill-Faze – the mud density in this section laid between 1.34 and 1.52 kg/l. Down to 3,625 m no problems occurred. At this depth some parts of a bit cone were lost. Four days of fishing brought some iron parts to surface. At 3,852 and 3,963 m the drill string got stuck but it got free with 185 t overload. A leak off test at 4,132 was performed and showed a fracture gradient of 1.70 SG. At 4,236 m some matrix parts of the bit were lost – 1 kg junk was caught the next day.

At 4,298 m the level in the annulus suddenly dropped. To compensate it 52 m³ of mud were pumped into the annulus and circulated. A pill was prepared and pumped (14 m³ losses). Two days later the first gas readings were recognized at 4,327 m. From 4,410 m on gas was measured frequently. As there were still gas readings at a depth of 4,823 m drilling was stopped and decided to case it. Eight months after the beginning of this section a casing board and a jacking system were mounted. During running casing (5 days) in total 83 m³ of mud losses occurred. When the pipes were cemented (CS ~ 4,823 m) – still losses occurred. A squeeze cementation with 1.44 SG and 120 bar was done. One core was taken in this section.

Section 5 – 8 3/4" bit

A leak off test was done after drilling the casing show. Drilling was started with a mud density of 1.65 SG and continuously increased. At 4,920 m three bit cones were lost but on the surface next day. The drill string got five times stuck (4,967, 5,080, 5,102, 5,708 and 6,073 m) but got free with 170 – 240 t. At 5,495 m and influx of 2.9 m³ was recognize and the MW was increased to 1.90 kg/l. Gas readings at 5,540 m made a mud density of 1.94 SG necessary. Two leak off test were done at 5,731 m (MW 1.99 SG) and six cores taken in this section.

On the 20th of April 1984 a depth of 6,285 m was drilled (MW 2.05 SG). At this depth an influx of 8.5 m³ and gas readings (40 %) occurred. Due to an ECD of ~ 2.20 SG influx and losses at the same time happened. It took one month to control the well – in total 70.5 m³ influx and 151.8 m³ losses. As a Lynes packer which was set at 6,171 m was not tight a cement bridge from 6,114 to 5,914 m was set [32, 33].

6.3.2 Maustrenk ÜT1a

It was decided to drill a sidetrack from 6030 m. Basic well data is given in Table 10.

Operation:	11.06.1984 – 16.12.1984	Coordinates:	N 48° 33’ 06”
Drilling:	11.06.1984 – 14.09.1984		E 16° 43’ 21”
Sidetrack:	6,030 m	Sea level:	295.02 m
Final depth:	6,563 m	Drilling rig:	3120 – H 2500

Table 10: Well data Maustrenk ÜT1a [33]

Section 6 – 8 3/4" bit and 7 5/8” casing

At the beginning of this section the mud weight was reduced to 2.11 kg/l. The hole was drilled with an 8 3/4" bit in 28 days. The mud weight was continuous decreased to 2.05 SG. A 7 5/8” liner was run to 6,240 m – liner hanger at 4,648 m and liner head at 4,652 m – and cemented.

Section 7 – 6 1/4” bit and 5” casing

The drilling mud was changed to a HT XP-20 with a density of 2.20 kg/l. Below the casing shoe at 6,243 m a leak off test was done. Due to a gas influx at 6,298 m the mud weight was increased to 2.26 SG. Under high gas readings the well was drilled to 6,563 m where the drill string got stuck. With an overload of 175 t it got free but a 57.75 m fish was left in the hole.

Abandonment

Also the overshot was shortly stuck but came free. After one month of unsuccessful fishing the 5" liner was run to 6,498 m (liner head at 4,633 m) and cemented. From end of October till mid of December the well was perforated and tested. Cementing jobs were done before Christmas 1984 and the rig was disassembled until the 13th January 1985 [32, 33].

Due to the test results from November 1984 a production test was planned. A production in the 10" casing was not wanted (for safety reasons) and the well was preserved until the 7" and 6 5/8" casing was delivered. In autumn 1986 a 6 5/8" tieback to 3,355 m plus a 7" tie back to surface were run and cemented to top [34].

6.4 Aderklaa UT1 / 1a / 1b

The well Aderklaa UT1 was intended to determine an autochthonous sedimentary unit on the Crystalline of the Bohemian Massif - below the Neogene and the Alpine-carpathian Flysch nappe. The Palaeozoic, Mesozoic or the Molasse were eligible where carbonate or clastic reservoirs could be expected. The high of Aderklaa was proven as a structural condition. It was interrupted by the Bockfließ-Aderklaa system of faults in the west and northwest which developed additional traps to the high of Aderklaa [35].

6.4.1 Aderklaa UT1

The well Aderklaa UT1 is located three kilometres west of Aderklaa (Table 11). A 32" standpipe was set to 29 m by hammer drilling and cemented (1.86 SG). The spud mud was a fresh-water clay-base mud (MW 1.10 kg/l).

Operation:	12.07.1982 – 29.07.1983	Coordinates:	N 48° 16' 48"
Drilling:	12.07.1982 – 13.07.1983		E 16° 30' 10"
		Sea level:	119.52 m
Final depth:	5,328 m	Drilling rig:	3128 – E 3000

Table 11: Well data Aderklaa UT1 [35]

Section 1 – 23" x 29" bit and 24 1/2" casing

Drilling started on the 12th July 1982 with a 23" bit to a depth of 502 m. Afterwards the hole was opened to 29 inch. A 24 1/2" casing was run to 501 m and cemented via the drill string through a Baffel collar to top.

Section 2 – 23" bit and 18 5/8" casing

This section was drilled with a 23" bit to 2,001 m without any drilling problems (MW 1.14 – 1.18 SG). Only in two intervals (980 – 1,292 m and 1,656 – 1,980 m) a pendulum assembly was used. An 18 5/8" casing was run to 1,999 m and cemented with 185 m³ cement slurry (1.40 SG) to top.

Section 3 – 17 1/2" bit and 13 3/8” x 14” casing

Drilling down to 2,693 m with a mud density of ~ 1.18 SG made no problems. From this depth on mud losses occurred – Aderklaa Conglomerates from 2,700 – 2,885 m - but they were stopped with lost circulation material. The mud weight was increase from 1.20 to 1.35 SG due to high gas readings (up to 100 %) at a depth of 3,767 m – Frankenfels-Lunz nappe system from 3,607 – 4,350 m. The consequences were higher mud losses in a shorter time which got critical from 4,453 m when influx and losses at the same time occurred. This critical situation was stopped at a depth of 4,474 m for casing (MW 1.37 kg/l) and well logging was cancelled.

As the casing weight was such high (681 t in the air) it was decided to use a 1,000 t casing-jacking-system. The 14” casing was run to 3,686 m by the rig – the maximum pick off weight was 535 t. Then the jacking-system was used to bring the casing down to 4,473 m.

For the long cementation of 4,473 m a two-stage cementing was chosen. At the first stage the casing was cemented from 4,474 to 2,575 m – the upper cement from 4,380 to 2,575 m (planned 1,900 m) with 223 m³ of 1.50 SG and the lower cement from 4,474 to 4,380 with 30 m³ of 1.90 SG. From 1,900 m to surface slurry with 1.50 SG was pumped at the second stage.

Section 4 – 12 1/4" bit

After drilling the sliding side door, float valve and casing shoe with a 12 1/4" bit the mud was changed to an oil-base Drill-Faze (MW 1.35 kg/l). Down to a depth of 4,526 m the well was drilled with a mud density of 1.37 SG. Due to different borehole conditions – gas readings up to 100% and borehole instability – the mud was continuously increased to 1.76 SG (4,816 m). As a higher mud density was expected the compressive strength was determined several times.

At 5,328 m (MW 1.89 SG) the drill string got stuck due to borehole instability and well cratering. Many trials to get the string free failed and it was decided to drill a sidetrack. The string was unscrewed via Back-off at 5,246 m (at an 8” drill collar). A whipstock was set from 5,100 to 4,975 m for the sidetrack [35 - 36].

6.4.2 Aderklaa UT1a

The sidetrack was drilled with a steering tool and a turbine. From 5,060 m on the well was named Aderklaa UT1a. Additional well data is given in Table 12.

Operation:	30.07.1983 – 11.02.1985	Coordinates:	N 48° 16’ 48”
Drilling:	30.07.1983 – 23.01.1985		E 16° 30’ 10”
Sidetrack:	5,060 m	Sea level:	119.52 m
Final depth:	6,630 m	Drilling rig:	3128 – E 3000

Table 12: Well data Aderklaa UT1a [35]

Section 5 – 12 1/4" bit and 10” casing

The well was drilled with a mud density between 1.95 and 2.04 kg/l from 5,060 to 5,464 m. At this depth the drill string got stuck after a sudden salt water influx (gradient 2.14 kg/l) which was recognized too late. The high pressure zone was at the overthrust zone of the Kaumberg beds (Upper Cretaceous) and the Flysch (Eocene). The 8” drill collars were unscrewed via back-off without troubles and the 9 5/8” drill collars were washed over. As the lower part of the 9 5/8” DCs were not stuck the string was freed with overload. The rest of this section was drilled without bigger troubles to 6,119 m (MW 2.20 kg/l).

During running the 10” casing (at 194 m) a sudden mud loss occurred. Well logging and pressure tests detected a leak at the 14” casing at ~ 3,370 m. Nine squeeze cementations were necessary to get the casing tight again. After the repair jobs the well was circulated with 2.16 SG. A 10” casing string was run without float equipment to reduce the pressure at the cemented leak. For this long casing string a two-stage cementing job was chosen. The first stage was cemented with 63 m³ slurry of density of 2.22 SG from 6,119 to 4,198 m. The other 35 m³ cement slurry were placed from 4,193 to 3,019 m. A cement bond log showed a very bad bonding below the sliding side door. At a second trial to cement again the last three pipes the cementing string (with a RTTS packer) was cemented – over 300 m including drill pipes. The 5” DP string was washed over with a 7” diamond wash-over pipe and unscrewed via a reversing tool. Due to heavy buckling of the drill pipes the 6 1/2" DCs were milled – to take care of the 10” casing. In total 23 mills were used for 21.1 m drill collars. At the upper stabilizer it was started again to wash over down to the RTTS packer at 6,089 m – 148 m 6 1/2" DCs and 4 stabilizers. For unscrewing 200 m left-hand threaded pipes were used. The last part of the fish was brought to surface on the 4th of December 1984.

On the 12th of July 1984 during the above mentioned work the casing slip broke and the 10” column moved downwards. A mechanical unscrewing at 795 m worked but the couplings were damaged. A second trial via back-off at 948 m was successful. The casing was connected again and set in the preferred height.

Section 6 – 8 3/4" bit

The mud was already changed to a high temperature resistant Duratherm mud (HT XP-20). The well was drilled with an 8 3/4" bit to 6,630 m (23rd of February 1985) without relevant drilling problems and some cores were taken.

At 6,223 m the Altenmarkt beds were drilled. Below reservoir rocks of the Dogger were expected but direct below was already Crystalline of the Bohemian Massif [35 - 36].

6.4.3 Aderklaa UT1b

The well Aderklaa UT1a showed that below the autochthonous Mesozoic (Malmian marls and limestone) at 6,245 m the Crystalline followed. Due to the unusual facies conditions and thickness it was assumed that the Dogger formation was reduced by tectonic movement. The target of sidetrack UT1b was to proof the sequences of Malm and Crystalline via coring. Basic sidetrack data is given in Table 13.

Operation:	12.02.1985 – 29.07.1985	Coordinates:	N 48° 16’ 48”
Drilling:	12.02.1985 – 05.03.1985		E 16° 30’ 10”
Sidetrack:	6,145 m	Sea level:	119.52 m
Final depth:	6,256 m	Drilling rig:	3128 – E 3000

Table 13: Well data Aderklaa UT1b [35]

Section 7 – 8 1/2" bit

A cement bridge was set from 6,250 to 6,000 m and the well was deviated at 6,145 m into an azimuth of 90°. Due to the high bottom hole temperatures (170°C at 6,100 m) turbines without a bypass valve were used. From 6,220 to 6,256 m the contact between the Malmian sediments and the Crystalline was proven. A mud density between 2.20 and 2.24 kg/l was used.

Two cement bridges were set from 6,250 to 6,050 m and from 5,700 to 5,500 m. Formation tests in the Flysch and the Calcareous Alps were done but no economic production from the seven intervals was achieved [35 – 37].

6.5 Worldwide wells

As the focus of this thesis is on the ultra-deep wells of the Vienna Basin and due to less available information, the drilling operations of the other ultra/super-deep worldwide wells are summarized in a rather short way. The important experiences of those wells are described in Chapter 7.

6.5.1 Kontinentale Tiefbohrung (KTB)

The pilot hole of this project was spudded in September 1987 and finished in April 1989 with a total depth of 4,000 m (13,124 ft), after 560 days of drilling and logging. One year later in April 1990 - after several experiments and measurements such as hydrofracs, production tests and seismic work - the well was finally cased and cemented.

The superdeep (main) hole was spudded in the same year in October 1990. One of the largest land rigs in the world (UTB 1) was designed to handle the high loads. Rig capacities are given in Table 52 in Appendix A.1. Some important well data are given in Table 14.

Operation:	06.10.1990 11.10.1994	Coordinates:	N 49° 48’ 54”
Drilling:	06.10.1990 11.10.1994		E 12° 07’ 13”
		Sea level:	517 m
Final depth:	9,101 m	Drilling rig:	UTB 1

Table 14: Well data KTB [5, 6]

The first section was drilled with a 17 1/2" bit to 292 m and opened up to 28". During hole-opening already a 2.5° correction to deviation was made. A 24 1/2" casing was set at 290 m and cemented.

The next section to about 3,000 m was again drilled with a 17 1/2" bit and cased with a 16" casing to 3,000.5 m. Teething problems of the vertical drilling system (VDS) forced the crew to use a packed-hole assembly (PHA). For the third section to 6013 m a 14 3/4" bit was taken. Again the VDS system and PHAs were used alternating and deviation corrections were necessary. A 13 3/8" casing was run into the well and cemented from 6,013 to 4,350 m in April 1992.

Both VDS system and PHA with a 12 1/4" bit were used to drill the next section. In July 1992 the drill string got stuck at 6,760 m and parts of the bottom hole assembly got lost. As the fishing operation was unsuccessful, the well had to be plugged and a sidetrack at 6,461 m was done. Between 6,850 and 7,300 m a major fault system crossed the wellbore. The VDS system was not able to control deviation and further corrections were done. As the bottom hole temperatures got too high for the VDS system and its electronics, it was abandoned at 7,490 m. The well already reached a TD of 8,328 m when the string got stuck at 7,523 m during tripping out. The downhole motor housing broke and left a complicated fish which wasn't retrievable. The well was plugged again and a sidetrack started at 7,390 m. Due to further drilling problems in December 1993, a 9 5/8" liner was set from 7,785 to 5,893 m.

Drilling continued with an 8 1/2" bit to 8,730 m. Wellbore instability in this section again forced the crew to set a casing earlier. A 7 5/8" liner was set from 8,665 to 7,696 m. A sidetrack at 8,625 m through a precut window in the liner was made to bypass those unstable formations. After 476 m with a 6 1/2" bit drilling was stopped at the final depth of 9,101 m in October 1994. A 5 1/2" liner was set from 9,031 to 8,550 m. An interval of 70 m of open hole was left for future tests and measurements. From 1995 to 2001 the well was used for research and from 2002 on there is a long-term study about energy and fluid transport in continental fault systems [5 - 6, 57, 63].

6.5.2 Baden # 1-28

The well Baden No. 1 by the Lone Star Producing Company was drilled for hydrocarbons in the Anadarko Basin in Oklahoma, US in the early 1970s. A 2,000,000 pound (907 t) derrick called Loffland Bothers' Rig No. 32 was used. Further rig data is given in Table 52 in Appendix A.1. Basic well information is given in Table 15 below.

Operation:	04.09.1970 - 29.02.1972	Coordinates:	N 35° 18’ 33”
Drilling:	04.09.1970 - 29.02.1972		W 99° 31’ 37”
		Sea level:	595 m
Final depth:	9159 m	Drilling rig:	Loffland Bros #32

Table 15: Well data Baden # 1-28 [8, 55]

The well was spudded in September 1970 and drilled to 1,481 m. Information about the bit diameter is not available. A 20" casing was set to 1,457 m. The next section was drilled with a 17 1/2" bit down to 4,696 m. A 13 3/8" casing string was run to 4,690 m and cemented. Both sections were finished without considerable troubles.

The next section was drilled with an 11 7/8" bit to 7,544 m. Problems occurred during the cementing job of the 9 5/8" liner (7,428 m). Due to a failure of the top of the liner hanger and also cement retainers failed due to defective back-pressure valves. The whole cementing operation took 50 days. The last section was drilled with a 7 7/8" bit to 9,159 m. A tapered 5" x 7" casing string was run to 8,704 m - on top of the Hunton formation (Devonian dolomite) which was the target formation of this project. A 2 3/8" x 2 7/8" tubing string was run and the Hunton formation was acidized and tested. As there were no hydrocarbons the well was plugged back and a shallower formation was tested [7 - 8, 55 - 56, 62].

6.5.3 Bertha Rogers # 1-27

The primary target of this well was again the Hunton which was non-economic in the Baden well before. The location is 30 km east of Baden # 1-28 and 4 km south of the Clinton-Sherman Airport at Burns Flat. It was drilled with the same onshore rig as Baden #1. Basic well data is given in Table 16.

Operation:	26.11.1972 - 13.04.1974	Coordinates:	N 35° 18’ 33”
Drilling:	26.11.1972 - 13.04.1974		W 99° 11’ 34”
		Sea level:	578 m
Final depth:	9583 m	Drilling rig:	Loffland Bros #32

Table 16: Well data Bertha Rogers # 1-27 [8, 55]

The first section was drilled with a 17 1/2" bit to 1,433 m and opened afterwards to 26". A 20" casing was set to 1,404 m. Again a 17 1/2" bit was used which drilled down to 4,330 m. The open hole was cased with 14" to 4,330 m. In the next section a 12 1/4" bit was taken to drill down to 7,178 m. A 9 5/8" liner was set at 7,178 m. The last section was drilled with a 7 7/8" bit where a low concentration of H_2S was detected.

On the 13th of April 1974 a kick was occurred early in the morning. The BOP (pipe rams and Hydril) was closed, giving a shut-in casing pressure (SICP) of 8,550 psi or 590 bar. This gives a calculated downhole pressure of 24,900 psi or 1717 bar. Pipe rams and Hydril of the 13 5/8" 15,000 psi BOP stack began to leak. The mud weight was increased and circulation started down the drill string. A back-pressure between 255 and 490 bar was held on the casing and flow through the choke was allowed. Two days later sour gas reached the surface and was flared. Furthermore, sulphur crystals were brought with the gas which were later found to be elemental sulphur in both red and yellow crystals. Eighty hours after the kick the well was completely dead. The sulphur was believed to be molten at the estimated conditions - a bottom hole temperature of 450 °F or 232 °C and the calculated pressure of 1717 bar. Unfortunately, the drill string was split for unknown reason and 5,103 m of drill string were lost in the hole. So the well was plugged back [7 - 8, 55 - 56].

6.5.4 Kola SG-3

The project to research the earth's crust was already launched in 1962. In May 1970 the well (named with Roman numeral as I) was spudded and the first rig used was named Uralmash 4E. Almost continuous an 8 1/2" bit was used and then the hole was enlarged with a multi-stage hole opener to the desired diameter. The standpipe had a diameter of 28.35" and was set to 40 m [60]. The well was drilled with an 8 1/2" bit to 5,300 m. Wellbore breakouts due to strong water-bearing formations at about 1,800 m resulted in hole opening down to 2,000 m and a 12.8" casing was set and cemented.

At 7,263 m the rig was disassembled and the custom-built rig Uralmash-15,000 was installed. Further rig data is given in Table 52 in the appendix. Table 17 shows the basic well data of the Russian well. And an overview of the well path and the sidetracks is given in Figure 24 in the appendix.

Operation:	24.05.1970 - 1992	Coordinates:	N 69° 23’ 47”
Drilling:	24.05.1970 - 1989		E 30° 36’ 34”
		Sea level:	344 m
Final depth:	12262 m	Drilling rig:	Uralmasch-15000

Table 17: Well data Kola SG-3 [9, 59 - 61]

Nine years after spudding - on 6th June 1979 - the well reached a depth of 9,584 m beat the depth record of Bertha Rogers #1. On March, 10th 1980 the well reached a depth of 10,000 m. Further 1,660 m were drilled to 11,660 m but for unknown reasons the well was plugged and the first sidetrack (II) done. On December 27th, 1983 a depth of 12,000 m was achieved. One year of drilling break due to scientific and laboratory research was done. In September 1984 after only 66 m further drilling a 5,000 m (16,400 ft) section of the drill string twisted off and was lost in the hole. A new sidetrack (III) at about 7,000 m was started.

After drilling to 8,770 m a 9.65" liner was set to 8,770 m. The final casing program showed a liner from 8,770 m to 1,938 m and a tieback to surface. There's no detailed information about installation date and the liner hanger itself. Some years later in 1989 the record depth of 12,262 m (40,230 ft) was reached.

Due to the high temperatures (180° C or 356° F) and a plastic behaviour of the rock, no further drilling progress was achieved and drilling was stopped. Another sidetrack (IV) was started at about 9,000 m but only a depth of 10,500 m was reached. The whole drilling project was stopped in 1992. The most important events are summarized in Table 18 [9, 58 - 61].

Date	**Well**	**Depth [m]**	**Milestones/Event**
May 1970	I	0	Spudding
-	I	7,623	Rig change ➔ Uralmash-15,000
6th June 1979	I	9,584	Record of Bertha Rogers #1
10th March 1980	I	10,000	Record depth of 10 km
-	I	**11,660**	End of well I ➔ sidetrack
27th December 1983	II	12,000	Record depth of 12 km
27th September 1984	II	**12,066**	End of well II ➔ sidetrack at 7,000 m
1989	III	**12,262**	World record ➔ sidetrack at 9,000 m
1992	IV	**10,500**	Project stopped

Table 18: Time table Kola SG-3 [9, 58 - 61]

7 Experiences & Lessons Learned

The topic of this master thesis is to analyse the drilling operations made in the late 1970s and the early 1980s. Since that time no ultra-deep well has been drilled in Austria. It's important to discuss the drilling experiences and show the results of these wells. In this chapter the occurred problems are listed and how they were handled – either successful or not. The major question is which lessons can be learned and are they applicable for future exploration requirements.

7.1 Drilling

For a better overview the chapters are sorted by subjects instead of well order. It's easier to analyse the incidents as they overlap.

7.1.1 Drill bits

At the well Zistersdorf ÜT1 (to 6,851m) in total 82 roller bits and 4 Diamond bits were used in 129 round trips. From ÜT1a there is no bit data available. As well ÜT1a and ÜT2A nearly drilled the same formations the data from ÜT2A is as informative as of the first well.

Interval [m]	Trips	Diameter	Bits	Time [h]	ROP [m/h]	m/bit
0 – 265	2	29"	1	-	-	265.0
265 – 1,675	17	23"	8	548	3.05	176.3
1,675 – 4,336	50	17 1/2"	48	1,520	1.75	55.4
4,336 – 6,000	35	12 1/4"	31	1,194	1.14	53.7
4,336 – 4,685	8	8 1/2"	5	247	1.16	69.8
6,000 – 7,221	32	8 3/4"	31	1,951	0.62	39.4
7,221 – 8,553	29	6"	8	1,510	0.88	166.5
Total	173	-	132	6,970	1.227	67.4

Table 19: Drill bit data Zistersdorf ÜT2A [38]

Table 19 shows the number of used bits for each section and their performance at Zistersdorf ÜT2A. Well ÜT2 and the sidetrack ÜT2Aa is not included in this table. The given time is the real drilling time on bottom. With increasing depth the ROP declined below one meter per hour. In section three the most bits were used with an average of 55.4 m per bit. Below the marlstone klippe only 39.4 meters were drilled in average with one bit. Surprisingly the bit life in the deepest section with 166.5 m per bit in average is very high. The longest bit life in the last section had a 5 31/32" diamond bit P7374G which drilled in total 538 meters in 494 hours on bottom in nine different bit runs (average ROP 1.09 m/h). For this well 109 roller cone bits and 23 insert bits were used. At Zistersdorf ÜT2Aa in a depth of 7,007 m a cone of a bit was lost. Several fishing trials failed and so the well was abandoned.

For the well Maustrenk ÜT1a the bit data is incomplete but at least 87 roller bits and 21 insert bits were used. During drilling the well several bit incidents occurred. At 1,250 m the ROP dropped and on surface 40 missing inserts (Disken) of the bit were recognized. Junk catching at 1,250, 1,352, 1,560, 1,741 and 1,913 m didn't have any success. Due to the bad operation of a vibration dampening the inserts were broken or fallen out. Fortunately drilling could be continued.

In the 4th section two bit incidents happened. At 3,625 m some parts of a cone were lost but fishing brought the junk to surface. At 4,236 m some matrix parts of the bit were fished successfully. All three bit cones at a depth of 4,920 m were lost and caught. The most problems occurred in the Flysch and the Waschberg zone. The average ROP in the Flysch was 0.68 m/h for a roller cone bit and 0.97 m/h for a diamond bit. The bit gage was quick reduced due to high abrasiveness of the rock. So it was necessary to ream with a hard roller cone bit. For the Flysch the usage of a diamond-impregnated stabilizer is to recommend. In case of a reduced bit gage the stabilizers ream the hole to the desired caliber.

In total 98 bits (in 126 bit runs) were used at Aderklaa UT1 and UT1a. Section 3 was only drilled with roller cone bits (40 bits). The following two sections were almost deepened with insert bits (44 bits). For hydraulic optimization extended nozzles were tested but they didn't bring any improvement. To the final depth of 6,630 m and due to alternating types of formation only roller cone bits were in the hole – average ROP of the last section 0.96 m/h. The second sidetrack UT1b was drilled with four 8 1/2" diamond bits and the last six meters with a roller cone bit.

At Baden #1-28 well in Oklahoma 178 bits and at Bertha Rogers #1-27 124 bits were used. This gives an average performance of 51.5 resp. 77.3 meter per bit.

In general a large number of bits are necessary. Hard and compact formations cause a rather quick abrasion of the drill bits and the often roundtrips can damage the casing. Today highly developed drill bits are available which enable higher ROP in several formations [32, 35 – 40].

7.1.2 Drill string material

Several drill string incidents occurred at Zistersdorf and Maustrenk. After a wash-out of a drill collar pin the string broke at 1,793 m. Another DC pin (4 3/4") cracked at Zistersdorf ÜT1a in a depth of 6,793 m.

At Zistersdorf ÜT2 the pin of a DC cross-over cracked (MD 544 m). During 8 1/2" x 12 1/4" hole opening a cross-over pin broke at 4,495 m. Another 9 5/8” cross-over had a cracked pin at 5,648 m. At 7,296 m the 5 31/32” bit plus the stabilizer were left due to a box break of the stabilizer. Due to a high torque and the starting angle build-up in this section the box cracked. During coring at 7,347 m a pin of the 4 3/4" crossover between coring tool and drill collar cracked. The last drill string incident of this well happened at 8,059 m where a pin of the eleventh 4 3/4" drill collar cracked.

A 14” cross-over pin cracked at Maustrenk ÜT1 (MD 1,056 m). At ÜT1a another cross-over (11 3/4") cracked after the drill string stood up at the 18 5/8” casing shoe. At 6,563 m the drill string got stuck and pulling with 20 t overload the string got free – the pin of a new 4 3/4" x NC 35 drill collar cracked. The drill collar was only 16.5 hours in operation.

Deep drilling cause high torque and vibrations but the material failures occurred also in shallower depths. The pipes were inspected by Vetco in regular intervals. One recommendation in an internal well report of the Maustrenk well was to avoid the application of new drill collars in critical wells because most cracks occurred in the first usage. The multiple cracks of pins led to an investigation by the Montan University Leoben and Mr. Oberndorfer from OMV. The material should have been an AISI 4140 steel which was manufactured by SBS (Schoeller-Bleckmann Sales). The tests showed that the steel had no treatment – it was neither quenched nor tempered. This shows how important it is to do quality tests and material inspections before / during drilling operations and detailed reporting [23, 27 and 40].

Already at the Kola well light-weight aluminium alloy pipes were partly used in the 1970s. This resulted in much lower hook load and the usage of a download turbine reduced the torsion on the pipes. But the high temperatures in ultra-deep wells lower the strength of the material. At the KTB well high-strength steel alloys were used because the yield strength of aluminium alloys was reduced at high temperatures. Also Titanium alloys were refused due to the creep tendency at such temperatures [6 and 9].

7.1.3 Drilling problems

The main hole problems at Zistersdorf ÜT1a (beside the kick) were wellbore instability and overpressure. In the Waschberg Zone at around 6,751 m the drill string got stuck several times. The drill string got stuck at ÜT1 (4x) and also in the sidetrack ÜT1a (3 times) in this zone. In total the drill string got stuck 33 times at well Zistersdorf ÜT1 and ÜT2 but only two times a drill pipe broke from overpull and one time the drill string was twisted off.

A stuck BHA at Maustrenk ÜT1a was explained by differential pressure. The bottom hole assembly was not recovered and two oil pills at 6,317 m didn’t work either. Pumping 7 m³ oil and pipe lax by Halliburton to the stuck point at 6,293 m released the string.

In a depth of 5,328 m at Aderklaa UT1 the drill string got stuck due to well instability (MW 1.89 kg/l). A wash-over of a length of 52.49 m 9 5/8” DC was never done successfully at this time. It was decided to drill the sidetrack UT1a. To avoid that situation for the future the mud weight has to be increased in time and the 9 5/8” DC string should have a sufficient length for an over-wash.

Another troubles occurred at Maustrenk ÜT1 when the first section was drilled. The 23” pre-hole was drilled un-stabilized which caused a drift of 5 m below the casing shoe. It was not possible to run the 24 1/2” casing into the hole. Only with circulation the pipes went down. The 18 5/8” casing shoe at 733 m was damaged because no near-bit stabilizer was used when drilling out. The bit hang up and milling work was necessary to get through again. It’s very important to use near-bit stabilizer to get a straight wellbore after the casing shoe.

Particularly at Zistersdorf ÜT2A the inclination of the well brought many problems. Down to a depth of 6,000 m the inclination was below 3°. To reduce the torque the stabilizer diameter was reduced which caused an angle build-up. The focus was not set on verticality. The maximum inclination at ÜT2a was 18° at the final depth – at Zistersdorf ÜT1a no measurements were done in the last section.

A major problem at Zistersdorf ÜT2A was to hold the projected azimuth to reach the gas formation of Zistersdorf ÜT1a at a depth of 7,544 m. Figure 7 shows the well path ÜT2A from top view which went completely into the wrong direction (north-west) after drilling about 4,000 m. The well was stopped at 8,553 m and a sidetrack at 6,020 m was done with a planned azimuth of 123° and a deviation of 140 m. Due to stuck pipe problems and unsuccessful fishing operations, the well was abandoned at 7,007 m.

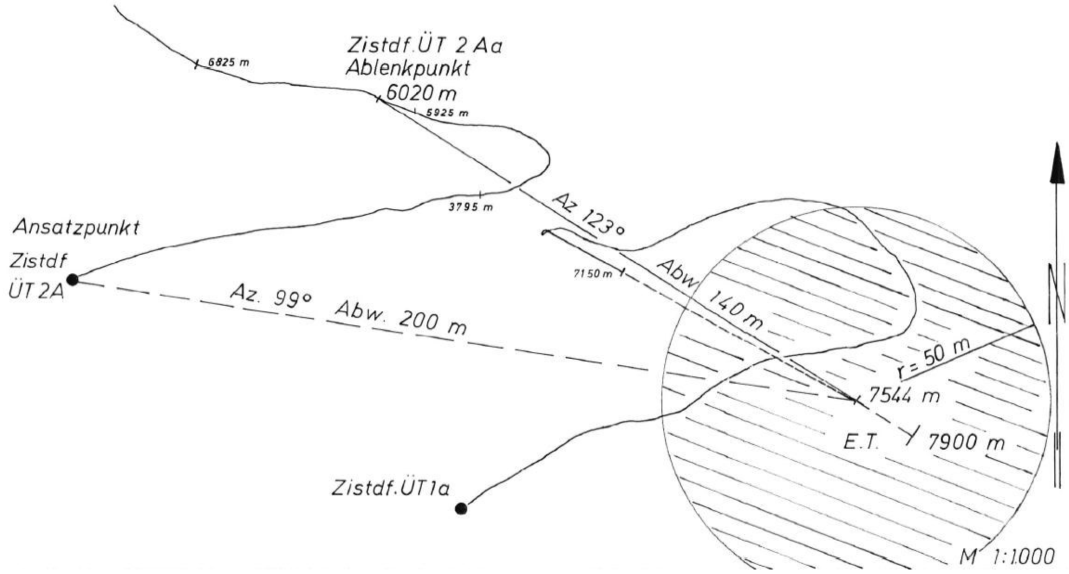


Figure 7: Deviation target of Zistersdorf ÜT2Aa [31]

With today available steering and inclination tools it's easier to control inclination and avoid dog legs and key holes but they are partly limited by high temperature regions [23, 27, 31, 36, 38, 40 - 41].

The main problem at the KTB well was wellbore instability. The heavily faulted formations and a high dip of 60° caused many breakouts. The mostly uniaxial wellbore breakouts are oriented 60 - 70° NE and are caused by hoop stress concentration at the borehole wall due to an anisotropy of the horizontal principle stress [5 - 6].

7.1.4 Fishing

Several fishing jobs in the four wells were necessary (described in chapter 6). Most of the fishing events (bit, BHA, DP, casing, coring or logging tool) were successful. The recovery of a 37.31 m fish at Zistersdorf ÜT1 was not achieved which led to the sidetrack ÜT1a. At Zistersdorf ÜT2 all fishing jobs were done successfully. The well Maustrenk ÜT1a was stopped drilling due to an unrecoverable fish at 6,563 m. For future operations the adequate fishing tools should be available as soon as possible. Another problem may occur before engaging the fish. Changes of the temperature and therefore related drill string extension make it difficult to detect the exact top of fish.

7.1.5 Equipment

The experience at Zistersdorf ÜT2A shows the high requirements of the drilling and logging equipment. Measurements up to 220 °C (dip-meter and caliber – 8,250 m) and up to 230 °C (IL and GR – 8,553 m) have been done at this well. The tools have to withstand temperatures more than 230° and up to 28,000 psi. The drilling turbines at Maustrenk and Aderklaa were worn out as the rubber melted due to the high temperatures. Many incidents can be avoid with higher resistant tools which are proofed for such high bottom hole conditions. Also an accurate maintenance and material inspection can reduce the risk of failures.

The usage of a casing-jacking system in Maustrenk and Aderklaa were necessary to handle the high loads. The hook load of rig E-3000 at Aderklaa was limited to 680 t and the 14” casing had 681 t in air. At Maustrenk the hook load of H-2500 was limited to 320 t and the 10” casing had 396 t. Another problem occurred with the casing tongs at Aderklaa which were not adequately dimensioned. Many connections of the 24 1/2" casing had to be torqued manually due to less power input.

Similarly problems to handle the high loads were also reported from Germany and the U.S. At the Bertha Rogers well the 13 3/8"string had a weight of 567 t (1,250,000 lb) in air. Much more weight had the 13 3/8" intermediate string at the KTB well with 706 t in air.

The Zistersdorf wells have shown the possible occurring pressures and the requirements for well control equipment. At Zistersdorf ÜT2A a 15,000 psi blow out preventer was used and for later a 30,000 psi christmas tree was ordered. This x-mas tree is at the educational trail in Prottes at the moment and could be used for future projects. The experiences at Maustrenk show the necessity of more safety precautions. A second choke-manifold may help to handle the high surface pressures up to 700 bar.

At Aderklaa a high wear of the shale shaker screens was observed. After the salt water influx at 5,465 m the high $CaCl_2$ concentration in the oil-based mud in combination with the temperature caused a chloride corrosion of the screens.

At the Bertha Rogers well an automatic mud mixer was used (continuous measurement, adding barite when necessary) to keep the mud weight constant.

Also the capacity of the mud pits, shakers, centrifuges and degassers should be dimensioned large enough for ultra-deep drilling. Already in the active system at the Bertha Rogers well 4,300 barrels (684 m^3) were used. There should be enough mud pits for reserve mud with different mud weight [6, 8, 35 - 37, 40, 42 - 43 and 56].

7.1.6 Mud type

A list of the used mud types for the four ultra-deep wells is given in Table 20.

Zistersdorf ÜT1a		**Maustrenk ÜT1a**	
0 – 4,598 m	KCl XP-20	0 – 1,913 m	KCl XP-20
4,598 – 7,544 m	Drill Faze (OBM)	1,913 – 6,243 m	Drill Faze (OBM)
Zistersdorf ÜT2A		6,243 – 6,563 m	HT XP-20
0 – 1675 m	Bentonite	**Aderklaa UT1a**	
1,675 – 4,340 m	KCl XP-20	0 – 4,475 m	Bentonite
4,340 – 7,221 m	Drill Faze (OBM)	4,475 – 6,119 m	Drill Faze (OBM)
7,221 – 8,553 m	HT XP-20	6,119 – 6,630 m	HT XP-20

Table 20: Mud types of the ultra-deep wells [23, 27, 32, and 35]

From Zistersdorf ÜT1a there is no mud experience reported. At Zistersdorf ÜT2A the water-based mud down to 4,340 m performed very well. Some troubles occurred during the cementing jobs which is described later in Chapter 7.3. From 7,221 to 8,553 m a high temperature resistant HT-XP 20 (Duratherm) mud was used. A higher ROP was achieved with this mud. It was seen in the 10 3/4" casing that the mud had an extreme gel strength built up – wireline measurement was only possible to a depth of 90 m. So it's not recommended to use that mud as a completion fluid.

The performance of the KCl XP-20 was not satisfied at well Maustrenk. The use of this mud in the shale formation in the upper part was not satisfied as the previous casing was not set as deep as planned. Due to the critical Flysch zone at the Maustrenk well and for better fluid performance the mud was changed to an oil-based Drill Faze. The Drill Faze performed very well with salt water influx and pumping heavy pills up to 3 kg/l. The Duratherm mud for high temperature and high pressure achieved a higher ROP. At this well a good cement job with Drill Faze and Duratherm was done.

As in the other wells an oil-based mud was used to drill the Flysch formations at Aderklaa. A big advantage of this mud is to keep the properties constant for several months without any circulation.

The drilling mud at the KTB well was a water-based purely anorganic system with a synthetic clay mineral as viscosifier. Later on the synthetic clay was replaced by a high temperature stable copolymer for a reduction in corrosion and a better filtration control. Higher temperatures and salt water influxes caused a reduction in rheological properties. A replacement by a Bentonite polymer system showed temperature stability and improvement in viscosity and filtration control.

In the US wells the first section was drilled with a brine-based mud. For the intermediate casing interval and for the liner an extended Bentonite-type fluid was used. The open hole interval (7,178 - 9583 m) was again drilled with a field NaCl brine-based mud [6, 23, 27, 32, 35, 40, 44 - 45 and 56].

7.1.7 Mud weight

Figure 26 to Figure 29 in the appendix show a mud weight vs. depth curve of the ultra-deep wells. The curves also show the important formation tops, the casing setting depth, coring depth, hole problems, gas influx and mud losses. The incidents relating to mud weight are discussed in the associated chapters. To show the importance of accurate mud conditioning the maximum mud weights are given in Table 21.

	Maximum mud weight	
	kg/l	**ppg**
Zistersdorf ÜT1a	2.25	18.8
Zistersdorf ÜT2A	2.28	19.0
Maustrenk ÜT1a	2.40	20.0
Aderklaa UT1a	2.25	18.8
KTB	n/a	n/a
Baden 1	n/a	n/a
Bertha Rogers 1	2.07	17.3
Kola SG-3	n/a	n/a

Table 21: Maximum mud weights of the ultra-deep wells [23, 27, 32, 35 and 56]

It can generally be mentioned that the mud weight is an important drilling factor to bring a well to its planned depth. For such great depth it’s necessary to know the pore pressure and the formation gradients. Also the mud behaviour under such temperatures and pressures can change immediately as the different drilling projects demonstrate. As there are low clearances in the mud weight window, it’s very important to keep the mud weight constant [22 - 23, 27, 32, 35 and 49].

7.1.8 Logging

Several logs have been recorded at the Austrian wells - Sonic, Master, 4-arm Caliper, Surface temperature and PCA (Pressure Control Analysis). Unfortunately only a few are available today and most of these available ones are in bad conditions or not readable. Furthermore there's no digital data available and so not usable for calculations. Some are only for graphical interpretation suitable.

One of the rare and readable logs is the PCA of Zistersdorf ÜT2A. Two selected sections are shown in Figure 25 in the Appendix. The lower section in a range between 7,500 and 7,550 m represents the gas formation of Zistersdorf ÜT1a. But there is no indication of a higher pore pressure. Well 2A is oriented some hundred meters north-west, so maybe there is a different formation structure.

More interesting is the upper section at about 4,340 m. A significant increase in pore pressure is shown. Not entirely coincidental is this the depth at Zistersdorf ÜT1a where the 9 5/8" casing collapsed in March 1980 and so dented the 7" casing inside.

7.1.9 High-pressure zones

A big challenge in ultra-deep wells is to detect and drill through high-pressure zones. At Zistersdorf ÜT1 the bottom of the Neogene is at 4,885 m where the Steinberg fault is located. The high-pressure formation starts already in the Sandschaler zone in the Badenian from 4,100 m. At Zistersdorf ÜT2A the transition zone starts at 4,150 m (Figure 8). The thickness of this zone is about 450 m (clay marl) and showed a better drillability than expected. An explanation for this high-pressure in the Neogene is that the pore water could not escape due to higher sedimentation rates. The incompressible fluid took the overburden which resulted in higher porosity and higher drillability in marly clays. The existence of high-pressure zones in the Badenian was confirmed by other wells (Palterndorf T1 and Ringelsdorf 3). The EMW increases from 1.10 kg/l at about 4,000m down to 1.92 kg/l at 4,950 m (Steinberg fault at 4,745 m). In the Flysch already the formation gradient gets stable and stays constant to final depth.

At Maustrenk ÜT1 no such strong high-pressure zone was observed. The mud weight was increased at 1,913 m to 1.35 SG due to strong well instability. Down to 4,823 m the MW was increased due to background gas. A salt water influx at 5,494 m (1.90 SG) forced to increase mud weight. A high-pressure zone at 6,285 m (2.05 SG) in the main borehole and at 6,298 m in the sidetrack (2.20 SG) bearing hydrocarbons was detected.

At Aderklaa UT1 the formation gradient increases slightly below the Badenian at 2,700 m. A strong change of this gradient is in the Flysch zone from 4,350 to 5,432 m – 1.37 to 2.20 SG. Below the gradient is nearly constant.

The critical Flysch formations in Lower Austria can be seen in Figure 23 in the appendix [24, 40, 42, 47 and 49].

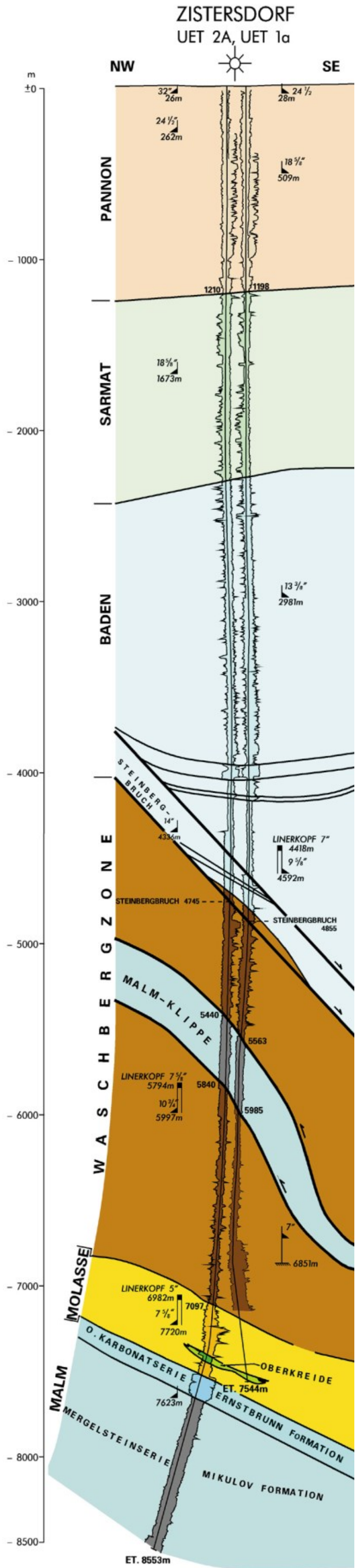


Figure 8: Well Profile Zistersdorf ÜT1a + ÜT2A [19]

7.1.10 Formation tests

Several leak-off tests have been done in the ultra-deep wells but only some data are available any more. From those LOTs and correlations (after Dresser) a rough mud weight window for both Zistersdorf wells was interpolated. For Maustrenk and Aderklaa there are not enough parameters available. It would be a great support for future projects to have more leak-off tests (LOT). Only a few tests were done to reduce the risk of well control incidents. Already in the final well reports one test after each formation change was demanded. The narrow mud weight window increases the risk of fracturing and mud losses. And for a clear interpretation of the tests the tightness of the casing shoe or liner head has to be ensured. Experiences from the Zistersdorf wells have shown that a prediction of a high-pressure zone and a detection of the pore pressure is very difficult. Due to the thrust tectonics there is no normal trend. Table 22 lists the fracture gradients in equivalent mud weight (EMW) of the confirmed LOT.

Zistersdorf ÜT1a	EMW [kg/l]	**Maustrenk ÜT1a**	EMW [kg/l]
4,592 m	2.16	1,913 m	1.70
4,984 m	2.31	4,823 m	2.16
5,059 m	2.40	6,239 m	2.30
Zistersdorf ÜT2A		**Aderklaa UT1a**	
4,346 m	2.34	4,477 m	2.27
6,005 m	2.43	4,816 m	2.27
7,221 m	2.44		

Table 22: Fracture gradient in EMW [23, 27, 32, and 36]

The available data of formation tests and pore pressure are plotted in a mud weight window which is shown in Figure 30 (Zistersdorf ÜT1a) and Figure 31 (Zistersdorf ÜT2A) in the appendix. From the other wells there is no data about formation tests available [20, 23, 27, 29, 40, 42 and 47].

7.2 Casing

This chapter discuss the planned or enforced casing setting depth, the chosen casing sizes and the used casing material and its failures.

7.2.1 Casing setting depth

The first two casing strings at Zistersdorf ÜT1a – 18 5/8” and 13 3/8” – were set at the planned depth. The 9 5/8” casing was planned to 5,300 m but the high-pressure zone starting from 4,100 m made it necessary to set the casing string earlier, at 4,592 m. The 7” casing was planned from maximum depth (7,500 m) to surface. As some of the casing couplings failed 2,111 m of the string were lost while running. A retrieval of the pipes was achieved and set in the previous 9 5/8” as liner. The casing shoe was at 6,705 m and the liner top at 4,412 m. Some month later after the kick a casing collapse of the 9 5/8” column between 4,352 and 4,357 m was detected and caused a reduction in diameter. The interval was enlarged with a casing swage to 6 1/2" to get into the

7” casing below again. To protect this zone a 4 1/2" liner was set from 4,909 to 4,298 m. A 7” tieback from 4,298 m to surface was run to isolate possible damages or leaks.

At Zistersdorf ÜT2A the 24 1/2" and the 18 5/8” casing was set as planned. The 14” casing string was set before the high-pressure zone as liner from 5,997 to 4,142 m and a tieback to surface. The 7 5/8” liner was set from 7,220 to 5,795 m due to the experiences from Zistersdorf ÜT1. The last casing string was set after reaching the final depth of 8,553 m. The 5” liner was set from 7,623 to 6,982 m.

Again the first two casing strings at Maustrenk ÜT1 were set as planned. Due heavy well breakouts and a high mud weight the 13 3/8” casing was already set at 1,913 m instead of 3,000 m. The 10” casing was set at 4,832 m (5,000 m planned) which means an open hole length of 2,910 m. The sidetrack ÜT1a was drilled only to a depth of 6,240 m because of the enormous influx at 6,285 m before. And the 7 5/8" liner was set from 6,239 to 4,652 m. Due to some drilling problems the 5” liner was set from 6,498 to 4,633 m and later on it was extended with a 6 5/8 x 7” tieback to surface.

At Aderklaa UT1 the 24 1/2" and 18 5/8” casing was set as planned. The next section was drilled with many mud losses and gas readings. From 4,453 m a combination of influx and losses at the same time occurred and the 14” casing was set at 4,473 m. The last casing section (10” casing string) was set at 6119 m [24, 33, 38 and 50].

7.2.2 Casing sizes/clearance

The well Zistersdorf ÜT1 was cased with usual casing sizes. Only a 4 1/2" liner was chosen to overcome the collapsed interval inside the 9 5/8" and 7" casing as mentioned above. The casing program of Zistersdorf ÜT2A was influenced from the experiences at the first well. At the second well already one size larger was started to have the possibility of a contingent casing string. Due to the high formation pressures heavy wall casing and proper couplings were necessary. A 14” casing with 0.693” ID was used instead of a 13 3/8” casing with 0.48” ID. The larger wall thickness was necessary due to collapse resistance and so a standard 12 1/4" bit was possible. The 10 3/4" casing is more difficult to run in a 12 1/4" hole than a 9 5/8” pipe but the larger ID of 9.164” enabled to drill with an 8 3/4” bit instead of an 8 1/2" bit. The same apply to the 7 5/8” liner. This was only possible by a special thin-wall box MUST-M which had the seal seat inside.

For the same reason a 10” string at Maustrenk ÜT1 was used to have a contingent casing with a 7 5/8” diameter. This enabled to drill with a 6 1/4" bit and run a 5” casing string. The top of the 5” liner was in the 10” casing and not in the 7 5/8” column. The ordered 5 x 10” liner hanger for Zistersdorf ÜT2 was available and so it was set in the 10” casing.

At Aderklaa also a 14” and a 10” casing were used. The lowest pipe of the 14” string was one 13 3/8” pipe with an ID of 12.415”. But the OD of the 10” casing couplings was 11”. This is a clearance of 1.415” and also between the couplings and the 14” pipes is a low clearance (1.559”). A slow and careful casing run was the necessary. For ultra-deep drilling there should be a well-conceived planning for the casing program.

For the KTB project a slim clearance casing program was developed to reduce the rock volume as much as possible. Only a clearance of 14.6 mm between casing and borehole wall was allowed. The longest and heaviest casing string was the 13 3/8" and 13 5/8" intermediate with 469 joints and a total weight of 706 t in air. The couplings had a reduced outside diameter for better running. After 5 ½ days the string reached the final casing setting depth of 6,013.5 m [6, 22, 40 and 51].

7.2.3 Casing material

During running the 7” casing at Zistersdorf ÜT1a a coupling failed and 2,100 m casing string was left in the hole. In total 430 pipes were fished and it pointed out that 9 couplings broke. At first H_2S was blamed for them because a steel grade V 150 was used. Also U 170 drill pipes were used but H-induced embrittlement was never observed. The couplings had a small area between the two sealing points for a gas tight connection. It was in the mid of January and so ice and snow were trapped in this area. With increasing temperature and pressure in the hole the following simplified reaction happened:

$$3\,Fe + 4\,H_20 \leftrightarrows Fe_3O_4 + 4\,H_2$$

This reaction produced atomic hydrogen which entered the steel and caused the embrittlement leading to the failure [26].

The collapse of the 9 5/8” casing at Zistersdorf ÜT1a was after the great kick at 16th January 1980. The pipes collapsed between 4,352 and 4,357 m and it was detected during tripping. The casing was enlarged with bear-shaped mills from 136 mm (5.4") to 171 mm (6.7"). The casing was already cemented in March 1978 so it was much unexpected.

The 10 3/4" casing at Zistersdorf ÜT2A was run in two parts due to the low clearance and a total weight of 750 t. The pipes were inspected by Tuboscope Vetco but a crack in a male part of the thread was found. The remaining pipes were again inspected in the plant in Düsseldorf. Seven further failures were detected. Another investigation at the Montan University of Leoben (Dr. Maurer) showed that the hardness was decreasing from outside to the inside. Furthermore small strips of martensite and non-metallic embedding were determined. The same differences in hardness were found at the 5” casing. This shows how important quality tests and material inspections are. The casing for extreme conditions should be proven by independent inspecting authorities.

At Aderklaa mud losses occurred during RIH the 10” casing due to a leak between 3,367.5 and 3,374 m in the 14” casing. At first a high inner pressure was considered. The previous leak-off test confirmed that the effective pressure of 444 bar was no problem for the 14” casing. Possible reasons for this failure are a material defect in the casing or a casing wear from tripping. The origin of this casing leak has never been determined [24, 26, 36 and 51].

7.3 Cementing

The results and the problems of the cementing operations at the four ultra-deep wells are discussed in this chapter.

7.3.1 Cement and mud type

Cementing of the 10 3/4" casing in the oil-based mud at Zistersdorf ÜT2A was done without troubles. The 7 5/8” liner was also cemented (two-stage job) in oil-based mud but when drilling continued the cement was not cured. The mud returns brought spherical cement particles with ca. 3 mm in diameter to surface – the cement ball phenomena. A cement-bond log was done which showed no bonding in the lower part. After a mud change (to water-based HT XP-20) a squeeze job was done through perforations done by Schlumberger.

Two and a half year after the cementation of the 10 3/4” casing a pressure build-up was detected. A continuous cement phase was in place but micro annuli over a distance of 4000 m were existent. A bad bonding between cement and pipes in presence of oil-based mud was the reason.

At Aderklaa some considerations have been done before cementing the 10” casing. To find the optimum retarder, tests at the Montan University of Leoben and the HOWCO lab were done. The result was a different thickening time due to very sensitive temperature changes. At the end a bad cementation like on Zistersdorf ÜT2A occurred.

The experiences at Zistersdorf and Aderklaa with oil-based mud had great influence for the cementing jobs at Maustrenk (7 5/8” liner). A change to water-based mud before cementing was not done. The density of the cement slurry was reduced to a minimum (2.15 SG) to keep the inert solids as low as possible. Also a special spacer (diesel oil and Hyflo) was used to separate mud and cement. The float collar was set 500 m above the casing shoe to avoid the pumping of mixed fluids out of the casing shoe. It was very important to do a successful cement job of the 7 5/8" liner and to avoid bad cement bonds as at Zistersdorf ÜT2A and Aderklaa UT1 [35, 36, 38, 40, 42, 45 and 52].

7.3.2 Cementing jobs

The main problems of the cementing jobs were either the big volumes or the pumping time. At Aderklaa the 18 5/8” casing was cemented from 1,999 m to surface. At the end of the job a mixture of 70 m³ (mud and cement) was pumped to surface. This means that there probably would be channelling in the cement. Also for the 14” casing a big cement volume of 320 m³ was only used for the first stage (4,473 to 1,900 m). At Zistersdorf ÜT2A the cementing of the 10 3/4" pipes required a rather low volume over a long distance (5,997 m). An alternating open hole diameter over such distances and possible losses into the formation make a big challenge for cementing jobs. Higher spacer volumes are required to avoid mixing of the fluids.

Several squeeze cementations were necessary due to cement losses or casing leaks (14” casing at Aderklaa). At Maustrenk during the 10” cementation high mud losses (38 m³) occurred. At second stage it was not able to bring circulation back to surface. The level dropped to 360 m and 120 m³ mud were necessary to fill up the annulus. As a cementation through the sliding side door was not possible, it was closed with a self-fabricated steel plug and the annulus was cemented from surface.

At Aderklaa UT1a a cement bond log showed that the whole casing string below the sliding side door was not or bad cemented. For this second trial the cement string with a packer was set 300 m above the casing shoe to achieve a good cement displacement. All this incidents demonstrate possible scenarios and can help to improve planning of future cement jobs.

At the Baden #1-28 a failure of the back-pressure valves in the cement retainers cost a lot of time. This failure at the top of the 9 5/8" liner permitted flow of cement around the drill pipe. In total this cementing operation required 50 rig days [8, 35 - 36, 40 and 52].

7.4 Hydrocarbons

This chapter deals with drilled hydrocarbons, the results of the Zistersdorf ÜT1a kick, the performed production tests and the production of Maustrenk ÜT1a.

7.4.1 Well Control

The experiences at the four ultra-deep wells are very important for future exploration wells. At the Zistersdorf wells already in the Neogene above the Steinberg fault higher compacted formations and hydrocarbons can be expected. In the marlstone klippe and below of it the occurrence of formation influxes or losses should be handled with care. As the Waschberg zone formations were drilled with an oil-based mud it is difficult to indicate oil or gas. This would be only possible with a gas chromatograph detection. Below the Steinberg fault there was often background gas measured so it would be easier to detect hydrocarbons with a water-based mud.

The large influxes and losses at Maustrenk at a depth of 6,285 m took one month until the formation was cemented. At the sidetrack at 6,298 m again a gas influx was detected. But the mud was changed to the HT XP-20 (water-base mud) before the critical formation and so it was easier to control the well.

The most influxes were controlled by increasing the mud weight to keep the formation pressure in balance. It was not always easy to keep the desired mud weight constant. Mud outline temperatures above 70°C cause higher mud densities due to vaporization losses of water-base mud which were seen at Maustrenk. For well control an accurate volume measurement of the mud pits is necessary. The old pit system of rig H-2500 made it difficult to detect volume changes.

The used Data Unit was a great support at the ultra-deep wells but it had some disadvantages. The data was transmitted every five minutes or every 25 cm of drilling – whichever comes first. This small time delay can have big consequences when talking about a gas influx. Today the data acquisition has improved very well and true real-time monitoring can be used.

After the kick at Zistersdorf ÜT1a the rig crew was trained regularly. Different kick scenarios were trained on the rig site to get more familiar with the procedures. This is one of the most important factors to safe a well [40, 47 and 49].

7.4.2 Kick

The only kick situation which was not immediately brought under control by the rig crew was the kick at Zistersdorf ÜT1a on the 16th of January 1980. A gas influx at a rate of more than 40 MMCFD (millions of cubic feet per day) was produced and flared - the flame from the flare stick was higher than 60 meters. The influx contained 98 % CH_4 and 2 % CO_2. After five days and several trials to bring the well under control the open hole collapsed. At the specific forum in Mailand in June 1981 two possible kick scenarios were discussed:

Scenario A: At 7,544 m fractured reef sediments were drilled. The mud losses (2.4 m³) were on top of this formation where higher porosities and permeabilities can occur. After the bit was picked up from bottom gas was swabbed into the well. Furthermore the turn off of the pumps encouraged the gas to enter – a change from dynamic (ECD 2.29 S.G.) to static (MW 2.23 S.G.) condition. The formation pressure lay between 2.23 and 2.29 kg/l.

Scenario B: The first influx was detected at 9:33 o'clock and the gas was on surface two hours later. As this time does not correspond with the calculated lag-time the opportunity of an earlier gas influx should be considered. A possible explanation is a communication between the reef and crevices in the Upper Cretaceous where the gas entered [47].

A detailed description of the incidents at Zistersdorf ÜT1a was already given in Chapter 6.

In April 1974 the Bertha Rogers well at 9,583 m (31,441 ft) suddenly kicked at a ROP of 5 feet per hour. The well was shut-in with a SICP of 590 bar (8,550 psi). The calculated pressure of the penetrated porous zone was 1,717 bar (24,900 psi). The mud weight was increased to 1.90 SG (16 ppg) and circulation was started with a back pressure of 490 bar (7,100 psi) on the casing. The surface pressure was continuously reduced to 34 bar (500 psi) as 48 hours after the kick sour gas surfaced. With it, sulphur crystals got to surface which were later found to be elemental sulphur (in both red and yellow crystals). After 80 hours the well was completely dead. One reason could be the sulphur, which was believed to be molten at the estimated bottom hole conditions, solidified and stuck the drill string. Another possibility is, that H_2S corrosion caused a disconnection of the drill string at about 4,481 m (14,700 ft). Fishing was seen impractical and the well was abandoned.

Several further kicks occurred at the ultra-deep wells but they are not mentioned here due to their minor relevance.

All these kick situations have shown the importance of well control training and preparation. In case of such high pressures the adequate well control equipment should be on site. Mud reserves and loss controlling material should be immediately available or already on the rig site. And the rig crew should be also trained in practical exercises and not only in theory.

7.4.3 Tests

In August 1980 a casing test at the interval 4,838 – 4,842 m was done but no inflow was achieved at Zistersdorf ÜT1a. Another test at the 245/10 'Untertorton' was done from September till December. The perforated interval (4,660 – 4,670 m) produced 45,600 m³ of gas in 50 production hours. The maximum flow rate was 3,000 m³/d and the reservoir pressure was 900 bar (4,665 m). As no economic production was achieved the well was abandoned [24 and 53].

Several production tests were done at Zistersdorf ÜT2A. The highest downhole temperature with 205 °C was measured at 7,450 m, a temperature of 230° at 8,553 m was assumed. The interpretation of the test results from interval 7,389 – 7,407 m shows a potential gas volume of 50,000 m³ and a permeability of 10^{-3} mD. Another interval (7,137 – 7,162 m) was tested. The reservoir fluid pressure was 1,544 bar at a bottom hole temperature of 200 °C. The tested formation had a porosity of 3 % and a permeability of again 0.001 mD. No economic production was obtained at this well [42 and 50].

The high gas readings in the Upper Cretaceous-Flysch formation were chosen for a production test. Nine intervals between 4,316 and 4,597 m were tested. In total only 21.8 m³ formation water was produced [34 and 54].

A long-term production test was done in the Malmian upper carbonates at interval 6,304 – 6,313 m. Production was started on the 12th of February 1986. The initial flow rate was 135 m³ oil per day and 64,000 m³ gas per day and the wellhead pressure was recorded at 950 bar. A decline curve analysis calculated an OOIP of 14,000 m³ and an OGIP of 8 million m³ in solution. The flow rate end of March 1987 was 20 m³ oil and 30,000 m³ gas per day at wellhead pressure of 22 bar. On the 1st of April the well stopped producing. In total 4,974 m³ oil and 2,925,900 m³ gas were produced [43 and 54].

At Aderklaa nine intervals between 3,780 and 5,445 m were tested. Only small gas amounts were detected at some intervals. As there was no positive production test the well was abandoned [35].

7.5 Planning

In this chapter there are some important experiences and considerations for future exploration wells.

7.5.1 Well location

A major decision is the well location of the planned drilling project. Already the location of the Zistersdorf wells was chosen to avoid drilling the Flysch formation. This should be considered again in future projects to minimize the risks of drilling critical formations.

One result of the four ultra-deep drilling projects was that the Autochthonous Mesozoic was the major source rock for the Vienna Basin - the Malmian marls at Zistersdorf ÜT2A had a thickness of more than 900 meters. But the Malmian marls and the Upper carbonates have also a potential as unconventional reservoir rock as the production of Maustrenk showed.

Another important well planning step is the well trajectory. The well should be drilled vertical as straight as possible. The angle build-up in the lowest sections of Zistersdorf ÜT2A resulted in high torque and massive wear. Time-consuming reaming and roundtrips were necessary to keep the desired diameter.

7.5.2 Sour gas H_2S

There was no H_2S in the four ultra-deep wells in Austria. For the drilling projects itself it was a great advantage. The whole drilling procedures are much easier to operate without sour gas.

Only at the Bertha Rogers well in Oklahoma H_2S appeared as already mentioned above. Already before the incident at final depth traces of H_2S were detected by a logging unit at 3,170 m. For that reason an all H_2S resistant Christmas tree was ordered [8 and 56].

7.5.3 Temperature

The measured bottom hole temperatures of both Zistersdorf wells and the Maustrenk well are given in Figure 9. The wells showed a nearly constant temperature gradient through bottom. Table 23 shows the average geothermal gradients of the wells.

	°K per 1 km	m per 1 °K
Zistersdorf ÜT1a	26.5	37.8
Zistersdorf ÜT2A	29.2	34.4
Maustrenk ÜT1a	27.0	37.0
KTB	27.6	36.2
Kola SG-3	25.0	40.0

Table 23: Geothermal gradients [69]

As the Zistersdorf ÜT2A well was the deepest, it has maybe a slightly higher temperature gradient than the others. The average of the three wells near Zistersdorf is 27.6 °K per km. For comparison, the temperature gradient of the KTB main hole is also 27.6 °K per km and about 25°K per km below a depth of 3 km at the Kola SG-3 well [5, 59].

In general, most equipment under such high temperatures (> 175 °C or 350 °F) are operating beyond their limit. Logging units and tools that could log at 30,000 feet with a bottom hole pressure of 20,000 psi and a bottom hole temperatures of 450 °F (232 °C) didn't exist before spudding the first US well (Baden #1-28). They had to be especially developed for such extreme conditions.

At the German KTB project the VDS system for vertical drilling was abandoned at 7,490 m, because bottom hole temperatures were too high for the electronics. Drilling was continued with a common downhole motor but the well deviated north got unstable within the main fault system.

For logging several tools like the high-temperature Formation MicroScanner tool was developed. It was upgraded to 260 °C (500 °F) with the usage of a Dewar flask outside the housing, while the inside temperature remains below 175 °C for up to 8 hours. The maximum temperature recorded at the first logging run to final depth was 240 °C (464 °F) and at the last run 250.5 °C (483 °F). The tool didn't take any damage inside [5 and 8].

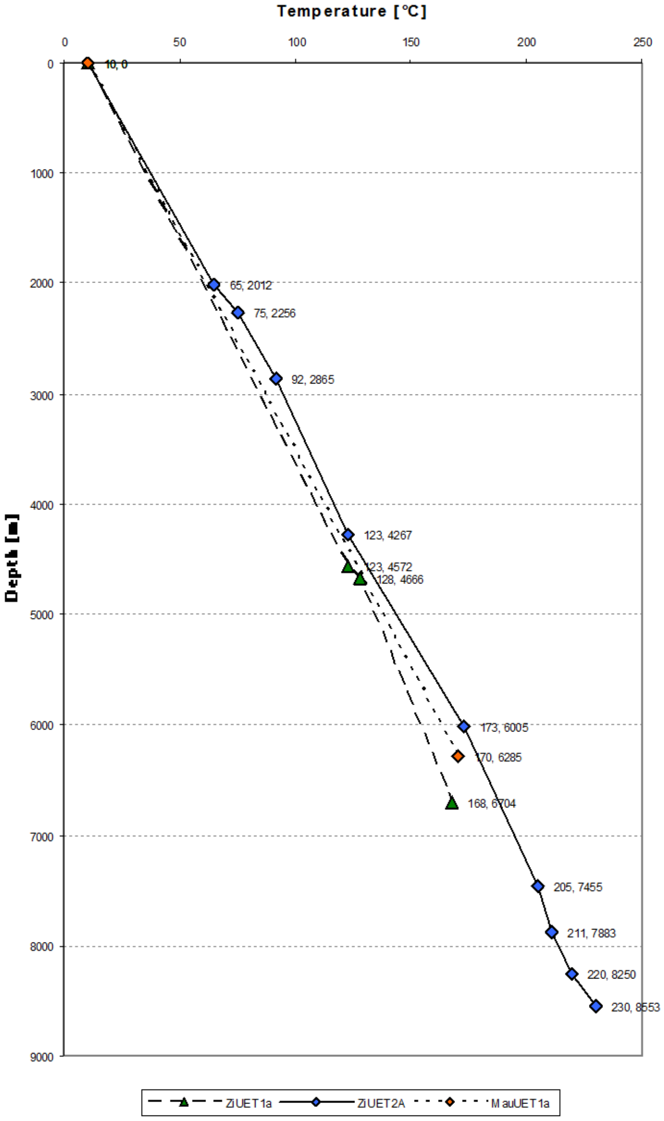


Figure 9: Temperature Profile ZiUET1a, ZiUET2A and MauUET1a [27]

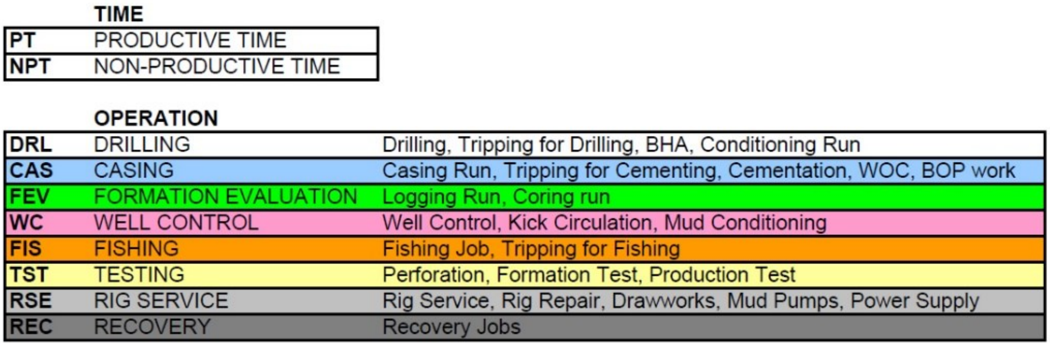
7.5.4 Fracturing

Another important consideration is a possible fracturing of the reservoir rock. The casing tests below 7,000 meters at Zistersdorf ÜT2A measured a rock porosity of 3 % and a permeability of 1 Microdarcy. To get access to a possible hydrocarbon bearing formation fracturing of the rock is necessary. Most of today's frac units are limited to 20,000 psi which is already the limit for such depths.

7.5.5 Drilling schedule

The planned project time is dependent on a lot of factors. The duration from spudding to the abandonment of the well was 1,065 days for Zistersdorf ÜT1a, 1,296 days for Zistersdorf ÜT2Aa, 825 days for Maustrenk ÜT1a and 1,114 days for Aderklaa UT1b. The operation of the main hole of the KTB project took 1,467 days. A rather fast job was done at Baden # 1-28 with 544 days and at Bertha Rogers # 1-27 with 504 days. A really time consuming project was the Kola SG-3 well in Russia. Drilling started in May 1970 but it took about 9 years to break the world depth record held by the Bertha Rogers well with 9,583 m. With some incidents the well was drilled to 12,066 m in September 1984. The final depth of 12,262 m was reached in 1989. So it took almost 19 years (with several interruptions) to drill this scientific well.

For analysis the typewritten daily drilling reports were taken and imported into a database (kind of well storyboards) for further processing. Only for the Maustrenk well and both Zistersdorf wells the reports were still available. So the further graphs and evaluations are concerning those three wells.



	TIME
PT	PRODUCTIVE TIME
NPT	NON-PRODUCTIVE TIME

	OPERATION	
DRL	DRILLING	Drilling, Tripping for Drilling, BHA, Conditioning Run
CAS	CASING	Casing Run, Tripping for Cementing, Cementation, WOC, BOP work
FEV	FORMATION EVALUATION	Logging Run, Coring run
WC	WELL CONTROL	Well Control, Kick Circulation, Mud Conditioning
FIS	FISHING	Fishing Job, Tripping for Fishing
TST	TESTING	Perforation, Formation Test, Production Test
RSE	RIG SERVICE	Rig Service, Rig Repair, Drawworks, Mud Pumps, Power Supply
REC	RECOVERY	Recovery Jobs

Table 24: Coding of Well Storyboards

To distinguish the different operations a coding was introduced. Table 24 shows the different operations and the associated action. Furthermore it was recorded whether it was productive or non-productive time. The available daily drilling reports allow only a separation in days.

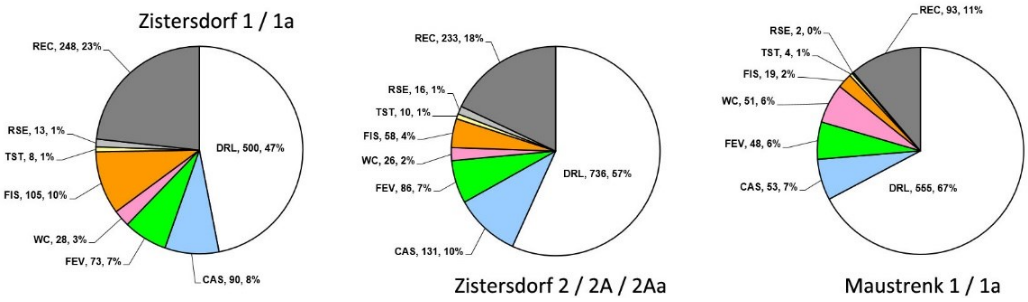


Figure 10: Well Operations at Zistersdorf and Maustrenk [23, 27 and 32]

The pie charts in Figure 10 shows the well operations of Zistersdorf ÜT1a, Zistersdorf ÜT2Aa and Maustrenk ÜT1a. The drilling operations itself took between 47 and 67 % of the total time. The next big part is defined as recovery time which mean the time after the last drilled meter and the abandonment of the well. Of course this operation has the biggest value at Zistersdorf ÜT1a with 248 days or 23 % due to the kick in January 1980 and the following well control actions. Casing, cementing and BOP work are between 7 and 10 % of total time. A rather high percentage of 105 days or 10 % is for fishing jobs at Zistersdorf ÜT1a.

The classification of productive and non-productive time (fishing jobs, well control, casing & cementing problems, waiting and other incidents) is very difficult. As already mentioned the daily drilling reports are mostly very short and the actions can only be classified into whole days for productive or non-productive time.

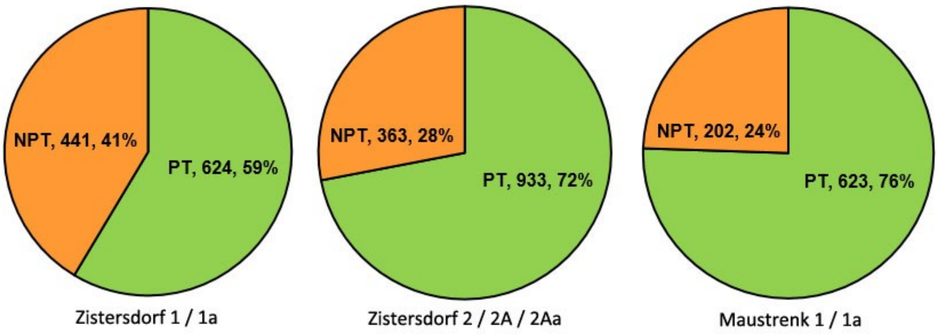


Figure 11: Total Productive and Non-productive Time [23, 27 and 32]

The distribution of productive and non-productive time is given in Figure 11. Zistersdorf ÜT2Aa and Maustrenk ÜT1a have nearly the same percentage with 28 % respectively 24 % for non-productive time (NPT). The well Zistersdorf ÜT1a has a very high NPT value of 441 days or 41 %. Excluding the recovery operations (REC) gives a NPT value of 24 % for Zistersdorf ÜT1a, 12 % for Zistersdorf ÜT2Aa and 15 % for Maustrenk ÜT1a.

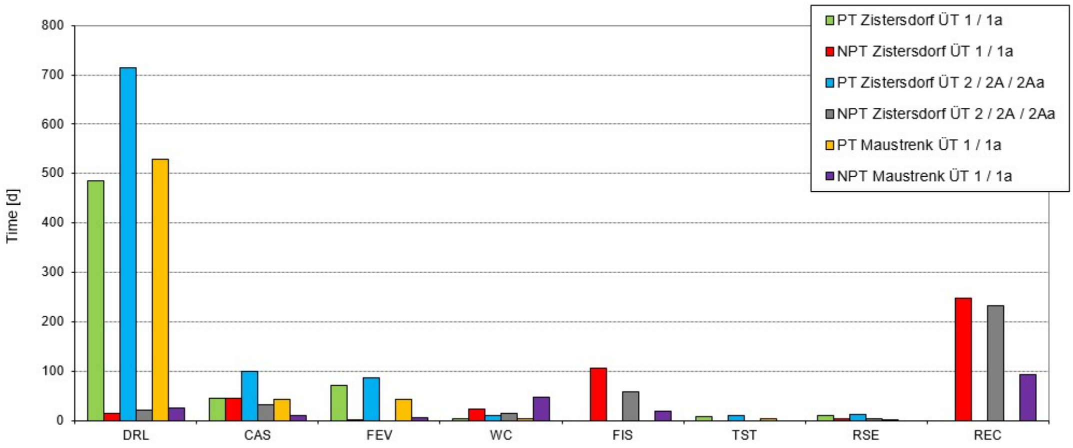


Figure 12: Operations and Productive Time [23, 27 and 32]

A more detailed overview of the operations and the productive time is given in the bar chart in Figure 12. Beside the high drilling time the recovery operations up to 250 days stand out. Also the non-productive fishing jobs up to 100 days can be recognized.

The time vs. depths curves of the Maustrenk and Zistersdorf wells are given in Figure 13. At the flattening of the curves the casing sections, the sidetracks and the recovery period can be seen. As there are no daily drilling reports from Aderklaa available there is no time vs. depth curve for this well.

A duration prediction for future drilling operations is very difficult but at least the non-productive time of 25 % can be saved. The most time can be reduced at the drilling operations. The usage of proper drill bits and logging tools can decrease the number of roundtrips. Also steerable systems (only in a temperature acceptable environment) avoid the change between stiff and pendulum assemblies. Accurate material inspections prevent drill string & casing string failures and decrease the number of fishing jobs. Appropriate mud conditioning reduces the number of losses or influx. Sufficient mud reserves and weighting material on-site prevent kicks and decrease the time consuming well control operations. Adequate preparation followed by a good cementing job separates the different pressure zones and reduces the risk of unknown influx like at Zistersdorf ÜT1a.

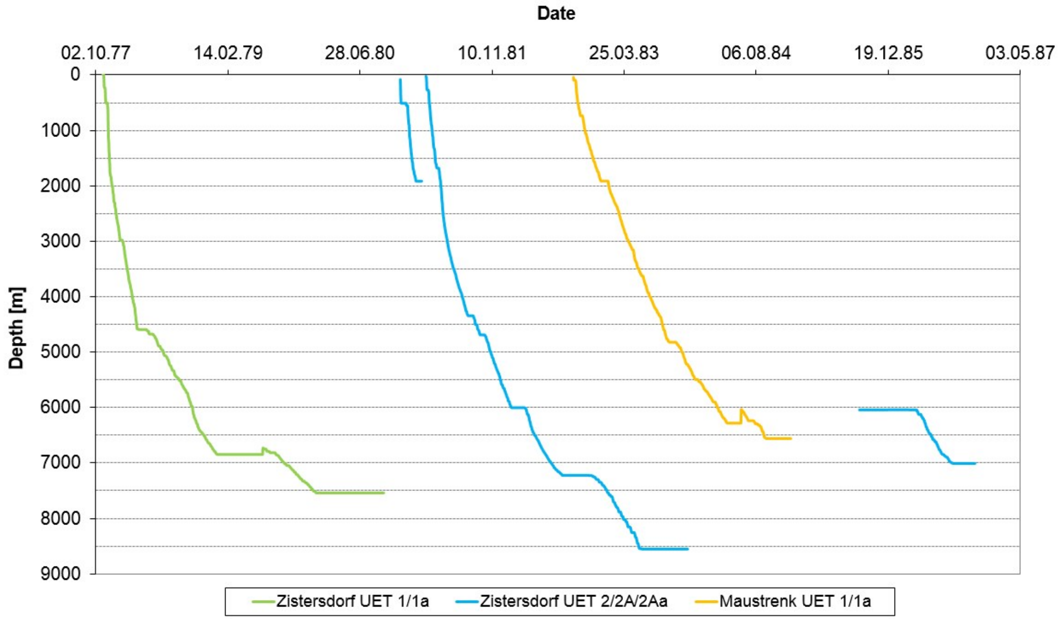


Figure 13: Time vs. Depth curves [23, 27 and 32]

7.5.6 Economics

Last, but not least, the economic considerations should be mentioned as they are from important role. Deep drilling occupy much time and costs. So such projects over several years requires an accurate financial planning.

An overview of the total project costs of selected wells are given in Table 25. At first the nominal value in the initial currency is given - dated at the end of the project. To compare the costs they were adjusted for inflation at the basis of 2015. For this adjustment an inflation converter of the national bank of Austria/Germany was used [76].

Well	Nominal Value	Real Value 2015	Cost per meter
Zistersdorf ÜT1a	ATS 412 million	€ 71.2 million	€ 9,434
Zistersdorf ÜT2A	ATS 710 million	€ 105.3 million	€ 12,311
Maustrenk ÜT1a	ATS 525 million	€ 73.7 million	€ 11,227
Aderklaa UT1b	ATS 545 million	€ 74.1 million	€ 11,177
KTB Project	DM 528 million	€ 381.5 million	€ 41,913

Table 25: Total costs of selected wells [5, 35, 42 - 43, 74, 76]

The wells of the Vienna Basin have almost similar expenditures. Zistersdorf ÜT2Aa has 44 % additional cost due to first abandoned well and the great depth. The sidetrack 2Aa which was drilled three years later is not included in this listing. The high expenditures of the KTB project arise from a different drilling strategy. Considerably more logging and coring operations were planned and accomplished. Only in the pilot hole 3,594 m of cores were recovered out from 4,000 m (including sidewall cores).

This trend can also be seen in the costs per meter drilled - again at a real value basis at 2015. The values are only for comparison and should not be considered for today's calculations. They also demonstrate the purchasing power of that period of time.

8 Preliminary Well Design

The last chapter showed the experiences and lessons learned from the ultra-deep wells. This chapter presents the outcome of the thesis.

The objective is to have a strategy for a future ultra-deep drilling project at the Steinberg fault at Zistersdorf, considering the experiences of the previous ultra-deep wells. It should easily and straight help to plan a Zistersdorf ÜT3 well. Where are the critical zones? Which parameters and gradients can be expected? Where to set which casing? Which equipment can be used? And which general considerations should be made for this new well?

8.1 Zistersdorf Ultra-deep 3

For a further ultra-deep well at Zistersdorf the following subchapters describe the main issues to drill a Zistersdorf ÜT3 well. This kind of intent-to-drill is based on given data and calculations are made with common drilling formulas (given in Appendix A.4). If assumptions were done, they are explicitly mentioned in the text. For a better overview a summary table with all important parameters is given at the end of this chapter (Table 50).

8.1.1 Geology

Source Rock Quality

In August 1980 an internal report about the source rock quality of the Zistersdorf ÜT1a well was presented. The cores and samples were analysed on organic carbon content (C_{org}), soluble organic material and extractability. The highest and best values had the Malmian Marls layer in the second floor and Autochthonous Malm in the third floor. Between 4,200 and 6,000 m is the oil window, below only gas can be expected. Considering all three parameters (quantity, quality and maturity), the Autochthonous Malm is the best source rock.

This conclusion is a precondition for large gas reservoirs and so for further drilling projects.

Stress indications

Figure 14 shows the azimuth of borehole elongation at both Zistersdorf wells. The red arrows point in direction of maximum horizontal stress (σ_{Hmax}). This correlates to the stress directions

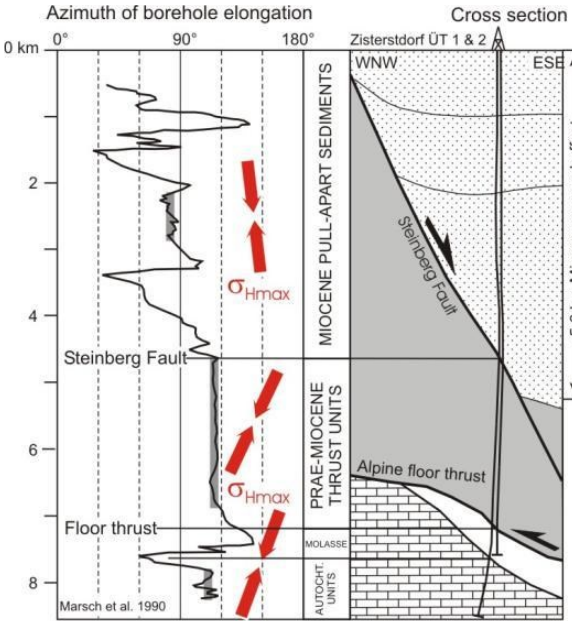


Figure 14: Stress directions at the Zistersdorf wells

from the World Stress Map - a global stress database provided by the Helmholtz-Zentrum Potsdam. The main stress direction in the upper Vienna Basin is north-east to south-west as in the second and third floor in the figure displayed.

8.1.2 Target

Target zone

The main objective is the gas reservoir from Zistersdorf ÜT1a. The Upper Cretaceous layer (as seen in Figure 8) can be expected at ~ 7,510 m, the gas bearing formation at about 7,540 m. The well Zistersdorf ÜT3 is planned down to 7,600 m.

Well site

The plan is to drill as vertical as possible. Due to the hilly and forested area, the well site selection is very limited. In Figure 15 the chosen well site for Zistersdorf ÜT3 is shown.

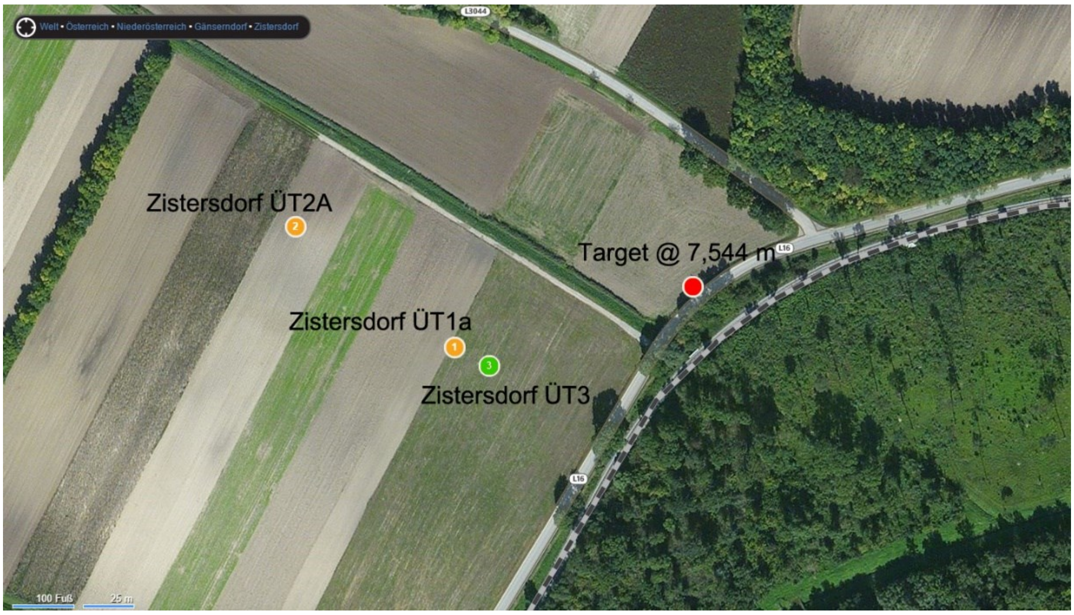


Figure 15: Planned well site and target of Zistersdorf ÜT3

The area next to the target with the coordinates N48°32'52", E16°47'40" is maybe too small. Furthermore is the driveway problematic due to embankments and a narrow curve for long vehicles. So the well site has been selected southwards with a better transport connection. The coordinates of the well are N48°32'51", E16°47'35".

Well trajectory

The target is in an azimuth of 73.1° and has a deviation of 107 m. The well trajectory is very simple planned. The well will be drilled down to 5,490 m vertically (kick-off point). A rather short build section (rate 1°/100 ft) to 5° follows down to 5,640 m. At 6,738 m the trajectory drops again to an inclination of zero degree with a rate of 1°/100 ft. A detailed overview of important depth is given in Table 26.

Depth	Azimuth	Rate	Inclination	Deviation
0 m	0°	-	0°	0 m
~5,488 m	73.1°	1°/100 ft	0°	0 m
~5,640 m	73.1°	-	5°	8 m
~6,738 m	73.1°	1°/100 ft	5°	101 m
~6,890 m	73.1°	-	0°	106 m
~7,600 m	73.1°	-	0°	106 m

Table 26: Well trajectory of Zistersdorf ÜT3

The deviation would also be possible in a higher section, but as the second floor has many brittle formations and due to the transition zone it would make no sense. To drill those sections vertically is challenging enough. Below 5,000 m there is a more uniform and wider mud weight window.

8.1.3 Critical zones

This is a very important topic as the second floor is throughout over-pressurized.

Overpressured zones

The transition zone for overpressure starts already at about 4,150 m in the Badenian. This zone is about 500 to 550 m thick. For some unknown reason already 490 m before the Waschberg Zone (respectively the Steinberg fault), a very high pore pressure was recognized later (casing collapse at Zistersdorf ÜT1a). This correlates to the start of the overpressured zone at the Maustrenk well (4,823 m), where the formation change from Flysch to the Waschberg zone. Equivalent mud weights between 2.0 and 2.4 SG can be expected deeper than 4,800 m. Table 27 shows the depths where the most probable drilling problems can occur.

Borehole instability

The most critical wellbore problems with borehole instability occurred at about 4,900 m (Waschberg zone) and 6,750 m (Waschberg zone) at Zistersdorf ÜT1a, and at about 7,590 m (Malmian Upper Carbonates) at Zistersdorf ÜT2A.

Mud losses

The main mud losses were at about 5,700 m (Malmian Marls) at Zistersdorf ÜT1a and at 7,220 m at Zistersdorf ÜT2A.

Depth	Issue	Remark
4,150 m	pressure	Start of transition zone
4,352 m	pressure	High pressure, Csg collapse ZiUET1a
4,900 m	borehole stability	Impaired marly clay formation
5,530 m	borehole stability	Very brittle marly clay
5,700 m	losses	27 m³ losses due to brittle marly clay
6,750 m	borehole stability	Stuck 6x / Stood up 3x - total in 88 days

7,220 m	losses	Reduced MW from 2.23 to 1.92 SG
7,590 m	borehole stability	Malmian Upper Carbonates

Table 27: Critical zones to expect at Zistersdorf ÜT3

8.1.4 Expected gradients

Pore pressure

In the first floor there is a normal pore pressure with a gradient of 0.442 psi/ft or 0.1 bar/m (saltwater 0.444 psi/ft). In the overpressured zone a gradient of 0.637 psi/ft or 0.144 bar/m can be estimated. At TD (7,600 m) a gradient of 0.966 psi/ft or 0.218 bar/m can be expected. This relates to an EMW of 2.23 SG. Figure 32 in Appendix A.3 shows the mud weight window expected for Zistersdorf ÜT3.

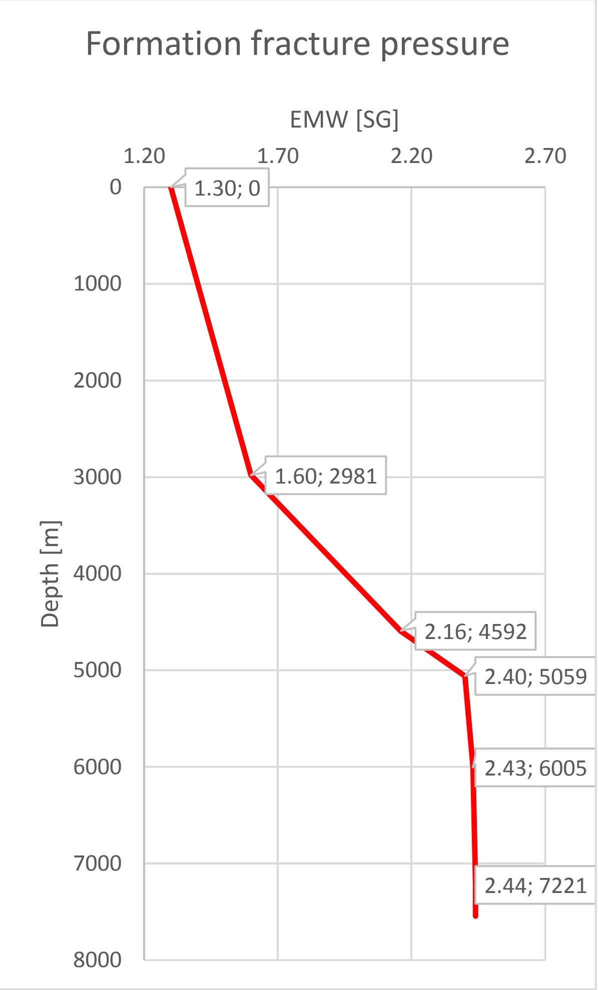


Figure 16: Formation fracture curve for Zistersdorf ÜT3

Fracture pressure

A frac gradient of 0.693 psi/ft (0.157 bar/m) can be estimated down to 3,000 m. A leak-off test at 4,592 m gave an equivalent mud weight of 2.16 SG (0.935 psi/ft or 0.212 bar/m). From 5,000 m to TD a nearly constant EMW for fracturing can be expected - 1.057 psi/ft or 0.239 bar/m at its maximum. All values originated from leak-off tests performed at Zistersdorf ÜT1a and ÜT2A are given in Figure 16.

Temperature

A temperature gradient of 27.6° K per km can be expected. Thus a bottom hole temperature of about 210 °C (410 °F) can be assumed at a depth of 7,600 m.

8.1.5. Equipment

Material selection

In general all equipment and tools should be temperature and pressure resistant for the estimated well conditions. Most standard downhole tools are designed up to temperatures of 350 °F or 177 °C. As bottom hole temperatures up to 210 °C are expected, HPHT (high pressure high temperature) tools should be used for the BHA and logging tools below 6,400 m. Safety in pressure issues is very important in terms of casing and well control.

Furthermore the material selection should be in a safe range for the expected forces and loads - tension/compression, torque and collapse/burst. Aluminium and Titanium alloys are getting more applicable. Aluminium alloy drill pipes for example has a 46.3%-reduced weight, but also a 47%-reduced strength in tensional and torsional yield. Pure aluminium has a yield strength up to 1,595 psi, while aluminium alloys can reach 29,000 - 87,000 psi (Titanium 120,000 psi). Steel drill pipes have a minimum yield strength of 95,000 psi (X-95), 105,000 psi (G-105), 135,000 psi (S-135) or 150,000 psi (V-150).

A further disadvantage of the alloys is the reduction of the yield strength (Al, Ti) and the creep tendency (Ti) with increasing temperature.

Drill pipes

The most common 5" aluminium alloy drill pipes (OD is 5.150") available are produced with the 2014-T6 aluminium alloy (yield strength 58,000 psi) with 90.4-95% Al, max 0.1% Cr, 3.9-5% Cu, max. 0.7% Fe and further components (Mg, Mn, Si, Ti, Zn). The alloy drill pipes have a yield strength of 442,000 lb and a torsional yield strength of 44,700 ft-lb. Their usage is not unlimited, as they are starting aging above 160°C (320°F) [79].

For the Zistersdorf ÜT3 project this means a usable depth down to 5,800 m - to be in a safe range.

The tensile yield strength itself would be high enough to drill the entire well with aluminium alloy drill pipes. Drilling only with aluminium alloy drill pipes results in a weight reduction of 53.7% comparing to S-135 steel pipes (25.6 lbm/ft, 5-1/2 FH). And the total weight of the drill string (without BHA) would be with 244,000 lb (at a mud weight of 1.98 kg/l) far below the yield strength of 442,000 lb. The limiting factor for alloy drill pipes is the reduced collapse resistance.

The use of alternative drill pipes for the given conditions is calculated and discussed later in Chapter 8.1.6.

Vertical drilling

It is absolutely necessary to drill the well vertically. For this reason a directional drilling system should be used as early as possible, preferably an active system like the rotary steerable system with straightforward directional control. Favourable would be a HPHT system to be able to drill down to TD.

Already rotary steerable systems up to 200°C or 392°F are available from service companies and can be used down 7,250 m at the Zistersdorf ÜT3 well.

Logging

The same challenges apply to the logging jobs. Also here service companies provide logging tools up to 200°C or 392°F for drilling operations.

Coring

As the wells getting deeper, the well conditions and challenges change. Higher vibrations, equipment wear/failure or technical capacity forces new developments in coring technique.

For this type of formation evaluation two types can be mentioned. The conventional technique with core bit and barrel on the drill string on the one side and sidewall coring with wireline on the other one.

Sidewall coring is done wireline and the cores be taken by the rotary or percussion technique. In a single run between 60 and 116 samples of 1.5" diameter can be taken (depending on system). This reduces the operation time to a minimum. Furthermore the systems are already resistant up to a temperature of 204°C (400°F), pressures up to 25,000 psi (1,720 bar) and should be considered for a prospective Zistersdorf project.

Data of some HPHT tools which are available on the market are listed in Table 28.

Use	Temperature	Pressure	Manufacturer	Name
RSS	200°C/392°F	30,000 psi	Schlumberger	PowerDrive ICE ultraHT RSS
Logging	200°C/392°F	30,000 psi	Schlumberger	TeleScope ICE ultraHT MWD
Coring	204°C/400°F	25,000 psi	Baker Hughes	PowerCOR Service (wireline)
Coring	204°C/400°F	25,000 psi	Halliburton	CoreVault System (wireline)

Table 28: Data of available HPHT tools [80 - 84]

8.1.6 Drill string design

The drill string design is for the determination of length, weight and grades of drill pipes. It depends on depth, hole size, mud weight and sizes of drill pipes/collars. The calculations are done for the lowest section. In this section the highest pressures and loads can be expected. For easier calculation, the weight of the drill collars are assumed for the whole bottom hole assembly. The design of the drill string is done for tension, collapse, torsion and buckling.

Drill string components

At first pipes of different specifications have been chosen. Important parameters are the outer diameter (OD), nominal weight (NW), average weight (AW), collapse resistance (CR) and tensile yield strength. For later purposes, like hydraulic calculations, also the inner diameter (ID) is of importance. There are a lot of different pipes available on the market. But only some meet the requirements for high pressures. Those selected pipes and their properties are given in Table 29.

The already mentioned Titanium alloy drill pipes were initially developed for short radius drilling (radius < 30m). Titanium alloy has a low modus of elasticity and high fatigue resistance. As a result ultra-short radius drilling with a diameter of 10 m (33 ft) is possible. Common pipes have a diameter of 2 3/4" and 2 7/8" and are therefore not proposed in this thesis.

OD [in]	NW [lbm/ft]	AW [lbm/ft]	Grade	Joint	ID [in]	CR [psi]	Yield strength [lb]
Drill pipes							
4.5	20.0	23.03	S-135	NC50 (IF)	3.640	23,335	742,244
5	19.5	22.61	S-135	NC50 (XH)	4.276	15,672	712,070
5	25.6	29.43	S-135	5-1/2 FH	4.000	24,300	954,259
5.15	10.2	13.64	2014-T6 Alum. Alloy		4.100	10,700	442,000
5.5	21.9	26.50	S-135	FH	4.778	12,679	786,809
Heavy-wall drill pipes							
4.5	24.3	25.0	HW-95	NC46	2.750	28,014	704,100
5	49.0	49.13	AISI4145	NC50	3.250	16,110	1,247,313
5.5	54.0	54.6	AISI4140	5-1/2 FH	3.500	35,700	1,700,000
Drill collars							
4.75	45.0	45.0	AISI4145	NC38	2.500	n.a.	n.a.
4.75	49.8	49.8	AISI4145	NC38	2.250	n.a.	625,000

Table 29: Drill string design - used pipes

Drill string design calculations

For the calculations some general assumptions have to be done before. A mud weight of 2.20 SG (18.36 ppg) was assumed for the lowest section. Thus results in a hydrostatic pressure of 1,640 bar (23,780 psi). A safety factor of 1.125 was taken for the different calculations. The total depth of the well is 7,600 m or 24,939 ft.

Further assumptions are a weight on bit of 20 t or 44,093 lb. For better hydraulics the 4 3/4" drill collars with a nominal weight of 45 lbm/ft and an inner diameter of 2.5 inch were chosen (discussion later in Chapter 8.1.9). With this parameters a minimum length of 1,532 ft for the BHA was calculated - the neutral point is at 1,362 ft (415 m).

Different steel and alloy strings were used for the necessary criteria. At first the strings consist of only one pipe type to identify the limits of each type. Only some of the tested strings can be listed here. Table 30 shows the results of the calculations of four selected drill strings.

	4.5" Steel	5" Steel	5.5" Steel	5.15" Alloy
Collapse pressure worst-case [psi]	22,321			
Collapse resistance [psi]	23,335	24,300	12,679	10,700
Design Factor [-]	1.05	1.09	**0.57**	**0.48**
Tension load - maximum [lb]	742,244	954,259	786,809	442,000
Tension load - calculated [lb]	412,104	512,857	466,731	264,281
MOP [lb]	255,916	345,976	241,397	133,519
Design Factor [-]	1.62	1.67	1.52	1.51
Torsional yield strength [ft-lb]	73,641	94,062	91,278	47,682

Tors. yield strength incl. tension [ft-lb]	64,366	79,323	73,484	38,930
Critical WOB 1st-order buckling [lb]	75,304	99,655	94,969	**44,084**
Critical WOB 2nd-order buckling [lb]	145,561	192,632	183,575	85,214

Table 30: Drill string design - calculations

A major criterion is the collapse resistance. For the worst case, the drill string is empty and full hydrostatic pressure of 22,321 psi is acting on the lowest drill pipe. Only the 4.5" and the 5" steel pipes can be operated in this range - with a safety of 5 - 9 %. If the 5.5" steel and the 5.15" alloy pipe were used alone for the whole string, design factors (DF) below 0.6 shows the limit of these strings.

For tension loads, all four strings would be in a safe range (DF between 1.51 and 1.67). The aluminium alloy string (with 2014-T6 alloy) has lower strength for torsion. Also in case of buckling the margin for the critical weight on bit with 44,084 lb (20 t) is very low (for sinusoidal buckling) for the aluminium alloy.

So the 5.5" steel pipe and the 5.15" alloy pipe alone is not an option for this well. Only the 4 1/2" (20.0 lbm/ft) and the 5" S-135 (25.6 lbm/ft) string can handle the occurring loads.

Drill string selection

A combined drill string is another possibility to optimize the string in weight reduction and higher resistance. Several combinations of steel and alloy pipes were tested for the optimal design. Four selected strings and their characteristics are given in Table 31. The first string is the already above listed 5" steel pipe string - for comparison. Due to the change to a smaller bit in the last section, a combined string of 4 1/2" and 5" drill pipe is required (string #2). A combination of three different steel pipes (4 1/2", 5" and 5.5" - all S-135) is used for string #3. String #4 is a combination of 5.15" aluminium alloy pipes, 5" and 4 1/2" steel pipes (S-135).

	String #1	**String #2**	**String #3**	**String #4**
Upper type	5" Steel	5" Steel	5.5" Steel	5.15" Alloy
Middle type			5" Steel	5" Steel
Lower type		4 1/2" Steel	4 1/2" Steel	4 1/2" Steel
Maximum length upper section [ft]	-	-	13,280	11,208
Collapse resistance	✓	✓	✓	✓
MOP [lb]	345,976	204,368	232,330	**31,287**
Design Factor [-]	1.67	1.38	1.46	**1.08**
Min. tors. yield strength + tension [ft-lb]	79,323	45,771	48,266	**16,639**
Critical WOB 1st-order buckling [lb]	99,655	72,758	72,758	**44,084**
Critical WOB 2nd-order buckling [lb]	192,632	140,640	140,640	85,214

Table 31: Drill string design - results

The combined strings are limited to a specific depths due to its collapse resistance. Alloy pipes can be only used to a depth of 11,208 ft (3,416 m), the 5.5" steel pipes only to 13,280 ft (4,048 m). So the resistance for worst-case collapse is given within the range for all four combined strings.

The design for tension shows design factors above 1.3 for string #1 to #3. Only for string #4 the margin of overpull with 31,287 lb (14.2 t) is very low and not sufficient for such depths. Further has the aluminium alloy string a very low torsional yield strength. And the critical WOB for sinusoidal buckling (44,084 lb or 20 t) is reduced to a lower modulus of elasticity (only 10,600 ksi for Aluminium).

From these calculations only string #2 and #3 are usable for a depth of 7,600 m. But string #1 doesn't fit for the diameter of the lowest section. The usage of possible strings, their performance in hydraulics considerations and the final selected string are discussed later in Chapter 8.1.9.

8.1.7 Casing design

Casing setting depth

Very important is to set a casing section before the overpressure zone at about 4,300 m. The transition zone starts already at 4,150 m but an excessive pore pressure was recognized at about 4,352 m. For this reason casing section #3 should be set before this zone.

Section #1 and #2 can be set at about 500 m respectively at 2,500 m. No major well problems should be expected for both sections. The second section is rather long with a diameter of 22 in open hole (17 1/2" pilot hole) and an 18 5/8" casing. There is a heightened risk to drill this distance in one section. The experiences at Zistersdorf ÜT1a and Zistersdorf ÜT2A showed that it is technical feasible. At Zistersdorf ÜT1a the second section with a length of 2,472 m open hole (511 m to 2,983 m) was drilled successfully with a 17 1/2" bit in 48 days and was cased in four days (13 3/8" casing). The second section at Zistersdorf ÜT2A from 262 m to 1,675 m (1,413 m open hole) had an open-hole diameter of 23 inch and was drilled in 35 days. The 18 5/8" casing was run within three days. The mentioned section at both wells were drilled without any borehole stability problems. Yes, this design contains some risk but it should be drillable.

Due to the narrow mud weight window section #4 has to be set earlier at about 5,300 m. Section #5 has to be cased before the massive borehole stability problems occur around 6,750 m. The last section down to TD at 7,600 m should be drillable in one section. In case of a failure there is no contingency string available. Section #5 and #6 have the same mud weight window and could be drilled theoretically in one way. But due to the long section (2,300 m) and high pressures, it seems to be better to plan two sections. Figure 32 in Appendix A.3 shows a proposal for the casing sections, the casing setting depth and the mud weight range for each section.

Casing sizes

The experiences of the previous wells showed, that a slim clearance casing program caused problems running casing. As the wells were not continuous vertical, long casing sections with slim clearance were difficult to set in place. Common casing sizes like 24", 18 5/8", 13 5/8", 9 5/8" and 7" should be used. A 5" liner plus 7" tie-back can be used for completion. The chosen casing sizes and specifications are given later in this chapter.

Pressure calculations

Pressure loads (collapse and burst) are calculated by the difference of the external and internal pressure. The net pressures are compared with collapse or burst casing ratings. For the Zistersdorf ÜT3 well three different pressure calculations have been done.

The first one is well evacuation due to mud losses. The mud level drops until the pore pressure and the mud column pressure is in balance. The critical depths for given pore pressure and mud weight are the depths with the lowest evacuation level. The results are given in Table 32.

Section	Depth	MW	Pore Pressure	Level drop
2	3,000 m	1.21 kg/l	1.08 SG	322 m
4	5,300 m	1.98 kg/l	1.88 SG	270 m

Table 32: Well evacuation calculation for Zistersdorf ÜT3

The most dangerous depth is at 5,300 m at the end of Section #4 where the mud level has to drop only 270 m to get in balance with the formation.

The next calculation was done for a cement operation. For this case a cement slurry with higher fluid density (frac gradient density) and the whole annulus filled with cement was assumed. The minimum collapse resistances are given in Table 33.

Section	Depth CS [m]	MW [SG]	Cement [SG]	Min. Collapse resistance [psi]
1	~ 500 m	1.15	1.35	142
2	~ 2,500 m	1.21	1.61	1,424
3	~ 4,300 m	1.43	2.06	3,857
4	~ 5,300 m	1.98	2.40	3,169
5	~ 6,600 m	2.20	2.40	1,879
6	~ 7,600 m	2.20	2.40	2,164

Table 33: Minimum collapse resistance for worst case cementing scenario at Zistersdorf ÜT3

The third analysis was done for the critical overpressure zone from Zistersdorf ÜT1a where the casing collapsed. The 9 5/8" casing collapsed early in 1980 between 4,352 and 4,357 m and was later opened again. Table 34 gives an overview of the specifications and the related gradients.

<table>
<tr><th>Csg</th><th>from [m]</th><th>to [m]</th><th>Length [m]</th><th>Grade</th><th>NW [lbm/ft]</th><th>CR [bar]</th><th>Connection</th></tr>
<tr><td>9 5/8</td><td>0</td><td>3,118</td><td>3,118</td><td>P-110</td><td>47.0</td><td>365</td><td>Buttress</td></tr>
<tr><td>9 5/8</td><td>3,118</td><td>4,396</td><td>1,278</td><td>P-110</td><td>43.5</td><td>304</td><td>Buttress</td></tr>
<tr><td>9 5/8</td><td>4,396</td><td>4,592</td><td>196</td><td>P-110</td><td>47.0</td><td>365</td><td>Buttress</td></tr>
<tr><th colspan="2">MW</th><th colspan="2">Depth</th><th colspan="2">Frac gradient</th><th colspan="2">Calculated Pore pressure</th></tr>
<tr><td colspan="2">1.75 kg/l</td><td colspan="2">4,352 m</td><td colspan="2">2.08 SG</td><td colspan="2">1,051 bar / 2.46 SG</td></tr>
</table>

Table 34: Analysis of 9 5/8" casing collapse at Zistersdorf ÜT1a

Just in the middle section where the collapse occurred, a casing with lower nominal weight/wall thickness was used. This casing has a lower collapse resistance of only 304 bar. The collapse was detected in February 1980, about one month after the great gas kick. At this time a mud weight about 1.75 kg/l was used. This gives an internal pressure of the mud column of 747 bar. Adding the pressure required to collapse the casing gives an annulus/pore pressure of 1,051 bar or 2.46 SG. This is the minimum pressure required for a deforming of the casing.

By chance at the same depths a pore pressure peak of approximately 2.50 SG was record at the PCA log of Zistersdorf ÜT2A (see Figure 25 in Appendix A.2). Two different theories can be assumed here. The first one is, that there is really an extreme overpressured zone (~ 2.50 SG). The other one is, that the gas migrated up from 7,544 m outside the casing, pressure was hold at this formation at about 4,352 m and was later on detected at the second Zistersdorf well.

Casing design calculations

The common casing design calculations are based on collapse, burst and tension loads. These simplified design calculations were done with the API recommended Design factors (DF) and for worst possible conditions which are listed in Table 35 below, Formulas in Appendix A.4.3.

Case	**Design factor**	**Worst possible condition**
Tension and joint strength	$DF_T = 1.8$	- No buoyancy effect
Collapse (external pressure)	$DF_C = 1.125$	- Casing empty on the inside (P_i=0) - No buoyancy effect - Max. mud weight at casing depth
Burst (internal pressure)	$DF_B = 1.1$	- No backup fluid on the outside (P_e=0) - Formation pressure at TD

Table 35: Casing design factors and worst possible conditions

A selected casing should fulfil all three cases - tension, collapse and burst. At first the burst pressure for the worst case was calculated and then the best fitting casing grade was chosen. Then the same was done for the collapse pressure. The casing grade which can handle both requirements was taken - see Table 36.

Section	**Casing [in]**	**Burst* [psi]**	**Available [psi]**	**Collapse* [psi]**	**Available [psi]**	**Best Casing grade**
2	18 5/8	3,844	4,460	4,307	1,620	N-80, 117.5 lbm/ft
3	13 5/8	7,867	10,030	8,755	5,930	HCQ-125, 88.3 lbm/ft
4	9 5/8	14,174	13,770	14,941	14,430	T-95, 75.6 lbm/ft
5	7	18,101	20,780	20,673	20,780	T-95, 57.1 lbm/ft
6	5	20,992	26,250	23,805	27,000	V-150, 24.1 lbm/ft

Table 36: Results of casing design calculations

It's obvious that not all requirements have been fulfilled, although the highest available casing grades were chosen. Due to the great depths it is not possible to match all the requirements. For this reason only the calculated loads without the design/safety factors are listed (marked with *).

At least the requirements for the important sections #5 and #6 have been fulfilled. The safety factors for section #5 are 1.15 and 1.01 (burst / collapse), 1.25 and 1.13 for section #6.

Afterwards the tension loads were calculated and compared, too. All the tension loads are in a safe range for all sections.

The experiences at Zistersdorf ÜT1a have shown, that a reduced casing quality in the middle section of the casing string led to a collapse. For safety reasons no different grades are selected within a casing string.

Casing data

The analysis and results of the previous subjects lead to the selected casing specifications. The chosen casing grades are given in Table 37.

Section	Depth [m]	Bit [in]	Casing [in]	Grade	Nom. weight [lbm/ft]	Coll. Resistance [psi]
1	500	17.5 x 28	24	K-55	163.2	1,000
2	2,500	17.5 x 22	18 5/8	N-80	106.0	1,150
3	4,300	17 1/2	13 5/8	HCQ-125	88.3	5,930
4	5,300	12 1/4	9 5/8	T-95	75.6	14,430
5	6,600	8 1/2	7	T-95	57.1	20,780
6	7,600	6	5	V-150	24.1	27,000

Table 37: Selected casing specifications for Zistersdorf ÜT3

The 18 5/8" casing was changed to a 106.0 lbm/ft grade because the inner diameter of the previous grade was too small for the 17 1/2" bit of the next section.

As not all sections met the requirements, the highest available casing grade was chosen. Also the last section was changed to a 5" diameter due to the rather low collapse resistance of the normally used 4 1/2" casing.

8.1.8 Cement design

For the cement design there are three major questions:

Where?	Hole size/depth, cement setting, volumes
What?	Cement slurries (density, classes)
How?	Cementing techniques

This chapter shows a rough design for the planned casing sections. The tables give an overview of the possible solutions for each section which have different requirements - depth, hardening time, pressure/temperature or the way the cement is set behind the casing.

The casing setting depths were already chosen in the previous chapter. The column height and the calculated slurry volumes are given in Table 38 below. The volumes are calculated with a design factor of 1.02 for the diameter to have some reserves. Of course the first section has to be cemented to surface. At the other sections (except #4) the top of cement is about 100 m above the upper casing shoe to have a suitable overlap. As the lowest sections (#5 and #6) are planned to case with a liner, the 9 5/8" casing (section #4) has to withstand the high pressures in case of a shut-in of the well. Therefore it should be cemented to surface to prevent the casing for a possible burst. This is why this section required the highest cement volume (235 m³).

Section	Casing size [in]	Casing Shoe [m]	Top of Cement [m]	Column Height [m]	Volume [m³]
1	24"	500	Surface	500	60.7
2	18 5/8"	2,500	400	2,100	170.4
3	13 5/8"	4,300	2,900	1,900	129.5
4*	9 5/8"	5,300	Surface	1,100	234.8
5	7" Liner	6,600	5,200	1,400	19.4
6	5" Liner	7,600	6,500	1,000	7.5

Table 38: Cementing heights and volumes

An overview of the available cement classes is given in Table 39. The types are classified by depth, temperature and usage. The possible classes for each section are listed in the last column. As there has no H_2S to be expected, class B is of minor interest. Class C is used when a high early strength is required and could be appropriate for longer sections. Class F and J are considered for extremely high pressures and temperatures and are of interest for the lower sections at Zistersdorf ÜT3.

Class	Depth [ft]	Temperature [°F]	Purpose	Section
A	0 - 6,000	80 - 170	No special	1
B	0 - 6,000	80 - 170	Moderate/high sulphate	1
C	0 - 6,000	80 - 170	High early strength	1, 2
D	6,000 - 10,000	170 - 290	Retarder (deep wells)	2
E	10,000 - 14,000	170 - 290	For HPHT	2, 3
F	10,000 - 14,000	230 - 320	For extremely HPHT	2, 3, 4
G	All depths		Basic well cement	1 - 6
H	All depths		Basic well cement	1 - 6
J	All depths	> 230	For extremely HPHT	4, 5, 6

Table 39: Cementing classes [89]

	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
Class	A	C	E	J	J	J
Density range [SG]	1.12 - 1.18	1.18 - 1.25	1.39 - 1.47	1.92 - 2.04	2.13 - 2.27	2.13 - 2.27
Technique	Inner string	Inner String 3-stage	Inner String 2-stage	Casing	Inner String (Liner)	Inner String (Liner)

Table 40: Selected cement class, densities and techniques

The selected classes and possible density ranges of the cement slurries are given in Table 40. Also the cementing technique is listed.

The first section (24" casing) has no special requirements, so a class A cement can be used. Due to the large diameter, the cement slurry should be pumped through the drill string. The 18 5/8" casing of the second section requires a large cement volume of 170 m³. Therefore a two-stage (or maybe a three-stage) cementing job would be suitable. Due to the high column (2,100 m) a class C cement with an early strength is recommended. The 13 3/8" casing string is set to 4,300 m and the cement column height is also relative high (1,900 m). A two-stage cementing via inner string should be sufficient.

The lower sections require a cement slurry for high pressures and high temperatures. Therefore a Class J cement should be used for sections #4 to #6. The high volume for the 9 5/8" casing to surface (235 m³) permits a pumping through the casing - with float collar and plugs. For both liners (7" and 5") the cement slurry is pumped through drill pipes again. As the clearances are getting smaller, also the volumes are very low for these sections.

8.1.9 Hydraulics

At first the preconditions for the hydraulics calculations have to be mentioned. The biggest challenge for bit and pump performance is the lowest section with the highest friction pressure losses. Therefore the lowest section to TD of 7,600 (24,934 ft) was taken.

General assumptions as done already before are listed in a short way. Again with a mud weight of 2.20 SG (18.36 ppg) and a flow rate of 1,200 l/min (317 gpm) was started. For the mud the Pyro-Drill drilling fluid for HPHT requirements was chosen. The mud rheology of this fluid is described in detail later in Chapter 8.1.10. For the cased hole a friction factor of 0.12 was assumed, 0.20 for the open hole.

The drill string consists of 1,500 ft bottom hole assembly, 900 ft of heavy-wall drill pipes and 22,600 ft of drill pipes. Several configurations were taken from the drill string design calculations (Chapter 8.1.6).

The results of the bit pressure loss calculations are given in Table 41.

Optimum flow rate	343 gpm
Nozzle size - for 5 nozzles	8/32 in
Bit area - 8 1/2 in	56.7 in²
Total flow area	0.2454 in²
Bit pressure loss	3,120 psi
Hydraulic Horsepower	625.9 HHP
HHP per in² of bit	11.0 HHP/in²

Table 41: Hydraulics - Bit pressure loss calculation

The optimum flow rate is 343 gpm (~ 1,300 l/min). This results in a nozzle size of 8/32 in for a 5-nozzle-bit for optimized bit performance and a total flow area of 0.2454 in². The pressure loss at the bit is 3,120 psi or 626 hydraulic horsepower (HHP).

For the pipe and annulus pressure losses the flow conditions were determined first. The entirely drill string shows a turbulent flow regime, the annulus a laminar one. The surface line was assumed 300 ft long. As the pressure losses at the surface have only minor influence compared to the drill string, a similar pressure loss as at the drill pipes was taken.

The analysis showed, that the friction pressure losses within the drill string due to the long well distance of 24,934 ft were incredible high. For this reason several string combinations were tested to find the optimized drill string.

Table 42 shows the system pressure loss calculation results from the best performing drill string combination (#3 of Chapter 8.1.6)

	[psi]	[HHP]	[%]
Surface pressure loss	11	2	0.1
Pipe pressure loss	3,768	756	51
Bit pressure loss	3,120	626	42
Annular pressure loss	510	102	7
Total	7,408	1,486	100
Total with 10 % safety	8,149	1,635	

Table 42: Hydraulics - System pressure loss calculation

The total friction pressure losses are 7,408 psi (511 bar). Due to the long drill string the pressure loss of 3,768 psi (260 bar) is very high. The bit pressure loss is 3,120 psi (215 bar) and has a percentage of 42. The pressure loss at the bit should have at least 50 % of the total losses, but cannot be achieved for the long drill string. It is already optimized for hydraulics and design requirements.

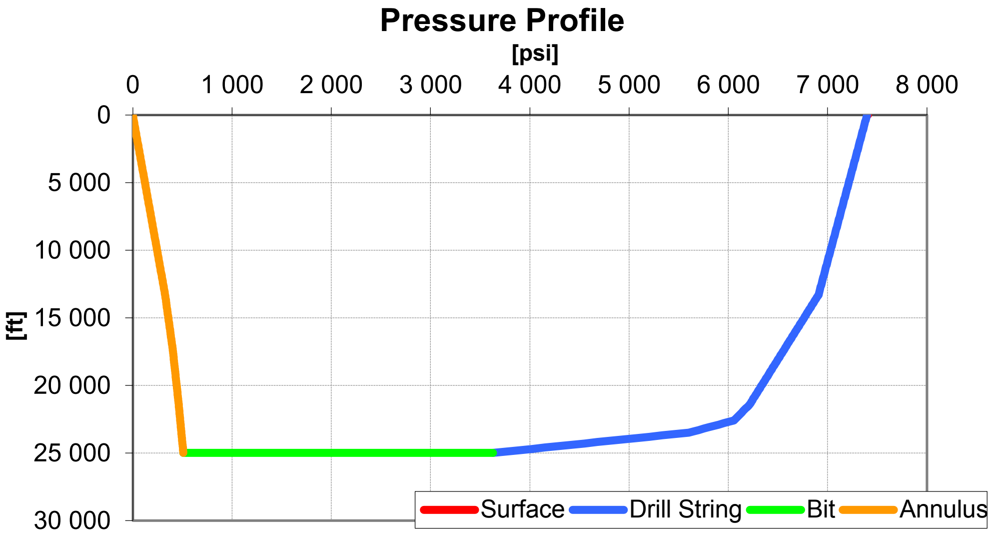


Figure 17: Pressure profile of system pressure losses

The pressure profile in Figure 17 shows the friction pressure losses at surface, within the drill string, at the bit and in the annulus. The surface pressure losses have minor influence and are hardly to see in the right upper part. The bend in the blue line indicates the change of the inner diameter of the drill string.

Type	OD [in]	Grade	Joint	NW [lbm/ft]	ID [in]	Length [ft]
DP	5 1/2"	S-135	FH	21.9	4.778	13,300
DP	5"	S-135	5-1/2 FH	25.6	4.000	8,100
DP	4 1/2"	S-125	NC50 (IF)	20.0	3.640	1,200
HWDP	4 1/2"	HW-95	NC46 (4 IF)	24.3	2.75	900
DC	4 3/4"	AISI 4145H	NC38	45.0	2.500	1,500

Table 43: Selected drill string components for the last section - 6 inch open hole

Several string combinations have been tested for optimum loads and hydraulics. The drill string components for the final design of the last section are given in Table 43.

The 5" drill pipes have the necessary resistance for collapse, burst and tension. But the inner diameter of 4 inch is not optimal for pressure losses. Therefore 5 1/2" drill pipes are used with a diameter of 4.778 in. To be in a safe range for collapse resistance, the pipes can be used down to a depth of 13,280 ft (4,048 m). Below in the 6-inch-open hole a reduced outer diameter is necessary to have enough clearance between drill string and open hole for cuttings transport. Below 6,600 m a 4 1/2" drill pipe S-135 with an inner diameter of 3.640 inch is used. For more stiffness and a smoother reduction of the inner diameter, 4 1/2" heavy-wall drill pipes are placed above the drill collars. The lowest part of the drill string are the 4 3/4" drill collars. The material is a chrome-molybdenum alloy (AISI 4145H) to get a greater inner diameter than common steel collars for better hydraulics. With this string design the last and difficult section can be drilled.

8.1.10 Drilling mud

Mud type

The major challenges for drilling mud in deep environments are thermal stability and pressure resistance. It is absolute essential to protect fluid integrity and keep the rheology properties stable. Already such HPHT drilling fluids have been developed especially for offshore operations. An overview of available water-based HPHT drilling fluids is given in Table 44. Both drilling fluids are polymer-based and developed for extreme environments up to 260°C (500°F) respectively to 316°C (600°F). They were already tested in the field under such stated conditions. Furthermore the required mud weights for a Zistersdorf ÜT3 well can be achieved.

Type	Temperature	Mud weight	Manufacturer	Name
WBM	260°C / 500°F	< 20 ppg	Schlumberger	DURATHERM
WBM	316°C / 600 °F	< 19.4 ppg	Baker Hughes	PYRO-DRILL^{SM}

Table 44: Available water-based HPHT drilling fluids [87 and 88]

There are oil/synthetic-based muds which fulfil these requirements, too. Due to several reasons (environment, detection of hydrocarbons etc.), the equivalent water-based mud should be used.

Mud weight

The mud weight range (up to 2.20 SG or 18.4 ppg) were already discussed in several chapters. The expected mud weights are shown in Figure 32 in Appendix A.2 and listed in Table 33.

The equivalent circulation density (ECD) is defined as the effective density exerted by a circulating fluid against the formation, considering the annular pressure loss. It is an important parameter in wells with a narrow window between pore and fracture pressure. For this reason the ECD was calculated for the critical sections #4, #5 and #6. The values of all sections are in a safe range. The results and the basic parameters are given in Table 45. Used formulas are given in Appendix A.4.2.

Section	Depth [m]	MW [kg/l]	Flow rate [l/min]	P_{pore} [SG]	P_{frac} [SG]	Max. ECD [SG]
4	4,300 - 5,300	1.98	2,000	1.30 - 1.88	2.06 - 2.41	2.04
5	5,300 - 6,600	2.20	1,600	1.88 - 1.93	2.41 - 2.43	2.25
6	6,600 - 7,600	2.20	1,200	1.93 - 1.94	2.43 - 2.44	2.26

Table 45: Equivalent circulating density for Zistersdorf ÜT3

In the lower sections (#4 to #6) equivalent circulating densities between 2.04 SG and 2.26 SG were calculated. The flow rate was adjusted to get the optimal hydraulics for each section. The mud weight is given from the planned casing setting depth and the resulting mud weight ranges. Pore and fracture pressures originate from the formations tests at Zistersdorf ÜT1a and Zistersdorf ÜT2A.

The mud properties for this calculation were taken from the Pyro-Drill drilling fluid of Table 44. The dial readings at 217°C (423°F) and 24,745 psi were 55 cp at 600 rpm and 32 cp at 300 rpm (thus a plastic viscosity of 23 cp and a yield point of 9 lb/100 ft²).

Mud reserves

The highest fluid volume in the well without drill string is 719 m³ (section #3). The active pit system should have a minimum capacity of 180 m³ (25% of highest well volume). At least this volume should be additionally as reserves on the well site.

8.1.11 Well Control

Bottom hole pressure

The bottom hole pressure of the gas formation at Zistersdorf ÜT1a was 1,717 bar or 24,903 psi. This pressure has to be expected again for a Zistersdorf ÜT3 well. Unfortunately there are no formation date like porosity or permeability available.

Pressure calculations

The calculations were done in two parts. For the first part only the formation pressure was taken. At the second part a gas influx and its migration to the surface was considered.

The basic parameters for all calculations are a TD of 7,600 m, a mud weight of 2.20 SG and a reservoir pressure of 1,717 bar. The used formulas are given in Appendix A.4.5. A minimum shut-in drill pipe pressure (SIDPP) of 1,326 psi or 91.4 bar can be expected after shut in the well. A minimum mud weight of 2.32 SG is needed to balance the formation pressure. The maximum allowable shut-in casing pressure (MASP) is 2,255 psi to prevent fracturing of the open hole at the casing shoe (at 6,600 m) - see Table 46.

Depth	MW [SG]	P_{form} [psi]	SIDPP [psi]	Kill Mud [SG]	MASP [psi]
7,600 m	2.20	24,903	> 1,326	> 2.32	2,255

Table 46: Results of pressure calculations for formation pressure only

The value of 2,255 psi (155 bar) of the MASP is relatively low. This relates to the casing shoe at 6,600 m (1,000 m open hole). The maximum allowable shut-in casing pressure would increase with lower depth of the casing shoe (e.g., 160 bar at 6,705 m, 177 bar at 7,500 m). The 9 5/8" casing to surface itself would withstand an internal pressure up to 13,770 psi.

The migration of the gas influx is a major critical issue in well control. Again the same basic parameters have been taken to calculate shut-in casing pressure (SICP) and bottom hole pressure (BHP). Table 47 shows the most relevant heights were the gas influx has migrated to.

Gas migration Depth [m]	SICP [psi]	BHP [psi]	Comment
3,600	**13,652**	37,229	Limit of 9 5/8" casing for burst resistance
4,750	**10,058**	33,635	Limit of 13 5/8" casing for burst resistance
6,580	**4,338**	27,916	Max. SICP of Zistersdorf ÜT1a (300 bar)
7,100	2,713	**26,291**	Limit of formation fracturing (last section)

Table 47: Results of pressure calculation for gas migrating

At a gas migration up to a depth of 3,600 m a shut-in casing pressure of about 13,600 psi is the burst limit for the 9 5/8" casing. Already at 4,750 m is the limit for the 13 5/8" casing, if the casing string would be to surface. At a depth of about 6,580 m the SICP is 300 bar - the maximum build-up pressure at Zistersdorf ÜT1a. But the real dangerous limit is already a migration depth up to 7,100 m where the bottom hole pressure is high enough to frac the formation. These calculations shows the narrow operation ranges and the risk for kicks or blowouts.

Equipment

Sufficient attention should be paid to the safety devices. Drilling pressure control equipment as blow out preventer (BOP), choke manifold or well head should be dimensioned adequately for high pressure operations.

The burst resistance of the 9 5/8" casing is 13,770 psi. So a pressure rating of 15,000 psi is a minimum requirement for this well. Available blow out preventer already reach a rating of 25,000 psi (as the Cameron 13 5/8" 25 ksi BOP). Choke manifolds for operation pressures up to 20,000 psi and temperatures up to 176°C (350°F) are on-hand. The valves of the 2 9/16" pipes itself have a pressure resistance of 30,000 psi.

Also well head systems up to 25,000 psi and 350°F are on the market. Alternative the 30,000 psi well head which was custom-built for Zistersdorf UT1a can be maintained and used. This Christmas tree is standing at the oil & gas educational trail in Prottes.

8.1.12 General considerations

Hydrogen sulphide

As the experience and analysis of the previous wells have shown, no hydrogen sulphide has to be expected and no special H_2S-euipment is needed.

Formation tests

It's absolute necessary to gather as much as possible on formation data. Especially the narrow mud weight window between 4,300 and 5,100 m and the high pressures requires careful drilling. Appropriate number of leak-off tests and core samples should be done to get high quality data of the formations.

Education

Regularly and good trained rig crew is a precondition for any drilling project. The situation with high pressures and high temperatures is an extra challenge and not an everyday job. So further education and training is necessary for ultra-deep wells. All rig staff should be familiar with the well control and safety procedures.

Maintenance

Appropriate maintenance of the rig and the equipment is necessary to avoid incidents. Material inspections of the drill string, drill line etc. should be done periodically. Regularly pressure tests of the safety equipment (BOP, choke manifold etc.) are essential for safe drilling operations.

Managed Pressure Drilling

Managed Pressure Drilling (MPD) is a drilling hazard mitigation technique to allow greater control of the pressure profile. A Rotating Control Device (RCD) establishes a closed and pressurized loop system and enables the control over drilling fluids into and out of the well. This system gives a better monitoring and detect/manage downhole anomalies more easily.

At the previous ultra-deep wells conventional techniques were used but with the opportunity of MPD now, drilling would be faster and more efficient.

8.1.13 Drilling rig

Loads

For the drill pipes only steel pipes (5 1/2", 5" and 4 1/2") were assumed to calculate the maximum weight. So the rig should have a minimum setback capacity of 321 t, including used drill collars and heavy-weight drill pipes.

The maximum hook load is reached under casing operations. To get the maximum value all casing strings were assumed for worst case - to surface and weighted in air. The setting of the 9 5/8" T-95, 75.6 lbm/ft casing (if run from bottom to surface) gives a minimum hook load of 596 t.

Pressure calculation

The hydraulics calculations were already done in Chapter 8.1.9. Some important values which are required for this chapter are given in Table 48, the formulas are given in Appendix A.4.4

Mud weight	Flow rate	Nozzles	Pump capacity	Cuttings transp. velocity
2.20 SG	1,600 l/min	5 x 10/32	415 bar / 1,637 HP	3.1 ft/s (0.94 m/s)
2.20 SG	1,200 l/min	5 x 8/32	511 bar / 1,635 HP	2.5 ft/s (0.76 m/s)

Table 48: Mud pumps calculation

The assumptions were done for a TD of 7,600 m, drilled with a 6" bit with 5 x 8/32 in nozzles for the deepest section. A stand-pipe pressure (SPP) of 511 bar (7,408 psi) can be expected - the required mud pump rating is 1,635 HHP with 10% safety. With this parameters a cuttings transport velocity of 2.5 ft/s can be assumed.

Section #5 to 6,600 m, a flow rate of 1,600 l/min and 5x 10/32" nozzles causes total friction pressure losses of 415 bar (6,025 psi). The required hydraulic horsepower for the pump(s) is 1,637 HHP and a cutting transport velocity of 3.1 ft/s is reached.

Rig selection

The minimum requirements for drilling rig selection are given in Table 49.

Rating	3,000 HP	**Mud pump capacity**	1,637 HP
Hook load	596 t	**SPP**	511 bar (7,408 psi)
Drilling depth	8,000 m	**Active mud system**	> 180 m³
Setback capacity	321 t	**BOP rating**	> 15,000 psi

Table 49: Minimum rig selection specifications

Several onshore rigs in Europe have been searched for. The demand for ultra-deep drilling rigs onshore is rather low, so the availability of such rigs is limited. Also detailed rig data is not always available from the drilling companies. Matching rigs are T-51 from KCA Deutag and Rig 27 from ITAG. Rig T-51 would be preferable due to its higher rating on hook load, casing load and pump capacity.

8.1.14 Summary

For a better overview all the important parameters - which were determined in this chapter - are given in Table 50 below.

Parameter	**Value**
Planned drilling depth	7,600 m
Overpressured zone	4,300 m - 7600 m, 2.0 - 2.4 SG
Temperature gradient	27.6 °K per km
Temperature expected at TD	210 °C (410 °F)
Pressure gradient	0.218 bar/m (0.966 psi/ft)
Pressure expected at TD	1,657 bar (24,030 psi)
Reservoir pressure expected	1,717 bar (24,903 psi)
Mud weight at TD	2.20 SG (18.4 ppg)
ECD	2.25 SG (18.8 ppg)
EMW Reservoir formation	2.30 SG (19.2 ppg)
EMW Formation fracture	2.44 SG (20.4 ppg)
Maximum cement slurry volume	235 m^3
Minimum hook load	596 t
Setback capacity	321 t
Minimum BOP rating	15,000 psi
Optimum flow rate at TD	1,300 l/min (344 gpm)
Stand-pipe pressure expected	511 bar (7,408 psi)
Minimum Mud pump capacity	1,637 HHP (1,221 kW)

Table 50: Summary of relevant parameters of Zistersdorf ÜT3

9 Conclusion

Since Aderklaa UT1a no more ultra-deep wells below 6,000 m have been drilled in Austria. Only these four wells reached the third floor of the Vienna Basin. The wells show the structure and the lithology of the deep underground. Not only has the oil business profited from this exploration wells. Also other branches like geological institutes can use this knowledge.

The Autochthonous Mesozoic has been proven as the source rock of the Vienna Basin. Possible gas reservoirs can be the Malmian marls & Upper carbonates and the Upper Cretaceous (in the Molasse) where the great gas kick at Zistersdorf ÜT1a occurred. The high potential of hydrocarbons in such depths makes the third floor attractive for future exploration activities.

The gas kick has shown the importance of well control. High-pressure equipment is as important as educated and trained rig crews. Formation anomalies becomes more important as the clearances get smaller in such depths.

Formation evaluation (leak-off tests, coring) should be done accurately to know relevant formation properties. The mud density and rheology are an important factor for ultra-deep drilling. The cutting transport over long distances requires the optimum rheology. Accurate measuring and balancing of the mud weight is necessary to get through the critical zones.

High pressure and high temperature are the major challenges of ultra-deep drilling. The temperature resistant for mud and for the equipment has to be given. The material should not be selected for H_2S but for high loads and pressures. The drill string and other equipment should be quality proofed and inspected frequently to avoid incidents.

The drilling principle is still the same but some of the technologies have been developed further. The use of improved technologies like rotary steerable systems or managed pressure drilling can accelerate the drilling progress and increases the chance of success. So HPHT operations are getting more important worldwide.

The thesis has shown the experiences (both positive and negative) from the ultra-deep wells and what can be expected in future deep drilling projects. The preliminary well design for a future Zistersdorf ÜT3 well gives a detailed overview of the well parameters to consider. With state-of-the-art drilling techniques and the determined data this ultra-deep well should be feasible and drilled in a safe way.

The search for oil and gas is ongoing. As more and more reservoirs are on the decline the exploration for hydrocarbons has to go deeper into the earth's crust. The third floor of the Vienna Basin has the precondition and the potential for deep gas. The hydrocarbons are still there and are waiting for discovery.

Abbreviations

ATS - Austrian Schilling (former Austrian currency)

AW - Average weight

BHA - Bottom hole assembly

BHP - Bottom hole pressure

BOP - Blow out preventer

CR - Collapse resistance

CS - Casing shoe

Csg - Casing

DC - Drill collar

DF - Design factor

DM - Deutsche Mark (former German currency)

DP - Drill pipe

ECD - Equivalent circulation density

EMW - Equivalent mud weight

gpm - Gallons per minute

GR - Gamma ray

HHP - Hydraulic Horsepower

ID - Inner diameter

IL - Induction log

LOT - Leak-off test

mD - Millidarcy

MAMW - Maximum allowable mud weight

MASP - Maximum allowable shut-in casing pressure

MD - Measured depth

MMCFD - Millions of cubic feet per day

MOP - Margin of overpull

MPD - Managed pressure drilling

MW - Mud weight

MWD - Measurement while drilling

NW - Nominal weight

OBM - Oil-based mud

OD - Outer diameter

OGIP - Original gas in place

OHT - Open hole test

OOIP - Original oil in place

PDC - Polycrystalline diamond compact

PHA - Packed-hole assembly

POOH - Pull out of hole

ppg - pounds per gallon

RIH - Run in hole

RSS - Rotary steerable system

SG - Specific gravity

SICP - Shut-in casing pressure

SIDPP - Shut-in drill pipe pressure

SPP - Stand pipe pressure

T - Tief / Deep

TD - Total depth

TVD - True vertical depth

UT - Ultratief / Ultra-deep

ÜT - Übertief / Ultra-deep

WBM - Water-based mud

WOB - Weight on bit

Unit Conversion

1 m = 3.28084 ft

1 mi = 1.60934 km

1 inch = 2.54 cm

1 bbl = 0.158987 m^3

1 gal = 3.78541 l

1 ft^3/d = 0.0283167 m^3/d

1 lbm = 0.45359 kg

1 kg/l = 8.345404 ppg

1 bar = 14.5038 psi

1°C = 5/9 (degF – 32)

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Appendix

A.1 Tables

Table 51: Used Drilling rigs - OMV [14, 21]

Internal number	3120	3127	3128
Type	**H-2500**	**H-3000**	**E-3000**
Manufacturer	Ideco SBS	Ideco	Ideco
Year	1962	1977	1982
Capacity 5"DP [m]	7,000	9,500	9,500
Total Power [HP]	3,693	4,140	4,800
Mast type	FVM 143 C 650-30	Lee C Moore 142x30x30	Lee C Moore 142x30x32
Mast height [m]	52.17	55.47	56.08
Substructure height [m]	7.07	9.14	9.75
Substructure load [t]	550	680	680
Max. Hook load [t]	320 (10 lines)	645 (12 lines)	645 (12 lines)
	330 (12 lines)	680 (14 lines)	680 (14 lines)
Max. Crownblock load [t]	435	816	816
Max. Casing load [t]	320	681	681
Setback capacity [t]	2 x 105	2 x 180	2 x 180
Elmago break	7838	7838	7838
Drawworks [HP]	2,150	-	-
Drill line diameter [in]	1 3/8"	1 5/8"	1 5/8"
Motor number & type	3 x D 398 A-TC	4 x D 399 TA (+1)	5 x D 399 TA
Motor power [HP]	2,139	4,140 / 4,920	4,800
Additional motor standby	2 x D 398 (777 HP)		
Mud Pumps	2 x F 1600	2 x FB 1600	2 x T 1600
Tank capacity water [m³]	23.6	44	49.8
Tank capacity mud [m³]	212.8	269.0	329.5

Table 52: Used Drilling rigs - Worldwide [5 - 6, 8, 56, 59, 62 - 63]

Well	KTB	Baden 1, Bertha Rogers 1	Kola SG-3
Name	**UTB 1**	**Loffland Brothers' #32**	**Uralmash-15000**
Manufacturer	Deutag	Loffland Brothers	Uralmash
First Usage	1990	1970	1970
Capacity 5"DP [m]	12,000	9,144	30,000
Length of DP stand [m]	40	-	36
DP material	Steel alloy	Steel alloy	Steel / Aluminiun alloy
Total Power [HP]	12,920	-	8,770
Mast height [m]	83.1	-	68
Derrick base [m]	11.5 x 11.5	-	25.0 x 25.0
Substructure height [m]	11.7	9.14	-
Substructure load [t]	800	650	-
Rig Floor [m]	13.0 x 13.0	-	25.0 x 25.0
Max. Hook load [t]	800	750 (14 lines)	400
Max. Crownblock load [t]	-	950	-
Setback capacity [t]	550	-	-
Drawworks [HP]	3,020	4,050	-
Drill line diameter [in]	1 3/4"	1 5/8"	1 1/2"
Mud Pumps [HP]	2 x 1,686 / 1x 843	2 x 1,350	2 x 1,060
Tank capacity mud [m³]	150	684	-
Mud reserves [m³]	300		-
BOP stack	18 3/4" - 10,000 psi	13 5/8" - 15,000 psi	-

Table 53: Geological Timetable [18, 65 - 66]

Eon	Era	Period		Epoch	mya
Phanerozoikum / Phanerozoic	Känozoikum / Cenozoic	Quartär / Quaternary		Holozän	0.017
				Pleistozän	2.6
		Tertiary	Neogen / Neogene	Pliozän	
				Miozän	23
			Paläogen / Paleogene	Oligozän	
				Eozän	
				Paleozän	65
	Mesozoikum / Mesozoic	Kreide / Cretaceous		Late-	
				Early-	145
		Jura / Jurassic		Malm	161
				Dogger	175
				Lias	200
		Trias / Triassic		Late-	
				Middle-	
				Early-	251
	Paläozoikum / Paleozoic	Jung- / Late	Perm / Permian	Zechstein	
				Rotliegendes	299
			Karbon / Carboniferous	Stephan	
				Westfal	
				Narnur	
				Vise	
				Tournai	359
		Alt- / Early	Devon / Devonian	Late-	
				Middle-	
				Early-	416
			Silur / Silurian	Pridoli	
				Ludlow	
				Wenlock	
				Liandovery	444
			Ordovizium / Ordovician	Ashgill	
				Caradoc	
				Liandeilo	
				Lianvirn	
				Arenig	
				Tremadoc	488
			Kambrium / Cambrian	Late-	
				Middle-	
				Early-	542
Präkambrium / Precambrian	Proterozoikum / Proterozoic				2,500
	Archaikum / Arcean				3,800
	Hadaikum / Hadean				4,600

Table 54: Casing data Zistersdorf ÜT1a, Zistersdorf ÜT2Aa [22]

Well	Type	Bit size in.	Drilled to m	Csg Size in.	From m	To m	Grade	NW lb/ft	ID in.	WT in.	Connection	CR bar	BR bar
ZiUET1		23	511	18 5/8	0	509	J-55	96.5	17.655	0.485	BUTT	61	176
		17 1/2	2,983	13 3/8	0	2981	N-80	68	12.415	0.480	BUTT	157	353
				9 5/8	0	3,117.75	P-110	47	8.681	0.472	BUTT		
				9 5/8	3,117.75	4,395.97	P-110	43.5	8.755	0.435	BUTT		
		12 1/4	4,598	9 5/8	4,395.97	4592	P-110	47	8.681	0.472	BUTT	373	514
	Liner added			7	4,412.63	5,023.68	V150	38	5.920	0.540	BDS P110	1,352	1,424
	Liner lost	8 1/2	**6,851**	7	5,023.68	6,705.40	V150	38	5.920	0.540	BDS V150	1,352	1,424
ZiUET1a	LH			9 5/8x7	4,296.90	4,309.04		35					
	Liner	5 27/32	**7,544**	4 1/2	4,309.04	4,909	P-110	22.18	3.476	0.512	BDS		
				7	0	3,297.92	C-90	38	5.920	0.540	BDS		
				7	3,297.92	3,722.16	P-110	32	6.094	0.453	BDS		
	Tie back			7	3,722.16	4,298.12	P-110	35	6.004	0.498	BDS		
ZiUET2	Stand pipe			32	0	26	St-00			0.394			
		17 1/2 x 24 x 29	504	24 1/2	0	499	J-55	140	23.425	0.531	BTC		
		23	**1,910**	18 5/8	0	1,910	J-55 + N-80	96.5	17.655	0.485	BTC		
ZiUET2A	Stand pipe			32	0	26	St-00			0.394			
		23 x 29	265	24 1/2	0	262	J-55	140	23.425	0.531	BTC	34	251
		23	1,675	18 5/8	0	1,673	J-55 + N-80	96.5	17.655	0.485	BTC	251	60
		17 1/2	4,340	14	0	4,336	MW-130	97		0.693	BDS-S	777	409
	Tie back			10 3/4	0	4,142	MW-125	84		0.793	MUST-M	1,113	1,065
	Liner	12 1/4	6,000	10 3/4	4,142	5,997	MW-125	84		0.793	MUST-M	1,113	1,065
	Liner	8 3/4	7,221	7 5/8	5,795	7,220	MW-125	56		0.772	MUST-M	1,604	1,561
				5	6,982	x	MW-125	27.38		0.650	BDS-S	1,944	2,123
	Liner	6	**8,553**	5	x	7,623	AF22/130	34.24		0.579	BDS-S	1,832	1,973
ZiUET2Aa		9	**7,007**										

NW…Nominal weight, ID…Inner diameter, WT…Wall thickness, CR…Collapse Resistance, BR…Burst Resistance

Table 55: Casing data Maustrenk ÜT1a, Aderklaa UT1b [22]

Well	Type	Bit size in.	Drilled to m	Csg Size in.	From m	To m	Grade	NW lb/ft	ID in.	WT in.	Connection	CR bar	BR bar
MauUET1	Stand pipe			32	0	16.9							
		23 x 29	92	24 1/2	0	90	J-55				BUTT		
				18 5/8	0	180	N-80	96.5	17.655	0.485	BUTT		
		23	733	18 5/8	180	733	J-55	96.5	17.655	0.485	BUTT	61	176
		17 1/2	1,913	13 3/8	0	1,913	P-110	68	12.415	0.480	BUTT	164	485
		12 1/4	4,823	10	0	4,823	MW-130				BDS		
		8 3/4	**6,285**										
MauUET1a	Liner	8 3/4	6,240	7 5/8	4,652.70	6,239.50	MW-125	46.25			BDS-S		
				5	4,633.50	5,500	MW-125	27.38			BDS-S		
	Liner	6 1/4	**6,563**	5	5,500	6,498.50	MW-125	30.24			BDS-S		
				7	0	3,355	MW-95S			0.843	BDS-S		
	Tie back			6 5/8	3,355	4,633.50	P-110			0.654	BDS-S		
AdUT1	Stand pipe			32	0	29		121	31.300				
		23 x 29	502	24 1/2	0	501	J-55	140	23.425	0.531	BUTT		
		23	2,001	18 5/8	0	1,999.40	N-80	96.5	17.655	0.485	BUTT		
				14	0	3,347.65	MW115	103	12.559	0.720	BDS		
				14	3,347.65	3,579.42	MW130	97	12.614	0.693	BDS		
				14	3,579.42	4,459.98	MW115	103	12.559	0.720	BDS		
		17 1/2	4,474	13 3/8	4,459.98	4,473.43	P110	68	12.415	0.480	BDS	164	485
		12 1/4	**5,328**										
AdUT1a				10 3/4	0	9.67	MW125	84	9.161	0.793	MUST-S		
		12 1/4	6,119	10	9.67	6,119	MW130	53.15	8.938	0.531	BDS		
		8 3/4	**6,630**										
AdUT1b		8 1/2	**6,256**										

NW…Nominal weight, ID…Inner diameter, WT…Wall thickness, CR…Collapse Resistance, BR…Burst Resistance

Table 56: Well stratigraphy [22]

From m	To m	Tectonic name	Formation age	Formation name
Zistersdorf ÜT1a				
0	402	Vienna Basin	Pontian	
402	1,198	Vienna Basin	Pannonian	
1,198	2,415	Vienna Basin	Sarmatian	
2,415	4,885	Vienna Basin	Badenian	
4,885	5,563	Waschberg Zone	Paleogene	
5,563	5,986	Steinitz Unit	Malm	Malmian Marls
5,986	7,206	Waschberg Zone	Paleogene	
7,206	7,512	Molasse Zone	Paleogene	
7,512	7,544	Autochthonous Mesozoic	Upper Cretaceous	
Zistersdorf ÜT2A				
0	407	Vienna Basin	Pontian	
407	1,203	Vienna Basin	Pannonian	
1,203	2,293	Vienna Basin	Sarmatian	
2,293	4,745	Vienna Basin	Badenian	
4,745	5,440	Waschberg Zone	Paleogene	
5,440	5,840	Steinitz Unit	Malm	Malmian Marls
5,840	7,097	Waschberg Zone	Paleogene	
7,097	7,455	Molasse Zone	Paleogene	
7,455	7,505	Molasse Zone	Eocene	
7,505	7,566	Autochthonous Mesozoic	Upper Cretaceous	
7,566	7,631	Autochthonous Mesozoic	Malm	Malmian Upper Carbonates
7,631	8,553	Autochthonous Mesozoic	Malm	Malmian Marls
Maustrenk ÜT1a				
0	379	Vienna Basin	Badenian	
379	490	Vienna Basin	Neogene	
490	679	Flysch - Sulz Unit	Maastrichtian	
679	1,215	Flysch - Zistersdorf Unit	Eocene	Steinberg Flysch
1,215	1,950	Flysch - Zistersdorf Unit	Paleocene	Glauconite Sandstone
1,950	2,725	Flysch - Zistersdorf Unit	Upper Cretaceous	
2,725	2,926	Flysch - Gösting Unit	Eocene	Steinberg Flysch
2,926	3,690	Flysch - Gösting Unit	Paleocene	Glauconite Sandstone
3,690	4,250	Flysch - Gösting Unit	Upper Cretaceous	
4,250	4,780	Flysch - Gösting Unit	Paleocene	
4,780	5,350	Steinitz Unit	Eocene	
5,350	6,050	Waschberg Zone	Oligocene	
6,050	6,240	Waschberg Zone	Malm	Malmian Marls
6,240	6,306	Waschberg Zone	Oligocene	
6,306	6,312	Waschberg Zone	Malm	Malmian Upper Carbonates
6,312	6,410	Waschberg Zone	Oligocene	
6,410	6,563	Autochthonous Mesozoic	Malm	Malmian Marls

Aderklaa UT1a

0	605	Vienna Basin	Pontian	
605	977	Vienna Basin	Pannonian	
977	1,690	Vienna Basin	Sarmatian	
1,690	2,700	Vienna Basin	Badenian	
2,700	2,885	Vienna Basin	Karpatian	Aderklaa Conglomerate
2,885	3,607	Vienna Basin	Karpatian	Aderklaa Beds
3,607	3,740	Calcareous Alps	Jurassic	
3,740	3,795	Calcareous Alps	Lower Cretaceous	
3,795	3,910	Calcareous Alps	Jurassic	
3,910	4,005	Calcareous Alps	Rhaetian	Koessen Beds
4,005	4,035	Calcareous Alps	Norian	Main Dolomite
4,035	4,060	Calcareous Alps	Rhaetian	Koessen Beds
4,060	4,100	Calcareous Alps	Norian	Main Dolomite
4,100	4,145	Calcareous Alps	Carnian	Opponitz Beds
4,145	4,172	Calcareous Alps	Rhaetian	Koessen Beds
4,172	4,350	Calcareous Alps	Jurassic	
4,350	4,855	Flysch	Eocene	Agsbach Beds
4,855	5,100	Flysch	Lower Eocene	Hois Beds
5,100	5,432	Flysch	Upper Cretaceous	Kaumberg Beds
5,432	6,050	Helveticum	Eocene	Steinitz Unit
6,050	6,228	Autochthonous Mesozoic	Malm	Malmian Marls
6,228	6,252	Autochthonous Mesozoic	Malm	Altenmarkt Beds
6,252	6,630	Bohemian Massif	Early Palozoic	

Table 57: Cores [22 - 24, 27, 32, 33, 35]

From [m]	To [m]	Length [m]	Core description
Zistersdorf ÜT1a			
4,125	4,130	5.0	Sandy dark-grey marly clay
4,585	4,590	5.0	Dark-grey marly clay with mica
4,694	4,703	9.0	Grey to dark-grey marly clay
4,760	4,768	8.0	Dark marly clay and grey sandstone
4,895	4,897	1.8	Grey-green marly clay with calcite crevices
5,069	5,074	3.5	Red clay to marly clay with green layers
5,248	5,252	2.5	Middle-grey to brown mudstone and sandstone
5,335	5,340	3.5	Middle-grey marly clay and sandstone
5,453	5,457	1.6	Grey marly clay
5,601	5,606	5.0	Grey marly clay and breccia
5,670	5,675	5.0	Black micatized marly clay
5,735	5,744	9.0	Dark-grey micatized marly clay
5,977	5,984	7.0	Black friable marly clay
6,193	6,199	1.3	Soft friable marly clay
6,292	6,297	1.3	Marly sandstone and marly clay
6,428	6,432	4.0	Marly clay with sandstone break
6,509	6,514	5.0	Grey-green to black mudstone
6,579	6,584	5.0	Mudstone with aposandstone break
6,653	6,658	4.0	Mudstone with sandstone break
6,794	6,798	2.5	Mudstone with inner breccia
6,750	6,752	1.0	Sandstone and marly clay
6,860	6,862	1.5	Clay slate and sandstone
7,017	7,023	4.6	Mudstone
7,125	7,131	2.1	Mudstone with sandstone break
7,209	7,216	6.4	Marly clay with lime-sand break
7,287	7,294	6.3	Carbonate sandstone with shale break
7,358	7,366	7.7	Breccia
7,511	7,519	8.0	Dark-grey marly clay
Zistersdorf ÜT2A			
4,500	4,503	2.5	Grey marly clay
4,586	4,591	5.0	Dark-grey marly clay
5,584	5,587	2.1	Fragile marly clay
5,883	5,888	5.0	Green to black mudstone
5,995	6,000	5.0	Mudstone with sandstone components
6,005	6,014	4.0	Dark-grey to black mudstone (Flysch)
6,014	6,023	4.5	Dark-grey to black mudstone (Flysch)
7,085	7,087	1.2	Black mudstone, marly lime and sandstone
7,120	7,127	7.0	Marly clay with sandstone break
7,184	7,193	9.0	Breccia, sandstone and marly clay alternating
7,251	7,256	5.0	Breccia, sandstone, mudstone and dolomite
7,347	7,354	4.7	Dark-grey marly clay
7,400	7,406	6.2	Sandy marly clay with glauconite
7,533	7,538	5.0	Breccia
7,601	7,609	8.0	Calcite
7,704	7,712	3.6	Dark-grey marly clay and marlstone with calcite crevices
8,019	8,025	4.5	Marlstone

8,153	8,161	7.4	Marly clay
8,544	8,553	7.0	Marly clay

Maustrenk ÜT1a

4,815	4,820	4.0	Marly clay - Mudstone
5,215	5,220	4.7	Fine to coarse-grained sandstone, mudstone-slate
5,427	5,432	5.0	Middle to coarse-grained sandstone with black mudstone
5,674	5,679	3.0	Streaky marly clay, below aposandstone
5,898	5,903	4.4	Fine sandstone, siltstone with calcite crevices
6,073	6,077	3.8	Marlstone, dark-grey calcareous marl
6,273	6,278	5.0	Clay slate, marlstone, dark-grey siltstone
6,265	6,272	6.5	Breccia, marly clay
6,298	6,306	4.0	Dark-grey marly clay with brown lime
6,543	6,552	9.0	Dark-grey marlstone with fine mica

Aderklaa UT1a / UT1b

3,742	3,745	3.0	Black disordered clay slate with coloured mudstone and sandstone
4,044	4,047	3.0	Black breccia and dolomite lime with marly clay
4,816	4,819	1.3	Grey aposandstone and dark-grey clay slate with calcite veins
5,583	5,588	4.8	Breccia of dark-grey clay slate, green quartzite and calcite
5,963	5,968	5.0	Dark-grey to green mudstone
6,078	6,083	5.0	Black marlstone
6,233	6,242	9.0	Middle to dark-grey endogen lime breccia
6,262	6,271	8.8	Fine-grained dark-grey hard slate (Crystalline)
6,488	6,497	9.0	Dark-grey to black phyllonite
6,625	6,630	4.0	Dark-grey to black quartzite-sericite-slate
6,220	6,229	9.0	Dark-brown marly clay and wackestone
6,229	6,238	9.0	Endogen lime breccia, wackestone and rudstone
6,238	6,247	8.8	Endogen lime breccia, wackestone and rudstone
6,247	6,256	9.0	Biotite-chlorite-sericite-slate of Bohemian Massif

A.2 Figures

Figure 18: Surface map of the Miocene of the Vienna Basin [19]

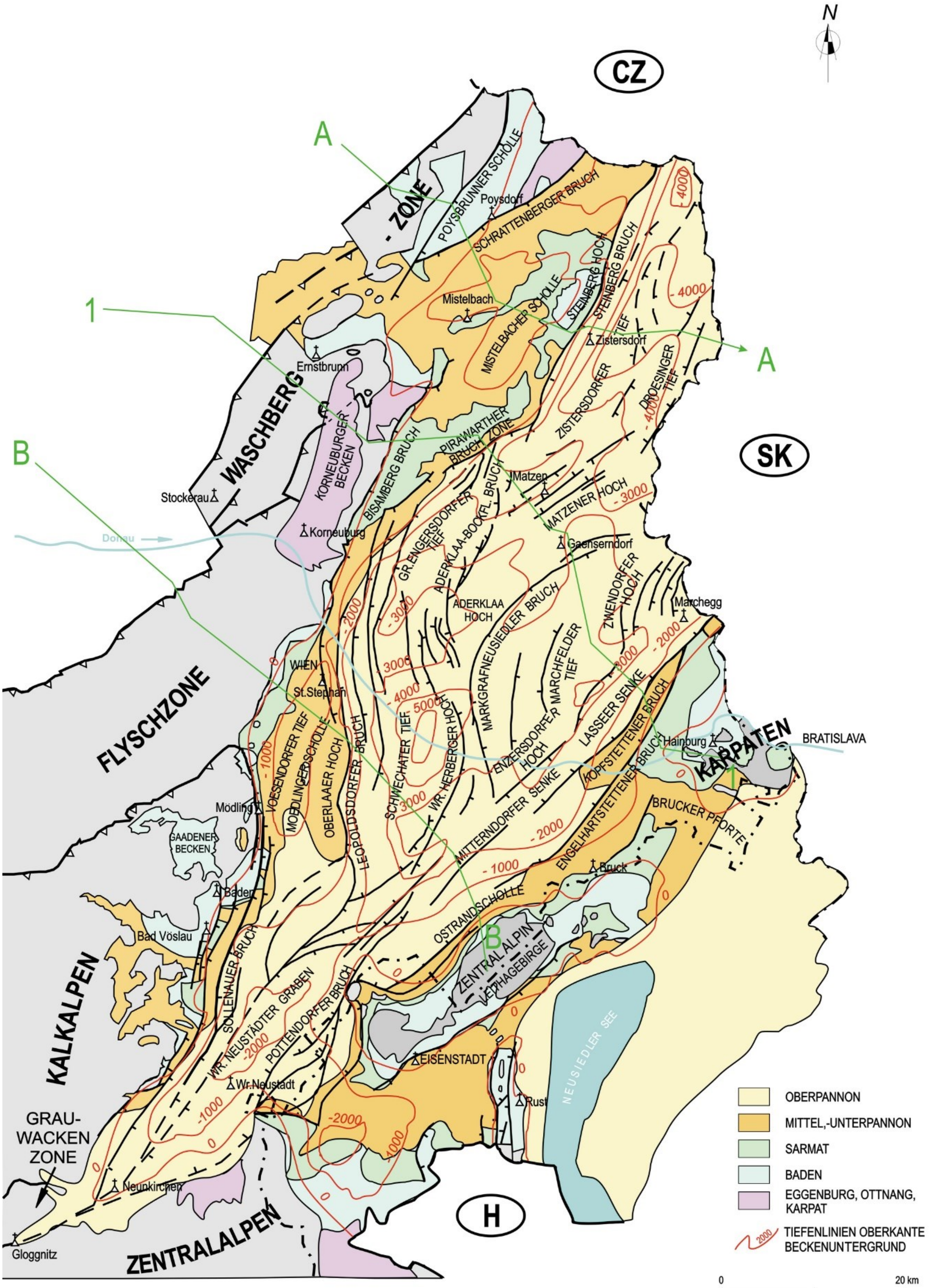


Figure 19: Relief of the cauldron subsidence – Structure map of the underground [19]

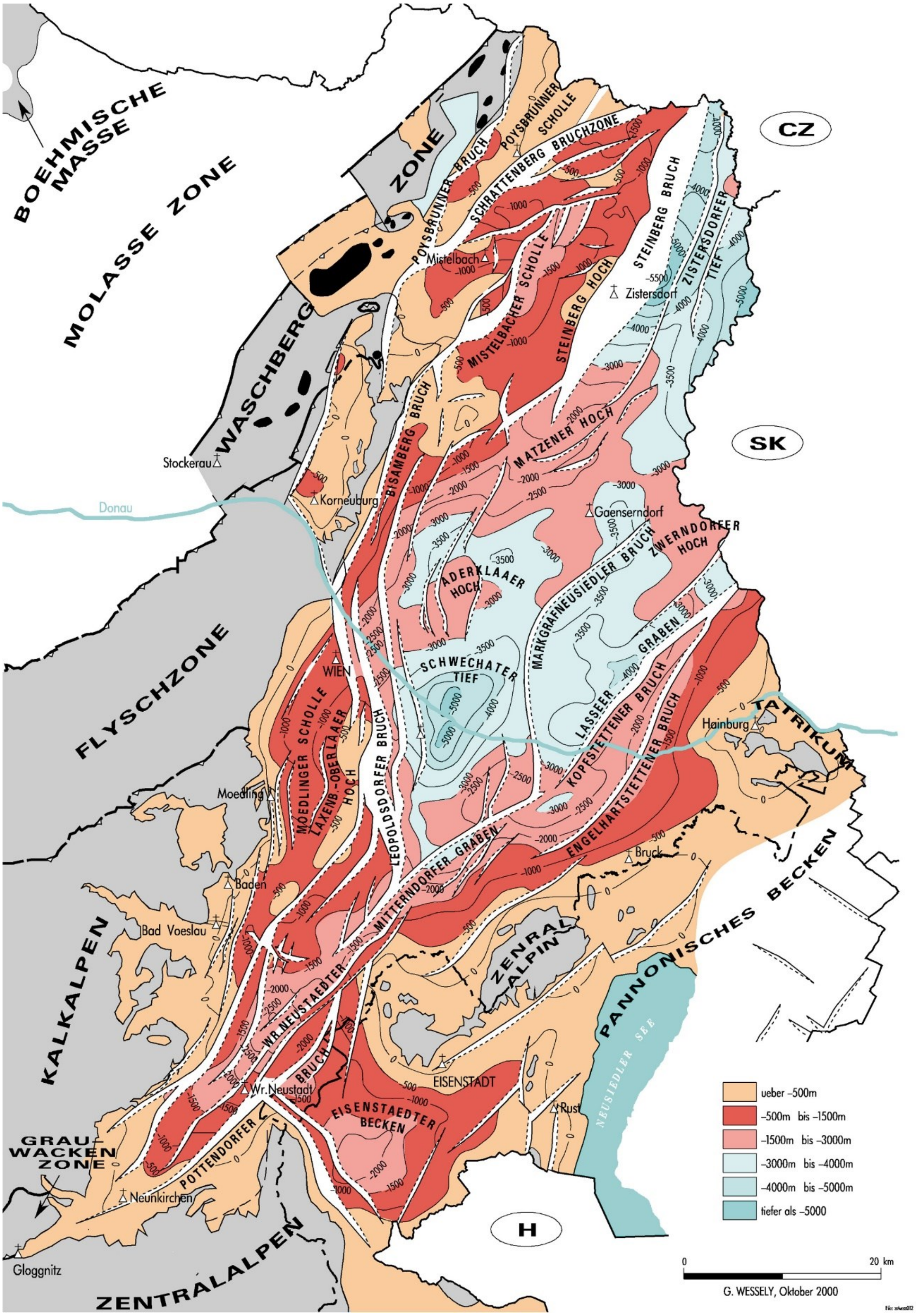


Figure 20: Sedimentary deposition in the Vienna Basin [19]

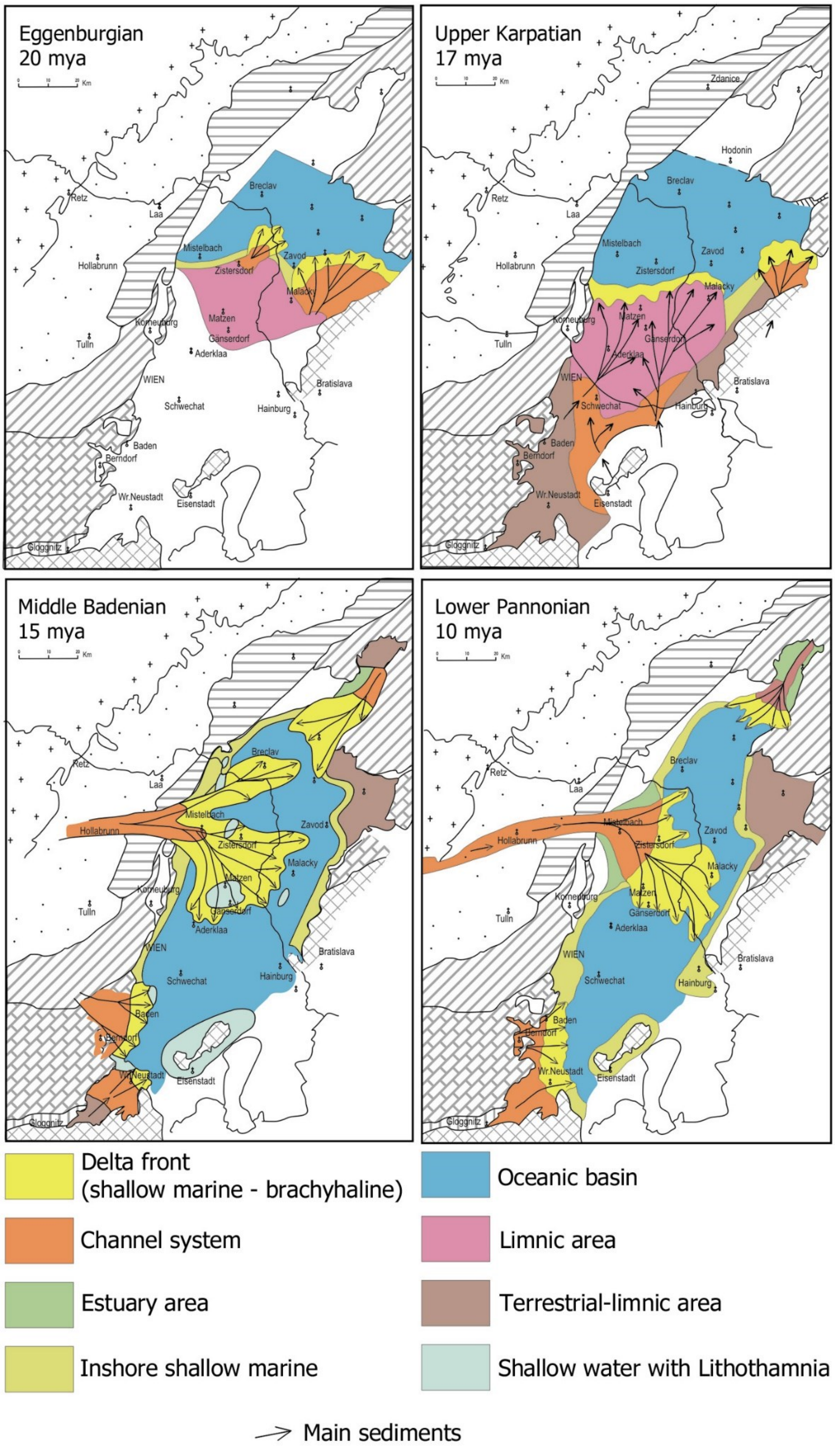


Figure 21: The biggest fault - Depth profile of the North Vienna Basin [19]

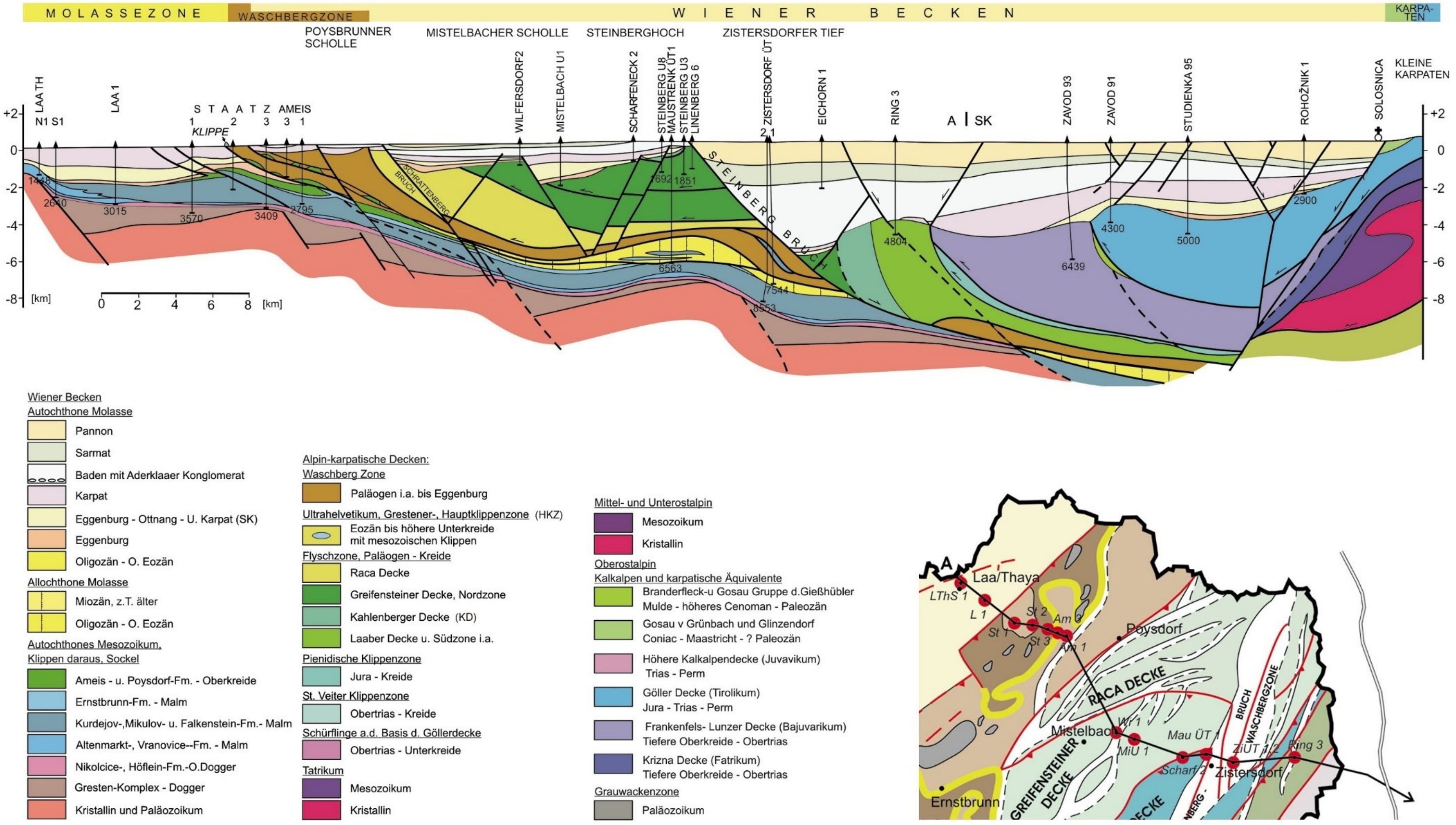


Figure 22: Calcareous Alps under lowland – Cross-section Aderklaa [19]

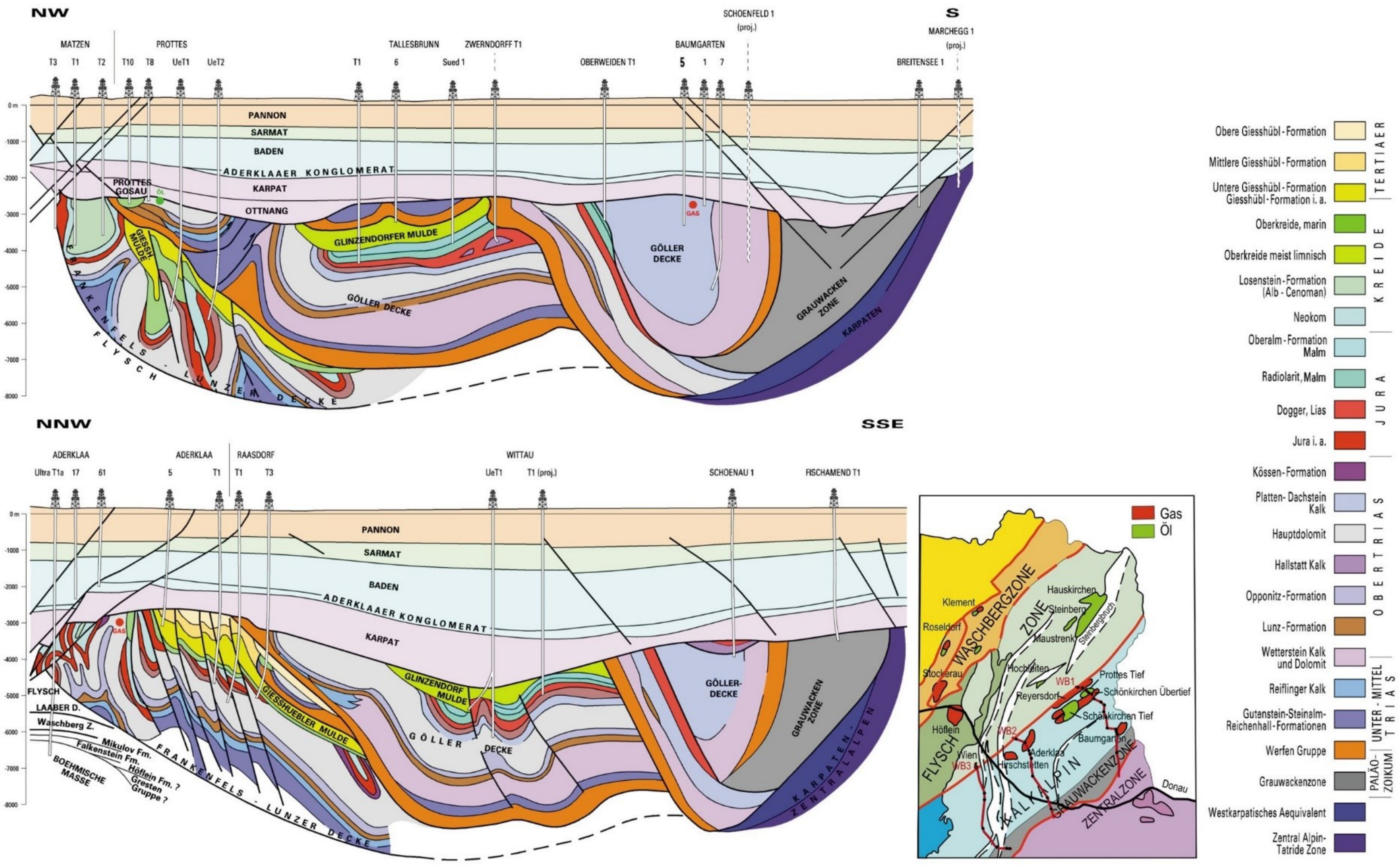


Figure 23: The Flysch zone in Lower Austria [19]

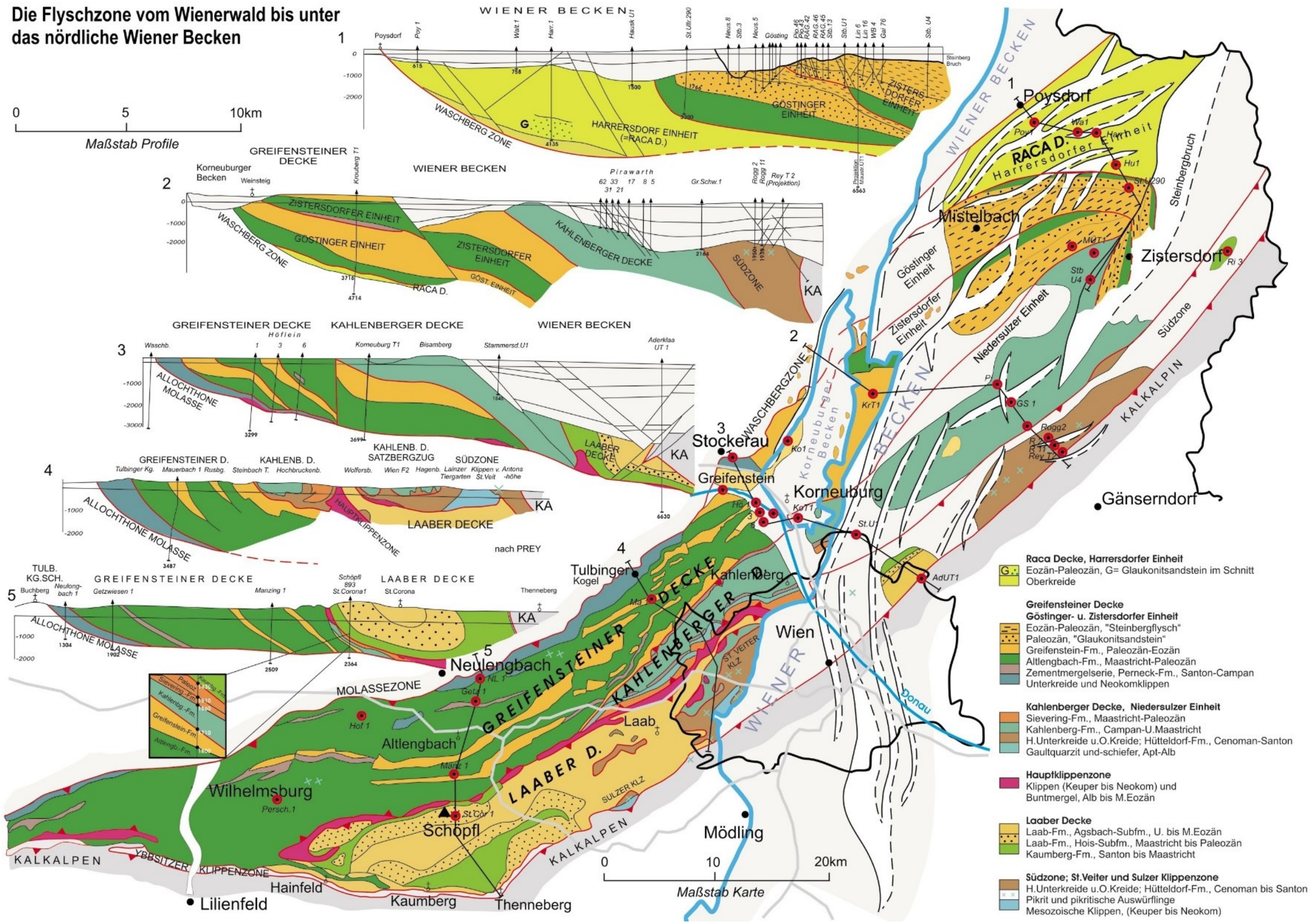


Figure 24: Well trajectory of the Kola SG-3 well [64]

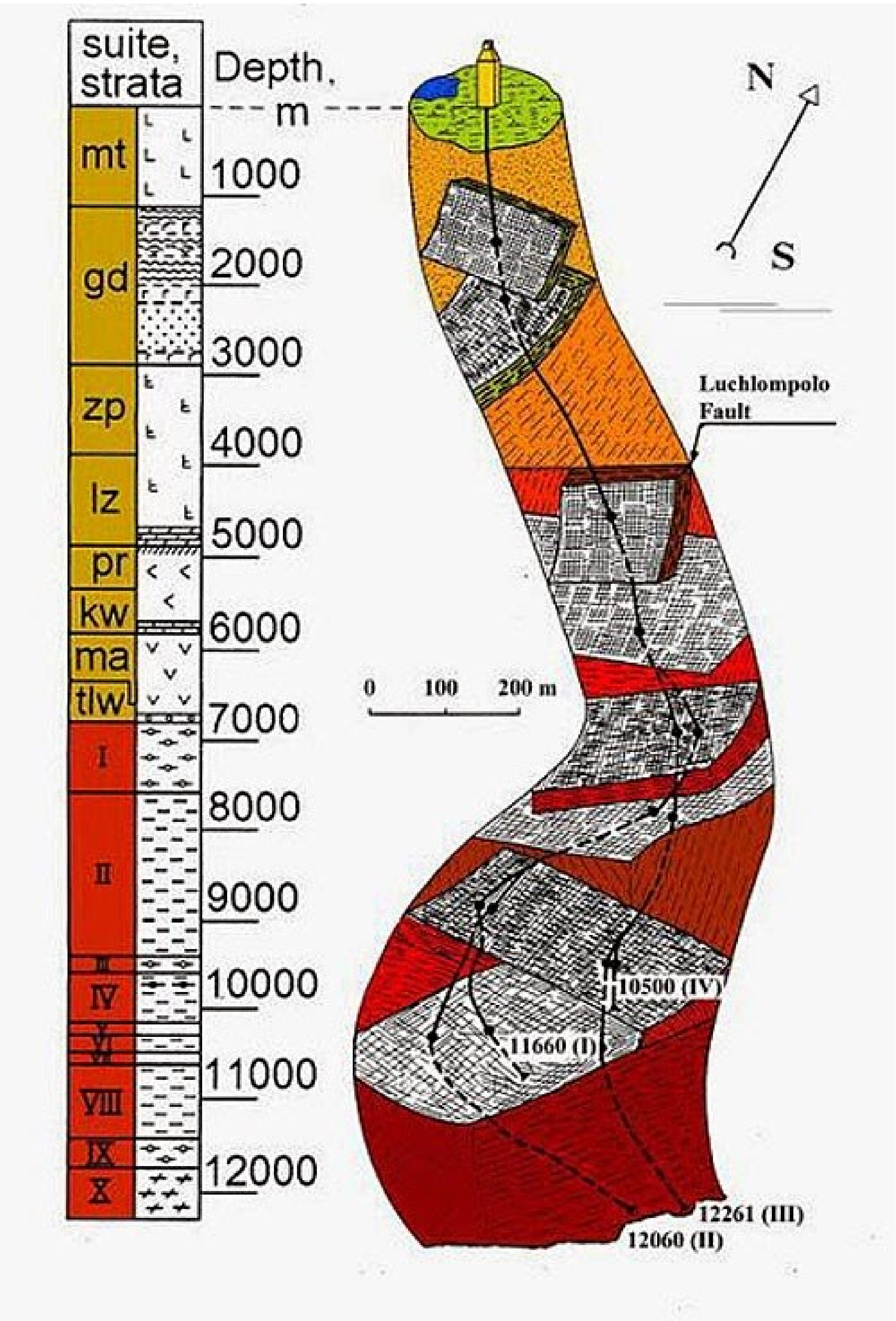
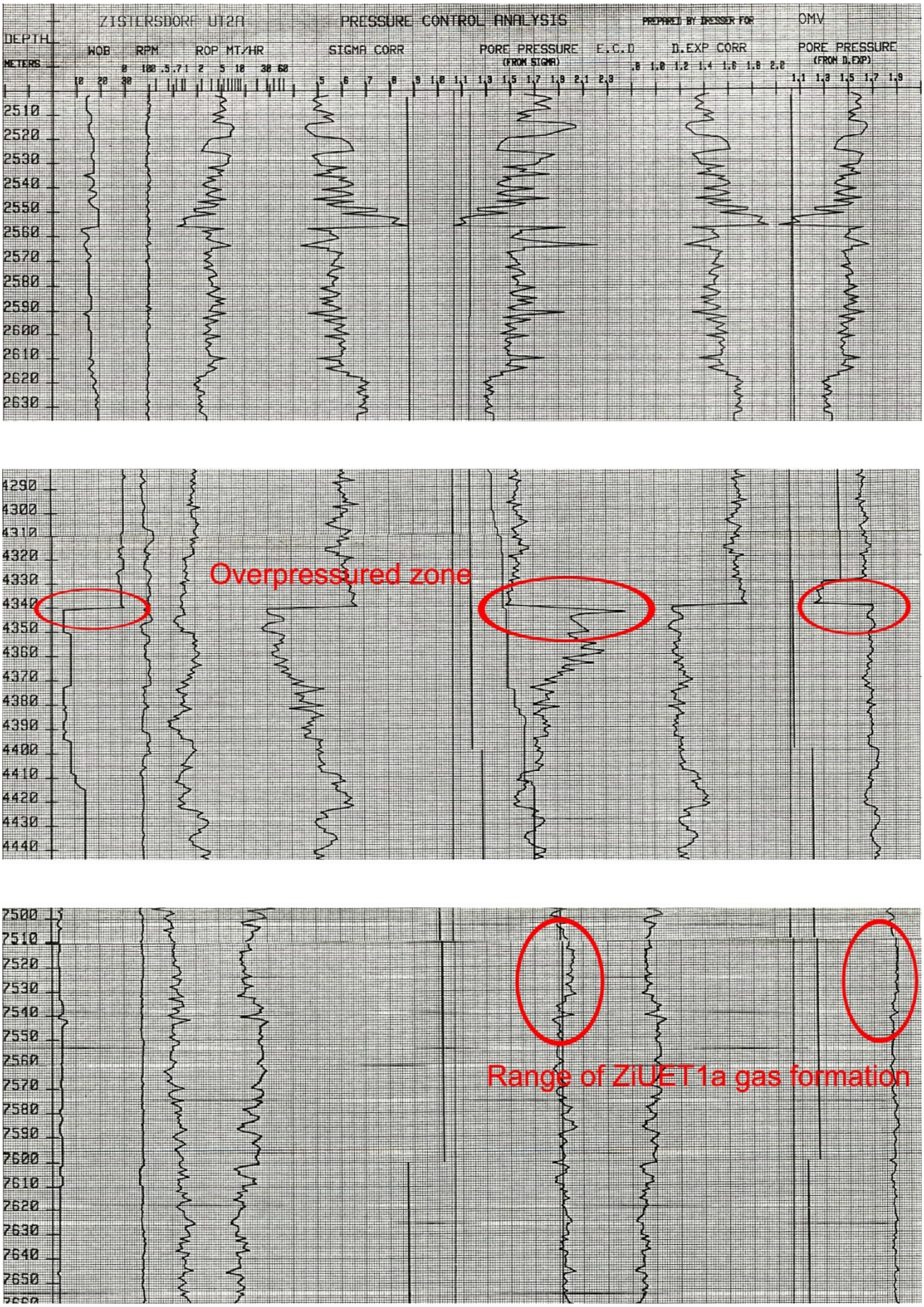


Figure 25: Pressure Control Analysis of Zistersdorf ÜT2A [77]



A.3 Charts

Figure 26: Mud weight vs. depth Zistersdorf ÜT1a [23]

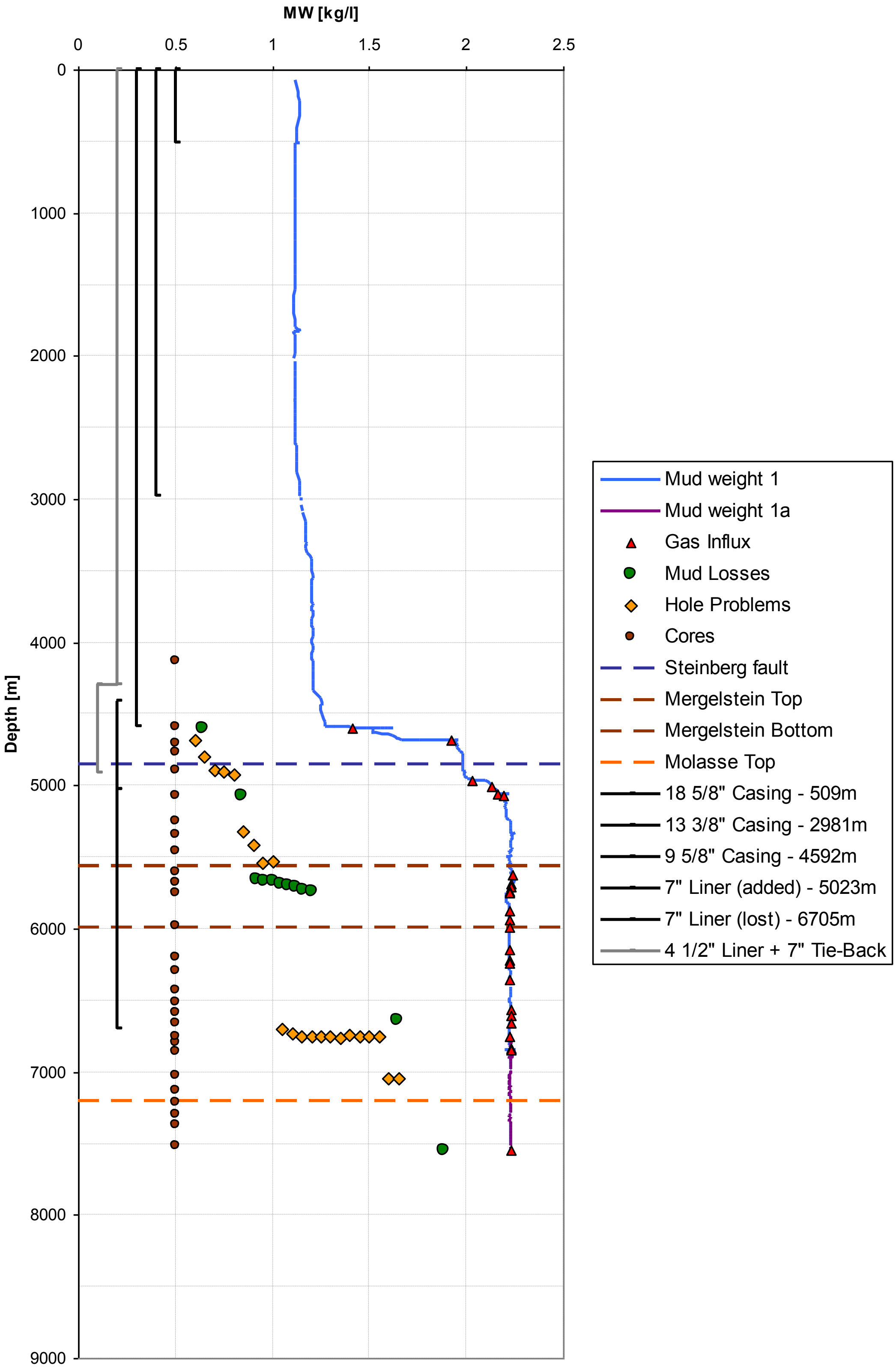


Figure 27: Mud weight vs. depth Zistersdorf ÜT2A [27]

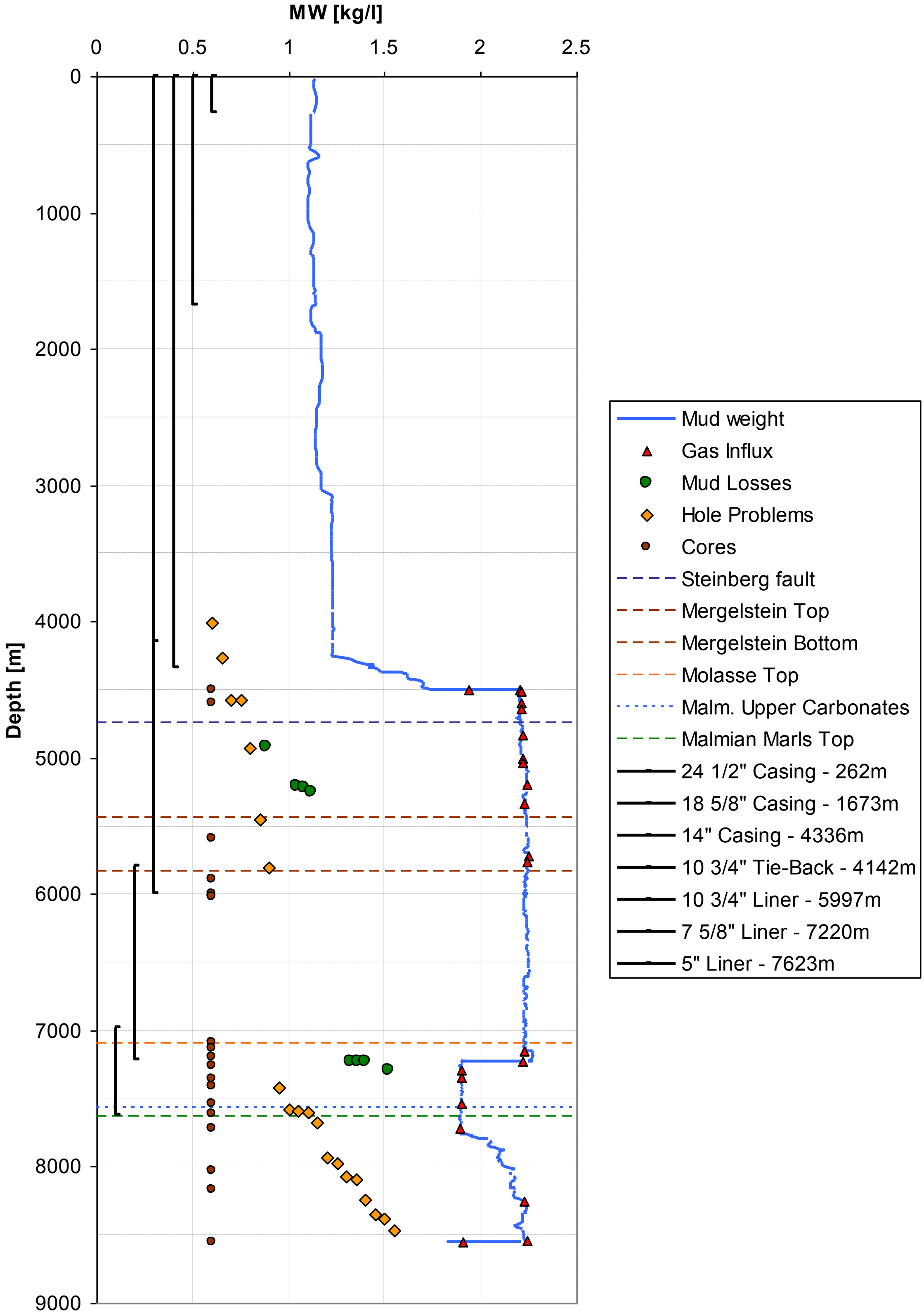


Figure 28: Mud weight vs. depth Maustrenk ÜT1a [32]

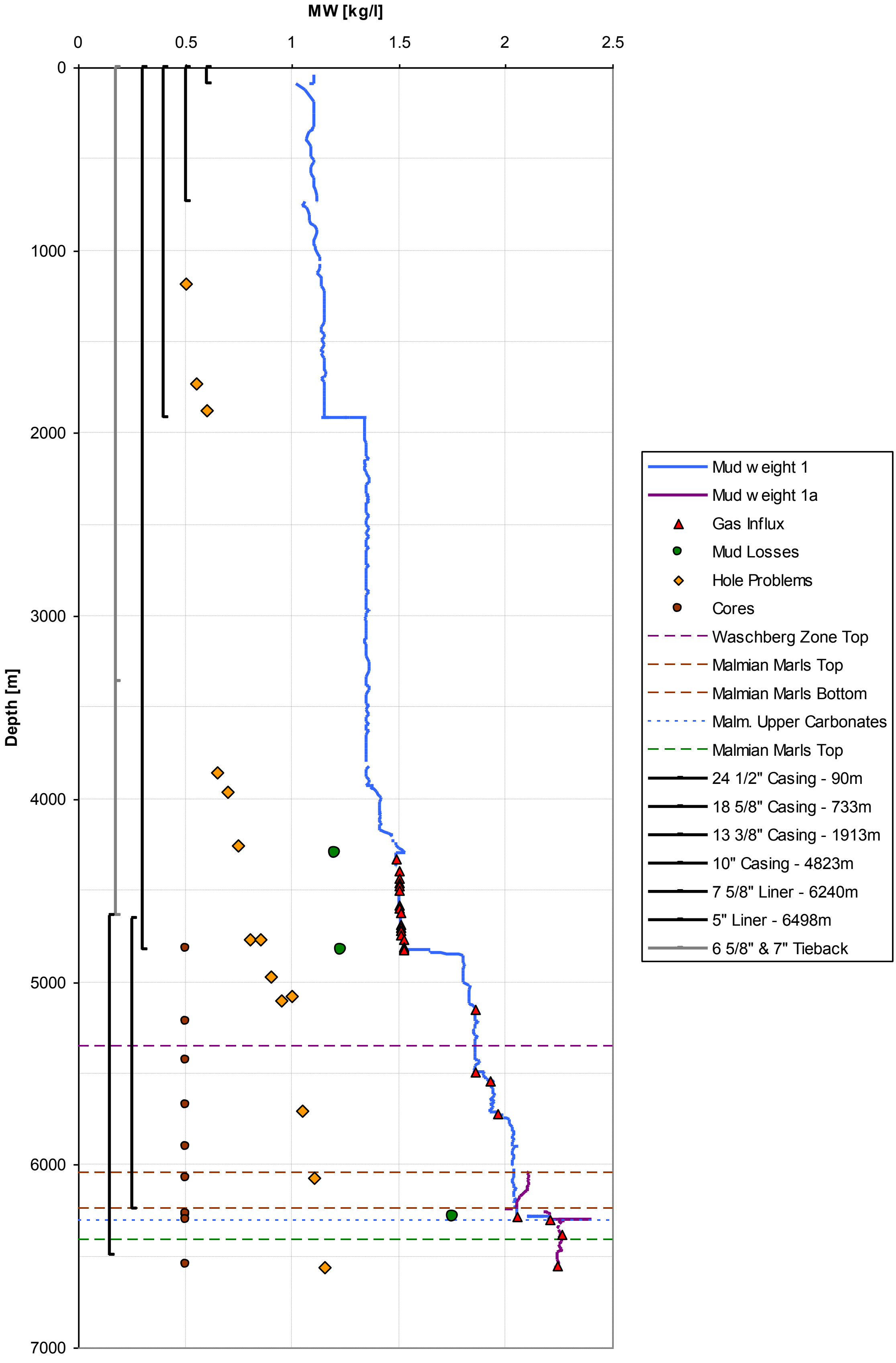


Figure 29: Mud weight vs. depth Aderklaa UT1a [22]

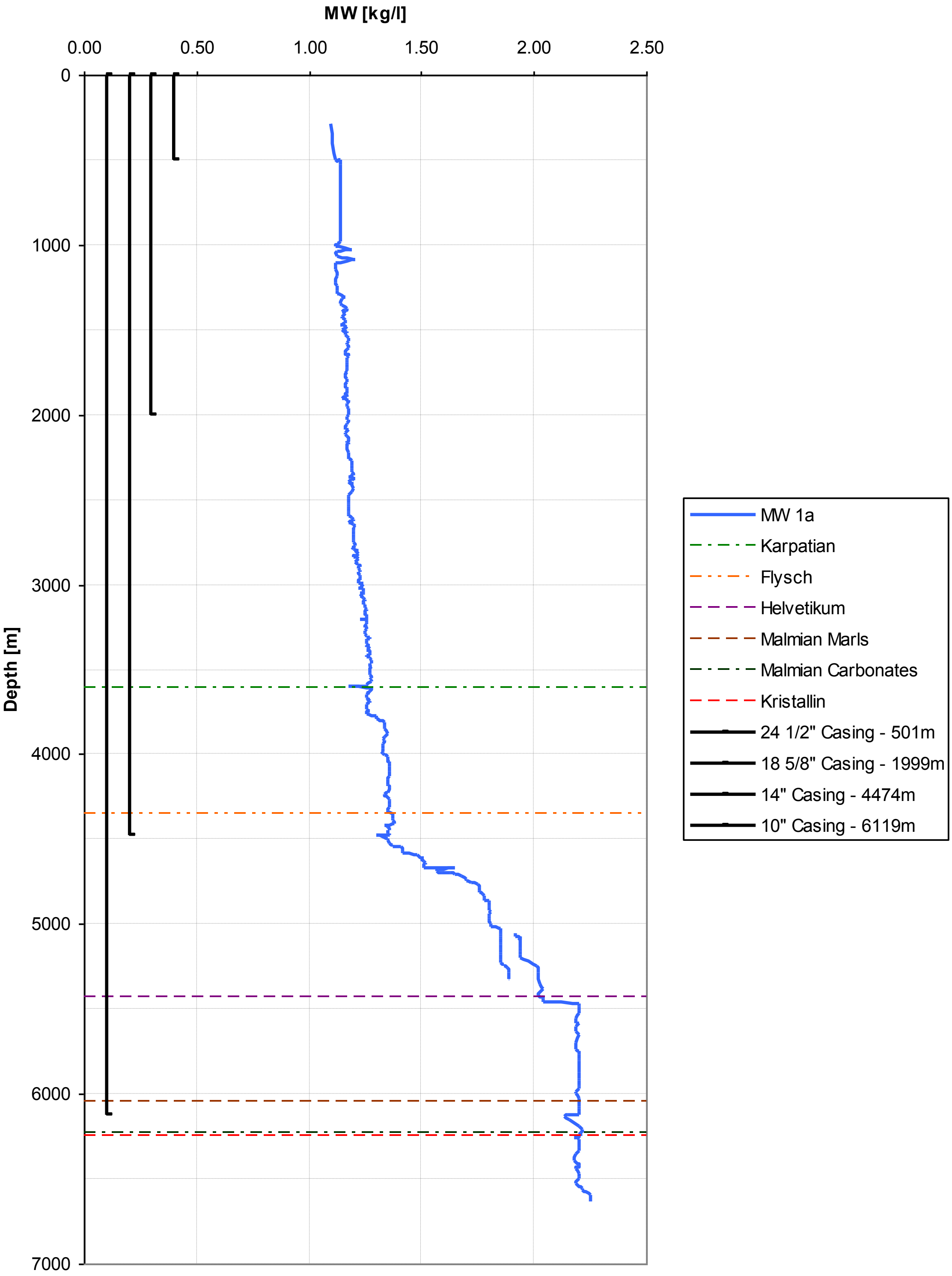


Figure 30: Mud weight window Zistersdorf ÜT1a [23]

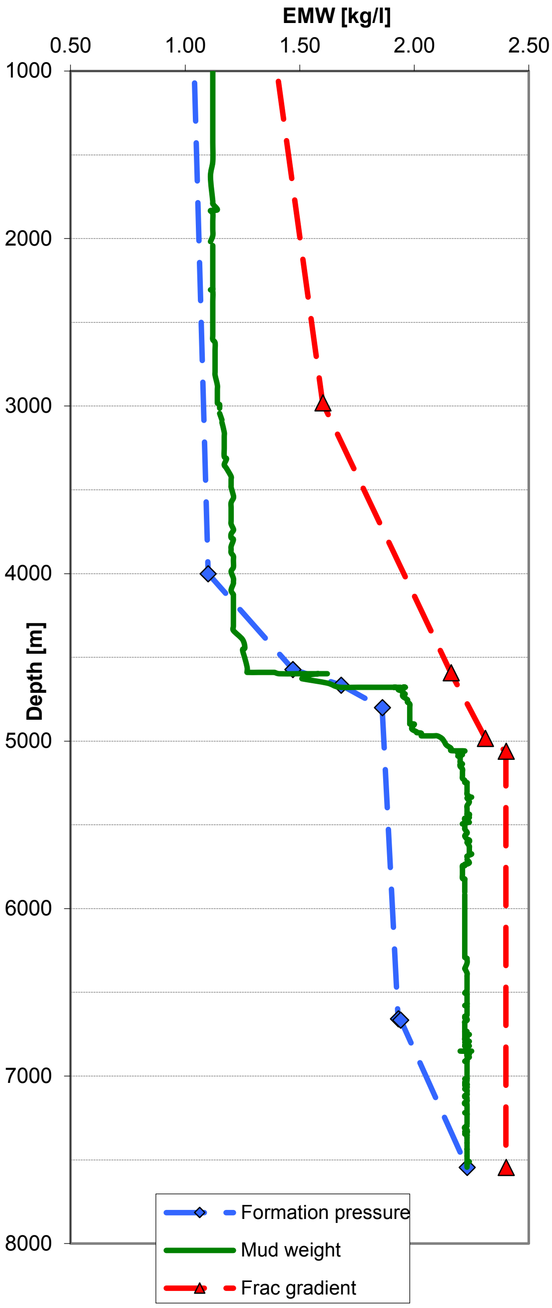


Figure 31: Mud weight window Zistersdorf ÜT2A [27]

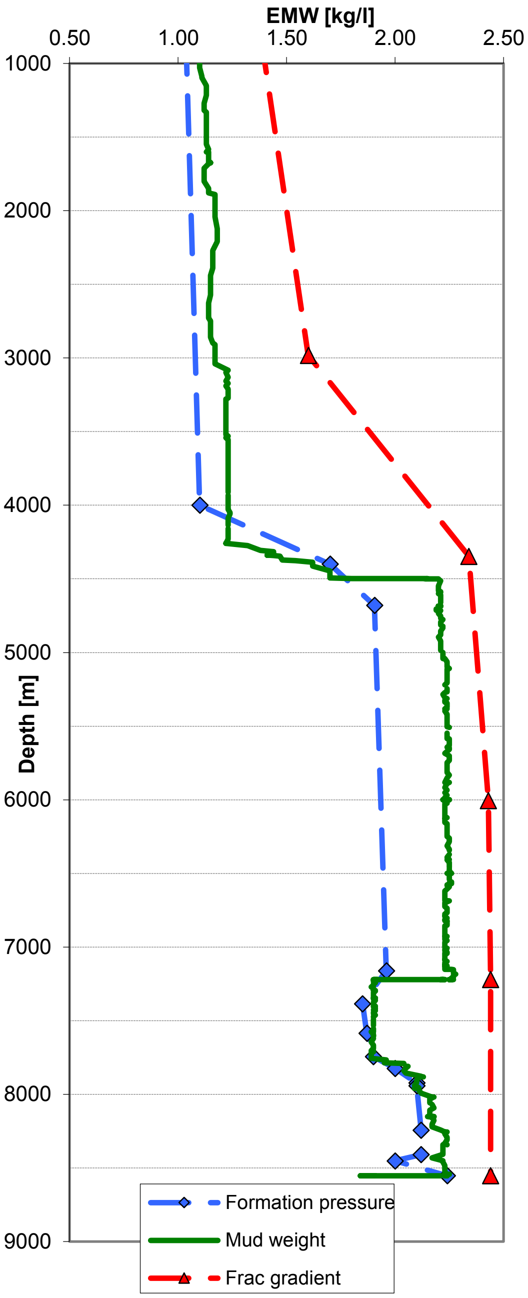
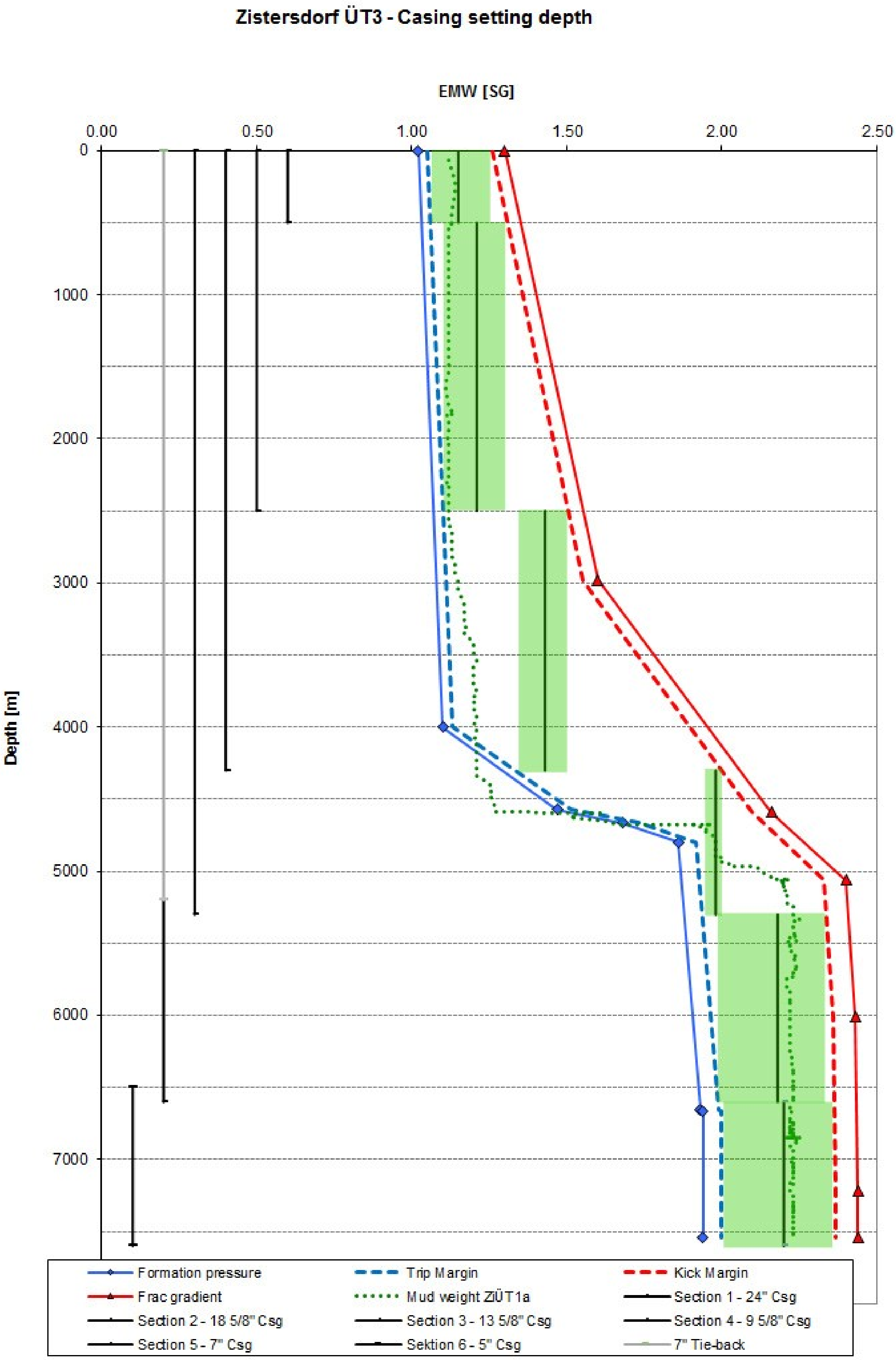


Figure 32: Casing setting depth Zistersdorf ÜT3



A.4 Formulas

A.4.1 General

Buoyancy factor: $BF = \frac{65.5 - mud\ weight\ (ppg)}{65.5}$

Pressure gradient: $\frac{psi}{ft} = mud\ weight\ (ppg) * 0.052$

Hydrostatic pressure: $P_{hydr} = mud\ weight\ (ppg) * 0.052 * true\ vertical\ depth\ (ft)$

Specific gravity: $SG = \frac{mud\ weight\ (ppg)}{8.33}$

Equivalent circulating density: $ECD\ (ppg) = \frac{annular\ pressure\ loss\ (psi)}{0.052 * TVD\ (ft)} + mud\ weight\ (ppg)$

Maximum allowable mud weight from leak-off test data:

$$MW\ (ppg) = \frac{leak{-}off\ pressure\ (psi)}{0.052 * TVD\ casing\ shoe\ (ft)} + mud\ weight\ (ppg)$$

A.4.2 Drill string design

Length of DCs for desired WOB: $Length\ (ft) = \frac{WOB * DF}{Wdc * BF}$

WOB… Weight on bit [lb]
DF… safety factor
W_{dc}… Drill collar weight [lb/ft]
BF… Buoyancy factor

Collapse pressure (DST). $P_c = \frac{L * \rho_1}{19.251} - \frac{(L - Y) * \rho_2}{19.251}$

P_c… Collapse pressure [psi]
L… Total depth of well [ft]
Y… Depth to fluid inside DP [ft]
ρ_1… Fluid density outside DP [ppg]
ρ_2… Fluid density inside DP [ppg]

Design factor: $DF = \frac{Collapse\ resistance\ of\ DP}{Collapse\ pressure}$

Tensile force: $P = (L_{DP} * W_{DP} + L_{DC} * W_{DC}) * BF$

P… Tension [lb]
BF… Buoyancy factor
L_{DP}… Length of drill pipe [ft]
W_{DP}… Weight of drill pipe [lbm/ft]
L_{DC}… Length of drill collar [ft]
W_{DC}… Weight of drill collar [lbm/ft]

Max. allowable design load: $P_a = 0.9 * P_t$

P_a… Max. allowable design load in tension [lb]
P_t… Theoretical yield strength from API tables [lb]

Margin of overpull: $MOP = P_a - P$

MOP… Margin of overpull [lb]

P_a… Max. allowable design load [lb]

P… Tension [lb]

Design factor:

$$DF = \frac{P_a}{P}$$

P_a… Max. allowable design load [lb]

P… Tension [lb]

Torsional yield strength:

$$Q = \frac{0.096167 * J * Y_m}{D}$$

Yield strength to torsion and tension:

$$Q = \frac{0.096167 * J}{D} \sqrt{Y_m^2 - \frac{P^2}{A^2}}$$

Q… Min. torsional yield [lb-ft]

J… Moment of inertia [in^4]

Y_m… Min. unit yield strength [psi]

D… Diameter [in]

P… Total load in tension [lb]

A… Cross-sectional area [in^2]

Stretch due to own weight:

$$\Delta L = \frac{L_{DP}}{9.625x10^7}(65.44 - 1.44) * \rho_m$$

ΔL… Stretch [ft]

L_{DP}… Length of drill pipe [ft]

ρ_m… Density of mud [ppg]

WOB during first-order buckling:

$$W_{crit} = 1.94 * \sqrt[3]{E * J * P^2}$$

WOB during second-order buckling:

$$W_{crit} = 3.75 * \sqrt[3]{E * J * P^2}$$

W_{crit}… Critical buckling load [lb]

E… Modulus of elasticity [lb/ft^2]

J… Moment of inertia [in^4]

P… Tension [lb]

A.4.3 Casing design

Minimum internal yield pressure:

$$P_B = 0.875 \left[\frac{2 * Y_p * t}{D}\right]$$

Yield strength collapse:

$$P_{Yp} = 2 * Y_p \left[\frac{\left(\frac{D}{t}\right) - 1}{\left(\frac{D}{t}\right)^2}\right]$$

Plastic collapse:

$$P_p = Y_p \left[\frac{A}{D/t} - B\right] - C$$

Transition collapse:

$$P_T = Y_p \left[\frac{F}{D/t} - G\right]$$

Elastic collapse:

$$P_E = \frac{46.95x10^6}{\left(\frac{D}{t}\right)\left[\left(\frac{D}{t}\right) - 1\right]^2}$$

P_B… Min. burst pressure [psi]

P_{Yp}…Yield strength coll. press. [psi]

P_T… Transition collapse pressure [psi]

P_E… Elastic collapse pressure [psi]

Y_p… Min. yield strength [psi]

t… Nominal wall thickness [in]

D… Nominal outside diameter [in]

A, B, C, F, G… Formula factors for given tables

Collapse pressure with axial stress:

$$Y_{PA} = Y_P \left\{\left[1 - 0.75\left(\frac{S_A}{Y_P}\right)^2\right]^{1/2} - 0.5\frac{S_A}{Y_P}\right\}$$

Y_{PA}… Yield strength of axial stress equivalent grade [psi]
Y_P… Minimum yield strength [psi]
S_A… Axial stress - tension is positive [psi]

A.4.4 Hydraulics

Optimum friction pressure: $$P_{fopt} = \frac{2*P_{smax}}{3.66}$$

Optimum pressure across bit: $$P_{bopt} = P_{smax} - P_{fopt}$$

Optimum flow rate: $$Q_{opt} = Q_a * antilog\left[\frac{\log(P_{fopt}/P_{fqa}}{1.66}\right]$$

Optimum bit flow area: $$A_{opt} = \sqrt{\frac{(8.3*10^{-5})*MW*Q_{opt}}{Cd^2*P_{bopt}}}$$

P_{smax}… Max. surface pressure [psi]
P_{bopt}… Optimum bit pressure [psi]
Q_a… Assumed flow rate [gpm]
A_{opt}… Optimum bit flow rate [in²]

P_{fopt}… Optimum friction pressure [psi]
Q_{opt}… Optimum flow rate [gpm]
P_{fqa}… Assume friction pressure [psi]
Cd… Nozzle coefficient

Average velocity: $$v_{av} = \frac{Q}{2.448*ID^2}$$

Reynolds number: $$Re = \frac{928*MW*v_{av}*ID}{\mu p}$$

Laminar friction pressure loss: $$\Delta pf_{lam} = \frac{\mu p*v_{av}}{1500*ID^2} + \frac{\tau_y}{225*ID}$$

Turbulent friction pressure loss: $$\Delta pf_{tur} = \frac{MW^{0.75}*v_{av}^{1.75}*\mu p^{0.25}}{1800*ID^{1.25}}$$

v_{av}… Average velocity [ft/s]
Q… Flow rate [gal/min]
MW… Mud weight [ppg]
Δpf… Friction pressure loss [psi]

Re… Reynolds number
ID… Inner diameter of pipe [in]
μ_p… Plastic viscosity [cp]
τ_y… Bingham yield point [lb/100 ft²]

Surface pressure loss: $$Surface\ pressure\ loss = Length * \Delta pf$$

Pipe pressure loss: $$Pipe\ pressure\ loss = Length * \Delta pf$$

Bit area: $$A = \frac{D^2*\pi}{4}$$

Total flow area: $$A_{flow} = \frac{\sum d^2}{1303.8}$$

Bit pressure loss: $$\Delta p_{bit} \frac{8.311*10^{-5}*Q*MW}{A_{flow}*Cd}$$

Hydraulic horse power of bit: $$HHP = \frac{\Delta p_{bit}*Q}{1714}$$

Hydraulic horse power per in² of bit: $$HHP(in^2) = \frac{HHP}{A}$$

A… Bit area [in^2]

A_{flow}… Total flow area [in^2]

D… Bit diameter [in]

d… Nozzle diameter [in/32]

Δpbit… Bit pressure loss [psi]

Cd… Nozzle coefficient

HHP… Hydraulic horse power [HP]

HHP(in^2)… HHP per in^2 of bit [HP]

Annular pressure loss:

$$Annular\ pressure\ loss = Length * \Delta pf$$

Hydraulic horse power:

$$HHP = \frac{\Delta p * Q}{1714}$$

Required pump capacity:

$$Total\ HHP = \sum \Delta p_{surf} + \Delta p_{string} + \Delta p_{bit} + \Delta p_{annulus}$$

Cuttings transport velocity:

$$v_{ann} = \frac{24.5 * Q}{(Dh^2 - Dp^2) * 60}$$

v_{ann}… Annular velocity [ft/s]

Q… Flow rate [gpm]

D_h… Inside diameter of casing or hole size [in]

D_p… Outside diameter of pipe, tubing or collars [in]

A.4.5 Well control

Shut-in drill pipe pressure:

$$SIDPP\ (psi) = formation\ pressure - hydrostatic\ pressure$$

Kill mud density:

$$ppg = \frac{SIDPP}{TVD * 0.052} + original\ mud\ weight\ (ppg)$$

SIDPP… Shut-in drill pipe pressure [psi]

TVD… True vertical depth [ft]

Max. allowable SICP:

$$MASP\ (psi) = 0.052 * (MAMW - MW) * TVD\ of\ casing\ shoe$$

MASP… Maximum allowable shut-in casing pressure [psi]

MAMW… Maximum allowable mud weight [ppg]

MW… Mud weight [ppg]

Shut-in casing pressure:

$$SICP = pressure\ of\ gas\ influx - P_{hydr}\ above\ gas\ influx$$

SICP… Shut-in casing pressure [psi]

P_{hydr}… Hydrostatic pressure [psi]

Bottom hole pressure:

$$BHP = hydrostatic\ pressure + SICP$$

BHP… Bottom hole pressure [psi]