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The Northern Upper Rhine Graben – Re-dawn of a mature petroleum province?

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Keywords: Upper Rhine Graben, exploration history, source rocks, fractured reservoirs, fracture corridors, relay ramps, fault-related folding

Abstract

The Upper Rhine Graben (URG) continental rift has a century long hydrocarbon exploration history but a rather unusual creaming curve. The largest oil discovery was made in 2003 which triggered a new wave of exploration activity. New research, modern 3D seismic and exploration drilling provide new insights into the petroleum systems of the URG. This paper summarizes the exploration history, source rocks, reservoirs, and structural architecture with the regional focus on the northern part of the URG where most oil and gas field were discovered.

The most prolific source rocks are the Lower Tertiary Rupelian Fischschiefer as well as the Lower Jurassic Posidonienschiefer and Arietenkalk. Several reservoirs are found in both, the Tertiary rift and the Mesozoic pre-rift sequences, respectively. The commercially most important ones are the clastic reservoirs of the Lower Tertiary Pechelbronner Schichten (PBS) and the Lower Triassic Buntsandstein. The PBS was only deposited within the rift depression and shows strong changes in lithofacies, reservoir development, and thickness due to synsedimentary tectonic activity, particularly in the northern URG. Conversely, the pre-rift Buntsandstein forms part of the regionally very extensive basement cover that was tilted to the south and progressively eroded to the north prior to the onset of the rifting. Apart from regional and burial related variations in lithofacies and diagenesis, the reservoir quality of the Buntsandstein is also strongly affected by vertical fracture corridors which contribute essentially to a prolific dual porosity/permeability reservoir system.

The URG originated from an extensional event in late Eocene and Oligocene which was replaced by a strike slip regime in early Miocene. The change of tectonic regime caused the fault pattern to re-orientate accordingly evidenced by early NNE-SSW oriented normal faults developing upward into a set of NNW-SSE oriented «en-echelon» faults. Modern 3D seismic imaging also reveals plenty of relay ramps between faults of the same orientation. Mostly the ramps are not breached by connecting faults as it was proposed by former 2D seismic interpretations. The 3D seismic also shows abundant fault-related folding along major faults. The Mesozoic overburden is bended above an active basement fault towards the proto-hanging wall. The syntectonic rift sediments onlap onto the down warped section of the Mesozoic cover giving the impression of tectonically cut-out section where there is a genuine hiatus. Finally, the much improved 3D seismic resolution and control provides ample opportunity to further develop new structural and stratigraphic plays.

Zusammenfassung

Der Oberrheingraben (ORG) ist ein kontinentales Rift-Becken mit einer mehr als 100-jährigen Explorationsgeschichte aber einer eher ungewöhnlichen kumulativen Reservenkurve («Creaming Curve»). Die größte Erdöllagerstätte im ORG wurde erst 2003 gefunden und löste eine neue Explorationsphase aus. Neue Forschungsarbeiten, moderne 3D-Seismik und Erdölbohrungen ermöglichen neue Erkenntnisse zum Petroleumsystem des ORG. Diese Arbeit gibt einen Überblick über die Explorationsgeschichte, die Mutter- und Speichergesteine sowie den Strukturbau des ORG mit dem regionalen Fokus auf den nördlichen Teil des Grabens, wo die meisten Erdöl- und Erdgasfelder gefunden worden sind.

Die ergiebigsten Muttergesteine im ORG sind die alttertiären Fischschiefer sowie die liassischen Posidonienschiefer und Arietenkalke. Speicherge-

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steine sind in den mesozoischen Prä-Rift-Sedimenten sowie in den tertiären Rift-Sedimenten entwickelt. Die kommerziell wichtigsten Speichergesteine sind die Klastika der alttertiären Pechelbronner Schichten (PBS) und der Buntsandstein. Die PBS wurden während der Riftphase abgelagert und zeigen, bedingt durch synsedimentäre Tektonik, insbesondere im nördlichen ORG regionale Unterschiede in ihrer Lithofazies, Speichergesteinsausbildung und Mächtigkeit. Im Gegensatz dazu ist der Buntsandstein ein Teil der präriftzeitlichen Sedimentabfolge, welche noch vor der tertiären Riftphase nach Süden hin verkippt und im Norden erodiert wurde. Abgesehen von regionalen und durch unterschiedliche Versenkungsteufen bedingte Unterschiede in der Lithofazies und diagenetischen Überprägung wurde die Speichergesteinsqualität des Buntsandsteins insbesondere durch vertikale Kluftkorridore verbessert.

Der ORG entstand durch Extension während des späten Eozäns und Oligozäns, welches während des Miozäns durch ein Blattverschiebungsregime abgelöst wurde. Diese Änderung des tektonischen Regimes führte zur Reorientierung des Störungsmusters. Dabei entwickelten sich frühe NNE-SSW-streichende Abschiebungen während des Miozäns in eine Reihe von NNW-SSE-streichenden «enechelon»-Störungen. Moderne 3D-Seismik zeigt häufig das Vorhandensein von «Relay Ramps» zwischen Störungen gleicher Orientierung. Meistens sind diese «Relay Ramps» nicht durch Querstörungen zerlegt wie frühere auf 2D-Seismik basierende Interpretationen nahelegten. Darüber hinaus zeigt die 3D-Seismik, dass in Bohrungen weder vermeintliche Schichtausfälle zwingend auf Störungen zurückzuführen sind noch Schichtwiederholungen auf regionale Einengungstektonik hinweisen. Ursächlich hierfür ist vielmehr die Verfaltung sedimentärer Prärift-Einheiten über reaktivierten Grundgebirgsstörungen. Die Verfaltung verursacht einen progressiven Onlap der Synriftsedimente auf die verkippten Präriftsedimente, in denen sich lokal Aufschiebungen bei regionaler Extensionstektonik entwickeln können.

Schließlich ermöglicht die deutlich verbesserte 3D-seismische Überdeckung die Entwicklung von neuen strukturellen und stratigraphischen «plays».

1 Introduction

The Upper Rhine Graben (URG) is the most conspicuous part of the European Cenozoic failed rift system north of the Alps. The NNE-SSW trending graben structure extends some 300 km between Frankfurt and Basel and its width ranges between 25 and 35 km. The graben boundary faults build pronounced escarpments and the graben shoulders can rise up to 1.000 m and more above the valley plain (Fig. 1).

The exploitation of hydrocarbons in the URG commenced some 400 years ago from surface seeps in the northern Alsace. Initially, the oil was mainly used for medicinal purposes and oil lamp fuel. Since then, the URG saw several exploration and production waves yielding in total 57 oil and gas fields across the URG with peak production occurring in 1963 with some 2 MMbbl/yr. However, in creaming terms, the curve looks rather unusual, as the largest discovery was made only a few years ago. This important discovery below the city of Speyer invalidated some of the former understanding of the petroleum systems and opened a new wave of exploration activity in the URG, strongly enhanced by the application of modern 3D seismic advanced well drilling and production technology.

This paper provides a summary of the exploration history as well as an overview of the hydrocarbon systems including source rocks, reservoirs, and structural architecture with the regional focus on the URG north of the town of Karlsruhe.

2 Lithostratigraphy in the URG area

The URG rift system became active in the late Eocene. In the northern part of the graben, the deposition of rift sediments has been continuing with some hiatuses until today. In general, the Oligocene and Miocene

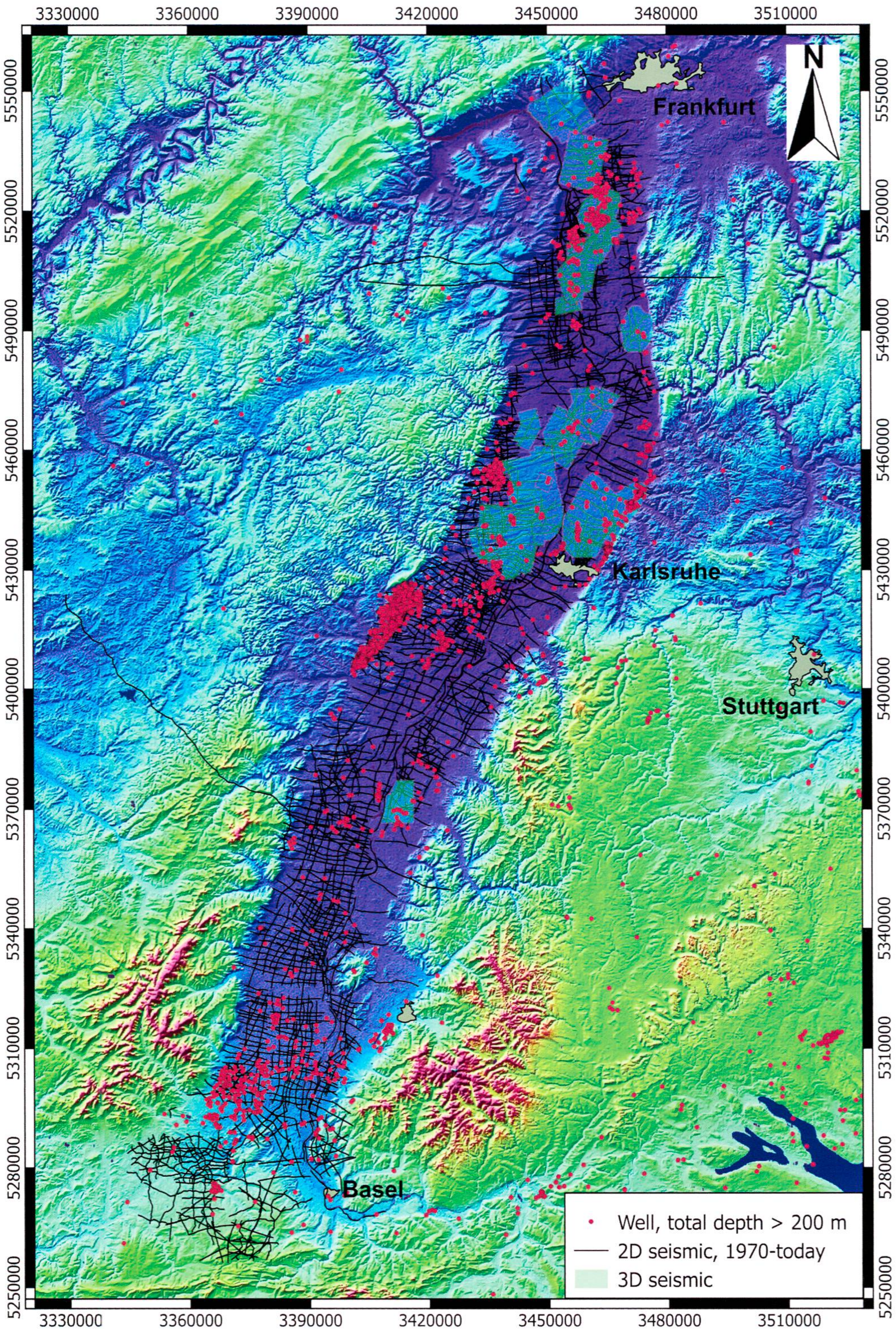

Fig. 1: Digital elevation model (DEM) of the Upper Rhine Graben (URG) and its graben shoulders including 2D and 3D seismic coverage and all wells with a total depth of → 200 m. DEM prepared by Geodetic Institute, Karlsruhe Institute of Technology, with SRTM data.

rift sediments tend to be composed to a large extent of shales, silts, and marls with intercalated streaks of porous sands (Fig. 2). In addition, coarser clastics can occur along the graben margins (e.g. Duringer 1997). Often it is observed, that coarse sediments delivered from the graben shoulders are trapped in narrow and elongated depo-centres controlled by syn-sedimentary dip-slip movements of the basin boundary faults.

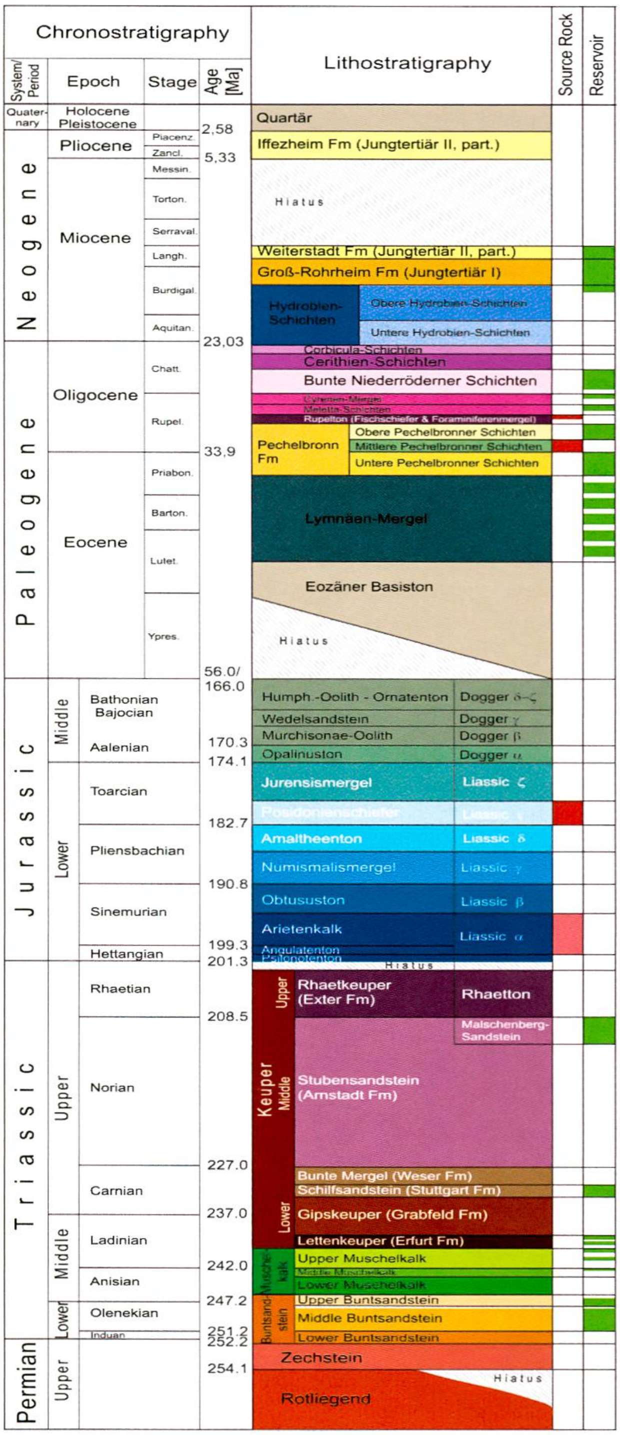

Fig. 2: Lithology, source rocks, and reservoir units of the Tertiary and Mesozoic in the URG area north of Karlsruhe; major source rocks marked with red outline. Time scales are different for Cenozoic and Mesozoic/Paleozoic sections.

During the Pliocene, the Rhine River broke through the watershed in the southernmost URG (Kaiserstuhl-Wasserscheide) and tapped the Aare River (Giamboni et al. 2004). With the Swiss Alps as an additional source area, coarse clastic material spread all across the URG area in the Quaternary, partly reaching significant thickness (i.e. Heidelberg-Mannheim Basin).
Regionally, the pre-rift section dips gently to the south. Hence, the base of the Tertiary sediments progressively cuts into older section towards the north. In the northernmost URG, Permian Rotliegend sediments and volcanics directly subcrop Oligocene Pechelbronner Schichten. Towards the south, Mesozoic units up to the Dogger zeta progressively subcrop the base of the Tertiary graben fill (e.g. Sittler 1965, GLA 1981).

3 HC exploration history

Oil seeps at Pechelbronn on the French side of the URG have been known since the 15th century. Oil sand mining started from the Pechelbronn field in the early 18th century, followed by the drilling of more than 5000 (!) shallow wells, which produced more than 24 MMbbl of oil until the abandonment of the field in 1964.

On the German part of the URG, oil production from mining and smouldering of Liassic oil shales outcropping along the eastern graben boundary north of Karlsruhe began in 1850. Early oil exploration started around 1900 when a first shallow exploration well was drilled in the oil shale mining region. Driven by the search for a German equivalent of the French Pechelbronn field, numerous and relatively shallow exploration wells were drilled purely on surface observations, but with little success. After the 1st world war, exploration efforts resumed and led to the first oil discovery in the German part of the URG in 1921 (Fautenbruch field; Moos 1934). In the 30s the «State Geophysical Programme» and the «State Drilling Programme» triggered the first large drilling campaign with around 87 exploration wells. This exploration effort led to the discovery of several small oil fields at shallow depth (Tab. 1).

After world war 2, 2D seismic was systematically acquired across the URG and more than 200 exploration and appraisal wells were drilled between 1948 and 1963. This second and largest exploration wave led to the discovery of generally bigger and also deeper oil and gas fields. Exploration came to halt in 1963 and recommenced only after the first oil crisis in 1973. More than 5000 line km of new 2D seismic were acquired until the mid 80s and some 40 exploration wells were drilled. However, the success of this last wave of the last century was marginal as only few new oil discoveries like Eich could be added. By the early 90s, the URG was considered fully explored and declared a mature oil province with only little remaining potential (Mauthe et al. 1993). Most exploration licenses were surrendered and nearly all old fields were abandoned by that time. E&P companies left the area and production was only maintained in 3 fields, namely Eich, Rülzheim and Landau which continued producing until today.

Some ten years later, a geothermal explorer accidently found oil in the Lower Triassic

Exploration Phases	Oil field	Year of Discovery	End of Production	No of Producers	Production [bbl]	Reservoirs
1st phase	**Fautenbruch-Forst**	1921/1934	1959	40	294.307	Tertiary/Mesozoic
	Weiher	1936	1960	46	405.420	Mesozoic
	Weingarten-Werrabronn	1936/1948	1964	94/26	561.735	Tertiary/Mesozoic
	Worms	1937	1940	1	4.855	Tertiary
2nd phase	**Stockstadt (incl. Kühkopf)**	1952	1994	28	7.591.307	Tertiary
	Rot	1953	1963	11	446.629	Mesozoic
	Landau	1955	still producing	60	32.981.670	Tertiary/Mesozoic
	Dudenhofen	1955	1963	3	141.357	Tertiary
	Hayna	1957	1962	2	15.834	Tertiary
	Huttenheim	1957	1963	1	39.756	Tertiary
	Leopoldshafen	1957	1986	12	1.481.953	Tertiary
	Minfeld	1957	1964	11	240.265	Tertiary
	Neureut	1958	1963	3	68.766	Tertiary
	Offenbach	1958	1963	6	150.993	Tertiary
	Wattenheim	1958	1976	3	190.048	Tertiary
	Hofheim	1958	1965	4	90.929	Tertiary
	Maximiliansau	1959	1962	1	12.833	Tertiary
	Rheinzabern	1959	1994	1	121.056	Tertiary
	Knielingen	1959	1964	2	73.212	Tertiary
	Büchenau	1959	1959	1	1.226	Tertiary
	Graben	1959	1965	2	55.838	Tertiary
	Deidesheim	1960	1960	1	3.263	Tertiary
3rd phase	**Winden**	1980	1988	3	31.748	Tertiary
	Offenburg	1983	1986	1	66.744	Mesozoic
	Eich-Königsgarten	1983	still producing	10	10.074.504	Tertiary
	Rülzheim	1984	still producing	1	303.906	Tertiary
4th phase	**Römerberg**	2003	still producing	4	7.238.790	Mesozoic
	Schwarzbach	2015	test production	1		Tertiary
Cumulative production [bbl]					**62.688.943**	

Tab. 1: Production data of oil fields in the German sector of the URG (compiled from LBEG annual production reports, Boigk 1981).

Buntsandstein beneath the city of Speyer in 2003. After 3D seismic coverage and several appraisal wells, the discovery named Römerberg was confirmed to be not only the largest oil field in the URG by far, but also one of the largest oil fields ever found onshore Germany.

Unsurprisingly, this success triggered a new exploration wave in the URG. Currently, most of the prospective acreage is taken by oil companies and more than 1000 km^3 of 3D seismic have been acquired since 2011 with more to follow. In parallel and due to increasing urbanization, environmental protection areas and population density, the process to

Exploration Phases	Gas field	Year of Discovery	End of Production	No of Producers	Production [MMm³]	Reservoirs
2nd phase	**Wolfskehlen**	1951	1989	21	206,702	Tertiary
	Subfield Büttelborn	1956				Tertiary
	Subfield Dornheim	1957				Tertiary
	Pfungstadt	1952	1975	8	161,160	Tertiary
	Stockstadt	1953	1980	26	524,934	Tertiary
	Eich	1955	1973	7	117,834	Tertiary
	Frankenthal	1959	1961	5	20,093	Tertiary
3rd phase	**Darmstadt-SW**	1981	1986	1	9,745	Tertiary
Cumulative test production 5 discoveries [MMm³]					11,194	
Cumulative production [MMm³]					**1.051,662**	

Tab. 2: Production data of mostly «biogenic» dry gas fields in the German sector of the URG. The gas discoveries Spöck (1955), Groß-Gerau (1956), Hagenbach (1959), Darmstadt (1960) and Eppstein (1980) never went into continuous production. (compiled from LBEG annual production reports, Boigk 1981).

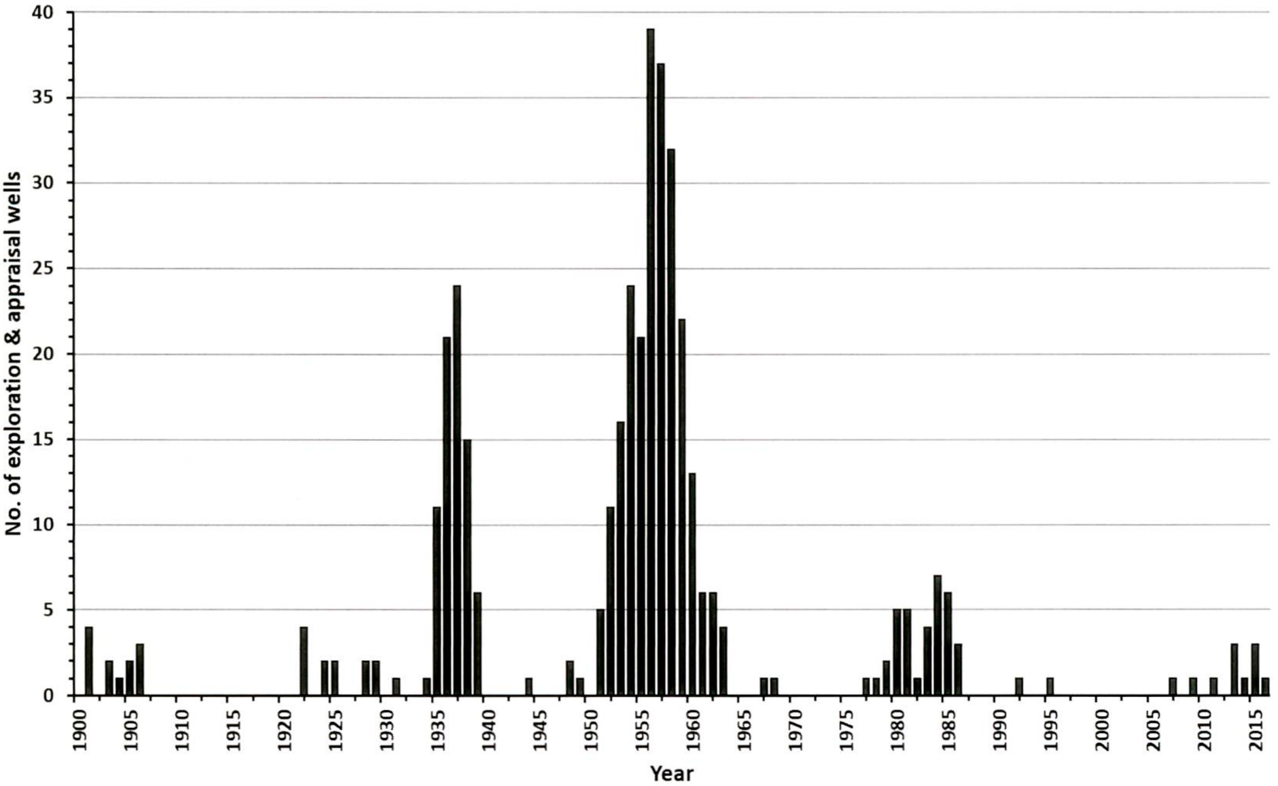

Fig. 3: Number of exploration and appraisal wells per year in the German sector of the URG (based on published data from the LBEG).

obtain permissions to drill has generally become more arduous, resulting in only 11 exploration and appraisal wells drilled from 2007 until today with modest success. In 2015, the Schwarzbach-1 well succeeded to extend prospective oil fairways by discovering the northernmost oil accumulation ever found in the URG, north of the once prolific Stockstadt and Kühkopf fields.

Overall, exploration led to 57 oil and gas discoveries since onset until now in the URG (including the French part), of which 29 oil fields and 6 gas fields have been or still are under exploitation in the German part of the URG (Durst 1991; Mauthe et al. 1993; own data). The discovered cumulative oil reserves for the German part of the URG exceed 125 MMbbl, whereby 48% comes from the Römerberg field, 26% from Landau, 14% from Eich, 6% from Stockstadt, and only 6% from the other 25 oil fields (Fig 4.). Hence, historic annual oil production reflects production history of these 4 big oil fields (Fig. 5). In 2015 around 8.4% of the total German oil production came from the URG with Römerberg as the 2nd biggest producing field in Germany after the offshore Mittelplate field in the German wadden sea.

4 Source rocks

Recent hydrocarbon research work focused mainly on the four main petroleum systems, oil families, and source rocks within the URG (e.g. Bruss 2000; Böcker & Littke 2014; Böcker & Littke 2016; Böcker et al. 2016; Perner et al. 2016). The by far most prolific source rocks comprise the Lower Tertiary Rupelian Fischschiefer and the Lower Toarcian Posidonienschiefer in the Jurassic pre-rift section (Fig. 6, Fig. 7).
Depending on the structural constellation and maturity level, both source rocks are proven to source Tertiary as well as Pre-Ter-

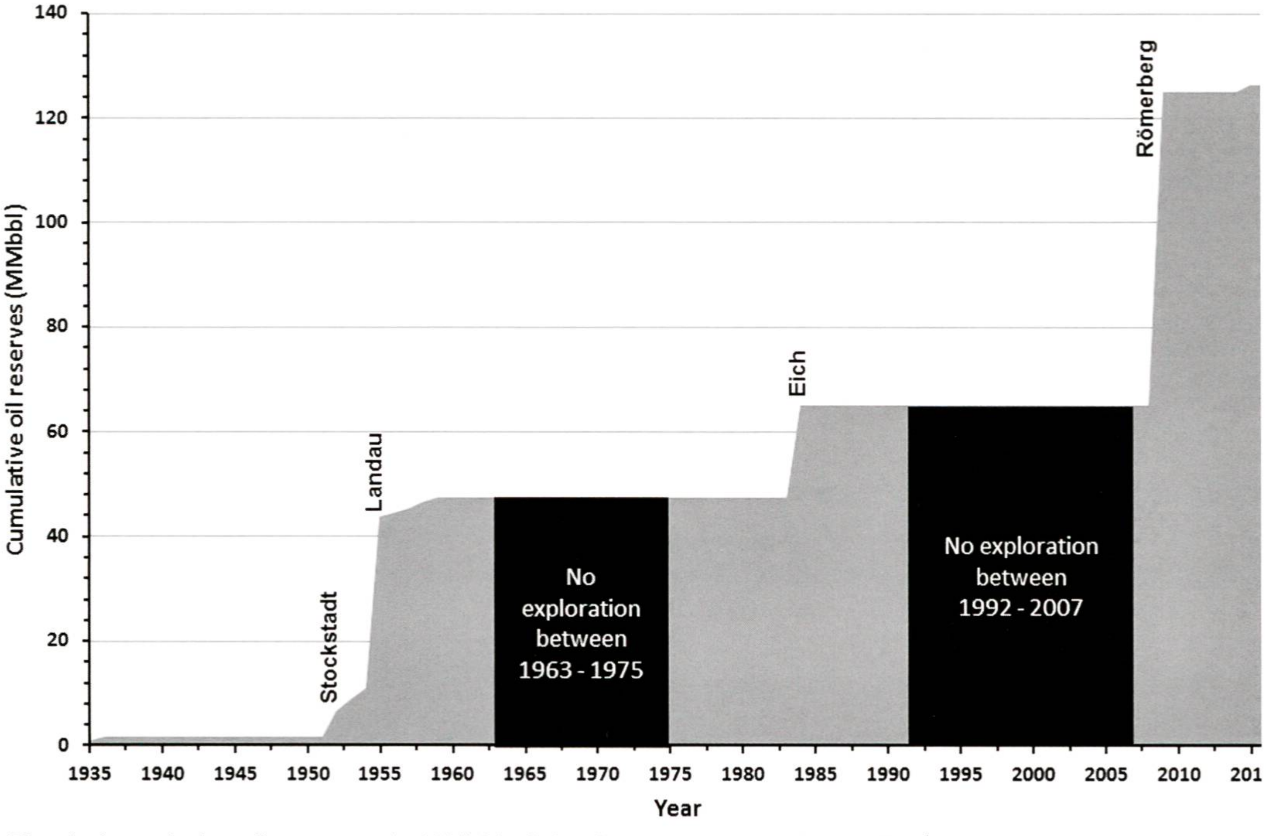

Fig. 4: Cumulative oil reserves in MMbbl of the German sector of the URG (compiled from Mauthe et al. 1993 and LBEG annual reports).

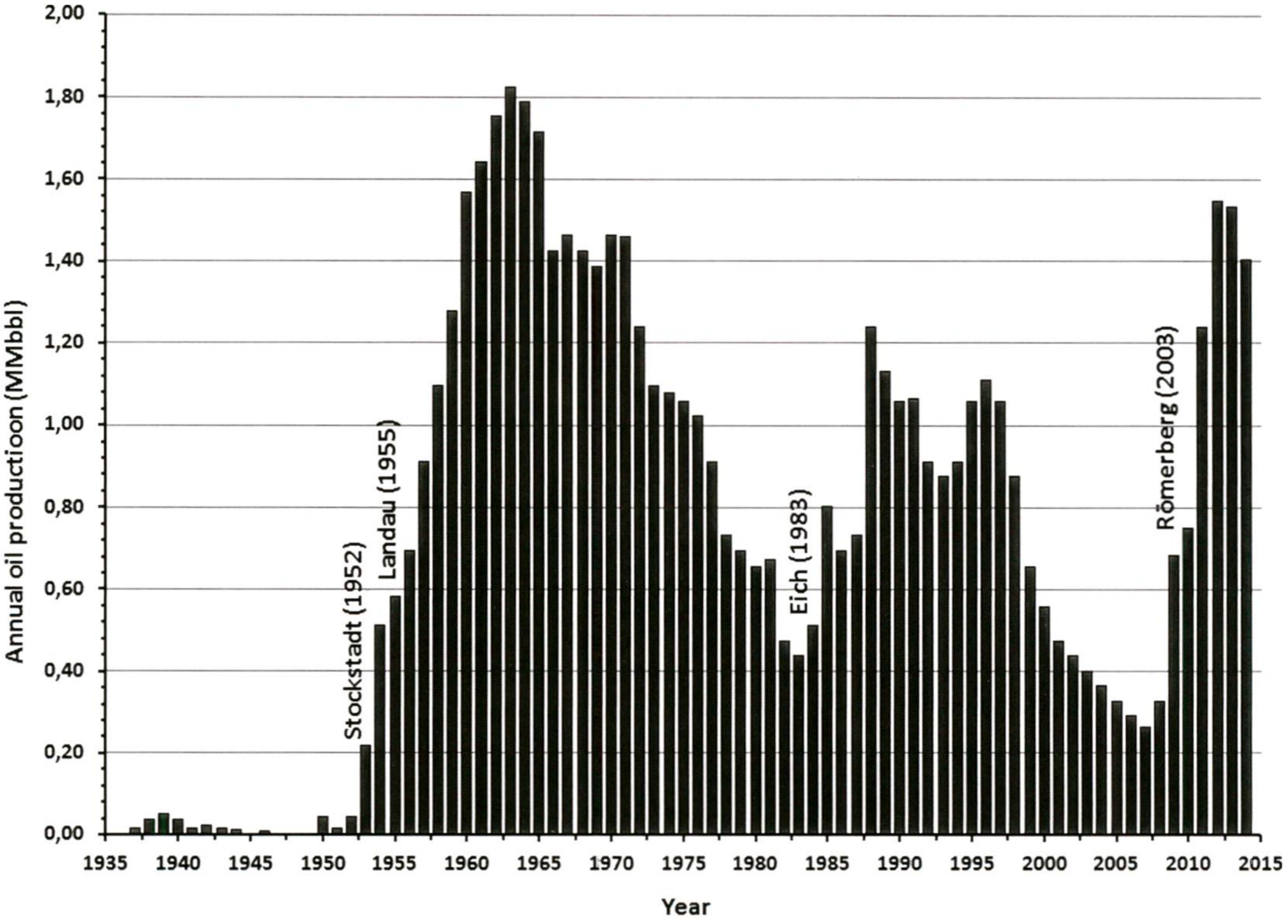

Fig. 5: Annual oil production in MMbbl of the German sector of the URG (compiled from LBEG annual reports).

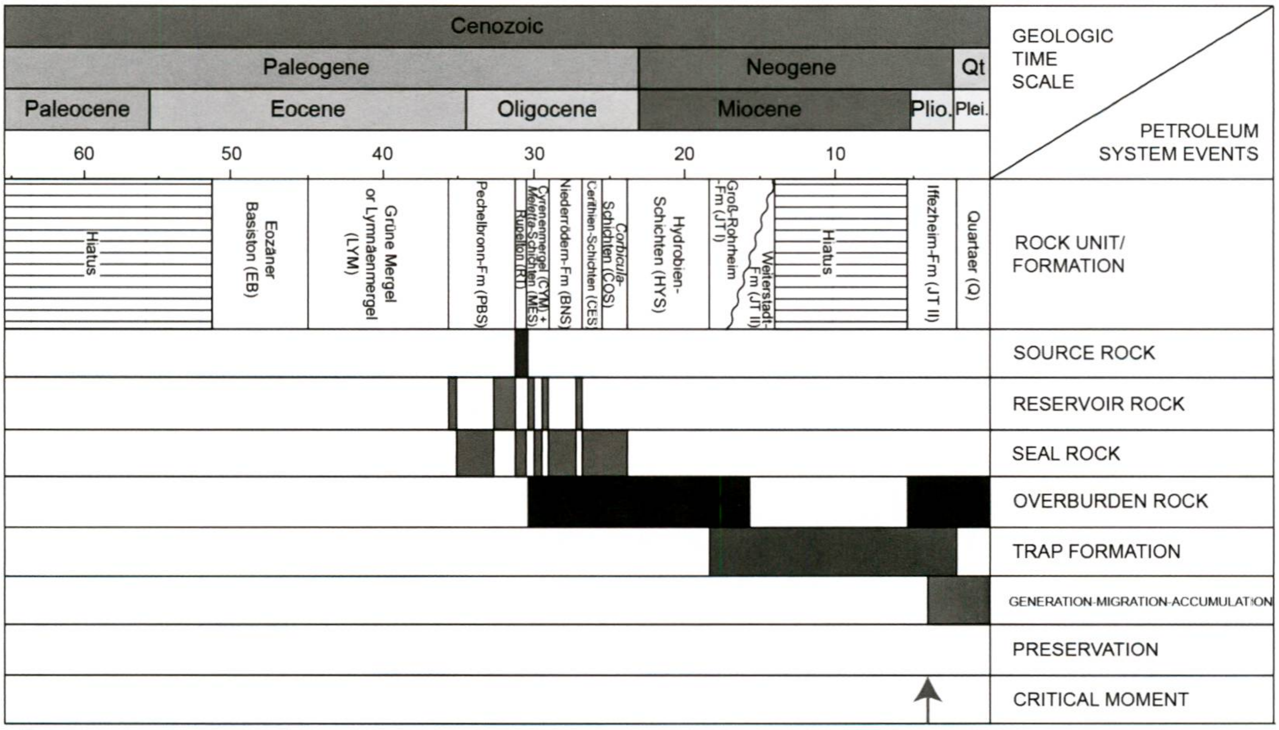

Fig. 6: Fischschiefer (part im Rupelton) Petroleum System chart (modified after Bruss 2000).

tiary reservoirs either solely or in varying mixtures, which in essence defines the different petroleum systems of the central and northern URG area (Fig. 6: Bruss 2000; Böcker & Littke 2014). While the northernmost part of the URG depends on the Tertiary source rocks alone, admixtures of Lower Jurassic Posidonienschiefer derived oil increases to the south.

The Lower Tertiary source rocks mark the oldest marine ingressions into the URG rift valley (1st and 2nd Rupelian transgression, Hardenbol et al. 1998). The Fischschiefer consists of interbedded clay- and siltstones with abundant calcareous nannoplankton laminae. The dark clastics are mostly bituminous and rich in pyrite and phosphatic fish remains. The Fischschiefer classifies as a prolific source rock with an original total organic carbon content (TOC) of 4-5% and original hydrogen index (HI) of 500 – 550 mg HC/g TOC (Böcker & Littke 2014). Organic matter analyses indicate oil-prone type II kerogen with a good to very good hydrocarbon generation potential. The formation has a nearly constant thickness of 10-15 m all over the area, due to a calm depositional environment in a restricted basin.

Another Tertiary source rock, but of comparatively rare and patchy occurrence restricted to the northern URG, is the sapropelic Messel formation. The laminated, organic rich mudstones were deposited in maar lakes during a short time span of 1 to 1.5 Ma in the Middle Eocene (Lutz et al. 2013). The organic matter is of mixed type I + III kerogen with high TOC contents of up to 50% (on av. 35%) and HI values around 620 mg HC/gTOC indicating an excellent hydrocarbon generation potential (Hillebrand & Leythaeuser 1991). However, their role as oil source in the regional petroleum system is of little relevance.

The principal Mesozoic source rocks in the central URG are the up to 40 m thick Lower Toarcian Posidonienschiefer (Lias epsilon) as well as the up to 25 m thick Sinemurian Arietenkalk (Lias alpha, Fig. 7; Bruss 2000; Böcker et al. 2016). Both Formations are composed of interbedded argillaceous limestones, calcareous marlstones, and organic rich black oil shales and both mark important anoxic events of regional to global scale.

Within the Posidonienschiefer, the oil shales can be especially well developed in the top 15 m section like in the Mingolsheim 1968 well (Hettich 1974; own data).
The Posidonienschiefer classifies as an excellent oil-prone source rock. It contains type II kerogen with a high total organic content (TOC) of 8% on average and high HI values around 580 mg HC/gTOC (Fig 8; Röhl et al. 2001; Böcker et al. 2016). TOC and quality vary vertically and laterally, likely as a consequence of periodically stagnant conditions combined with sea level fluctuations during deposition in Toarcian times (Röhl & Schmid-Röhl 2005).

Petroleum expulsion efficiencies (PEE) are extraordinarily high. More than 86% of the hydrocarbons are generated and expelled at a thermal maturity of 0.9 vitrinite reflectance equivalent and more than 96% at the end of the oil window (Rullkötter et al. 1988; Eseme 2006).

Thin oil shale intercalations within the Arietenkalk show also high albeit more varying TOC values of up to 14% (Fig. 8; Böcker et al. 2016; own data) composed of heterogeneous, mixed gas- and oil-prone kerogen types II + III (Böcker et al. 2016).
The base Tertiary unconformity truncates the Liassic source rocks which are absent north of a truncation line running E-W roughly from Landau-Speyer to Heidelberg.

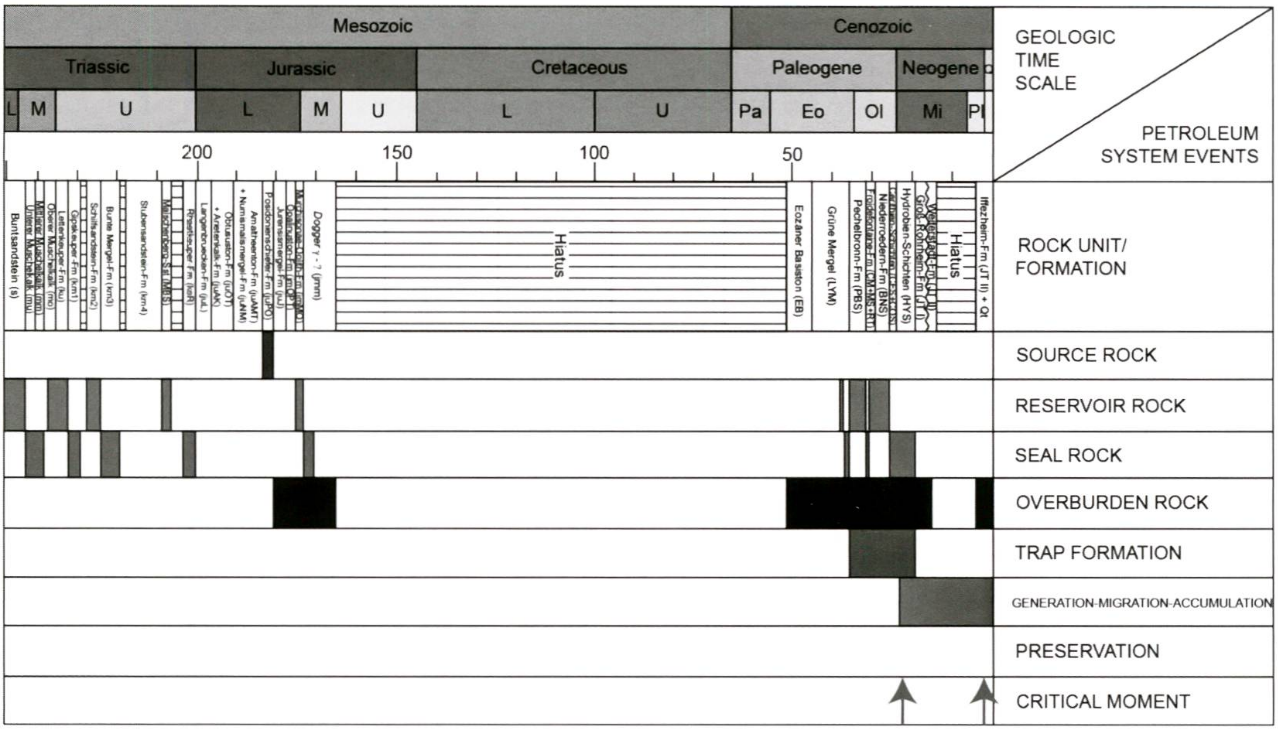

Fig. 7: Lower Toarcian Posidonienschiefer Petroleum System chart (modified after Bruss 2000).

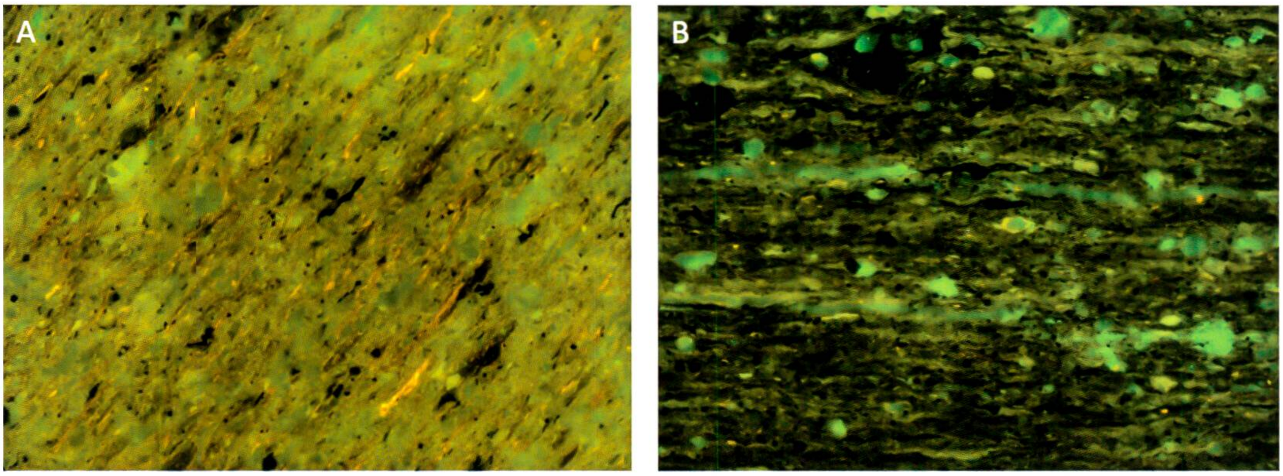

Fig. 8: Thin section photographs under fluorescence (blue light) mode showing abundance of organic matter within Liassic oil shales from well Mingolsheim 1968. A: Posidonienschiefer, TOC 7.5%. Organic material mostly composed of yellow fluorescing alginite and some sporinite. Black material mostly pyrite, dead oil and few inertinite within a calcareous marly matrix. B: Arietenkalk, TOC 10.4%. Organic material dominated by non-fluorescing vitrinite and to a less extent inertinite with a few yellow fluorescing sporinite within a calcareous marly matrix. Horizontal length of photographs: 8 mm.

5 Reservoir Rocks

5.1 Tertiary Reservoirs

Main Tertiary reservoir rocks in the northern URG are the sandstones of the Upper Eocene to Lower Oligocene Pechelbronner Schichten (PBS), which are productive in several fields including Eich, Stockstadt and Schwarzbach as well as in Pechelbronn. Thickness and sediment distribution of the PBS in the northern URG are on a regional scale (>5-10 km) controlled by syn-sedimentary tectonic activity (Fig. 9). Half-grabens were active during deposition and are often visible as sediment wedges on 3D seismic. On a basin scale, gross thickness increases from a few metres in the north of the URG to more than 600 m in the central part of the URG basin (Doebl 1967). The PBS in the northern URG are litho-stratigraphically subdivided in three intervals: The Lower, Middle and Upper PBS respectively (Straub 1962; Plein 1992, Fig. 9). The Lower PBS are represented by a sequence of massive, coarse grained (conglomeratic) sandstones with frequent shale intercalations. Deposition took place in a fluvial environment with rivers generally draining south-westward through a lake and moor landscape. The upper part of the Lower PBS tends to show an increasing degree of marine influence, usually represented by a fining-upward trend. The shale dominated Middle PBS represent a marine flooding event characterized by marine to brackish depositional environments. The Upper PBS interval was deposited during a period of sea level fall in the transition zone of freshwater lakes and fluvial dominated deltas advancing from the west and inter-fingering with the remnant brackish/marine settings (lagoons?) of the basin centre (Gaupp & Nickel 2001). The Upper PBS interval is characterized by a coarsening upward sequence, with generally medium bedded, fine-grained calcareous sandstones. Provenance analysis of drilling cutting material indicates a clastic sediment influx from both, western and eastern graben shoulders during the deposition of the PBS (Perner 2015). Primary clastic input from the western graben shoulder is characterized by eroded and re-deposited Rotliegend sediments. Conversely, minor clastic influx from the eastern graben shoulder is composed of granitic and gneiss rock fragments from the Mid-German Crystalline Rise along the Odenwald hills (Perner 2015).

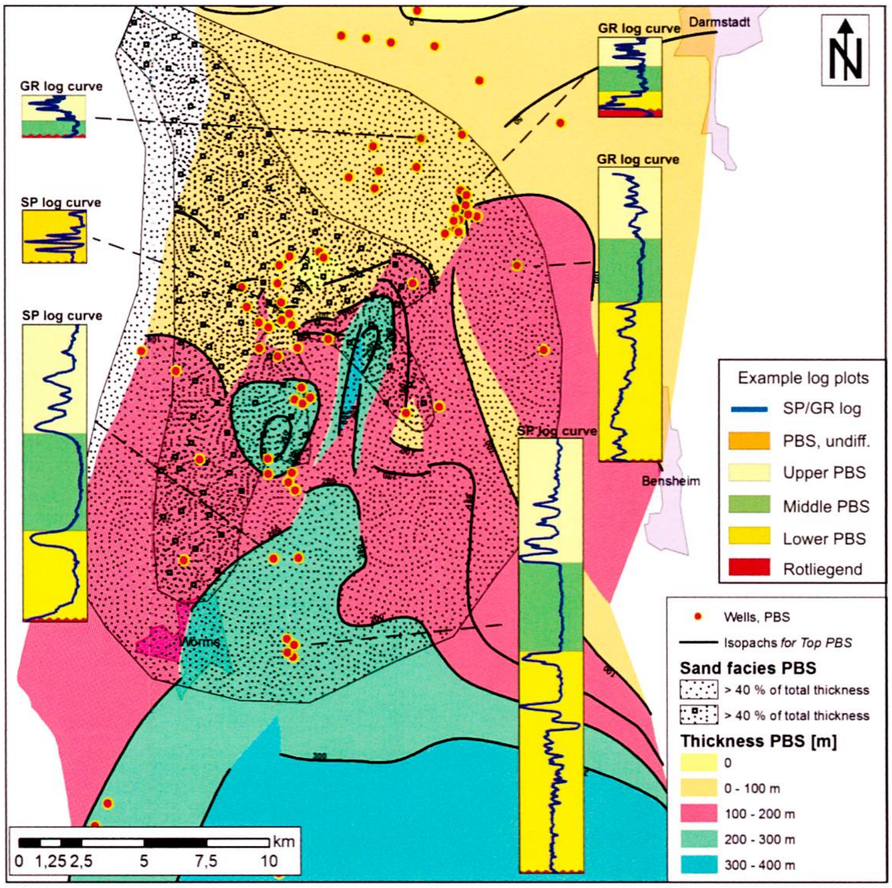

Fig. 9: Thickness map of the PBS in the northern URG with typical SP/GR-log signatures. (SP logs modified from Derer 2003; GR logs from own data).

In addition, thin streaks of porous sandstones with limited lateral extent are intercalated mainly in younger sediments of Oligocenian age. They were productive in several fields within the central URG, e.g. Leopoldshafen, Rülzheim, and Graben. The Bunte Niederroederner Schichten (BNS) were deposited during Latest Rupelian?/Early Chattian in a graben-wide system of lakes and braided rivers, a period in which communication with the wider marine realm was interrupted at both graben ends. The widely and uniformly distributed Cyrenen-Mergel (CM) was deposited in a varying marine/brackish environment (predominantly brackish) under a temperate to humid climate (Grimm et al. 2011). Sedimentation took place mostly under low-energy conditions but sequential coarser sediment input inferring some regional higher-energy fluvial involvement. The depositional environment during sedimentation of the Rupelian Meletta-Schichten (ME) was marine at the base and became more brackish to the top. During deposition of the ME the sea flooded also the eastern and western graben shoulders, with main palaeocurrents moving to the north (Martini & Müller 1971, Martini 1982).

5.2 Mesozoic Reservoirs

Before the Römerberg Buntsandstein oil discovery, Mesozoic reservoir targets were considered to be of minor importance. Where developed, they were not overly productive like in Rot, Weiher, and Offenburg fields. The main reservoirs include sandstones of the Middle Keuper (Schilfsandstein, Malschenberg-Sandstein) and the sandstones from the Middle and Upper Buntsandstein, minor ones are the carbonates of the Lower Keuper and Upper Muschelkalk. South of Karlsruhe the oolitic carbonates of the Mid Jurassic Hauptrogenstein (Bajocian-Bathonian) are another reservoir (Wetzel et al. 1997). The reservoir

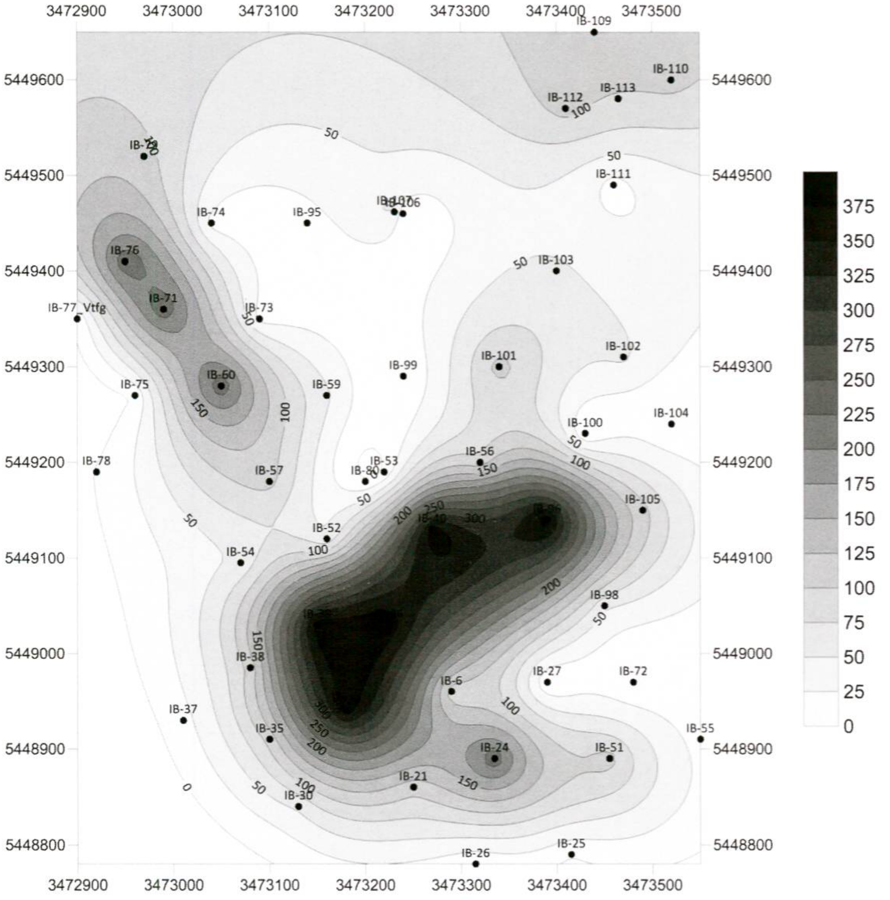

Fig. 10: Initial average production rates [bbl] of the Weiher field. Higher production rates can be correlated with larger reservoir thickness of a NE-SW trending channel fill and a NW-SE oriented fault defined by 3D seismic (production data compiled from Wirth 1950).

quality of the Mesozoic reservoirs is controlled by lithofacies, diagenetic overprint, and occurrence of open fractures.

Lateral reservoir heterogeneity is well documented in the Middle Keuper Schilfsandstein reservoirs by more than 50 wells in the Weiher field. Fluvial channel fill sandstones grade laterally and vertically into flood plain shales over short distances (Wurster 1964; Ricken et al. 1998). Furthermore, the rather unpredictable production behaviour of the Schilfsandstein reservoirs is best explained as channel fill sandstones with varying porosity and dissected by faults and fracture corridors (Fig. 10) which can be well below 3D seismic resolution.

The Lower Triassic Buntsandstein has become the most important reservoir in the Mesozoic since the Römerberg discovery. The Buntsandstein consists almost exclusively of fluvial sandstones (Leiber et al. 2011). The reservoir extends from the base of the Middle Buntsandstein up close to the top of the Upper Buntsandstein. Some wells drilled a total thickness of up to 350-400 m for this interval (wells listed in Backfisch 1984; Junghans 2003; Leiber et al. 2011). Lithofacies, depositional patterns as well as diagenetic overprint influence reservoir properties like in overlying Mesozoic reservoirs (Wachutka & Aigner 2001; Haffen 2012; Soyk 2015). In addition, natural fractures enhance matrix permeability considerably. Outcrops and mines in the graben shoulders show a fracture network of orthogonal cross joints north of Karlsruhe (e.g. Röhrer 1916, Joachim & Smykatz-Kloss 1985). The time of emplacement of hydrothermal veins in the fracture network and the tilting of fault-bounded blocks along the graben margins allow to date the formation of the fracture network in relation to the onset of rifting. Own data suggest that the development of the fractures predates the evolution of the URG.

Single joints of both sets often end at clay seams along bedding surfaces. This restricts their spatial dimensions and consequently the connectivity of the fracture network. However, with regard to production performance, the most important feature enhancing the production are fracture corridors. They consist of parallel joints clustered in narrow vertical zones, only a few meters wide (Fig. 11).

Fracture corridors tend to follow the orientation of the orthogonal cross joints but their dimensions are quite different. Vertically, they extend across the entire reservoir thickness of the Buntsandstein and, at some

Fig. 11: Fracture corridor in the Upper Buntsandstein in the quarry of Langensoultzbach, Alsace, France (R 3407640, 5428450; GK3, DHDN/PD, Rauenberg, Bessel). The fracture corridor stops at the shale unit at the top of the Buntsandstein (Röt Formation).

places, they even propagate into younger Mesozoic strata. Their horizontal length can reach several kilometers. Seismic fracture detection techniques on 3D seismic as well as fracture mapping in mines in the graben shoulders are instrumental to appreciate their geometrical architecture, orientation, and extent.

Fracture corridors propagate at the cost of other joints (Olson 2004). This explains why the rock between such corridors shows little jointing. The spacing between such fracture corridors can be very wide such that even in large quarries they are rarely seen (e.g. Haffen 2012). Also, the relationship between joint spacing and bedding thickness (e. g. Ladeira & Price 1981) does not hold for fracture corridors.
The degree of inter-fracture-corridor connectivity is very high. This can be ascribed to the simultaneous development of fracture corridors in orthogonal directions to each other as well as to the large vertical and lateral dimensions. There is no dominance of a certain fracture orientation, i.e. there is no secondary joint set which terminates at a primary one. In contrast to the single joint sets, the fracture corridors add essential reservoir permeability in an already producible reservoir.

Outcrop studies in other clastic reservoirs of the Mesozoic indicate that they are susceptible for a clustering of joints as well. However, their lower reservoir thickness in comparison with the Buntsandstein degrade the spatial dimensions of the fracture corridors and their degree of connectivity. Therefore, the lithofacies and the diagenetic overprint are still the primary factors controlling the reservoir properties for these other clastic reservoirs.

6 Structural style and hydrocarbon traps

The long exploration history spawned plenty of publications on the structural architecture of the URG. For example, the compilations of Breyer (1974), GLA/BRGM (1979), GLA (1981), and GeORG-Projektteam (2013) contain structure depth maps for several stratigraphic horizons on a regional scale. Durst (1991) summarized the different types of hydrocarbon traps in the URG. He focussed primarily on structural traps like fault-bounded three-way dip closures along the central graben axis (e.g. Leopoldshafen field) and horst blocks (e.g. Eich field). However, due to the relatively sparse 2D seismic coverage, little detail has been published on the structural style of the URG. This changed with the availability of 3D seismic, albeit in a rather patchy way.

The structural style and the associated hydrocarbon traps are the combined result of multiple tectonic phases in the Cenozoic. The tectonic phases overprinted the preexistent basement fault patterns. An extensional regime in an approximate WNW-ESE direction prevailed during late Eocene and in the Oligocene. It was followed by sinistral wrench faulting starting in the late Oligocene. It remains active to date with a regional maximum horizontal stress ($\sigma H = \sigma 1$) running NNW-SSE to NW-SE (e.g. Illies 1975; Schumacher 2002).

Both the multiphase evolution and the structurally heritage contributed materially to a complex structural style embracing the following tectono-sedimentary features:

6.1 Abutting relationships of faults

Faults active during the early rifting run mainly in a NNE-SSW direction. They are very prominent features ranging horizontally from a few kilometers to tens of kilometers in length. Upon re-orientation of the regional stress field, faults of clearly smaller dimensions developed in a NNW-SSE direction. On 3D seismic it can be clearly observed how some of the early NNE-SSW oriented faults morph upward into the NNW-SSE oriented faults (Fig. 12) which are arranged in «en-echelon» pattern up to a few kilometers apart. The re-orientated faults often root in the Cerithien-Schichten and Corbicula-Schichten of the late Oligocene.

Major NNE-SSW oriented faults can cut through the whole sequence of Tertiary sediments. The NNW-SSE trending faults usually abut against these major faults. Local depocentres developed at the junctions between both fault trends. The depocentres follow the NNE-SSW oriented faults (Fig. 13). The occurrence of depocentres is due to a strain partitioning between both fault trends. The NNW-SSE oriented faults accommodate the deformation by normal faulting whereas strike slip or minor transtensional slip dominate on the NNE-SSW oriented faults.

6.2 Strain localization and fault density

The footwall blocks of major NNE-SSW oriented faults are often free of secondary faults. Analogues from outcrops indicate that the strain was focused onto the fault

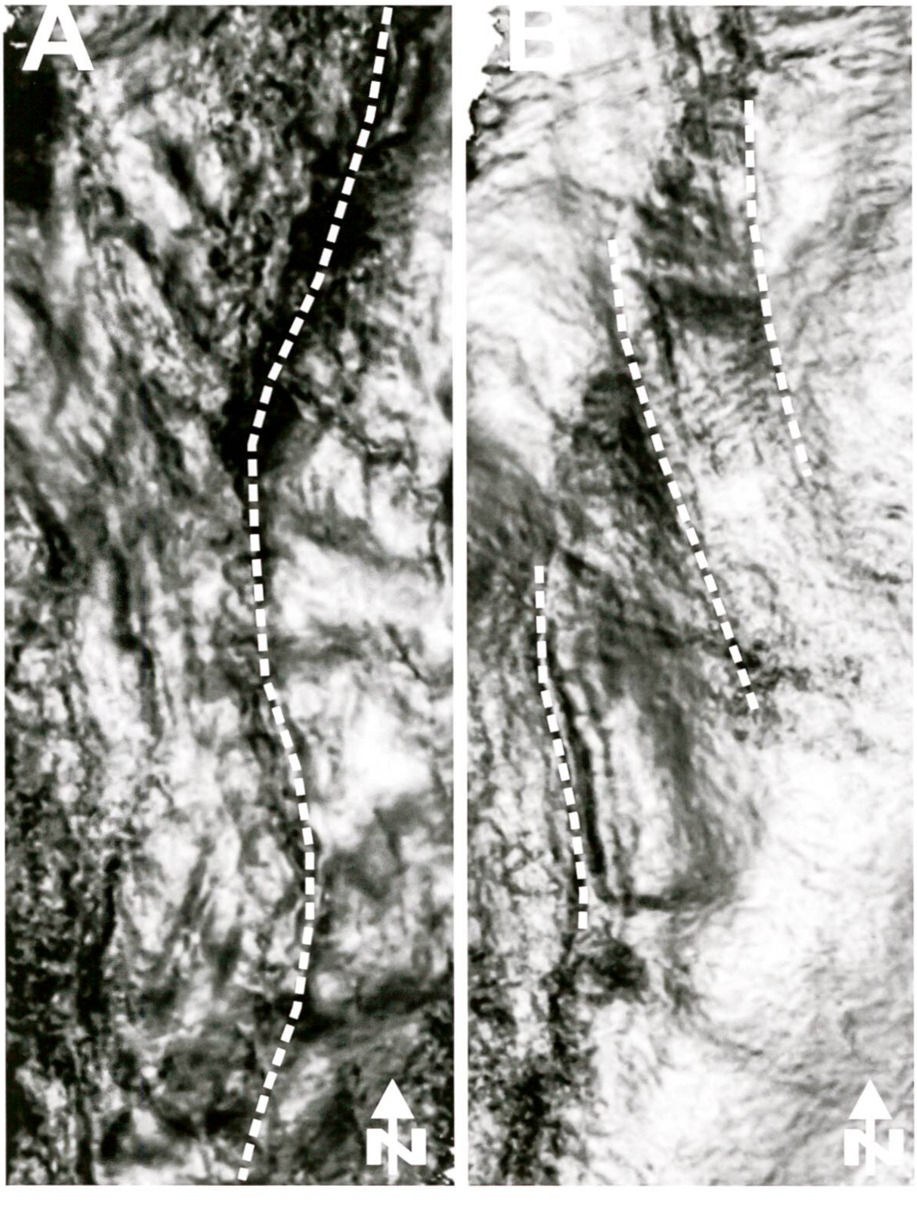

Fig. 12: Time slices of a 3D seismic as a coherency attribute. A: Time slice through the early rift sediments with an NNE-SSW oriented fault zone. B: Time slice through the Miocenian rift sediments in the same area. The fault zone morphed into three «en-echelon» faults.

planes (Ackermann & Schlische 1997). In the footwalls stress shadows developed where the differential stress was too low to generate secondary faults.

Conversely, NNW-SSE oriented faults are numerous especially in the sediments of the late Oligocene and early Miocene (Cerithienschichten – Untere Hydrobienschichten). As this section consists of partly unconsolidated or poorly consolidated sediments, tectonic strain is accommodated in a more ductile way by forming abundant minor faults. This explains why seismic sections often show the highest fault density in the sediments of late Oligocene and early Miocene (Fig. 14).

6.3 Relay ramps

The 3D seismics exhibit a high density of transfer zones between faults of the same orientation. Different styles of the transfer zones can be distinguished in line with the classification scheme of Morley et al. (1990). Their common feature is that the transfer zones are relay ramps according to the definition of Peacock et al. (2000), i.e. the area of tilting between the faults is not dissected by connecting faults (Fig. 15). This observation is independent of the fault orientation.
The occurrence of relay ramps indicates an accommodation of low finite strain (Schlische et al. 2002). Higher strains would result in a breach of the relay ramp by a connecting fault (Peacock 2002). The abundance of relay ramps is probably increased by the weak consolidation of the Tertiary sediments. This favours a ductile deformation.

The published maps based on interpretation of 2D seismic rarely resolve relay ramps.

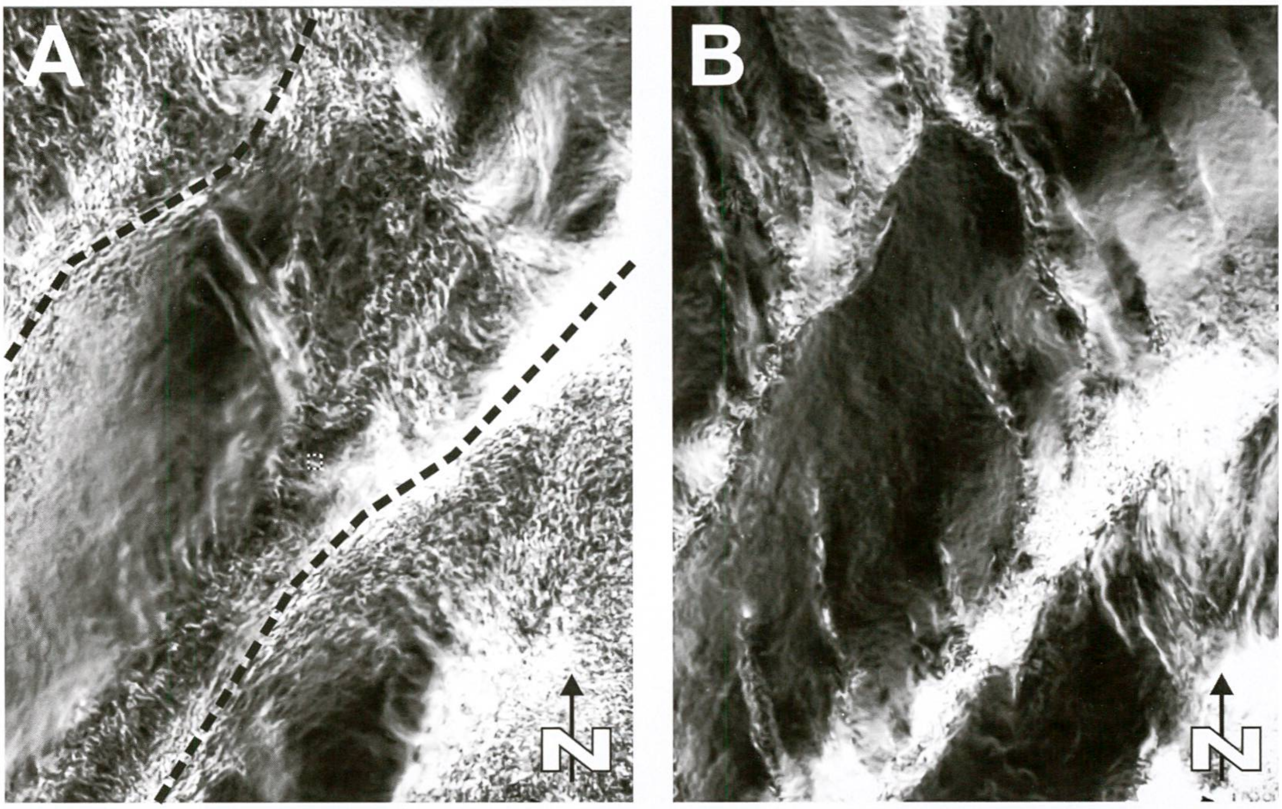

Fig. 13: Time slices of a 3D seismic as a coherency attribute. A: Time slice through the early rift sediments with two major NNE-SSW oriented faults (dotted lines) dipping to the west, NNW-SSE oriented faults nearly absent. B: Time slice through the post-rift sediments in the same area. NNW-SSE oriented faults are very prominent as thin white streaks. They stop at the major faults with the orientation NNE-SSW. Downward dip slip at NNW-SSE trending faults and oblique slip on NNE-SSW oriented faults entail a string of local depo-centres (white patches) in the strike direction NNE-SSW.

Instead, the maps often show transfer faults in an approximate E-W orientation. Some of the transfer faults seem to extend even all across the URG. The other fault trends are interpreted to stop at these transfer faults. However, the 3D seismic available to the authors do not image transfer faults at all, at least above the vertical resolution of the 3D seismic. Unfortunately, any 2D seismic interpretation is impaired by scarce and poor quality data in the URG area (s. Fig. 1). Line spacing is often larger than the lateral dimension of a relay ramp. Thus, 2D seismic interpretation is hampered by aliasing issues. This results in a misalignment of fault trends, overestimation of fault lengths, and postulation of transfer faults. We find that bimodal fault length distributions often indicate aliased interpretation results.

6.4 Fault-related folding

Laubscher (1982) and Ford et al. (2007) report on fault-related folding in the southernmost part of the URG. 3D seismic data confirm their observations as a ubiquitous feature for the URG where a sedimentary cover is present. Generally, a fault-related fold develops in the sedimentary cover above a basement fault. Initially, reactivation of a basement fault bends the unfaulted cover towards its proto-hanging wall. Ongoing movements along the basement fault lead to the evolution of a fault zone within the bended sedimentary cover (Fig. 16). Finally, the breach of the cover results in a highly complex fault pattern within the bended zone (Withjack et al. 1990). A syntectonic deposition in the hanging-wall pro-

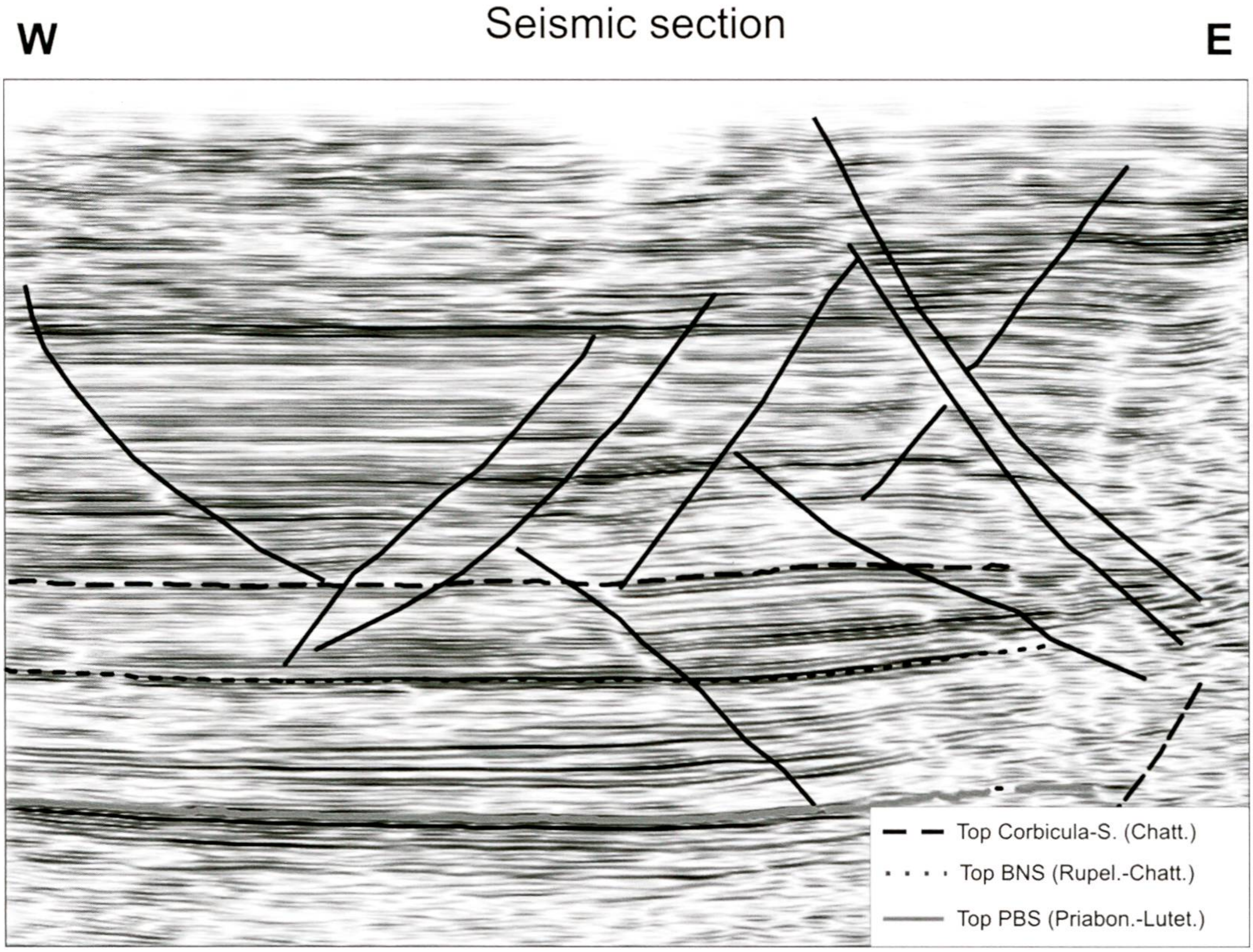

Fig. 14: Seismic section showing the vertical variation of fault density in the rift sediments. The Corbicula-Schichten of the late Oligocene display the highest fault density.

duces an onlap onto the pre-rift sequence.

Taking into account the block rotation due to the isostatic relaxation in rift settings (e.g. Weissel & Karner 1989), the Cenozoic strata dip into the opposite direction of the Mesozoic sediments. At depth, Mesozoic sediment closures against a major fault are frequent in the URG. In contrast, the Cenozoic sediments show an antithetic dip towards major faults, at some places even with crestal collapse features.

Some authors assumed faults in order to explain the absence of early synrift sediments in the vicinity of the graben boundary (e. g. Wirth 1962). However, on 3D seismic an onlap of the Tertiary units onto the tilted Mesozoic strata is clearly visible. Furthermore, the repetition of strata in wells close to the graben boundary was taken as a result of a regional inversion in the URG area (e. g. Illies & Greiner 1976, Hauber 1991). Withjack et al. (1990) and Schlische et al. (2002) modelled an intricate fault network between the hinge lines of the fault-related fold containing even reverse faults and overturned normal folds, all triggered by an event of regional extension. Applying this to the URG, we suggest that the repeated sections in wells located between the hinge lines of the fault-related folds are not a conclusive evidence of regional compressive tectonics in the URG. It can be caused by a regional extension as well if the sedimentary cover is folded above an active basement fault.

In summary, the 3D seismics captured a complex structural style in the URG area. The understanding of the structural style is a precondition for successful hydrocarbon exploration. In some instances, the 3D seismic even discarded structural traps where

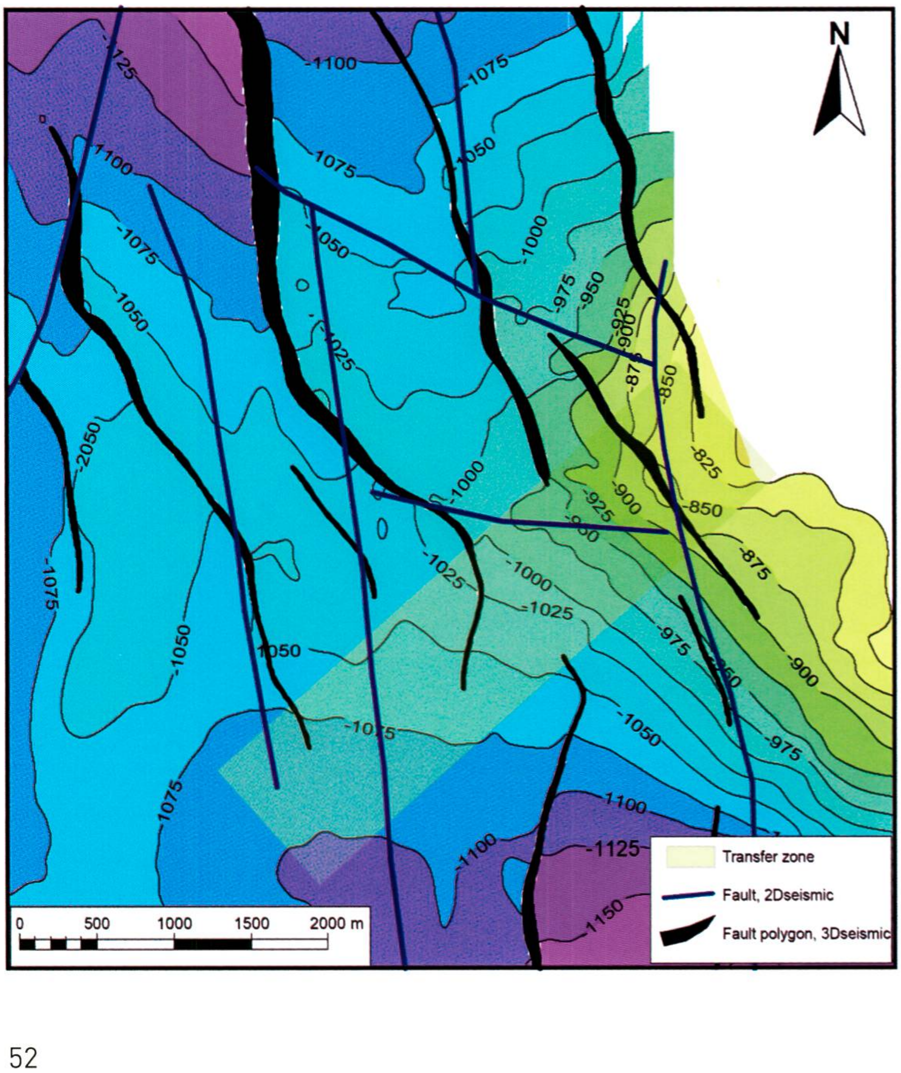

Fig. 15: Horizon slice in two-way traveltime from a 3D seismic. Several relay ramps form a NE-SW trending transfer zone. No connecting faults exist in the transfer zone. The fault lines from 2D seismic do not honor the transfer zone and the fault trend. They delineate transfer faults in an orientation WNW-ESE which is not seen in the 3D seismic.

hydrocarbon discoveries were made pointing to the existence of stratigraphic traps. The structural style has also a marked influence on the stratigraphic record. For example, relay ramps affect locally the facies distribution (Gawthorpe & Hurst 1993; Athmer & Luthi 2011). They act as a local conduit for sediment transport as Gaupp & Nickel (2001) and Derer (2003) suggested it for the PBS of the northern URG (s. Fig. 9).

7 Conclusions

Triggered by the large Roemerberg oil discovery in 2003, the long history of hydrocarbon exploration and research in the URG received a renewed impulse resulting in new insights into the petroleum systems and the structural evolution of the URG rift basin.

- Both, pre-rift (Posidonienschiefer) and syn-rift (Fischschiefer) oil shales are the most prolific source rocks. Their occurrence, areas of maturity, and mixing of expulsed hydrocarbons result in a variety of different oil families. While Tertiary oils dominate in the north, more mixed oil provenances are observed in the central URG where the Posidonienschiefer are preserved below the base of the rift sequence.

- Similarly, pre-rift Lower Triassic Buntsandstein and syn-rift lower Tertiary Pechelbronn beds provide the key clastic reser-

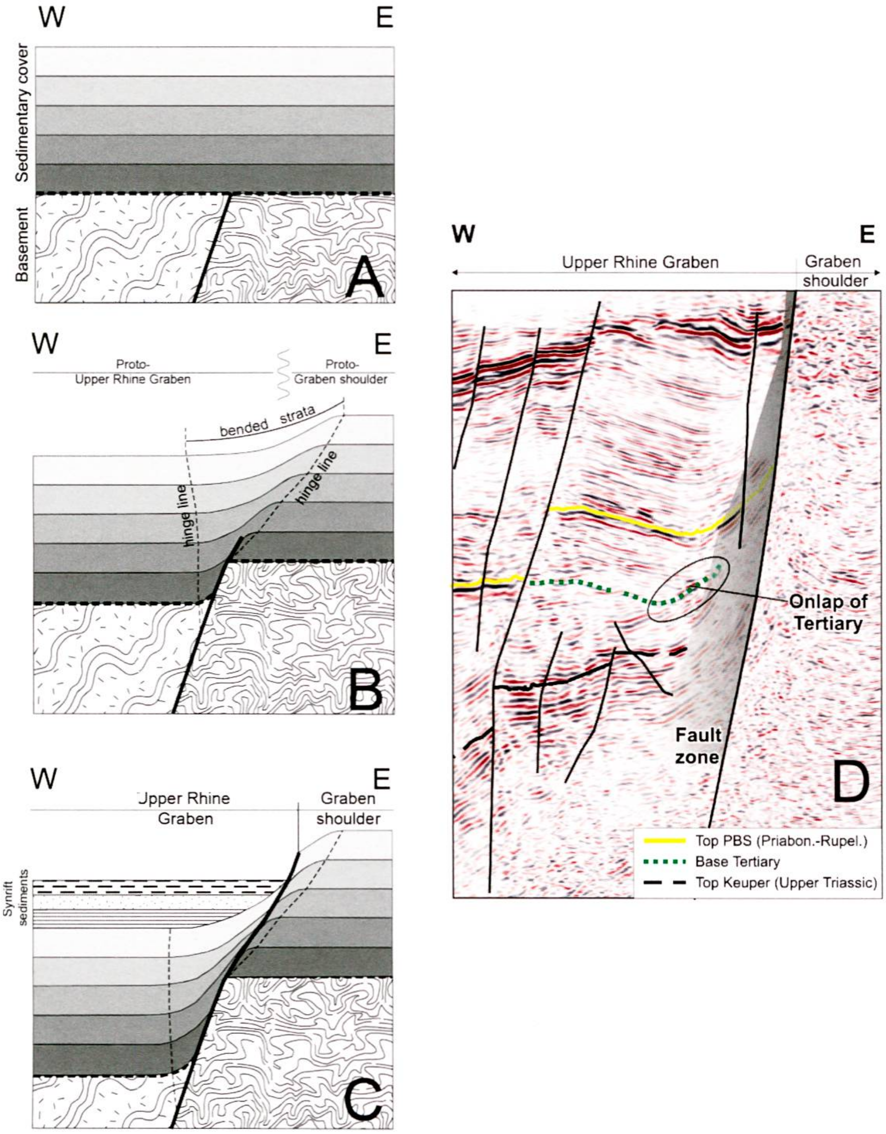

Fig. 16: Fault-related folding in the URG. A-C: Development of a fault-related fold at the graben boundary. The bended strata within the hinge lines of the fold are riddled with secondary faults as shown by Withjack et al. (1990), but not shown here for the sake of simplicity. D: Seismic section with fault-related folding. The Mesozoic strata dips towards the graben centre in the west, the Cenozoic dips to towards the graben boundary in the east.

voirs in combined fault-dip trapping configurations. PBS reservoir development can vary strongly due to the syn-rift depositional setting. Conversely, the regionally extensive Buntsandstein reservoirs are most affected by diagenetic effects and / or burial overprints. The development of fracture corridors can add substantially to reservoir productivity in combined fracture/matrix reservoir systems.

- Tertiary targets prevail in the northern URG, while combined Mesozoic and Tertiary plays are developed more in the central part due to preservation of a more complete section below the Tertiary unconformity.
- A key contributor to the greatly improved structural understanding of the URG is the growing 3D seismic coverage. It reveals a multiphase structural evolution of the basin and explains hitherto poorly understood structural settings including shifting tectonic stress regimes over time and complex constellation particularly along the basin boundary fault zones. It is envisaged that further 3D coverage and detailed seismic interpretation may add significant new structural as well as stratigraphic hydrocarbon potential.

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