Germany – Overview about Renewed Petroleum Activities*

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Introduction

Germany has a long history of hydrocarbon exploration. Modern-type oil and gas operations date back to the late 19th century, with the peak indigenous oil production achieved during the 1960s and gas production in the 1980s (Figure 1).

The country's petroleum provinces are found in the Northwest and Northeast German basins, Thuringian Basin, Upper Rhine Graben, and Molasse Basin (Figure 2). Hydrocarbon development of these areas is linked to a polyphase tectonosedimentary history that led to the formation of a variety of reservoirs. The most prolific petroleum province, holding the vast majority of to-date discovered resources, is in NW Germany. Next to traditional petroleum plays, since mid-2000s, increased activity relates to exploration of the natural gas from organic-rich shales and coals (CBM).

The following briefly describes the aforementioned petroleum provinces and lists the traditional, as well as emerging, hydrocarbon systems, drawing attention to a few recently unfolding activities.

Northwest German Basin

The onshore/offshore basin (Figure 3), part of larger epicontinental sag, extends for 550 km in the E-W and 350 km in the N-S directions. It is subdivided into several tectonic units, of which the Lower Saxony Sub-basin and the West Holstein troughs are the most prolific. The evolution of the basin started in the late Early/early Late Carboniferous. The Carboniferous- Quaternary basin fill is approximately 10 km thick and overlies unconformably the basement composed of the Lower Paleozoic successions deformed during the Caledonian orogeny.

The principal source rocks in the basin are formed by Upper Carboniferous coals, which are the main source of gas. The Lower Carboniferous argillaceous series likely form an additional source. Marine Liassic shales (Posidonia) represent the primary source rock for oil, responsible for charging the bulk of the basin's accumulations, including the country's largest oil field, Mittelplate (West Holstein

Trough). The Berriasian lacustrine paper shales (Bückeberg Formation) form a minor oil and gas source. The reservoirs are found in the Upper Carboniferous to Pleistocene series and include: Upper Carboniferous fluvial sandstones, Lower Permian fluvio-aeolian sandstones, Upper Permian carbonates, Triassic fluvial and marginal marine sandstones and marine limestones, Jurassic and Lower Cretaceous shallow marine sandstones and limestones, Upper Cretaceous chalk and shallow marine sandstones, as well as Tertiary shallow-marine sandstones. The principal gas reservoir in the basin is the Lower Permian (Rotliegend) aeolian sandstone, while the main oil reservoirs are shallow-marine sandstones of the Middle Jurassic (Dogger) and Lower Cretaceous (Berriasian-Hauterivian) age.

An early phase of methane gas generation just north of the Lower Saxony Sub-basin is proposed to have formed during the Late Carboniferous-Early Permian. The then generated gas was lost, likely due to poor seal integrity. The initial generation phase was followed by a major period of methane gas generation during the Triassic-Middle Jurassic (gas generation from the Namurian source was likely exhausted during this period). The Triassic/Jurassic gas was probably also lost to a great extent due to uplift and erosion during the Late Jurassic-Cretaceous. When burial was reestablished during the Tertiary, more methane gas with nitrogen was generated. In the regions in the northern part of the basin, where the Carboniferous series is found at great depth (>5,000 m), methane gas (and nitrogen) generation commenced during the Late Carboniferous-Early Permian. Gas generation potential of the Namurian source was likely exhausted during this period, and only minor volume of gas was generated in the Mesozoic times. During the Tertiary, nitrogen gas with minor methane gas was generated.

The Jurassic source (Posidonia) generated oil during two main phases: Hauterivian-Santonian and Eocene-Miocene, interrupted by latest Cretaceous basin inversion (the unit, in places, is considered active at the present day). The Berriasian shales generated oil during the Albian-Santonian in the deepest parts of the basin and during the Tertiary times in the other areas, when burial was restored following the Late Cretaceous uplift (early trapped hydrocarbons were lost due to inversion). Noteworthy, trap formation in large portion of the Northwest German Basin is closely related to the movements of the Zechstein evaporites.

Three petroleum systems are recognised in the basin:

1) Upper Carboniferous – Rotliegend
   The system accounts for approximately 90% of all discovered gas and condensate.
2) Jurassic (Posidonia) – Mesozoic/Tertiary
   The system accounts for >80% of the oil found in the Lower Saxony Sub-basin.
3) Lower Cretaceous (Bückeberg) - Upper Jurassic-Lower Cretaceous
   The system is known in a number of oil/gas pools in the western part of the basin.

The Northwest German Basin holds over 400 fields/discoveries (*cf*. Figure 2) and is mature for hydrocarbon exploration. A number of still existing exploration prospects is associated with stratigraphic and structural traps that have so far proven difficult to image. The Permian series is considered to still have good remaining hydrocarbon potential and has been targeted in recent years. The Carboniferous reservoirs prove a good exploration target, as well. Recent activities relate to tapping into the remaining potential within the Jurassic and Cretaceous series.

Valid exploration permits cover all the prospective acreage in northern and northwestern Germany. Although the operators are chiefly engaged in maintaining the existing production, e.g. redevelopment of the Emlichheim oil field, new exploration projects are being put forward. For example, in 2010, wildcat Goldenstedt Z23 successfully tested the Carboniferous series, while the wells Böstlingen Z2/Z2a and Gritsiel West Z1 tested gas in the Rotliegend strata. Furthermore, in the vicinity of the Mittelplate oil field, domestic operator intends to drill up to four wells to prove the area's remaining hydrocarbon potential, estimated at some 160 million barrels of oil.

Since 2006/2007, increased activity is associated with exploitation of the natural gas from organic-rich shales and coals (CBM). The players on the unconventional scene hold over a dozen contracts/applications in the Lower Saxony (Niedersachsen) and Nordrhein-Westfalen political provinces. In addition, some domestic operators are conducting feasibility studies of the prospective areas.

Six wells were drilled so far to unravel the hydrocarbon potential of the Jurassic (Posidonia) shales. Next to gaining the information on the petrophysical characteristics of the unit, at least one well was stimulated/tested and yielded encouraging initial results. Additional wells were drilled near Osnabrück to assess the potential of Carboniferous coals. The operations are currently on-hold, as the authorities of the implicated political provinces ordered an environmental study on the effects of the hydraulic stimulation. The outcome of the study is awaited with much interest.

Northeast German Basin

The basin is located onshore/offshore northeast Germany (Figure 4), extending into Poland. Its axes are roughly 700 km in the NW-SE and 330 km in the NE-SW directions. The Northeast Mecklenburg and Northeast Brandenburg are its most important sub-basins.

Though the Northeast German Basin shows a similar geotectonic development as the Northwest German Basin, a marked contrast is observed in the distribution of source rocks/reservoirs in both basins.

The main source rocks in the Northeast German Basin are Upper Carboniferous coals, forming the primary source of gas, and Upper Permian (Zechstein) marine shales, Kupferschiefer and Stinkschiefer, which are the primary sources of oil. Where present, marine shales of the Silurian, Devonian, Triassic, and Jurassic age could potentially form an additional source for gas.

Reservoirs are found in Lower Permian (Rotliegend) fluvial-aeolian sandstones (gas reservoir) and Upper Permian (Zechstein) carbonates (oil/gas reservoir), in particular in the Stassfurt evaporitic cycle, containing the Main Dolomite (Hauptdolomit) unit. These reservoirs hold close to 99% of all discovered hydrocarbons in the basin. Where preserved, Carboniferous shallow-marine sandstones/carbonates, Upper Carboniferous fluvio-deltaic sandstones and Keuper marginal marine sandstones are considered to bear some reservoir potential.

Hydrocarbon generation is believed to have taken place during the Early Triassic-Late Cretaceous (peak oil generation in Late Cretaceous) and during the Late Tertiary-Quaternary, interrupted by the latest Cretaceous inversion that likely resulted in loss of gas from some

pre-existing traps. Traps were set by the end-Carboniferous and end-Permian for the respective reservoirs, with seal provided by the interbedded and/or overlying shales/evaporites. Expulsion may have commenced as early as in the Late Carboniferous.

Two proven petroleum systems and a hypothetical one are discerned in the basin:

1) Upper Carboniferous - Upper Carboniferous/Permian
   The system accounts for 2/3 of discovered hydrocarbons and is responsible for the majority of gas generation (>70%).
2) Zechstein - Zechstein/Triassic
   The system accounts for approximately 1/3 of the discovered hydrocarbons and is responsible for the majority of oil generation.
3) Silurian/Devonian/Carboniferous - Late Paleozoic
   Source is assumed in Silurian/Devonian/Carboniferous marine shales (some bituminous), with potential reservoirs in Carboniferous sandstones.

The Northeast German Basin holds some 60 fields/discoveries (*cf*. Figure 2), including the Salzwedel-Peckensen group of fields. The basin is considered mature for hydrocarbon exploration and thus was dormant during the last decade, though the Permian plays are believed to have good remaining hydrocarbon potential, and the Carboniferous series are the object of new interest in Poland.

Since late 2000s, a group of operators is exploring for the residual hydrocarbon potential on the fringes of the Permian palaeobasin. A company holding four onshore/offshore tracts over the northern edge of the basin acquired 2D/3D seismic, and, in mid-2011, it drilled two wells targeting oil in Zechstein carbonates. It is understood at least one well was successfully tested.

New acreage covering the southern limit of the Permian basin has yet to tested by a drillbit, but the operations are planned. Additionally, a project on the Salzwedel-Peckensen cluster of fields is underway: in 2010 wildcat Lüchow Z1 was announced as a successful operation in the Lower Permian Rotliegend series.

Thuringian Basin

The basin, located in central Germany (Figure 5), is roughly 300 km long and 100 km wide. The Thuringian Basin was initiated as an intramontane basin during the Late Carboniferous-Early Permian Variscan events. It contains up to 2.5 km of series, mostly of the Permo-Carboniferous to Triassic age, unconformably overlying older metasediments and granitic plutons.

Main source rocks in the basin include Carboniferous coals (primary gas source) and Upper Permian (Zechstein) marine mudstones (primary oil and wet gas source). The Mesozoic organic-rich shale succession(s) could be a potential source.

The principal reservoir is formed by the platform carbonates of the Upper Permian Stassfurt cycle. Additional reservoirs include Lower Permian (Rotliegend) fluvial-aeolian sandstones and fluvial sandstones of the Triassic (Buntsandstein). Possible reservoirs include Carboniferous fluvial sandstones and fractured Paleozoic basement.

Gas generation, expulsion and migration are thought to have taken place during the Early Triassic-Late Cretaceous (although expulsion may have commenced in the Late Carboniferous). Upper Carboniferous coals are mature to overmature at present, while Upper Permian mudstones are mature for oil/wet gas generation. Two petroleum systems are identified in the Thuringian Basin:

1) Upper Carboniferous - Zechstein/Buntsandstein
   The system accounts for approximately 50% of discovered hydrocarbons and is likely the majority of gas generation and accumulation.
2) Zechstein - Zechstein/Buntsandstein
   The system accounts for approximately 50% of discovered hydrocarbons, chiefly oil.

The Thuringian Basin includes some 15 fields/discoveries (*cf.* Figure 5) and is mature. The Permian plays could hold some remaining hydrocarbon potential, while the Carboniferous series are seen as a target for both conventional and unconventional exploration. One explorer is currently active in the Thuringian Basin. It holds three blocks, targeting a series of known and potential reservoir horizons, conventional and unconventional.

Upper Rhine Graben

The SSW-NNE-trending basin is a collapsed area along the southern part of Germany-France border (Figure 6). It formed over a pre-existing Hercynian shear zone during middle Eocene-early Miocene extension. Two principal source rocks in the basin are Liassic shales and the Rupelian Grey Beds (Foraminifera Marls, Fish Shale, Meletta Beds).

The reservoir units include Buntsandstein series, Muschelkalk limestones, Oxfordian (Rauracian) strata, and Tertiary sandstones (i.e., Pechelbronn beds, Rupelian/Chattian Niederrödern series, and Miocene/Pliocene Jungtertiär sequences) and carbonates (i.e., Hydrobia Beds). Tertiary clastic reservoirs are of limited extent.

Burial sufficient for the early generation of hydrocarbons from the Liassic source could have been achieved prior to the Cretaceous/Early Tertiary times. A high heat-flow increase occurred at the beginning of the early Eocene rifting phase and is believed to be responsible for maturation of the Mesozoic sources that entered the oil window around 30 Ma. The Grey Beds series is currently mature in the northern sector of the basin, and thus oil generation and migration is believed to be still ongoing.

Two main petroleum systems are identified in the basin:

1) Liassic – Triassic/Jurassic/Tertiary
   The system is active throughout much of the basin and has generated most of the oil and gas.
2) Oligocene – Tertiary
   The system is active in the northern part of the basin.

Recent activities in the basin relate to the development of the Römerberg 1 oil discovery (incidental oil) that holds the reservoir in the Buntsandstein series. Similar structures are believed to be present in the vicinity, and a group of active operators is preparing new exploration programmes.

Molassse Basin

The basin extends for approximately 900 km from France to eastern Austria (Figure 7), traversing southern Germany where it is up to 120 km wide. The Molasse Basin is a Cenozoic foredeep, formed as a flexural response to load induced by advancing Alpine thrust units, overlapping series of the Permo-Carboniferous and/or Mesozoic ages. The thickness of the molasse deposits is close to 5000 m.

The principal source rocks in the series underlying the Tertiary units are Stephanian coal seams (gas), with Permian shaly series holding potential for oil and gas. The Middle Jurassic shales are believed to be potential source rock. The main proven sources found within the basin-fill of the central Paratethyan domain are the lower Oligocene series of the lower Marine Molasse, i.e., the Schöneck Formation, Dynow Marlstone, Eggerding Fomation, and Zupfing Formation.

The reservoir units in the Mesozoic sections include the Muschelkalk Trigonodus dolomite, Keuper Kiesel sandstone, Stuben sandstone and the Rhaetian sandstone, as well as the Lias alpha and Dogger beta sandstones, Upper Jurassic carbonates, Aptian-Albian greensand units, Cenomanian- Turonian glauconite sandstones and the upper Campanian sandstone. Reservoirs of the Tertiary basin fill include the upper Eocene Basal sandstone, Ampfing sandstone and Lithothamnia limestone, as well as middle Oligocene Isen sandstone. The Lower Marine Molasse comprises also the middle/upper Oligocene Baustein Beds and the Puchkirchen sandstones developed in turbidite/debris flow facies (often host rock of dry biogenic gas). The Upper Marine Molasse contains the Burdigalian Gendorf Sandstone, with its equivalent Hall Formation in Austria. Both Freshwater Molasse successions are devoid of productive reservoirs.

Maturity and the timing of hydrocarbon generation from the Permo- Carboniferous sources could have either been attained during the Paleozoic times (Kempter, 1987) or during the Mesozoic-Cenozoic (Kettel and Herzog, 1988). Early gas generation from the lower Oligocene series likely occurred from the latest Oligocene/Miocene times onward, and the process may still be ongoing in the kitchens beneath the thrusts. Oil generation from lower Oligocene Schöneck shales started in the Miocene and may still be continuing. Biogenic gas identified in the reservoirs in the eastern sector of German Molasse is thought to have been generated mainly from middle/upper Oligocene and basal Miocene marine shales.

Two petroleum systems are discerned in the Cenozoic basin fill:

1) Lower Oligocene – Cretaceous/Neogene
   The system is restricted to the Austrian and German sectors of the basin. Charge requesting long-distance migration is thought to have resulted also by the tectonically juxtaposed successions.
2) Oligocene/Miocene - Oligocene/Eocene/Lower Miocene

The system represents chiefly bacterial decomposition of the organic matter.

The Permo-Carboniferous/Mesozoic series could hold two hypothetical systems:

1) Permo-Carboniferous - Triassic/Jurassic
   The system would be confined to narrow grabens.
2) Jurassic - Cretaceous/Neogene
   The system would be controlled by the combined effects of facies changes and erosion.

Given the decades of exploration activities in the German Molasse Basin and a rather modest volume of hydrocarbons discoveries to date, the basin is mature in terms of exploration. Further opportunities exist, though, and relate to yet-to-be-fully-explored plays and to enhanced recovery in already known areas.

The operators currently active in the western and central sectors of the Molasse Basin are studying the possibility of exploiting conventional and unconventional targets, both in the Permo-Carboniferous/Mesozoic series, as well as within the Molasse.

In the eastern sector of the basin, activities concentrate on testing the potential existing targets within the imbricated/undeformed Molasse series. The last successful operation dates back to early 2011, when Assing R-1 was announced a gas well in the Oligocene series; two more wells are firm.

Conclusions

Germany's petroleum provinces are mature and well, to very well explored. It is nevertheless believed that the areas can still offer substantial rewards to a dedicated exploration company. To avert the long-since observed trend of declining indigenous oil and gas production, a range of new projects have been instigated in the past few years to unravel the remaining hydrocarbon potential of the individual petroleum provinces. Some of the projects have produced a remarkable degree of success (*cf.* increased recovery projects in the Northwest German Basin, revival of carbonate play in northeast Germany, substantial oil discovery in the Upper Rhine Graben, renewed interest in the Molasse area). In addition, developments on the unconventional scene unfolding since mid-2000s have yielded promising early results. If the activities receive further endorsement, the efforts to unravel the country's new potential could increase in the coming years.

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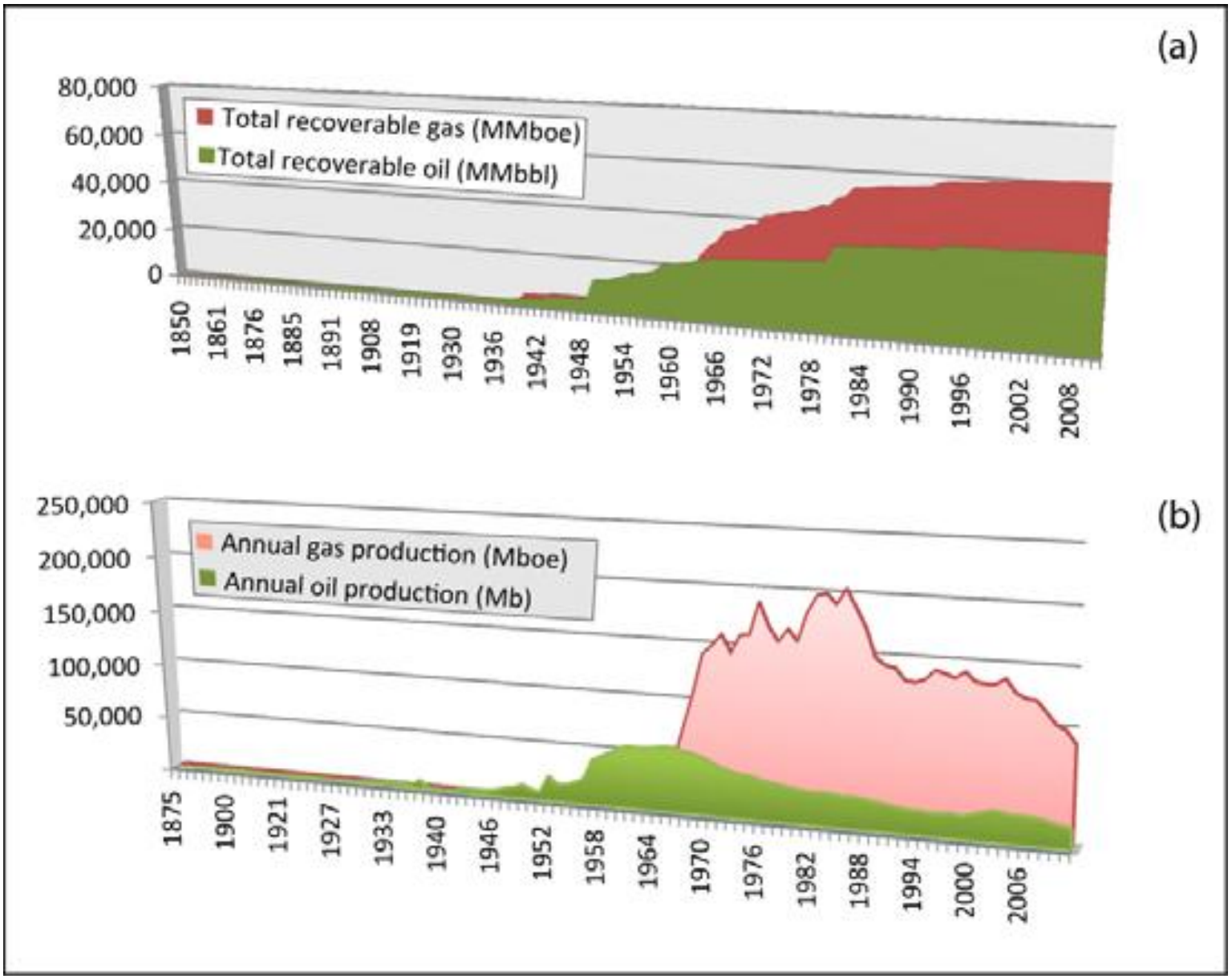

Figure 1. History of Germany--reserve addition (a) and hydrocarbon production (b).

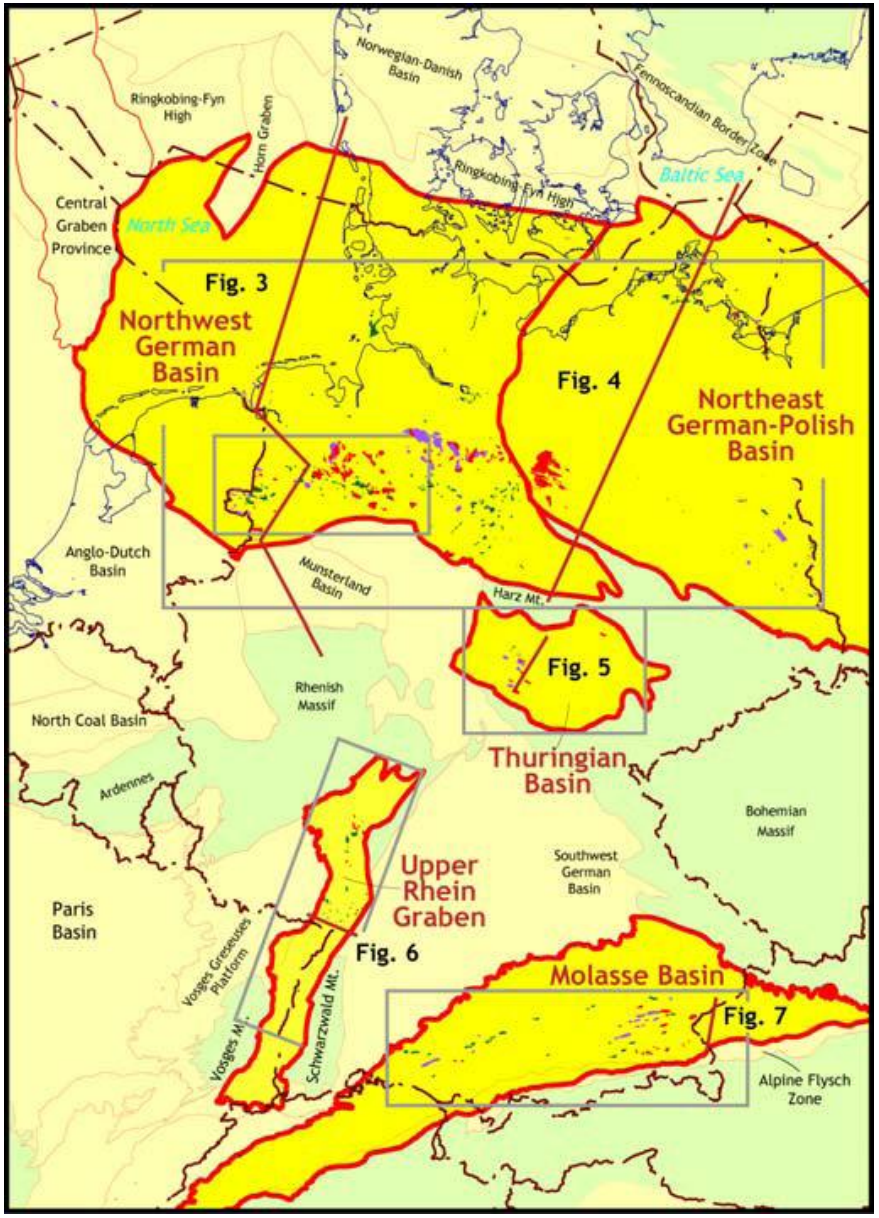

Figure 2. Map showing petroleum provinces of Germany (green - nonprospective areas). Lines indicate location of regional cross-sections in Figures 3-7.

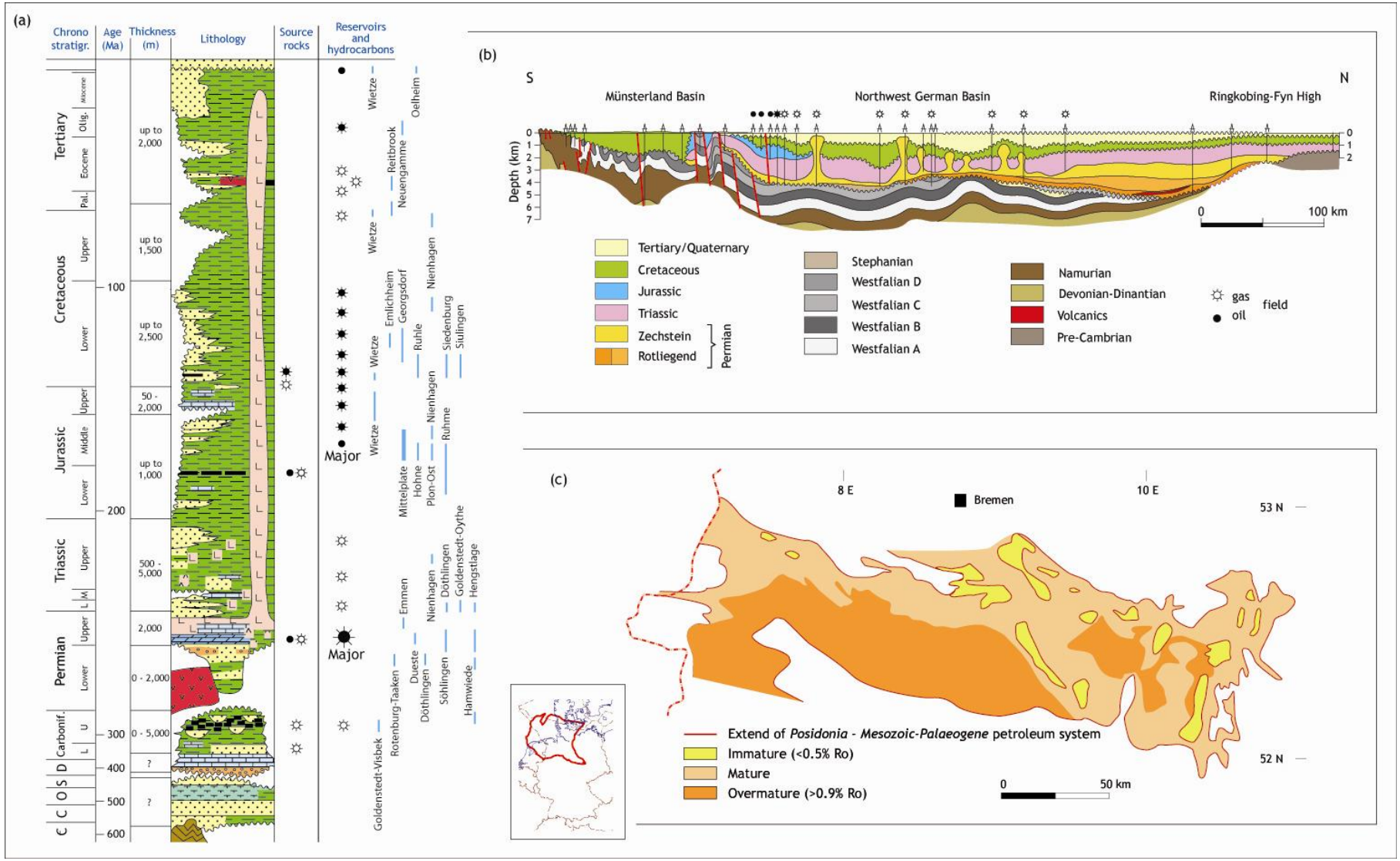

Figure 3. Overview figure of the Northwest German Basin: (a) generalised lithostratigraphic chart showing distribution of the source rocks, reservoirs, and main hydrocarbon fields, (b) regional cross-section of the basin (modified after Schröder et al., 1991) and (c) map showing extent of the Posidonia – Mesozoic/Palaeogene petroleum system in the Lower Saxony Sub-basin (modified after Kockel et al., 1994).

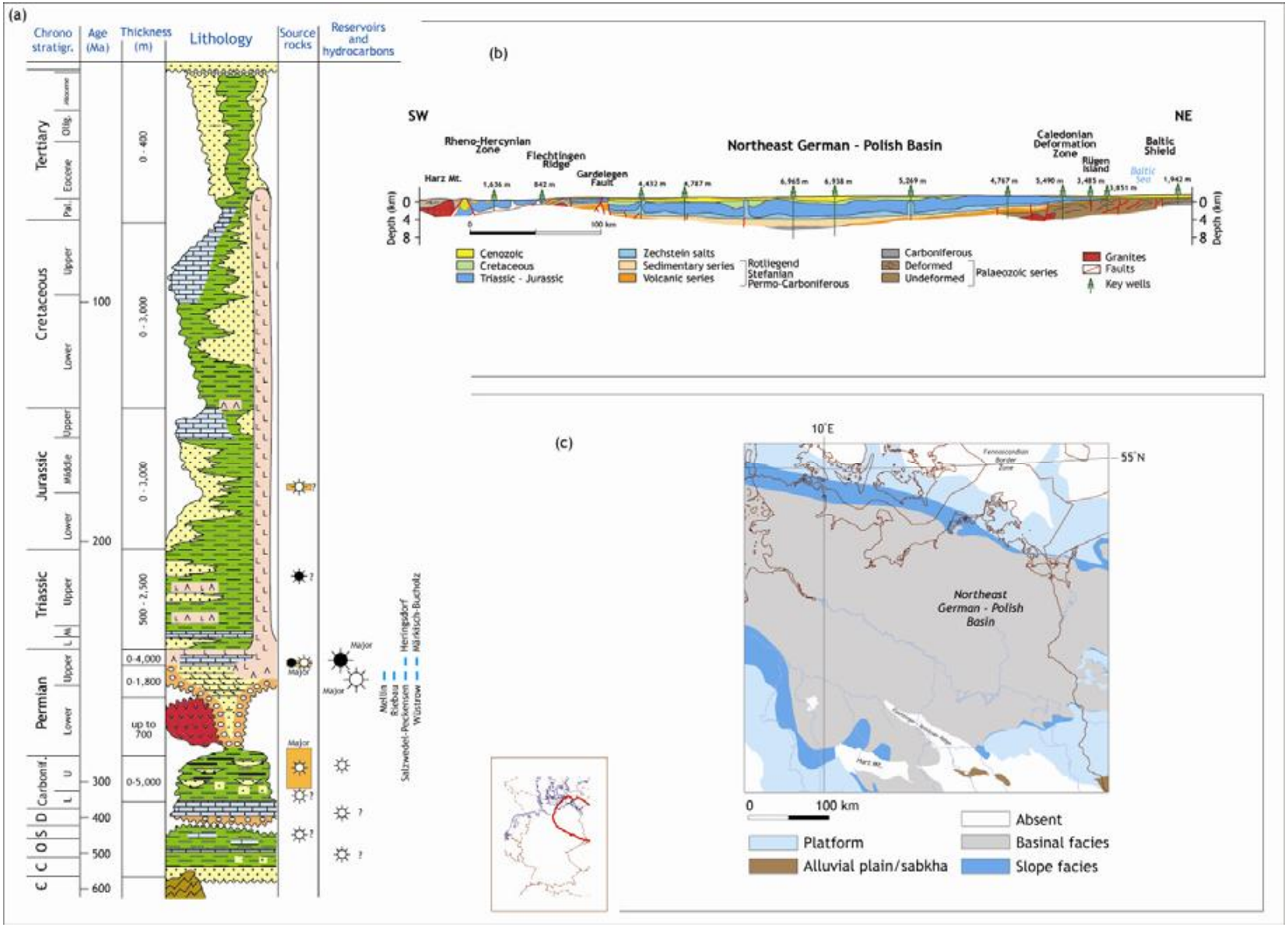

Figure 4. Overview figure of the Northeast German-Polish Basin: (a) generalised lithostratigraphic chart showing distribution of the source rocks, reservoirs, and main hydrocarbon fields, (b) regional cross-section of the basin (modified after Bachmann et al. (DECORP), 1999) and (c) map showing present day distribution of the Stassfurt facies (based on Geluk, 2005; Doornenbal and Stevenson (eds.), 2010).

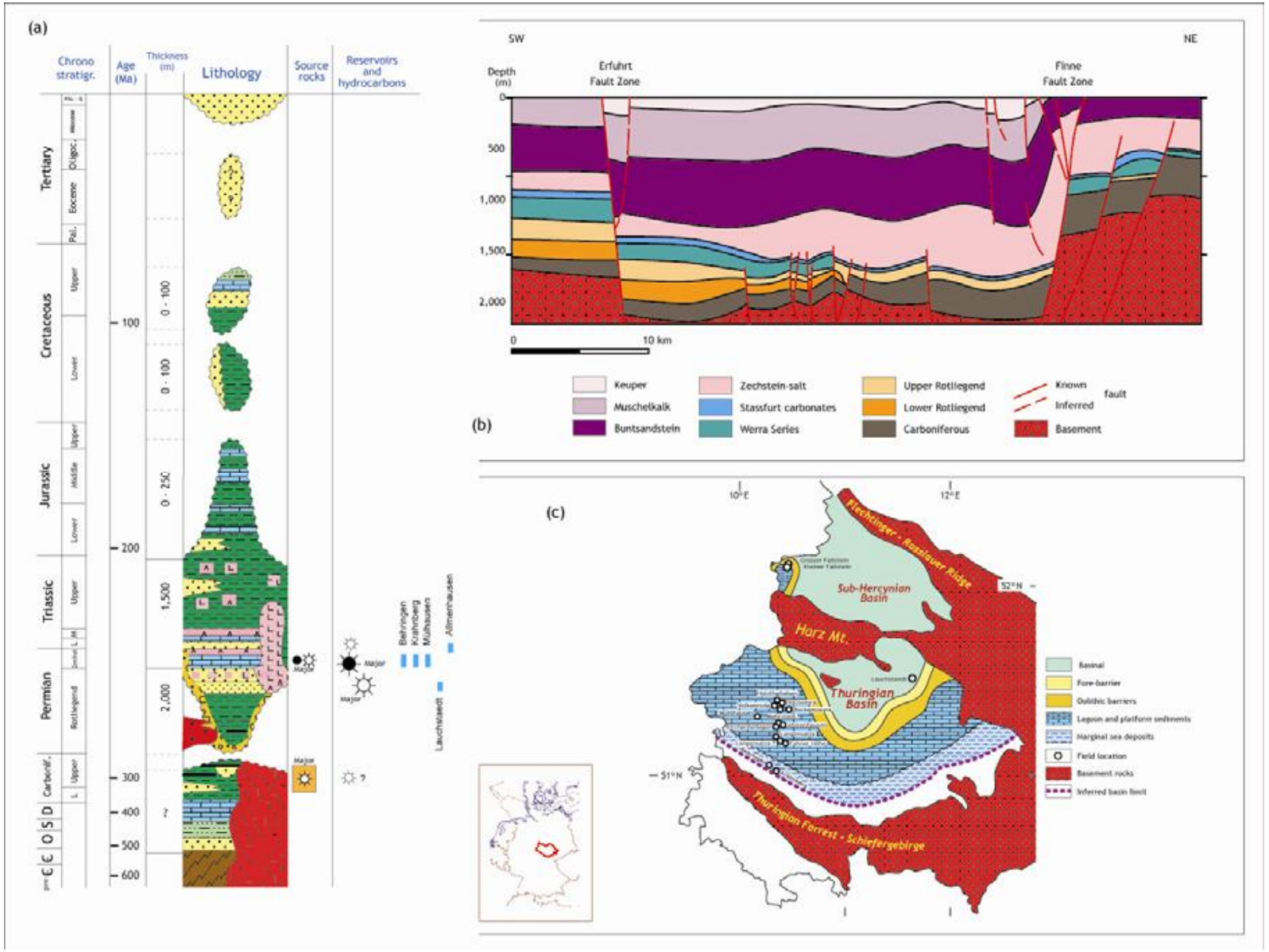

Figure 5. Overview figure of the Thuringian Basin: (a) generalised lithostratigraphic chart showing distribution of the source rocks, reservoirs, and main hydrocarbon fields, (b) regional cross-section of the basin (modified after Karnin et al., 1996) and (c) map showing present-day distribution of the Stassfurt facies (based on Teumer et al., 1990).

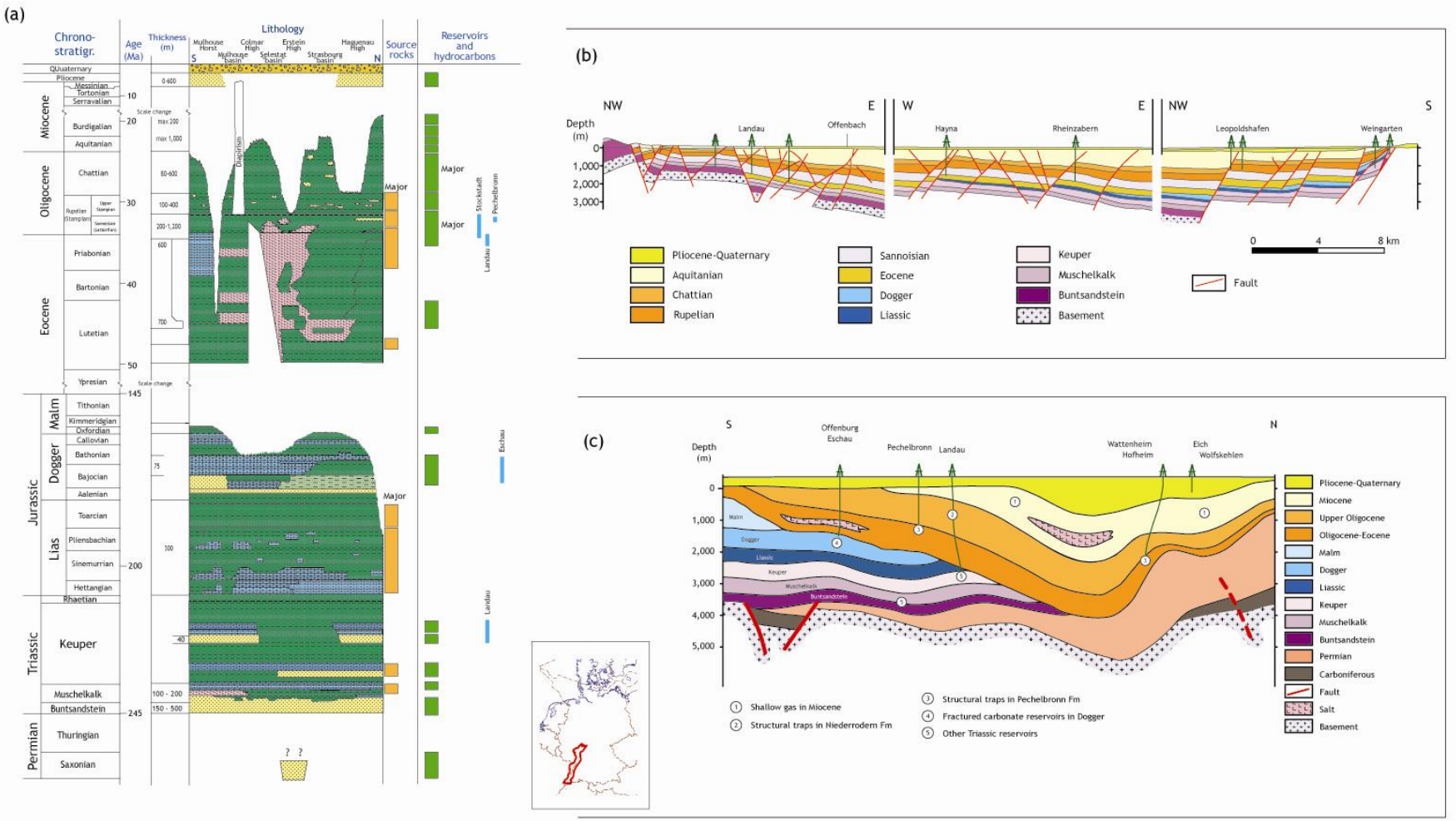

Figure 6. Overview figure of the Upper Rhine Graben: (a) generalised lithostratigraphic chart showing distribution of the source rocks, reservoirs, and main hydrocarbon fields, (b) cross-section of the northern sector of the basin (after Schad, 1962; Illies, 1970) and (c) diagram of play distribution (after Schad, 1962; Illies, 1970).

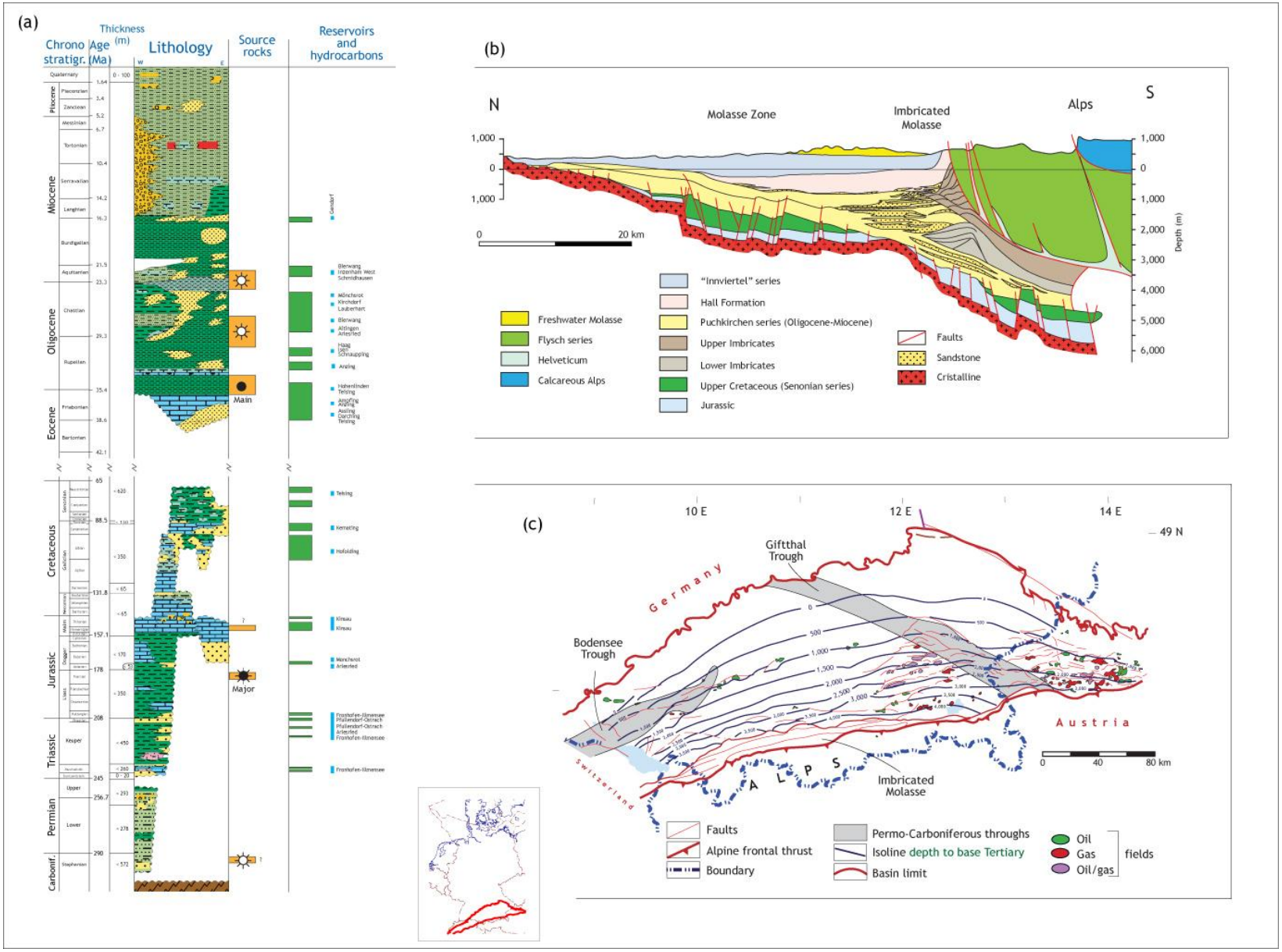

Figure 7. Overview figure of the Molasse Basin: (a) generalised lithostratigraphic chart showing distribution of the source rocks, reservoirs, and main hydrocarbon fields, (b) regional cross-section of the foreland (modified after Wagner, 1986) and (c) contour map of the depth to the base of the Tertiary displaying also location of the Permo-Carboniferous troughs.