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Oil and Gas in Austria

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Abstract

Since the beginning of hydrocarbon exploration in Austria, more than 4,400 wells have been drilled; the deepest reaching 8533 m. In addition, extensive geophysical surveys have been conducted. Cumulative Austrian production is equal to 108,5 MM tonnes of oil and 72.1 Bm^3 of gas.

The most important hydrocarbon provinces of Austria are the Vienna basin, the Molasse Zone and the Northern Alps. The first of these areas, the intramontane Vienna Basin, has produced by far the largest volumes of hydrocarbons and also provided Austria's earliest production. Oil and gas production in the Vienna basin has come from Neogene basin-fill sandstones (termed the First Floor) and from underlying allochthonous Upper Triassic dolomites of the Calcareous Alpine Zone and Flysch sandstones (Second Floor). Whilst some exploration of deep, autochthonous, mainly Jurassic-age, sub-thrust reservoirs under the Neogene of the Vienna Basin (Third Floor) has been conducted this had to be abandoned on economic grounds.

60 years of exploration has provided detailed knowledge of the structural and sedimentological history of the Vienna Basin. In the past structural traps, associated with the Steinberg fault (maximum displacement 6,000 m) and large intra-basin highs (Matzen, Aderklaa) were targeted. More recently, stratigraphic traps have been successfully explored. The primary targets within the second floor are dolomitic reservoirs sealed either by overlying Neogene marls (relief deposits) or by tight Calcareous Alpine sequences (internal deposits). The main source rock for the hydrocarbon accumulations of the Vienna Basin is thought to be autochthonous Malmian-age marls.

No commercial discoveries have yet been made in other Austrian intramontane basins e.g. the Pannonian or Styrian basins.

The frontal Alpine Molasse Zone is Austria's second most important hydrocarbon province containing many oil and gas fields mainly reservoired in Tertiary sandstones. Oil discoveries are confined to Eocene shallow marine sands trapped against southerly dipping non conformable faults. Gas has been found in Oligocene and Miocene deep marine fan deposits, within stratigraphic traps and compaction-related closures. Minor amounts of hydrocarbons have been recovered from Cretaceous sandstones and Jurassic carbonates beneath the Molasse Zone. Imbricated Molasse sequences close to the Alpine thrust front provide additional targets. Source rocks within the Molasse Zone are Oligocene fish shales in Upper Austria and Salzburg and Malmian-age marls in Lower Austria. The extensive exploration of the area including the acquisition of a dense seismic grid allowed for detailed geodynamic and sedimentological models of the Molasse Zone.

Within the Northern Alps, the main exploration targets have been the thrust units of the Northern Calcareous Alps and the sub-thrust floor. Fractured dolomite reservoirs within the Northern Calcareous Alps provide a reservoir target sealed by tight sequences of Cretaceous Gosau Group, Lunz and Werfen Formations.

The Helvetic unit and the Rhenodanubian Flysch unit are viewed as marginally prospective. Reservoirs within the subthrust zone comprise Jurassic carbonates and Cretaceous sandstones. A commercial gas field (Höflein) reservoired in Middle Jurassic cherty sandstones has been discovered beneath the Flysch Zone. The distribution of source rocks for the sub-thrust zone is similar to that described for the Molasse Zone.

Exploration and Production of Hydrocarbons in Austria – An Overview

Hydrocarbon exploration and production in Austria (Fig. 1) began in the 1930's. At that time shallow and geologically simple targets were the focus. Subsequently, deeper reservoirs were targeted. This development culminated in the drilling of wildcats to depths greater than 8,000 m in the 1980's.

These activities were accompanied by constant upgrading of exploration, production and drilling tools. Surface mapping and clusters of shallow wells in the Vienna Basin were followed by single-fold and six-fold 2D seismic in the 1950's, leading to a new geological understanding of the basin and to the discovery of the giant Matzen field with approximately 80 MM tonnes of oil (570 MMBO) initial reserves.

As drilling advanced from using simple rigs with restricted depth capacity and security to modern drilling technology, deeper and more complex traps were explored. Drilling depths continuously increased from 1940 onward and reached a peak in 1980, with the drilling of Zistersdorf UT2A to a depth of 8,553 m (SPÖRKER, 1984). Curves of drilling activity reflect times of intense or stagnant exploration, and development of new fields (Fig. 2).

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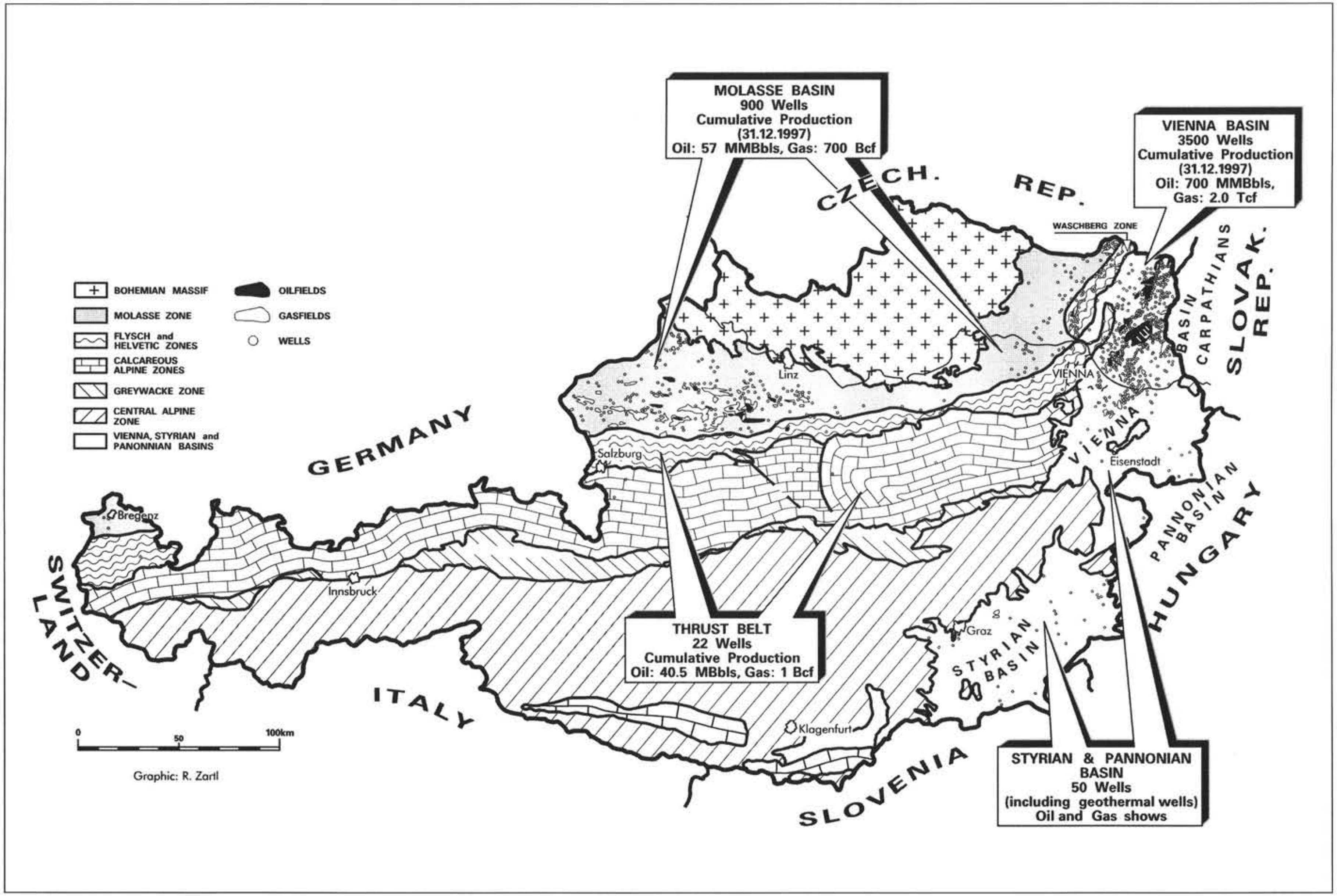


Fig. 1
Oil and gas producing regions in Austria.

Fig. 2
Vienna Basin, drilling statistics.

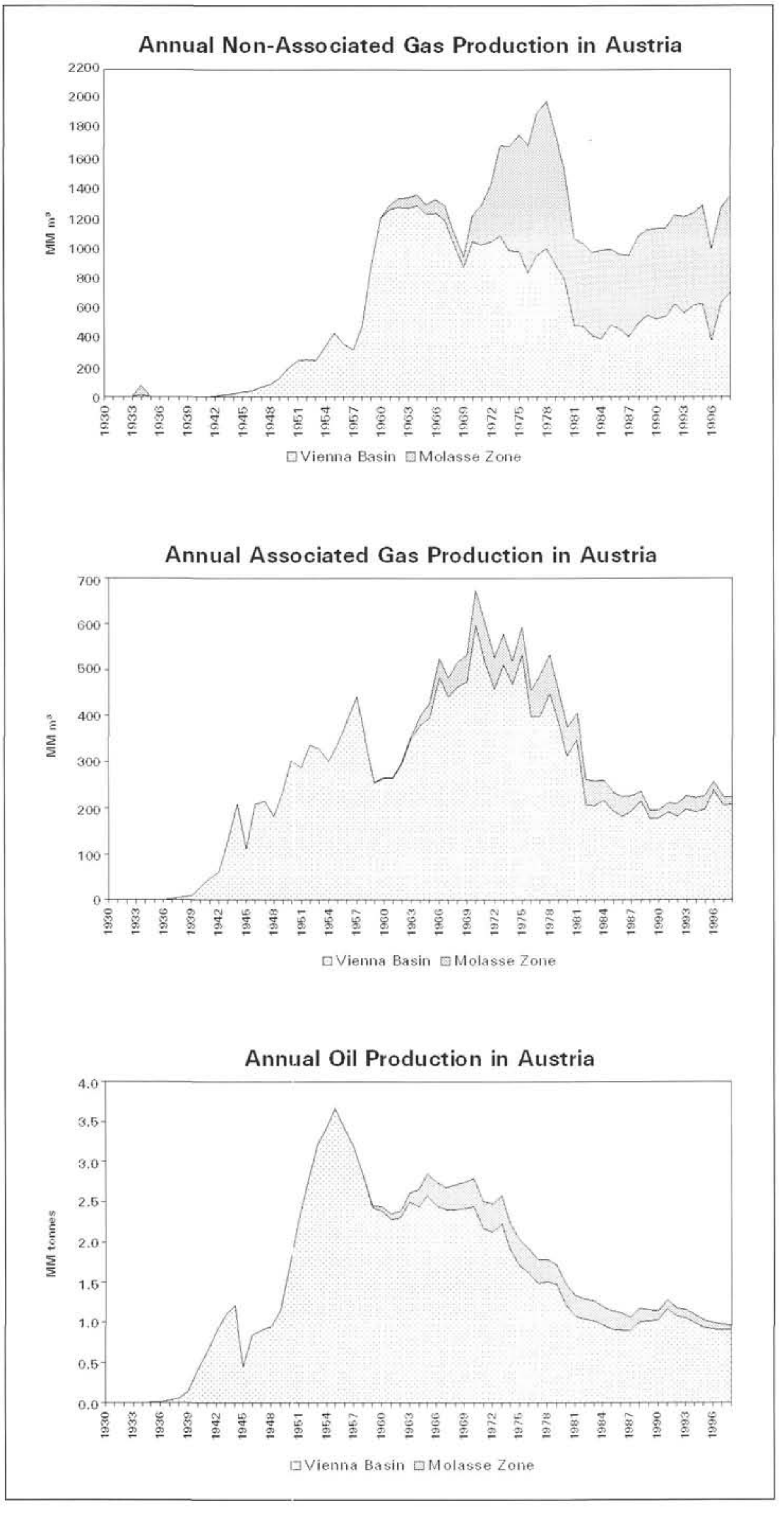


Fig. 3
Austria, production statistics.

After limited exploration success between 1983 and 1991, *economic considerations* led to renewed exploration for shallow targets, especially around existing fields, using 3D seismic. The introduction of 3D seismic has revealed previously unknown structural and stratigraphic traps and in some cases direct hydrocarbon detection could be used for prospect definition.

In Austria, 108.5 MM tonnes/oil (c.752 MMBO) and 72.1 Bm^3 gas (c.2.7TCF) have been produced; 99.5 MM tonnes/oil (c.700 MMBO) and 52.4 Bm^3 gas (c.2.0TCF) from the Austrian part of the Vienna Basin (Fig. 3).

Austria contains parts of several important elements of European geology: The Bohemian massif, the Molasse zone, the Alpine-Carpathian chain and intramontane basins (the Vienna Basin, the Styrian Basin and the Pannonian Basin). Hydrocarbon exploration has been conducted in several areas, the most important being the Vienna Basin and Molasse Zone. Significant hydrocarbon exploration efforts in the Pannonian and Styrian Basins have not yet led to economic success. The Northern Alps are productive beneath the Neogene of the Vienna Basin. Some, mostly non-commercial, discoveries were made within and below the Northern Alps outside of the Vienna Basin.

Three "floors" (distinct sequences, each with a separate structural history) can be distinguished in the Vienna Basin. The First Floor consists of Neogene sediments as infill upon the subsided Second Floor, composed of allochthonous Alpine-Carpathian thrust sheets, thrust over the Third Floor, the autochthonous Tertiary and Mesozoic basement cover (Fig. 4).

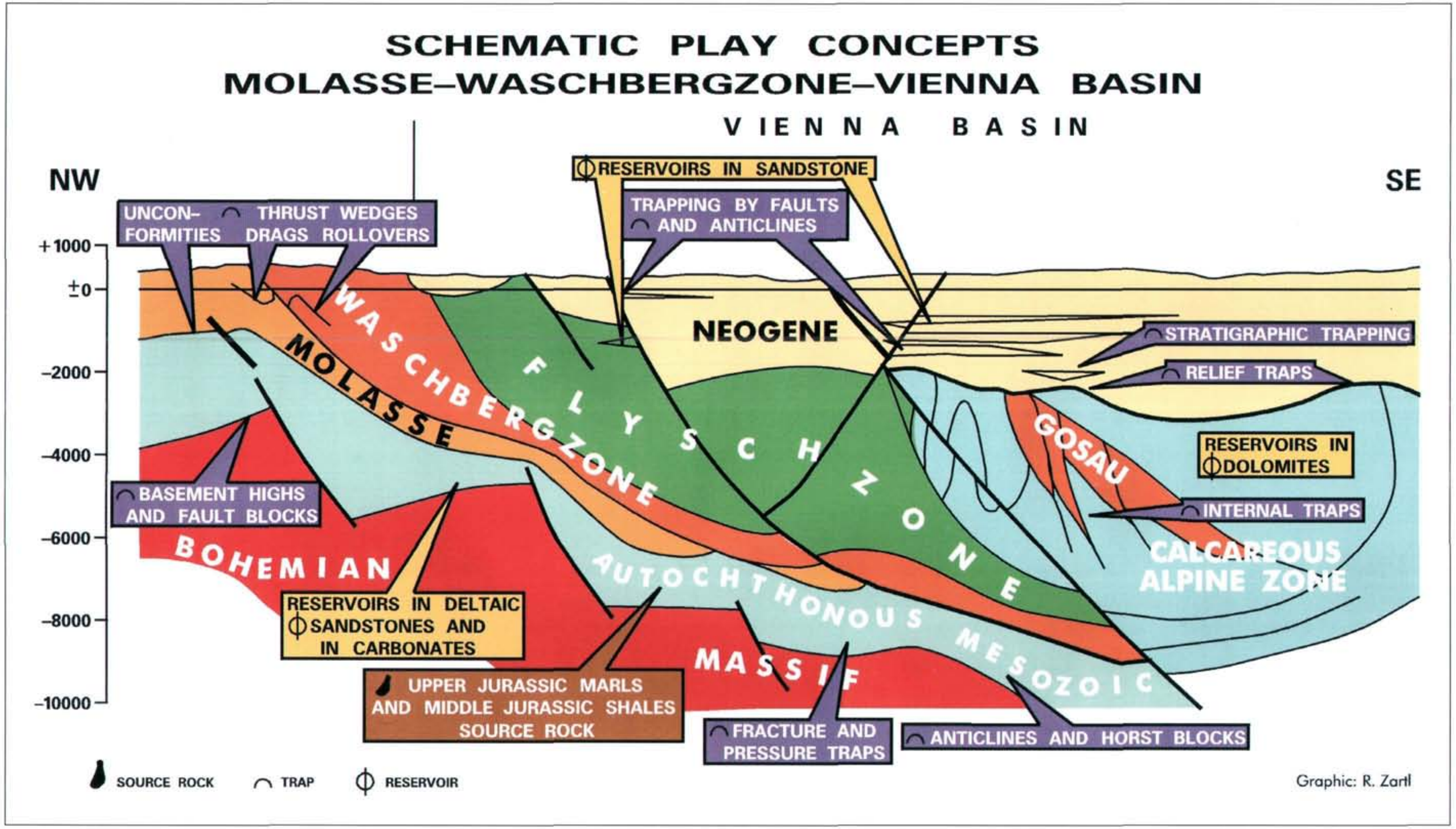


Fig. 4
Generalised cross-section with play types through the Vienna Basin.

Exploration of the First Floor began in present-day Slovakia at Egbell in 1913. In Austria (Fig. 5), first economic production began near Zistersdorf from the Gösting 2 well (1934). This field was found by surface mapping done by the Austrian oil pioneer FRIEDL. A large number of fields were discovered between 1938 and 1949, mostly along the "Steinberg fault" (FRIEDL, 1937). In 1949, Matzen, the largest oil field in Central Europe, was discovered. The Matzen field was found by shallow drilling, which provided data for mapping an Upper Pannonian horizon near the surface. The size of the field is approximately 10×7 km. A large number of Miocene horizons are oil and gas bearing, the most productive being the 16^{th} TH (16^{th}.TH = 16. Badenian horizon), the 8^{th} TH and 9^{th} TH Badenian horizons (KREUTZER, 1993a). Later, more fields, including the Zwerndorf and Fischamend gas fields and the Aderklaa, Pirawarth and Hochleiten oil fields were discovered. Recent exploration has concentrated on the peripheral areas of large oil and gasfields (Matzen NW to E; Ebenthal), targeting both structural and stratigraphic traps. Further, the Matzen field itself is a target for enhanced recovery through the application of 3D seismic and sequence stratigraphy. The Rhenodanubian Flysch, a unit of the Second Floor, was explored contemporaneously with the First Floor; especially in the Steinberg area.

In 1959, a new phase of exploration began with the discovery of gas in dolomites of the Northern Calcareous Alpine Zone of the Second Floor (KAPOUNEK et al., 1964; KRÖLL and WESSELY, 1973; HAMILTON et al., 1990; WESSELY, 1992, 1993).

Three main thrust units of the Calcareous Alps can be followed below the Neogene basin fill from the western border of the basin to the Carpathians. Each of these units contains gas and oil in fractured Upper Triassic Hauptdolomit or Dachstein Limestone, sealed by either Miocene marls (such as the Aderklaa Tief, Schönkirchen Tief, Prottes Tief and Baumgarten fields) or by internal cap rocks (such as Schönkirchen-Gänserndorf Übertief). The first, called relief deposits (buried hills), produce from depths up to 2,600 m, while the latter, called internal deposits, were encountered between 5,000 m and 6,350 m depth. They were a great challenge for drilling (complicated structures) and production technology (sour gas containing H_2S).

Between 1977 and 1987, the main objective for exploration was the autochthonous Third Floor of the Vienna Basin. Exploration of this floor was based on high oil and gas prices, which allowed the drilling of expensive wells to depths of between 6,000 m and 8,553 m. Four wells penetrated the Neogene sediments and the Alpine-Carpathian thrust sheets and reached the autochthonous cover of the crystalline basement. The crystalline basement was reached by one well (Aderklaa UT1). The Zistersdorf UT2A well was the deepest exploration well for hydrocarbons outside the USA. Within two years a final depth of 8,553 m was reached (WESSELY, 1990; MILAN and SAUER, 1996).

The resulting geological information provided important knowledge about the structure of the Vienna Basin and its basment units. The autochthonous reservoirs, known from the foreland, could be proved in the deep parts of the basin. Malmian marls provide a large source rock potential. The oil and gas shows while drilling demonstrate a supply of free hydrocarbons, which may be the objective for future exploration. Unfortunately today's low oil prices do not allow for further Third Floor exploration activities.

The late 1950's and 1960's focused on another new area for exploration, the Molasse Zone (Fig. 6). Oil and gas were discovered in Eocene and Upper Cretaceous sandstones, as well as in Oligocene and Miocene clastics in the Molasse Zone of Upper Austria (WAGNER, 1996; WAGNER and WESSELY, 1997). Exploration has been based on a tight net of 2D seismic. Gas was also found in the Miocene Molasse of Lower Austria and later in Malmian carbonates (1972, Roseldorf field) (BRIX et. al., 1977). Recently, exploration successfully targeted the imbrication zone in front of the Alpine Flysch Zone where mostly overpressured Paleogene sandstones yield hydrocarbons.

Although exploration in the Northern Alps started at the end of the 1950's, it took twenty years to develop and properly manage seismic acquisition and exploratory drilling in this highly complicated and expensive region. The justification for Alpine exploration was based on the positive exploration results from the autochthonous Mesozoic and the Upper Triassic Hauptdolomit in the Vienna Basin and the Tertiary of the Molasse Zone in Upper Austria.

To date 32 wildcats have been drilled within the Austrian Calcareous Alps and the Flysch Zone, covering a 740×55 km area. 24 wells were located in the Flysch Zone and eight wells in the Northern Calcareous Alps. One well investigated Helvetic Jurassic sequences. In 1982, an economic gas-condensate field was found in the Höflein area in a Middle Jurassic sequence below the Rhenodanubian Flysch Zone. An oil discovery was made in an autochthonous Cretaceous sandstone below the Calcareous Alps, a gas discovery within the folded Calcareous Alpine thrust sheets. Both discoveries were not commercial. The depths of the Alpine wells range from 1,300 m to 6,028 m.

Intramontane Basins

The Vienna, Styrian and Pannonian basins have been the focus of exploration for hydrocarbons in Austria. These basins were created by lateral movements and subsidence during and after the Alpine orogeny. High volumes of sediments containing reservoir rocks and cap rocks, fault traps, anticlines and stratigraphic elements, and source rocks with adequate thermal history have been the trigger for continued interest of the oil and gas industry. Exploration activities in the Styrian Basin and the Austrian part of the Pannonian Basin have not yielded positive results. The Miocene and Pliocene geodynamics of these intramontane basins do not provide viable source rocks. The Vienna Basin on the other hand, underlain by allochtonous and subthrust floors, with excellent reservoir and source rocks, offers all the necessary ingredients for successful oil and gas exploration and production. It is by far the largest and deepest of these intramontane basins.

Vienna Basin

Development and Main Structures

The development of the Vienna Basin has been the subject of many studies and publications (i.e. JANOSCHEK, 1951; KRÖLL, 1980). Modern data acquired by deep drilling, recent seismic surveys and surface investigations resulted in updated interpretations concerning sedimentation and geodynamics (JIRICEK and TOMEK, 1981; ROYDEN, 1985;

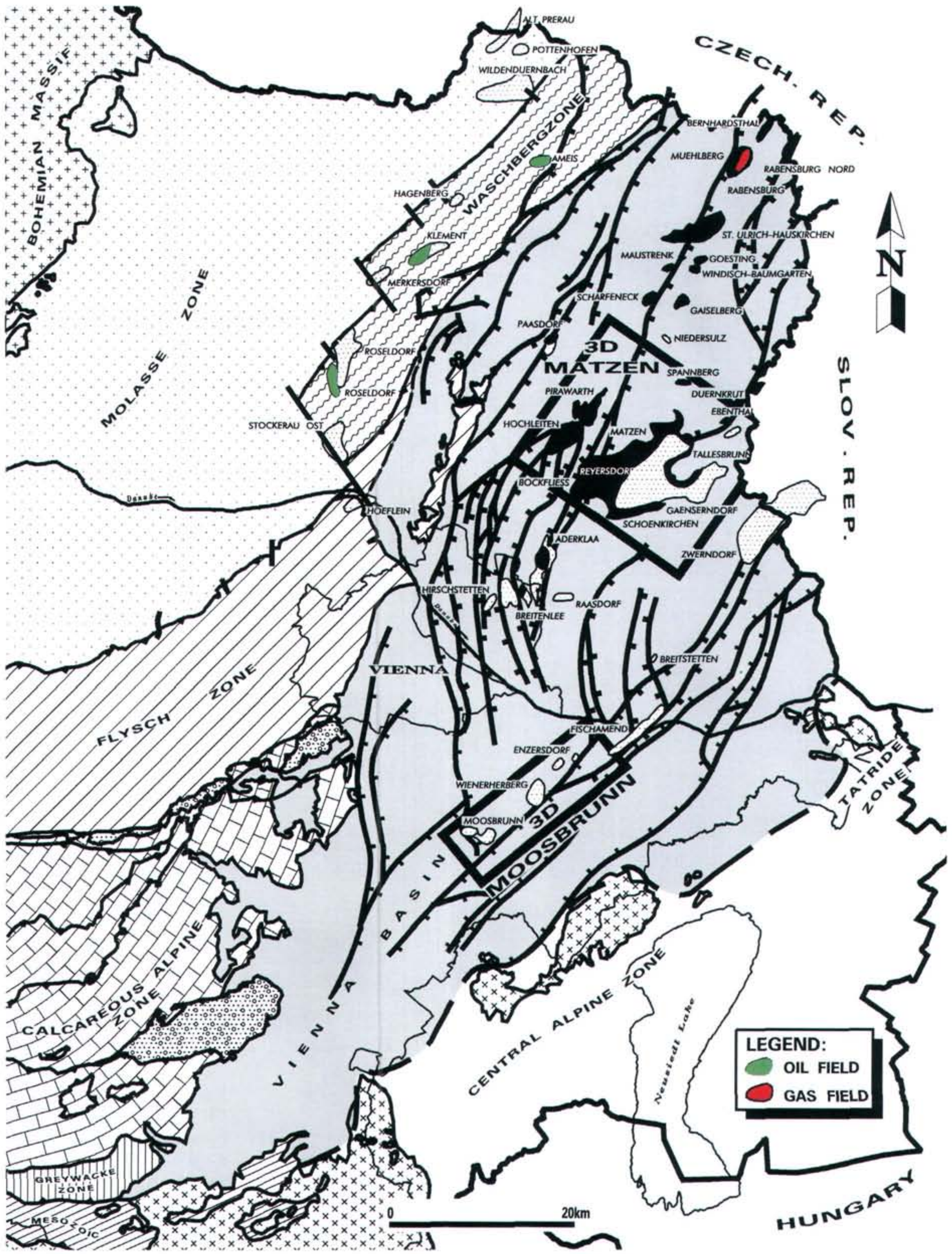
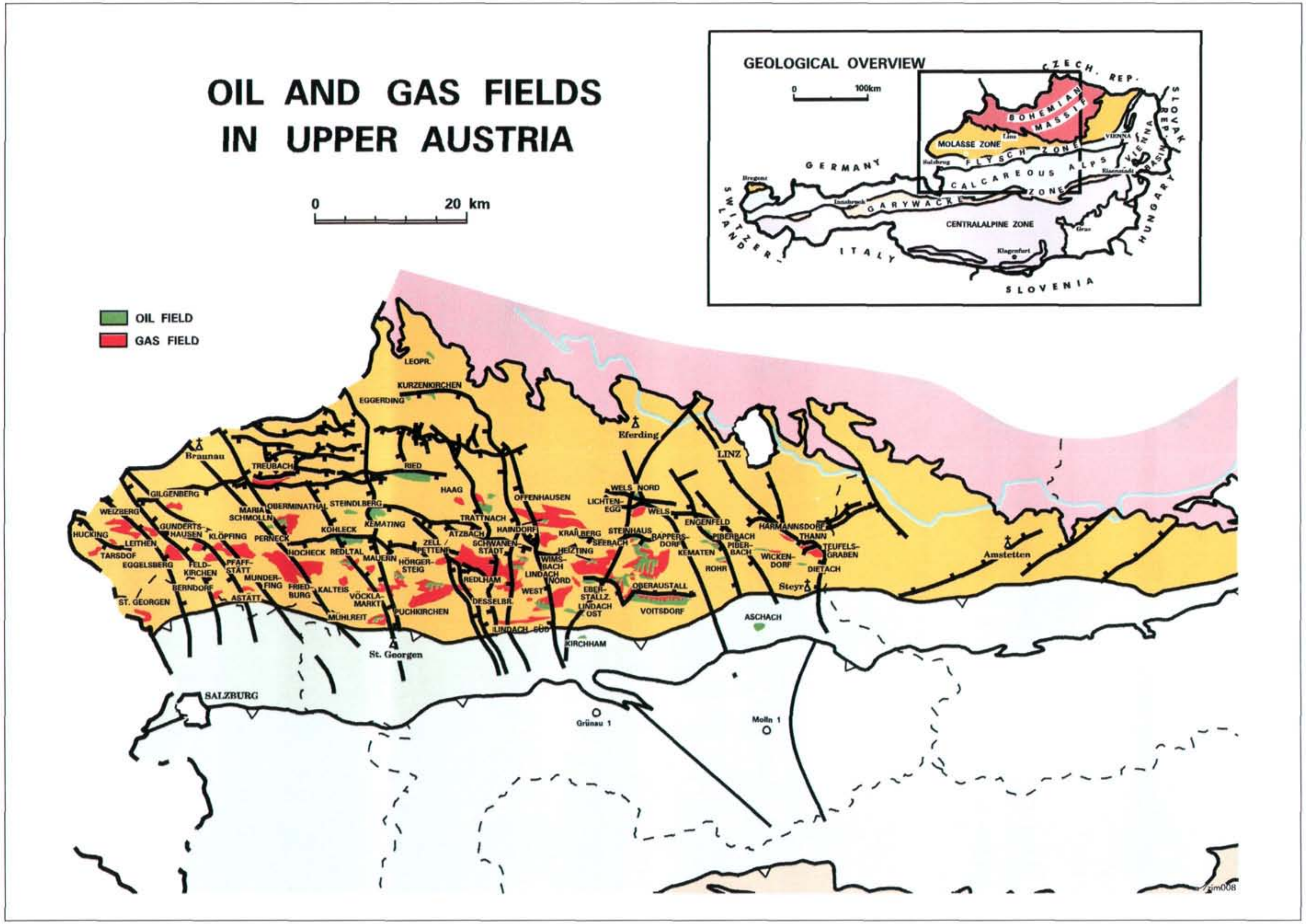


Fig. 5
Oil and Gas fields in the Vienna Basin, the Molasse Zone and the external Alpine-Carpathian regions of Lower Austria.


OIL AND GAS FIELDS
IN UPPER AUSTRIA
0
20 km
OIL FIELD
GAS FIELD
GEOLOGICAL OVERVIEW
0
100km
CZECH. REP.
SLOVAK REP.
BOHEMIAN MASSIF
MOLASSE ZONE
FLYSCH ZONE
CALCAREOUS ALPS
GARYWACKE ZONE
CENTRALALPINE ZONE
VIENNA BASIN
GERMANY
SWITZERLAND
ITALY
SLOVENIA
HUNGARY
VIENNA
Linz
Salzburg
Innsbruck
Graz
Klagenfurt
Bregenz
LEOPR.
KURZENKIRCHEN
EGGERDING
Braunau
TREUBACH
RIED
HAAG
GILGENBERG
WEIZBERG
MARIA SCHMOLLN
OBERMINATHAL
STEINDLBERG
KEMATING
KOHLECK
GUNDERTSHAUSEN
KLÖPFING
PERNECK
HUCKING
LEITHEN
TARSDOF
EGGELSBERG
FELD-KIRCHEN
PFAFF-STÄTT
MUNDER-FING
BERNDORF
ASTÄTT
ST. GEORGEN
HOCHECK
REDLTAL
MAUERN
ZELL PETTENF.
HÖRGER-STEIG
FRIED-BURG
KALTEIS
VÖCKLA-MARKT
MÜHLREIT
PUCHKIRCHEN
St. Georgen
TRATTNACH
ATZBACH
HAINDORF
OFFENHAUSEN
SCHWANEN-STADT
REDLHAM
DESSELBR.
LINDACH SÜD
WIMS-BACH
LINDACH NORD
WEST
KRAILBERG
HEIZING
SEEBACH
STEINHAUS
EBER-STALLZ.
LINDACH OST
KIRCHHAM
Eferding
LICHTEN-EGG
WELS NORD
WELS
OBERAUSTALL
VOITSDORF
LINZ
ENGENFELD
BAPPERS-DORF
KEMATEN
PIBERBACH
PIBER-BACH
ROHR
WICKEN-DORF
HARMANNSDORF
THANN
TEUFELS-GRABEN
DIETACH
Steyr
ASCHACH
Amstetten
SALZBURG
Grünau 1
Molln 1

WESSELY, 1988; JIRICEK and SEIFERT, 1990, SAUER et al., 1992; SCHOPPER, 1992; KREUTZER, 1992, 1993b; FODOR, 1995; LANKREIJER et al., 1995; DECKER and PERESSON, 1996; SEIFERT, 1996; LANKREIJER, 1998).

A "Proto-Vienna Basin" developed during an early phase of pull-apart activity in Eggenburgian to Karpatian time and was followed by a "Neo-Vienna Basin" from Badenian to Pliocene time. The Proto-Vienna Basin subsided along synsedimentary faults with important strike-slip components pointing to an early pull-apart effect. Its fill consists of Parautochthonous Molasse (STEININGER et al., 1986). The proto-basin was restricted to the northern part of the present basin with marine sediments. The southern part of the basin is characteristic of lacustrine sediments in Late Karpatian time. Alpine thrusting caused a piggy-back transportation of this older basin toward the NE during this time. The direction of thrusting was influenced by the deeper autochthonous basement: the south-western flank of the spur of the Bohemian Massif retarded the progress of thrust sheets and caused their counter-clockwise rotation.

An important inversion followed after the Proto-Vienna Basin phase, large amounts of sediments were eroded and Badenian sediments transgressed unconformably on various layers of Lower Miocene and Rhenodanubian Flysch in the northern Matzen area.

The Neo-Vienna Basin subsided within an almost stabilised stack of Alpine thrust sheets. It got the todays shape and developed deep depocenters. The central part of the Vienna Basin is defined by several high zones. These highs have been extremely important for oil and gas exploration. Most faults are synsedimentary normal faults with a sinistral component. Their en-echelon arrangement, the depocenters and an obvious rhombic shape of the basin point to pull apart effects (ROYDEN, 1985) during the basin development. The main faults appear to originate from the base of Alpine units, but could be further controlled by the tectonic behaviour of the basement (WESSELY, 1988; LANKREIJER, 1998).

The structure of the Vienna Basin is a result of tectonic movements since 22.5 Ma years. The older tectonic elements are preserved in deeper positions of the basin, the younger higher up to the surface, but interfering also with the deeper tectonic elements of the basin, hence the tectonics get more complex downwards to the basin bottom.

Lower Miocene synsedimentary faults have been proven in the Mistelbach area by drilling (LADWEIN et al., 1991) and in the Rabensburg area by seismic (KÖVES in KREUTZER, 1993a). More examples of older faults or depressions sealed by later events must be assumed in other areas of the basin.

The main features of the basin in the Austrian part are the marginal blocks along the western border, the most extended ones are the Mistelbach and Mödling blocks (Fig. 7). The Mistelbach block is bound to the west by the ESE dipping Schrattenberg and Bisamberg faults and to the east by the ESE dipping Steinberg fault system with its displacement of about 6,000 m. The Mödling block is bound to the west by minor faults (Baden fault, Sollenau fault etc.) and to the east by the Leopoldsdorf fault system, with its displacement of about 4,000 m. Along the Steinberg and Leopoldsdorf faults the deep depressions of Zistersdorf and Schwechat on the down-thrown blocks are contrasted by the extreme elevations of the Steinberg high and the Oberlaa-Laxenburg high on the upthrown blocks. The depocenters were subsiding mostly between Badenian till Late Pannonian time, the Schwechat depocenter already in Late Karpatian time. The displacement of the Steinberg fault dies out rapidly to the NE and SW. Towards the SW, a replacement of subsidence by smaller right stepping en echelon faults took place. The amount of the strike-slip component along the Steinberg fault is difficult to calculate, along the Leopoldsdorf fault system no remarkable strike-slip occurred, as drilling results proved.

A series of median high zones extends from the Rabensburg-Eichhorn ridge to the Matzen and Aderklaa high zones. The western limitation of the Matzen and Aderklaa high zones is the Bockfliess-Aderklaa synsedimentay en echelon fault system dipping toward West. Southeast of the median highzones the SE to ESE dipping noticeably curved Markgrafneusiedl fault delimits the Marchfeld depression towards the NW.

Along the eastern flank of the Vienna Basin a system of grabens as the Wiener Neustadt basin, the Mitterndorf graben, the Lassee-Zahor Plavecky graben are connected to a young SW-NE striking sinistral strike-slip fault cutting through the basin and continuing into the Mur-Mürz fault system, which crosses the Central Alpine units. It is active up to recent time and accompanied by more intense seismicity (GUTDEUTSCH and ARIC, 1988). Sedimentation lasted up to Pliocene and Quaternary times with thick coarse clastics. Small young subsidiary pull apart basins have been developed along this structure. At the NW striking borderzone of the graben system highzones as the Enzersdorf and Zwerndorf uplifts are developed. Its south-eastern border forms the NW dipping Pottendorf and Kopfstetten/Engelhartstetten faults with vertical displacements up to 1000 m, including strike-slip components of displacements of uncertain amount. These faults accompany the south-eastern marginal blocks as the Leithagebirge block, the Deutsch Altenburg spur and the Male Karpaty blocks.

Miocene Basin Fill (First Floor)

Classical paleontological and stratigraphic studies on surface and more than 70 years of exploration for hydrocarbons provided information about the stratigraphic, sedimentological and structural subdivision of the basin. Compilations of literature were given by SAUER et al. (1992) and BRIX and SCHULTZ (1993). Most recent studies and overviews have been given by SEIFERT (1996) and WEISSENBÄCK (1995, 1996).

Sedimentation (Fig. 8) starts in the northern part of the basin in Eggenburgian time with Molasse-type sediments (parautochthonous Molasse according to STEININGER et al., 1986). The Lucice Formation contains marine to restricted marine sediments (sandstones, some conglomerates and marls) of Eggenburgian and Ottnangian time. Thickness reaches more than 1,000 m: oil has been found in these sandstones. The Lower Miocene sedimentation continued with about 500 m thick marine Karpatian marls and sandstones of the Laa Formation. Towards the south, the Matzen-Spannberg ridge is an area of erosion. South of this ridge the base of the Neogene is formed by remnants of

← Fig. 6
Oil and gas fields in the Molasse Zone of Upper Austria.

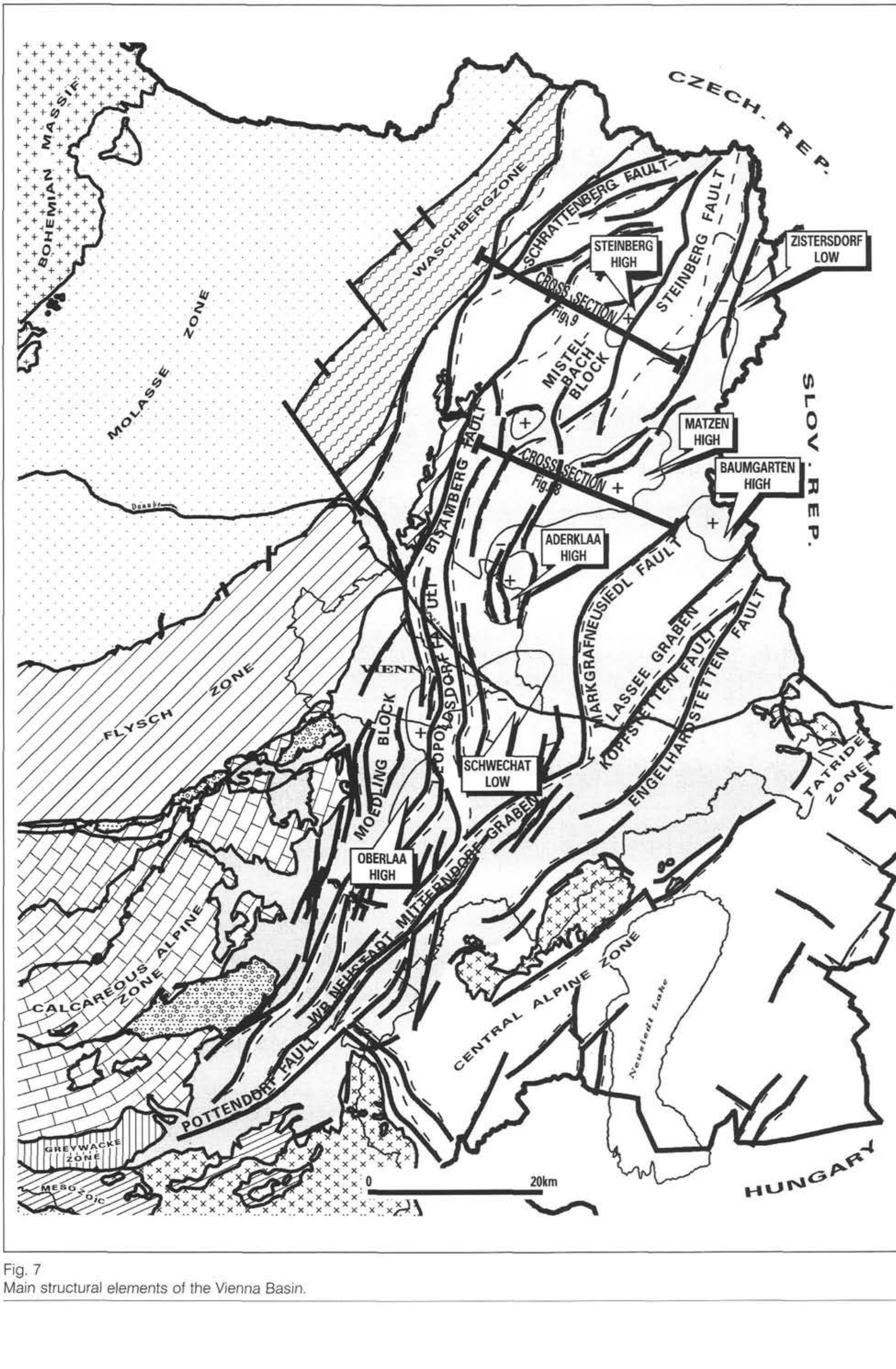


Fig. 7
Main structural elements of the Vienna Basin.

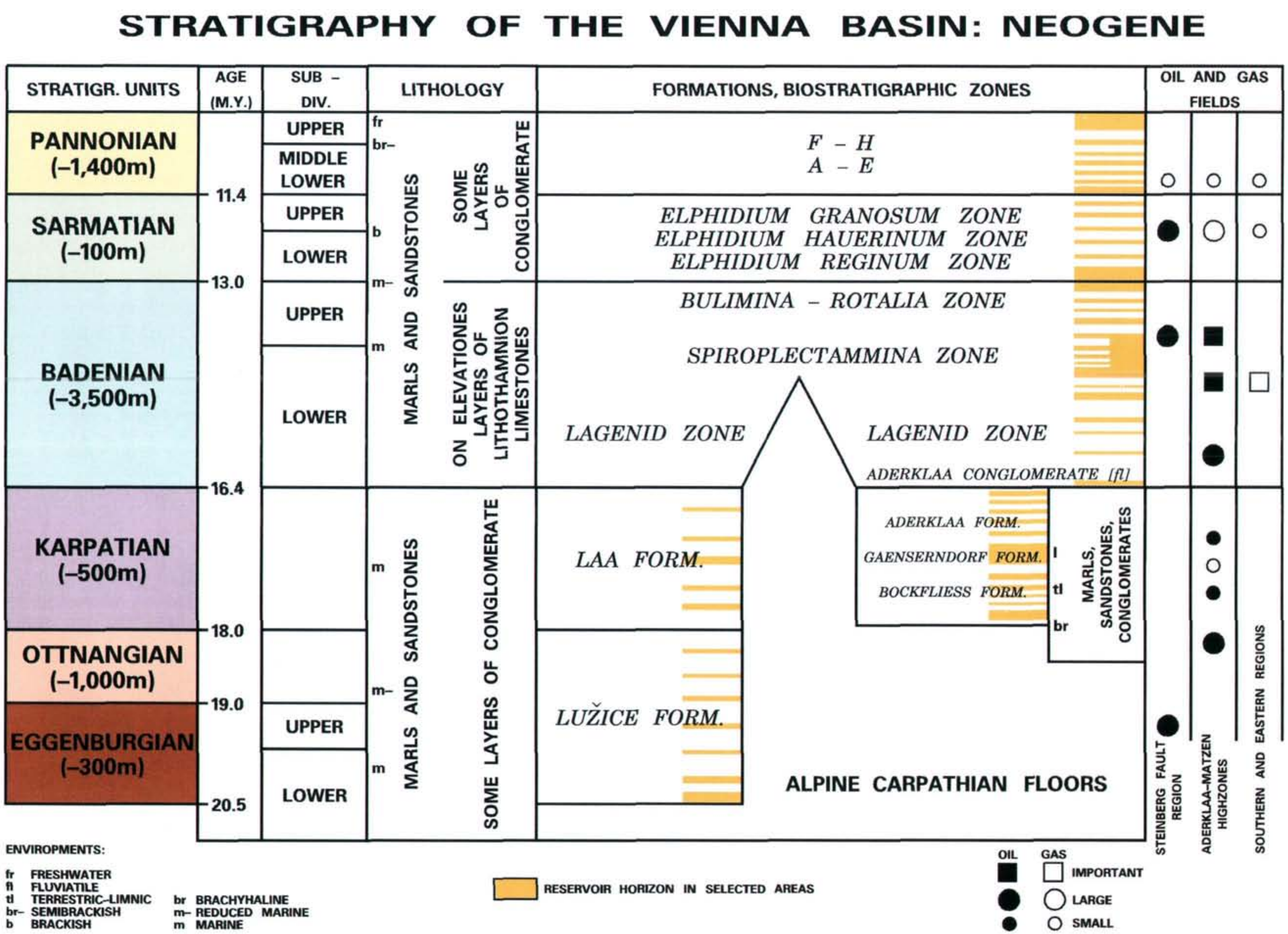


Fig. 8
Neogene stratigraphy of the Vienna Basin.

littoral Eggenburgian and about 500 m thick sandstones and marls of the Bockfliess Formation, recently interpreted as Karpatian (personal information by FUCHS, OMV), similar to the main basin fill of the Korneuburg basin. Along the Matzen ridge oil production has been achieved from sandstones of the Bockfließ Formation. The Gänserndorf Formation was deposited on top of the Bockfließ Formation, separated by an unconformity (HLADECEK, 1965). Basal fluvial conglomerates (Gänserndorf Conglomerates) were followed by lacustrine-terrestrial, partly variegated marls and sandstones, occasionally containing hydrocarbons in low porosity sandstones. In Aderklaa this formation rests directly upon the basin bottom. This sequence continues with gray marls and sandstones of the Aderklaa Formation with specific lacustrine ostracods and reaches a thickness of more than 1,000 m (JIRICEK and SEIFERT, 1990). The Aderklaa Formation extends far into the southern Vienna Basin and becomes thickest in the developing depocenters. At the same time the sand/shale ratio diminished (WEISSENBÄCK, 1996). Gas has been found in Aderklaa. The hydrocarbons of the Matzen-Schönkirchen area migrated into horizons unconformably covering the Aderklaa Formation.

The pre-Badenian inversion caused erosion of the Bockfließ-Gänserndorf and Aderklaa Formations along the Matzen-Spannberg ridge up to an amount of more than 300 m (WEISSENBÄCK, 1995). A new phase of sedimentation in the Vienna Basin started with the transgression of the Badenian. North of the Matzen-Spannberg ridge basal sandstones were deposited and south of it the Aderklaa Conglomerate. The crest of the ridge was reached by a transgression at the time of the *Spiroplectammina* zone. The base of the predominantely fluvial Aderklaa Conglomerate forms a sequence boundary (according to WEISSENBÄCK, 1996). The subsidence is reflected by the thickness of the conglomerate: some tens of meters on the up-thrown block of the synsedimentary Leopoldsdorf fault in contrast with 320 m in the Schwechat depression on the down-thrown block. After the deposition of the Aderklaa Conglomerate there followed generally marine conditions, although in the Schönkirchen-Auersthal area lacustrine deposition occurred, partly in connection with conglomeratic layers (Auersthal Formation).

During Badenian time, the main phase of sedimentation in the Vienna Basin, a rich facies diversity developed (SEIFERT, 1996). At shallow positions at the paleo-coast lines and within the basin (for example in the Steinberg and Matzen areas) carbonates with abundant lithothamnians were formed beside shallow marine sands. Marls, rich in marine fauna and flora (molluscs, foraminifers, ostracods, nannofossils) were deposited in the central basin. A stratigraphic subdivision by foraminiferal assemblages was established by GRILL (1941, 1943) (Fig. 8) for this part of the basin. Later planctonic *(Globigerina, Orbulina)* and benthonic *(Uvigerina)* foraminifera were also used for age determination (PAPP and TURNOVSKY, 1953). The environmental influence caused a strong impact on the faunal composition (RUPP, 1986). In littoral and terrestrial zones many faunal elements are missing or replaced by coastal shallow water organisms known as "mono"-fauna assemblages (i.e. *Ammonia*, especially in the *Rotalia* Zone). River deltas brought sediments mainly from the west forming shallow marine sands at the delta fronts pinching out towards the centre of the basin. The sand/shale ratios reveal the terrestrial influence at different stages in different areas. East of Vienna for example this ratio is zero or low in the Lower *Lagenid* and *Spiroplectammina* Zone (WEISSENBÄCK, 1996). The value rises in the Upper *Lagenid* Zone because of interfingering sand layers. Some of these are productive in the Aderklaa area.

After deposition of the Aderklaa Conglomerate, which has its northern limit at the SE-flank of the Matzen high zone, a diachronous transgression first deposited the afore-mentioned marine to lacustrine transition beds and then the "Matzen Sand" (16th TH) reaching the age of the *Spiroplectammina* Zone. During the *Bulimina-Rotalia* Zone, sand, sourced by distributary channel systems from the west, formed lobes with varying thickness and prograded toward the basin (KREUTZER, 1993b). The Matzen lobe system contains 16 main sand horizons, most of them oil bearing. The most prolific horizons are the 16th TH, 9th TH and 8th TH. To the west, the Pirawarth oil field shows a very high sand/marl ratio from the *Lagenid* Zone up to the *Bulimina-Rotalia* Zone. This is also reflected by a poor microfauna.

North of the Matzen-Spannberg ridge several sand lobes extend far to the east and southeast (SEIFERT, 1996). One of them forms the thick Zwerndorf Sand, including the *Spiroplectammina* and Upper *Lagenid* Zones and, underlain by some meters of *Orbulina* Marls only, resting on top of the Aderklaa Conglomerate. The Zwerndorf Sand contains the large, already depleted gas field Zwerndorf.

The Zistersdorf-Ringelsdorf-Rabensburg area is characterised by large sand input in the upper sections of the Badenian (Mühlberg oil field). The Lower Badenian section is predominantely marly.

The Lowest Sarmatian, with mostly "mono"-fauna assemblages (*Ammonia* and *Cibides*), is developed above the sand dominated Upper Badenian. Then follows a series of marls and sand horizons with rare conglomeratic intercalations. The microstratigraphic subdivision (GRILL, 1941, 1943) of the marly facies is valid over the entire basin and reflects a salinity decrease. In coastal regions oolites, algal limestones and coquinas formed. Thickness varies from 200-400 m on up-thrown blocks to 1,000 m in depressions. The Matzen field shows 10 horizons, most of which are gas-bearing. Gas is also entrapped in Sarmatian sands in the southern and northern Vienna Basin. Along the Steinberg fault some oil fields are productive in Sarmatian sands (for example Gösting and Gaiselberg).

A slight decrease of resistivity within marls marks the boundary to the Pannonian on electric logs. The clastic-pelitic sedimentation continued, but the salinity changed to brackish with ostracods and molluscs enabling a biostratification (zones A-H). A river transported gravel across the Mistelbach block toward the basin centre, forming sand channels and fans (SEIFERT, 1996). Some of the channels incised into the Sarmatian marls. Up-thrown blocks are characterised by sediment starving and minimal thickness, whereas structural lows show considerable thickness of the Pannonian. Correlations and sand thickness relationships have been documented by KREUTZER, 1990. Five Lower Pannonian and four Middle Pannonian, partly gas-bearing sand horizons are developed in the Matzen field. Pannonian sands also contain gas along the Steinberg fault and in the southern Vienna Basin. In the Upper Pannonian fluvial and lacustrine freshwater sediments were deposited with large amounts of sand, gravel and variegated marls. Pliocene and Pleistocene gravel is preserved only in young depressions and form terraces of the Danube river. In cold phases of the Pleistocene the aeolean Löss was accumulated.

Pre-Neogene Alpine-Carpathian Thrust Sheets (Second Floor)

The Alpine-Carpathian thrust belt crosses the basin below the Neogene fill of the Vienna Basin (Fig. 9). Some of the thrusted units, such as the Flysch Zone and the Northern Calcareous Alpine Zone, contain oil and gas fields (KRÖLL et al., 1993; WESSELY, 1993).

The Flysch Zone reservoirs are restricted to Paleogene sandstones of the Steinberg area, which exhibit good production when fractured. Enhanced production can be achieved by drilling horizontal wells and perpendicular to the open fractures.

The fractured Upper Triassic dolomites of the Northern Calcareous Alpine Zone are prolific reservoirs mainly in the high zones of Aderklaa, Schönkirchen/Matzen/Prottes and Baumgarten/Zwerndorf. The dolomite is regionally developed and has been documented in the lowermost thrust sheet (Frankenfels/Lunz Nappe), in the Göller Nappe and within the uppermost Calcareous Alpine units.

The Calcareous Alpine stratigraphy ranges from Permian to the Paleocene (Fig. 10). The Permian and Lower Triassic is composed of continental siliciclastic and evaporitic facies (Werfen Formation). This is followed by carbonates in the Middle and Upper Triassic, and by the partly continental Lunz Formation at the base of the Upper Triassic. In Jurassic and Early Cretaceous time, sedimentation splits into various carbonate and carbonate-pelitic facies belts developed mostly along structural strike. The Late Cretaceous is characterised by mainly marine clastic facies (syn- and post-orogenic sediments), which gradually changes into a deep water turbiditic environment in the Upper Maastrichtian and Lower to Middle Paleocene (Gießhübl Group). The main reservoirs are Upper and Middle Triassic dolomites. Hydrocarbons have been found in the Hauptdolomit of the Schönkirchen and Aderklaa area and within dolomitic layers of the Dachstein Formation in Baumgarten (Fig. 9). Shales and tight sandstones of the Gosau- and Gießhübl Groups and possibly the Lunz and Werfen Formations are the most important cap rocks.

Sour gas fields have been found in the lowermost units (Frankenfels-Lunz nappe) (Fig. 10). They are trapped in dolomites at the crests of steep anticlines. In Aderklaa, Hirschstetten and in Reyersdorf the seals are Neogene marls, in Reyersdorf the eastern part of the seal is Upper Cretaceous. At a depth of about 4,000-6,000 m the Schönkirchen Übertief sour gas field is trapped in a steep anticline. The net gas column is about 1,000 m thick. This is the largest gas field in Austria. The anticline is affected by a reverse fault, which subdivides the reservoir into the northern Schönkirchen Übertief and the southern Gänserndorf Übertief production units. Sediments of the Gosau and the Gießhübl Group of the Gießhübl monocline serve as cap rocks. The base of this cap rock contains breccias and is also gas saturated. The smaller Aderklaa Tief field (Ad 81, Ad 98) shows a similar structural style on the flank of the Gosau/Gießhübl monocline, but at shallower depth (c. 3,000 m).

The lowermost thrust sheet system and its cover of Upper Cretaceous-Paleogene sediments were overthrust by the Göller Nappe. This thrust sheet has a backthrust frontal portion defined by a syncline with Hauptdolomit in its core, which contains the Schönkirchen Tief and Prottes Tief oil and gas fields. These are buried hill structures sealed by Neogene marls. On the flanks of these buried hills, fans of dolomite debris also contain produceable oil. The westernmost and deepest of these fields contains gas, the middle area (Schönkirchen Tief field) oil and gas, and the highest and easternmost (Prottes Tief field) almost only oil. This is a vivid example of the "Gusow rule" showing differential migration. A small oil field has been found recently by 3D seismic south of the Prottes main structure. The top of the southern part of the Göller Nappe consists of a 2,000 m thick sequence of mainly lacustrine Upper Cretaceous Gosau Formation which serves as a cap rock.

Sour gas has been found in the vertical-dipping Dachstein Formation of an Upper Calcareous Alpine unit within the high zone of Zwerndorf-Baumgarten. The gas seems to be concentrated in dolomitic laminae layers (Member B of the Lofer cyclothems according to FISCHER, 1964).

In spite of very deep drilling reaching depths of 6,009 to 6,346 m (Schönkirchen T 32 and Gänserndorf ÜT 1, both successful gas wells) no well has yet penetrated the entire Northern Calcareous Alpine section to explore deeper units.

Subthrust Autochthonous Mesozoic (Third Floor)

The pre-requisites for exploration of this subthrust floor were: 1) the assumption of an autochthonous sedimentary cover resting on the Bohemian crystalline massif below the Alpine thrust sheets. Deltaic Dogger clastics and Malmian carbonates show reservoir potential and Malmian marls serve as source rocks (LADWEIN, 1988). The Jurassic and Cretaceous sequence below the Tertiary Molasse sediments has been documented by many foreland wells; 2) the theory of deeply buried basement highs with associated anticlines. This could be supported by gravity and fragmentary seismic; and 3) the occurrence of oil and gas fields in the shallower parts of these anticlinal features.

The first ultra-deep well was drilled in the region of the Steinberg high near Zistersdorf (Fig. 11, location see Fig. 17). A shallow anticlinal structure coupled with supporting seismic interpretation and a geologic model for the Authochtonous were the trigger for the well Zistersdorf ÜT1. It penetrated the Neogene, the Steinberg fault at a depth of 4,855 m, the Waschberg Zone, autochthonous Molasse and suffered a gas kick at a depth of 7,544 m in breccias on top of a Malmian limestone. About 1.3 MMm³/d of overpressured gas flowed over a period of several days. The well collapsed and a replacement well (Zistersdorf ÜT2A) was drilled. This well penetrated the Malmian limestone and encountered more than 900 m Malmian marls down to the final depth of 8,553 m. The gas zone of the first well could not be found again, though only 260 m away. The well was plugged and abandoned. One important result is the high matrix porosity of the Malmian marls (up to 7%) caused by overpressure, due to late gas generation within this very thick Malmian source rock (MILAN and SAUER, 1996).

The well Maustrenk ÜT1a (6,563 m), situated west of Zistersdorf (Fig. 17) on the Steinberg high zone penetrated Neogene, four thrust sheets of the Rhenodanubian Flysch Zone, external Carpathian nappes (Waschberg Zone), allo-

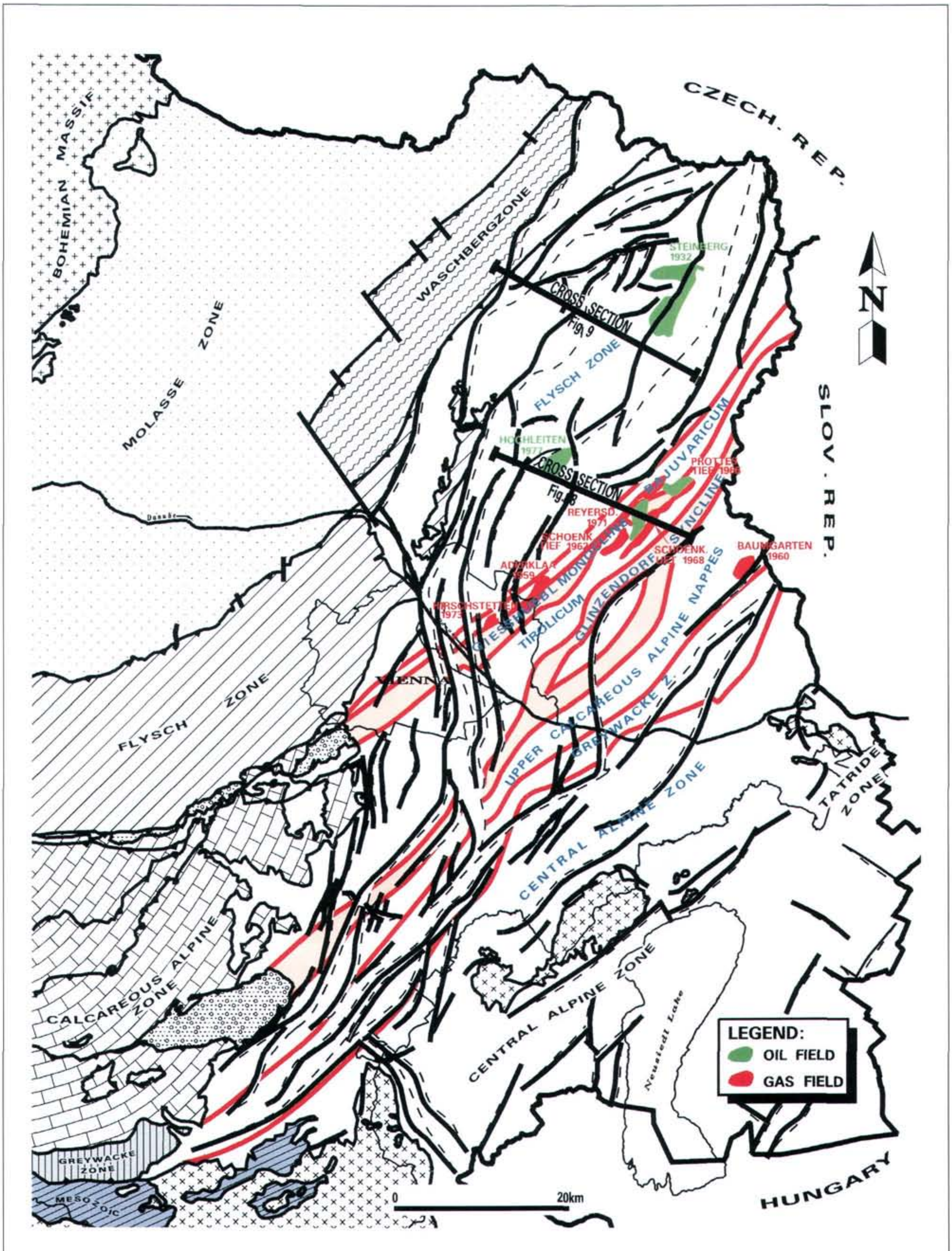


Fig. 9

Simplified geological/structural map of the top Second Floor and its relation to the western basin's frame. Oil and gas fields of the Second Floor.

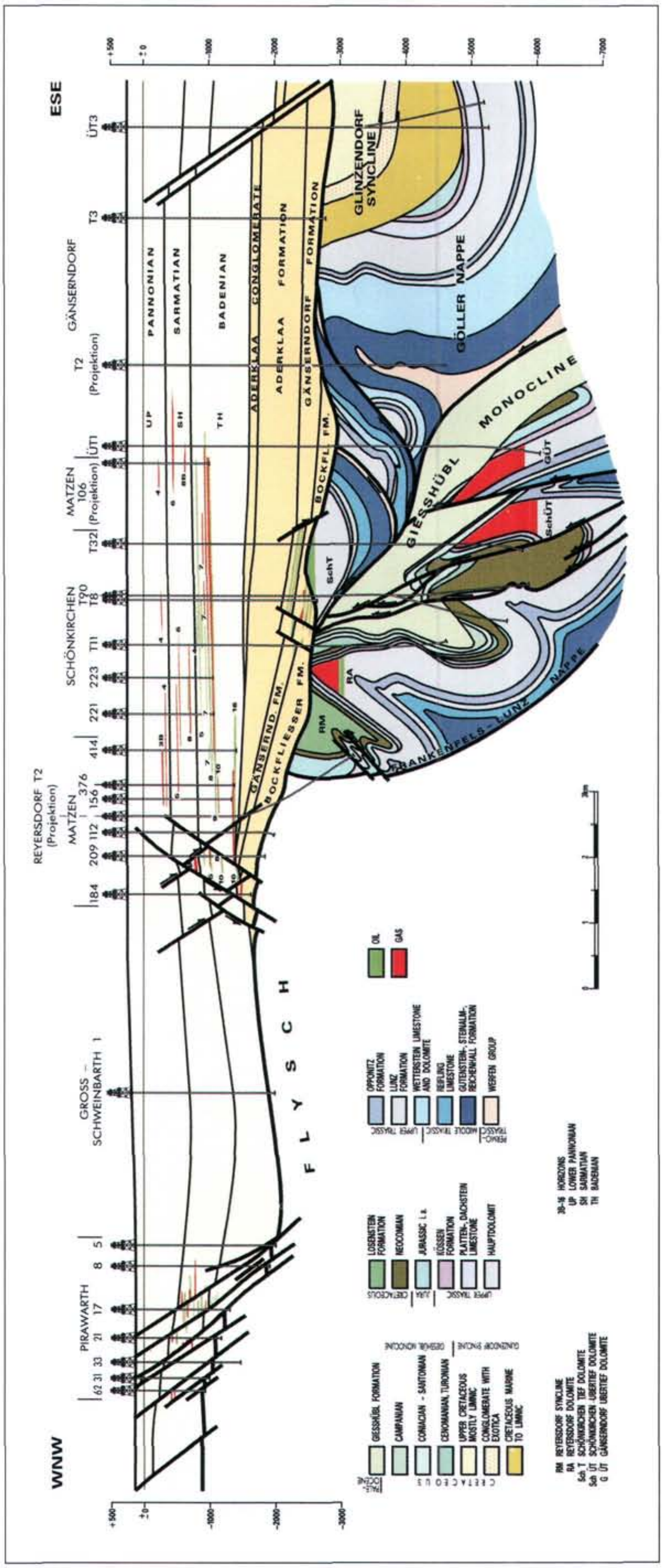


Fig. 10
Cross-section through the Pirawarth-Matzen-Gänserndorf area.

chthonous Molasse and encountered a limited oil reservoir in a carbonatic thrust sheet on top of the autochthonous Mesozoic.

Only the well Aderklaa ÜT1a (location see Fig. 17), drilled through the autochthonous Mesozoic to a final depth of 6,630 m, reached the crystalline basement. Unfortunately the Middle Jurassic delta sediments and carbonatic sandstones with cherts were missing, probably due to condensed sedimentation on the basement high.

Types of Oil and Gas Accumulations

The Vienna Basin is known for its structural complexity and its small-scale depositional settings. These facts explain the rich diversity of trap types in this basin. The Matzen field with its more than 400 production units is a vivid example of the complex combination of structural, stratigraphic and combined traps. Especially the stratigraphic and the combined traps are not yet well understood in the Matzen field. Studies are on the way to shed light on these questions. The aim ultimately is to enhance recovery from this field by better understanding the trap configuration and the depositional environment of the reservoirs and sealing rocks.

Two main types of structural traps can be observed in the Vienna Basin: the anticlinal structure and the fault-related trap. Each can be subdivided into a variety of sub-types. The anticlinal, four-way dip closures are related to compressive events during Late Miocene time (Ollersdorf area) and to paleo-highs with reservoir rocks draping over these paleo-high cores (i.e. Matzen structure).

The second important structural trap type is related to faults. One of the main structural elements of the Vienna Basin is the Steinberg fault system, which runs from the Vienna area to the NNE, crossing borders to the Czech Republic. A maximum throw of almost 5,000 m has been proved. The majority of the basin's oil fields are located along this fault trend, showing not only the working migration pathways along this major fault, but also its importance for entrapment of hydrocarbons These trap types are documented by KREUTZER (1993a). Experience has shown the sealing integrity of most faults in the Vienna Basin is intact. Even sand-to-sand contacts between hanging wall

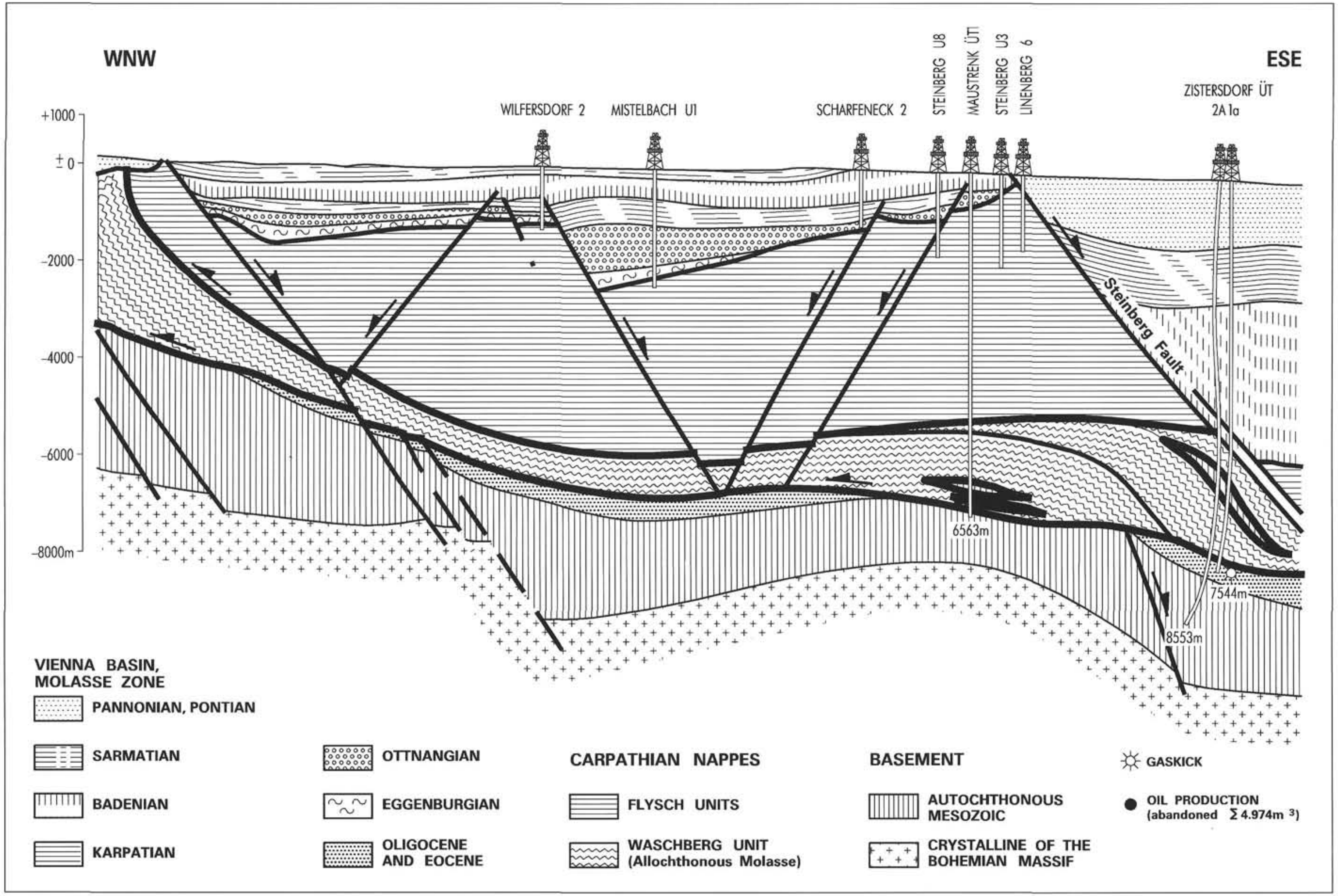
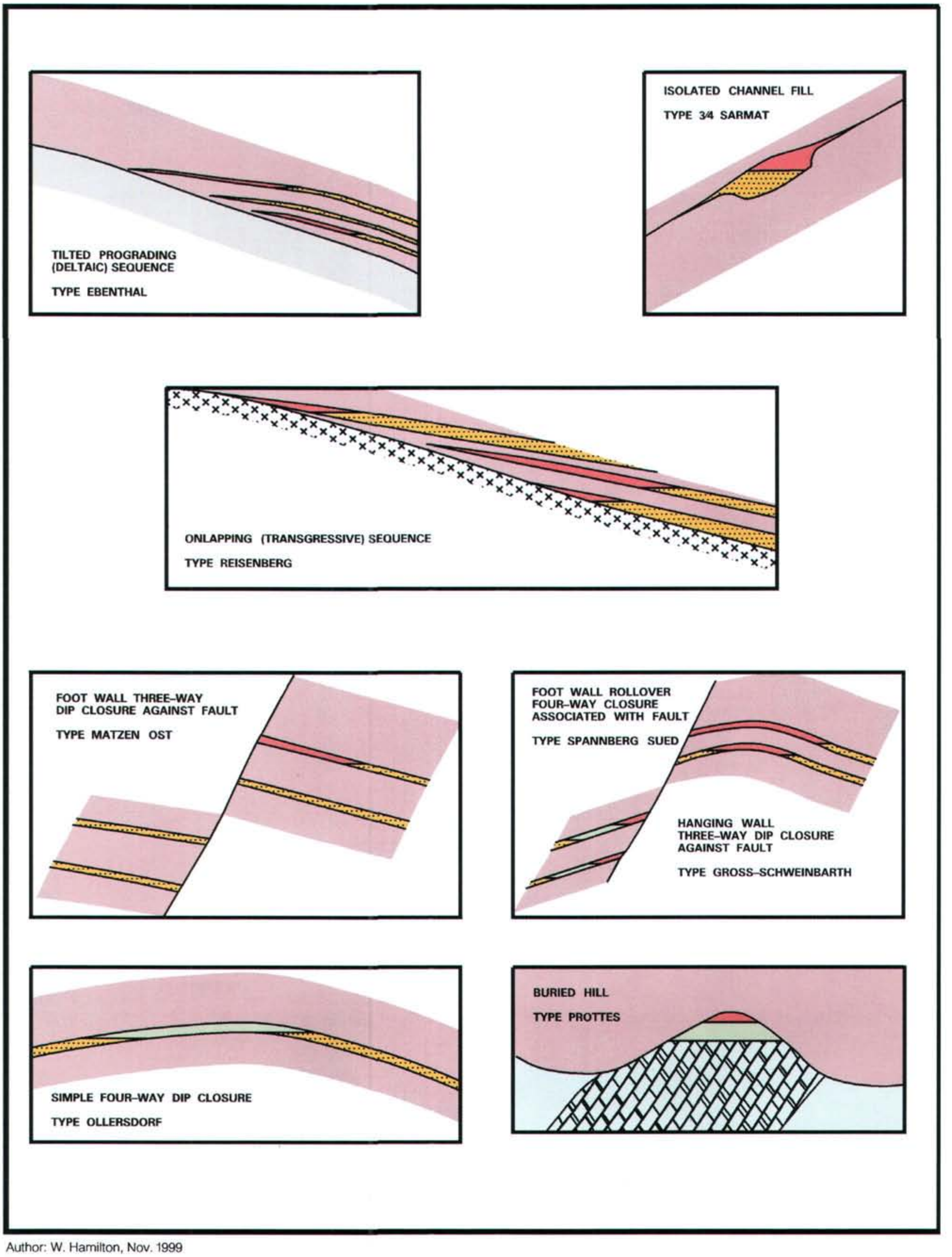


Fig. 11
Cross-section showing some of the deepest wells in Austria.



Author: W. Hamilton, Nov. 1999

Fig. 12
Vienna Basin, structural and stratigraphic play types of the central and southern Vienna Basin.

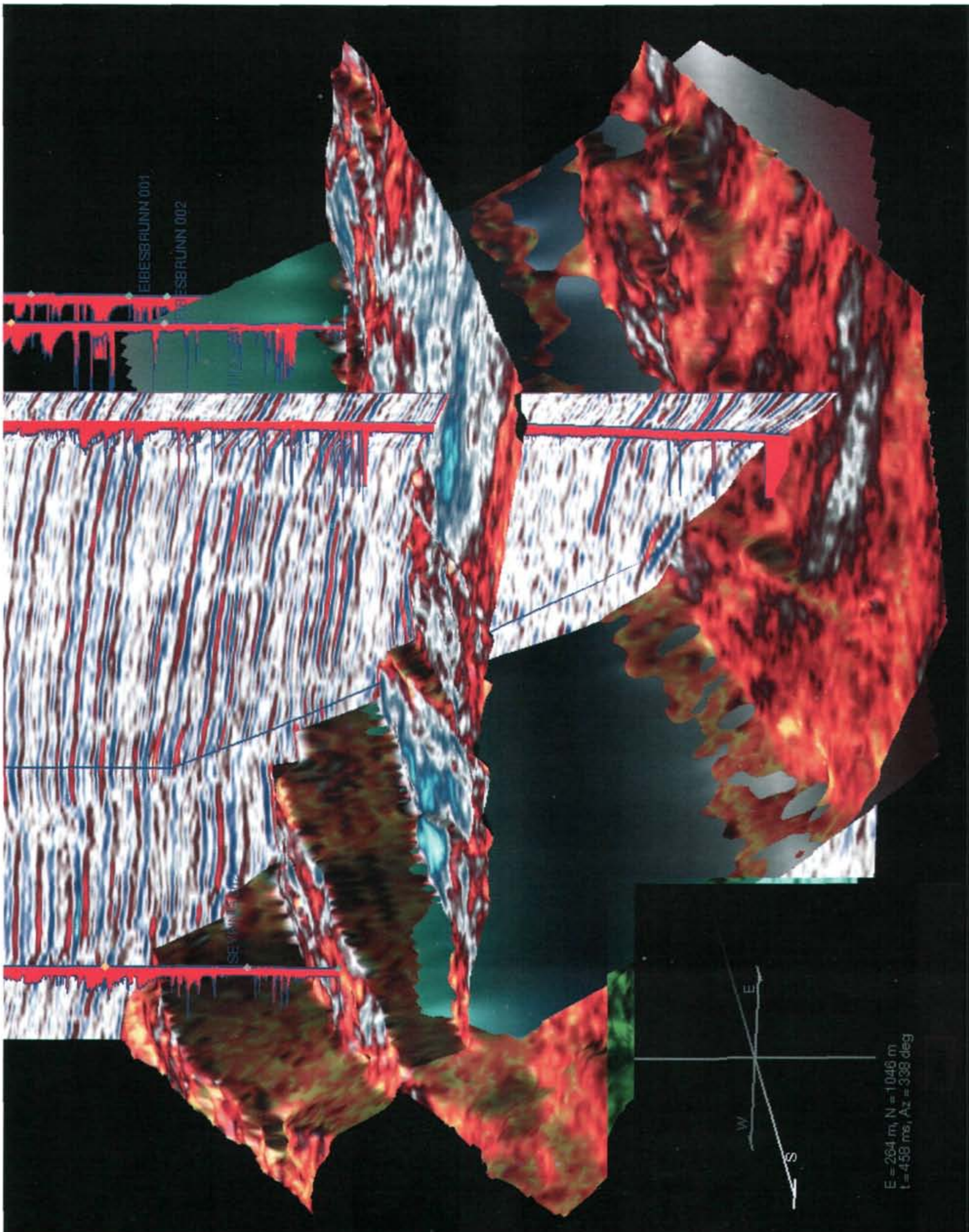


Fig. 13
Seismic 3D display of the Seyring area south-west of Matzen.

and foot wall rarely cause cross fault leakage. This is not true though for very thick sands like the 16th TH (Badenian). Sands can be hydrocarbon bearing in a hanging wall and a foot wall "up-dip against the fault" environment (Fig. 12), all it needs is a roll-over parallel to the sealing fault (i.e. Matzen Ost field) or additional sealing faults compartmentalising the reservoir (i.e. en-echelon faults of the Hochleiten field). A combination of four-way dip closure and fault trap can be observed at the Mühlberg field. This structure is a classic roll-over into the Steinberg fault and was found by surface mapping in the 1940's.

The idea of stratigraphic traps in the Vienna Basin has long been neglected, although some old fields (i.e. Ebenthal) clearly do not show any obvious structural components. Increasing seismic accuracy (3D) and the use of sequence stratigraphic principles led to new results, emphasising the importance of stratigraphic traps in the Vienna Basin. One of the most interesting play types is the combination of tilted surfaces and meandering delta plain channels (Fig. 12). The sand filled channels, sealed by surrounding shaly overbank deposits are the main ingredients for some gas fields (i.e. Spannberg Süd) in the upper Middle Miocene (Sarmatian). A second important type of stratigraphic entrapment is the regional pinch-out of clastic shelf deposits into a shale dominated basin (Fig. 12) in lower Middle Miocene times (Badenian). These sand pinch-outs are tilted up-dip against the Matzen high. They form important traps (i.e. Ebenthal field, Dürnkrut area). Substantial work has been done in the recent past to unfold the potential of these stratigraphic traps. The parts north of Matzen towards the Czech border have not been investigated seriously yet (no 3D). The potential for stratigraphic traps in this area is high, given the known regional geological setting.

A further type of trap is the buried hill type structure. It is very common at the base of the Miocene sediments (First Floor). This base represents a massive erosional event during Eocene, Oligocene and Early Miocene times. This constitutes the stratigraphic component of the trap. The Northern Calcareous Alps of the Second Floor were eroded. Brittle dolomites and limestones (i.e. Hauptdolomit, Dachstein Limestone) resisted erosion better than softer shales and sandstones (i.e. Gosau Beds, Werfen Beds) and formed a pronounced relief. This relief was sealed by shales and marls in late Early Miocene (Ottnangian, Karpatian) and left behind fractured dolomites and limestones as cores of four-way dip structures (buried hills). Miocene sediments were draped over these structures and form the structural component of the trap. Some of the most prolific oil and gas fields were found in this setting (i.e. Aderklaa Tief, Schönkirchen Tief).

The modern search for combined traps, which are structural traps with stratigraphic components has just begun in the Vienna Basin. The complex depositional settings (deltaic environment) of some Sarmatian horizons, coupled with the tectonic evolution of the basin are the most important factors for this type of trap. It is likely that more of these traps will be discovered in the basin as exploratory work progresses.

Recent Exploration Results

The Vienna Basin has been actively explored for almost 70 years. Several thousand kilometres of 2D seismic have been shot and more than 3000 wells drilled in the Vienna Basin making it a mature hydrocarbon province. In 1993, OMV-AG started to acquire 3D seismic; first over the prolific Matzen field (Fig. 13), then in other parts of the basin. The aim was to provide a better geological understanding of this mature field (HAMILTON and JOHNSON, 1999) and to accelerate and facilitate exploration for undiscovered oil and gas reservoirs. Not only 3D seismic, but also the rigorous application of sequence stratigraphic concepts and a new approach to the tectonic history of the basin have been integral elements of this approach. To date approximately 650 km^2 3D seismic have been shot. Until the end of 1998, out of 29 exploration and appraisal wells drilled in the new 3D seismic areas, 21 wells have found commercial amounts of oil and gas. Discoveries have been made in the Miocene basin fill and in dolomites of the Second Floor (buried hills). More exploration prospects await drilling in the years to come.

Pannonian Basin

The westernmost part of the Pannonian Basin extends from Hungary into the area of northern Burgenland (Fig. 7) and, south of the Central Alpine Basement elevation of Rechnitz (Fig. 14) (highly metamorphosed Penninic Mesozoic series), into southern Burgenland and Styria.

The western border of the Pannonian Basin in northern Burgenland is the swell of Bruck and the Rust ridge, in southern Burgenland and Styria the Süd-Burgenland swell.

The basement of northern Burgenland (mainly "Seewinkel") is composed of crystalline rocks of the Lower Austro-Alpine Units. Predominantely anchimetamorphic Paleozoic phyllites and carbonates form the basement in southern Burgenland and Styria (KRÖLL et al., 1988).

The Pannonian Basin's Lower and lower Middle Miocene sediments are not as thick and complete as in the Styrian and the Vienna Basin. They exist only as thin littoral remnants in many areas of the Pannonian Basin, such as the Leitha Limestone. The main subsidence started in Pannonian time (upper Middle Miocene). At that time brackish, later limnic and fluvial marls and sandstones, in some cases gravel were deposited; considerably thickening towards the east, respectively some sandstones pinching out westward updip. Often Pannonian sediments rest directly upon crystalline basement.

The westernmost part of the Pannonian Basin is characterised by an extended areal subsidence, especially in Pannonian time. A gentle regional dip of the basement and the basin fill into the basin without faulting characterises the eastern edge of the basin. The maximum depth of the basin is more than 2,000 m at the Austrian/Hungarian border. Gas shows have been noticed in several wells. Devonian carbonates contain fresh water in shallow positions along the Southern Burgenland swell.

Sixteen wells were drilled in the Pannonian Basin and its border zones without economic success.

The Styrian Basin

The Styrian Basin is a sub-basin of the Pannonian Basin (Fig. 14). They are separated in the subsurface by the Burgenland swell (KOLLMANN, 1960, 1965, SACHSENHOFER et al., 1996). The Styrian Basin is a Miocene extensional basin. Approximately 30 wells have been drilled in the Styrian Basin.

The basement is composed of high-grade metamorphic crystalline and anchimetamorphic Paleozoic phyllites and carbonates of the Austroalpine nappe complex.

The basin started in Early Miocene-Ottnangian time to form with flood plain and swamp shale, sands, breccias

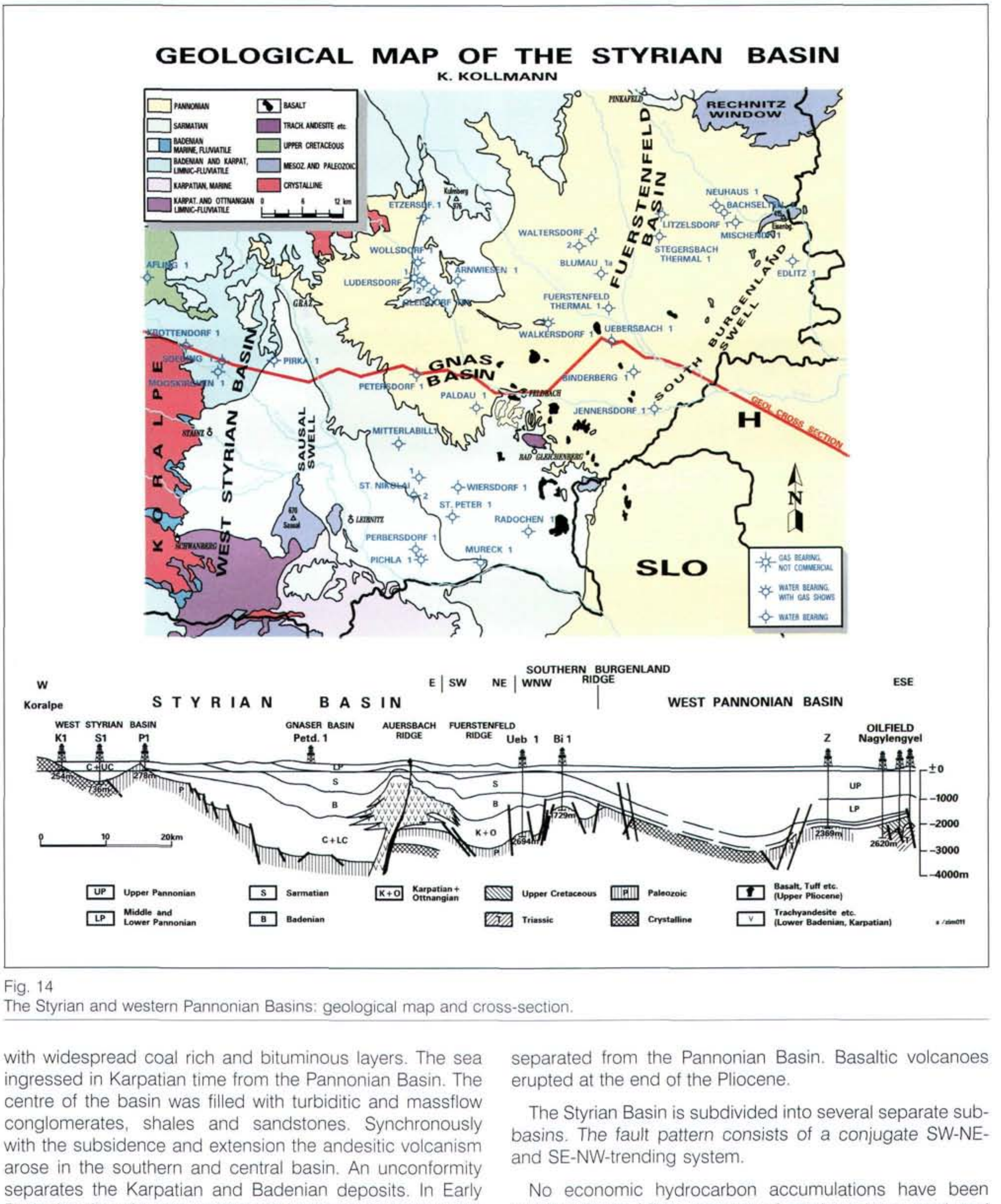


Fig. 14
The Styrian and western Pannonian Basins: geological map and cross-section.

with widespread coal rich and bituminous layers. The sea ingressed in Karpatian time from the Pannonian Basin. The centre of the basin was filled with turbiditic and massflow conglomerates, shales and sandstones. Synchronously with the subsidence and extension the andesitic volcanism arose in the southern and central basin. An unconformity separates the Karpatian and Badenian deposits. In Early Badenian time the sea reached its largest extent and in the centre of the basin were again deep marine turbiditic conglomerates, shales and sandstones sedimented. Along the margins of the basin and on local highs at the slopes of volcanic islands coral and red algae reefs evolved. The volcanism continued in Lower Badenian, but the activity shifted to the North. The Upper Badenian and Sarmatian is characterised by the regression of the Pannonian sea. In Sarmatian and Pannonian time the Styrian Basin became separated from the Pannonian Basin. Basaltic volcanoes erupted at the end of the Pliocene.

The Styrian Basin is subdivided into several separate subbasins. The fault pattern consists of a conjugate SW-NE- and SE-NW-trending system.

No economic hydrocarbon accumulations have been found in Styria. Minor amounts of gas have been produced from a shallow reservoir in the Badenian limestones. Traces of oil occurred in the hot water in geothermal wells from the Paleozoic carbonates. Potential source rocks occur in Ottnangian and Karpatian in outcrops and in wells. Basin modelling studies predict oil and gas. All acreage for hydrocarbon exploration was given up by the end of 1996. Some of the wells found geothermally heated water now used in spas and recreational facilities.

Molasse Zone

Tectonic Setting and Stratigraphic Record

The Molasse Zone is delineated to the north by the outcropping basement of the Bohemian Massif and the margin to the south is marked by the overriding Rhenodanubian Flysch-Helvetic nappes of the Alpine-Carpathian thrust front (Fig. 15). Therefore, the Molasse Zone represents the narrow remnant of the northernmost portion of the undisturbed, imbricated and piggyback transported Molasse sediments and its Mesozoic basement. This pile of Mesozoic and Cenozoic sediments plunges to the south below the Alpine thrust sheets.

The autochthonous Mesozoic succession overlies the crystalline basement of the Bohemian Massif and locally preserved Paleozoic siliciclastic deposits (NACHTMANN and WAGNER, 1987; WAGNER, 1996, 1998). The erosive remnants of the fluvial to shallow marine Lower and Middle Jurassic sandstones and shales and the shallow marine Middle and Upper Jurassic along both sides of the uplifted spur of the Bohemian Massif. The karst surface of the Jurassic carries a sequence of up to 1000 m thick glauconitic sandstones and shales from Lower or Middle Cretaceous to Upper Cretaceous age.

The oldest Tertiary sediments of the Molasse Zone are the Late Eocene fluvial and shallow marine sandstones, shales and carbonates. The sequence transgressed further up on the metamorphic crystalline basement during Oligocene and Miocene time. The several hundred meters thick Oligocene and Miocene deep marine deposits are derived from the Central Alps. The NW- and NE-trending fault systems already existed in Paleozoic times. The faults became reactivated in Early Jurassic, Early Cretaceous and Early Tertiary. Through these periods of tectonic activity the crystalline basement and its cover were pulled apart using the old fault planes. During the latest Eocene and earliest Oligocene a dense network of W-E-trending antithetic and synthetic extensional faults developed. During the Tertiary and Quarternary the pre-Tertiary and Early Tertiary extensional fault system became reactivated by a dextral and sinistral transpression with shear, strike-slip and overthrust structures.

Oil and Gas Accumulations

The Early Oligocene shales and banded marls of the Schöneck Fish-Shale and the Eggerding Formation are the correlated source rocks for the oil and thermal gas in Upper Austria. They were generated mainly beneath the Alpine thrusts. The generation started in the Miocene and may still be continuing.

The oil for the Molasse Zone in the east was derived from the Upper Jurassic source rock in the area of the Vienna Basin. Reservoirs are fluvial and shallow marine sandstones and carbonates of Dogger, Cretaceous (Cenomanian, Turonian and Campanian), Late Eocene and Oligocene (Kiscellian and Egerian) age. The oil is trapped in fault, stratigraphic, combined stratigraphic and fault structures, anticlinal and imbrication structures.

Reservoirs for biogenic gas are Oligocene and Miocene turbiditic sandstones and sandy conglomerates and shallow marine to brackish sands. The Middle to

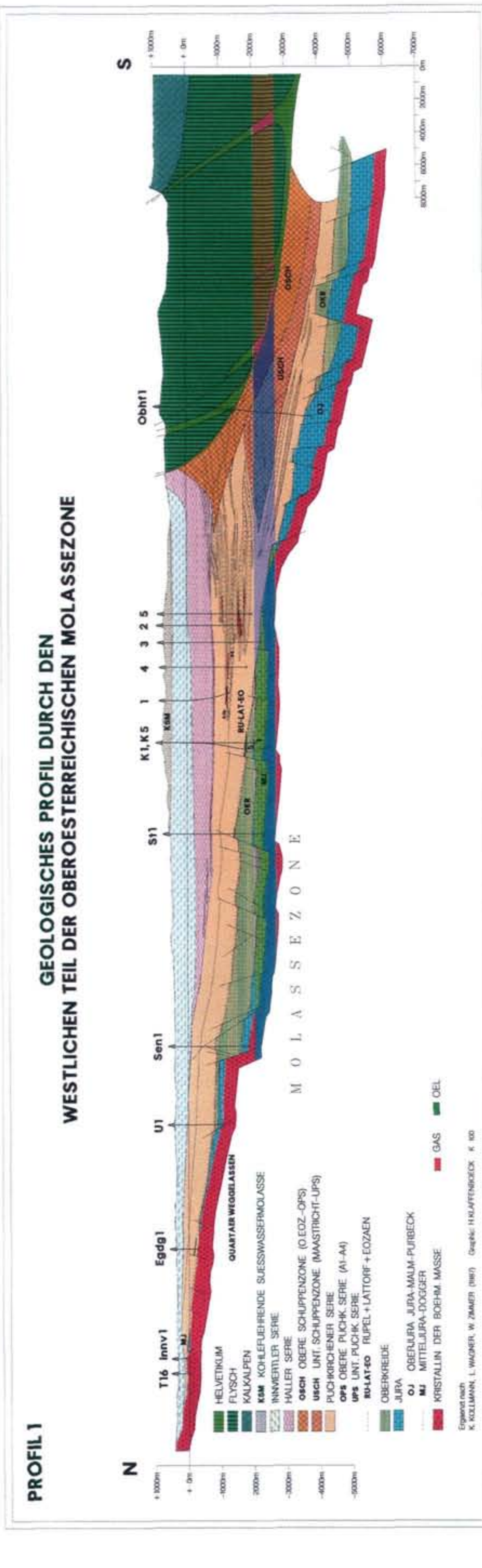


Fig. 15
Cross-section through the western part of the Molasse Zone of Upper Austria.

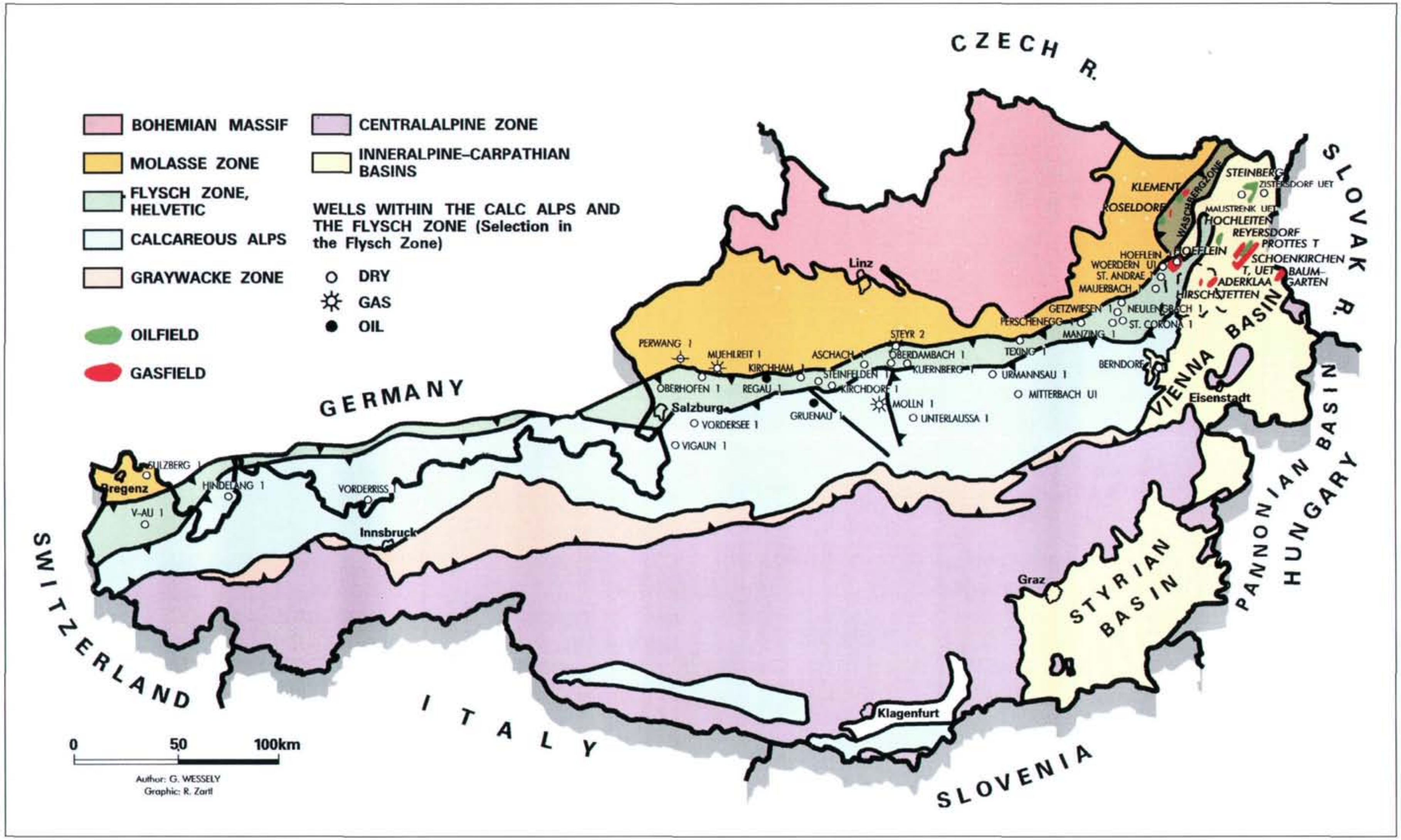


Fig. 16
Wells exploring thrust and sub-thrust plays.

Late Oligocene Fish-Shales of the Ebelsberg Formation could have supplied the organic matter for the bacterias. The gas is trapped mainly in stratigraphic and compaction structures or in a combination of both types and imbrication structures. Strike-slip faulting influenced and delineated the distribution of the reservoirs.

57 MMBBO of oil and 700 BCF of gas have been produced from the Molasse Basin until 1997. The drilling activity in this area triggered the utilisation of hot water for geothermal energy. This water has been mostly found in Malmian carbonates.

Exploration Activities

Approximately 900 deep wells have been drilled in the Austrian Molasse Zone. The exploration activity in the Austrian part of the Molasse Zone is restricted to the areas of the autochthonous, and allochthonous Molasse with thick Tertiary deposits in Upper Austria and Salzburg. In recent years the shallow areas have been relinquished. The main targets are the gas bearing reservoirs of Oligocene and Early Miocene age at moderate depths between 800 and 3000 m. The main drilling activities take place close to the older gas fields and along the thrust front in the area of the imbricated Molasse.

Northern Alps

The targets of Alpine exploration are the Alpine nappe complex and the subthrust autochthonous Mesozoic and basal Tertiary Molasse (Figs. 16, 17, 18). Both systems have distinct stratigraphic-structural properties (WESSELY and ZIMMER, 1993).

The source rocks for Alpine plays are Early Oligocene "Fischschiefer" Shale and shales of Kiscellian age (Molasse) in the west and Malmian marls (autochthonous Mesozoic) in the east. Some formations of the Northern Calcareous Alps could contribute hydrocarbons, if they had a suitable thermal history.

Intrathrust Targets

Northern Calcareous Alps

The stratigraphic range and the facies position of reservoir rocks and sealing rocks are comparable to the sub-Neogene floor (Second Floor) of the Vienna Basin (Fig. 10). Fractured Hauptdolomit and Wetterstein Dolomite are abundant reservoir rocks in the Northern Calcareous Alps. Pelites and tight sandstones of the Cretaceous-Paleocene Gosau Group, shales of the Lunz Formation and shales and evaporites of the Werfen Formation serve as cap rocks. Folds, imbricates and unconformities below the transgressive Gosau Group are the most common trap types.

The well Molln 1 tested gas from a 300 m thick column at a depth of more than 3,000 m in a fractured Middle Triassic limestone. The well Urmannsau 1 had oil shows within the Triassic to Neocomian sequences.

Rhenodanubian Flysch Zone

No oil or gas has been found to date within the Rhenodanubian Flysch thrust sheets. Lack of traps and unfavourable reservoir properties are believed to be the main reasons for this fact.

Helvetic Zone

Favourable reservoir conditions may exist in the Helvetic Middle Jurassic clastics and Malmian to Cretaceous carbonates in western Austria. The well Hindelang 1 (MÜLLER et al., 1992) in Germany (5,653 m) near the Austrian border tested gas within Lower Cretaceous limestones of the Helvetic nappe system ("Säntis" nappe s.l.). No commercial production was achieved, due to low permeability (BACHMANN and MÜLLER, 1981). Nevertheless, in Helvetic Jurassic sediments in other German wells showed good porosities, but were water saturated (MÜLLER, 1985). The well Vorarlberg-Au 1 (4,297 m) found tight Jurassic formations. The Helvetic units become remarkably thick and can be found throughout Vorarlberg. Various hydrocarbon shows have been observed on the surface in Vorarlberg (COLINS et al., 1990).

Subthrust Targets

The basement below the Northern Alps dips gently southward. Long distance northward thrusting of the Alpine allochthonous units was proved by seismic and several wells (i.e. Berndorf 1, Molln 1, Grünau 1). Three regional exploration areas can be defined on the basis of different reservoir and source rocks (Fig. 17).

1) The area of the spur of the Bohemian Massif, extending far under the Alps. It is covered only by Molasse with basal clastics of Oligocene age and some Eocene to the west. Molasse marls are a likely source in this region. Onlapping Mesozoic sediments onto the crystalline basement are expected toward the south and southeast.

2) The area east of the Bohemian spur: Transgressive Dogger clastics and Malmian carbonates represent the reservoir rocks. Malmian marls are believed to be the source rocks. They reach a maximum thickness of c. 1,000 m in the Vienna Basin. The gas-condensate field Höflein, at a depth about 3,000 m, is located in this area. The main reservoir is a sandstone cemented by dolomite, uppermost Dogger in age containing abundant chert.

3) The area west of the Bohemian spur: Triassic (only in the westernmost part) to Jurassic and Cretaceous clastics and carbonates rest on a stable platform. This platform is structured into swells with predominantely erosion and non-deposition and sub-basins with sediments preserved from erosion. The autochthonous sediments covering the crystalline basement can be imaged by seismic to the southern border of the Northern Calcareous Alps. Overpressured oil was discovered at the well Grünau 1 at a depth of c. 4,900 m within sandstones of the uppermost Lower Cretaceous (Fig. 19). The initial production was 117 tonnes per day (824 barrels per day). Daily production dropped sharply due to the compartmentalised nature of the reservoir. The cumulative production was 3,466 tonnes (24,412 barrels). A zone of thick Upper Cretaceous deltaic clastics along the southwestern flank of the Bohemian spur could be an additional target.

The traps styles are basement elevations, faults, pinch out positions and diagenetic limits. The source rocks are Molasse marls and probably Jurassic shales to the south. The Tannheim subthrust lead – the final target of the Hinde-

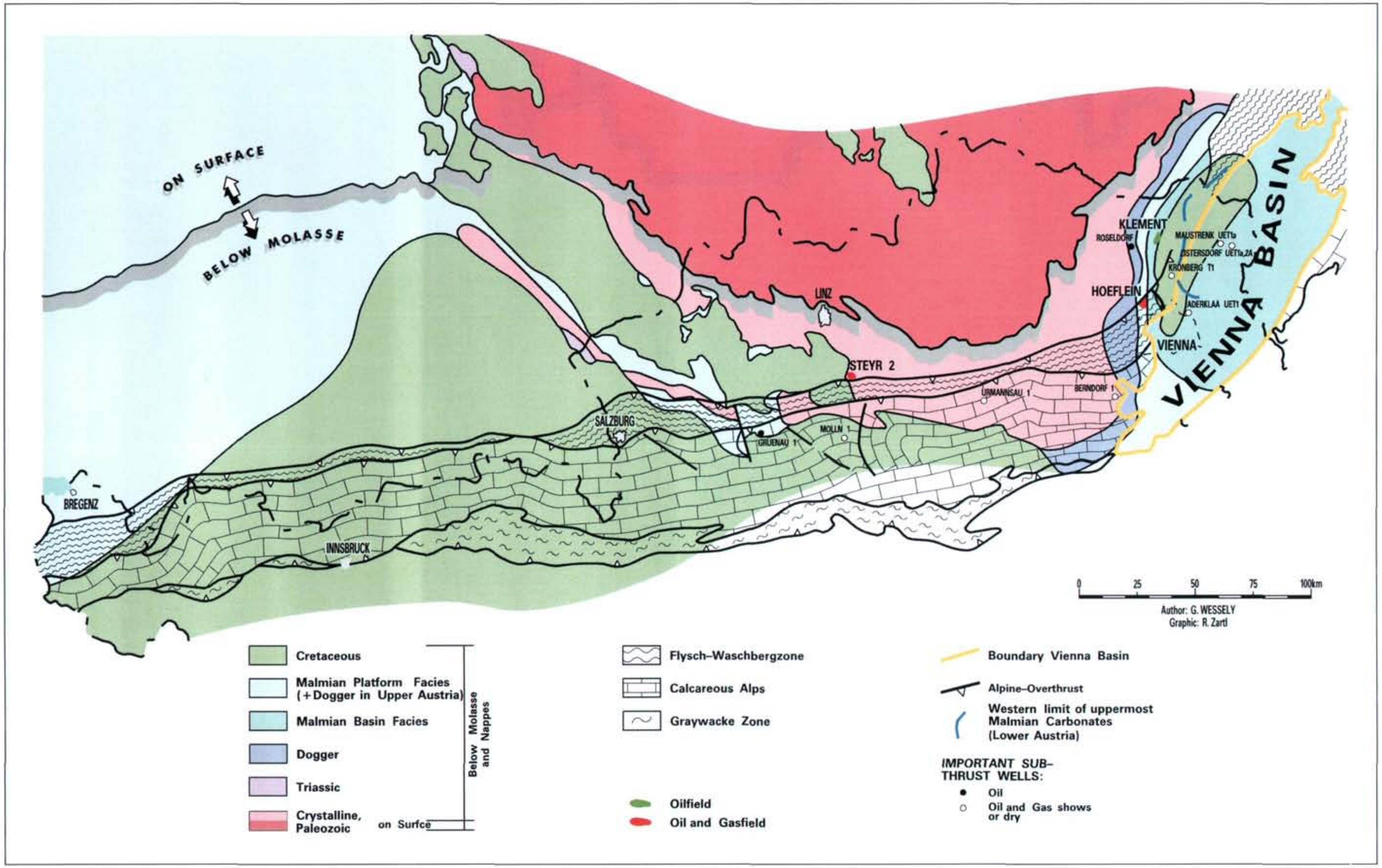


Fig. 17
Sub-crop map of the autochthonous Mesozoic below Molasse Zone and Alpine thrust sheets.

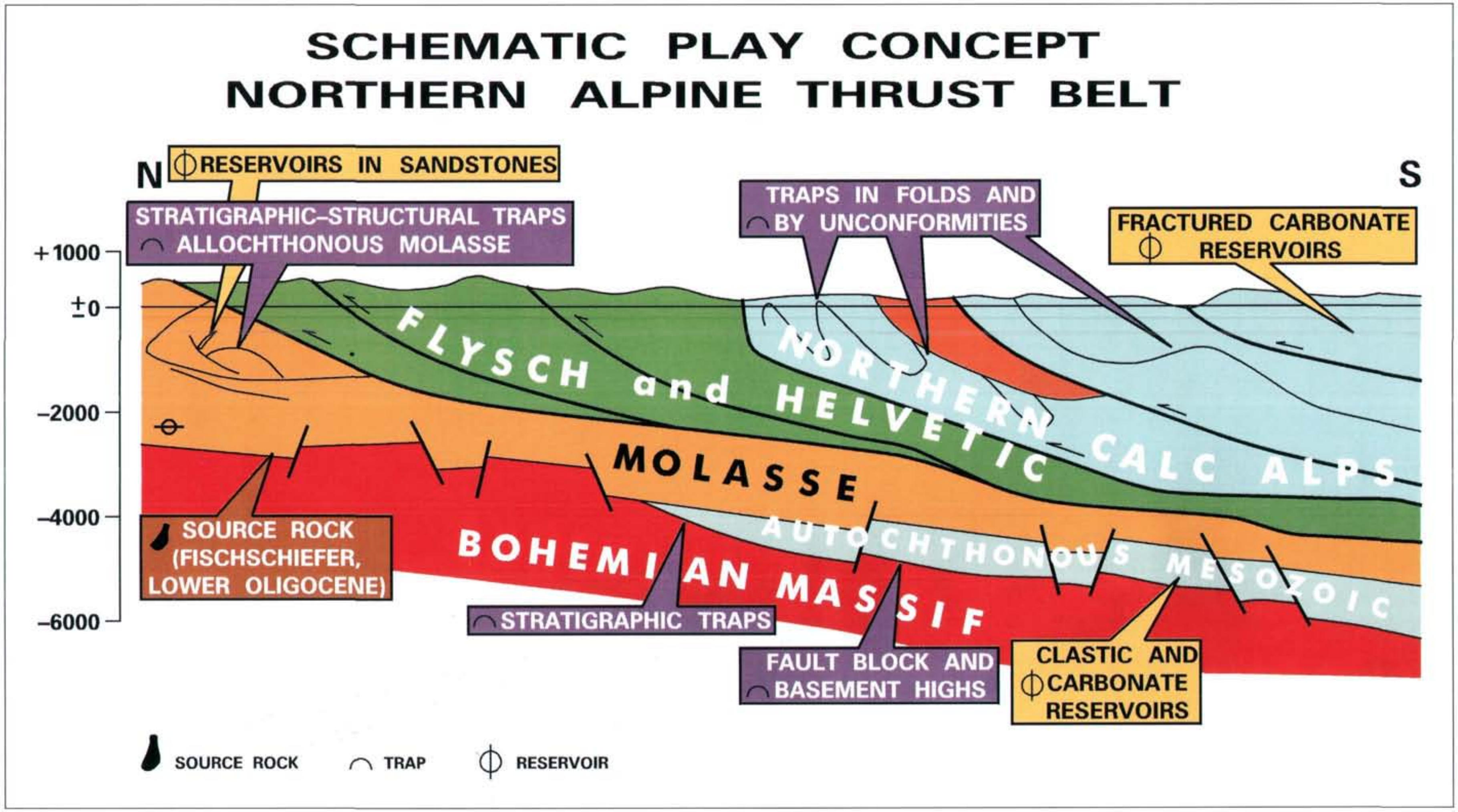


Fig. 18
Generalised cross-section with play types through the Northern Alps.

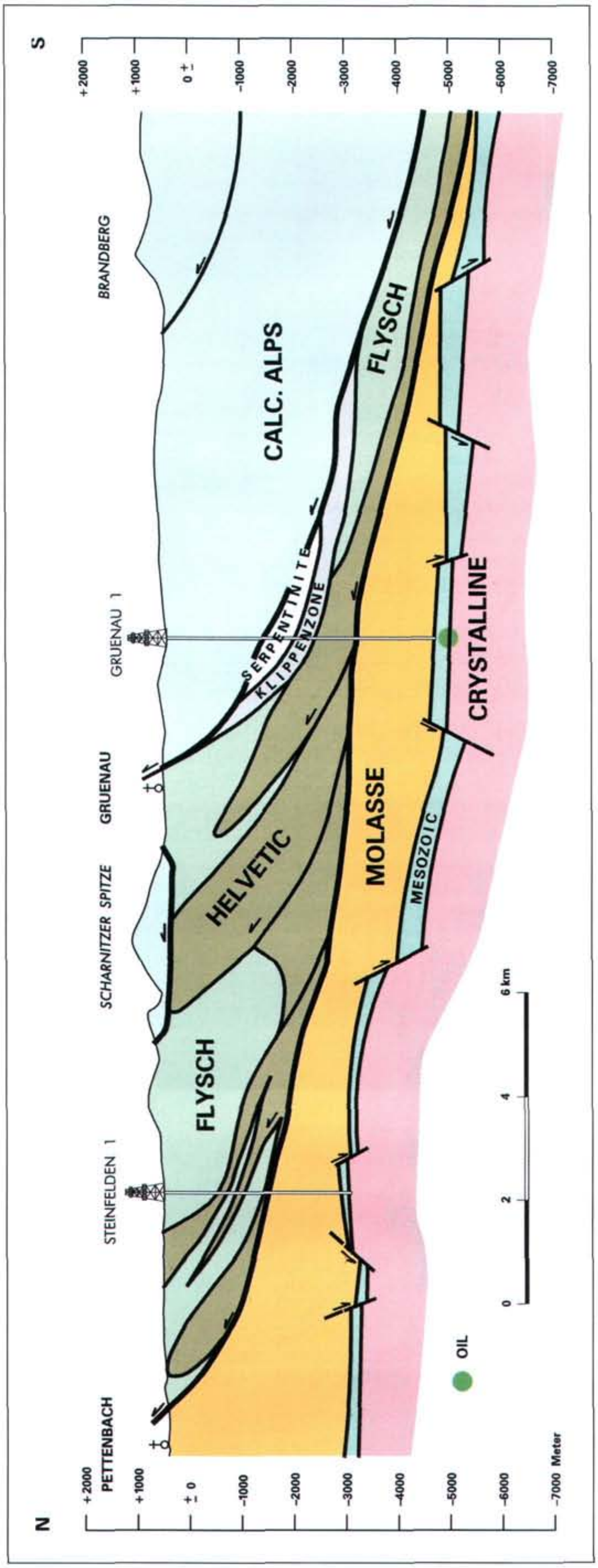


Fig. 19
N-S cross-section through the Grünau 1 well.

lang 1 well, which stopped short because of pressure problems – represents a pronounced basement high at a depth of about 6,500 m (MÜLLER and NIEBERDING, 1996). According to seismic investigations the top of the autochthonous Mesozoic is shallower in the eastern part of the Northern Calcareous Alps (4,600-6,000 m) and deeper in the western part, i.e. Salzburg and Tyrol (6,000-7,000 m). In Vorarlberg the basement rises to the Rhine valley.

Exploration Outlook

Exploration density within the Northern Calcareous Alps is very low. Units there provide a variety of reservoirs, but the sealing and trapping conditions are rather poor. Drilling depths range from 2,000-5,000 m. The subthrust units generally show rather poor reservoirs, while the sealing and trapping conditions are fair. Drilling depths range from 4,600-7,000 m. While the Flysch prospectivity is low, the Helvetic units have some remaining exploration potential. The allochthonous Molasse has proved to be a viable exploration target.

The difficult geology and topography of the Alps requires the most sophisticated exploration tools available and in-depth knowledge of the Alpine surface and sub-surface geology. Drilling is costly and difficult, due to environmental concerns, slow drilling and likely overpressures in many thrust and sub-thrust formations. Low oil prices make serious exploration impossible in most of the Alpine areas described. On the other hand, the Northern Calcareous Alps remain an exploration target for the future. As soon as today's economic framework changes, many of the plays described above will become interesting again for the oil and gas industry.

References

BACHMANN, G. H. & MÜLLER, M. 1981: Geologie der Tiefbohrung Vorderriß 1 (Kalkalpen Bayern). – Geol. Bavarica, 81, 17-53.

BRIX, F., KRÖLL, A. &. WESSELY, G. 1977: Die Molassezone und deren Untergrund in Niederösterreich. – Erdöl-Erdgas-Zeitschrift, 93, Sonderausgabe, 12-35.

BRIX, F. & SCHULTZ, O. 1993: Erdöl und Erdgas in Österreich. – Sec. ed., 688 p., Naturhist. Museum Wien und F. Berger, Horn.

COLINS, E., NIEDERBACHER, P. & SAUER, R., 1990: Kohlenwasserstoffexploration in Vorarlberg – Ergebnisse der Bohrung Vorarlberg – Au1. – Mitt. Österr. Geol. Ges., 82, 91-104.

DECKER, K. & PERESSON, H., 1996 Tertiary kinematics in the Alpine-Carpathian-Pannonian system: Links between thrusting, transform faulting and Crustal extension. IN: G. WESSELY & W. LIEBL, (eds.): Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. – EAGE Special Publication No. 5, 69-77, London.

FISCHER, A. G., 1964: The Lofer cyclothems of the Alpine Triassic. In: MERRIAM, D. W. (ed) Symposium on Cyclic Sedimentation. - Kansas Geol. Surv. Bull., 169, 107-149.

FODOR, L., 1995: From transpression to transtension: Oligocene-Miocene structural evolution of the Vienna Basin and the East-Alpine-West-Carpathian junction. - Tectonophysics, 242, 151-182.

FRIEDL, K., 1937: Der Steinbergdom bei Zistersdorf und sein Ölfeld. - Mitt. Geol. Ges. Wien, 29 (F. E. Süß-Festschrift), 21-290.

GRILL, R., 1941: Stratigraphische Untersuchungen mit Hilfe von Mikrofaunen im Wiener Becken und den benachbarten Molasseanteilen. - Oel und Kohle, 37/31, 595-602.

GRILL, R., 1943: Über mikropaläntologische Gliederungsmöglichkeiten im Miozän des Wiener Beckens. - Mitt. Reichanst. Bodenforschung, 6, 33-44.

GUTDEUTSCH, R. & ARIC, K., 1988: Seismicity and Neotectonics of the East-Alpine-Carpathian and Pannonian area. In: L. ROYDEN & F. HORVATH, (eds.): The Pannonian basin, a study in basin evolution. - AAPG Memoir, 45, 183-195.

HAMILTON, W., JOHNSON, N.E.G. 1999: The Matzen Project – Rejuvination of a Mature Field. – Petroleum Geoscience, 5(2).

HAMILTON, W., JIRICEK, R. & WESSELY, G., 1990: The Alpine-Carpathian floor of the Vienna Basin in Austria and CSSR In: D. MINARIKOVA & H. LOBITZER, (eds.): 30 years of Geol. cooperation between Austria and Czechoslowakia. - Fed. Geol. Survey Vienna and Geol.Survey Prague.

HLADECEK, K., 1965: Zur Schichtfolge und Lagerung des Helvets von Matzen. - Phil.Diss. Universität Wien.

JANOSCHEK, R., 1951: Das Inneralpine Wiener Becken. In: F. X. SCHAFFER, ed., Geologie von Österreich. - pp. 525-639, Deuticke, Wien.

JIRICEK, R. & TOMEK, C., 1981: Sedimentary and structural evolution of the Vienna Basin. - Earth Evol. Sci, 3-4, 195-204.

JIRICEK, R. & SEIFERT, P., 1990: Paleogeography of the Neogene in the Vienna Basin and the adjacent part of the foredeep. In: D. MINARIKOVA & H. LOBITZER, (eds.): 30 years of geol. cooperation between Austria and Czechoslowakia. - Fed. Geol. Survey Vienna and Geol. Survey Prague.

KAPOUNEK, J., KAUFMANN, A., KRATOCHVIL & H., KRÖLL, A., 1964: Die Erdöllagerstätte Schönkirchen Tief im alpin-karpatischen Bekkenuntergrund. - Erdölzeitschrift, 80/8, 305-317.

KOLLMANN, K., 1960: Das Neogen der Steiermark (mit besonderer Berücksichtigung der Begrenzung und Gliederung). - Mitt. Geol. Ges. Wien, 52, 159-167.

KOLLMANN, K., 1965: Jungtertiär im Steirischen Becken. - Mitt. Geol. Ges. Wien, 57, 479-632.

KREUTZER, N., 1990: The lower Pannonian sands and the Pannonian-Sarmatian boundary in the Matzen area of the Vienna Basin. In: D. MINARIKOVA & H. LOBITZER, (eds.): 30 years of geol. cooperation between Austria and Czechoslowakia. - Fed.Geol.Survey Vienna and Geol.Survey Prague.

KREUTZER, N., 1992: Matzen field, Vienna Basin, Austria. A field study for the Treatise of Petroleum Geology – AAPG, Tulsa.

KREUTZER, N., 1993a: Lagerstätten im Neogen des Wiener Beckens und dessen Untergrund. In: F. BRIX & O. SCHULTZ, (eds.): Erdöl und Erdgas in Österreich. 403-434. – Naturhist.Museum Wien und F. Berger, Horn.

KREUTZER, N., 1993b: Das Neogen des Wiener Beckens. In: F. BRIX & O. SCHULTZ, (eds.): Erdöl und Erdgas in Österreich. pp. 232-248, Naturhist. Museum und F. Berger, Horn.

KRÖLL, A., 1980: Die österreichischen Erdöl- und Erdgasprovinzen: Das Wiener Becken. In: F. BACHMAYER, (ed.): Erdöl und Erdgas in Österreich. pp. 147-179, Naturhist.Museum Wien und F. Berger, Horn.

KRÖLL, A., FLÜGEL, H. W., SEIBERL, W., WEBER, F., WALACH, G. & ZYCH, D., 1988: Erläuterungen zu den Karten über den prätertiären Untergrund des steirischen Beckens und der Südburgenländischen Schwelle, Karten 1:200.000. – Geologische Bundesanstalt, Wien

KRÖLL, A., HEINZ, H., JIRICEK, R., MEURERS, B., SEIBERL, W., STEINHAUSER, P., WESSELY, G. & ZYCH, D., 1993: Erläuterungen zu den Karten über den Untergrund des Wiener Beckens und der angrenzenden Gebiete. Karten 1:200.000. – Geologische Bundesanstalt Wien

KRÖLL, A. & WESSELY, G., 1973: Neue Ergebnisse beim Tiefenaufschluß im Wiener Becken. 7 Abb., Erdöl-Erdgas Zeitschr., 89/11, 400-413.

LADWEIN, W., 1988: Organic geochemistry of Vienna basin: Model for hydrocarbon generation in overthrust belts. - AAPG Bull., 72/5.

LADWEIN, H. W., SCHMIDT, F., SEIFERT, P. & WESSELY, G., 1991: Geodynamics and generation of hydrocarbons in the region of the Vienna Basin, Austria. In: A. M. SPENCER, (ed.): Generation, accumulation and production of Europe's hydrocarbons. – Spec. Publ. Europ. Ass. Petr. Geologists, 1, 289-305.

LANKREIJER, A. C., KOVAC, M., CLOETHING, S., PITONAK, P., HLOSKA, M., & BIERMANN, C., 1995: Quantitative subsidence analysis and forward modelling of the Vienna and Danube basins: Thin-skinned versus thick skinned extension. - Tectonophysics, 252, 433-451.

LANKREIJER, A.C., 1998: Rheology and basement control on extensional basin evolution in Central and Eastern Europe; Variscan and Alpine-Carpathian-Pannonian tectonics. – Thesis Free University of Amsterdam.

MILAN, G. & SAUER, R., 1996: Ultra deep drilling in the Vienna Basin – a review of geological results. In: G. WESSELY & W. LIEBL, (eds.): Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. – EAGE Spec. Publ., 5, 109-117.

MÜLLER, M., 1985: Maderhalm 1 und Kierwang 1. Zwei Tiefbohrungen in das Helvetikum des bayrischen Allgäus. – Jb. Geol. Bundesanst., 639-641.

MÜLLER, M., NIEBERDING, E. & WEGGEN, K., 1992: Hindelang 1 (Bavarian Alps): a deep wildcat with inplications for future exploration in the Alpine thrustbelt. In: SPENCER A. M., (ed.): Generation, Accumulation and Production of Europe's Hydrocarbons. – EAPG Spec. Publ., 2, 185-192.

MÜLLER, M. & NIEBERDING, F., 1996: Principles of abnormal pressure related to tectonic develoments and their implication for drilling activities (Bavarian Alps, Germany). In: G. WESSELY & W. LIEBL, (eds.): Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. – EAGE Spec. Publ., 5, 119-126.

NACHTMANN, W. & WAGNER, L. 1987: Mesozoic and Early Tertiary evolution of the Alpine foreland in Upper Austria and Salzburg, Austria. – Tectonophysics, 137, 61-76.

PAPP, A. & TURNOVSKY, K., 1953: Die Entwicklung der Uvigerinen im Vindobon (Helvet und Torton) des Wiener Beckens. – Jb. Geol. Bundesanst., 94/1, 117-142.

ROYDEN, L. H.1985: The Vienna Basin. A thin skinned pull apart basin. In: Strike slip deformation, basin formation and sediments. In: K. T. BIDDLE & N. CHRISTIE-BLICK, (eds.): - Soc. Econ, 310-338.

RUPP, CH., 1986: Paläökologie der Foraminiferen in der Sandschalerzone (Badenien, Miozän) des Wiener Beckens. - Beitr. Paläontologie Österreich, 1-97.

SACHSENHOFER, R. F., SPERL, H. & WAGINI, A., 1996: Structure, development and hydrocarbon potential of the Styrian Basin Pannonian Basin system. In: WESSELY, G. & LIEBL, W., (eds.): Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. – EAGE Spec. Publ., 5, 393-414.

SAUER, R., SEIFERT, P. & WESSELY, G., 1992: Guidebook to Excursions in the Vienna Basin and the adjacent Alpine-Carpathian thrustbelt in Austria. – Mitt. Österr. Geol. Ges., 85, 5-239.

SCHOPPER, TH., 1992: Strukturgeologische Untersuchungen als Hilfe für die tektonische Deutung des Bewegungsmechanismus des Wiener Beckens. – Mitt. Österr. Geol. Ges., 84, 101-134.

SEIFERT, P., 1996: Sedimentary-tectonic development and Austrian hydrocarbon potential of the Vienna Basin. In: WESSELY, G. & LIEBL, W., (eds.): Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. – EAGE Spec. Publ., 5, 331-342.

SPÖRKER, H., 1984: Die Entwicklung der Tiefbohrtechnik in der OMV Aktiengesellschaft. Erdöl-Erdgas Z., 100/5.

STEININGER, F. F., WESSELY, G., RÖGL, F. & WAGNER, L., 1986: Tertiary sedimentary history and tectonic evolution of the eastern Alpine foredeep. Giornale Geol., ser. 3, 48(1-2), 285-297.

WAGNER, L. 1996: Stratigraphy and hydrocarbons in the Upper Austrian Molasse Foredeep (Active Margin). In: G. WESSELY & W. LIEBL, (eds.): Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. – EAGE Spec. Publ., 5, 217-235.

WAGNER, L. 1998: Tectono-stratigraphy and hydrocarbons in the Molasse Foredeep of Salzburg, Upper and Lower Austria. In: MASCLE, A., PUIGDEFABREGAS, C., LUTERBACHER, H. P. & FERANDEZ, M. (eds.): Cenozoic Foreland Basins of Western Europe. – Geol. Soc. Spec. Publ., 134, 339 -369.

WAGNER, L. & WESSELY, G., 1997: Exploration opportunities. In: Hydrocarbon potential of Austria. – Ministery of Economic Affairs and Geol. Survey of Austria.

WEISSENBÄCK, M., 1995: Ein Sedimentationsmodell für das Unter- bis Mittelmiozän (Karpatian – Badenian) des zentralen Wiener Beckens. PhD thesis Institute of Geology, University of Vienna.

WEISSENBÄCK, M., 1996: Miocene sedimentation in the Vienna Basin. In: G. WESSELY & W. LIEBL (eds.): Oil and Gas in Alpidic Thrustbelts and Basins of Central and Eastern Europe. – EAGE Spec. Publ., 5, 355-363.

WESSELY, G., 1988: Structure and Development of the Vienna Basin in Austria. In: L. H. ROYDEN & F. HORVATH (eds), The Pannonian basin, a study in basin evolution. – AAPG Memoir, 45, 333-346.

WESSELY, G., 1990: Geological results of deep exploration in the Vienna Basin. – Geol. Rundschau 79/2, 513-520.

WESSELY, G. 1992: The Calcareous Alps below the Vienna Basin in Austria and their structural and facial development in the Alpine-Carpathian border zone. – Geologica Carpathica, 43, 347-353.

WESSELY, G., 1993: Der Untergrund des Wiener Beckens. In: F. BRIX & O. SCHULTZ, (eds.): Erdöl und Erdgas in Österreich. pp. 249-280, Naturhistorisches Museum und F. Berger, Horn

WESSELY, G. & ZIMMER, W., 1993: Alpine Kohlenwasserstoffexploration in Österreich. – Bull. Ver. schweiz. Petroleum. – Geol. Ing., 60, 137, 33-49.

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