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# Total Petroleum Systems of the North Carpathian Province of Poland, Ukraine, Czech Republic, and Austria

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**U.S. Department of the Interior**
**U.S. Geological Survey**

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By Mark Pawlewicz

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**U.S. Department of the Interior**
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# Conversion Factors

## SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| gram (g) | 0.03527 | ounce, avoirdupois (oz) |
| centimeter (cm) | 0.3937 | inch (in.) |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |

## Abbreviations

| | |
|---|---|
| API | American Petroleum Institute |
| BCFG | billion cubic feet of gas |
| MMBNGL | million barrels of natural gas liquids |
| MMBO | million barrels of oil |
| MMCFG | million cubic feet of gas |
| | |
| °C/km | degrees Celsius per kilometer |
| $g/cm^3$ | grams per cubic centimeter |
| $g/m^3$ | grams per cubic meter |
| HC/g TOC | Hydrocarbon/gram of total organic carbon |
| km | kilometer |
| m | meters |
| mD | millidarcies |
| mg | milligrams |
| ppt | parts per thousand |
| $R_o$ | vitrinite reflectance |
| wt percent | weight percent |

# Total Petroleum Systems of the North Carpathian Province of Poland, Ukraine, Czech Republic, and Austria

By Mark Pawlewicz

## Foreword

This report was prepared as part of the World Energy Project of the U.S. Geological Survey. In the project, the world was divided into 8 regions and 937 geological provinces. The provinces have been ranked according to the volumes of discovered oil and gas within each (Klett and others, 1997). Then, 76 “priority” provinces (exclusive of the United States and chosen for their high ranking) and 26 “boutique” provinces (exclusive of the United States and chosen for their anticipated petroleum richness or special economic importance to a region) were selected for appraisal of oil and gas resources. The petroleum geology of these priority and boutique provinces is described in this series of reports. A detailed report containing the assessment results is available separately (U.S. Geological Survey, 2000).

The purpose of this effort is to aid assessment of the quantities of oil, gas, and natural gas liquids that have the potential to be added to reserves within the next 30 years. These volumes either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit (variable, but at least 1 million barrels of oil equivalent), or they occur as reserve growth in fields already discovered.

The total petroleum system constitutes the basic geologic unit of the oil and gas assessment. The system includes all genetically related petroleum that occurs in shows and accumulations (discovered and undiscovered) that have been generated by a pod or by closely related pods of mature source rock, and that exist within a limited mappable geologic space, together with the essential mappable geological elements (source, reservoir, seal, and overburden rocks) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum (Magoon and Dow, 1994). The minimum petroleum system is that part of a total petroleum system encompassing discovered shows and accumulations together with the geologic space in which the various essential elements have been proved by these discoveries.

An assessment unit is a mappable part of a total petroleum system in which discovered and undiscovered fields constitute a single relatively homogenous population such that the chosen methodology of resource assessment based on estimation of the number and sizes of undiscovered fields is applicable. A total petroleum system might equate to a single assessment unit or it may be subdivided into two or more assessment units such that each is sufficiently homogeneous in terms of geology, exploration considerations, and risk to assess individually. Assessment units are considered “established” if they contain more than 13 fields, “frontier” if they contain 1–13 fields, and “hypothetical” if they contain no fields.

A graphical depiction of the elements of a total petroleum system is provided in the form of an events chart that shows the times of (1) deposition of essential rock units; (2) processes, such as trap formation, necessary to the accumulation of hydrocarbons; (3) the critical moment in the total petroleum system; and (4) the preservation of hydrocarbons.

A numeric code identifies each region, province, total petroleum system, and assessment unit; these codes are uniform throughout the project and will identify the same item in any of the publications. The code is as follows:

### Example

| | |
|---|---|
| Region, single digit | **4** |
| Province, three digits to the right of the region code | 4**047** |
| Total petroleum system, two digits to the right of province code | 4047**01** |
| Assessment unit, two digits to the right of petroleum system code | 404701**01** |

The codes for the regions and provinces are listed in Klett and others (1997).

Oil and gas reserves quoted in this report are derived from Petroleum Exploration and Production database (Petroconsultants, 1996) and other area reports from Petroconsultants, Inc., unless otherwise noted.

Boundaries of total petroleum systems, assessment units, and pods of active source rocks were compiled by using geographic information system software. Political boundaries and cartographic representations were taken, with permission, from Environmental System Research Institute's ArcWorld 1:3 million digital coverage (1992), have no political significance, and are displayed for general reference purposes only. Oil and gas center points are reproduced, with permission, from Petroconsultants (1996).

# Abstract

Three total petroleum systems were identified in the North Carpathian Province (4047) that includes parts of Poland, Ukraine, Austria, and the Czech Republic. They are the Isotopically Light Gas Total Petroleum System, the Mesozoic–Paleogene Composite Total Petroleum System, and the Paleozoic Composite Total Petroleum System. The Foreland Basin Assessment Unit of the Isotopically Light Gas Total Petroleum System is wholly contained within the shallow sedimentary rocks of Neogene molasse in the Carpathian foredeep. The biogenic gas is generated locally as the result of bacterial activity on dispersed organic matter. Migration is also believed to be local, and gas is believed to be trapped in shallow stratigraphic traps.

The Mesozoic–Paleogene Composite Total Petroleum System, which includes the Deformed Belt Assessment Unit, is structurally complex, and source rocks, reservoirs, and seals are juxtaposed in such a way that a single stratigraphic section is insufficient to describe the geology. The Menilite Shale, an organic-rich rock widespread throughout the Carpathian region, is the main hydrocarbon source rock. Other Jurassic to Cretaceous formations also contribute to oil and gas in the overthrust zone in Poland and Ukraine but in smaller amounts, because those formations are more localized than the Menilite Shale.

The Paleozoic Composite Total Petroleum System is defined on the basis of the suspected source rock for two oil or gas fields in western Poland. The Paleozoic Reservoirs Assessment Unit encompasses Devonian organic-rich shale believed to be a source of deep gas within the total petroleum system. East of this field is a Paleozoic oil accumulation whose source is uncertain; however, it possesses geochemical similarities to oil generated by Upper Carboniferous coals.

The undiscovered resources in the North Carpathian Province are, at the mean, 4.61 trillion cubic feet of gas and 359 million barrels of oil. Many favorable parts of the province have been extensively explored for oil and gas. The lateral and vertical variability of the structure, the distribution and complex geologic nature of source rocks, and the depths of potential exploration targets, as well as the high degree of exploration, all indicate that future discoveries in this province are likely to be numerous but in small fields.

# Introduction

In this report the petroleum systems that compose the North Carpathian Province, which includes parts of Poland, Ukraine, Czech Republic, and Austria (fig. 1), are discussed. In the Carpathian overthrust belt of southeastern Poland, the first oil well was drilled in 1854 and gas production began in 1921 (Karnkowski, 1996). As of 1993 in that part of the province, 67 oil fields and 15 gas fields had been discovered.

# North Carpathian Province

## Province Boundaries

The North Carpathian Province within Poland, Austria, and the Czech Republic is part of the western Carpathian Mountains, whereas the Ukraine part of the province lies within the eastern Carpathian Mountains (fig. 2). The western Carpathian Mountains are part of the Alpine chain (Winkler and Slaczka, 1992). The region is bounded by the Central European platform to the north and northeast and by the Eastern European platform to the east. The Pieniny klippen belt is a salient forming the boundary south of the province (figs. 2, 3), and the Carpathian–Balkanian basin lies southwest of the province. The Pannonian basin to the south of Austria and the Czech Republic delimits the province. The North Carpathian Province comprises two of the three segments of the Carpathian fold and thrust belt, the western Carpathian Mountains and the eastern Carpathian Mountains; the third segment, the southern part of the Carpathian Mountain chain, is part of the Carpathian–Balkanian Province. The North Carpathian Province is also divided into an inner and an outer segment. The inner segment encompasses thrust sheets that involve basement strata, and the outer segment consists of allochthonous Cretaceous and Paleogene terrigenous sequences (flysch) that were thrust northeastward onto the European foreland (Roca and others, 1995).

The north edge of the North Carpathian Province straddles the tectonically disturbed southern boundaries of the Eastern and Central European platforms. This northern margin marks the limit of undisturbed, or autochthonous, Miocene marine deposits (that is, molasse). The Pieniny klippen belt (figs. 2, 3), a composite unit of continental and oceanic crust covered by Jurassic and Cretaceous sedimentary rocks folded and thrusted during the Late Cretaceous (Winkler and Slaczka, 1992), forms the south edge of the province. This

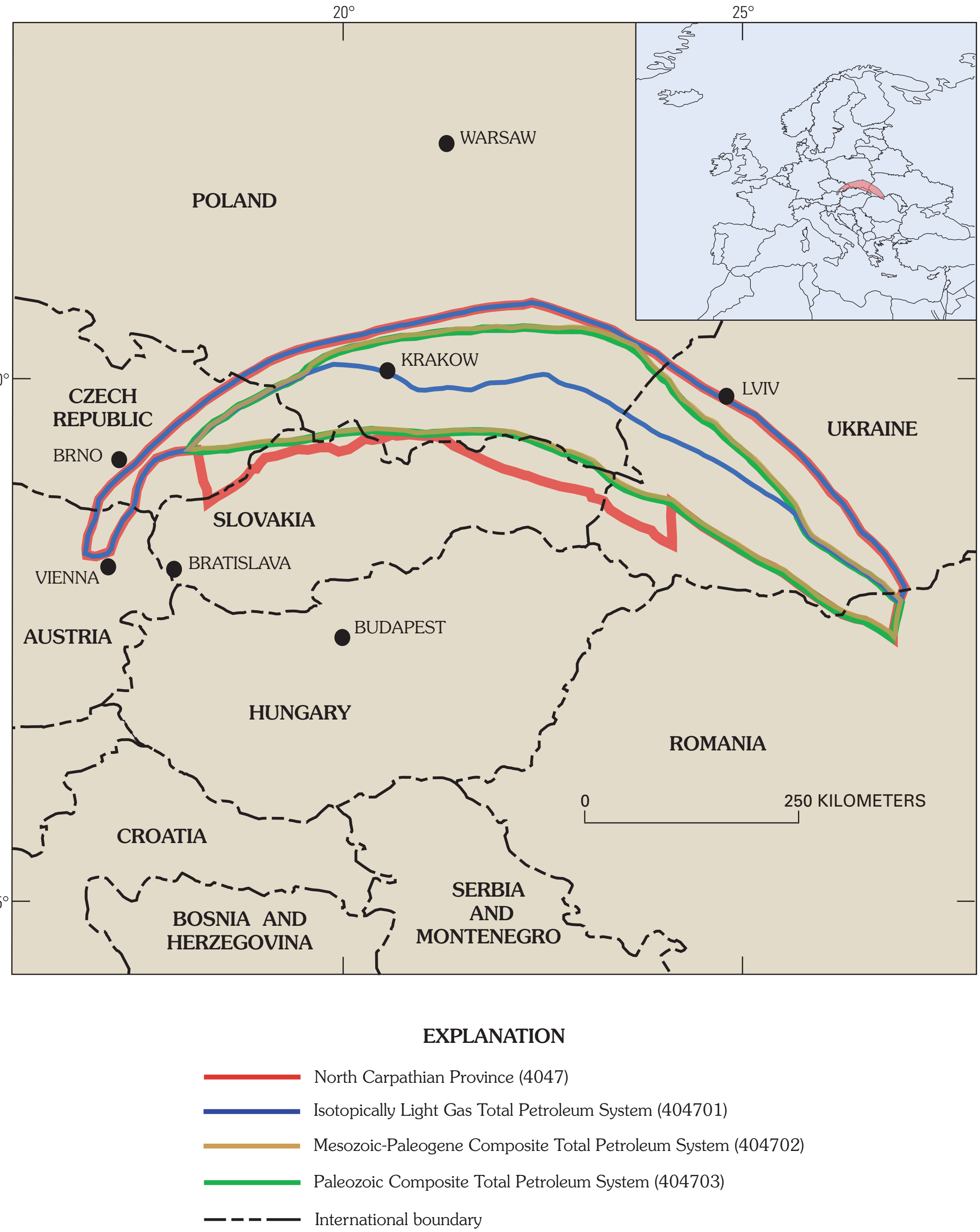


**Figure 1.** Map showing location of North Carpathian Province and outlines of total petroleum systems in Eastern Europe (from U.S. Geological Survey World Energy Assessment Team, 2000).

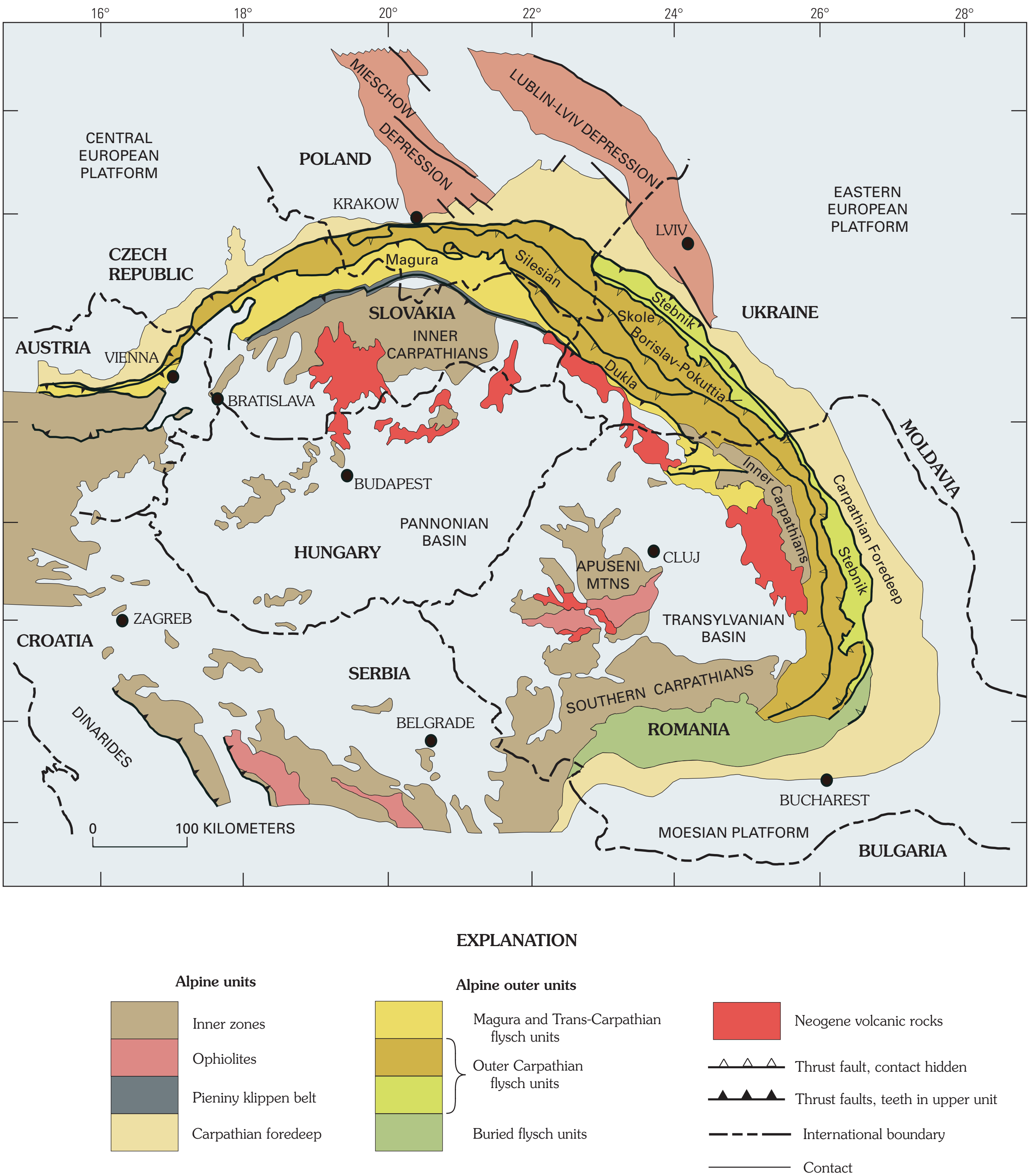


**Figure 2.** Map showing location of Carpathian Mountains and other features in Eastern Europe (after Roca and others, 1995).

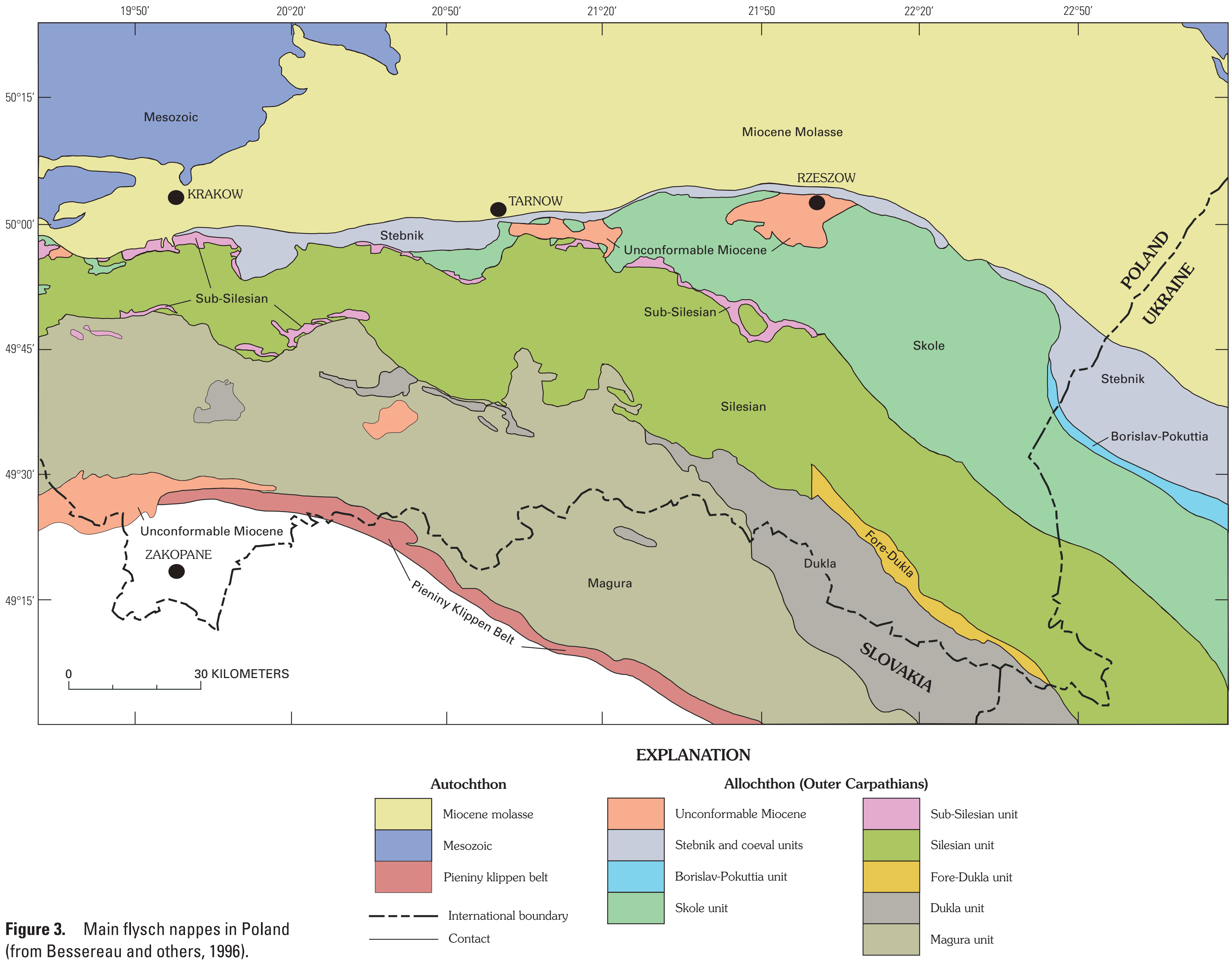


**Figure 3.** Main flysch nappes in Poland (from Bessereau and others, 1996).

feature separates the inner Carpathian Mountains from the outer Carpathian Mountains, the former being outside the assessment region. The western end of the province contains gas fields on an extension of the foredeep molasse depositional environment in Austria and the Czech Republic. The eastern end of the North Carpathian Province is the geographic boundary between Ukraine and Romania, where, as of 2005, oil and gas production has been limited.

## Structural Setting

In the northern and eastern parts of the North Carpathian Province during Devonian to Permian time, the Western and Eastern European platforms were altered by widespread Variscan deformations that produced a series of northwest-southeast-trending horsts and grabens. Late Permian to Jurassic rifting and Late Cretaceous to Paleocene inversions altered these structural features (Bessereau and others, 1996). Thick Paleozoic and Mesozoic sequences were deposited in the grabens, which became individual flysch depositional basins. The rocks in each basin later were thrust north and northeast over the stable European platforms during Cretaceous through Miocene time (figs. 2–4). Additionally, the flysch nappes overrode molasse deposits that were filling, from the north, a foreland basin (the Carpathian foredeep) created in response to the thrusting. The disturbed part of the molasse zone, referred to as the "allochthonous Miocene zone," is located at the point where the molasse deposits are stratigraphically integrated with the flysch units, near the middle of the province. Molasse deposition persisted through Neogene time, and Neogene deposits unconformably overlie the nappes on their northern edge (fig. 3).

The outer Carpathian Mountains (also known as the Flysch Carpathians; figs. 2–4), which form the next major tectonostratigraphic assemblage south of the autochthonous, undisturbed Miocene molasse, consist of major Cretaceous through Oligocene flysch nappes. These nappes are a succession of sandstone and shale units thrust to the north over Miocene rocks of the Carpathian foredeep (northern boundary delimited by the extent of the Miocene marine deposits and southern boundary by the Carpathian overthrust; Karnkowski, 1994). The flysch strata show highly variable lateral and vertical facies and large thickness changes because the basin floor was segmented into highlands and subbasins during successive compressional events (Bessereau and others, 1996; Karnkowski, 1999). These variations result from the diachronous nature of the Carpathian Mountains, which formed during the collision of Africa with southern Europe during Cretaceous through Miocene time. The collision deformed the Carpathian Mountains from southwestern Poland through Ukraine and into Romania and Bulgaria in a clockwise direction. The flysch strata overlie Paleozoic–Mesozoic and Precambrian rocks (Karnkowski and Ozimkowski, 1998).

The loading of the European foreland by a succession of thrust nappes caused its progressive flexural subsidence and the development of the Paleocene Carpathian foreland basin (Oszczypko, 1997). In places this north-northeast thrusting resulted in as much as 180 km of crustal shortening (Ellouz and Roca, 1993; Roure and others, 1993). From the late Oligocene onward, the tectonic pattern was modified by progressive emplacement of the outer Carpathan nappes and emergence of structural highs, which supplied sediments to adjacent basins. In middle Miocene time, the foredeep was formed and filled from the north with molasse, a fine and coarse clastic series deposited in a marine environment (Bessereau and others, 1996). Postorogenic uplift and erosion prevailed in the outer Carpathan Mountains from late Miocene time.

In western Poland, flysch overthrusts generally take a low-angle structural attitude, but near the Poland-Ukraine border a prominent Precambrian basinal high interfered with overthrusting and deflected several of the thrust sheets, impeding their northeasterly directed progress and forming thick, complex, stratigraphic packages in which beds are repeated and source and reservoir rocks of different ages are juxtaposed.

In Austria and the Czech Republic, the molasse units of the outer Carpathan Mountains rest upon autochthonous Paleogene to Neogene rocks, which in turn overlie Mesozoic strata. The molasse, consisting of sandstones, shales, and conglomerates, is younger than the molasse of Poland and Ukraine owing to the asynchronous nature of the thrusting and resulting foredeep development.

## Stratigraphy

The Carpathian foreland basin is divided into two major units: the folded and thrusted flysch belt and the Carpathian foredeep (fig. 2). Within Poland, Upper Cambrian–Permian sedimentary rocks overlie a Precambrian metamorphic and crystalline basement. The Paleozoic strata contain thick Devonian red clastic and carbonate rocks overlain by Lower Carboniferous carbonate rocks and several hundred meters of Namurian clastic rocks that accumulated in grabens partially inverted during the Paleocene (Bessereau and others, 1996). At the southern edge of the area underlain by Miocene molasse, the flysch interfingers with and is folded into the molasse, which it also partly overthrusts.

In the western part of the region, the foredeep is a narrow, relatively shallow basin (about 500 m deep); it widens and deepens to the east (fig. 2). It is filled with autochthonous Miocene molasse sediments (Winkler and Slaczka, 1992; Bessereau and others, 1996; Koster and others, 1998a) consisting mainly of a fine to coarse clastic series deposited in a marine environment.

The autochthonous molasse is divided into three major lithological units, which are mainly of middle Miocene age (Badenian and Sarmatian) (fig. 5): (1) a lower unit of red algal limestone, sandstone, and shale as much as 70 m thick, which originated mainly as deltaic and turbidite sediments; (2) a middle unit, as much as 45 m thick, of evaporates, gypsum, anhydrites, and rock salts; and (3) an upper siliciclastic unit that contains gray-green claystones in the lower part, 30–180 m thick, overlain by a thick (as much as 1,800 m)

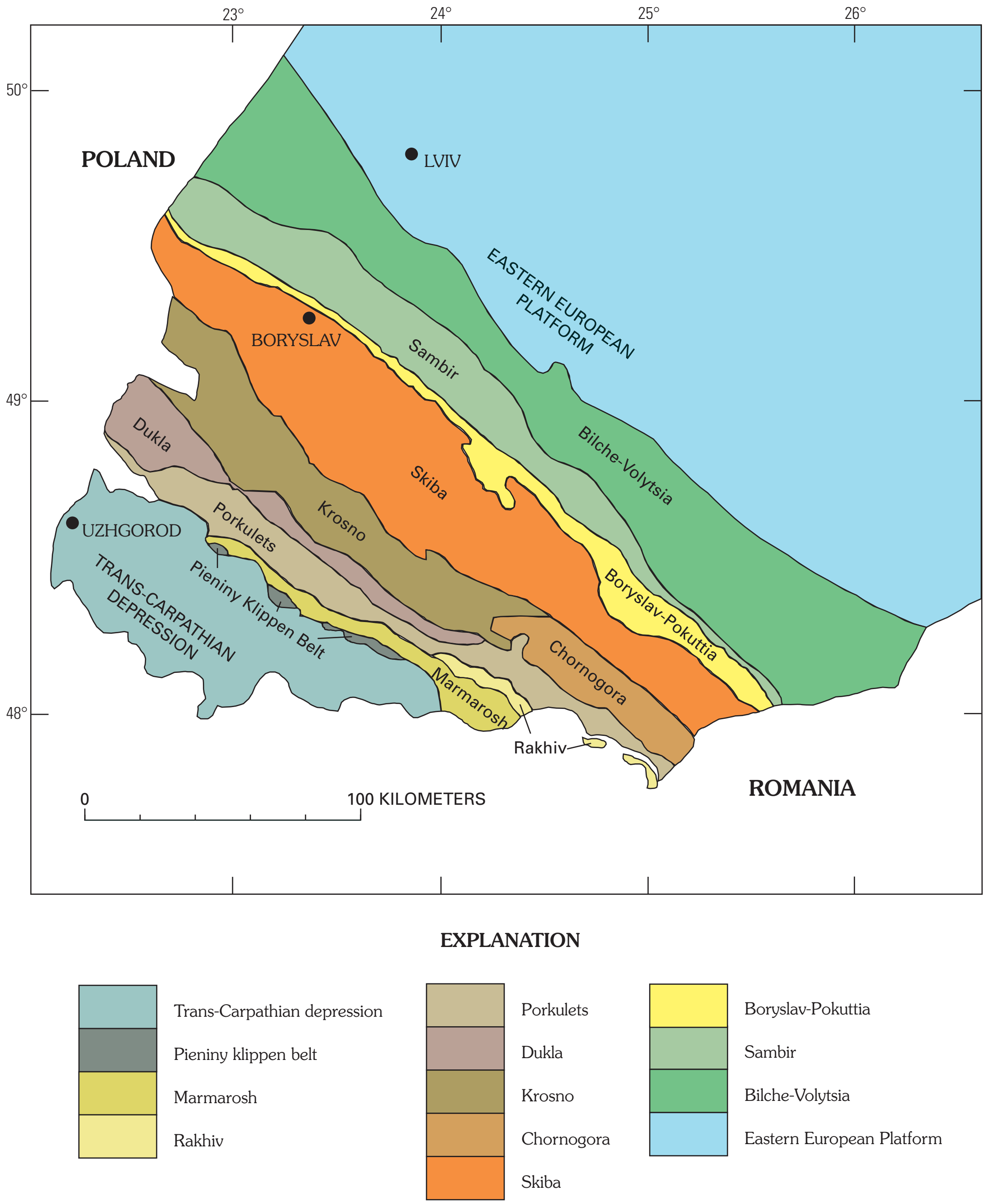


**Figure 4.** Main flysch nappes in Ukraine (from Koltun and others, 1998).

claystone–sandstone sequence of Sarmatian age (Karnkowski and Ozimkowski, 1998).

Much of the flysch is a complex of submarine fan facies consisting of interbedded, predominantly terrigenous, gravity-flow and hemipelagic deposits (Izotova and Popadyuk, 1996). In Poland, the flysch nappes, named in order from north to south (figs. 2–4), are (1) the Skole nappe, in the eastern part of the Polish outer Carpathian Mountains and in Ukraine, composed of Lower Cretaceous to lower Miocene sediments; (2) the sub-Silesian nappe, a thin sequence of Cretaceous and Paleogene strata; (3) the Silesian nappe, present in the entire outer Carpathian Mountains and composed of uppermost

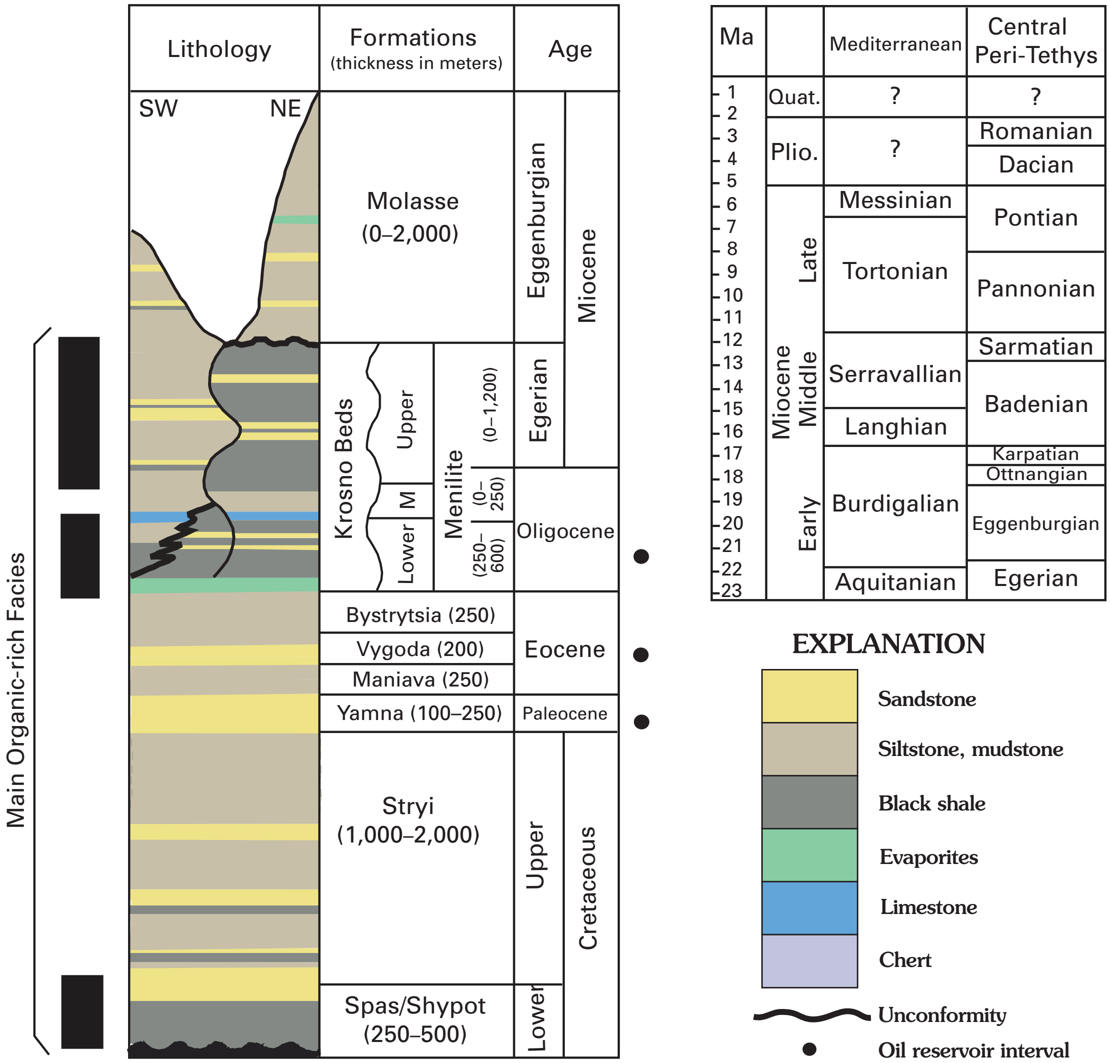


**Figure 5.** Stratigraphic column for the flysch belt in Ukraine (from Koltun and others, 1998). Plio., Pliocene; Quat., Quaternary.

Jurassic to Oligocene rocks; (4) the Dukla nappe, the uppermost tectonic unit of the outer Carpathian Mountains, which is composed of thick, highly deformed Cretaceous to Paleogene deep-water flysch and late Oligocene and earliest Miocene (Aquitanian) molasse sequences; and (5) the Magura nappe, which comprises the Cretaceous to middle Miocene flysch succession.

In Ukraine, the flysch nappes forming the external Carpathian Mountains are Early Cretaceous to early Miocene. The Boryslav–Pokuttia nappe, the northeastern most nappe (fig. 4), which is present only in Ukraine, consists of a stack of duplexes made up of Upper Cretaceous to lower Miocene flysch overlain by molasse. To the southeast are the Skiba (equivalent to the Skole nappe in Poland), Krosno (equivalent to the Silesian nappe in Poland), Chornogora, Dukla, Porkulets, Rakhiv, and Marmarosh nappes (fig. 4). Located northeast of the Boryslav–Pokuttia nappe are two molasse units the Sambir, composed of folded molasse strata of early Miocene (Eggenburgian to Ottnangian) age (Koltun and others, 1998), and the Bilche–Volytsia (Koltun and others, 1998). A zone of deformation marks the contact between the nappes and molasse.

# Geochemistry of Oil in Poland and Ukraine

The Carpathian foredeep and the Carpathian nappe complex are part of one of the largest petroleum provinces in central Europe (Ulmishek and Klemme, 1990). Four potential hydrocarbon source rocks, ranging in age from Devonian to Miocene, are identified within the North Carpathian Province. Owing to the complex geologic structure, the diachronous emplacement of the thrust sheet, and extensive erosion, a given source rock can be immature in one place and overmature in another as a function of its stratigraphic position or its position in an individual thrust sheet. ten Haven and others (1993) recognized two oil families within the Carpathian nappes and the Polish part of the foredeep. Reservoir oils and seeps from Cretaceous to Oligocene reservoirs within the Carpathian nappes were sampled, as were reservoir oils from Carboniferous to Miocene in the foredeep. In addition, rock samples from Lower Cretaceous rocks and Menilite Shale (fig. 6) in the nappes were examined for correlations between oil and source rock.

The first oil family is represented by a sample from the Nosowka-1 well, which penetrates a Lower Carboniferous carbonate reservoir in the foredeep (fig. 11). To date, no source rock is specifically associated with this oil. The second oil family includes all nappe oils and a number of foredeep samples except for Nosowka-1. Oleanane and other biomarkers derived from angiosperms (land plants) indicated a probable Cretaceous or Tertiary source. Further divisions were made within the second oil family on the basis of biomarkers and sulfur content. Sulfur content of these samples ranged from <0.1 to 2.27 percent, and the foredeep oils had sulfur content higher than that of oils from the nappes. The lateral and vertical variations in the types of organic matter in the Menilite Shale likely cause these differences.

To determine petroleum-generation potential of the main organic-rich sequences that extend across a basin in the flysch belts, Koltun and others (1995) examined Lower Cretaceous strata and the Oligocene–Miocene Menilite Shale from the Skole unit of the Polish Carpathian Mountains (figs. 3, 6) and the Boryslav–Pokuttia and Skiba units of the Ukrainian Carpathian Mountains (fig. 4). Rock-Eval results showed that the Menilite Shale had favorable source-rock properties on a basin-wide scale: total organic carbon values were as much as 18.5 percent and were commonly 4–6 percent in the Ukrainian samples. Samples from the Polish Carpathian Mountains were as much as 7.35 percent and were commonly 2–4 percent. The Cretaceous Spas beds in Polish samples contained favorable total organic carbon values that were as much as 4.13 percent and were commonly 1–2 percent; in Ukrainian samples, total organic carbon values were as much as 4.87 percent and were generally 2–4 percent.

ten Haven and others (1993) analyzed rock samples from the Oligocene–Miocene Menilite Shale and from Lower Cretaceous rocks. They measured total organic carbon values that ranged from 2.15 to 22.15 percent and hydrogen index values that ranged from 300 to 650 milligrams of hydrocarbon per gram of total organic carbon (mg HC/g TOC). The Cretaceous sample had a TOC value of 3.47 percent and a hydrogen index of 53 mg HC/g TOC. From these data they determined that the Menilite Shale is a good potential source rock. The Cretaceous sample did not show similar promise as a source rock, even though it contained organic matter of type II (marine origin) and type III (terrigenous origin). In light of the biomarkers and total organic carbon values, the Menilite Shale (the source for the second oil family) appears to be the major source for the hydrocarbons in the nappe sequence.

Koster and others (1998b) recorded total organic carbon values as high as 18 percent in the Menilite Shale; more than 80 percent of the organic matter was present in the black shale unit. A mean total organic carbon value of 3.5 percent was calculated for all rock types in the formation in southeastern Poland (black and gray shale, sandstone, gray mudstone, chert, and siliceous shale) (Koster and others, 1998a). Koster and others (1998b) examined facies differences between the upper and lower Menilite Shale and suggested that differences in the depositional sites explain variations in the organic matter. That is, continental slopes that receive organic matter but little clastic material tend to accumulate sediments in which the organic matter has a higher hydrogen index. In contrast, samples from the upper Menilite that had a higher clastics content would result in a correspondingly lower hydrogen index produced by a mix of organic matter that contained larger amounts of recycled, or previously deposited, organic matter.

The hydrogen index was observed to differ among the various thrust sheets in southeastern Poland. Values as high as 350 mg HC/g TOC were measured in black shale samples from the lower Menilite Shale in the Skole and the Fore-Dukla units (fig. 3), whereas lower hydrogen index values, <300 mg HC/g TOC, were measured in samples from the upper part of the sequence in the Skole unit (Koster and others, 1998b). Variation in hydrocarbon index is related to differences in the type and concentration of organic matter in different locations.

Thermal maturity is measured by $T_{max}$ (a laboratory-derived thermal maturity indicator) and vitrinite reflectance. The Menilite Shale is generally thermally immature to marginally mature in southeastern Poland, depending on the thrust sheet. $T_{max}$ values for samples from the Skole unit ranged from 400° to 418°C and the $R_o$ was 0.3–0.35 percent—a value that is well below the generally accepted threshold of oil generation of about 0.7 percent. The low maturity values show that the various units did not undergo sedimentary or tectonic burial during Neogene overthrusting (Koster and others, 1998a). In contrast, samples from the Fore-Dukla and the Dukla nappe near the Ukraine border had $T_{max}$ values in the overmature range for oil generation. ten Haven and others (1993), in an analysis of isotopic composition of 33 oils from the foredeep and overthrust region in

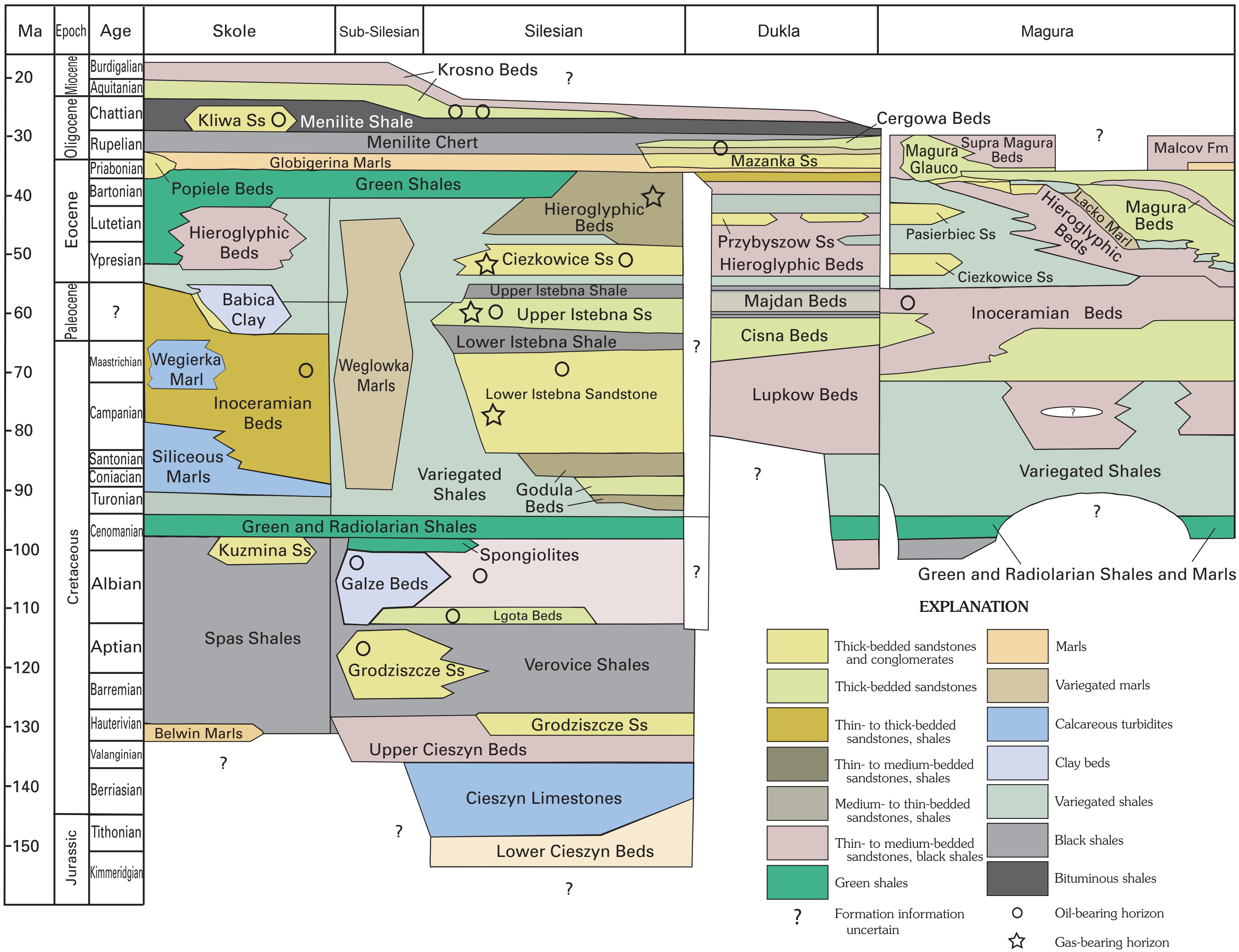


**Figure 6.** Stratigraphic chart of flysch strata in Polish nappes (from Slaczka, 1996). Fm, Formation; Ss, sandstone. Color blocks in Explanation refer to lithology.

Poland, found that all but one sample plot within a group that is associated with an algal origin and that contains oleanane, an indicator of an angiosperm origin. The exception is an oil from the Nosowka-1 well that has a notably lighter isotopic signature.

Oil in the Lower Cretaceous–Oligocene flysch units is aliphatic and sulfur-free and contains 3.5–7.0 percent paraffin. Density ranges from 0.75 to 0.93 g/cm$^3$. The Carpathian foreland oils in Upper Cretaceous sandstones and Jurassic limestone and Carboniferous rocks are light to medium in weight. Density ranges from 0.81 to 0.86 gm/cm$^3$, sulfur content from 0.45 to 0.85 percent, and paraffin content from 2.32 to 9.37 percent (Gorecki and Weil, 1998) oil contains 0.5–0.7 percent paraffin by weight and as much as 7 percent sulfur by weight (Slaczka, 1996).

In the Bilche-Volytsia zone, oil in small oil fields producing from Jurassic limestones has a specific gravity of 0.973–1.014. The gravity of oil samples from southeastern Poland ranged from 14° to 60° API; the majority of the samples lay between 31° and 44° API. The lower values are believed to be due to biodegradation. Sulfur in the same Carpathian samples ranged from <0.1 to 2.27 percent. Oils sampled from the foredeep generally had higher sulfur content than oils from the overthrust units (ten Haven and others, 1993).

# Miocene Gas

Early studies of Miocene gas in Poland and Ukraine reported its source to have been Paleozoic–Mesozoic strata (Kotarba and others, 1987), but later studies demonstrated that Miocene rocks themselves (mainly autochthonous Badenian and lower Sarmatian) were the actual source (Bessereau and others, 1996; Kotarba and others, 1987, 1998). Kotarba (1992, 1998) assigned a biogenic origin to all of the gas in the Miocene molasse of Poland, and Koltun and others (1995) reached the same conclusion for gas in the Ukrainian molasse. In the molasse area of Austria, most of the produced gas is also of biogenic origin (Ladwein, 1988).

Kotarba and others (1987) report high wet gas (methane content) values of 0.992 and carbon isotope values in the –62.8 to –70.8 range. The combination of these values, along with a lack of correlation of these values with depth, is evidence for an anaerobic microbial source for the gases.

Analyses of 80 samples of marine shale from the autochthonous Miocene molasse from the western, central, and eastern Polish Carpathian Mountains recorded low values of total organic carbon (0.5–0.8 percent) and of hydrogen index (<120). Additional tests indicated a probable terrigenous source for the organic matter. Gas in the Carpathian foredeep has a high methane and low nitrogen content.

# Potential Source Rocks

## Oligocene and Miocene Potential Source Rocks

In Poland, gas fields are found only in Miocene molasse. West of Krakow these strata are of Badenian and Karpatian age (figs. 5, 6), whereas to the east they are lower Sarmatian and Badenian. The lower Sarmatian and upper Badenian sediments are a clayey-sandy facies of mostly deltaic sediments, and the lower Badenian sequence comprises chemical deposits and shallow-water detrital clay sediments (Kotarba and others, 1987). The thickness on the western side approaches 1 km and on the eastern side exceeds 3.5 km.

Concentrations of kerogen in Sarmatian and Badenian strata attain as much as 2.1 percent (average 0.82 percent) and 3.4 percent (average 0.88 percent) total organic carbon, respectively (Kotarba, 1992). These concentrations indicate potential for hydrocarbon generation. Petrographic analyses determined that the organic matter was terrigenous type III. A $T_{max}$ produced by pyrolysis was 435°C and vitrinite reflectance ranged from 0.40 to 0.68 percent; these values indicate a level of maturity representing the beginning the oil window. The geothermal gradient of 34°C/km is low, and temperatures measured 2.5 km north of the edge of the overthrust were a maximum of 90°C (Kotarba and others, 1987). Low $T_{max}$ values indicate that the Miocene rocks at depths of 3.2–3.3 km are immature. Below 3.3 km, strata lie at the onset of thermogenic processes under the Carpathian flysch overthrust (Kotarba and others, 1998).

The isotope carbon values appear to indicate that generation conditions are consistent with depth and that gases were generated mainly as a result of anaerobic microbial action on the organic matter (Kotarba and others, 1987).

The sources of isotopically light gas in Poland are upper Badenian and lower Sarmatian rocks of the autochthonous Miocene sequence in the Carpathian foredeep. These rocks contain type III organic matter in concentrations of 0.02–3.22 wt percent, concentrations that indicate probable immaturity to a depth of 3.2 km. Insignificant changes in other geochemical parameters (total organic carbon, hydrogen index, and vitrinite reflectance) laterally and with depth indicate a consistent depositional environment (Kotarba and others, 1998). Carbon isotope values of methane range from –70.8 to –62.8 ppt (parts per thousand).

### Menilite Shale

In the flysch Carpathian region, the Oligocene Menilite Shale (identified as Oligocene–lower Miocene in Koltun and others, 1998) is the principal source of hydrocarbons. The formation is at the top of the flysch complex and is unconformably overlain by molasse. Source rocks in Ukraine are primarily in the Boryslav–Pokuttia and Skiba units (fig. 4), but in the Polish Carpathian Mountains they are only within the Skole flysch unit (Koltun and others, 1995). The thickness and organic content of the Skole are variable across the region owing, at least in part, to a northeasterly shifting depositional basin. The lower facies of the Menilite Shale was slowly replaced by the Krosno Formation in southeast Poland and southwest Ukraine, as marked by the changing volume and type of organic matter. Mainly amorphous type II matter, which contains little terrestrial plant material, was diluted as pelagic and hemipelagic, anoxic, depositional regions began receiving increasing amounts of clastic material. The boundary between the Menilite Shale and Krosno Beds (fig. 6) is diachronous owing to the easterly shift of the basin depocenter (Koltun, 1992). (The age designation of the Krosno Beds (fig. 5) and Menilite Shale is variable, apparently by location. For example, the Krosno Beds are identified as Oligocene near eastern Poland by Karnkowski and Ozimkowski (1998) and as Oligocene-lower Miocene near western Ukraine by Koltun and others (1998)).

The Menilite Shale in Poland is characterized by dark gray and black, mostly laminated, noncalcareous shales with intercalated chert and siliceous shales (Koster and others, 1998b). The formation is as much as 100 m thick in the Silesian thrust sheet and 900 m thick in the Dukla basin; combined with the Krosno Formation, thickness ranges from 1,200 m in the Skole basin to 4,000 m in the Dukla basin. In Ukraine, the Menilite Shale reaches a maximum thickness of more than 1,500 m in the Skole nappe but is only a few tens of meters thick in the innermost part of the outer Carpathian Mountains. Subsequent overthrusting and folding of much of the Carpathian region led to the development of packages of source, reservoir, and seal rocks over a wide area. The formation is mature in some places but immature in others; in southeast Poland, it is immature to marginally mature at outcrop. The thermal maturity of the organic matter in outcrop increases from the outer flysch nappe units toward the inner units. Lateral variations also exist within individual inner units (Koster and others, 1998b).

In Poland, total organic carbon values for the Menilite Shale are as much as 22.15 percent, and hydrogen indices are as much as 700 mg HC/g TOC (ten Haven and others, 1993; Bessereau and others, 1996). Koltun and others (1995) reported total organic carbon values as high as 7.35 percent (mainly in the 2–4 percent range) in surface and subsurface samples of Menilite Shale near the Ukraine border. Koster and others (1998a) listed 3–10 wt percent for the black shales in southeastern Poland. On the basis of three sample sites in Poland (two from the Silesian basin and one from the Skole basin), the highest values of total organic carbon and hydrogen index consistently are from the lowest part of the formation, just above a marl facies interval. Organic matter is predominantly amorphous marine, but there is also a slight amount of terrigenous material (Bessereau and others, 1996). As in Ukraine, both total organic carbon and hydrogen index decrease higher in the stratigraphic section. In Poland and Ukraine, type II organic matter from a marine, sapropelic source predominates. Kruge and others (1996) analyzed Menilite Shale and mudstone samples from southeast Poland and found total organic carbon values from 0.6 to 10.7 percent; hydrogen indices from 400 to 860 mg pyrolyzate/g TOC, and oxygen indices from 18 to 197, indicative of a type I/II kerogen. Rock-Eval values indicated immature samples north of the Ukraine border; they increased in maturity toward the border. Predominant alginite organic matter but minimal vitrinite was visible in a petrographic examination.

Koster and others (1998b) reported, on the basis of Rock-Eval analyses, that Menilite Shale samples from the Skole flysch nappe and the Silesian flysch nappe in southeastern Poland were thermally immature. The thermal maturity of exposed Menilite Shale is at a pretectonic (immature) level because the rocks did not undergo deep sedimentary burial. Burial owing to overthrusting, however, caused the general increase in maturation levels (Koltun and others, 1995).

In Ukraine, the Menilite Shale extends across the entire flysch belt (external Carpathian Mountains), though it is primarily in the Boryslav–Pokuttia and Skole (equivalent to Skiba unit in Ukraine) flysch nappes (fig. 4). This formation is the youngest part of the Carpathian flysch sequence and is overlain unconformably by the Neogene molasse (Koltun, 1992). The Menilite Shale reaches a maximum thickness of 1,500 m in the outer Skole nappe. Owing to thrusting, the formation crops out in some places and is buried as deeply as 6 km in others. It is differentiated into lower, middle, and upper units that differ in areal extent, thickness, and content of organic material. The lower unit, because of its basin-wide extent and high organic matter content (exceeding 20 percent locally; average 4–8 percent) in the outermost tectonic units, is considered the principal source rock in the flysch zone and in the foredeep (Koltun and others, 1998). The other two units are deficient as source rocks. Organic matter is sparse in the middle unit and of only local extent in the upper unit. The Menilite Shale is immature to a depth of about 4 km, and it appears to maintain petroleum potential to about 6 km (Koltun and others, 1995, 1998).

## Krosno Formation and Menilite Shale Equivalents

In Poland, the Oligocene-Miocene Krosno Formation had low total organic carbon (<1 percent) and a low hydrogen index (<200) at all sampled localities. As compared with the Menilite Shale, it is interpreted to have been deposited in deeper, more oxygenated water (Koltun, 1992). Its type III organic matter is low in quality and quantity, which probably makes this formation a substandard source rock.

In Ukraine, as one moves to the southwest within the flysch units, the lower, organic-rich section of the Menilite Shale is systematically replaced by the Oligocene Krosno Beds (figs. 4, 5), a shale and sandstone unit with organic carbon content commonly <1 percent. The diminishing organic content from northeast to southwest across the basin accounts for the variability of the Krosno Beds as a source rock and limits its potential to generate hydrocarbons.

## Cretaceous Potential Source Rocks

### Spas and Shypot Formations

In Ukraine and Poland, the Lower Cretaceous (Barremian to Albian) Spas Formation lies at the base of the flysch complex in the outer part of the Carpathian Mountains (figs. 5, 6). This formation is present only within the Skiba (Skole) nappe (fig. 3), where the lower part consists of more than 200 m of black shale with minor sandstones and siltstones; in that lower part the total organic carbon is generally greater than 2 percent and may exceed 7 percent. Organic matter is types II and III, mostly from a terrestrial source. Although burial through time by overthrusts increased the maturation levels (Koltun and others, 1995), outcrop samples were thermally immature, and at a depth of more than 4.4 km the rocks are still within the oil window (Koltun and others, 1998). In Ukraine, the Lower Cretaceous (Barremian to Albian) Shypot Formation (fig. 5) lies in the more internal nappes—the Chornogora, Dukla, and Krosno (fig. 4). The formation has 300 m of black shale and minor sandstones and siltstones at its base. Total organic carbon values are as much as 8 percent but average 2–4 percent of mostly types II and III organic matter. On the basis of $T_{max}$ thermal maturity values of 454°–458°C, samples as deep as 3.6 km corresponded with the beginning of the oil window. The two formations are considered to have potential as petroleum source rocks (Koltun and others, 1998).

In Poland, the Lower Cretaceous Spas Formation is predominantly black shale with thin interbedded sandstones in the lower part. It is present throughout the Skole basin in eastern Poland (figs. 2, 3) and also at the base of the flysch zone in the outer Carpathian Mountains. Total organic carbon values ranged from 1.5 to nearly 4 percent and average 2 percent; hydrogen indices ranged from 90 to 180. A $T_{max}$ value of 442°C placed the organic matter in the early oil window range. Koltun and others (1995) reported total organic carbon values as high as 7.35 percent, but generally they are in the 2–4 percent range; organic matter is type II and III kerogen and thus more apt to produce gas. Kruge and others (1996) reported vitrinite reflectance values of 0.45 and 0.47 percent (immature to marginally mature) in two shale samples from southeastern Poland. The measurements were apparently made on recycled organic matter and therefore may represent a higher maturity than actually exists. Because type III kerogen predominates, this formation may be a viable source rock within the Skole basin.

### Other Potential Source Rocks

Another potential source rock in Poland is in the upper part of the lower Neocomian Cieszyn Shale, though geochemical analyses indicated that its potential is much lower than that of the Menilite Shale (fig. 6). The upper Cieszyn unit is as much as 300 m thick, has total organic carbon values of 1.5–3 percent (average 2 percent from type III organic matter), and a hydrogen index of 100 mg HC/g TOC. The hydrogen index is considered too low for the Cieszyn Shale to be a high-quality source rock, and it is unlikely that this unit has contributed hydrocarbons to oil and gas pools (Bessereau and others, 1996).

The Upper Cretaceous–Paleocene Istebna beds (fig. 6), in the eastern Polish Carpathian Mountains, have a gross thickness of 50–1,800 m and are composed of thick-bedded sandstones separated by thin-bedded sandstones and black shales. Two major depositional facies are present in the formation: channel-fill and lobe deposits, and channel-fill submarine mudflow deposits (Klecker and others, 2001). Samples from the Istebna and Inoceramian strata (fig. 6) yielded low average total organic carbon (0.6 percent) and low hydrogen indices (<130 mg HC/g TOC) that indicate minimal source-rock potential.

A single sample of lower Neocomian (Lower Cretaceous) shale showed more favorable results: total organic carbon was as high as 1.5 percent and the hydrogen index was 120. These findings were balanced by a $T_{max} > 455$, which represents the high end of the oil window. This rock unit's source potential appears to be limited (Bessereau and others, 1996).

The Lgota Formation covers a wide area of the Silesian and sub-Silesian basins and the Fore-Dukla zone in Poland (fig. 3). In this formation (on the basis of limited sampling), average total organic carbon was 1 percent and hydrogen index was 100 mg HC/g TOC; these values are low and indicate limited potential as a source rock.

## Jurassic Potential Source Rocks

In Ukraine, the Middle Jurassic Kokhanivka Formation, organic-rich shale about 500 m thick, is present in the northwest part of the foredeep. In samples from 2.3 to 2.5 km depths, analyzed by Rock-Eval, total organic carbon values exceeded 12 percent locally and a type II kerogen was present, which indicates excellent petroleum potential. Thermal maturity parameter $T_{max}$ ranged from 434° to 438°C, values that indicate maturity at the beginning of the oil window (Koltun and others, 1998).

In southeastern Poland, an Upper Jurassic carbonate rock is believed to be the source of a thermogenic gas in an area that otherwise would be expected to produce only biogenic gas. A cross section by Kotarba (1998) shows Jurassic rocks lying beneath a thin sequence of lower Badenian rocks, presumably containing oil-prone, marine organic matter at a maturation level of 1.1–1.6 percent. Although production is unusual for this area of the Carpathian foredeep, some oil is produced from this interval (Kotarba, 1998).

A nearly 500-m-thick Middle Jurassic organic-rich shale sequence (with minor sandstones and siltstones) is present in the northwestern part of the foredeep. Locally these rocks have a high total organic carbon content, greater than

12 percent, and Rock-Eval showed a type III kerogen with excellent petroleum potential. $T_{max}$ values of 434°–438°C indicated that the formation is in the initial stages of oil generation (Koltun and others, 1998).

## Paleozoic Potential Source Rocks

Because of limited drilling, not much is known about the source-rock potential of older rocks in the North Carpathian Province. Data indicate that Lower Carboniferous black shale or silty shale in the northernmost Skole nappe have total organic carbon values of about 1.5 percent but low hydrogen indices (near 100 mg HC/g TOC). Additionally, these data indicate that Lower Carboniferous coal from the west end of the Polish Carpathian Mountains showed good petroleum potential—total organic carbon values of 47 percent and hydrogen index values of 450 (Bessereau and others, 1996). In western Poland, southwest of Krakow, drilling also revealed a Devonian source rock beneath the folded and thrusted flysch nappes. The Lachowice-1 well was drilled through 3.2 km of flysch and 750 m of autochthonous Miocene rocks to Devonian carbonate rocks to establish the first gas field in the western Carpathian Mountains (Pietsch and others, 1997) (fig. 11). Oil from the isolated Nosowka area appears to be from Devonian or Carboniferous shales (fig. 11).

More than 500 m of Silurian rocks are present in the autochthonous foreland, partially overthrust by the Carpathian allochthon. Rock-Eval analyses found total organic carbon values from 0.24 to 0.68 percent but no $S_2$ peak. The rocks appear to have no generative potential (Koltun and others, 1998).

## Other Potential Source Rocks

Another potential source rock in Poland is in the upper part of the lower Neocomian Cieszyn Shale, though geochemical analyses indicate that its potential is much lower than that of the Menilite Shale (fig. 6). The Cieszyn unit is as much as 300 m thick, has total organic carbon values of 1.5 to 3 percent (average of 2 percent from organic matter type III), and a hydrogen index of 100 mg HC/g TOC. The hydrogen index is considered low for it to be a high-quality source rock, and whether it has contributed hydrocarbons to oil and gas pools is questionable (Bessereau and others, 1996).

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# Reservoir Rocks

Biogenic gas forms the main hydrocarbon accumulation in the Carpathian foredeep, which includes the Bilche-Volytsia zone (in the little-deformed Carpathian foredeep) and in the frontal Carpathian structures of the Sambir unit (in the Carpathian thrust belt; figs. 2, 3). Reservoir potential of the autochthonous foreland is restricted to Upper Jurassic carbonate rocks and Lower Cretaceous, Paleogene, and Neogene sandstones (Sovchik and Vul, 1996). In the Bilche-Volytsia zone (fig. 4), commercial oil flow rates were obtained from Paleogene sandstones in several fields at depths ranging from 4,080 to 5,796 m.

Upper Cretaceous and Upper Jurassic rocks in the southeast part of the foredeep host oil accumulations beneath the flysch that are sealed by Miocene molasse.

Cretaceous and Eocene sandstones are highly productive within the Silesian nappe of eastern Poland (fig. 6). Eocene–Oligocene sandstones are productive in the Skole (Poland) and Skiba (Ukraine) units, and sandstones within the Krosno Beds are the youngest productive horizons of Oligocene age (Karnkowski, 1996). In the Carpathian Mountains, oil is present in narrow, predominantly steep, overthrust and imbricated folds as much as 30 km long. These folds are commonly dissected by transverse and longitudinal faults that bound numerous blocks (Karnkowski, 1996).

The Kliwa Sandstone, enclosed within the Menilite Shale, the Ciezkowice Sandstone, and both Lower and Upper Cretaceous sandstone (fig. 6) are the most productive reservoir rocks in the flysch Carpathian Mountains. The most productive structural unit is the Silesian nappe (fig. 6) (Karnkowski and Ozimkowski, 1998, Karnkowski, 1999).

The Paleozoic and the Mesozoic basement are considered to have the best potential for reservoirs after the flysch sequences.

## Seals

In Ukraine, shale units at the base of the major nappes are the seals for traps in the allochthonous Carpathian flysch. In addition, the subthrust autochthonous sedimentary sequence contains Lower Cretaceous and Neogene seals such as the Menilite Shale (Sovchik and Vul, 1996).

Shale units within the various flysch units also provide seals for numerous oil and gas fields in Poland. Internal nappes are characterized by greater structural complexity than the external nappes, lower relief, and large anticlinal roll-overs. In contrast, the frontal thrust sheets of external nappes are generally steep and depend on fault closure to complete the reservoir compartment (Sovchik and Vul, 1996). In western Poland, Devonian reservoirs are sealed by thick, flat-lying flysch nappes. Lower Cretaceous shales provide a subregional seal for Upper Jurassic carbonate reservoirs.

# Assessment Units

## Isotopically Light Gas Total Petroleum System

The Isotopically Light Gas Total Petroleum System is contained wholly in Miocene strata of Poland, Ukraine, and Austria (fig. 7). In Poland, the main stratigraphic package that generates gas is the clayey and sandy, predominantly deltaic facies within strata of the upper Badenian and lower Sarmatian. East of Krakow, the thickness of this package ranges from 0 to 1,700 m and 0 to 2,900 m, respectively (Kotarba and others, 1998). The autochthonous Miocene rocks of the Neogene Carpathian foredeep in Poland contain only biogenic gas (Koltun and others, 1995), which is generally 98 percent methane and 2 percent higher gaseous hydrocarbons, such as ethane and propane. Most of the gas lies within the autochthonous reservoirs of the undeformed Miocene molasse; the lower Sarmatian contains 90 percent of the identified resources (Karnkowski, 1996). Folded Miocene rocks of the Stebnik unit from the inner part of the Polish Carpathian foredeep (fig. 2) are thought to be unimportant for petroleum exploration (Kotarba, 1998). In Austria, the gas from the molasse is mostly biogenic (Ladwein, 1988).

Gas accumulation in the outer (northern) parts of the Carpathian foredeep was facilitated by a high sedimentation rate (Kotarba and Jawor, 1993), typified by the rhythmic and cyclic deposition of clays and sands as well as by methane hydrate. The gas was trapped in stratigraphic and in structural traps, especially in the overthrusted areas. Reservoir rocks (mostly sandstones) are present throughout the autochthonous Miocene sequence, which ranges from about 200 m to more than 3,000 m thick (Zagorski, 1996).

Generation of gas started almost contemporaneously with deposition. Primary migration of the gas was limited but increased as the compaction of the Miocene sediments increased. Secondary, longer-range migration resulted from the synsedimentary interaction of the flysch overthrusts and the Miocene sediments, such that structural traps formed in the northward-dipping Miocene strata at the edge of the overthrust (Kotarba and others, 1987).

Reservoir properties differ greatly. Porosity values range from 3 to 23 percent (commonly 5–20 percent), and permeability ranges from 0 to 4,000 millidarcies (mD) but is most commonly a few tens of millidarcies. Permeability and porosity both decrease with depth (Zagorski, 1996). Sandstone content can be 5–95 percent, though commercial production is from horizons containing 5–20 percent sandstone (Zagorski, 1996).

Seals for the Miocene gas accumulations are primarily shale and claystones that overlie coarser sediments, but seals are also formed by shale interbeds or massive anhydrite in places. The autochthonous Miocene contains numerous structural traps in the zone in contact with the nappes; it also contains stratigraphic traps related to wedging-out of the reservoirs or to the facies changes that are common north of the Carpathian overthrust margins (Kotarba and Jawor, 1993). Generation of biogenic gas began contemporaneously with deposition of the molasse and has continued since, but likely only on a local scale and in minimal amounts. Figure 8 shows the timing of critical geologic events during the evolution of the Foreland Basin Assessment Unit. On the basis of this assessment, an estimated 141 gas fields and 78 oil fields remain to be discovered; these fields have calculated mean resources of 2,321 billion cubic feet of gas (BCFG) and 9 million barrels of natural gas liquids (MMBNGL) respectively.

## Mesozoic–Paleogene Composite Total Petroleum System

Most of the petroleum fields in the Ukrainian Carpathian Mountains are in the Paleogene flysch nappes of the outer tectonic units (figs. 2, 4, 9). In Poland, the main oil fields were discovered in both the Paleogene and in the Cretaceous flysch units and in the Paleozoic–Mesozoic basement (figs. 2, 3, 9).

The most important oil and gas fields in western Ukraine are in the Boryslav–Pokuttia unit of the foredeep and in the flysch sequence of the outer Carpathan belt, primarily the Skole nappe (fig. 3). Both settings involve deep-seated folds from which hydrocarbons are produced by combined Paleocene, Eocene, and Oligocene sandstone reservoirs in structural traps that are mostly sealed by Miocene molasse. A few oil and gas accumulations lie within the pre-Miocene foreland sequence that was overridden by the Carpathian nappes. In the foreland of the Carpathian Mountains, and beneath the external nappes, two oil fields, one gas field, and one gas and condensate field produce from Upper Jurassic carbonate rocks. These four fields also include pay sections in Cretaceous and Miocene sandstones where karstification created good reservoir porosities and permeabilities in parts


**Figure 7.** Map showing location of Isotopically Light Gas Total Petroleum System within the North Carpathian Province of Eastern Europe.

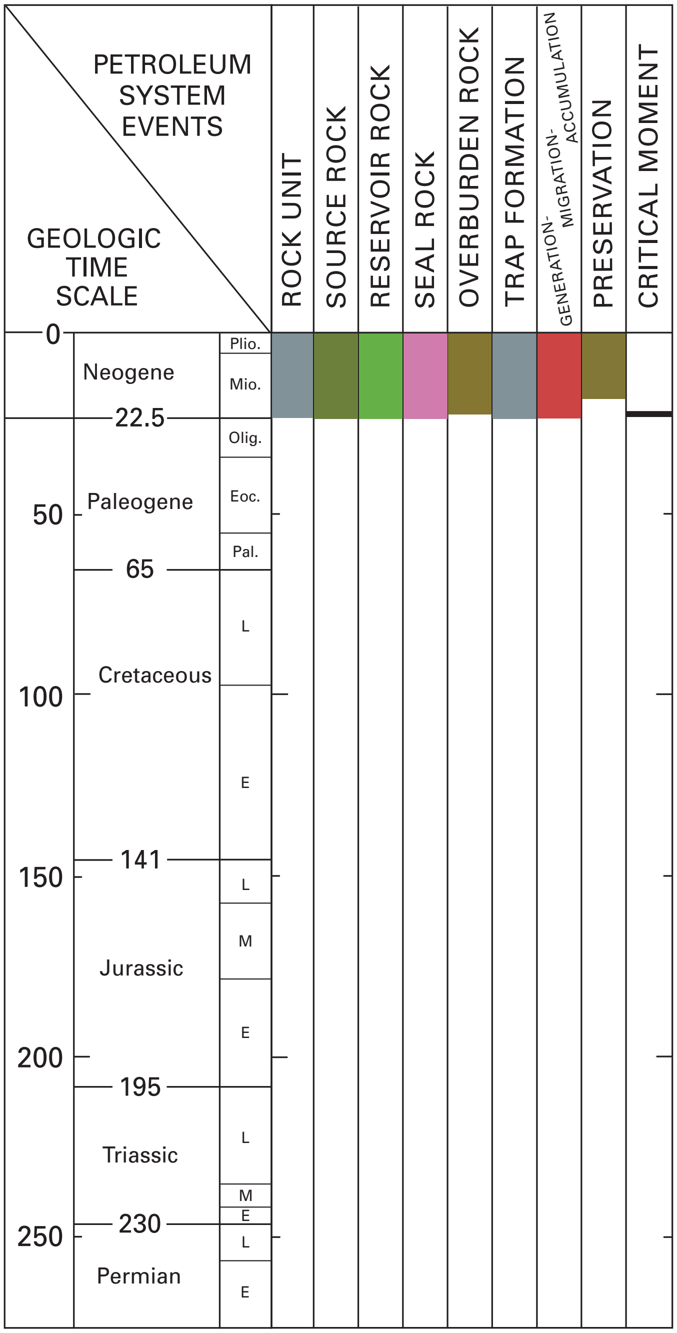


**Figure 8.** Events chart for the Foreland Basin Assessment Unit of the Isotopically Light Gas Total Petroleum System of the North Carpathian Province. Chart shows the relative timing of critical geologic events in the evolution of the assessment unit. E, Early; M, Middle; L, Late; Pal., Paleocene; Eoc., Eocene; Olig., Oligocene; Mio., Miocene; Plio., Pliocene.

of the Jurassic reef core. In back-reef areas, the best reservoirs are associated with friable limestones characterized by textures that range from mudstones to grainstones (Izotova and Popadyuk, 1996). The oil fields producing from Upper Cretaceous sandstone and Upper Jurassic limestone reservoirs are also sealed by Miocene molasse. Turbidites throughout the Lower Cretaceous into the Oligocene–lower Miocene sequence in the eastern Silesian and Skole nappes contain traces of oil (Slaczka, 1996).

Lower Cretaceous shales seal Upper Jurassic carbonate reservoirs of northwest Ukraine (fig. 5). In other locations, Miocene shales and evaporites, or shales of the flysch nappes, provide the reservoir seal. Hydrocarbon accumulations are contained in two types of trap: erosional highs and low-amplitude rollover structures. These two trap styles are associated with the Paleogene erosional phase and subsequent development of the Carpathian foredeep, which, in turn, modified the structural configuration of the Upper Jurassic carbonate shelf in western Ukraine (Izotova and Popadyuk, 1996).

In Poland, the principal oil fields were discovered in the Paleogene flysch, the Cretaceous flysch, and in the Paleozoic–Mesozoic basement (Koltun and others, 1995). Oil accumulated within narrow, predominantly steep, imbricated folds, some with lengths as much as 30 km, that were thrust over one another. Lower Cretaceous through Oligocene formations have the most prolific hydrocarbon accumulations as well as the best seals. The most productive beds are Lower Cretaceous sandstones (Karnkowski, 1996). Most of the gas fields produce from Miocene rocks, but some also produce from Mesozoic strata. In the Polish molasse autochthon, the Cretaceous and most Jurassic reservoirs are sealed by the shaly and evaporitic basal series of the Badenian molasse (Bessereau and others, 1996).

Traps within the northern Carpathian Mountains are associated primarily with folds and fault blocks, but stratigraphic traps are also abundant. Accumulations sealed by thrust sheets are the most prospective traps for hydrocarbon exploration in the region (Slaczka, 1996).

Oil was generated in the Carpathian Mountains mostly during the Neogene, but the distribution of and variations in sulfur content of the oils suggest limited generation in the Paleogene before thrust loading of the foredeep by the flysch nappes.

Hydrocarbon in Poland migrated mainly to the north early in the evolution of the nappe basins. Later migration was influenced by the shape of the basins and the shifting of depocenters and by tectonic movements. In the Silesian basin, hydrocarbon initially migrated mainly north. Later, migration direction changed to the south after the axis of deposition shifted to the north, and the southern part of the basin was folded and uplifted (Slaczka, 1996). Short-distance migration directly from juxtaposed source and reservoir rock characterized accumulations in the structural complexes and imbrications along the Carpathian front as well as along numerous fault zones in this tectonically disturbed region.

The events chart in figure 10 summarizes the relation of timing and source rock, reservoir rock, seal rock, overburden rock, trap formation, generation, migration, accumulation, and preservation in the Deformed Belt Assessment Unit. Calculated resources (mean value) are 344 million barrels of oil (MMBO), 2,345 million cubic feet of gas (MMCFG), and 75 MMBNGL.


**Figure 9.** Map showing location of the Mesozoic–Paleogene Composite Total Petroleum System in the North Carpathian Province of Eastern Europe.

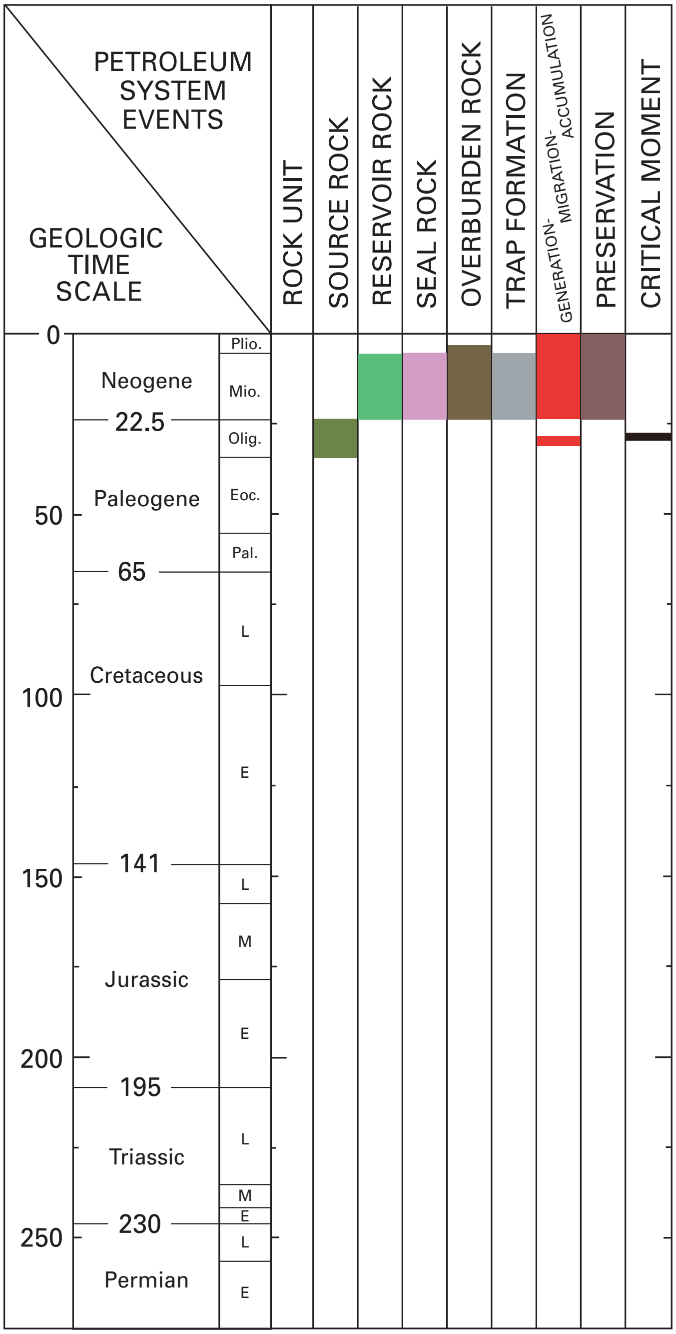


**Figure 10.** Events chart for the Deformed Belt Assessment Unit of the Mesozoic–Paleogene Composite Total Petroleum System of the North Carpathian Province. Chart shows the relative timing of critical geologic events in the evolution of the assessment unit. E, Early; M, Middle; L, Late; Pal., Paleocene; Eoc., Eocene; Olig., Oligocene; Mio., Miocene; Plio., Pliocene.

## Paleozoic Reservoirs Assessment Unit of the Paleozoic Composite Total Petroleum System

The Paleozoic Reservoirs Assessment Unit is a gas unit encompassing Paleozoic rocks that lie beneath molasse and flysch in the area extending from the eastern Czech Republic along the southwest border of Poland and into southwestern Ukraine (fig. 11). Devonian rocks rest directly on the Precambrian basement or on erosional remnants of pre-Devonian strata. Lower Devonian rocks are predominantly variegated sandstone and red shale with variable thicknesses as much as 200 m; Middle and Upper Devonian rocks are mostly carbonate (Pietsch and others, 1997).

The assessment unit was defined on the basis of two wells. The Lachowice-1 well, southwest of Krakow, was drilled into Devonian strata lying beneath the west Carpathian fold and thrust belt; gas was discovered in carbonate reservoirs. The Nosowka-1 well east of Krakow produces oil, also from Devonian strata (fig. 11).

The oil in the Nosowka field has an isotopically light signature and lacks the biomarker oleanane, which excludes a Cretaceous or younger source (such as the Menilite Shale). A Paleozoic source is therefore considered likely.

Lower Carboniferous black shale and silty shale from the foredeep have a total organic carbon value of about 1.5 percent but a low hydrogen index of 100 mg HC/g TOC that is considered insufficient for a good source rock. An Upper Carboniferous coal, however, has favorable geochemistry of 47 percent TOC and a hydrogen index of 450 mg HC/g TOC. The geochemical fingerprints of the shale and coal samples show some similarities (Bessereau and others, 1996). In western Poland, a 246-m-thick section (Numurian A) at the boundary between upper Lower Carboniferous and Upper Carboniferous is composed of fine-grained sandstone overlain by shales and mudstones interbedded with sapropelic shales and coals. Above that section are gray mudstones and shales with coal and some sandstone (Pietsch and others, 1997), a possible source of hydrocarbons within the Devonian reservoirs in this western region. A reported higher hydrocarbon content (C3–C7) = 66.8 g/m$^3$ indicates that Devonian rocks may have reached the wet gas stage (Pietsch and others, 1997).

In western Poland, the Precambrian–Paleozoic platform sedimentary rocks are strongly deformed and are overlain by Neogene molasse (lower Miocene and Badenian age). The molasse, which has a maximum thickness of 2.6 km, is in turn is overlain by Carpathian flysch, which comprises the Skole, sub-Silesian, Dukla, and Magura units (fig. 3) (Paul and others, 1996).

Flat-lying overthrust sheets of folded Carpathian flysch provide a tectonic seal for possible gas and oil reservoirs in deeper Carboniferous and Devonian strata (Pietsch and others, 1997). The Lachowice gas field is considered to be a combined structural and stratigraphic trap associated


**Figure 11.** Map showing location of the Paleozoic Composite Total Petroleum System within the North Carpathian Province of Eastern Europe.

with a posterosional surface and fracture zone sealed on the south by a longitudinal fault. The pay zone is thought to be about 10 km$^2$ and 100 m thick and to contain an estimated reserve of 175–350 MMCFG (Pietsch and others, 1997). Longitudinal faults formed during the Variscan orogeny and transformed into reverse faults during Carpathian compression; these faults bound narrow grabens to form potential hydrocarbon traps, such as in the Lachowice field and in others places.

In Carboniferous rock units, sandstones of the same age may also be a reservoir facies, as indicated by porosity of 14 percent in one well (Potrojna IG 1). Upper Carboniferous rocks have had oil and gas shows at a depth of 4,858 m in this western part of Poland. Possible Cambrian sandstone in the Stryszawa area near Lachowice also possesses good reservoir qualities (Pietsch and others, 1997).

Pietsch and others (1997) believe that gas accumulations in Carpathian autochthonous rocks in the Lachowice area are confined to fractured, cavernous zones of weathering in Devonian dolomite and to a diagenetically altered carbonate, which is separated from the dolomite by an erosional surface. Gas traps are formed by small fault-confined anticlines sealed by longitudinal strike-slip faults. Gas may accumulate on the downthrown side of the fault, as at Lachowice, or in the upthrown wall of the fault, as at Stryszawa. Structural and stratigraphic conditions within autochthonous Miocene rocks provide trap seals.

Present-day maturation patterns mainly postdate nappe emplacement. Source rocks probably matured initially during the precompressional stages in the southern part of the Silesian basin and the Dukla-equivalent basins, owing to accumulation of thick sediment sequences (Bessereau and others, 1996). Hydrocarbons migrated relatively short distances from the source into fault-bound traps that were sealed by the flysch units. Figure 12 shows the critical geological aspects of the Paleozoic Composite Total Petroleum System. Calculated resources for the Paleozoic Reservoirs Assessment Unit (mean value) are 47 MMBO, 383 BCFG, and 19 MMBNGL.

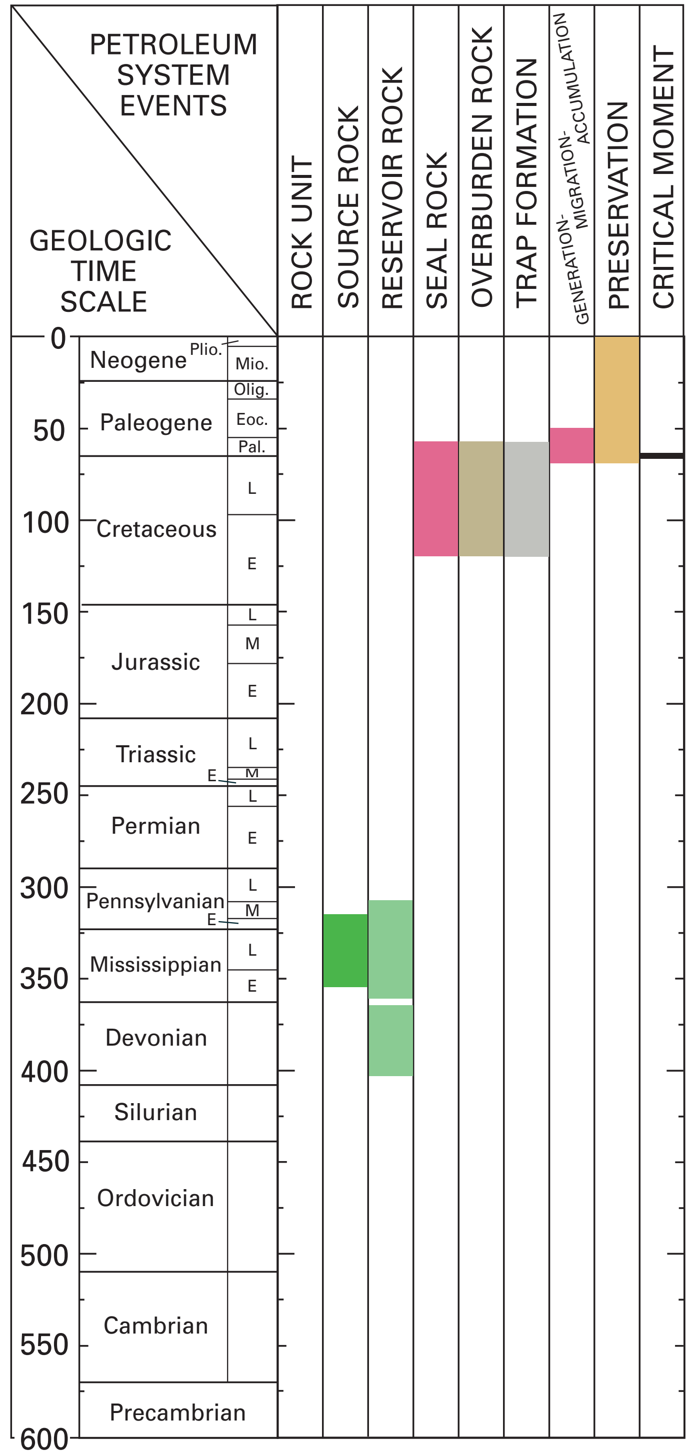


**Figure 12.** Events chart for the Paleozoic Reservoirs Assessment Unit of the Paleozoic Composite Total Petroleum System of the North Carpathian Province. Chart shows the relative timing of critical geologic events in the evolution of the assessment unit. E, Early; M, Middle; L, Late; Pal., Paleocene; Eoc., Eocene; Olig., Oligocene; Mio., Miocene; Plio., Pliocene.

## Assessment Results and Summary

Tables 1 and 2 summarize the allocated oil and gas resources in the North Carpathian Province. Assessment units are listed for each total petroleum system. The resources are grouped into fractals, which are a means of assigning a risk factor to the actual discovery of these resources; that is, the “F” value represents that chance of the amount tabulated being discovered. Although the Carpathian region of Poland and Ukraine presents a difficult challenge for future petroleum exploration and production, owing to its complex geologic structure and stratigraphic variability, the potential exists for the discovery of additional large amounts of oil and gas, but most probably in small fields (figs. 13, 14).

**Table 1.** Summary of allocated oil and gas resources, North Carpathian Province (4047), as evaluated per assessment unit.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MFS, minimum field size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one field equal to or greater than the MFS. Results shown are fully risked estimates. For gas fields, all liquads are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at lease the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

| Code and Field Type | MFS | Prob. (0-1) | Undiscovered Resources | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Oil (MMBO) | | | | Gas (BCFG) | | | | NGL (MMBNGL) | | | |
| | | | F95 | F50 | F5 | Mean | F95 | F50 | F5 | Mean | F95 | F50 | F5 | Mean |
| **404701** | **Isotopically Light Gas Total Petroleum System** | | | | | | | | | | | | | |
| 40470101 | Foreland Basin Assessment Unit (100% of undiscovered oil fields and 100% of undiscovered gas fields allocated to ONSHORE province 4047) | | | | | | | | | | | | | |
| Oil Fields | 1 | 1.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gas Fields | 6 | | | | | | 852 | 2,129 | 4,420 | 2,321 | 6 | 17 | 38 | 19 |
| Total | | 1.00 | 0 | 0 | 0 | 0 | 852 | 2,129 | 4,420 | 2,321 | 6 | 17 | 38 | 19 |
| **404702** | **Mesozoic/Paleogene Composite Total Petroleum System** | | | | | | | | | | | | | |
| 40470201 | Deformed Belt Assessment Unit (100% of undiscovered oil fields and 100% of undiscovered gas fields allocated to ONSHORE province 4047) | | | | | | | | | | | | | |
| Oil Fields | 1 | 1.00 | 111 | 316 | 660 | 344 | 306 | 925 | 2,105 | 1,032 | 17 | 54 | 133 | 62 |
| Gas Fields | 6 | | | | | | 405 | 1,211 | 2,526 | 1,313 | 4 | 12 | 27 | 13 |
| Total | | 1.00 | 111 | 316 | 660 | 344 | 711 | 2,136 | 4,631 | 2,345 | 21 | 66 | 160 | 75 |
| **404703** | **Paleozoic Composite Total Petroleum System** | | | | | | | | | | | | | |
| 40470301 | Paleozoic Reservoirs Assessment Unit (100% of undiscovered oil fields and 100% of undiscovered gas fields allocated to ONSHORE province 4047) | | | | | | | | | | | | | |
| Oil Fields | 1 | 1.00 | 12 | 42 | 96 | 47 | 25 | 91 | 223 | 103 | 1 | 5 | 14 | 6 |
| Gas Fields | 6 | | | | | | 71 | 254 | 576 | 280 | 3 | 11 | 27 | 12 |
| Total | | 1.00 | 12 | 42 | 96 | 47 | 95 | 345 | 800 | 383 | 4 | 16 | 41 | 19 |

**Table 2.** Summary of allocated oil and gas resources, North Carpathian Province (4047).

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MFS, minimum field size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one field equal to or greater than the MFS. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

| Code and Field Type | MFS | Prob. (0-1) | Undiscovered Resources | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Oil (MMBO) | | | | Gas (BCFG) | | | | NGL (MMBNGL) | | | |
| | | | F95 | F50 | F5 | Mean | F95 | F50 | F5 | Mean | F95 | F50 | F5 | Mean |
| **4047** | **Total: Assessed onshore portions of North Carpathian Basin Province** | | | | | | | | | | | | | |
| Oil Fields | | 1.00 | 123 | 359 | 756 | 391 | 331 | 1,016 | 2,328 | 1,135 | 18 | 59 | 147 | 68 |
| Gas Fields | | | | | | | 1,328 | 3,594 | 7,523 | 3,914 | 13 | 39 | 91 | 44 |
| Total | | 1.00 | 123 | 359 | 756 | 391 | 1,659 | 4,610 | 9,851 | 5,049 | 31 | 98 | 239 | 112 |
| **4047** | **Total: Assessed offshore portions of North Carpathian Basin Province** | | | | | | | | | | | | | |
| Oil Fields | | 0.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gas Fields | | | | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | | 0.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **4047** | **Grand Total: Assessed portions of North Carpathian Basin Province** | | | | | | | | | | | | | |
| Oil Fields | | 1.00 | 123 | 359 | 756 | 391 | 331 | 1,016 | 2,328 | 1,135 | 18 | 59 | 147 | 68 |
| Gas Fields | | | | | | | 1,328 | 3,594 | 7,523 | 3,914 | 13 | 39 | 91 | 44 |
| Total | | 1.00 | 123 | 359 | 756 | 391 | 1,659 | 4,610 | 9,851 | 5,049 | 31 | 98 | 239 | 112 |

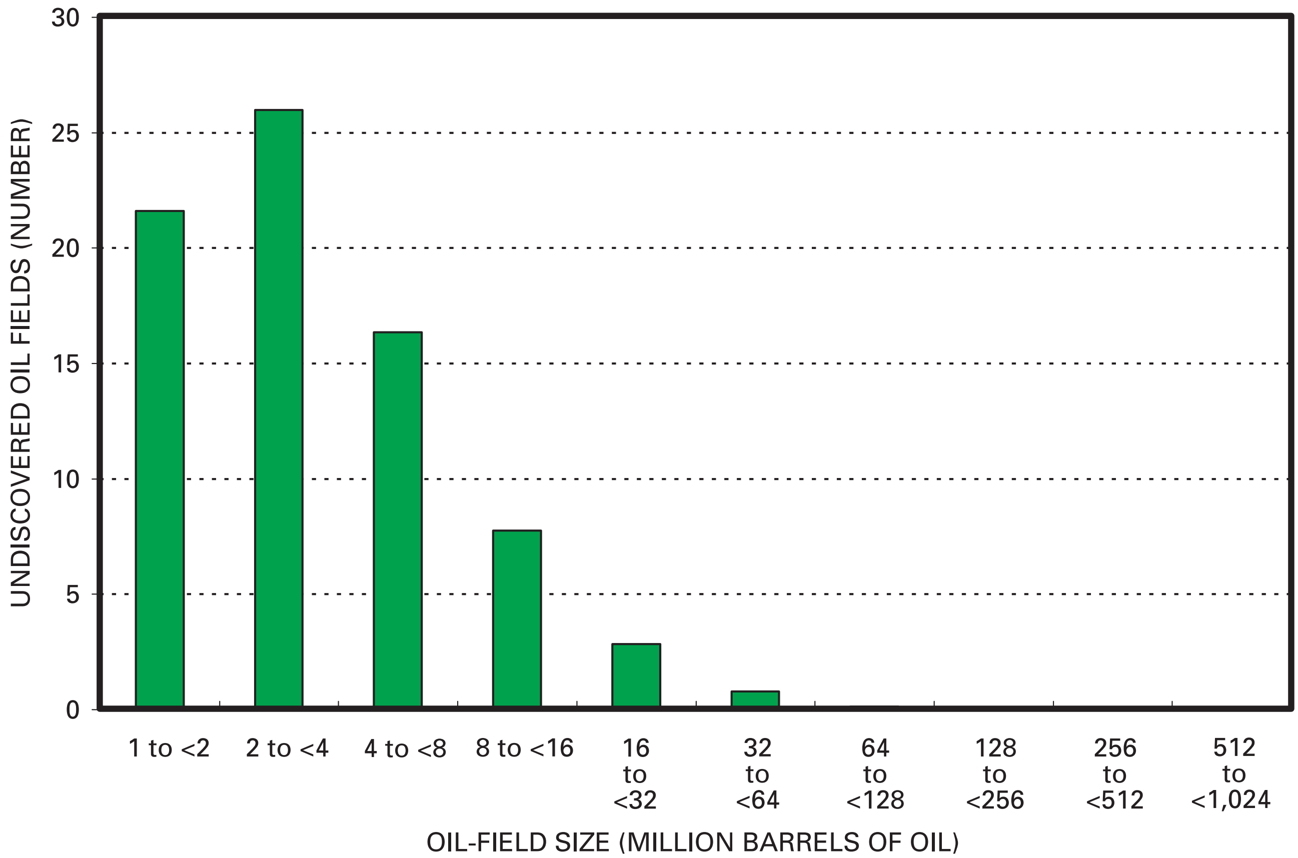


**Figure 13.** Diagram showing estimated number and size of undiscovered oil fields in the North Carpathian Province of Eastern Europe.

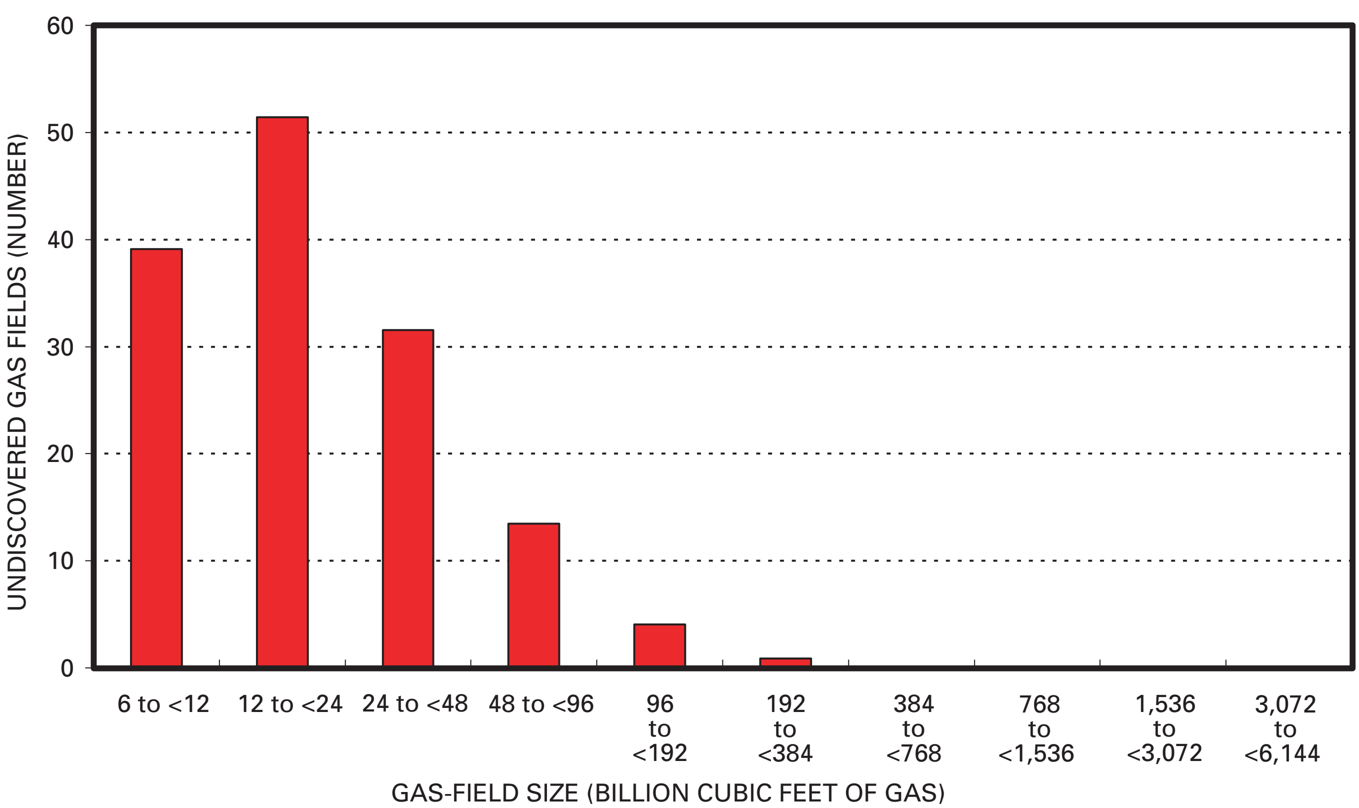


**Figure 14.** Diagram showing estimated number and size of undiscovered gas fields in the North Carpathian Province of Eastern Europe.

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