Total Petroleum Systems of the Carpathian–Balkanian Basin Province of Romania and Bulgaria

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U.S. Department of the Interior
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By Mark Pawlewicz

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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 were first 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 with respect to the Carpathian–Balkanian Basin Province is as follows:

Example

Region, single digit	**4**
Province, three digits to the right of the region code	4**061**
Total petroleum system, two digits to the right of province code	4061**01**
Assessment unit, two digits to the right of petroleum system code	406101**01**

The codes for 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 using geographic information system software. Political boundaries and cartographic representations were taken, with permission, from Environmental Systems Research Institute’s ArcWorld 1:3,000,000 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).

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Abbreviations

API	American Petroleum Institute
BCFG	billion cubic feet of gas
HC/g TOC	hydrocarbon/gram of total organic carbon
MMBNGL	million barrels of natural gas liquids
MMBO	million barrels of oil
MMCFG	million cubic feet of gas
TOC	total organic content (usually, total organic carbon)
°C/km	degrees Celsius per kilometer
g/cm^3	grams per cubic centimeter
g/m^3	grams per cubic meter
km	kilometer
m	meter
Ma	Mega-annum
mD	millidarcy
mg	milligram
ppt	parts per thousand
R_o	vitrinite reflectance
wt percent	weight percent

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
kilometer (km)	0.6214	mile (mi)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)

Total Petroleum Systems of the Carpathian–Balkanian Basin Province of Romania and Bulgaria

By Mark Pawlewicz

Abstract

The U.S. Geological Survey defined the Moesian Platform Composite Total Petroleum System and the Dysodile Schist–Tertiary Total Petroleum System, which contain three assessment units, in the Carpathian–Balkanian Basin Province of Romania and Bulgaria.

The Moesian Platform Assessment Unit, contained within the Moesian Platform Composite Total Petroleum System, is composed of Mesozoic and Cenozoic rocks within the Moesian platform region of southern Romania and northern Bulgaria and also within the Birlad depression in the northeastern platform area. In Romania, hydrocarbon sources are identified as carbonate rocks and bituminous claystones within the Middle Devonian, Middle Jurassic, Lower Cretaceous, and Neogene stratigraphic sequences. In the Birlad depression, Neogene pelitic strata have the best potential for generating hydrocarbons. In Bulgaria, Middle and Upper Jurassic shales are the most probable hydrocarbon sources.

The Romania Flysch Zone Assessment Unit in the Dysodile Schist–Tertiary Total Petroleum System encompasses three structural and paleogeographic subunits within the Pre-Carpathian Mountains region: (1) the Getic depression, a segment of the Carpathian foredeep; (2) the flysch zone of the eastern Carpathian Mountains (also called the Marginal Fold nappe); and (3) the Miocene zone (also called the Sub-Carpathian nappe). Source rocks are interpreted to be Oligocene dysodile schist and black claystone, along with Miocene black claystone and marls.

Also part of the Dysodile Schist–Tertiary Total Petroleum System is the Romania Ploiesti Zone Assessment Unit, which includes a zone of diapir folds. This zone lies between the Rimnicu Sarat and Dinibovita valleys and between the folds of the inner Carpathian Mountains and the external flanks of the Carpathian foredeep. The Oligocene Dysodile Schist is considered the main hydrocarbon source rock and Neogene black marls and claystones are likely secondary sources; all are thought to be at their maximum thermal maturation.

Undiscovered resources in the Carpathian–Balkanian Basin Province are estimated, at the mean, to be 2,076 billion cubic feet of gas, 1, 013 million barrels of oil, and 116 million barrels of natural gas liquids.

Introduction

The Carpathian–Balkanian Basin Province lies in northern Bulgaria and southern and eastern Romania (fig. 1). The boundaries are (1) the Romania-Ukraine national border on the north, (2) Moldavia (of the former Soviet Union) and the Black Sea on the east, (3) the southern extent of the Moesian platform in central Bulgaria on the south, and (4) the Transylvania Basin and the southern Carpathian Mountains on the west (figs. 2, 3). As defined, the western and northern parts of the province are dominated by a series of extensive nappes (fig. 4) that form much of the Carpathian Mountains chain, whereas the eastern and southern parts are characterized by a relatively stable structural platform containing several intraplatform basins. Petroleum is produced mainly in the northern and western parts. On the basis of known petroleum volumes (amount produced to date plus remaining reserves), the province is ranked 42d in the world (exclusive of the United States and Canada), with 5.9 billion barrels of oil, 7.3 trillion cubic feet of gas, and 100 million barrels of natural gas liquids, for a total of 7.2 barrels of oil equivalent (Klett and others, 1997).

For purposes of this study, the Carpathian–Balkanian Basin Province is divided into two total petroleum systems (TPS) and three assessment units (AU): (1) the Moesian Platform Composite TPS, containing the Moesian Platform AU; and (2) the Dysodile Schist–Tertiary TPS, containing the Romanian Ploiesti Zone and Romania Zone AUs (fig. 1).

Geology of the Carpathian–Balkanian Basin Province

Structural Setting

The Moesian platform, a broad crustal block formed by Hercynian deformation during Late Devonian to Early Triassic time, occupies all of northern Bulgaria and extends north and west under the Danubian lowlands into Romania where it borders the foredeep of the Carpathian Mountains (figs. 2, 4). The structure of the region was shaped by two principal events, one that formed large and moderately faulted anticlines during

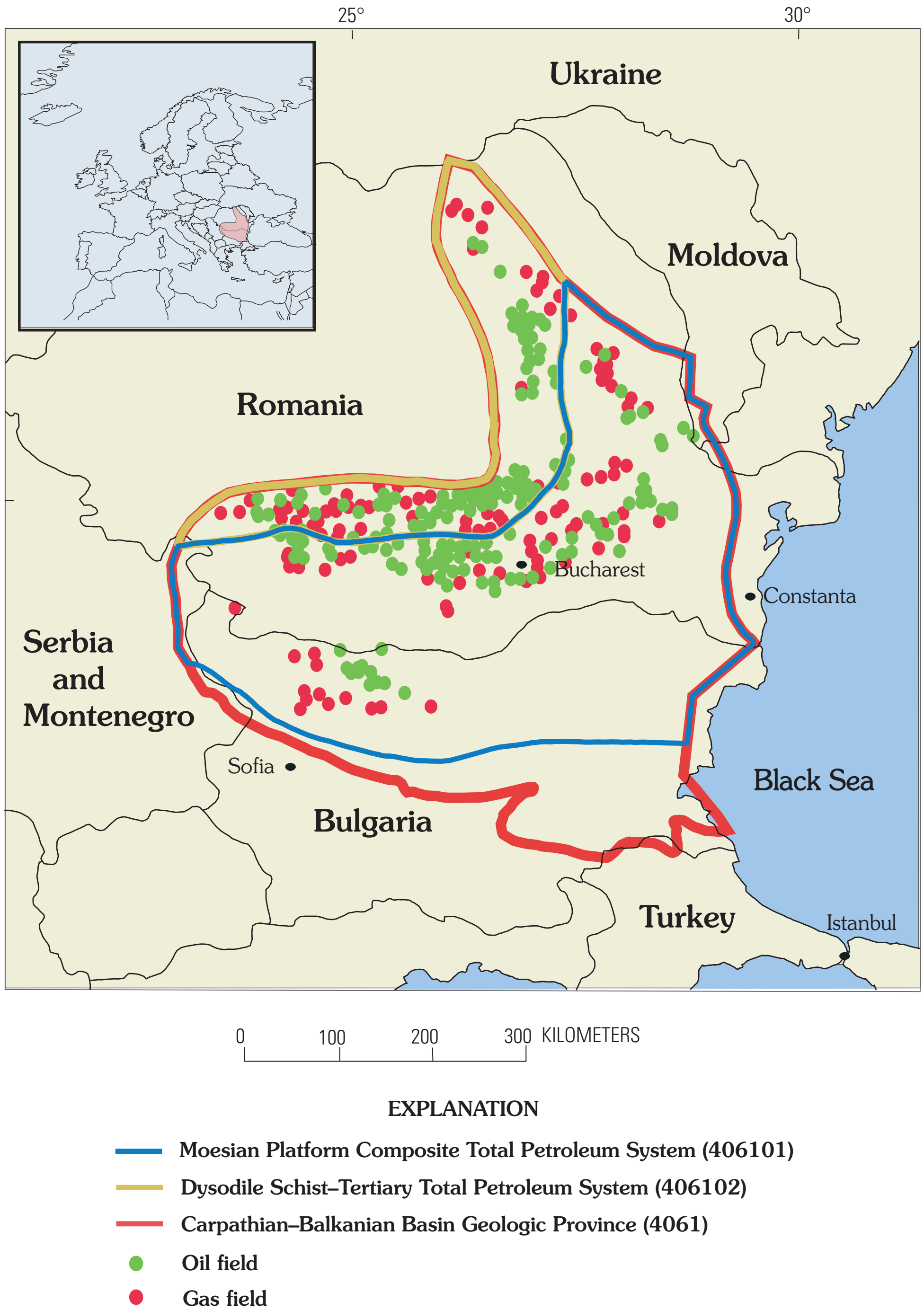

Figure 1. Carpathian–Balkanian Basin Province (4061), Romania and Bulgaria, showing boundaries of the Moesian Platform Composite Total Petroleum System and the Dysodile Schist–Tertiary Total Petroleum System and locations of oil and gas fields.

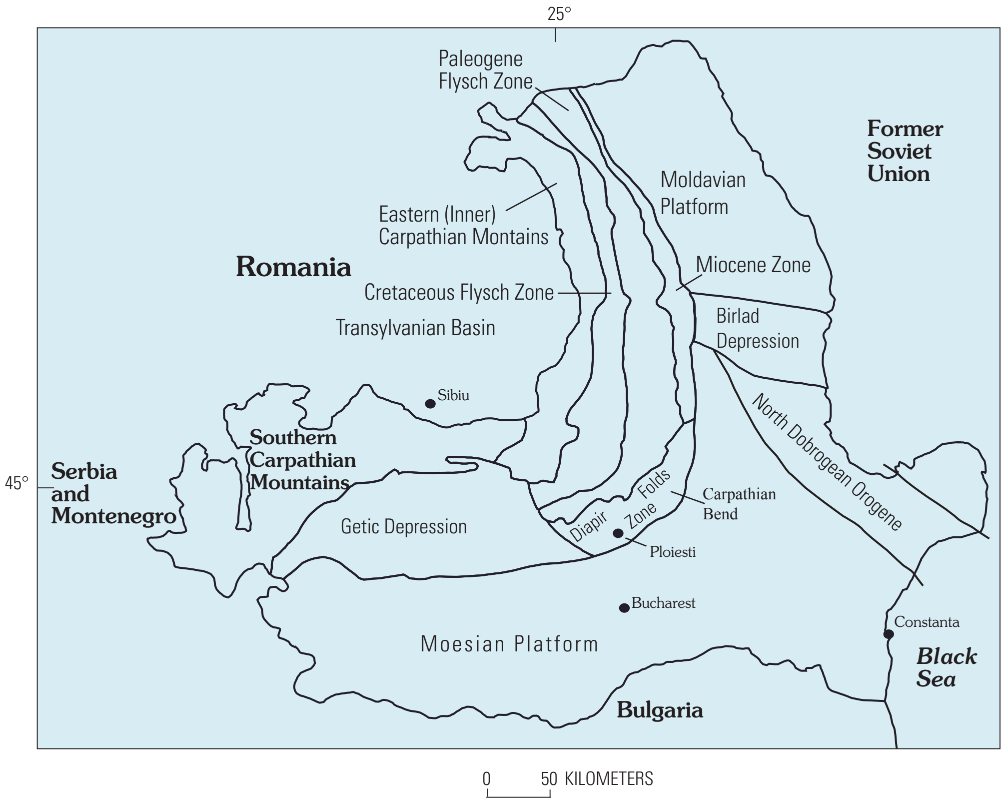

Figure 2. Generalized geological and geographic features of the Carpathian–Balkanian Basin Province, Romania and Bulgaria.

Paleozoic to Triassic time and another that formed a north-dipping homoclinal feature in post-Triassic time. The platform was uplifted and exposed subaerially during the Early Jurassic, and during Late Jurassic and Early Cretaceous time it formed a north-facing Tethyan passive margin that accumulated marine sediments while continuously subsiding. Another period of uplift during the Early Cretaceous (Aptian) was followed by subsidence until the end of the Cretaceous, after which the platform was again uplifted and remained exposed until the middle Miocene (Stefanescu and others, 2000).

In Bulgaria, the Moesian platform was a relatively stable block with several superimposed structural or sedimentary basins receiving sediments until the Tertiary (Vuchev and others, 1993). Along its south margin, Early Triassic to Early Jurassic intercratonic rifting, followed by compression, shortened the overall width of the basin and produced a south-vergent fold and thrust belt (figs. 5, 6). Another phase of compression began in the Early Cretaceous and continued through the middle Eocene. This tectonic activity created normal fault–bounded rotated blocks in an autochthonous section below a detachment fault and elongate, asymmetrical anticlines in an overlying allochthonous section (fig. 5) (Emery and Georgiev, 1993; Ionescu, 1993).

A geologic feature in the northeastern part of the Carpathian–Balkanian Basin Province is the Birlad depression (fig. 2), a graben that plunges to the west beneath the Carpathian foredeep. The depression has a depth to basement of more than 6 km.

In Romania, compressional forces of the Alpine orogeny formed the Paleogene flysch and Neogene molasse basin of the eastern Carpathian Mountains and the Paleogene and Neogene molasse basin of the southern Carpathian Mountains (fig. 2) and then gave rise to an extensive series of nappes that were thrust east over the foreland (Dicea, 1993). The eastern Carpathian Mountains are 650–700 km long and as much as 100 km wide, and they consist of a stack of sedimentary nappes of a Lower Cretaceous to Miocene flysch series that extends 75 km eastward over the foredeep; total crustal shortening is about 250 km (Ziegler and Roure, 1996). During the middle Miocene (Badenian), the Tarcau and Marginal Fold nappes of the eastern Carpathian Mountains were emplaced (fig. 4) (Sandelescu, 1988), followed by emplacement of the nappes of the outermost Carpathian orogen during the middle late Miocene (Sarmatian). Also in the late Miocene, the Paleogene and Neogene nappe sequence was underthrust by the foreland platforms that form the autochthon of the Sub-Carpathian, Marginal Folds, and Tarcau nappes, in the eastern as well as the southern Carpathians (Dicea, 1996) (fig. 4). Stefanescu and others (2000) estimated post-Oligocene shortening to be greater than 100 km. Salt diapirs, created by alternating episodes of extension and compression that began in early Burdigalian and Badenian (early to middle Miocene) time, are located in the transitional zone between the Getic depression and the eastern Carpathian Mountains, where the Sub-Carpathian nappe becomes progressively shallower from the west toward the east and northeast (Stefanescu and others, 2000) (fig. 4). The Carpathian foredeep is filled with upper Pliocene–lower Pleistocene molasse that resulted from erosion of the Carpathians; the molasse covers most of the external units of both the eastern and the southern Carpathians, along with part of the surrounding platforms.

Stratigraphy

Within the Moesian platform region, the Middle Cambrian to upper Carboniferous sequence is divided into three lithologic subunits (fig. 7). Upper Cambrian to Middle Devonian rocks are mainly arkosic and quartzitic sandstones

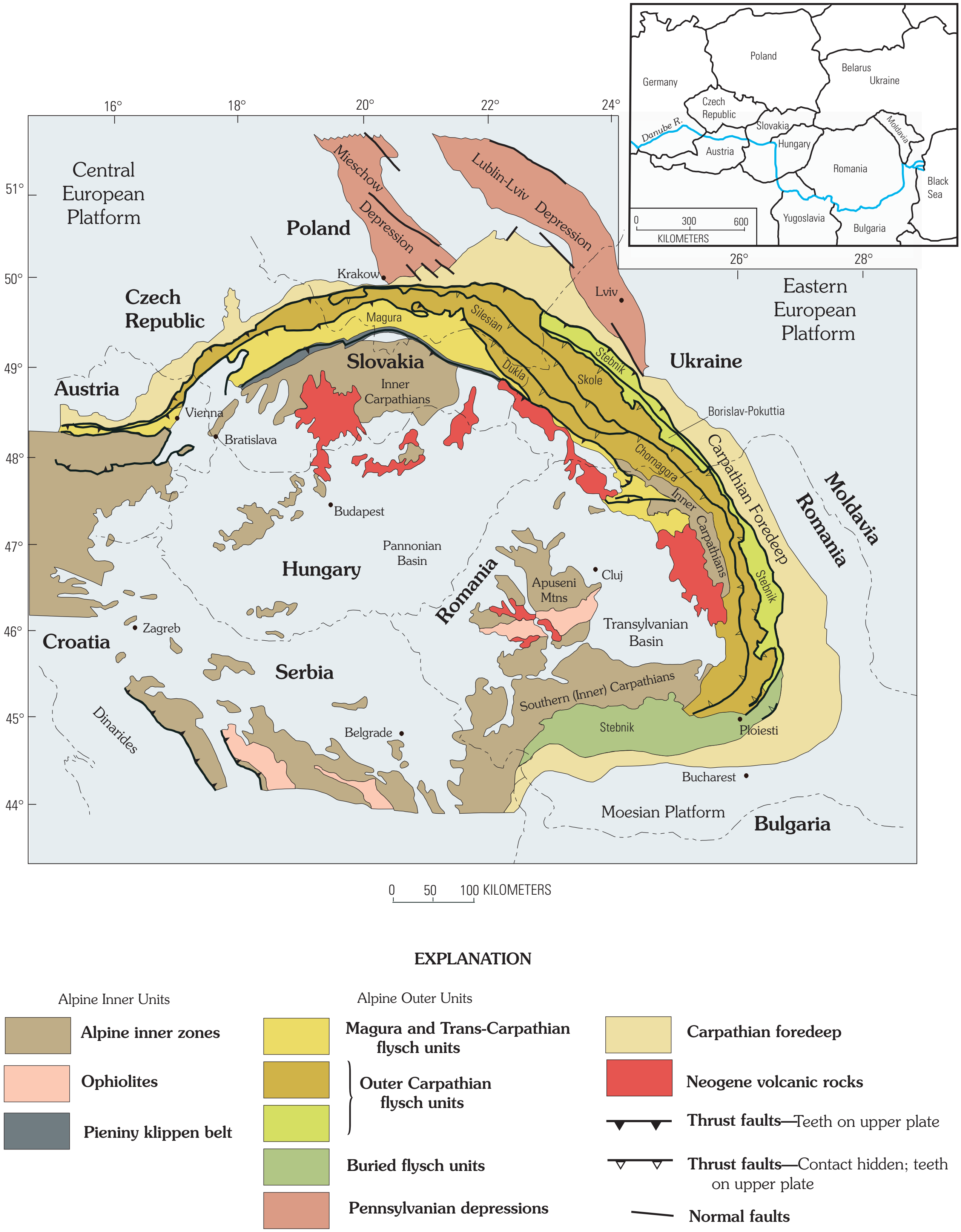

Figure 3. Location and structural features of Carpathian Mountains region in eastern Europe. After Roca and others (1995).

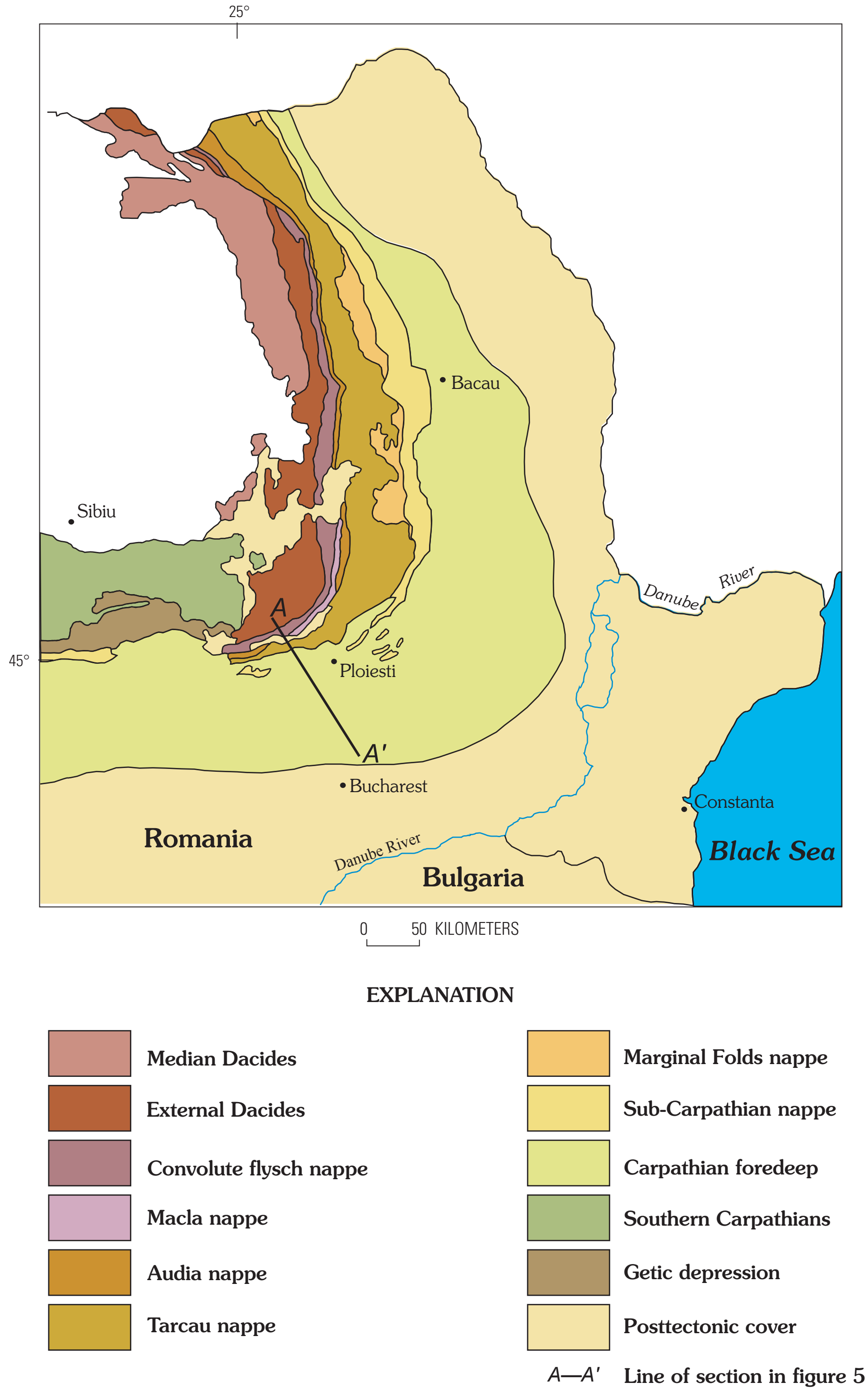

Figure 4. Geological features of eastern Carpathian Mountains in Romania.

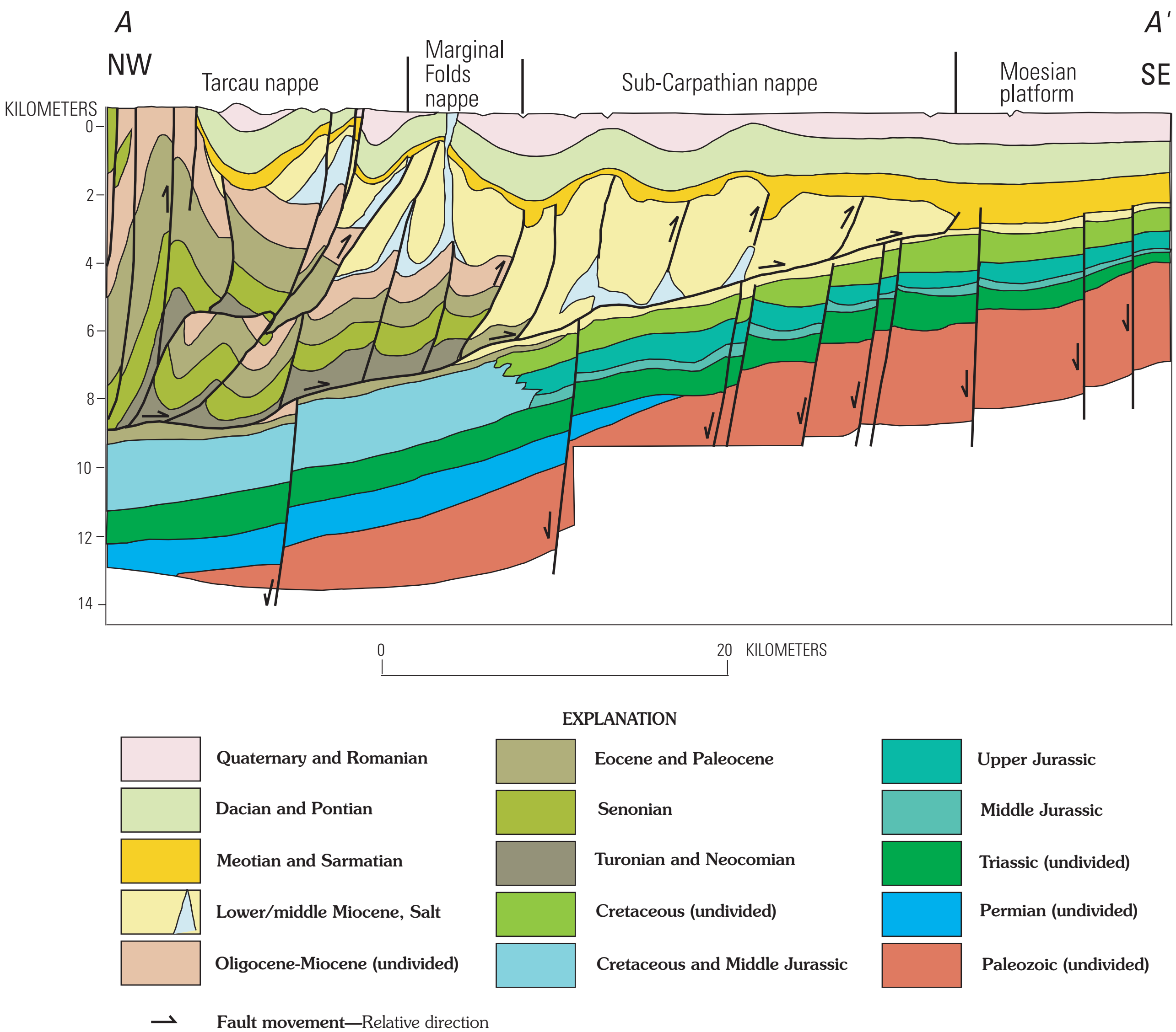

Figure 5. Cross section showing complex nappe geology near the Carpathian bend in Romania. After Stefanescu, 2000. Vertical exaggeration is 2. Line of section shown in figure 4.

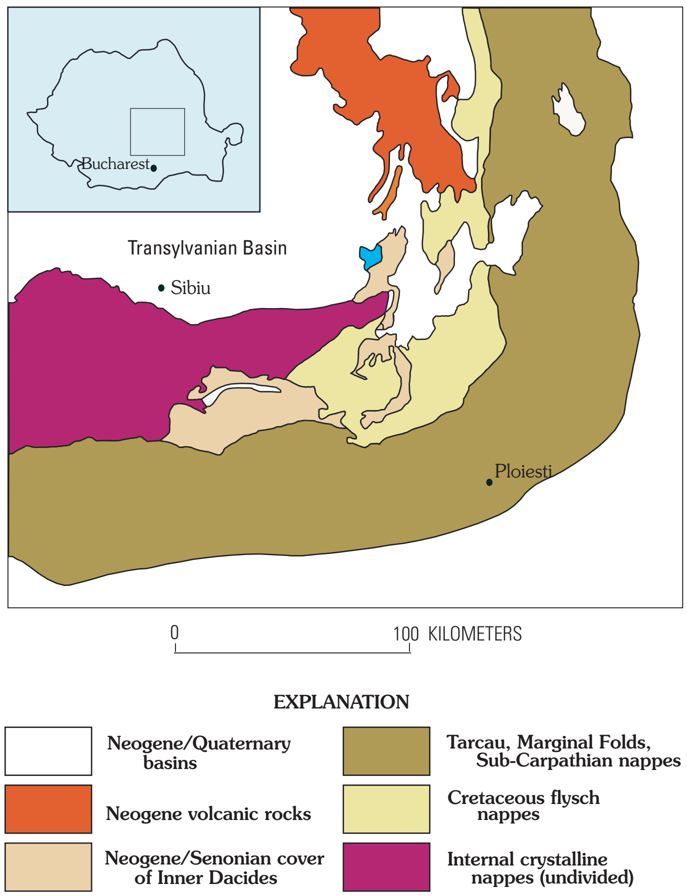

Figure 6. Geological features in Romania. After Stefanescu, 2000.

with some siltstone, shale, limestone, and conglomerate intercalations (some Silurian shales contain graptolites); Middle Devonian to Carboniferous rocks are composed primarily of massive limestones and dolomites with lesser amounts of bituminous limestones and evaporites; and middle to upper Carboniferous clastic rocks are coal bearing in part. This sequence is overlain by siltstones, marls, and sandstones (Tari and others, 1997).

Two sequences of Permian to Triassic strata are mainly of terrestrial origin. A Permian through Lower Triassic red clastic sequence consists largely of interbedded claystone, siltstone, quartzitic sandstone, calcareous sandstone, and conglomerate with minor dolomitic limestone, anhydrite, and salt; an Upper Triassic sequence is mostly shales, marls, sandstones, and conglomerates (Tari and others, 1997). A third sequence in the Middle Triassic, in contrast, is predominantly limestones and dolomite with interspersed marl and anhydrite or salt. Additionally, magmatic activity was common, especially at the beginning of the Permian and into the Middle to Late Triassic.

From Jurassic to Cretaceous time, clastic sedimentation was uneven across the Moesian platform; it began earlier on the south side than on the north side. Subsequently, massive carbonate rocks with interbedded siliciclastic rocks were deposited, including a thick turbidite sequence south of the platform (Vuchev, 1993). Following a period of erosion or nondeposition, limestone was again deposited, more abundantly on the east side than on the west side of the platform (Tari and others, 1997).

A physiographic feature in eastern and south-central Romania, termed the Pre-Carpathian depression, is situated between the Mesozoic crystalline core of the Carpathians on the west and the adjacent forelands to the east. It has been divided into several subunits—the Paleogene Flysch zone (also known as the Marginal Fold nappe), Miocene (Diapir Folds) zone, Miocene-Pliocene zone, and Getic depression (fig. 2)—that are differentiated on the basis of stratigraphic, structural, and paleogeographic features. The associated flysch and molasse sequences range in age from Cretaceous to Pliocene (Ionescu, 1993).

The Paleogene Flysch zone is primarily detrital; it is composed of sandstones, marls, claystones, dysodile schist (a plastic, slightly elastic, yellow or greenish-gray hydrocarbon-bearing schist), and black shale (fig. 5; see fig. 4 for location of line of section A-A´). Thickness of this zone exceeds 7 km. The Miocene zone (also called the Sub-Carpathian nappe; fig. 5) is characterized by detrital molasse units that contain sandstones, shales, and marls. The Miocene-Pliocene zone (also called the Diapir Folds zone; fig. 2), mainly sandstones, black shales, and dysodile shales, is distinguished by having salt diapirs that play a large part in trap formation. Thick, late synorogenic and in part postorogenic molasse deposits cover the Carpathian foredeep, the Sub-Carpathian nappes, and the more internal nappes (fig. 5; Dicea, 1996). The Getic depression is a section of the Carpathian foredeep between the Carpathian Mountains and the Moesian platform that contains sandstones, black claystones, and shales (Ionescu, 1993) (fig. 2).

Deposition was uneven during Paleogene to Neogene time. Deposits of sandstone, marl and, locally, carbonate rocks are as much as 1,600 m thick in the southern part of the Moesian platform, but they are thin to absent in the northern part. In contrast, during the Miocene more than 5.5 km of sandstones and carbonate rocks was deposited near the north edge of the platform. In late Miocene time, carbonate rocks were deposited in a brackish environment, indicating increased isolation from the sea during the Messinian, and extensive salt and evaporite deposits accumulated (Tari and others, 1997).

Source Rocks

Source rocks within the Moesian region include both clastic and carbonate rocks, although two lithologies—dysodile schist and black clay-rich shales—predominate in the most prolific hydrocarbon-producing regions of Romania. In these regions, known as the Getic depression, the Miocene zone, and the Paleogene Flysch zone (figs. 1, 2, 3), the main source rocks are Oligocene-Miocene dysodile shales. The shales contain Type-II and -III organic matter or kerogen, and are at a maturation level ranging from 1.0 to 1.15 percent vitrinite reflectance

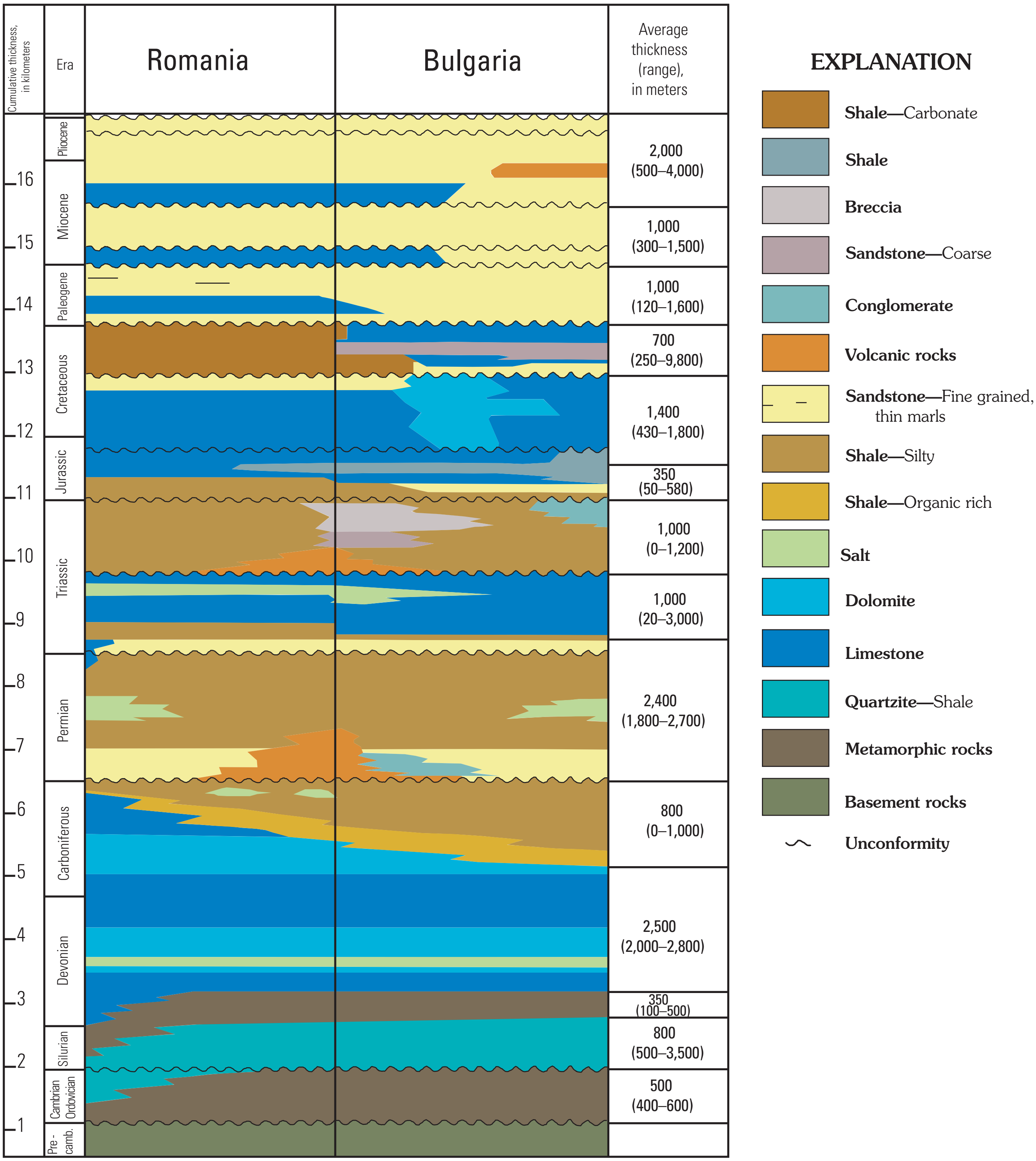

Figure 7. Generalized stratigraphic column of the Moesian platform, Romania and Bulgaria. After Tari and others (1997). Plio., Pliocene; Precamb., Precambrian.

(R_o). In these shales, the total organic content (TOC) ranges from 0.35 to 2.5 percent, and calcareous shales it is as much as 7.6 percent in (Popescu, 1995). In the region of the Marginal Fold nappe (figs. 4, 5), lower Oligocene (lower Rupelian) rocks comprise two shale sequences (fig. 8). Together, these formations range in thickness from 80 to 280 m. An upper interval of dysodile shale ranges from 50 to 100 m thick (Dicea, 1996). Source rocks for the Paleogene Flysch zone (Marginal Folds nappe) are Paleogene dysodile schist and menilites. In the Carpathian fold and thrust belt, lower Oligocene–lower Miocene (Rupelian–lower Burdigalian) dysodile shales are the most important source rocks, because they contain a reported 3.7 to 29.8 percent TOC (Dicea, 1996).

Source rocks for the Diapir Folds zone are the Oligocene dysodile schist and possibly middle Miocene and Pliocene black shale (Dinu and others, 1996). Within the Marginal Folds nappes (fig. 6), the strata consist of the lower Menilite Shale (fig. 8) and dysodile shales and their equivalents. Hydrocarbons produced from the molasse deposits in the Carpathian foredeep (fig. 3) appear to be from the Oligocene–lower Miocene bituminous formations of the Marginal Folds and Sub-Carpathian nappes (Miocene zone) (Ionescu, 1991). Hydrocarbon sources in the Getic depression are thought to be Oligocene shales and Miocene black claystones (Dinu and others, 1996). Source rocks within the Birlad depression (fig. 2) are thought to be pelitic intercalations of Neogene (Badenian and Sarmatian) age, although the Middle Jurassic rocks are also a possible source (Ionescu, 1993). The Oligocene Menilite Shale is generally present in the eastern Carpathian Mountains (fig. 2) and contains a reported 10 percent TOC (Ziegler and Roure, 1996). The organic matter of the Cretaceous nappes of eastern Romania contain rocks that change in percent TOC and degree of maturity from one nappe to another; depending on structural position, and location of the organic-bearing rocks, maturation level ranges from mature to overmature.

The hydrocarbon-generation potential of the western portion of the Moesian platform was estimated for the region by using TOC analyses and type of organic material. Ratios of hydrogen to carbon (H/C) and of oxygen to carbon (O/C) suggest that the organic material is Type-Ia kerogen of marine origin that produces mainly liquid hydrocarbons from Ordovician and Silurian shales. In Upper Devonian bituminous limestones and dolomites, the organic material appears to be both Type-I and -II (Type-II also derives from a marine source but yields fewer hydrocarbons than Type-I), but Type-I is predominant. The content of middle Carboniferous rocks varies vertically but is predominantly Type-III (humic, from a terrestrial source) (Pene, 1996a). Organic matter from Middle Jurassic and lowermost Sarmatian rocks is mostly Type-II (Pene, 1996a).

In the northwestern Moesian platform of Bulgaria, Middle Jurassic black shales and silty claystones as much as 400 m thick may have the highest potential for generating hydrocarbons, although they contain only 0.35 percent TOC; Middle to Upper Triassic carbonate rocks also have potential (Popescu, 1995). Pene (1996a) believed that Devonian bituminous limestones, in addition to Silurian, middle Carboniferous, Middle Jurassic, and Sarmatian shales, are the main hydrocarbon source rocks in western Romania.

In the most northern part of the Moesian platform in Romania (south of the outer Carpathian flysch units shown in fig. 3), Paleozoic and Lower Cretaceous (Albian) strata contain the most likely source rocks. Silurian-Ordovician shales, which have an R_o of 2.75 percent, are near the end of the dry-gas-generation window. Carboniferous dolomites have a modest TOC content of 0.3 to 1.7 percent (Type-II and -III kerogen) and an R_o of 1.3 percent. Carboniferous paralic shales have TOC content of 0.3 to 1.0 percent and an R_o of 1.25 per-

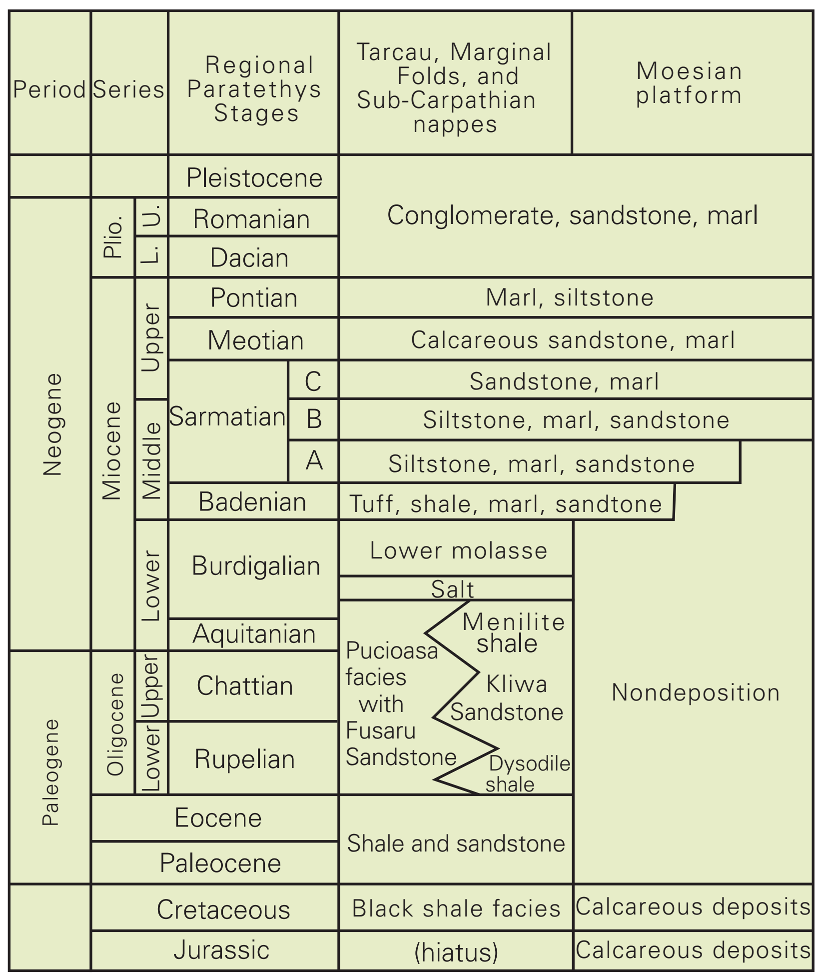

Figure 8. Simplified stratigraphic column of eastern Carpathian Mountains and Moesian platform, Romania. After Stefanescu (2000). L., Lower, U., Upper, Plio., Pliocene. Not to scale.

cent (near the onset of gas generation) with Type-III kerogen. Although analytical data are lacking, Oligocene shales are also thought to be a potential source of hydrocarbons.

In the Getic depression (fig. 2), source rocks are in the Eocene, Oligocene, and middle to upper Miocene; geochemical data are insufficient to determine whether Cretaceous rocks also contribute (Dicea, 1996).

Overall, numerous formations in Bulgaria can be considered as potential source rocks (Vuchev and others, 1993), but no major field has been discovered for several decades. Either favorable geologic conditions do not exist or any hydrocarbons that were generated have been lost; hence, Bulgaria appears to have few good future prospects.

Reservoirs

Upper Miocene clastic rocks, largely derived from the Carpathian Mountains, are typically the main reservoir on the Moesian platform. However, the first post–World War II field in Romania, discovered in the late 1940s, produced oil from a Lower Cretaceous carbonate reservoir on the Moesian platform. Productive horizons are now known to range from fractured Paleozoic carbonate rocks through reservoirs of Triassic, Jurassic, and Cretaceous age (Benton, 1997). Oil and gas fields have been discovered in Devonian, Triassic, Lower to Upper Jurassic, Lower to Upper Cretaceous, upper Miocene, and Pliocene rocks (Ionescu, 1993) and in both clastic and carbonate rocks.

Oil and gas in the Moesian platform is produced mainly in Romania, where reservoirs in the producing fields are distributed throughout much of the stratigraphic column and possess a variety of lithologies. Most of the reserves within the platform area are also concentrated in Romania, and most of the fields produce oil. More than two-thirds of the oil and gas or condensate pools are in Mesozoic rocks, and they are equally distributed between the Permian-Triassic, Middle Jurassic (Dogger), and Cretaceous (Tari and others, 1997). Principle reservoir lithologies are (1) carbonate rocks in the Middle or Upper Devonian to lower Carboniferous, Middle Triassic, Upper Jurassic–Lower Cretaceous, and Upper Cretaceous; (2) sandstones in the Permian-Triassic and Middle Jurassic; (3) glauconitic sandstones in the Lower Cretaceous; (4) calcarenites in the Upper Cretaceous; (5) limestones in the upper Miocene; and (6) sandstones, some of which are poorly consolidated, in the middle Pliocene (Stefanescu, 1991; Tari and others, 1997).

In western Romania, reservoir rocks consist of dolomite and limestone in Devonian, Middle Triassic, Upper Jurassic, and Lower Cretaceous strata, and sandstones in Lower and Upper Triassic, Middle Jurassic, Upper Cretaceous, middle Miocene (Sarmatian), and lower Pliocene strata (Pene, 1996a). Depth to production in the Moesian platform in Romania ranges from 350 to 5,000 m; deeper reservoirs are located in the northern part. Regionally, oil is produced mainly in the western part and gas is produced mainly in the eastern part (Ionescu, 1993). Rifting during the Permian-Triassic created geologic conditions favorable for the generation, migration, and trapping of hydrocarbons within parts of the Moesian platform. Reservoir rocks in this sequence have been discovered only in the northwestern part of the platform in Romania (Pene, 1996b).

In the Carpathian “bend” zone (region around Ploiesti, Romania; fig. 2) and in the Getic depression, Oligocene, Miocene, and Pliocene formations contain many pairs of reservoir and seal. The lower to middle Miocene (Burdigalian and Badenian) salts (fig. 8) provide seals for many accumulations in the external Carpathians (Dicea, 1996). Within the Getic depression, oil and gas fields produce mainly from sandstones with porosities ranging from 15 to 25 percent and permeability ranging from 10 to 500 millidarcys (mD) (Dinu and others, 1996). Drilling depths exceed 4,000 m.

Reservoirs in the Birlad depression (fig. 2) are in Jurassic and Paleozoic quartzitic sandstones at an average depth of 4,200 m (Ionescu, 1993); average porosity is 4–9 percent and average permeability is 1–5 mD.

The main reservoirs in the Paleogene Flysch zone (fig. 2) are the Kliwa Sandstone and the Fusaru Sandstone (Oligocene-Miocene) (fig. 8), where drilling depths exceed 4,000 m, porosities range from 10 to14 percent, and permeabilities range from 2 to 100 mD (Dinu and others, 1996). In the eastern Carpathian Mountains and adjoining foreland basins, the Kliwa Sandstone is also a reservoir unit whose thickness ranges from 20 to 170 m. Secondary reservoirs consist of unnamed Oligocene and Miocene sandstones and conglomeratic beds ranging in thickness from 60 to120 m (Dicea, 1996).

In the Miocene zone (Sub-Carpathian nappe, fig. 4), hydrocarbon has accumulated in Oligocene and in lower and upper Miocene sandstones. The porosity of reservoirs ranges from 12 to14 percent and permeability from 5 to 70 mD (Dinu and others, 1996). In the Diapir Folds zone farther south (fig. 2), the reservoirs are mainly sandstones with high porosities, 14 to 25 percent, and permeabilities ranging from 10 to 500 mD (Dinu and others, 1996). Reservoir characteristics, such as porosity, hydrocarbon content, and net pay thickness, change within short lateral distances. In eastern Romania, the various Cretaceous nappes also contain reservoir rocks—mainly sandstones, conglomerates, and different flysch facies—but lithology changes from one nappe to another (Stefanescu and Baltes, 1996).

In northern Bulgaria, clastic reservoirs are quartz-rich sandstones that contain reduced intergranular and dissolution porosity (Emery and Georgiev, 1993). Lower Triassic rocks are predominantly fluvial, braided, sandstone sequences with interbedded eolian clastic rocks (Ajdanlijsky, 1997). Triassic carbonate rocks and Lower and Middle Jurassic clastic rocks are the reservoirs for all known oil and gas accumulations in the Bulgarian portion of the Moesian platform. They are at depths of about 3,000 m (Vuchev and others, 1993).

Traps and Seals

Trap types within the Carpathian–Balkanian Basin Province differ throughout this geologically complex region. The traps are primarily structural in areas deformed by thrusting and folding or by salt diapirism, but in less structurally deformed areas, such as the Moesian platform, stratigraphic traps produced by facies changes or by unconformable relations are more common.

In Romania, east-west trending Neogene normal faults are the primary control on the distribution of oil fields, whereas in Bulgaria most fields combine structural and stratigraphic traps. Structural traps are associated with all nappe units, and unconformities related to different compressional phases form additional traps (Dicea, 1996). Established oil fields are contained within relatively shallow structures that attained their present configuration during late Pliocene deformation (Dicea, 1996). The Birlad depression is characterized by structural and lithostratigraphic traps, and the seals are middle and upper Miocene (Badenian, Sarmatian) and Pliocene marls and claystone. Reservoir traps are mainly faulted anticlines and monoclines on the west end of the Moesian platform, and the associated reservoir seals are marls and evaporites (Pene, 1996a).

In the Getic depression (southern Carpathians), hydrocarbons originated from Oligocene and Miocene source rocks and accumulated in both structural and stratigraphic traps. In the Paleogene Flysch zone, traps are formed by faulted anticlines, folds, duplexes, and imbricate structures (Dinu and others, 1996). In the eastern Carpathian Mountains, traps are mainly structural and may be anticlines, partly cut by thrust faults, or structures modified by salt diapirs; stratigraphic pinchouts and unconformity traps are secondary (Dicea, 1996). In the Tarcau nappe region, seals are provided by Pliocene rocks (Dicea, 1996).

Hydrocarbon Generation and Migration

Popescu (1995) believed that most of the hydrocarbons in Romania were expelled or remigrated into reservoirs after the Styrian orogeny about 12 to 14 Ma (middle Miocene); hydrocarbons presumably migrated updip along north-south- and east-west-trending normal faults and along unconformities. In the northern part of the Getic depression, Oligocene source rocks are thought to be at the beginning of the oil window at depths of 3,500–4,000 m. Generated hydrocarbons migrated updip to the south into structural and stratigraphic traps (Dicea, 1996). Oil from Silurian shales may have migrated before traps formed and was lost. Migration pathways for hydrocarbons and migration distances were directly controlled by the location and timing of thrusting (Larfargue and others, 1995).

The time during which oil and gas accumulated in the Moesian platform is not well known. One interpretation is that the hydrocarbons formed in a succession of stages beginning in the Paleozoic and were frequently remobilized and redistributed. A second interpretation is that hydrocarbons formed in only one period of generation, the Neogene, when all source rock units reached maturity owing to subsidence during Carpathian thrusting (Tari and others, 1997). Evidence supports the latter interpretation (Dicea, 1996), although a question remains as to the possibility of early generation during the Hercynian orogeny, about 370 to 220 Ma (Late Devonian–Late Triassic) (Tari and others, 1997). One more approximation for the onset of generation in the Paleogene Flysch zone is in the early Miocene (Burdigalian); however, this episode may have been only local owing to the geologic complexity of the flysch zone (Popescu, 1995). In the Moesian platform, onset of hydrocarbon generation is believed to have been during the middle Miocene (Popescu, 1995). In the Birlad depression, source rocks are buried to depths greater than 4,000 m and generation of hydrocarbons is thought to have begun in the late Miocene (Sarmatian) (Pene and others, 1997).

Resource Assessment

Moesian Platform Composite Total Petroleum System, Moesian Platform Assessment Unit

The Moesian Platform Composite Total Petroleum System (TPS) (fig. 1), which includes the Moesian Platform AU, is composed of Mesozoic and Cenozoic rocks within the Moesian platform region of northern Bulgaria and southern Romania and also of the Birlad depression in the northeastern platform area. Jurassic, Cretaceous, and Tertiary formations within the platform are in a monocline that dips north and west beneath the Carpathian foredeep (fig. 5). Faulting is prevalent; some faults are oriented east-west parallel to the Carpathian orogen, and others are oriented north-south or northwest-southeast. The main lithofacies is molasse derived from the Carpathian Mountains.

The greatest volume of discovered oil in Romania is in the Moesian platform, where upper Miocene clastic rocks are the main reservoir. Triassic, Jurassic, and Cretaceous strata also contain several productive horizons. In the Birlad depression, middle to upper Miocene strata are thought to have the best potential for hydrocarbon source rocks; the Middle Jurassic is considered to be a possible secondary source rock. Most oil and gas discoveries in Bulgaria have been in a structural depression in the northwest, one of several superimposed structural and sedimentary basins in the Moesian platform region.

In Romania, source rocks are interpreted as carbonate rocks and bituminous claystones of Middle Jurassic, Early Cretaceous, and Oligocene ages; Ordovician-Silurian shales, as well as Carboniferous dolomite and shale, may have generated limited amounts of dry gas. Middle and Upper Jurassic shales in Bulgaria are considered the sources most likely to have generated oil and gas but to have had less capacity than the sources in Romania.

An events chart (fig. 9) summarizes the ages of and relations among source, reservoir, seal, and overburden rocks and the timing of trap formation and the generation, migration, accumulation, and preservation of hydrocarbons in the Moesian Platform AU. Hydrocarbon generation is believed to have occurred in Permian-Triassic time, but only to a limited extent; any hydrocarbons generated then would probably have been lost owing to the lack of good reservoir seals. Late Neogene time is proposed for the principle generation period, because burial of source rocks in Paleogene and lower Neogene strata had become great enough for maturation of the organic matter. Gas generated from molasse deposits located within the Moesian platform may have followed a path similar to that of gas generated in the northern Carpathian Mountains of Poland and Ukraine, where the generation of biogenic gas is nearly contemporaneous with deposition of the source rocks (Kotarba, 1998). The proximity of source rocks and reservoirs assured a relatively short migration distance into stratigraphic and structural traps, probably less than 5 km in most cases, and into reservoirs ranging in age from Paleozoic to mid-Pliocene. Carbonate and sandstone are the main reservoir lithologies in Romania. In the Bulgarian portion of the Moesian platform, reservoirs of all known oil and gas production are contained within Triassic carbonate rocks and Lower and Middle Jurassic clastic rocks.

Estimated undiscovered resources (mean values) for the Moesian Platform Zone AU are 171 million barrels of oil (MMBO), 561 billion cubic feet of gas (BCFG), and 20 million barrels of natural gas liquids (MMBNGL (table 1).

Dysodile Schist–Tertiary Total Petroleum System, Romania Ploiesti Zone and Romania Flysch Assessment Units

The Dysodile Schist–Tertiary TPS (fig. 1) is composed of the Romania Flysch Zone AU and the Romania Ploiesti Zone AU, which differ in their structural configuration but share a number of closely related geological features. The Romania Flysch Zone AU includes the Getic depression, the Marginal Folds zone (part of the Paleogene Flysch zone of the eastern Carpathian Mountains), and the Miocene zone (or Sub-Carpathian nappe) (fig. 2). Oil with subordinate gas is produced from each assessment unit.

An events chart (fig. 10) summarizes, for the Dysodile Schist–Tertiary TPS, the ages of and relations among source, reservoir, seal, and overburden rocks and the timing of trap formation and the generation, migration, accumulation, and preservation of hydrocarbons. The sources of the oil for the AUs are two particularly rich source rocks: Oligocene dysodile schist and black claystones, and Miocene shales, black claystones, and marls. The dysodile schists are divided into lower and upper parts, whose thickness ranges from 50 to 100 m and 80 to 200 m, respectively. Reported percent TOC ranges from 3.7 to greater than 29; thus, the schists are exceptionally good sources of hydrocarbons. The main productive intervals in the Romania Ploiesti zone are in Oligocene, lower and upper Miocene, and Pliocene rocks. In the Getic depression, oil accumulations are closely related to the distribution of Paleogene formations; gas-prone Miocene-Pliocene rocks are the source for upper Miocene and Pliocene reservoirs.

The complex structure of the Ploiesti region is characterized by numerous overthrusts and folds and by deformation

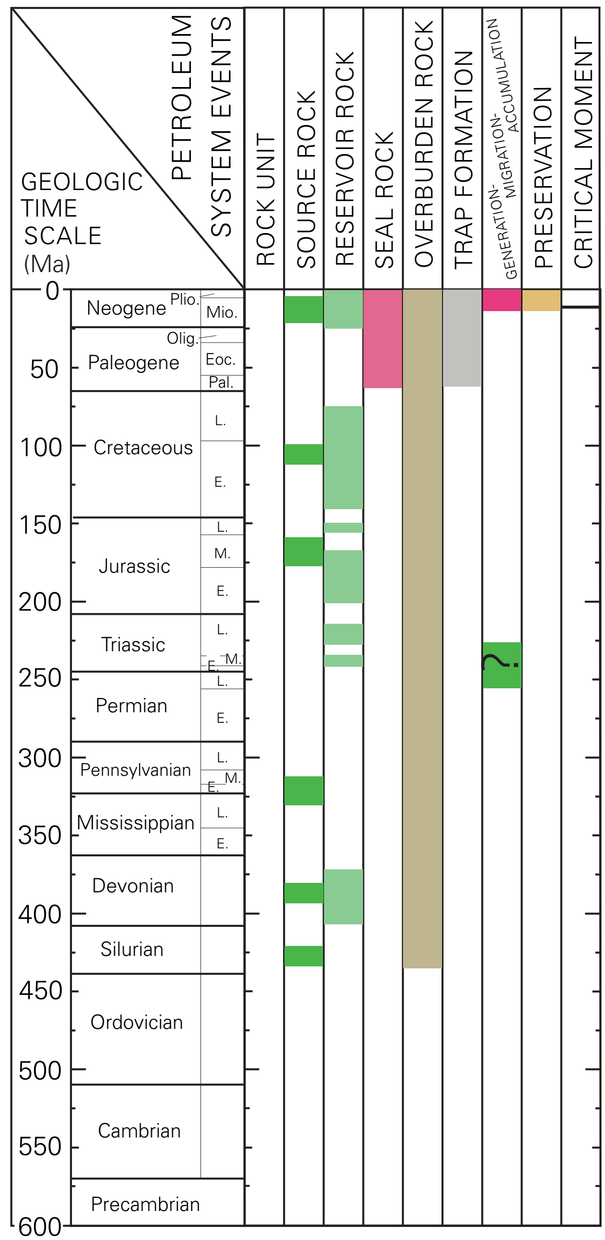

Figure 9. Events chart for the Moesian Platform Composite Total Petroleum System, illustrating relative timing of critical geologic events in the evolution of the total petroleum system. E., Early; M., Middle; L., Late; Eoc., Eocene; Mio., Miocene; Olig., Oligocene; Pal., Paleocene; Plio., Pliocene.

Table 1. Summary of allocated oil and gas resources, Carpathian–Balkanian Basin Province (4061), 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 (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 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
406101 **Moesian Platform Composite Total Petroleum System**														
40610101 Moesian Platform Assessment Unit (100% of undiscovered oil fields and 100% of undiscovered gas fields allocated to ONSHORE province 4061)														
Oil Fields	1	1.00	67	160	310	171	74	187	399	205	2	5	13	6
Gas Fields	6						103	323	726	356	4	13	31	14
Total		1.00	67	160	310	171	176	509	1,125	561	6	18	43	20
406102 **Dysodile Schist-Tertiary Total Petroleum System**														
40610201 Romania Flysch Zone Assessment Unit (100% of undiscovered oil fields and 100% of undiscovered gas fields allocated to ONSHORE province 4061)														
Oil Fields	1	1.00	230	529	1,001	564	208	518	1,076	565	6	15	34	17
Gas Fields	6						391	1,454	3,352	1,612	15	56	142	64
Total		1.00	230	529	1,001	564	599	1,973	4,428	2,177	20	71	176	81
40610202 Romania Ploiesti Zone Assessment Unit (100% of undiscovered oil fields and 100% of undiscovered gas fields allocated to ONSHORE province 4061)														
Oil Fields	1	1.00	57	240	626	278	63	280	779	333	2	8	24	10
Gas Fields	6						41	101	199	108	2	4	8	4
Total		1.00	57	240	626	278	105	381	979	441	3	12	33	14

caused by salt diapirs, all of which placed potential reservoirs and source rocks in proximity (maximum distance 1–3 km). This proximity facilitated hydrocarbon migration along faults, both vertically and horizontally, into clastic rocks reservoirs with porosity as much as 25 percent and permeability as much as 500 mD and into fractured carbonate reservoirs. One sandstone reservoir in the external Carpathians and the foreland basin, the Kliwa Sandstone (fig. 8) is 20 to 170 m thick, and other unnamed sandstones and conglomeratic beds range in thickness from 60 to120 m. Reservoir characteristics, such as porosity, hydrocarbon content, and net pay thickness, can change laterally over short distances throughout the Dysodile Schist–Tertiary TPS. In the Tarcau nappe of the Romania Flysch Zone AU (fig. 4), hydrocarbons are produced from the Eocene Tarcau Sandstone, Oligocene Kliwa Sandstone, and Oligocene–lower Miocene Fusaru Sandstone (fig. 8). In the Getic depression, reservoirs are in Paleogene, Miocene, and Pliocene sandstones with porosity ranging from 15 to 25 percent, and permeability from 10 to 500 mD. Generally throughout the total petroleum system, hydrocarbon accumulations are contained within a variety of reservoir lithologies and are sealed primarily by claystones, evaporites, and marls; however, fault planes seal many of the structural traps.

Generation of hydrocarbons is proposed to be late Neogene (fig. 10), at which time source rocks were buried sufficiently deep by various nappes and molasse deposits to mature. Estimated undiscovered resources (mean values) in the Romania Flysch Zone AU are 564 MMBO, 2,177 BCFG, and 81 MMBNGL; in the Romania Ploiesti Zone AU these mean values are 278 MMBO, 441 BCFG, and 14 MMBNGL (table 1).

Assessment Results and Summary

Table 1 summarizes the allocated oil and gas resources in the Carpathian–Balkanian Basin Province of Romania and Bulgaria. Assessment units are listed for each total petroleum system. The resources are grouped into fractiles, which provide a means of assigning a risk factor to the actual discovery of these resources; that is, the higher the “F” value, the higher the confidence that new reserves will be discovered in the next 30 years. For example, at the F95 level, a 95 percent chance exists that at least the estimated amount of oil or gas will be discovered. Total undiscovered resources for the province, estimated at the mean (F50 values), are 1,013 MMBO, 3,179 BCFG, and 116 MMBNGL (table 2). Although the province 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 large amounts of additional oil and gas, most probably in small fields (figs. 11, 12).

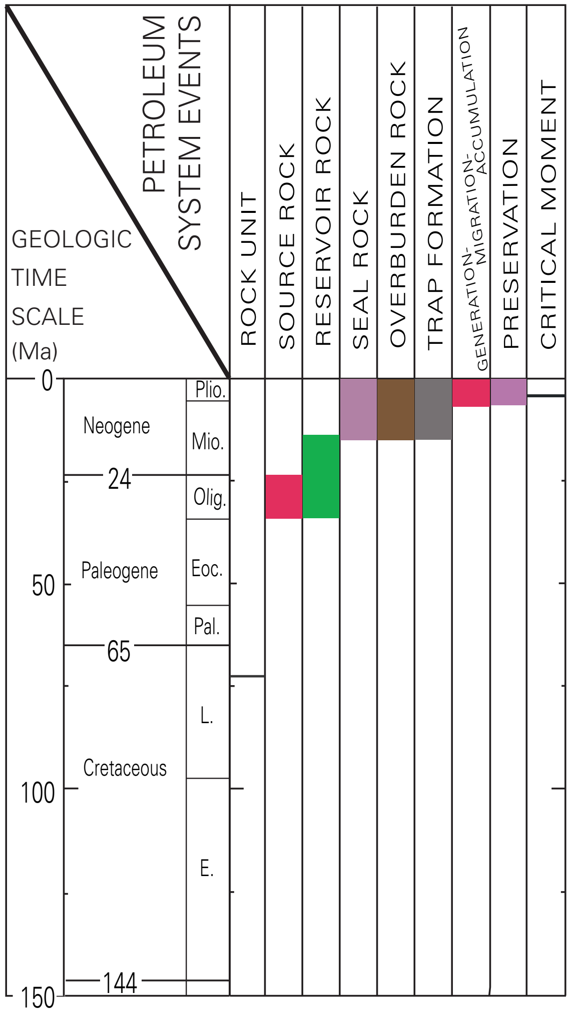

Figure 10. Events chart for the Dysodile Schist–Tertiary Total Petroleum System, illustrating relative timing of critical geologic events in the evolution of the total petroleum system. E., Early; L., Late; Eoc., Eocene; Mio., Miocene; Olig., Oligocene; Pal., Paleocene; Plio., Pliocene.

Table 2. Summary of allocated oil and gas resources, Carpathian–Balkanian Basin Province (4061).

[BCFG, billion cubic feet of gas; MFS, minimum field size assessed (1 MMBO or 6 BFCG); MMBNGL, million barrels of natural gas liquids; MMBO, million barrels of oil. Prob., probability (including both geologic and accessibility probabilities) of at least one field equal to or greater than the minimum field size. Results shown are fully risked estimates. For gas fields, all liquids are included under the natural gas liquids (NGL) 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
4061	**Total: Assessed onshore portions of Carpathian-Balkanian Basin Province**													
Oil Fields		1.00	354	929	1,937	1,013	345	986	2,254	1,103	10	29	71	33
Gas Fields							535	1,878	4,277	2,076	20	73	181	83
Total		1.00	354	929	1,937	1,013	880	2,863	6,531	3,179	30	102	252	116
4061	**Total: Assessed offshore portions of Carpathian-Balkanian 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
4061	**Grand Total: Assessed portions of Carpathian-Balkanian Basin Province**													
Oil Fields		1.00	354	929	1,937	1,013	345	986	2,254	1,103	10	29	71	33
Gas Fields							535	1,878	4,277	2,076	20	73	181	83
Total		1.00	354	929	1,937	1,013	880	2,863	6,531	3,179	30	102	252	116

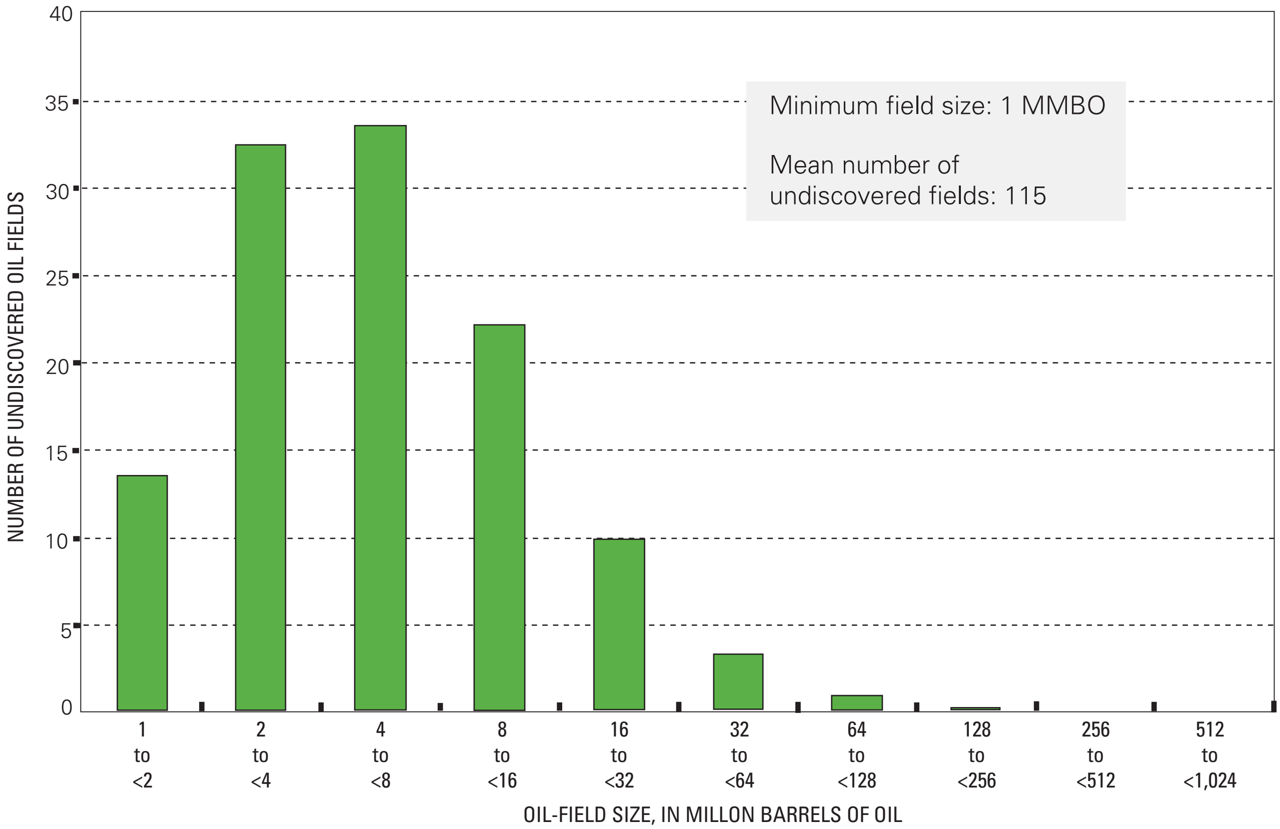

Figure 11. Estimated number and size of undiscovered oil fields in Carpathian–Balkanian Basin Province (4061) of Eastern Europe. MMBO, million barrels of oil.

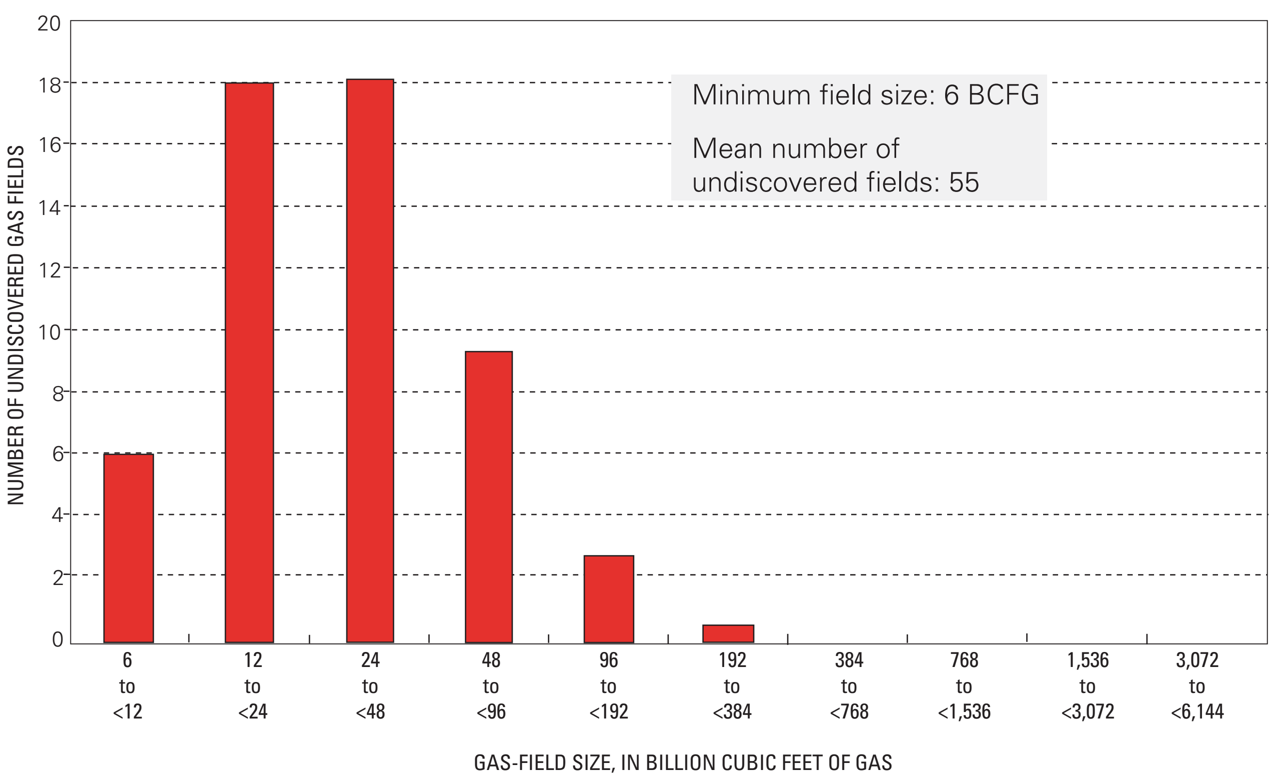

Figure 12. Estimated number and size of undiscovered gas fields in Carpathian–Balkanian Basin Province (4061) of Eastern Europe. BCFG, billion cubic feet of gas.

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