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Pannonian Basin Province, Central Europe (Province 4808)—Petroleum Geology, Total Petroleum Systems, and Petroleum Resource Assessment

Bulletin 2204–B

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

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By Gordon L. Dolton

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Foreword

This report was prepared as part of the U.S. Geological Survey World Petroleum Assessment 2000 (U.S. Geological Survey World Energy Assessment Team, 2000). The primary objective of World Petroleum Assessment 2000 is to assess the quantities of conventional oil, natural gas, and natural gas liquids outside the United States that have the potential to be added to reserves in the next 30 years. Parts of these assessed volumes reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit; the cutoff value varies, but it must be at least 1 million barrels of oil equivalent. Another part of these assessed volumes occurs as reserve growth of fields already discovered. However, the contribution from reserve growth of discovered fields to resources is not covered for the areas treated in this report.

In order to organize, evaluate, and delineate areas to assess, the Assessment Methodology Team of World Petroleum Assessment 2000 developed a hierarchical scheme of geographic and geologic units. This scheme consists of regions, geologic provinces, total petroleum systems, and assessment units. For World Petroleum Assessment 2000, regions serve as organizational units and geologic provinces are used as prioritization tools. Total petroleum systems (TPS) and assessment units (AU) were delineated for each province considered for assessment. The boundaries of the TPS and AU need not be entirely contained within a geologic province. The TPS includes all genetically related petroleum that occurs in shows and accumulations (both discovered and undiscovered) generated by a pod or closely related pods of mature source rock. TPSs exist within a limited mappable geologic space along with the geologic elements (source, reservoir, trap, seal, and overburden rocks) necessary for hydrocarbon accumulation. These geologic elements control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum within the TPS. The AU is the basic element assessed in this study. It is a mappable part of a total petroleum system in which discovered and undiscovered oil and gas fields constitute a single relatively homogeneous population such that the methodology of resource assessment is applicable.

The world was divided into 8 regions and 937 geologic provinces. These provinces have been ranked according to the discovered known (cumulative production plus remaining reserves) oil and gas volumes (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) were selected for appraisal of oil and gas resources. Boutique provinces were chosen for their anticipated petroleum richness or special regional economic or strategic importance.

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Abstract

This report deals with the Pannonian Basin Province of Central Europe and summarizes the petroleum geology, which was the basis for assessment, and presents results of that assessment. The Pannonian Basin Province consists of a large compound extensional basin of Neogene age overlying Paleogene basins and interior elements of the greater Alpine foldbelt (fig. 1). Within it, six total petroleum systems (TPS) are defined and six assessment units established for estimation of undiscovered oil and gas resources. Other speculative TPSs were identified but not included for quantitative assessment within this study.

Introduction

This report deals with the Pannonian Basin Province of Central Europe and summarizes the petroleum geology, which was the basis for assessment, and presents results of that assessment. The report relies largely on a synthesis of published geologic information.

The Pannonian Basin Province consists of a large compound extensional basin of Neogene age overlying Paleogene basins and interior elements of the greater Alpine foldbelt (fig. 1). The Neogene basin system is approximately 600 km from east to west and 500 km from north to south, excluding the associated Transylvanian and Vienna Basins. Geographically, it lies within the Alpine mountain belts of east-central Europe and is bounded by the Carpathian Mountains to the north and east, the Southern Carpathian or Dinaric Alps to the south, and the Southern and Eastern Alps to the west. It is located mostly within the confines of Hungary, Croatia, Romania, and Serbia-Montenegro (formerly Yugoslavia) and also occupies parts of Austria, Slovakia, Ukraine, Bosnia and Herzegovina, Slovenia, and Poland.

The Neogene Pannonian Basin historically has been the primary petroleum exploration target in the province and is composed of a complex system of extensional subbasins lying within the arc of the Carpathian Mountains (figs. 1, 2, and 3). Subbasins are separated from one another by uplifted basement blocks but are tied together by a widespread blanket of younger Neogene and Quaternary sediment fill (Horváth and Royden, 1981; Royden and Horváth, 1988). Among the principal subbasins are those of the Great Hungarian Plain, including the Jászság, Derecske, Nyíség, Nagykunság and Békés Basins and Makó trough; the Zala Basin, Dráva and Sava depressions, and Graz (Styrian) Basin; the Danube (Little Plain) Basin and the Transcarpathian (East Slovak) Basin. These basins rest on thrust sheets of the Inner Carpathian foldbelt in northern and central areas and, to the south, on those of the Dinarides and associated Vardar Zone (fig. 1). Not included within this assessment are the Vienna and Transylvanian Basins, which are sometimes considered as parts of the overall Pannonian system (Royden and Horváth, 1988). Within the geologic framework of the province, six total petroleum systems are defined and six assessment units established for estimation of undiscovered oil and gas resources. Three other TPSs were identified but not quantitatively assessed.

Acknowledgments

The author wishes to acknowledge the invaluable research by a wide range of authors concerning the geologic framework of this area, upon which this paper relied. The manuscript has benefited greatly from critical and constructive reviews by Gregory Ulmichek, Tim Klett, and Kathy Varnes. The author thanks Rick Scott for a constructive edit of the manuscript. The author is grateful to Susan Walden and Margarita Zyrianova for preparation of digital illustrations and wishes to acknowledge authorship for those figures, which have been derived or modified from published sources.

Figure 1. Index map showing main tectonic and geographic units of Alpine Foldbelt and Alpine-Carpathian-Dinaric Mountains, and the names of Tertiary basin units inside these mountains, shown in white, to which the collective name Pannonian Basin is generally applied, including the associated Transylvanian and Vienna Basins. Modified from Horváth, 1985b. The Pannonian Basin Province (4048) boundary is shown in blue.

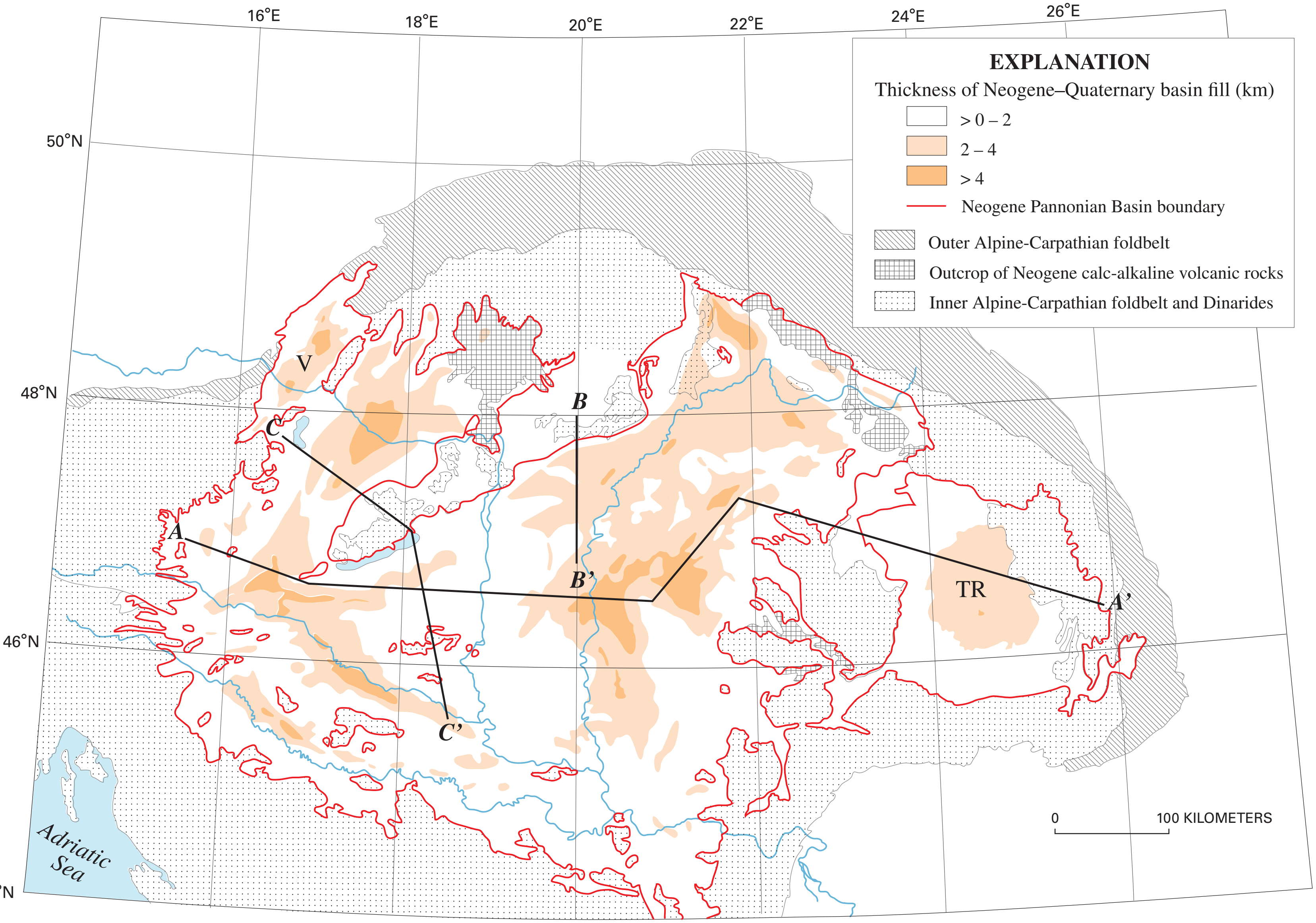

Figure 2. Map of the Neogene Pannonian Basin, showing depocenters of the subbasins. The associated Transylvanian (TR) and Vienna (V) basins are shown. Modified from Horváth (1985a). Cross sections are in figure 3.

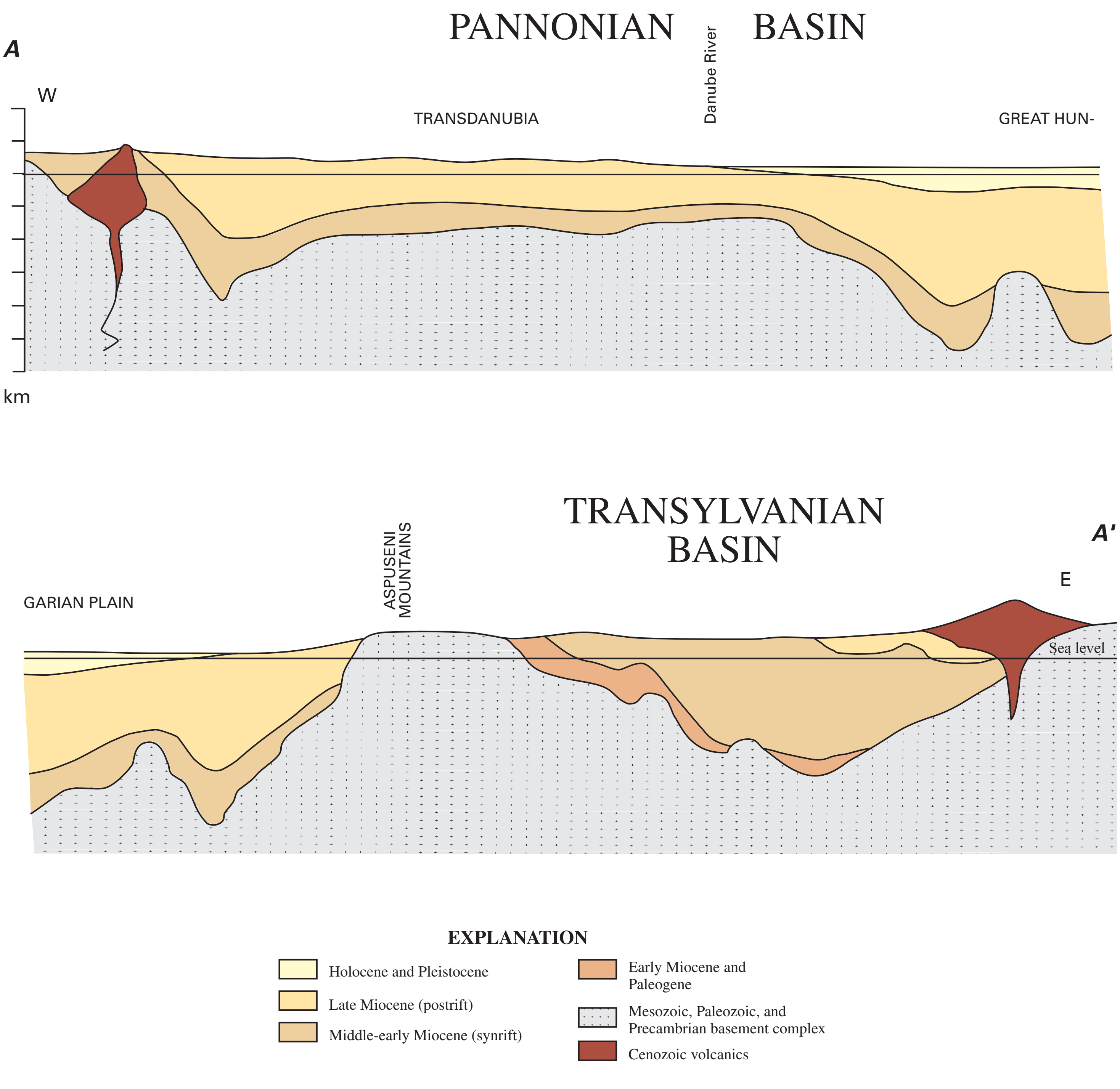

Figure 3. Diagramatic cross sections of the Pannonian Basin. Section *A-A′* modified from Horváth and others (1996); section *B-B′* modified from Sztanó and Tari (1993; with permission from Elsevier); section *C-C′* modified from Haas (1989). Locations of cross sections are shown in figure 2. (Figure continued on next page.)

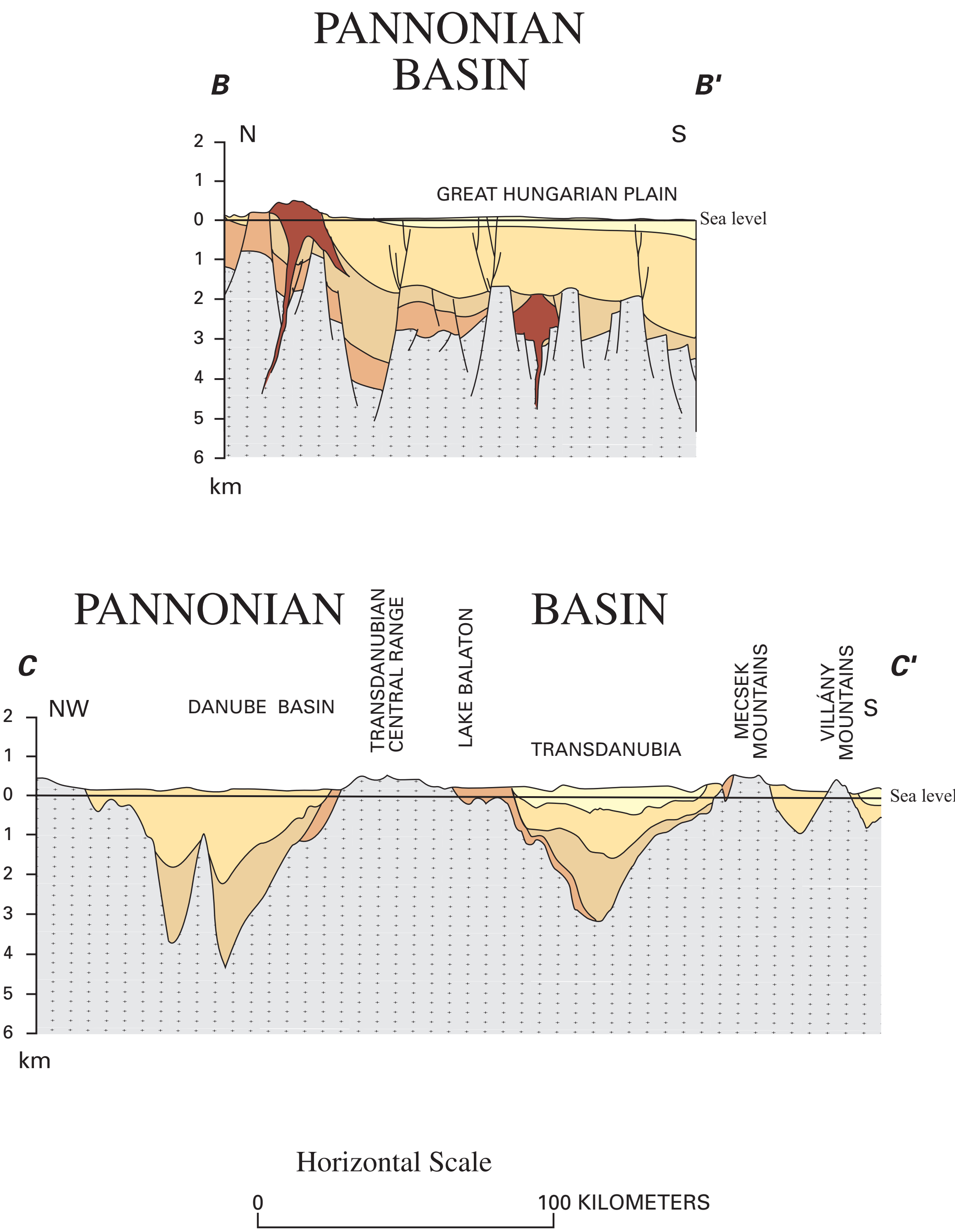

Figure 3. Continued.

General Geologic Setting

Tectonic History

The present tectonic setting of the Pannonian Basin Province is characterized by a major system of Cenozoic basins superimposed on inner elements of highly deformed and complexly faulted nappes of Mesozoic, Paleozoic, and Precambrian rocks of the Alpine-Carpathian foldbelt (fig. 4).

Paleozoic events affecting the Pannonian Basin Province are poorly known; however, the Hercynian (Variscan) orogeny of middle and late Carboniferous time involved local crustal elements in the collision between Gondwana and Laurentia. This collision resulted in closure of the Tethys Sea, a suture along the margin of the European plate immediately west of the present Pannonian Basin, metamorphism of older Paleozoic rocks in the area, and the creation of Pangea.

Collapse of the Hercynian orogen in Late Permian time was followed by reopening of the Tethys Sea and rifting and foundering of marginal crustal fragments, including the Apulian, south European, and Tisza blocks. Rift basins were superimposed on Hercynian structural trends and became sites of predominantly continental and evaporitic deposition.

Triassic time was characterized by continued opening of the Tethys Sea and graben formation on adjoining crustal blocks (Yilmaz and others, 1996). Basin and platform paleogeography persisted into the Jurassic. Pelagic sediments were deposited in troughs and on open-marine shelves, and shallow-water marine carbonates commonly occupied platforms where they were generally succeeded by marine shelf sediments. Plate motions between Africa and Europe were largely sinstral from Late Jurassic through Early Cretaceous time but included counterclockwise rotation of Apulia and development of a subduction zone with flysch sedimentation at its margin, accompanied by calc-alkaline volcanism.

During the late Mesozoic and Cenozoic, closure of the Tethys Sea resumed, accompanied by collision of the European plate with small crustal fragments ahead of an advancing African plate. This collision produced the Paratethys and the foldbelts of the Alpine orogen upon which the Tertiary Pannonian Basin system rests (fig. 4). Disparate crustal elements were assembled into the Inner Carpathian foldbelt during Cretaceous and Paleogene time, and outer parts, comprising the Outer Carpathian foldbelt, were deformed during the Neogene.

Separate Apulian, Tisza, and Pelso crustal blocks impinged on the European plate by the Late Cretaceous, and Sandulescu (1988) suggests that virtually the whole inner Carpathian realm attained its present structure and morphology by Late Cretaceous, with the result that, “during Cenozoic time, these areas of Cretaceous deformation acted roughly as rigid blocks, and their differential movement was accommodated by large strike–slip faults.” More recent work by Yilmaz and others (1996) indicates that the Tisza block separated from Europe in Late Jurassic time and became attached to Apulia, before again colliding with Europe in Eocene time. In any case, interior elements of the foldbelt were modified by Cenozoic compression, shearing, and compression. Balla (1990) reconstructed the evolution of the present Pannonian crustal fragment, comprised of the Pelso and Tisza blocks, as beginning in the Eocene, with its final assembly in the middle Miocene. Compressional deformation of Paleogene flysch sediments on margins of the Pelso and Tisza blocks and within the Szolnok trough accompanied this assembly (see fig. 7).

During Eocene and early Oligocene time, convergence had pushed the Apulian, Pelso, and Tisza blocks farther into the European plate, accompanied by transpression and rotation, and caused development of epicontinental basins on the Pannonian fragment, most prominently the Hungarian Paleogene Basin and flysch basins at margins of crustal blocks (see fig. 7). The epicontinental basins have been viewed as wrench basins by several authors (Royden and Báldi, 1988; Csontos and others, 1992; Nagymarosy, 1990), whereas other investigators have proposed a flexural basin model of a retroarc foredeep basin system south of the backthrust inner West Carpathians (Tari and others, 1993). This system persisted into the early Miocene. The Hungarian Paleogene Basin underwent structural inversion in the middle Oligocene, accompanied by development of an offset trough to the east, followed by general uplift and erosion.

By late Oligocene or early Miocene, assembly of the present Pannonian crustal fragment took place, accompanied by considerable rotation—particularly of the Tisza block—and behaved as a loose knot within the collision zone between the Apulian and European plates, and, with continuing compression, began escaping to the east, accompanied by rotation and shearing, producing the Carpathian arc at its verge (Royden and Báldi, 1988; Balla, 1987; Balla, 1990; Csontos and others, 1992). Thrusting and strong folding in the Outer Carpathian arc began in the early Miocene, moving progressively north and east, with associated compressional features of the Dinarides Alpine system seen at the southern margin of the Pannonian crustal fragment.

As the elevated Pannonian fragment overrode the European plate, extension, crustal thinning, and fragmentation began with adjustments along normal and strike-slip faults and development of a complex system of successor extensional basins behind the Carpathian arc (fig. 5). As a consequence, the basement and earlier Paleogene basins were overprinted by Neogene back-arc rift basins, which were essentially coeval with the compressive deformation in the Outer Carpathians. According to Royden (1988), extension within the system was diachronous, beginning first in the most external subbasins in Ottnagian–Karpatian time (early Miocene; see fig. 6 for stratigraphic stages), shifting to more interior basins through time. Rifting was characterized by local high relief, deep grabens, and synrift sedimentation, followed by a general relaxation and differential thermal subsidence and widespread, rapid postrift sedimentation.

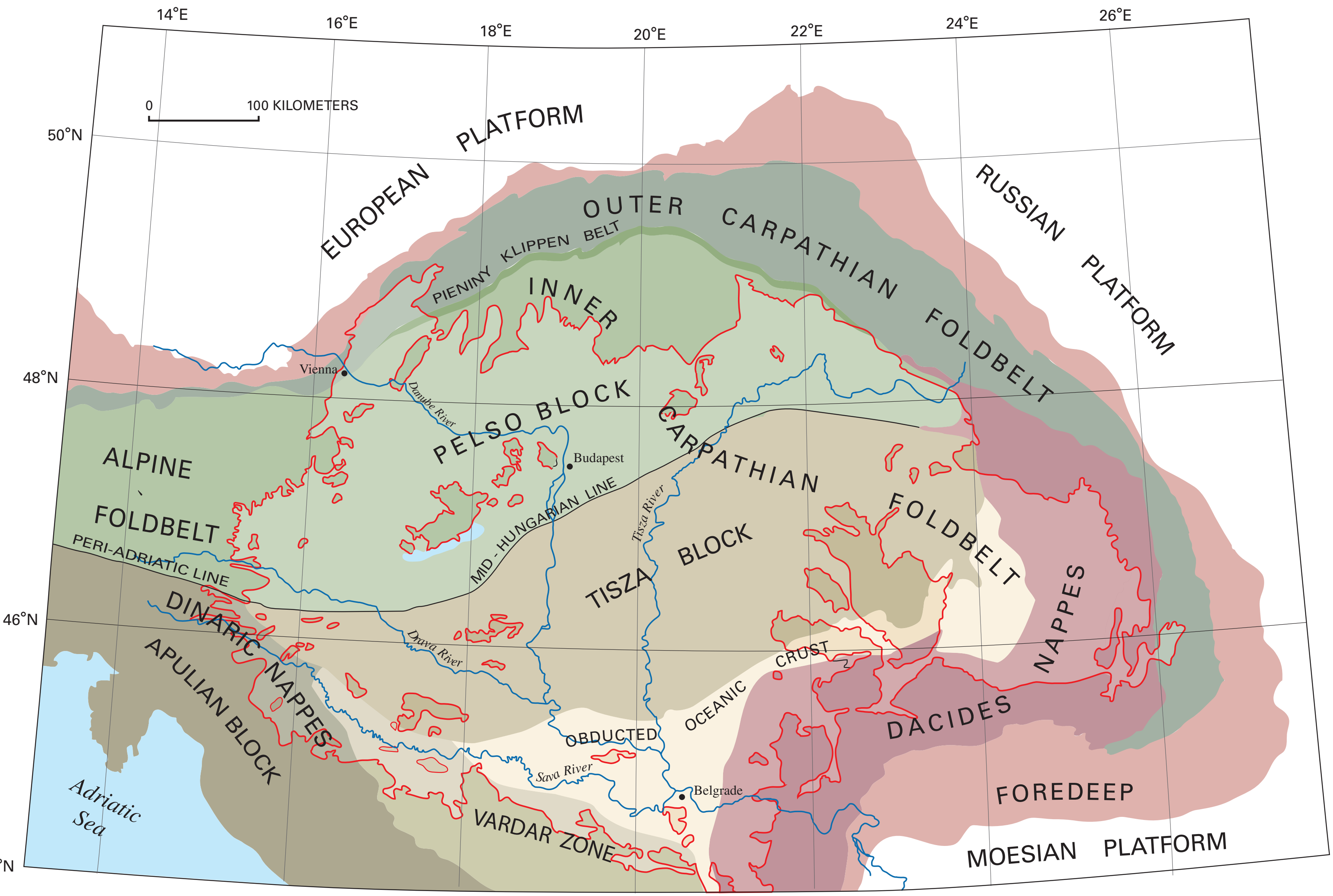

Figure 4. Generalized map of major structural elements of Alpine-Carpathian orogen. Areas overlain by Pannonian Basin Cenozoic rocks are shown in lighter shade within red outline. The Pelso and Tisza blocks compose the Pannonian crustal fragment of the Inner Carpathian foldbelt. Modified from Sandulescu (1988); Brezsnyanszky and Haas (1989); Csontos and others (1992); Sztanó and Tari (1993; figure used with permission from Elsevier).

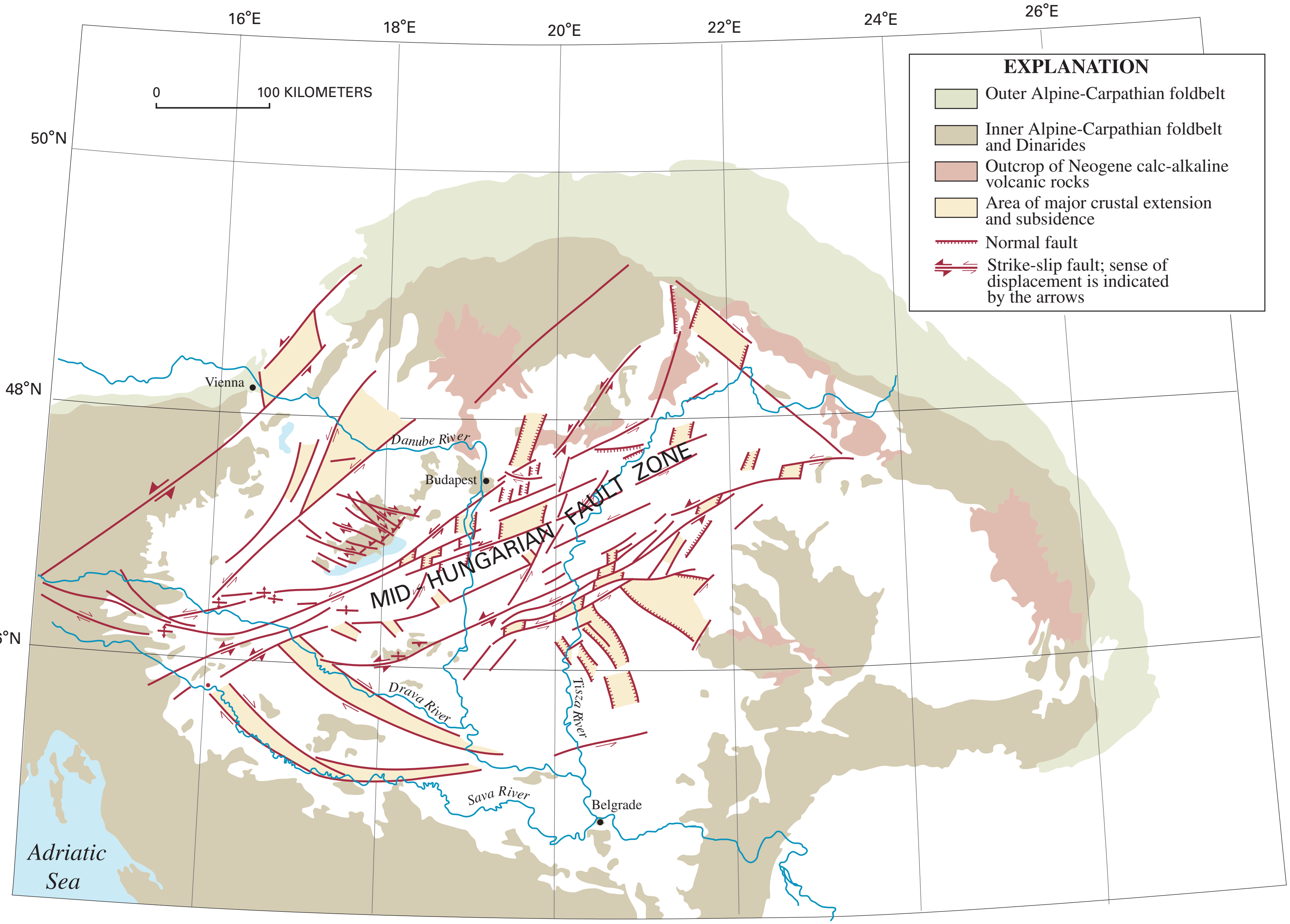

Figure 5. Tectonic map of the Pannonian Basin and surrounding regions showing the main extensional faults of Neogene age. After Rumpler and Horváth (1988). Area of Pannonian Basin Tertiary rocks within the Alpine-Carpathian foldbelts shown as white.

Volcanism accompanied extension and climaxed in the middle Miocene as a result of subduction of European continental crust beneath the fold-thrust belt. Rhyolite tuff volcanic activity was intense during the synrift phase, and several cycles of eruption produced thick tuffaceous layers, particularly throughout the northern Pannonian Basin system (Póka, 1988). Along with shearing in late Miocene, reverse faulting is found in several subbasins, particularly in the Sava Basin at the southern margin of the Pannonian Basin (Baric and others, 2000).

Major extension largely stopped by the end of Miocene time. Mild extension, with strike-slip and normal faulting, continued into Pliocene time, as did uplift around the margins of the Pannonian Basin system, and accompanied compression in the Eastern Carpathians. The Pannonian Basin presently shows a complex system of faults and deformation related to late strike-slip movements and wrench faulting involving very young sediments. Many of these faults appear to be reactivations of old features, including the Mid-Hungarian lineament or fault zone, which separates the Tisza and Pelso basement terranes. Nevertheless, the Pliocene generally reflects a waning of tectonic activity. By the late Pliocene, most of the horst blocks within the Pannonian Basin system were buried, excepting the uplifts of the Transdanubian Central Range and North Hungarian Range and the margins of the basin system. During the Quaternary, the Panonnian Basin showed general uplift around its margins, continued subsidence in central parts, and late strike-slip adjustments (Horváth and others, 1996). Detail of the structural evolution of the basin is subject to varied interpretation, and for overviews the reader is particularly referred to Hámor and Bérczi (1986), Sandulescu (1988), Royden and Báldi (1988), Balla (1990), Kókai and Pogácsás (1991), Csontos and others (1992), Tari and others (1993), and Morley (1993).

Structure

The Pannonian Basin Province is characterized by a major system of Neogene basins superimposed on inner elements of highly deformed and complexly faulted nappes of Mesozoic, Paleozoic, and Precambrian rocks of the Alpine-Carpathian foldbelt (figs. 2 and 4).

In the northern part of the province, an additional system of Paleogene to early Neogene basins (fig. 7) were produced during Alpine deformation by transpression and shearing, accompanying rotation of the Pannonian crustal fragments (Royden and Báldi, 1988; Csontos and others, 1992; Nagymarosy, 1990) or within a flexural basin setting, as proposed by Tari and others (1993), and locally underlie Neogene rocks. Most prominent of the epicontinental basins is the Hungarian Paleogene Basin, which contains thick sequences of extensionally deformed and faulted, largely marine, epicontinental sedimentary rocks, now mostly uplifted and eroded. In addition, compressively deformed Paleogene flysch sediments rest on margins of the Pannonian crustal fragments and within the Szolnok trough.

The most prominent feature of the province is the large Neogene extensional Pannonian Basin within the loop or arc of the Outer Carpathian foldbelt. Resting on highly deformed older rocks of the Inner Carpathians and the Paleogene basins, the basin is actually a complex composed of many subbasins separated by basement horst blocks and uplifts. These subbasins typically contain early to middle Miocene age synrift sediments and intercalated volcanics and are, in turn, blanketed by a postrift late Neogene fill that covers the entire system and defines the present Pannonian Basin. Pervasive syndepositional rifting, growth faulting, and strike-slip deformation characterized the synrift stage, whereas the postrift stage was marked by a structural setting in which thermal subsidence and rapid sedimentation took place. The latter stage was accompanied by differential subsidence without major deformation, continuing from the late Miocene to the Holocene (Royden, 1988; Grow and others, 1994; Milicka and others, 1996).

The Neogene subbasins occur as pull-apart features and as graben structures, the latter particularly common south of the Mid-Hungarian fault zone (fig. 5) (Rumpler and Horváth, 1988; Royden, 1988). The deeper basins are commonly bounded by sets of normal faults of large displacement, some listric in nature. Locally, low-angle extensional normal faulting appears to play a particularly important role, as in the Danube Basin, commonly interacting with old basement features as noted by Tari (1996). Syndepositional structural growth caused deformation and faulting of sediments and, as noted by Pogácsás, Mattick, Tari, and Várnai (1994), “the opening of these basins resulted from strike slip motion along a set of roughly NE–SW trending, left-lateral shears accompanied by a conjugate set of NW trending, right-lateral shears.” A resultant complex fault pattern is observed within the system, dominated by the large Mid-Hungarian fault zone, which separates major basement terranes (fig. 4), as well as structural inversions noted in some areas. Thermal subsidence and rapid sedimentation of the following postrift stage were accompanied by differential sagging and caused relatively flat lying, undisturbed postrift sediments to rest unconformably on synrift sequences in most subbasins and on basement rocks of old highs.

Of the Neogene depressions, eight reach depths of greater than 3,000 m, namely the Danube Basin, the Zala Basin and Dráva and Sava troughs or depressions, the Transcarpathian Basin, and the Jászság, Drescske, Békés-Makó-Nagykunság subbasins of the Great Hungarian Plain. The Békés Basin-Makó trough alone exceeds a depth of 7,000 m, largely consisting of postrift sediments. Most subbasins are less than 70 km in long dimension, though the Danube Basin exceeds 150 km, as do the Sava and Dráva depressions. Very young sediments are involved in a complex system of faults and deformation related to late strike-slip movements and wrenching within the Pannonian Basin system.

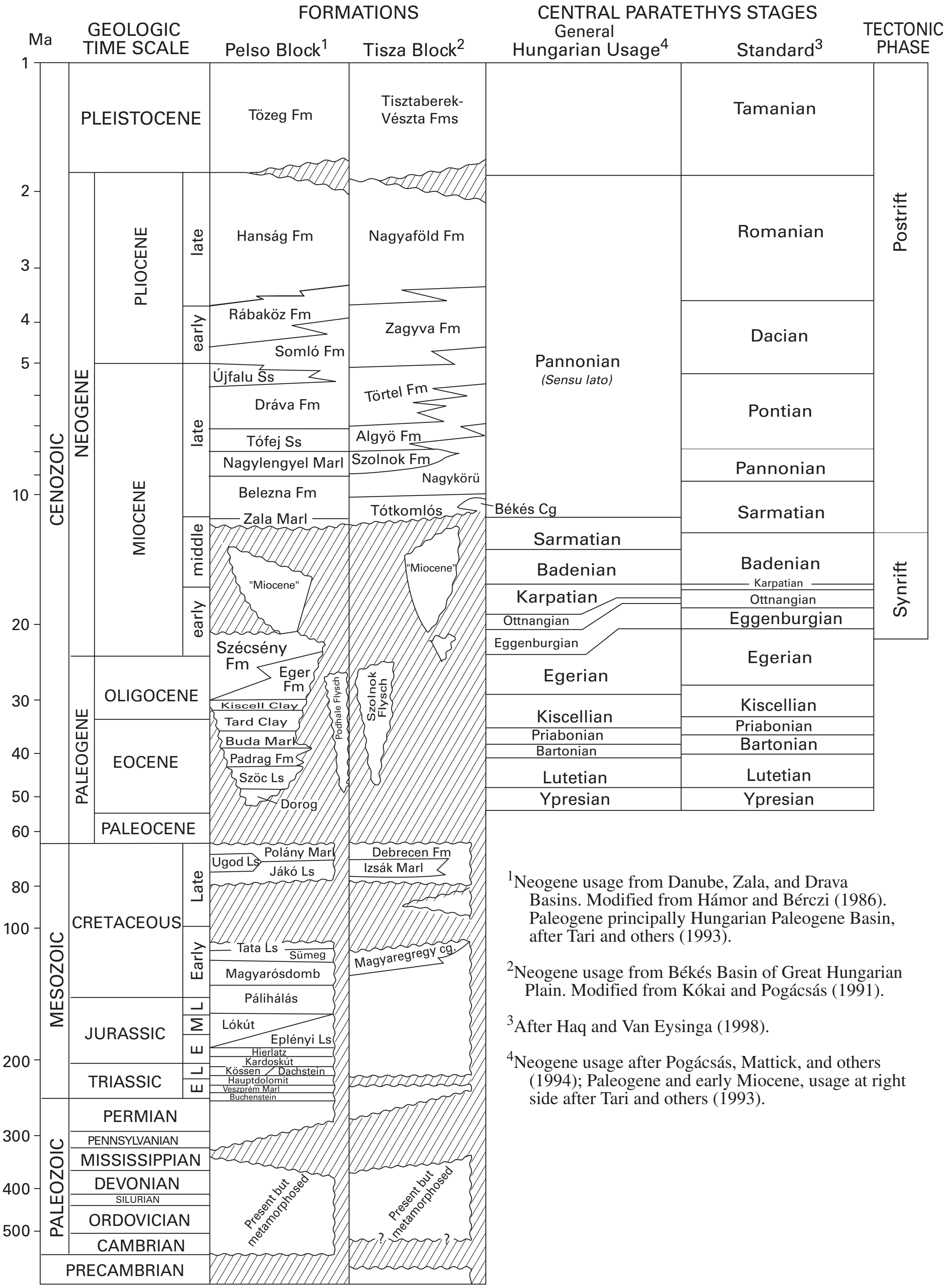

Figure 6. Generalized stratigraphic columns of Pannonian Basin Province showing selected formations. Volcanic rocks not represented.

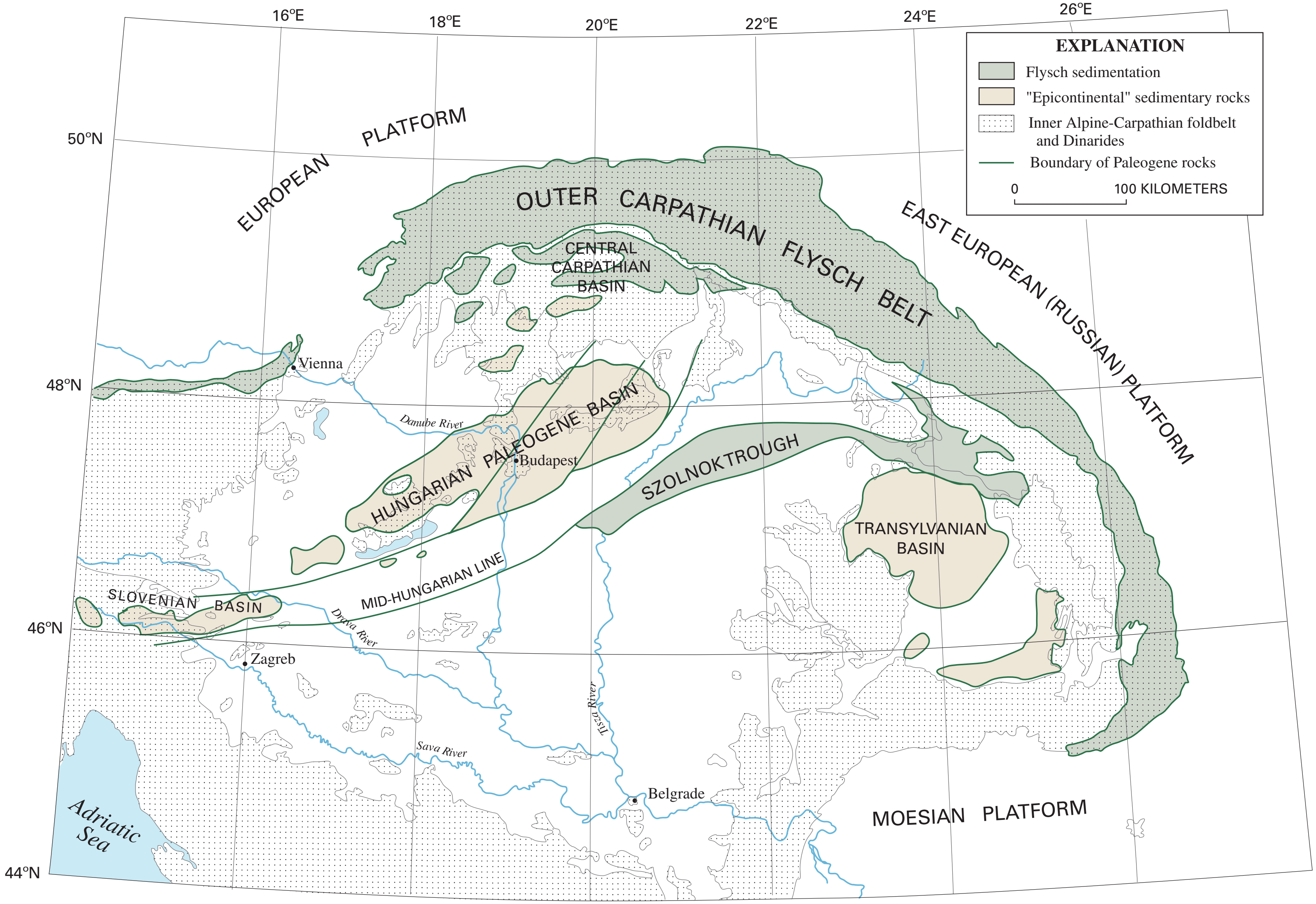

Figure 7. Distribution of Paleogene rocks showing principal basins. Modified from Nagymarosy (1990), Hámor (1989), and Tari and others (1993; figure used with permission from Elsevier).

Stratigraphy

The stratigraphy of the Pannonian Basin Province is characterized by a Tertiary basin-fill sequence resting on a highly deformed substrate of Proterozoic, Paleozoic, and Mesozoic rocks of the Inner Carpathian foldbelt (figs. 4 and 6). The pre-Tertiary basement rocks represent two geographically separated and distinct terranes, the Pelso and Tisza blocks (fig. 4). Within these blocks, virtually every nappe has its individual character and stratigraphic nomenclature (Csontos and others, 1992; Brezsnyanszky and Haas, 1989). Paleogene and lowermost Neogene rocks reflect the histories of their respective crustal units, whereas succeeding Neogene rocks show a largely shared depositional history. Stratigraphic nomenclature is complex due to the large area involved, varied depositional and lithologic facies, political and language divisions, and local usage. Cenozoic rocks are assigned to regional stages of the Central Paratethys (Haq and Van Eysinga, 1998). The chronostratigraphy used here is essentially that of Hungarian usage, and representative formation names are not intended to be inclusive.

Basement Rocks

The pre-Tertiary basement of the Pannonian Basin system consists of a complex of igneous, metamorphic, and sedimentary rocks of Precambrian, Paleozoic, and Mesozoic age that have been strongly folded, faulted, and assembled in nappes of the Inner Carpathian foldbelt (Csontos and others, 1992; Brezsnyanszky and Haas, 1989). These rocks occur within two terranes, the Pelso (or North Pannonian) and Tisza blocks (fig. 4), and include a variety of continental rocks as well as obducted Jurassic and Cretaceous oceanic crust. The Pelso block of the northern and western parts of the Pannonian system is characterized by a Mesozoic sedimentary sequence of Calc-Alpine facies, including the Triassic Hauptdolomit, Dachstein Limestone, and Kössen Marl; Upper Permian sedimentary rocks; and a Paleozoic metamorphic-igneous complex (fig. 6). At the northern margin of the Pannonian Basin, Tertiary rocks in the Vienna Basin lap onto the Cretaceous–Paleogene flysch of the Outer Carpathian foldbelt. A zone of marine lower Paleozoic and predominantly carbonate-facies Mesozoic basement rocks is present in the area of the Mid-Hungarian lineament and fault zone (figs. 5 and 6). South of this line, the Tisza terrane is characterized by rocks composed of Precambrian and Paleozoic metamorphic and igneous rocks; upper Paleozoic and Mesozoic sedimentary rocks, including a Permian–Triassic sequence similar to that found in Germany; and Cretaceous and Jurassic sedimentary rocks. Subassemblages are recognized within these terranes, and the basement exhibits much heterogeneity due to tectonic juxtaposition.

Metamorphic and igneous rocks include the Ordovician–Silurian quartz phyllite series in the Transdanubian Central Range uplift of the Pelso block and Precambrian and Paleozoic metamorphics and intrusives in the central and southern part of the Tisza block. However, no pre-Hercynian crust is known to occur within the old Apulian block south of the Peri-Adriatic line (fig. 4) (Yilmaz and others, 1996). Precambrian crystalline rocks and Paleozoic metamorphic rocks pierced by acidic intrusions of various ages are exposed in the Apuseni Mountains and Southern Carpathians as well as in interior basins of the Pannonian system. In the Mecsek Mountains (refer to fig. 1), Paleozoic metamorphics are associated with a Permian quartz phorphyry and are overlain by a Triassic sedimentary sequence. Upper Paleozoic quartz porphyry and crystalline metamorphic complexes date from the Hercynian in several areas, and metamorphosed Devonian and middle to upper Carboniferous sedimentary rocks are present. The basement composition exhibits much heterogeneity, for example, in the Békés Basin, granite, mica schist, quartzite, and quartz porphyry are present and provide oil and gas reservoirs in buried fractured and weathered basement highs.

Sedimentary rocks of the basement generally occur as fault-fragmented sequences. Older Paleozoic sedimentary rocks are strongly metamorphosed; however, some lightly metamorphosed to unmetamorphosed middle to upper Carboniferous sedimentary rocks are present and include neritic and marine shelf sequences as well as continental sequences deposited around uplifts related to Hercynian tectonism (Yilmaz and others, 1996). Upper Permian sedimentary rocks include continental sequences deposited in rift basins and neritic marine rocks deposited on shelf areas. In the Transdanubian area of the Pelso block, the Permian is represented by a red detrital, fluviatile-lacustrine sequence, whereas to the northeast, continental sediments are replaced by a lagoonal anhydrite-dolomite sequence, overlain by shallow-water marine limestones. In eastern parts of the Pelso block, most Paleozoic and Mesozoic sedimentary rocks have been metamorphosed.

On the Tisza block, Lower Triassic sedimentary rocks include varigated terrigenous shale, red sandstone, and anhydrite, grading upward into cherty carbonates. In the Mecsek Mountains, Triassic beds directly overlie Permian quartz porphyry. By Middle Triassic time, marine platforms accumulated shelf carbonates, reefal limestones, and evaporites. Upper Triassic rocks are locally represented by red siltstone, sandstone, and gray limestone of the Carpathian Keuper and equivalents.

In the Pelso block, the Lower Triassic is composed of sandstone overlain by evaporites and shale, succeeded by marine carbonates. Rift-basin and platform sedimentation continued into Late Triassic time, producing shallow-water carbonates and reefal limestones on platforms—especially the Hauptdolomit and Dachstein Limestone—and organic-rich shales and marlstones in adjacent anoxic troughs, including the Kössen and Veszprém Marls. In the Transdanubian Central Range, the basal Upper Triassic is a succession of dark-gray marls of restricted basin facies and limestones, with reef-limestone bodies to the southwest, succeeded by great thicknesses of dolomite and limestone of backreef facies comprising the Haupdolomit and Dachstein. These rocks contain source rocks and reservoirs for oil and gas.

Jurassic rocks on the Pelso block unconformably overlie the Triassic and comprise mostly marine shelf and neritic sediments deposited upon an increasingly fragmented basement. Basins accumulated deep-water sediments, including benthic limestones and radiolarites, before again shallowing in latest Jurassic time. A Lower Cretaceous pelagic argillite facies is seen in the Transdanubian Central Range grading into marl and flysch. Elsewhere, the Lower Cretaceous is represented by nearshore facies and limestone breccias, succeeded by marls interbedded with thin sandstone layers. Commonly, these rocks were slightly metamorphosed during the Alpine orogeny and are now of limited distribution.

During the Early Jurassic, a mix of shales, marls and limestones were deposited on the Tisza block, and significant coal-bearing sequences are found in Middle and Upper Jurassic sequences, as in the Mecsek Mountains. Upper Jurassic and Lower Cretaceous rocks are characterized by limestones, as in the Villany Mountains and Békés Basin, where shallow-water marine limestones of Early Cretaceous age rest on Upper Jurassic strata. Over parts of the Tisza block, the Lower Cretaceous is commonly represented by an open-marine pelite facies; however, no Lower Cretaceous rocks occur in the Mecsek Mountains and in some other areas. As noted by Kókai and Pogácsás (1991), the middle part of the Cretaceous Period is characterized by erosion, nondeposition, and karst and bauxite formation on both the Pelso and Tisza blocks.

The Upper Cretaceous appears as varied lithotypes on both Pelso and Tisza blocks and includes sandstones, breccias, and argillites. On the Pelso block, shallow-marine units such as the Jákó Marl, Ugod Limestone, and Polány Marl unconformably overlie Halimba Breccia and older Jurassic and Triassic rocks. On the Tisza block, sandstones of the Debrecen or equivalent argillites and marls rest unconformably on older rocks. At the same time, deep-marine silty marls and bathyal clays and turbidite sandstones of the Carpathian and Magura Flysches of the Carpathian foredeep were deposited anterior to the ancestral Carpathian arc. An inner proximal flysch, including the Podhale Flysch, lapped onto the Pannonian fragment and into the Szolnok trough and, at the south margin of the Tisza block, flysch was deposited (fig. 7).

Cenozoic Basin-Fill Sediments

Within the area of the Pannonian Basin, Cenozoic sediments, following a major hiatus, overlie deformed pre-Tertiary basement. From late Eocene through early Miocene time, a wrench-basin complex (Royden and Báldi, 1988; Nagymarosy, 1990; Nagymarosy and Báldi-Beke, 1993) or, alternatively, a retroarc foredeep basin complex developed (Tari and others, 1993). It included the Hungarian Paleogene Basin, where epicontinental, largely marine sediments accumulated, while flysch sediments accumulated in marginal areas and troughs (fig. 7). Sedimentation was controlled largely by tectonic and eustatic processes (Sztanó and Tari, 1993; Kókai and Pogácsás, 1991).

As the Pannonian crustal fragment subsequently overrode the European plate, the elevated Pannonian lithosphere underwent active back-arc extension and attenuation, producing a compound system of Neogene rift basins characterized by initial synrift sedimentation overlain by a generally thick blanket of relatively undeformed postrift sediments (Horváth and Royden, 1981; Royden and Horváth, 1988). Neogene sedimentation was dominated by both tectonic and eustatic processes, and depositional sequences commonly were bound by unconformities (Kókai and Pogácsás, 1991; Sztanó and Tari, 1993; Csató, 1993). Synrift sediments, although dominantly terrigenous, included marls, algal limestones, evaporites, nonmarine clastics, and coals. Tuffs and pyroclastics are also common, and extensive blankets of rhyolite tuff were deposited in the middle Miocene, mainly in the northern half of the Pannonian Basin (Póka, 1988). Synrift sedimentation ended with a regional unconformity over much of the Pannonian Basin system, often of pronounced angularity, except in deep interior subbasins where continuous sedimentation appears to have occurred. Postrift sedimentation was rapid and dominated by relaxation, thermal subsidence, and differential downwarping. The rift basins were covered by a widespread blanket of relatively undeformed sediments that expanded to encompass the present Pannonian Basin and overlap most high blocks by the late Pliocene (Grow and others, 1994). The postrift stage records the final isolation of the Pannonian Basin from the Tethys Sea with evolution of a large lacustrine body and its reduction by fluvial-dominated delta progradation (Royden and Horváth, 1988; Kázmér, 1990; Müller and others, 1999). The postrift sequence is marked by a suite of largely nonmarine, lacustrine, deltaic, and fluvial clastic facies.

As noted by Royden (1988), “the older sedimentary rocks within each basin were deposited mainly during active faulting and generally lie within well defined fault-bounded troughs that form the deepest part of each basin and are overlain, often unconformably, by younger, flat lying, posttectonic deposits” and, as characterized by Pogácsás, Mattick, Tari, and Várnai (1994), “the style of sedimentation within individual basins is influenced by proximity of the basin to active thrusts of the bounding Outer Carpathians and Dinarides. Basins located close contain a thick, synextensional faulted sedimentary rock section overlain by a thin post tectonic section. Basins located in a more internal position in the Pannonian Basin are characterized by the dominance of a post extension unfaulted flat-lying sedimentary sequence.”

Paleogene and Early Neogene

During the Paleogene and early Neogene, a predominantly structurally controlled depositional pattern persisted (fig. 7). Initially, the Pannonian crustal blocks (Pelso and Tisza) were high-standing, and sedimentation was restricted to the adjoining Carpathian foredeep where flysch sediments consisting of deep-marine silty and marly clay and turbiditic sandstones were deposited, as represented by highly deformed Carpathian and Magura Flysches of the Outer Carpathian foldbelt. Deposition continued there, and, during the Eocene and Oligocene, a flysch belt also developed interior to the arc, producing the Podhale, Szolnok, and Transcarpathian Flysches, which lapped onto the margins of the Pannonian crustal blocks and into the Szolnok trough and became involved in subsequent Neogene compressive deformation. As a consequence, moderately folded and thrust Podhale Flysch rests on highly deformed Mesozoic rocks along the present northern margin of the Pannonian block, as do equivalent Szolnok and Transcarpathian Flysches elsewhere (fig. 7).

Within the interior of the Pelso block, rocks of Eocene and Oligocene age were deposited in an epicontinental basin setting (fig. 7) (Royden and Báldi, 1988; Nagymarosy, 1990; Nagymarosy and Báldi-Beke, 1993; Tari and others, 1993). The large Hungarian Paleogene Basin accumulated both marine and nonmarine sediments. Within it, middle Eocene rocks are represented by the Szöc Limestone and lagoonal sequences containing paralic coal seams—these sequences are followed by mostly marine rocks in the upper Eocene, including bathyal marls and neritic sandstones. Structural inversion of the Hungarian Paleogene Basin in late Eocene time produced a trough immediately east of the uplifted earlier basin, and an upper Eocene–lower Oligocene sequence—represented mainly by marls, laminated clays, and silty clays of the Buda Marl, Tard Clay, and Kiscell Clay—is followed by bathyal silty, marly clay and silty sandstone of the Szécsény Formations in axial areas and the Eger Sandstone and equivalents in marginal areas. During the following Egerian time (late Oligocene to early Miocene), bathyal siltstones and shales of the upper Szécsény Formation were deposited in deep parts of the basin, and sublitoral marine, clayey and sandy silt, and brackish littoral sand, silt, gravel, and conglomerate and minor coals were deposited in marginal areas. This continued into late Eggenburgian (early Miocene) time and terminated with a regional unconformity, except in deep basinal areas where sedimentation appears to be virtually continuous. In the Slovenian Paleogene Basin, upper Eocene limestones were succeeded by euxinic silty clay of the Oligocene Sotzka beds and local paralic coal seams; Nagymarosy (1990) further suggests that the Slovenian Basin represents a part of the Hungarian Paleogene Basin that was left behind during rifting along a Balaton and Mid-Hungarian transform.

Middle to Late Neogene

The back-arc extensional basin system, which was established in the Miocene on deformed older rocks in the Central Paratethys region, was characterized by a thick, marine, brackish, lacustrine, continental, and fluvial clastic fill (figs. 2 and 3). The surrounding Carpathian Mountains were mildly uplifted during most of the period, although marine connections were intermittently maintained with adjoining Mediterranean and Caspian seaways. Initial sedimentation consisted of an early–middle Miocene synrift-stage deposition that reflected a dominant role of extension, strike-slip deformation, and rifting during sedimentation. During this stage, the principal basins of the Pannonian system took shape and accumulated locally thick sequences, separated by horsts and upwarps of basement blocks. This was followed in middle to late Miocene time by a postrift stage dominated by thermal subsidence, differential downwarping, and rapid accumulation of a widespread, often thick, blanket of relatively undeformed sediments, which buried most high blocks by late Neogene (Royden and Horváth, 1988; Grow and others, 1994).

Synrift Sediments

Synrift sediments were deposited in a framework of multiple, active, pull-apart basins, grabens and half-grabens, and shear basins (fig. 5). Deposition was initially limited to marginal subbasins of the Pannonian system, and became more widespread through time, resulting in proportionally large thicknesses of synrift rocks in marginal areas, such as in the Transcarpathian Basin. In much of the interior Pannonian Basin area, such rocks are thin or absent. Nearshore and shallow-marine conditions surrounded scattered islands and uplifted blocks; island areas were gradually covered by successive transgressive sequences controlled largely by tectonic and eustatic processes (Bérczi and others, 1988; Kókai and Pogácsás, 1991; Csató, 1993). Conglomerates were commonly deposited on margins of subbasins, whereas interior parts were characterized by finer sediments, including sandstones and silty marls and, in clear-water reef environments, lithothamnion-bearing limestones. In general, marginal subbasins contain coarser grained facies than those of the interior. Thicknesses of synrift rocks range from a few meters to more than 3,000 m. Sequences are characterized by lateral discontinuities, faulting and rotation, truncation and rapid thickness changes, and by bounding unconformities. The synrift phase is generally terminated by a regional unconformity in Sarmatian time (middle Miocene), except in deep basinal areas where deposition appears to have been continuous.

Synrift sedimentation was initiated with a rapid transgression in Eggenburgian time (early Miocene) with a massive influx of terrigenous sediments derived from faulted and uplifted blocks into marginal subbasins of the Pannonian system. In subbasins of the southwest, coarse-grained fluvial sediments and variegated shales are overlain by transitional and shallow-marine conglomerates, sandstones, marls, and limestones. In northern Hungary, transgression produced nearshore facies of conglomerate, limestone, and sandstone; shallow-marine deposits of glauconitic sandstones; clays and siltstones in basinal areas; and lignites in lagoonal areas.

In Ottnangian time (early Miocene), a widespread volcaniclastic sequence was deposited in the west and south, largely rhyolite tuff and ignimbrites, accompanied by andesite intrusions. In the southernmost Pannonian Basin system, shallow-marine breccias and conglomerates, marls, and sands were deposited on volcanics (including andesites, dacites, and pyroclastics), especially bordering the Dinarides. Locally, coarse-grained clastic sediments with intermittent lignite seams are found. In northern Hungary, pebbly variegated terrigenous rocks are overlain by a sandstone and shale sequence containing limnic and paralic lignite seams. The paleogeographic pattern of both the late Eggenburgian and Ottnangian is dominated by a rough northeast-trending structural grain modified by northwest structures and contains many areas of nondeposition, particularly in interior parts of the Pannonian Basin system.

During succeeding Karpatian time (early Miocene), marine conditions transgressed further into the depressions of the Pannonian Basin system. These rocks overlie a well-defined unconformity at the Ottnangian-Karpatian boundary in most areas, particularly at basin margins. The oldest beds are commonly of brackish water origin, overlain by nearshore-marine facies and by an open-marine facies in a narrow northeast-striking axial depression of the system. In littoral environments, sandstone and conglomerate were deposited, as in the Transdanubia area where the basal Karpatian is a coarse-grained sequence with intercalations of shale and siltstone and variegated, brackish, lignitic, and lagoonal sediments. In much of the Great Hungarian Plain, coarse clastics rest directly upon a folded basement of Mesozoic and Paleozoic rocks. In neritic zones, clay and siltstone are found. Lagoonal rocks dominated by the close of Karpatian time. In late Karpatian time, volcaniclastics were widely deposited, and andesites, dacites, and rhyolites erupted.

Badenian (middle Miocene) rocks represent a widespread transgression in which open-marine and nearshore rocks surrounded many small, emergent basement blocks. Basal deposits are conglomerates along the margins of the basin system but are usually sandstones in the central Pannonian area. Sedimentation was affected by differential subsidence, resulting in considerable local variation in facies. Marls and clays were deposited in open-marine areas, including hemipelagic sequences, while limestones of littoral and shallow-water origin were deposited in shelf-margin reef complexes and shallow, offshore banks. Brackish-water lagoonal sediments, including lignites, also accumulated along basin margins. Tuffs and andesite and rhyolite intrusives are locally intercalated in the sequence, particularly in upper parts, and are especially prominent in the northeastern Pannonian Basin.

This block-faulted tectonic framework and depositional setting persisted into late Badenian and early Sarmatian (middle Miocene) time, accompanied by uplift of the Carpathian Mountains. An increase in subsidence produced a late Badenian marine transgression, causing these beds to rest unconformably on lower Badenian beds in marginal subbasins of the system. Sedimentation was widespread and typically marked by an argillaceous marl sequence containing upwardly increasing reef intercalations. Shales and marls occupied basinal settings, and limestone facies of littoral and shallow-water origin were deposited along local shelf margins in reef complexes and in offshore banks. Andesite, rhyodacite, and rhyolite tuffs are locally intercalated in the late Badenian sequence, and andesites and rhyolites are locally intruded. The late Sarmatian is marked by regression, a predominance of littoral facies, and the appearance of lagoonal and halite- and gypsum-bearing deposits, which are particularly well developed in the Transcarpathian Basin (refer to fig. 1). Brackish water limestones that grade into silty and shaly rocks and marls also appear during this time.

Postrift Sediments

The postrift depositional cycle records the isolation of the Pannonian Basin from the Tethys Sea and the evolution of a large lake that was subsequently filled by sediment brought in largely from the north and west, as summarized by Royden and Horváth (1988) and Müller and others (1999). The sequence represents a major sediment influx, and most of the fill of the Pannonian Basin system belongs to this postrift stage, especially in the interior subbasins. Differential subsidence was pronounced, and thicknesses that reach 6–7 km occur in some of the deepest troughs, as in the Békés Basin. Sediments are largely undeformed and unfaulted except for compaction features over basement highs and deformation associated with late strike-slip faults. They generally rest with regional unconformity on synrift rocks or on pre-Tertiary basement, as in much of the central Pannonian system, but locally appear to rest conformably on synrift sediments in several basinal areas. By the late Neogene, sediments had buried most high blocks and expanded to encompass the present Pannonian Basin.

Postrift sedimentation began in late Sarmatian (latest middle Miocene) and early Pannonian time (late Miocene) and continued into the Quaternary. The Pannonian sequence exhibits considerable variation in thickness due to differential subsidence. In individual subbasins in central parts of the system, it is represented by a thick sequence overlain by a relatively thin Pleistocene blanket. According to Mattick and others (1985), the infilling, as reflected in the Békés Basin, resulted from a single cycle of sedimentation starting with water depths locally greater than 1,000 m, followed by gradual shallowing. During this time, deposition changed from marine conditions to lake, fluvial, and marsh conditions. As noted by Bérczi (1988), this was the final marine withdrawal in the central Paratethys region, during which marine faunal assemblages gave way to brackish and freshwater faunas. The lithic sequence is made up primarily of a varied mix of fine- and coarse-grained clastic rocks and subordinate, locally important, coals.

The base of the Pannonian sequence is commonly marked by transgressive sandstones and conglomerates, particularly around margins of the system and uplifted blocks. This is succeeded by generally marly sediments deposited in deep brackish-water basins, followed by a mixed clastic sequence of sand, silt, clay, and marl, including occasional turbidites in basin axial areas. The upper Pannonian sequence shows a more variable composition, especially in uppermost parts where paludal, fluvial, and lacustrine interbeds become increasingly common. Succeeding Quaternary sediments are characterized by highly variable paludal, fluvial, and delta-plain deposits.

Petroleum Geology

Reservoir Rocks

Reservoir rocks of the Pannonian Basin province are varied in age and lithology. According to Dank (1987), Neogene reservoir units account for 61 percent of discovered petroleum resources in Hungary; Mesozoic and Paleozoic units account for 33 percent; and Paleogene rocks account for 7 percent. More recent data from Kókai (1994) indicate that 62 percent of oil production is from Tertiary sedimentary rocks, and 24 percent of oil production is from Mesozoic carbonates; 70 percent of natural gas production is from Tertiary reservoirs. Production is often from multiple zones, particularly in large anticlinal closures.

Fractured and weathered crystalline Paleozoic and Precambrian basement rocks are the oldest reservoirs in the province and include a variety of igneous and metamorphic types. They often produce along with overlying Cenozoic sedimentary rocks and, in some instances, as combined reservoirs, particularly on the Great Hungarian Plain. The Algyö field (fig. 8), which is the largest oil and gas field in Hungary, produces from fractured Paleozoic metamorphics, a basal Pannonian conglomerate, and overlying Miocene sandstones. In the Battonya field, production is from weathered and fractured Paleozoic granites and quartz porphyries and Miocene conglomerates and marls. In the Sarkadkeresztúr field, production is from fractured and fissured mica schist and Miocene conglomerate. In the large Pusztaföldvár field, production is from mica schist as well as Pannonian sandstones (refer to fig. 8 for field locations). Fractured Devonian carbonate schist reservoirs are productive in the northwest Dráva trough.

Crystalline basement reservoirs constitute about 5 percent of reservoirs in the Pannonian Basin system, and, in them, porosities range from 1 to about 20 percent and commonly average less than 11 percent. Fractured Devonian carbonate schist reservoirs in the Dráva Basin exhibit average porosities around 2 percent, with fractured Lower Triassic quartzites and meta-arenites ranging from 0–5 percent (Baric and others, 1991).

Mesozoic sedimentary rocks are important reservoirs in the Zala and Dráva subbasins. At Nagylengyel field, they include Cretaceous rudistid limestone (Ugod Limestone) and Upper Triassic Haupdolomit and, elsewhere, include marls and lightly metamorphosed limestones. In the Serbian part of the Dráva Basin, Lower Jurassic and Middle Triassic dolomites and coarse clastic reservoirs are productive, with reported porosities of 12 percent, 8 percent, and 3 percent, respectively (Baric and others, 1991). Triassic limestones are also productive in the Hungarian Paleogene Basin. Reported average porosities of Mesozoic reservoirs in the Pannonian Basin system range from 2 to 25 percent and average about 14 percent. Fracture enhancement of these reservoirs is everywhere important.

Eocene and Oligocene sandstones, tuffaceous sandstones, limestones, and marls—particularly the Eocene Szöc Limestone and the Oligocene sandstones associated with the Kiscell Clay—constitute primary reservoirs in the Hungarian Paleogene Basin (Kókai, 1994). Conglomerates, sandstones and siltstones, along with marls, shales, and limestones are reservoirs in the Szolnok Flysch and in the Podhale Flysch and equivalents of the Central Carpathian area, where they include coarse-grained arenaceous reservoirs, which average 8 to 10 percent porosity (Nemcok and others, 1996). Others are of low matrix porosity, and fracture enhancement is important for reservoir development.

Neogene rocks are the principal reservoirs of the Pannonian Basin Province and account for more than 80 percent of all reservoirs reported. Of these, sandstones make up about 95 percent, and, of these, about 90 percent are Miocene in age; the balance are Pliocene. Badenian, Sarmatian, and lower Pannonian reservoir units are the most productive and include shallow-water sandstones and conglomerates of fluvial, marine, and lacustrine origin, as well as turbidites, marls, algal limestones, and freshwater limestones. The Pliocene produces relatively small amounts of oil and gas, including scattered gas accumulations of biogenic origin. Quaternary rocks also produce small quantities of gas in a few areas. Algal limestone reservoirs are largely limited to the synrift sediments, particularly in Badenian sequences. A few Neogene volcanoclastic reservoirs are reported. According to Kókai and Pogácsás (1991), the eastern and southwestern Hungarian subbasins contain the following Neogene reservoir types: basinal and prodelta turbidites (40 percent), delta-slope turbidites (30 percent), mouth bars (15 percent), channel fills (8 percent), barrier bars (3 percent), and point bars (2 percent).

Data from Petroconsultants (1996) indicate that average porosities for Neogene synrift sandstone reservoirs range from 5 percent to more than 30 percent, and cluster around 16 percent. Average porosities for postrift reservoirs are somewhat higher, ranging from 8 percent to 40 percent, and average around 22 percent.

Source Rocks and Maturity

The oldest known source rocks in the region are Triassic organic-rich shales and marlstones, namely the Rhaetian Kössen Marl and Carnian Veszprém Marl of the basement complex (Kókai and Pogácsás, 1991). They are locally present on the Pelso block and provide potential source rocks where not thermally overmatured prior to Cenozoic burial. According to Pogácsás and others (1996), total organic carbon (TOC) of the Veszprém ranges from 3 to 5 percent, whereas that of the Kössen ranges from 3 to 20 percent; both source rocks contain type-I and type-II kerogen. Kössen Marl has yielded most of the oil in the Zala Basin according to Clayton and Koncz (1994b). There, at least five fields contain oils of Triassic origin, including the giant Nagylengyel field. In this area,

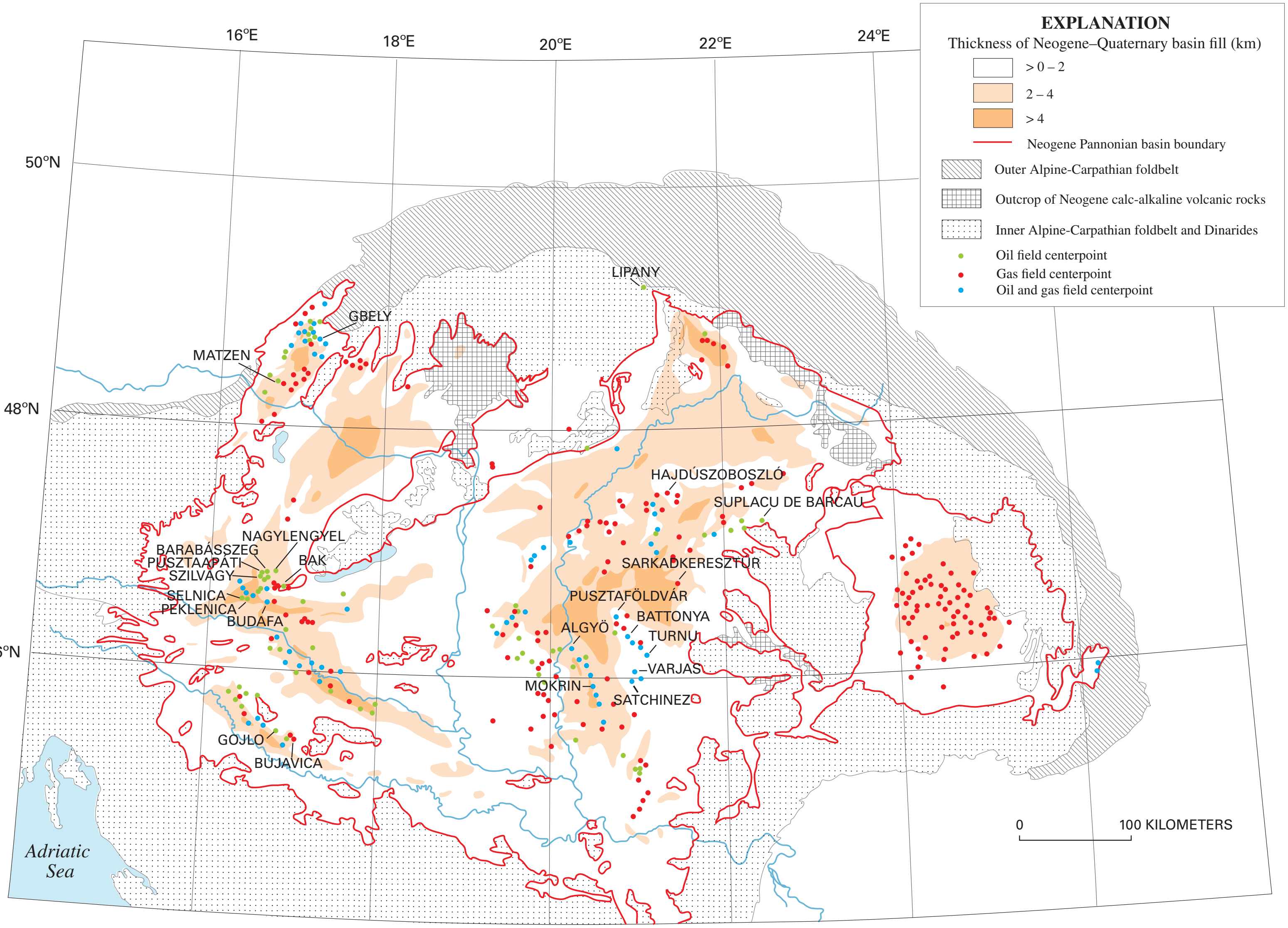

Figure 8. Map showing oil and gas fields of the Pannonian Basin Province (4048) and associated Vienna and Transylvanian Basins. Fields mentioned in text are named.

generation and expulsion began in the Miocene, according to Clayton and Koncz (1994b).

Equivalent rocks may be present in several other parts of the Pelso block; however, their distribution is poorly known. Milička and others (1996) call on an early stage of generation prior to the Tertiary for Mesozoic rocks in the northern Danube Basin, although Mattick and others (1996) suggest that, in the Hungarian part of this basin, upper Paleozoic or Mesozoic rocks probably were not subjected to significant thermal maturation until Miocene time. As with the Cenozoic, the top of the oil-generation zone is generally in the 2,200- to 2,500-m depth interval; the bottom of the wet-gas generating zone is around 4,000 m, and that for dry gas is placed at 5,000 m (Kókai, 1994).

Upper Jurassic marl of the overridden European plate provided most of the oil in the Vienna Basin. According to Ladwein (1988) and Seifert (1996), this source has a high content of type-II and type-III kerogen, locally exceeds 1,500 m in thickness, and matured during Miocene loading. The result was oil migration upward through fault systems of the flysch belt into nappes of the inner foldbelt and the overlying Tertiary. Where sufficiently buried elsewhere along the margin of the Inner Carpathian foldbelt, equivalent rocks, if present, may provide sources for oil and gas to nappes of the Inner Carpathian foldbelt.

Jurassic rocks elsewhere also have source-rock potential. In the central part of the Pannonian Basin, fine-grained pelagic sediments of Early and Middle Jurassic age have been identified as source rocks of fair to good potential (Milota, 1991; Kókai, 1994; Kókai and Pogácsás, 1991; Pogácsás and others, 1996). The most prospective of the Jurassic sources is reported as having an average total organic content (TOC) of 8 percent (Pogácsás and others, 1996). Kókai and Pogácsás (1991) and Pogácsás and others (1996) indicate that Lower Jurassic coaly formations provide possible sources within the Tisza block and are viewed primarily as potential sources for gas.

Within the Hungarian part of the Pannonian Basin, Kókai (1994) indicates that 7 percent of the Upper Cretaceous volume of sedimentary rocks could be source rocks. Pogácsás and others (1996) specifically identify the Jáko and Polány Marls of the Pelso block as potential source rocks of Cretaceous age, though of relatively low TOC and containing gas-prone kerogen.

Upper Cretaceous and Paleogene shales, marls, and marly clays of the Carpathian Flysch and equivalents in the Outer Carpathian Flysch belt are potential source rocks at the northern margin of the Pannonian province. Oil and source-rock correlations and biomarkers indicate the Oligocene flysch series to be an important source rock in the Outer Carpathian foldbelt (Ziegler and Roure, 1996), and Francu and others (1996) suggest that they may have generated or co-sourced some of the Vienna Basin oils. Where sufficiently underthrust elsewhere beneath the Inner Carpathian nappes, these rocks may provide hydrocarbons, although other than in the Vienna Basin and in the Central Carpathian Paleogene Basin, effective seals for the overlying nappes appear largely lacking.

Important Paleogene source rocks of the Hungarian Paleogene Basin include the upper Eocene–lower Oligocene euxinic Tard Clay and lower Oligocene Kiscell Clay (Kókai and Pogácsás, 1991). These rocks have good source potential for oil and gas, as probably do equivalent beds in the Slovenian Paleogene Basin. In northern Hungary, the Tard and Kiscell Clays have an average TOC content of 0.5–1.0 percent, with local concentrations of 0.8–1.8 percent to as much as 4.5 percent (Kókai, 1994; Milota and others, 1995). Their kerogen is mostly type I and type II, but type-III kerogen is present in the upper part of the sequence and in the oil-generating zone at depth. According to Milota and others (1995), much of the Oligocene sequence in the southern part of the Hungarian Paleogene Basin lies in the zone of hydrocarbon generation, with the maturation level of the principal source intervals equivalent to the wet-gas zone in the south and to the main oil-generation zone in the north. Maturation is hypothesized to have occurred during maximum heat flow in the late Miocene or Pliocene (6–2 Ma), and, according to Ziegler and Roure (1996), the Oligocene Series in the Pannonian Basin accounts for significant hydrocarbon reserves. In the Central Carpathian Paleogene Basin, Nemcok and others (1996) report two organic-rich intervals of Eocene age, the first containing between 0.1 to 1.5 percent total organic content (TOC) and the latter containing between 1.1 and 10.3 percent. They contain mostly type-III kerogen, along with some type-II kerogen. Maturity within the area varies considerably due to local variation in structural and burial histories, but locally, these rocks are documented to be in the oil and wet-gas generative windows. In the more distant Szolnok trough (fig. 7), Kókai and Pogáscás (1991) indicate that the Cretaceous–Paleogene Szolnok Flysch and Debrecen Formation may have source potential.

Neogene rocks of Miocene age are considered to be the principal source for oil and gas in most of the province. They are generally middle to upper Miocene shale, clay-marl, and marl. Szalay and Koncz (1991) indicate that potential source-rock thickness in the Hungarian part of the Pannonian Neogene Basin system ranges from less than 1 m to 4 km, but the rocks are generally of low quality. These rocks contain mostly type-II and type-III kerogen. However, middle Miocene shale and marl locally contain the richest source rocks (TOC as high as 5.0 weight percent), and upper Miocene rocks, in particular lower Pannonian lutites, locally contain good source beds, as the Tótkomlós Formation of the Békés Basin (as much as 2 weight percent TOC, of mostly type-III kerogen). The Tótkomlós is the probable source of the oil in fractured Paleozoic metamorphic basement rocks and the basal Pannonian conglomerates in the Békés Basin (Clayton, Koncz, and others, 1994; Clayton, Spencer, and Koncz, 1994). Source-rock evaluation and correlation of extracts with oils indicate three separate genetic oil types for the Neogene of the Békés Basin, originating from different beds within the sequence (Clayton, Koncz, and others, 1994).

In the Zala Basin, according to Clayton and Koncz (1994b), one of the oil types is probably from Miocene source rocks, although its variable composition suggests more than one unit. In the nearby Dráva and Sava depressions, Baric and others (1998, 2000) indicate that, based on geochemical studies, the oils originate from Miocene source rocks. In the Hungarian part of the gas-prone Danube Basin, Mattick and others (1996) document the Neogene as a poor, largely gas-prone, source rock; Milićka and others (1996) indicate Neogene sources for the Slovakian part of the basin, particularly lower Pannonian, Sarmatian, middle Badenian, and lower Miocene rocks, which contain largely type-III kerogen.

The average geothermal gradient in the Pannonian system is about 3.6°C/100 m, and in places exceeds 5.8°C/100 m. Because of the high geothermal gradients, organic-rich rocks provide sources for oil and gas at relatively shallow depths. Although heat flow and depth of the oil window are variable regionally (as noted by Horváth and others, 1988; Dövényi and Horváth, 1988; and evident in isotherm maps published by Kókai, 1994), investigators generally suggest onset of thermal generation in much of the system at about 2,000 m for immature oils and at about 2,500 m for mature oils (Dövényi and Horváth, 1988; Clayton, Koncz, King, and Tatár, 1994; Clayton, Spencer, and Koncz, 1994). Rocks below about 5,000 m are typically in the gas-generative realm. (Areas of inferred mature Neogene source rocks are shown in fig. 13.)

Oil generation in Neogene sediments started about 8–5 Ma and has progressed so that sediments below a depth of 4–5 km have passed through the oil-generation window (Horváth and others, 1988; Szalay, 1988; Clayton, Koncz, and others, 1994; Horváth and others 1996). The upper 2 to 3 km of the Neogene sedimentary rocks are immature throughout the basin system, and, as a result, upper Pannonian organic-rich beds are insufficiently buried to have generated thermal hydrocarbons. However, in several areas, young sediments contain dry hydrocarbon gases consisting of isotopically light, biogenic or diagenetic methane derived from humic sources, including lignite and brown coal layers (Clayton and others, 1990; Koncz and Etler, 1991; Clayton and Koncz, 1994a).

Oil and gas reservoirs are often situated in thermally immature rocks above basement highs or are laterally removed from areas of generation, indicative of pervasive vertical and lateral migration. Oil fields are commonly located on the perimeters of gas-generative areas, suggesting that gas may have displaced oil from areas more proximal to generation. Local chemical and isotopic analyses of gases and characteristics of oils, indicate that significant vertical and lateral migration has occurred, particularly for gas (Clayton and Koncz, 1994a; Clayton, Koncz, and others, 1994). Concurrently, the lower Miocene sequence commonly appears to be overpressured (Szalay, 1988; Spencer and others, 1994; Baric and others, 1991).

Throughout the Pannonian Basin system, gas reservoirs commonly contain substantial quantities of CO_2 as a result of high geothermal gradients and carbonate decomposition in deeply buried basement rocks (Clayton and Koncz, 1994a). Values of CO_2 content range from 0.5 to 99.5 percent (Kertai, 1968) and average 28 percent (Kókai, 1994). In the Danube Basin, in particular, the CO_2 content is so high as to make most of the gas unusable.

Traps and Seals

Producing traps in the Pannonian Basin Province (4048) range in depth from 80 m to about 5,000 m, with most oil occurring between 800 and 3,000 m and most gas occurring somewhat deeper (figs. 9 and 10). A wide variety of structural, stratigraphic, and combination trap types are present. Within the Cenozoic basin fill, productive structural traps are common, particularly compactional anticlines over basement highs, fault-closed features, roll-overs associated with growth faults, and closures in flower structures along strike-slip faults (Kókai, 1994). Inversion structures are noted in some areas as a result of shear and compression, such as at Budafa anticline in the Zala Basin. In most structurally controlled accumulations, stratigraphy plays a secondary role; however, many stratigraphic traps occur in the Tertiary rocks, including pinch-outs in fluvial, shallow-water, and turbidite sandstones and conglomerates, and in patch reefs and at truncations—particularly at the unconformity between synrift and postrift rocks. Seals in the Tertiary fill are provided by associated fine-grained sediments, particularly middle to upper Miocene shale, clay-marl, and marl.

Traps involving the basement complex include paleotopographic highs, folds and faults in the nappes, and truncations at the Tertiary unconformity. They involve strongly folded and faulted Mesozoic sedimentary rocks as well as crystalline rocks. Seals are provided by associated fine-grained rocks and by overlying Tertiary sediments, such as mudstones and marls of Sarmation and early Pannonian age, which are often overpressured.

Exploration Status

The Pannonian region has a long history of petroleum exploration. Virtually all initial exploration was focused on the Neogene of the Pannonian Basin, and the principal producing subbasins are those of the Great Hungarian Plain (primarily the Jaszsag, Derecske, Nagykunság, and Békés Basins and Makó trough) and subbasins of southwestern Hungary and adjoining Croatia and Slovenia (comprising the Zala Basin and the Dráva and Sava troughs or depressions) (see fig. 1). Petroleum discovered through 1995 totals approximately 2.1 billion barrels of oil and 11.2 trillion cubic feet of gas, mostly in Hungary, followed by Croatia, Romania, and Serbia and Montenegro (Petroconsultants, 1996). In Hungary alone, Kókai (1994) reports 668 million barrels of recoverable oil (MMBO) and 8.5 trillion cubic feet (TCF) of recoverable gas as having been discovered, and, as of January 1, 1995, annual Hungarian petroleum production was 11.6 MMBO and 187 BCF of natural gas, with reserves estimated at 132.7 MMBO and 3.0 TCFG (Hungarian Geological Survey, 1996).

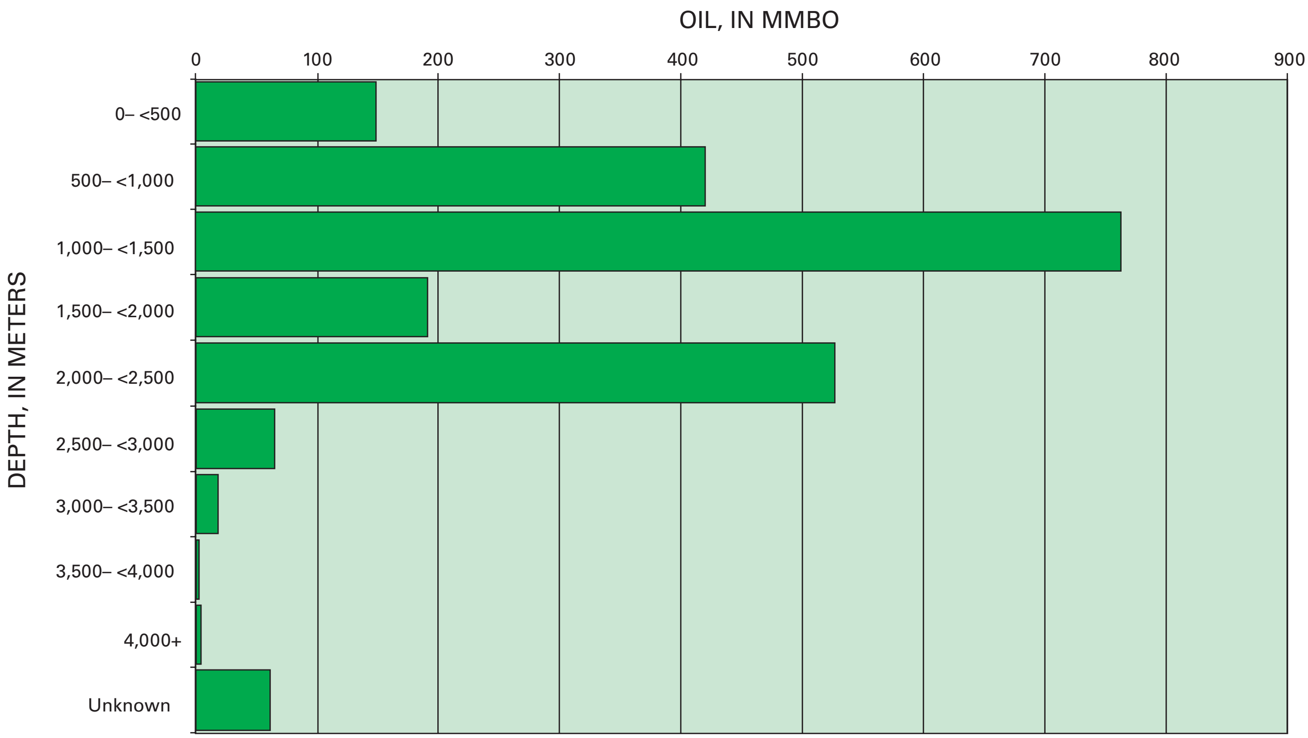

Figure 9. Discovered oil by depth interval. Data from Petroconsultants (1996).

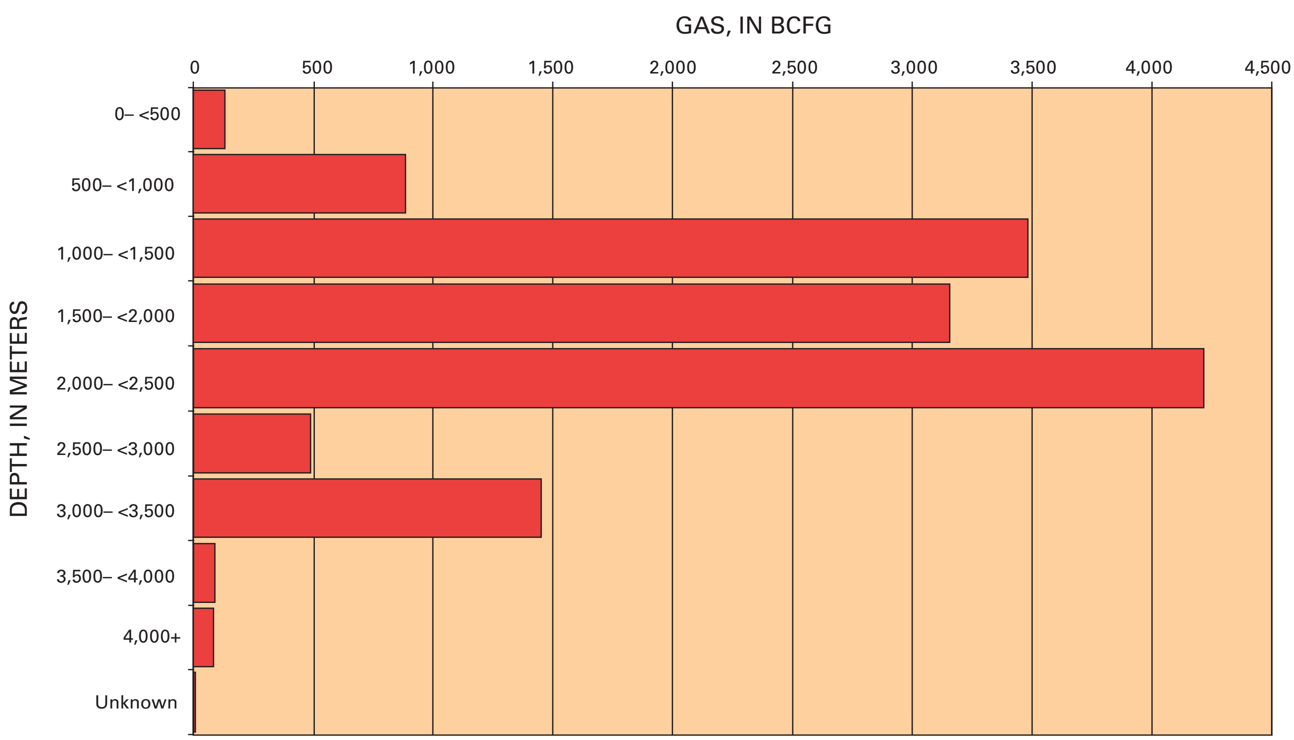

Figure 10. Discovered gas by depth interval. Data from Petroconsultants (1996).

About 500 fields have been discovered (fig. 8). The size distribution of fields estimated to be greater than 1 MMBO or 6 BCFG, based on Petroconsultants' data (1996), is shown in figures 11 and 12. Production is primarily from middle Miocene reservoirs, largely Badenian and Sarmatian synrift rocks, and upper Miocene Pannonian postrift sediments. More than one quarter of the oil discovered in the province is found in three fields: Nagylengyel and Algyö (Hungary) and Suplacu de Barcau (Romania). Approximately one-third of the gas is in two fields: Algyö and Hajdúszoboszló (both in Hungary).

Although oil was produced from hand-dug wells as early as 1856 in Croatia (Filjak and others, 1969), the first commercially significant field in the country was discovered in 1917 in the Sava trough at Bujavica gas field; this was followed by the Gojlo oil and gas field in 1930.

The initial discovery of commercial oil in Hungary was made at Budafa field in the Zala Basin in 1937 in lower Pannonian sandstones in an anticline identified by surface mapping and further delineated by gravity and seismic surveys. In this area, the giant Nagylengyel field, one of the largest fields of the basin, was found in 1951, and has since produced more than 128 million barrels from a Miocene (Karpatian) sandstone, Upper Cretaceous rudistid limestones, and Triassic dolomites (Kokai, 1994; Clayton and Koncz, 1994b). In the Dráva depression, oil was first discovered in 1942, in Slovenia. Today, the largest gas and gas-condensate accumulations in the southwestern Pannonian Basin system occur in the Sava and Dráva troughs, principally in Miocene reservoirs and in fracture-enhanced Mesozoic basement reservoirs (Filjak and others 1969; Baric and others, 1991).

Systematic exploration for oil and natural gas in the northern part of the greater Pannonian region began in 1909, spurred by use of the Eotvos torsion balance, and, in 1913, resulted in discovery of oil at the Egbell field (Gbely) in the nearby Vienna Basin (within the Austro-Hungarian Empire, now Slovakia). Although not included in this assessment, the Vienna Basin represents the northernmost element of the overall Pannonian Basin system and provides useful perspective. Following discovery of oil at Gbely, oil was found in a number of small fields within the present Czech, Slovak, and Austrian sectors of the Vienna Basin and, in 1949, the Matzen oil field complex, the largest oil field in central Europe, was discovered. This field contained an estimated recovery of 564 MMBO from multiple Miocene sandstone reservoirs and fractured Triassic carbonates of the underlying nappe system (Rieder, 1996). In the Vienna Basin, Sarmatian and Badenian sandstones are the principal reservoirs, and most traps are related to faulted anticlinal structures.

In 1915, exploration began in the Great Hungarian Plain and Transdanubian areas in Hungary, and initially yielded discouraging drilling results. The first seismic survey was done there in 1937, and this was followed after World War II by intensive reflection and refraction seismic geophysical efforts. These efforts resulted in discovery of a major gas field (approximately 434 BCFG) at Pusztaföldvár in the Békés Basin in 1958 (Kovács and Teleki, 1994), which produced mostly from lower Pannonian sandstones and conglomerates on a large anticlinal feature over a basement high. Numerous other fields associated with basement highs on the peripheries of the subbasins have since been discovered. Among these is the Algyö field, the largest oil and gas field in Hungary (more than 200 MMBO and 3,000 BCFG), discovered in 1965, which produces from fractured Precambrian crystalline basement and upper Pannonian sandstones on a structural high between the Békés Basin and Makó trough. Throughout Hungary, anticlinal features (particularly compactional anticlines over basement uplifts), paleogeographic highs, horst blocks, growth faults, and rollover structures play significant roles in trapping. Most large fields are associated with structural highs or with combination structural-stratigraphic traps around margins of the deeper subbasins. Most of these structural-stratigraphic traps are situated in the area of the Great Hungarian Plain, where today they account for major reserves of both oil and gas. According to Kókai (1994), more than 5,200 exploratory wells were drilled between 1935 and 1990 in the Hungarian part of the Pannonian Basin system. Drilling there reached a peak in 1943, followed by a brief decline, which was succeeded in 1947 by another long period of intense drilling activity that lasted into the late 1980s.

In the Romanian part of the Pannonian Basin system, as elsewhere, anticlinal features, paleotopographic highs, growth faults, and rollover structures play a significant role in trapping. Exploration activity began in 1942, and, according to Ionescu (1994), the first field was discovered in 1963 at Turnu, although Petroconsultants (1996) indicates discovery of Suplacu de Barcau in 1956. More than 70 oil and gas fields have since been identified, mainly in Miocene and Pliocene sandstone reservoirs and weathered metamorphic and igneous basement rocks (Ionescu, 1994). The largest oil field in the Romanian sector is Suplacu de Barcau, with approximately 144 MMBO, followed by Varjas and Satchinez, each with somewhat more than 40 MMBO.

In Serbia and Montenegro of the former Yugoslavia, in the south-central part of the Pannonian Basin, production was first established in 1951. The largest field is the Mokrin oil and gas field, which was discovered in 1961.

Most production in the Pannonian Basin system is concentrated in and around deep subbasins that contain mature source rocks. Many of the gas fields are rich in condensate and commonly contain substantial amounts of carbon dioxide from thermal decomposition of carbonate rocks in the basement (Clayton and others, 1990; Clayton, Koncz, and others, 1994; Clayton and Koncz, 1994a; Mattick and others, 1994).

Because of extensive exploration, most of the obvious structural and paleotopographic features have been tested and the largest oil and gas accumulations probably have been found, especially within the Neogene. However, Neogene turbidite sequences in basinal areas and on flanks of structures, pinch-outs and truncations of fluvial, marine, and lacustrine strandline and deltaic sandstones, and biohermal

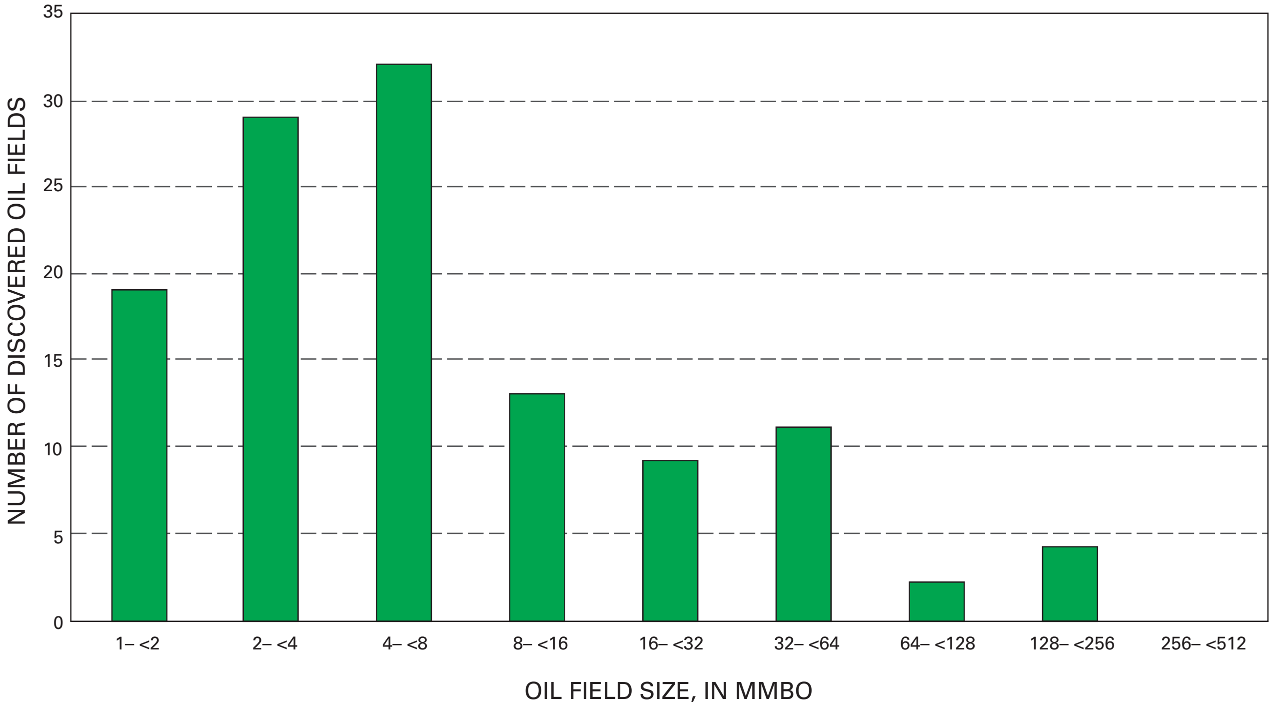

Figure 11. Size distribution of discovered oil fields with reported known sizes greater than 1 MMBO in the Pannonian Basin Province (4048). Data from Petroconsultants (1996).

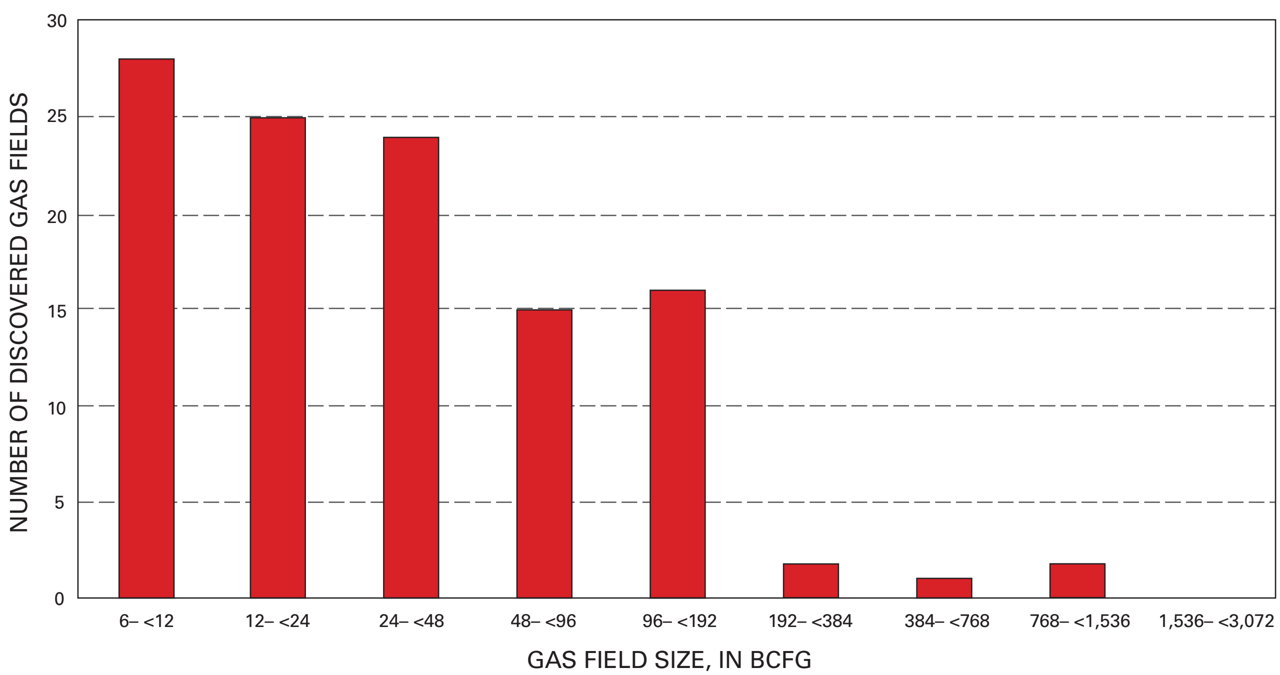

Figure 12. Size distribution of discovered gas fields with reported known sizes greater than 6 BCFG in the Pannonian Basin Province (4048). Data from Petroconsultants (1996).

buildups appear not to be fully explored, particularly in deep basinal areas, and Paleogene rocks are relatively unexplored, especially in the northern part of the Pannonian Basin system. Basement nappe structures involving Mesozoic sedimentary sequences also offer significant exploration targets. With reference to Hungary, Pogácsás, Mattick, Tari, and Várnai (1994) indicate, in particular, that, "...potential traps associated with Neogene strike-slip zones have not been explored adequately and … little is known about the fractured and fissured traces of these zones in the pre-Tertiary basement complex," a condition applicable to much of the basin.

Total Petroleum Systems

As used here, a total petroleum system (TPS) includes all genetically related petroleum in both discovered and undiscovered accumulations that has been generated by a pod or related pods of source rocks. A TPS exists within mappable geologic space together with the essential geologic elements of source, reservoir, trap, and seal that control the fundamental processes of oil and gas generation, expulsion, migration, accumulation, and preservation. A number of TPSs have been defined in the Pannonian Basin system. Virtually all show some indication of being composite and are variously sourced by organic-rich beds ranging in age from Mesozoic to Neogene. They commonly appear not to be well confined and often show evidence of substantial vertical migration and mixing, with different oils or gases in associated reservoirs and with mixed oils within individual reservoirs and, in some cases, the petroleum systems do not appear to be isolated to individual subbasins. On a regional basis, it is difficult to determine the relative contributions of specific source beds to individual reservoir and trap sequences because geochemical data sufficient for correlation of oils and source rocks are available only locally. Subbasins may be individually treated in some cases, as done with the Békés Basin by Clayton, Spencer, and Koncz (1994) and the Dráva and Sava depressions by Baric and others (1998, 2000). However, for this assessment, the petroleum systems are grouped into geographic areas that appear to have common or similar geologic characteristics and histories and within each TPS, the assessment units (AU), as defined, are coincident with their associated TPS. Events charts for the total petroleum systems summarizing the age of the source, seal, and reservoir rocks and the timing of trap development and generation and migration of petroleum are provided in discussions of each TPS.

The following table 1 names the TPSs that were defined for the Pannonian Basin Province. For each, a single AU was defined and is listed here with that TPS. The boundaries of each TPS and its associated AU are coincident (fig. 13). The ages of the TPS allow some grouping and generalization in the following discussion.

Neogene Total Petroleum Systems

[Greater Hungarian Plain Neogene TPS (404801); Danube Neogene TPS (404803); Transcarpathian Neogene TPS (404804); part of Zala-Dráva-Sava Mesozoic/NeogeneTPS (404802)]

These systems represent petroleum generation and migration from Neogene source rocks into underlying basement rocks and into reservoirs of the Neogene basin fill. Extensive vertical and lateral migration has occurred. The systems are widespread and partially segregated geographically into individual deep basinal areas where optimum conditions for thermally generated oil and gas are found. Traps include a variety of tectonic, compactional, syndepositional, and stratigraphic types in the Neogene and fractured and weathered Mesozoic, Paleozoic, and Precambrian basement rocks in paleotopographic and structural highs. The systems commonly contain multiple source units, primarily of early and mid-late Miocene age. In those basins deep enough to have generated gas during late stages of burial, the abundance of oil fields on the perimeters of gas-generative areas and their lack within the interior suggests that gas may have displaced oil from traps proximal to gas generation. A burial history diagram from the Greater Hungarian Plain Neogene TPS is shown in figure 14 and that of the Danube Neogene TPS is shown in figure 15. Generalized events charts for TSPs are shown in figures 16, 17, and 18.

Mixed Mesozoic-Neogene Total Petroleum System

[Zala-Dráva-Sava Mesozoic/Neogene TPS (404802)]

This system consists of oils generated locally by Mesozoic source rocks that migrated into reservoirs of the pre-Tertiary basement complex and into reservoirs of the overlying Tertiary basin fill and consists, more generally, of oil and gas generated and migrated from Neogene source rocks into reservoirs of the Neogene basin fill (burial history plot, fig. 19; events chart, fig. 20). Traps consist of compactional and tectonic anticlines, folds, faults, and stratigraphic traps (including paleotopographic, truncation, and porosity pinch-out traps in both the basement and the Tertiary basin fill). Although the Upper Triassic Kössen Marl is the main source rock of the oils in the Zala Basin, Cenozoic source rocks appear to have generated hydrocarbons and, in areas where Mesozoic source rocks are absent, such as in the Dráva and Sava depressions, Neogene rocks alone appear to have generated the hydrocarbons (Baric and others, 1998, 2000). A TPS involving both Mesozoic and Neogene source rocks may also be present in the Danube Basin, where presently overmature Mesozoic source rocks may be hypothesized, although not documented, and is suggested in the events chart shown in figure 20.

Table 1. Total petroleum systems and associated assessment units.

Total petroleum system (TPS)	Assessment unit (AU)	Age of source rock
Greater Hungarian Plain Neogene (404801)	Greater Hungarian Plain Basins (40480101)	
Danube Neogene (404803)	Danube Basin (40480301)	Neogene
Transcarpathian Neogene (404804)	Transcarpathian Basin (40480401)	
Zala-Drava-Sava Mesozoic/Neogene (404802)	Zala-Drava-Sava Basins (40480201)	Neogene–Mesozoic
Hungarian Paleogene (404806)	Hungarian Paleogene Basin (40480601)	
Central Carpathian Paleogene (404805)	Central Carpathian Paleogene Basin (40480501) (not assessed quantitatively)	Paleogene

Paleogene Total Petroleum Systems

[Hungarian Paleogene TPS (404806); Central Carpathian Paleogene TPS (404805)]

The Hungarian Paleogene TPS (404806) occurs in epicontinental Paleogene basins (fig. 7) and encompasses a suite of structural, stratigraphic, and combination trap types in Paleogene sequences that are strongly influenced by syndepositional tectonic controls and charged by associated Paleogene source rocks. Within the Hungarian Paleogene Basin, Slovenian Paleocene Basin, and possibly the Graz (Styrian) Basin, the euxinic Tard Clay and Kiscell Clay and equivalents of late Eocene and early Oligocene age appear to provide source potential for oil and gas. According to Milota and others (1995), much of the Oligocene sequence in the southern part of the Hungarian Paleogene TPS lies in the oil window, with the maturation level of the source complex equivalent to the wet-gas zone in the extreme south and to the main oil-generation zone in the north. Maturation is hypothesized to have occurred during maximum heat flow in late Miocene or Pliocene time (6–2 Ma). Source rocks may also charge underlying basement rocks. A burial and thermal history of the Oligocene source rocks in the Hungarian Paleogene TPS is shown in figure 21 and a generalized events chart in figure 22.

The Central Carpathian Paleogene TPS (404805) occurs in the Central Carpathian Paleogene Basin of Slovakia, north of the Neogene Pannonian Basin system. Source rocks are principally Eocene organic-rich beds that have charged associated reservoirs and underlying basement reservoirs. Nemcok and others (1996) determined that these source rocks reached maturity in late Paleogene or early Miocene time. A separate system also exists in the Paleogene flysch sequence of the Szolnok trough, but this was treated as a subordinate contributor to the principal overlying Neogene system. A generalized events chart for the Central Carpathian Paleogene TPS is shown in figure 23.

Other Total Petroleum Systems

Additional total petroleum systems were recognized or hypothesized within the province or adjacent to it but were not separately assessed. They were incorporated either in assessments of adjoining petroleum provinces or considered as subordinate contributors to the preceding assessed total petroleum systems. They include the following:

Frontal Carpathian Jurassic TPS.—This system contains oils generated in Jurassic and other source rocks of the overridden European plate. The oil has migrated upward into reservoirs of marginal nappes of the Inner Carpathian foldbelt and into reservoirs of the overlying Tertiary basin fill, as demonstrated in the Vienna Basin (Ladwein, 1988; Francu and others, 1996; Seifert, 1996). Folds, faults, and unconformities provide traps within the nappes of the Inner Carpathian foldbelt, accompanied by structural and stratigraphic traps in the overlying Tertiary basin fill. This hypothetical system is limited to the margin of the Inner Carpathian foldbelt, particularly in the Central Carpathian Paleogene area, but was not assessed due to lack of data.

Frontal Carpathian Paleogene TPS.—This system contains oils generated in Cretaceous and Paleogene source rocks of the Outer Carpathian flysch belt that have migrated into marginal nappes of the Inner Carpathian foldbelt, into reservoirs of the Paleogene and Cretaceous flysch, and into overlying Neogene basin fill. The Paleogene fill of the Carpathian foredeep is probably sufficiently underthrust beneath the marginal Inner Carpathian nappes to have provided hydrocarbons locally to the extreme northern edge of the Pannonian Basin Province and, according to Francu and others (1996) and Seifert (1996), this Paleogene fill may have generated or co-sourced some Vienna Basin oils. The presence of a Tertiary seal appears to be a virtual requisite for traps within the nappes of the Inner Carpathian foldbelt, where traps are anticipated to be complex and much faulted. Although not assessed,

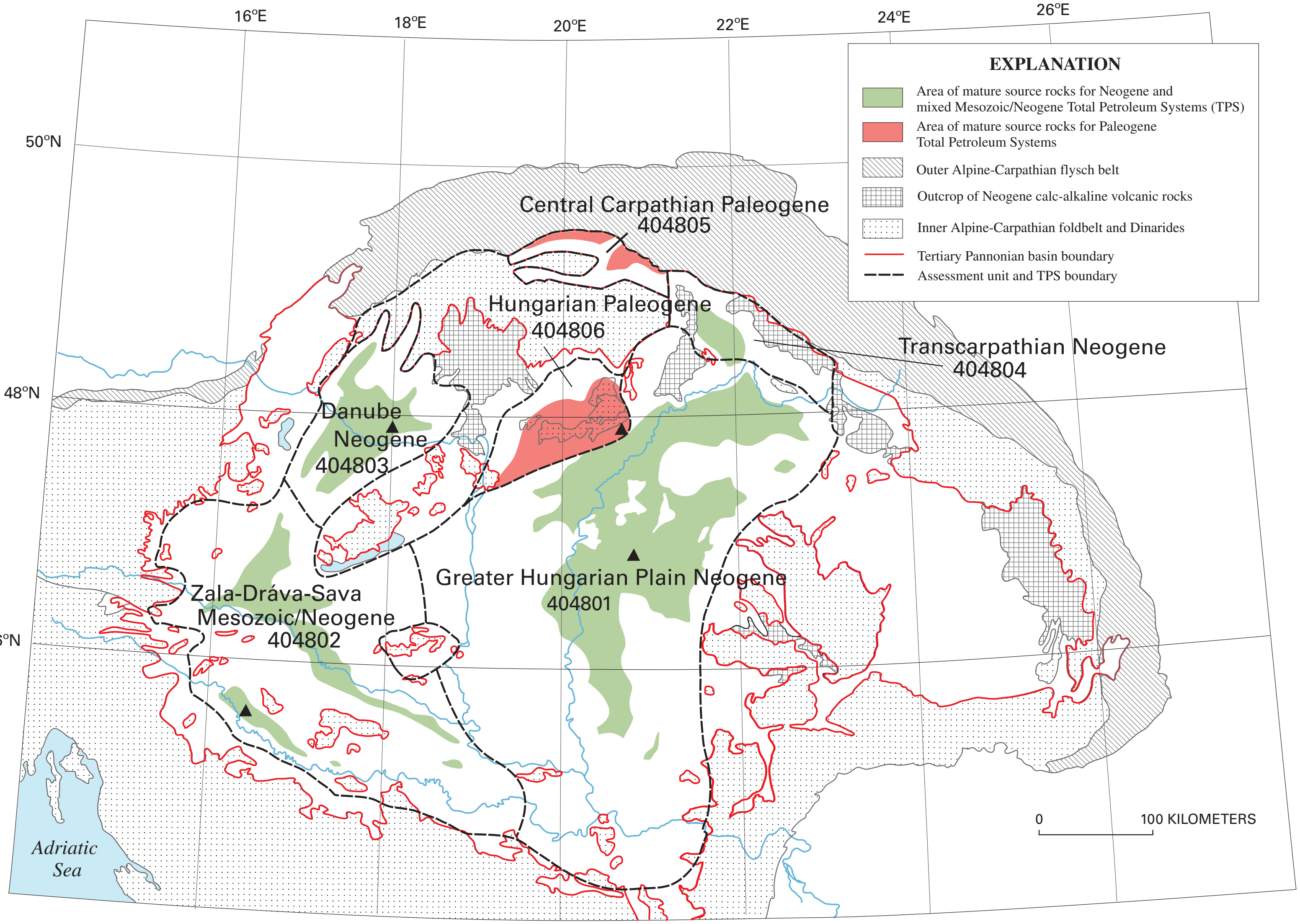

Figure 13. Map showing boundaries and names of TPSs in the Pannonian Basin Province (4048), with areas of inferred mature source rock for Paleogene systems in red and Neogene and mixed Mesozoic/Neogene source rocks in green. Boundaries of associated assessment units correspond with those of the TPS (see table 1). Source rocks in the Vienna and Transylvanian Basins are not shown. Approximate locations of burial history plots are shown by triangles.

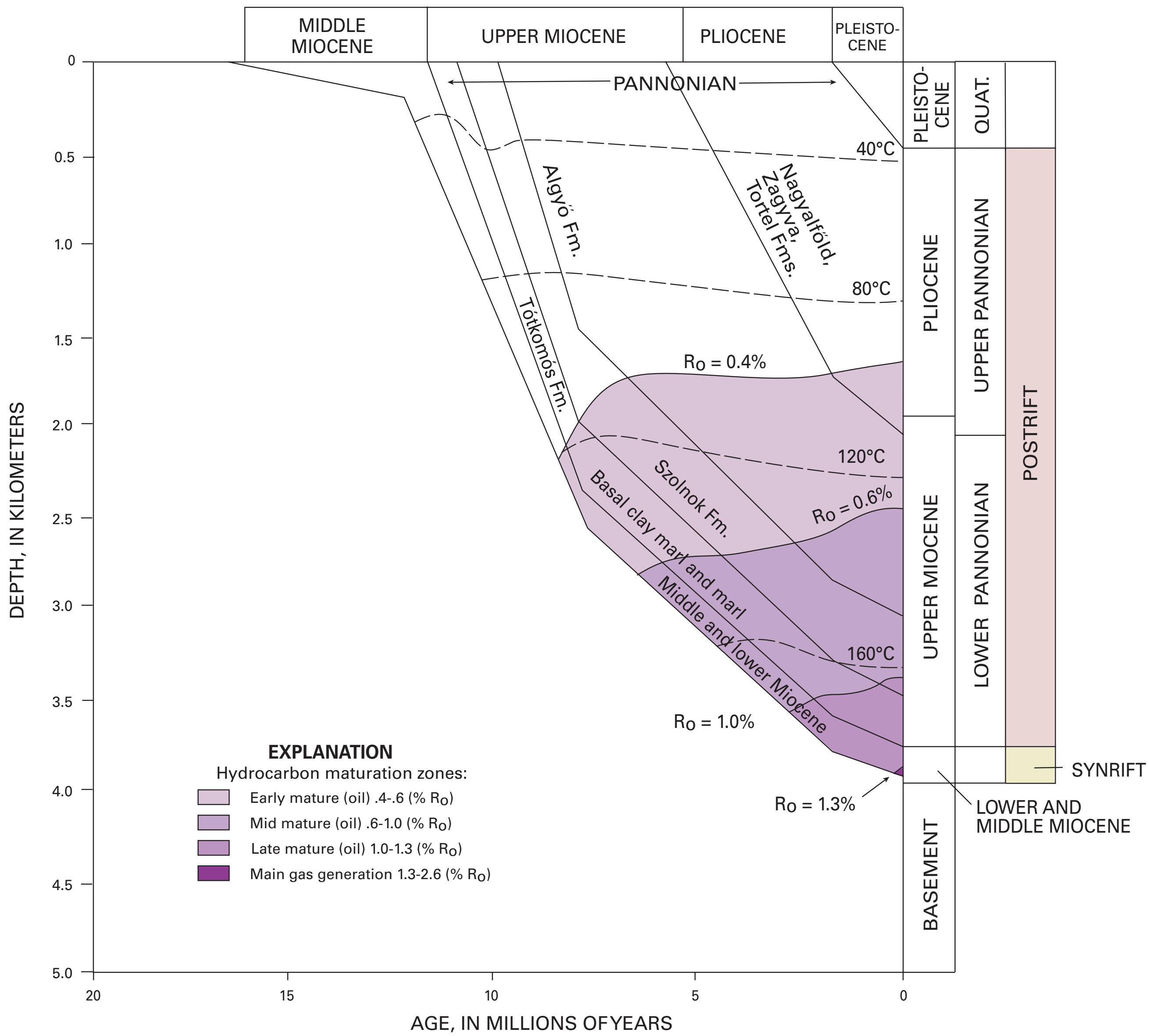

Figure 14. Burial history plot of the Greater Hungarian Plain Neogene TPS (404801). Location shown in figure 13. Source rocks are principally lower Pannonian and lower-middle Miocene. Modified after Clayton, Spencer, and Koncz (1994).

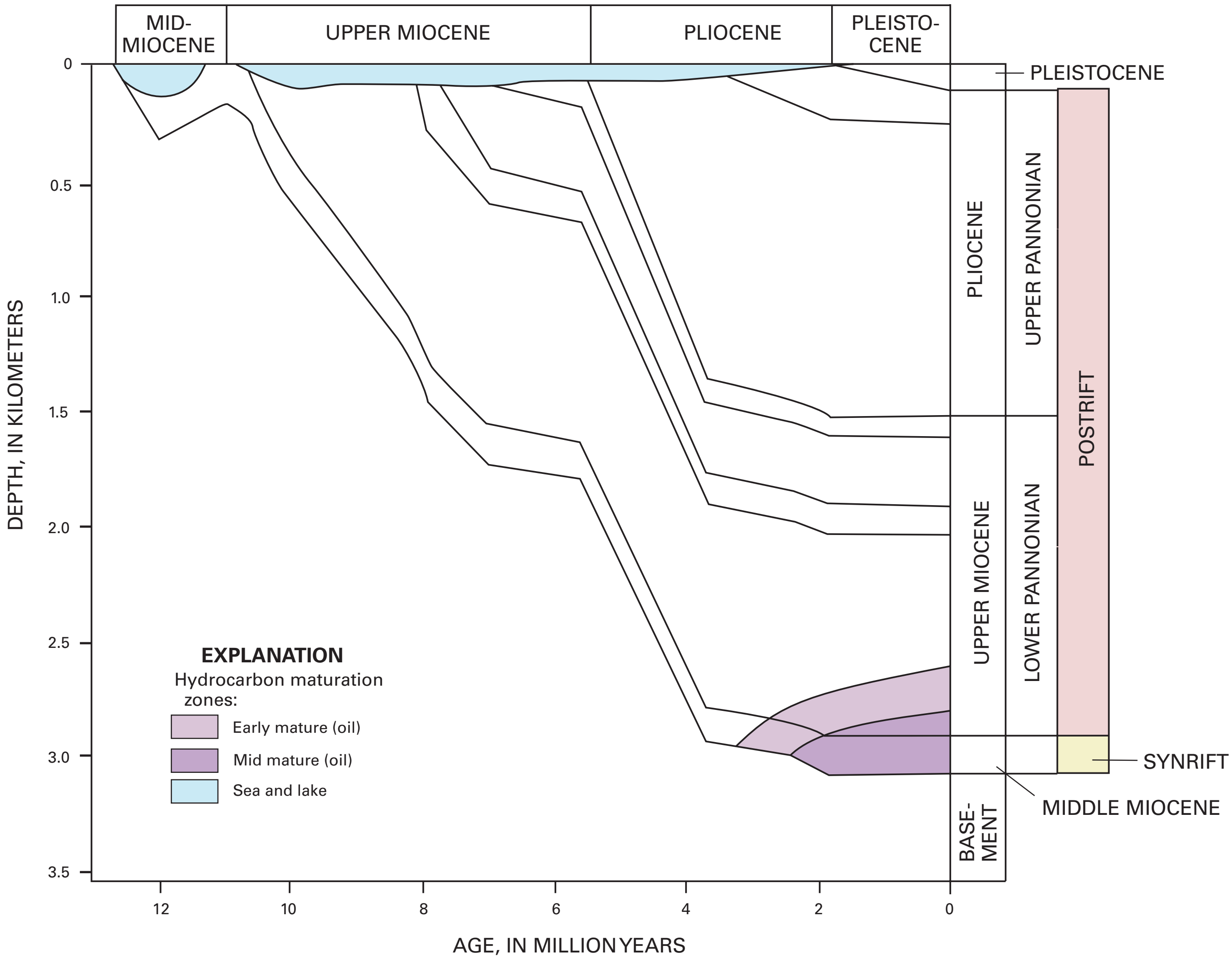

Figure 15. Burial history plot and hydrocarbon generation zones of the Danube Neogene TPS (404803). Location shown in figure 13. Principal source rocks are in the lower Pannonian and middle Miocene. Modified from Milićka and others (1996).

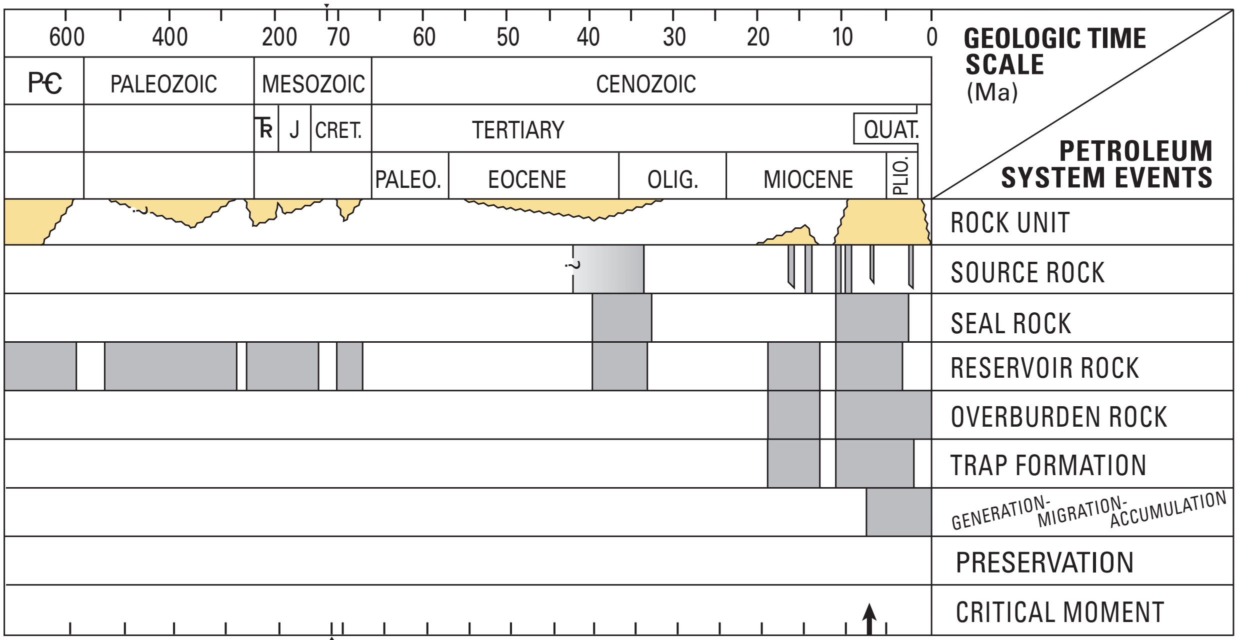

Figure 16. Generalized events chart for the Greater Hungarian Plain Neogene Total Petroleum System (404801).

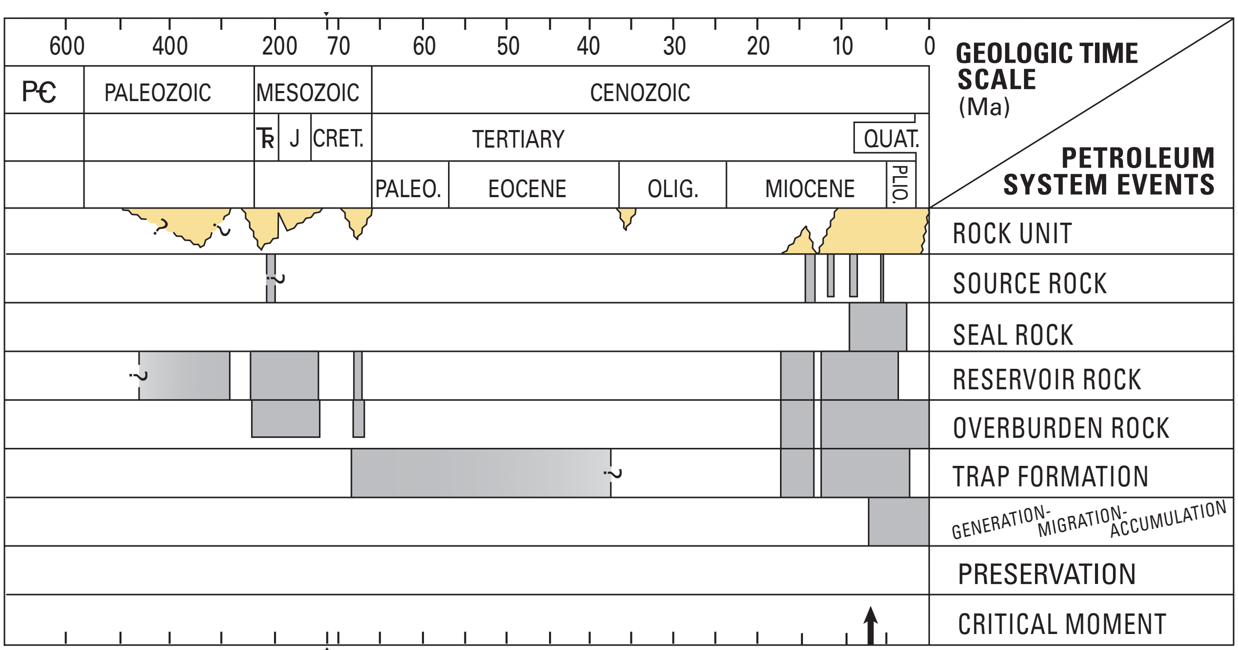

Figure 17. Generalized events chart for the Danube Neogene Total Petroleum System (404803).

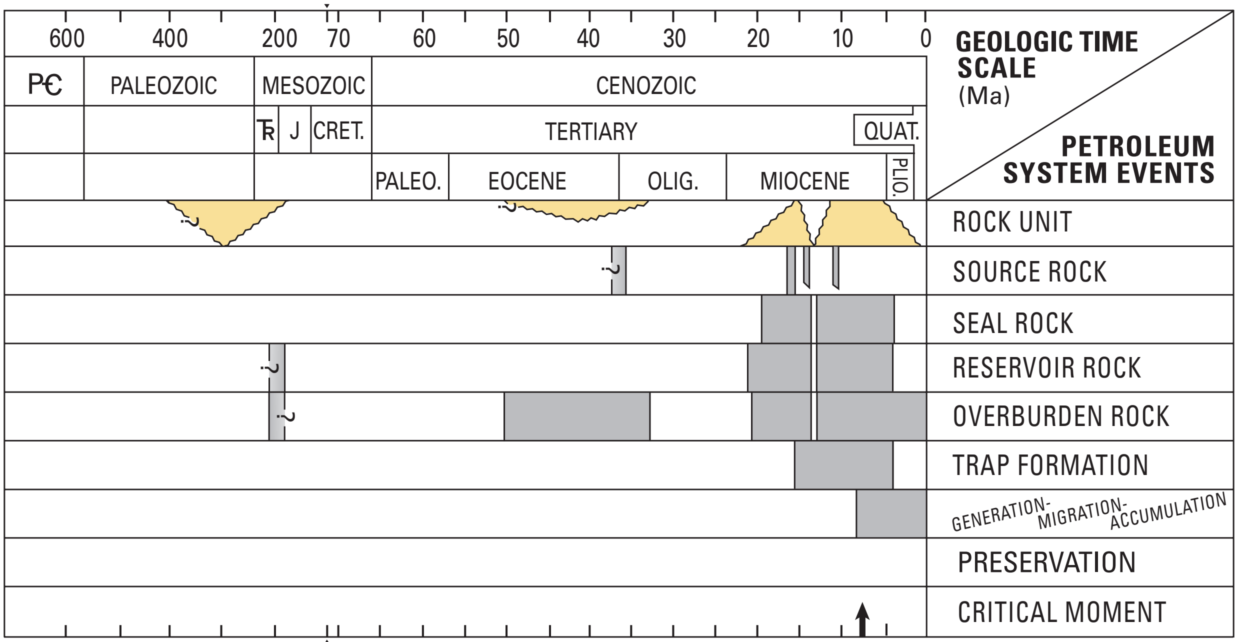

Figure 18. Generalized events chart for the Transcarpathian Neogene Total Petroleum System (404804).

this system may have contributed to the Central Carpathian Paleogene TPS (404805) in the Central Carpathian Paleogene Basin of Slovakia.

Neogene Biogenic Gas Total Petroleum System.—Pliocene sediments locally contain dry, hydrocarbon-rich gases of isotopically light, biogenic methane derived from immature upper Pannonian organic-rich sediments that contain lignite and brown coal layers (Clayton and others, 1990; Koncz and Etler, 1991; Clayton and Koncz, 1994a). According to Seifert (1996), nearby small gas fields south of the Danube River in the Vienna Basin and along its east flank also contain biogenic gas generated from the middle to upper Miocene section. Quantities of gas in this TPS are generally small, and the system was included as a minor component of the principal Neogene Total Petroleum Systems.

Assessment Units

Six assessment units (AU) were defined within the Pannonian Basin Province. They were based on geographic sets of subbasins containing what was considered to be an operative total petroleum system (fig. 13; table 1). Each assessment unit therefore equates to a corresponding total petroleum system (TPS) that may include several source beds that have contributed hydrocarbons to a shared trap and reservoir sequence:

- Greater Hungarian Plain Basins AU (40480101)
- Zala-Dráva-Sava Basins AU (40480201)
- Danube Basin AU (40480301)
- Transcarpathian Basin AU (40480401)
- Hungarian Paleogene Basin AU (40480601)
- Central Carpathian Paleogene Basin AU (40480501)

General geologic characteristics of the assessment units are described below. The reader is referred to U.S. Geological Survey Digital Data Series DDS-60 (2000) for statistical detail of the individual assessment units, assessment input, methodology, and results.

Greater Hungarian Plain Basins AU (40480101)

Description.—This assessment unit represents an area of petroleum generation and migration from Neogene source rocks into reservoirs of the Neogene basin fill of the Great Hungarian Plain and locally into underlying reservoirs of the Alpine thrust system. Vertical and lateral migration is pervasive. The coincident Greater Hungarian Neogene Total Petroleum System (404801) contains five or six depocenters within which source rocks have passed through the oil-generative into the gas-generative phase. Traps in the Tertiary fill are structural, stratigraphic, and combination, including a variety of compactional and syndepositional types. Paleogene reservoir rocks within the geographic limits of this assessment unit, excepting those within the Hungarian Paleogene Basin Assessment Unit are also included, particularly the Szolnok

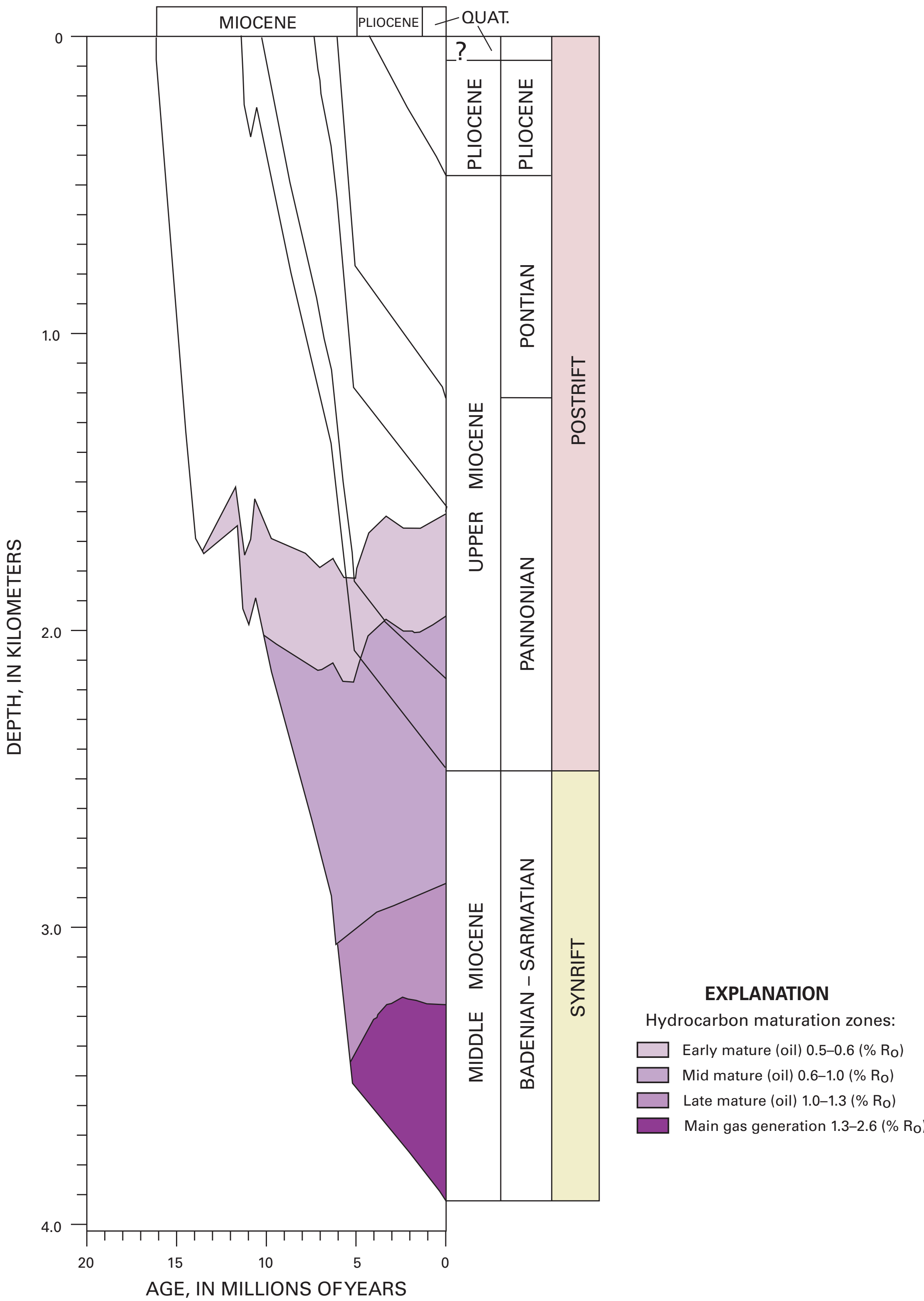

Figure 19. Burial history plot of the Sava depression (Zala-Dráva-Sava Mesozoic/Neogene Total Petroleum System (404802)). Location is shown in figure 13. Principal source rocks are of early Pannonian and Badenian age. Note that Mesozoic source rocks are not present in this part of the Zala-Dráva-Sava Mesozoic/Neogene TPS (404802). Modified after Baric, Ivkovic, and Perica (2000).

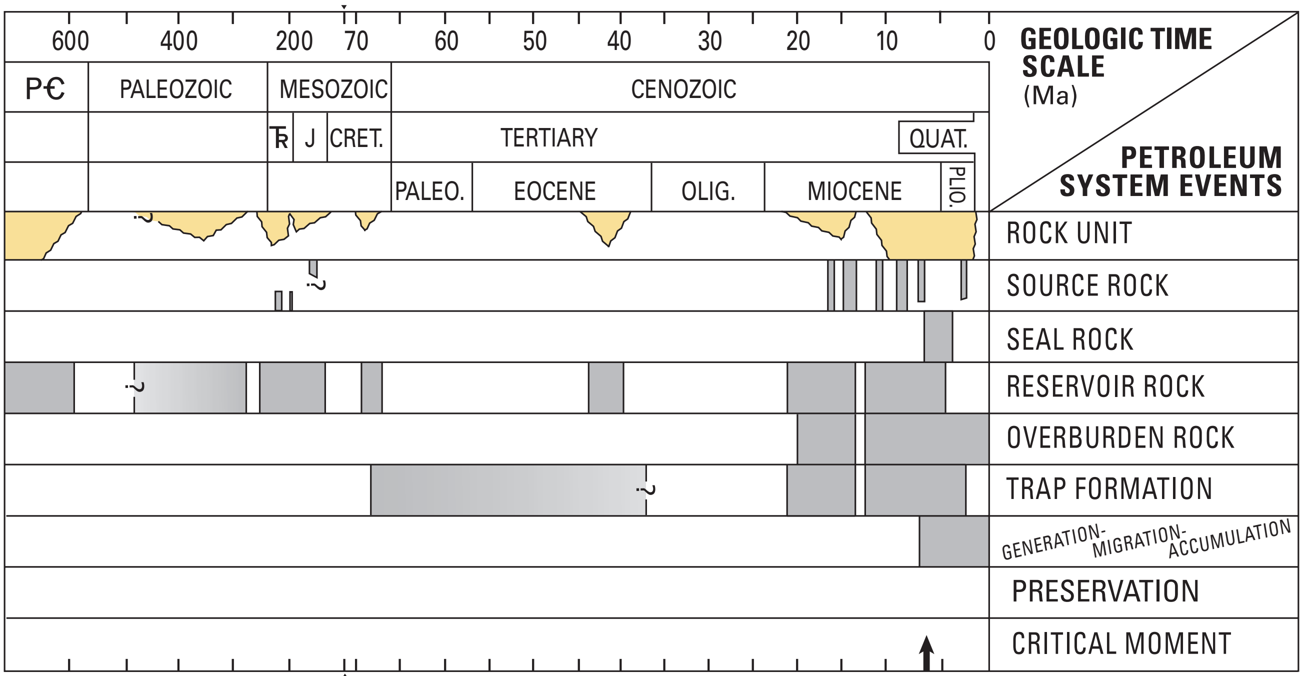

Figure 20. Generalized events chart for the Zala-Dráva-Sava Mesozoic/Neogene Total Petroleum System (404802).

Flysch of the Szolnok trough. An events chart for the involved petroleum system is shown in figure 16.

Source rocks.—Miocene (Badenian and Sarmatian) and Pannonian sediments are considered the principal sources of oil and gas. Geochemical and biomarker analysis has shown that, in general, source-rock quality is poor, although individual units of better quality are present. They are generally middle–upper Miocene shale, clay-marl, and marls. Source rocks commonly contain type-III and, locally, type-II kerogen (Szalay and Koncz, 1991). As an example, several Miocene source beds are documented within the Békés Basin, where source-rock evaluation and correlation of extracts with oils indicate three genetic oil types with separate Neogene sources in the lower Pannonian containing principally type-II kerogen (Clayton, Koncz, and others, 1994; Clayton, Spencer, and Koncz, 1994). They are the probable source of the oil produced both from the fractured Paleozoic metamorphic rocks as well as Miocene reservoirs. Pliocene organic-rich rocks locally appear to have produced small accumulations of biogenic gas in shallow sediments.

Maturation.—According to recent work, hydrocarbon generation from middle and upper Miocene source rocks started about 7–6 Ma and is still in progress (Clayton, Koncz, and others, 1994; Horváth and others, 1996). Horváth and others (1988) indicate that hydrocarbon generation has progressed so that sedimentary rocks currently below a depth of 4–5 km have passed through the oil-generation window, but indicate that the upper 2 to 3 km of the sedimentary rocks are immature. As an example, oil generation begins in the Bekes Basin at a depth between 2 and 3.5 km and ends at 3.5 to 5 km, as noted by Clayton, Koncz, and others (1994). Rocks are generally in the gas-generative stage below 5 km. In some cooler areas, maturity zones are somewhat depressed. In most of the system, oil was generated at maturation levels corresponding to present-day burial depths (refer to fig. 14). The entrapped gas locally contains CO_2 as a result of thermal decomposition of carbonates in basement nappes (Kertai, 1968; Clayton and Koncz, 1994a).

Migration.—The timing of migration is favorable with reference to trap formation (refer to figs. 14 and 16). Lateral migration is evident, although most fields are within or in close proximity to areas of mature source rocks. Vertical migration appears extensive, with oil and gas found in basement rocks beneath the Tertiary basin fill and in immature sediments above mature sources—confirmed by geochemical analyses of gases, oils, and source rocks (Koncz and Etler, 1991; Clayton and Koncz, 1994a; Clayton, Koncz, and others, 1994; Clayton, Spencer, and Koncz, 1994; Spencer and others, 1994). In those basins deep enough to have generated gas in late stages, oil fields are often situated on the peripheries of gas-generative areas and are virtually lacking within them; this suggests that gas may have displaced oil from the more proximal traps. The leaky character of this system probably stems from extensive faulting and high sandstone content within the Neogene rock column.

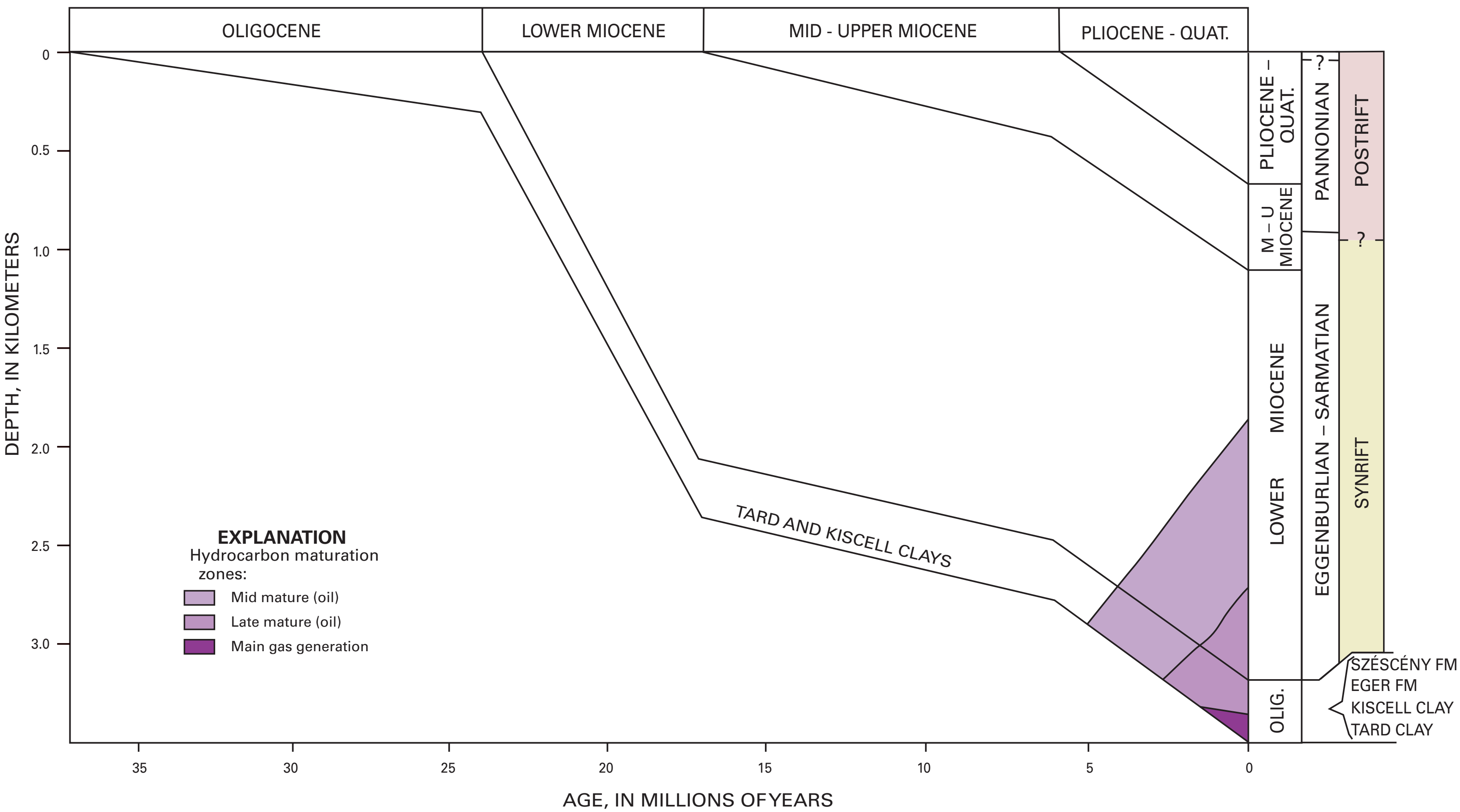

Figure 21. Burial history plot of the Hungarian Paleogene Total Petroleum System (404806). Principal source rocks are the Oligocene Tard and Kiscell Clays. Location is shown in figure 13. Modified from Milota, Kovács and Galicz (1995).

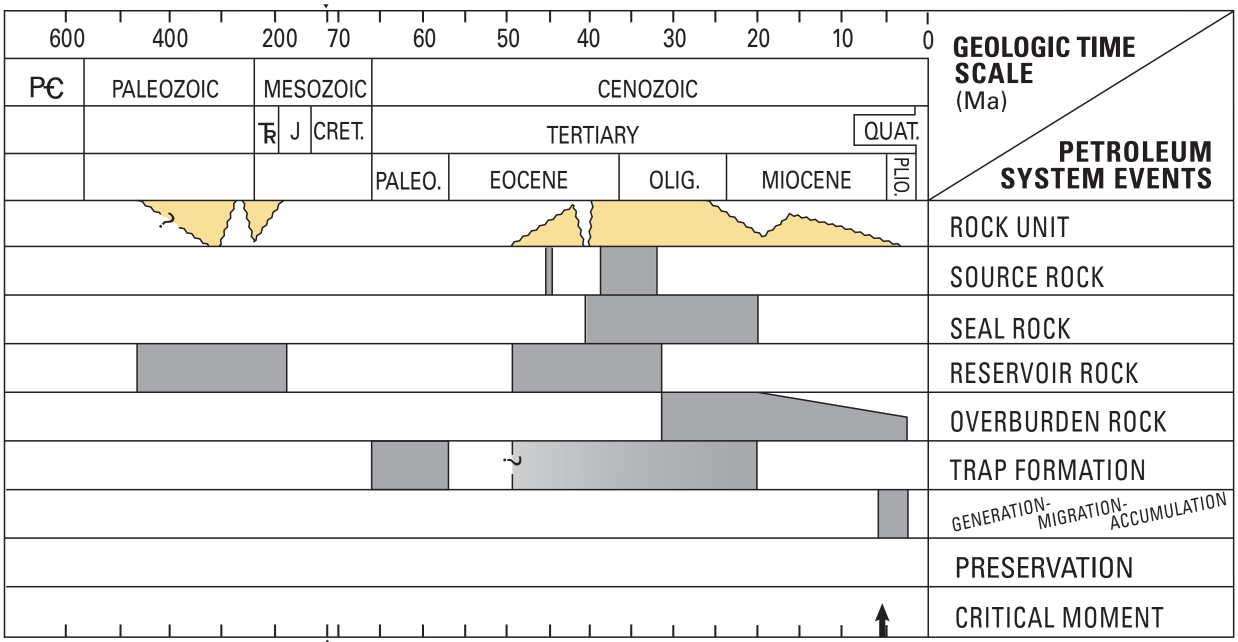

Figure 22. Generalized events chart for the Hungarian Paleogene Total Petroleum System (404806).

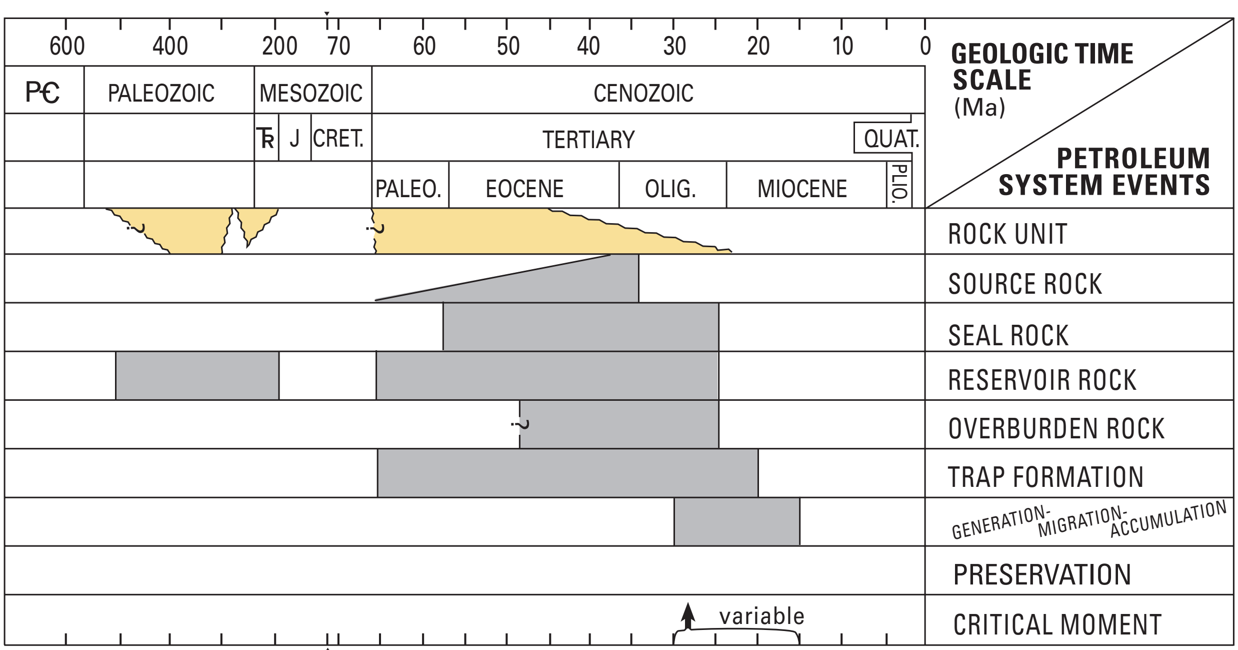

Figure 23. Generalized events chart of Central Carpathian Paleogene Total Petroleum System (404805).

Reservoir rocks.—Reservoir rocks range in age from Precambrian to late Pliocene. The oldest are fractured and weathered igneous and metamorphic rocks of the basement complex. The most important reservoirs are Neogene sedimentary rocks, particularly Miocene lower Pannonian sandstones and conglomerates, brecciated pre-Pannonian Miocene marls and, locally, upper Pannonian and Pontian (Miocene) sandstones. The sandstones are of highly varied origin, representing marine, lacustrine, and deltaic settings. Miocene patch reefs, which produce in the Vienna Basin and elsewhere, provide analogs for similar pre-Pannonian reservoirs within the Sarmatian and Badenian units, as in the Békés Basin (Szentgyörgyi and Teleki, 1994). Basal conglomerates (namely, Békés Conglomerate) often overlie crystalline basement or brecciated synrift Miocene sedimentary rocks and sometimes form a common reservoir. Small amounts of mostly biogenic gas are produced from upper Pannonian sandstones. In the area of the Szolnok trough, Paleogene reservoirs are also anticipated, including sandstones, marls, and bioherms within the Szolnok Flysch.

Reservoirs of the basement complex are largely weathered and fractured crystalline rocks of Paleozoic and Precambrian age (and occasional Mesozoic metamorphosed carbonates and marls). Matrix porosity is low, and fracturing is important in reservoir development. In Battonya field, gas production is chiefly from weathered and fractured Paleozoic granites and quartz porphyries in association with overlying lower Pannonian conglomerate and Miocene marls. Algyö field (the biggest oil and gas field of Hungary) and Sarkadkeresztúr field also produce from fractured Paleozoic metamorphic rocks and basal Pannonian conglomerates, as well as from younger reservoirs, all sourced from Miocene shales and marls. The Derecske Basin has fractured Precambrian metamorphic basement reservoirs that yield gas, as well as Mesozoic and Paleozoic reservoirs and production from Tertiary basin fill (Pogácsás, Mattick, Tari, and Várnai, 1994).

Traps/seals.—Traps in the Neogene fill are structural, stratigraphic, and combination. Historically important are those associated with growth faults and compaction features over basement highs. Also important are faulted uplifts, growth faults, and flower structures along strike-slip faults and pinch-outs in fluvial, shallow-water, and turbidite sandstones and conglomerates, patch reefs, and traps at unconformities—particularly at the regional unconformity between synrift and postrift sequences. Stratigraphic traps include subtle features in basinal areas and on flanks of structures as well as the more obvious pinch-outs of marine, strandline, and deltaic sandstones. Traps in fractured and weathered Mesozoic, Paleozoic, and Precambrian basement rocks include paleotopographic and basement structural highs. Seals for both Neogene and basement reservoirs are provided by fine-grained rocks of the Neogene basin fill.

Exploration status.—This assessment unit has had a long exploration history. Structural traps are associated with basement highs and features along strike-slip faults. Existing production is largely from relatively simple structures, the larger of which are compaction anticlines cored by basement rocks. Because of extensive exploration, the largest of these traps probably have been discovered. Subtle traps associated with stratigraphic pinch-outs and syndepositional features and unconformities appear to offer significant potential, particularly those associated with displacements along listric normal faults and unconformities, and those involving turbidites. Paleotopography at the unconformity at the top of the basement and localized porosity zones within the basement, especially on the flanks of structures, offer potential. Although many of the more prominent features have been tested, many subtle unconformity traps and localized porosity trends probably remain untested. See table 2 for estimates of undiscovered oil and gas in this AU.

Zala-Dráva-Sava Basins AU (40480201)

Description.—This assessment unit deals with traps and accumulations in the Cenozoic basin fill of the Zala Basin and Dráva and Sava depressions and in the underlying basement that were charged variously by Neogene or Mesozoic source beds. The assessment unit is coincident with the Zala-Dráva-Sava Mesozoic/Neogene TPS. Significant vertical and lateral migration characterizes this unit. Structural, stratigraphic, and combination traps are present in the Neogene (including growth faults, compaction features over basement highs, and pinch-outs in fluvial, shallow-water, and turbidite sandstones and conglomerates) as well as unconformity traps, particularly at the regional unconformity between Miocene synrift and Pannonian postrift rocks. Traps in the basement complex include Mesozoic and Paleozoic rocks in paleotopographic highs and structural high blocks, basement structures, fracture zones, and unconformity traps beneath the Tertiary. An events chart for the involved petroleum system is shown in figure 20.

Source rocks.—Principal source rocks are in the Neogene basin fill and, locally, organic-rich rocks within the basement complex. In the Zala Basin, principal source rocks are considered to be Upper Triassic Kössen Marl and equivalents, and Miocene source beds; some Cretaceous source rocks may have locally contributed petroleum. According to Clayton and Koncz (1994b), Upper Triassic source rocks have yielded most of the oil in the Zala Basin but have not been recognized over much of the adjoining area. They appear to be limited to the Pelso block and absent from areas to the south, including the Dráva and Sava depressions. Where exposed in the Transdanubian Central Range in western Hungary, Upper Triassic Kössen Marl has excellent source-rock potential. Fields producing Triassic oils in the Zala Basin include Bak, Barabásszeg, Nagylengyel, Pusztaapáti, and Szilvágy.

Neogene rocks are considered as source rocks over most of the assessment unit. Those of the Zala Basin are considered to be Miocene Badenian and Pannonian rocks, and studies by Baric and others (1991, 1998, and 2000) have established the existence of mature, organic-rich source rocks of predominantly Pannonian and Badenian age in both the Dráva and Sava depressions.

Maturation.—Miocene source rocks in the Dráva and Sava troughs reached maturity in middle to late Miocene (Baric and others, 1991; Baric, Ivkovic and Perica, 2000). In the Zala Basin, generation and expulsion in both Triassic and Miocene source rocks also began in late Miocene (Clayton and Koncz, 1994b). However, some workers document a break in the vitrinite profile, indicating a pre-Neogene thermal event that affected the Triassic sequence, followed by burial and heating in the Neogene (Laczo and Jambor, 1988). Within these basins, the Neogene is in an active oil- and gas-generative phase. The entrapped gas locally contains CO_2 as a result of thermal decomposition of carbonates in basement nappes (Kertai, 1968).

Migration.—Timing of migration is favorable with reference to trap formation. In the Zala Basin, generation and expulsion began in late Miocene time during rapid subsidence, accompanied by extensive vertical migration, according to Clayton and Koncz (1994b). Similarly, Baric and others (1991, 1998, and 2000) conclude that source rocks of Miocene age in the Dráva and Sava troughs reached maturity with generation and expulsion in middle to late Miocene. Accumulations in all subbasins are largely within areas of mature source rocks. The overall system is characterized by extensive vertical migration and less pronounced lateral migration.

Reservoir rocks.—Two reservoir sequences occur within this assessment unit, that is, Neogene reservoirs of the basin fill, and Mesozoic and Paleozoic reservoirs of basement nappes. Neogene reservoirs are principally sandstones, but also include marls and occasional biohermal buildups (patch reefs). Sandstones are widely distributed and are especially important in the Miocene Badenian, Sarmatian, lower Pannonian, and Pontian intervals.

Reservoirs of the basement complex are largely dolomites, limestones, and sandstones. They include Cretaceous rudistid limestone and Upper Triassic dolomites (particularly the Hauptdolomit) and, in other areas, marls and slightly metamorphosed limestones. In the Zala Basin, reservoirs include the Cretaceous Ugod Limestone and Cretaceous sandstones. The Croatian part of the Dráva trough contains Lower Jurassic and Middle Triassic dolomite reservoirs, Lower Triassic quartzite reservoirs, and Devonian schist reservoirs. In the Sava trough, the older reservoirs include weathered Paleozoic crystalline rocks (Baric, Ivkovic, and Perica, 2000). In all instances, fracturing is important in reservoir development.

Traps/seals.—Traps in the basin fill include a variety of tectonic, compactional, stratigraphic, and syndepositional types. Many are primarily structural, often related to basement highs and positive structures along strike-slip faults. Subtle traps are associated with stratigraphic pinch-outs and syndepositional features and unconformities, particularly those associated with the regional unconformity between middle Miocene (synrift) and late Miocene Pannonian (postrift) rocks and in turbidite sequences. Seals are associated fine-grained rocks.

Traps in the basement complex include Mesozoic and Paleozoic reservoirs in highs and structural closures within the nappes, including anticlines, fault blocks, elevated thrust elements, paleotopographic features, and truncation traps beneath the Tertiary—all in a basement further complicated locally by extensional, shear, and reverse faults. Traps are sealed by fine-grained Tertiary rocks and impervious rocks within the basement sequence.

Exploration status.—As a result of extensive successful exploration, the assessment unit has produced substantial oil and gas. Significant traps are associated with basement highs and with structures along strike-slip faults. Reservoirs within nappes of the pre-Tertiary basement constitute important exploration objectives; however, they are pervasively faulted and fractured, and their distribution and structural configurations are not well known.

Subtle traps in the Tertiary are not well explored, including those associated with stratigraphic pinch-outs and syndepositional features and unconformities, including those in turbidite sequences. Structural, stratigraphic, and unconformity traps in the basement remain incompletely explored.

Although the largest fields have most likely been discovered, significant potential remains for subtle structural, stratigraphic, and combination traps in both the Tertiary and underlying basement. Most of these traps are expected to be of modest or small size. As noted by Pogácsás, Mattick, Tari, and Várnai (1994), "…potential traps associated with Neogene strike-slip zones have not been explored adequately [in Hungary]; however, little is known about the fractured and fissured traces of these zones in the pre-Tertiary basement complex." See table 2 for estimates of undiscovered oil and gas in this AU.

Danube Basin AU (40480301)

Description.—This assessment unit deals with traps and accumulations within the Neogene basin fill of the Danube Basin and within the Mesozoic basement complex, both of which are charged by Tertiary and (or) Mesozoic organic-rich source rocks. This assessment unit is coincident with the Danube Neogene TPS. Traps in the basin fill include a variety of structural, stratigraphic, and combination types, including growth faults; compaction features over basement highs; pinch-outs in fluvial, shallow-water, and turbidite sandstones and conglomerates; unconformity traps, particularly at the regional unconformity between synrift and postrift rocks; and traps associated with strike-slip zones. Basement traps include structural and paleotopographic highs beneath the Tertiary fill and unconformity traps. The assessment unit appears to be characterized by vertical and lateral migration, pervasive extensional faulting, and a high sandstone content within the Neogene sequence. Local Eocene sedimentary rocks are treated as subordinate components of the assessment unit. An events chart for the involved petroleum system is shown in figure 17.

Source rocks.—Neogene rocks, principally in the Sarmatian and Badenian sequences, are the primary source rocks. These source rocks are of poor quality and are largely gas prone within the Hungarian part of the basin, with kerogen being primarily type II and type III (Mattick and others, 1996). Milićka and others (1996) infer that, in the Slovakian part of the basin, the sources are also Neogene rocks, particularly lower Pannonian, Sarmatian, middle Badenian, and lower Miocene sediments, which contain primarily type-III kerogen.

The Upper Triassic Kössen Marl, which is a principal source rock of the oils in the nearby Zala Basin, has not been identified in the Danube Basin. The Middle Triassic Veszprém Marl has been tentatively identified as a possible source rock, although it is of low organic content (Mattick and others, 1996). Where exposed in the adjoining Transdanubia Central Range, the Kössen Marl and Veszprém Marl are documented as good source rocks, although they are thermally immature (Clayton and Koncz, 1994b). In outcrop west of the basin, the organic-rich Reifling Formation of Middle Triassic age has been described, but it is overmature (Milicka and others, 1996).

Maturation.—Maturation of both Tertiary and Mesozoic source rocks began in late Miocene in the Hungarian part of the basin (Mattick and others, 1996). In Slovakia, the alteration of organic matter in the basement has been interpreted to have been reached before the Tertiary, possibly during the mid- to Late Cretaceous, followed by Tertiary burial and heating (Milićka and others, 1996) (fig. 15). Mesozoic source rocks are so deeply buried in much of the basin that they are in a gas generative stage. Milićka and others (1996) indicate that early oil generation was achieved at approximately 2,600–3,000 m, with onset of primary oil generation from about 2,800–3,300 m, and exclusive gas generation below about 4,000 m. They indicate that generation began in late Pannonian time and continues to the present.

Migration.—Timing of migration is favorable with reference to trap formation. All fields are located on the perimeter of the deep generative area of the basin. This suggests lateral migration and diffusion; vertical migration appears pervasive, accompanied by abundant CO_2.

Reservoir rocks.—Reservoir rocks range in age from Paleozoic to late Pliocene. The principal reservoirs are sandstones within the Neogene basin fill, particularly the Badenian, Sarmatian, and lower Pannonian sequences of Miocene age, although some gas is produced from upper Pannonian sandstones. Reservoirs include lower Pannonian conglomerate and Miocene marls and may include occasional biohermal buildups, as shown by analogs in the Vienna Basin and elsewhere. Fractured Paleozoic metamorphic and igneous rocks and Mesozoic carbonates and sandstones are inferred as possible reservoirs.

Traps/seals.—The basin shows a considerable structural and stratigraphic complexity (Hrusecky and others, 1996; Mattick and others, 1996). Traps include structural, stratigraphic, and combination types, including growth faults; compaction features over basement highs; pinch-outs in fluvial, shallow-water, and turbidite sandstones and conglomerates; and unconformity traps, particularly at the regional unconformity involving synrift and postrift rocks. Existing production is largely from relatively simple structures, largely compaction anticlines cored by basement rocks and in closures along faults. Traps also result from a combination of tectonic, lithologic, and stratigraphic factors, including fault-closed anticlinal features and roll-over structures associated variously with uplifts, growth faults, and flower structures. Prospects are likely in deeper zones where hydrocarbons could have accumulated in more subtle stratigraphic and unconformity traps and in the fractured basement. Included also are Miocene patch reefs, turbidite sequences in basinal areas and on flanks of structures, and pinch-outs of marine, strandline, and deltaic sandstones. Basement traps at the unconformity include paleotopography, truncations, and localized porosity zones along fractured and fissured traces of shear zones. Within basement nappes, traps include anticlinal features, fault blocks, and elevated thrust elements. Traps are sealed by associated fine-grained Tertiary rocks and impervious rocks within the basement.

Exploration status.—Discoveries have been disappointing in spite of a long history of exploration (Mattick and others, 1996; Blizkovsky and others, 1994). Other than oil shows and a noncommercial oil discovery in the Hungarian part of the basin, only gas fields have been discovered in Neogene rocks. CO_2 is a widespread and abundant contaminant, presumably due to thermal decomposition of carbonate rocks of the underlying nappes. The largest hydrocarbon traps probably have been tested, but opportunity for smaller traps remains, particularly subtle traps associated with stratigraphic pinch-outs and syndepositional features and unconformities in the Neogene, and traps associated with strike-slip zones. Basement reservoirs have not been well tested and include paleotopographic highs, unconformity traps, anticlinal and fault-related structures, and traps internal to the nappes themselves. Gas quality and prediction of reservoirs and traps within basement nappes remain problematic, and vertical leakage along faults and fractures is of concern, considering the pervasive extensional faulting of the thrust sheets. See table 2 for estimates of undiscovered oil and gas in this AU.

Transcarpathian Basin AU (40480401)

Description.—This assessment unit consists of traps and accumulations in the Neogene basin fill of the Transcarpathian Basin that have been charged by Cenozoic organic-rich rocks. The assessment unit is coincident with the Transcarpathian Neogene TPS. Traps include structural, stratigraphic, and combination traps, including growth faults; compaction features over basement highs; pinch-outs in fluvial, shallow-water, and turbidite sandstones and conglomerates; and unconformity traps. Significant vertical and lateral migration characterize this unit. Also included in the assessment unit are reservoir rocks in the underlying Paleogene and Mesozoic basement. An events chart for the AU/TPS is shown in figure 18.

Source rocks.—Inferred source rocks are of early Karpatian, Badenian, and early Sarmatian ages (middle Miocene). Their average concentration of organic matter is less than 1 to 1.3 percent, and kerogen is mainly humic; however, known hydrocarbons are seemingly derived from these rocks inasmuch as the pre-Tertiary rocks were overmature prior the Paleogene (Blizkovsky and others, 1994). Contributions from Paleogene source rocks remain unknown.

Maturation.—Maturation of source rocks in the central part of the basin appears to have been achieved prior to Pliocene sedimentation. Early generation was reached at depths of about 1.7 to 2.0 km, followed by main oil generation from 2 to 2.8 km, and wet gas from 2.8 to 3.4 km (Blizkovsky and others, 1994). The gas is generally accompanied by CO_2. Biogenic methane also occurs in shallow reservoirs at depths less than 1.2 km.

Migration.—Timing of migration is favorable with reference to trap formation. Vertical migration appears pervasive.

Reservoir rocks.—Principal reservoirs are sandstones in the Miocene lower Sarmatian and upper Badenian sequences. They are largely fine-grained calcareous sandstones with clay intercalations that have porosities ranging from 0.1 percent to 12.5 percent (Danko and Lacny, 1996). Potential reservoirs include marls and biohermal buildups (patch reefs) within the Neogene. Paleogene sandstones are productive in two fields, and, in another, Mesozoic dolomite in a basement nappe is productive. See table 2 for estimates of undiscovered oil and gas in this AU.

Traps/seals.—Traps include a variety of structural, stratigraphic, and combination types, including growth faults; compaction features over basement highs and pinch-outs in fluvial, shallow-water, and turbidite sandstones and conglomerates; and unconformity traps. Most production is associated with compactional anticlines above basement highs and with structures along faults, including growth faults and flower structures. According to Blizkovsky and others (1994), the structure of the basin was strongly influenced by the presence of salt layers, by differential compaction, by synsedimentary faults, and by volcanic activity. Blizkovsky and others (1994) report hydrocarbon shows on the slopes of buried stratovolcanoes. A variety of stratigraphic traps are also considered prospective, including Miocene patch reefs, turbidite sandstones, and pinch-outs of marine, strandline, and deltaic sandstones. Traps in Neogene rocks are sealed by associated clays or salt layers, whereas basement reservoirs situated in structural traps, paleotopographic highs, and unconformity traps beneath the Tertiary are sealed by fine-grained Tertiary rocks.

Exploration status.—Exploration in this basin, beginning in 1966, has produced a relatively few gas fields of small size, all in Slovakia. Four fields are currently in production (Danko and Lacny, 1996). Discoveries are largely from relatively simple fault-closed anticlinal features, roll-over structures associated variously with uplifts and growth faults, and in compaction anticlines cored by basement rocks. The largest accumulations probably have been discovered, but potential traps in the basement are relatively unexplored, and a variety of stratigraphic traps are considered prospective, including Miocene patch reefs, turbidite sandstones in basinal areas and on flanks of structures, pinch-outs of marine, strandline, and deltaic sandstones, and combination traps associated with syndepositional features and unconformities. See table 2 for estimates of undiscovered oil and gas in this AU.

Hungarian Paleogene Basin AU (40480601)

Description.—This assessment unit contains reservoirs and traps occurring in Paleogene rocks of an epicontinental Hungarian Paleogene Basin that are hypothesized to have been charged by indigenous Paleogene source rocks. Also included are underlying basement reservoirs, similarly charged. Rocks of the Paleogene Szolnok Flysch of the Szolnok trough, however, are not included here, but are treated within the assessment of the Greater Hungarian Plain Basins AU (40480101). The Hungarian Paleogene Basin AU is coincident with the Hungarian Paleogene TPS. An events chart for the ASU/TPS is shown in figure 22.

Source rocks.—The euxinic Tard Clay of late Eocene and early Oligocene age and the early Oligocene age Kiscell Clay have good source potential for oil and gas, as probably do equivalent beds of the Slovenian Paleogene Basin. It is reported that the Tard and Kiscell anoxic clays in north Hungary have an average TOC content of 0.5–1.0 percent, with local concentrations of 0.8–1.8 percent to as much as 4.5 percent (Kókai, 1994; Milota and others, 1995). Their kerogen is mostly types I and II, but type-III kerogen is present in the upper part of the sequence.

Maturation.—Given the high thermal gradient and presence of several small oil and gas fields, Paleogene source rocks are considered to be in the oil window at depth. According to Milota and others (1995), much of the Oligocene sequence in the southern part of the basin lies in the oil window, with the maturation level of the source complex equivalent to the wet-gas zone in the south and to the main oil-generation zone in the north. Maturation is hypothesized to have occurred in late Miocene or Pliocene, during maximal heat flow (6–2 Ma) (fig. 21).

Migration.—Timing of migration appears to be favorable with reference to trap formation; however, preservation of hydrocarbons may be a significant problem due to trap disruption during an active tectonic history.

Reservoir rocks.—Reservoirs include Paleogene sandstones, limestones, and marls. Principal reservoirs include the Eocene Szöc Limestone and sandstones of the Oligocene Kiscell Clay, largely turbidites, some of which are tuffaceous. Producing reservoirs also include Triassic limestones of the basement.

Traps/seals.—This epicontinental Paleogene basin is characterized by deep sedimentary troughs bounded by sets of large-displacement faults and shears. Traps include a suite of structural, stratigraphic, and combination types in sequences that were strongly influenced by syndepositional tectonic controls. Structural traps include fault blocks and other structures related to basement tectonics, secondary fault closures, and anticlinal features. Stratigraphic traps such as truncations by unconformities and pinch-outs in shallow-water and turbidite sandstones are expected, as are combination traps involving growth faults and roll-overs. Locally, traps in the Mesozoic basement beneath the Tertiary unconformity offer potential. Seals are provided by fine-grained rocks within the Paleogene sequence and, for basement traps, by overlying Neogene rocks or fine-grained rocks within the Mesozoic sequence.

Exploration status.—The Hungarian Paleogene Basin is relatively unexplored, although it contains a thick sedimentary rock section. One gas field and one oil field exceeding 1 MMBO equivalent have been found, along with six fields of smaller size. Hydrocarbon exploration has been hampered by complicated tectonics; nevertheless, the probability of modestly sized undiscovered accumulations is considered good. See table 2 for estimates of undiscovered oil and gas in this AU.

Central Carpathian Paleogene Basin AU (40480501)

Description.—This AU, although identified, was not quantitatively assessed. This assessment unit deals with traps occurring in Paleogene rocks of the marginal Central Carpathian Paleogene flysch basin, shown in figures 7 and 13. It is coincident with the Central Carpathian Paleogene TPS and includes a suite of structural, stratigraphic, and combination trap types in sequences that were strongly influenced by syndepositional tectonic controls. Traps are hypothesized to have been charged from Paleogene source rocks. This AU includes underlying basement reservoirs, similarly charged. An events chart for the ASU/TPS is shown in figure 23.

Source rocks.—Source rocks are considered to be within the Paleogene Podhale Flysch and equivalents and are of fair to excellent quality. They contain as much as 1.5 weight percent TOC, although now mostly depleted due to a high thermal history (Blizkovsky and others, 1994). Nemcok and others (1996) report two organic-rich intervals of Eocene age, the first containing between 0.1 to 1.5 percent total organic content (TOC) and the latter containing between 1.1 and 10.3 percent. These contain mostly type-III kerogen, along with some type II.

Maturation.—Maturity varies considerably due to variations in structural and burial histories. The vitrinite reflectance for Paleogene units is typically more than 1.2 percent at the surface and reaches 1.8 percent at 1-km depth. Nemcok and others (1996) indicate that maturity within the area varies considerably due to local structural and burial histories, and that source rocks are within the oil and wet gas generative windows locally, where they have been sufficiently buried to have undergone high thermal flux. Maximum kerogen maturity in the Paleogene corresponds to the end of oil-generation and wet-gas stages, as where the thickness of Paleogene resting on the Mesozoic–Paleozoic units of the Central Carpathians reaches 3,000 m toward the bounding Pieniny Klippen Belt, whereas underlying Mesozoic rocks are in the wet- and dry-gas window.

Migration.—Timing of hydrocarbon generation and migration appears favorable with reference to trap formation, and a small amount of oil and gas has been discovered at Lipany field. Both horizontal and vertical migration is likely. Maximum burial occurred during Oligocene–early Miocene, and was concluded by thrusting, uplift, and erosion.

Reservoir rocks.—Eocene and Oligocene rocks locally contain abundant coarse- and fine-grained clastics within the Podhale Flysch and its equivalents (Nemcok and others, 1996) and provide reservoirs of poor to fair quality, with porosity on the order of 8–10 percent. Fractured claystones and marlstones have produced a small amount of oil and gas at Lipany field, and potential reservoirs elsewhere also include fractured sandstones and siltstones, generally with low matrix porosity.

Traps/seals.—A suite of structural, stratigraphic, and combination trap types are expected. The only discovery, Lipany field, is located on a Mesozoic basement high. Intense compressive structural deformation, beginning in Eocene, may have adversely affected integrity and sizes of traps. Seals within the sequence associated with the reservoirs are considered to be of good quality where unbroken (Nemcok and others, 1996).

Exploration status.—There has been a lack of significant exploration success to date (Blizkovsky and others, 1994; Nemcok and others, 1996). Fractured claystones and marlstones have produced a small amount of oil and gas at Lipany field, but exploration drilling elsewhere has been very light. Poor to fair reservoir characteristics, a complexly folded and faulted structural setting, and subsequent deep erosion seemingly contribute to a relatively unfavorable environment for substantial oil and gas resources, and the unit was not quantitatively assessed.

Frontal Inner Carpathian AU

Description.—This AU, although described here, was not quantitatively assessed. This assessment unit consists of oil trapped largely in Mesozoic reservoirs of the marginal nappes of the Inner Carpathians that override Cretaceous and Paleocene source rocks of the Outer Carpathian flysch belt. The reservoirs may be charged from autochthonous Mesozoic beds or from subthrust Paleogene source rocks. Traps are largely structural in character and consist of folds, faults, and unconformity traps internal to the nappes and local structural and stratigraphic traps within the overlying Tertiary. The assessment unit is associated with the Frontal Carpathian Jurassic TPS and Frontal Carpathian Paleogene TPS and is limited to the northern margin of the Inner Carpathian foldbelt. Where the nappes are blanketed by Tertiary sediments, as in the Central Carpathian Paleogene Basin, this unit may be of particular interest for exploration.

Source rocks.—Organic-rich rocks of the overridden European plate and Outer Carpathian Flysch belt (fig. 7) may provide hydrocarbon sources along the edge of the Inner Carpathians. Most of the oils in Neogene reservoirs of the analogous Vienna Basin belong to an autochthonous Upper Jurassic source and have migrated upward through the fault systems of the flysch zone into reservoirs of the Inner Carpathian nappes and the overlying Tertiary (Seifert, 1996; Francu and others, 1996). The Oligocene synflexural fill of the Carpathian foredeep, involved in the Outer Carpathian foldbelt, also may be sufficiently underthrust beneath the Inner Carpathian nappes to provide hydrocarbons to the extreme northern margin of the Pannonian Basin system.

Based on oil/source-rock correlations and biomarkers, the Oligocene Series is believed to be the most efficient source rock in the Outer Carpathians (Ziegler and Roure, 1996) and may account for some of the oil in the Vienna Basin where most of the oils originate from an Upper Jurassic source. There, source rocks of Paleogene age in the flysch nappes or autochthonous Paleocene generated or at least co-sourced some of the oils, according to Francu and others (1996), although Seifert (1996) indicates that the contribution to the oil and gas fields in the Vienna Basin from the Oligocene formations in the outer thrust belt is insignificant.

Generation and migration.—In the area of the Vienna Basin and elsewhere along the frontal Carpathians, Paleogene and autochthonous Mesozoic source rocks reached maturity in late Miocene and were properly situated to provide hydrocarbons to the extreme northern marginal nappes of the Inner Carpathians. Migration along faults and fractures is required and locally probably has occurred, considering the pervasive faulting of thrust sheets and the evident vertical migration in the Vienna Basin.

Reservoir rocks.—Reservoirs include Mesozoic sandstone and carbonate rocks within nappes of the Inner Carpathians and sandstones within the blanketing Tertiary. Reservoirs are commonly fractured. According to data provided by Rieder (1996), approximately 10 percent of the initial oil in place found in Matzen field in the central part of the Vienna Basin is from the Upper Triassic Hauptdolomit, whereas the remainder is from stacked sandstone reservoirs in the Tertiary sequence. Flysch reservoirs within the overridden Outer Carpathian foldbelt are principally fractured sandstones and siltstones.

Traps.—Traps are principally structural and consist of folds and faults of the strongly folded Inner Carpathian thrust complex and of the overridden flysch and structural and stratigraphic traps within the Tertiary cover. Trap types involving the Inner Carpathian nappes include paleotopography, stratigraphic pinch-outs, structural closures, and unconformities internal to the nappes, where they are associated with sealing impermeable rocks, including overlying Tertiary. Traps within the overlying Tertiary include anticlinal features over basement highs, fault-bounded structures, and stratigraphic closures. At the giant Matzsen field in the Vienna Basin, the trap is an anticlinal Tertiary compaction feature over a high of thrusted Mesozoic rocks.

Exploration status.—This largely speculative AU may be favorably situated for hydrocarbon accumulations in several areas. However, outside of the Vienna Basin, it has not proven productive to date. Because of the structural complexity and lack of data, available information does not allow adequate resolution, and the assessment unit was not quantitatively assessed.

Estimated Undiscovered Resources

Estimates of undiscovered oil, gas, and natural gas liquids were made for each of the assessment units and aggregated for the province as a whole. The assessment procedures and methodology are reported in Klett, Charpentier, and Schmoker (2000), and the reader is referred to U.S. Geological Survey Digital Data Series DDS-60 (2000) for statistical detail of the individual assessment units, assessment input, methodology, and results.

Undiscovered resources as estimated for the individual assessment units are shown in table 2. Collectively, these units indicate that between 153 and 631 million barrels of oil (MMBO) and 1.7 and 7.4 trillion cubic feet of gas (TCFG), at the F95 and F5 probability levels, remain undiscovered within the Pannonian Basin Province. Mean values of undiscovered resources for the province are 359 million barrels of oil and 4.1 trillion cubic feet of gas, although the quantity is better represented by the range of possible values. Estimated field sizes and numbers accompanying the mean estimates reflect a modest future field size expectation, suggesting that most large fields in the area have been discovered.

The most important of the assessment units is the Greater Hungarian Plain Basins AU (40480101), followed by the Zala-Dráva-Sava Basins AU (40480201), and Hungarian Paleogene Basin AU (40480601). The Central Carpathian Paleogene Basin AU (40480501) was not quantitatively assessed, although fractured claystones and marlstones have produced a small amount of oil and gas at Lipany field in Slovakia. Exploration has been light, but because of lack of significant exploration success combined with generally poor reservoir characteristics in a deeply eroded and complexly folded and faulted structural setting, the area is believed to be a relatively unfavorable environment for substantial resources. The Frontal Carpathian Assessment Unit also was not quantitatively assessed due to its hypothetical character and lack of data, thereby omitting some unknown quantity of undiscovered resources for the province.

Table 2. Assessment results summary for undiscovered resources Pannonian Basin Province (4048).

[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
404801	**Greater Hungarian Plain Neogene Total Petroleum System**													
40480101	Greater Hungarian Plain Basins Assessment Unit													
Oil Fields	1	1.00	90	188	326	196	77	187	410	208	3	7	17	8
Gas Fields	6						925	2,111	3,684	2,188	23	61	125	66
Total		1.00	90	188	326	196	1,002	2,298	4,094	2,395	26	68	142	74
404802	**Zala-Drava-Sava Mesozoic/Neogene Total Petroleum System**													
40480201	Zala-Drava-Sava Basins Assessment Unit													
Oil Fields	1	1.00	54	108	194	114	45	108	241	121	2	4	10	5
Gas Fields	6						500	970	1,759	1,030	12	28	59	31
Total		1.00	54	108	194	114	545	1,078	2,000	1,151	14	32	69	36
404803	**Danube Neogene Total Petroleum System**													
40480301	Danube Basin Assessment Unit													
Oil Fields	1	1.00	0	0	0	0	0	0	0	0	0	0	0	0
Gas Fields	6						43	132	299	146	1	3	6	3
Total		1.00	0	0	0	0	43	132	299	146	1	3	6	3
404804	**Transcarpathian Neogene Total Petroleum System**													
40480401	Transcarpathian Basin Assessment Unit													
Oil Fields	1	1.00	0	0	0	0	0	0	0	0	0	0	0	0
Gas Fields	6						29	100	236	112	1	2	5	2
Total		1.00	0	0	0	0	29	100	236	112	1	2	5	2
404806	**Hungarian Paleogene Total Petroleum System**													
40480601	Hungarian Paleogene Basin Assessment Unit													
Oil Fields	1	1.00	9	42	111	49	10	49	140	59	0	1	4	2
Gas Fields	6						59	249	605	280	2	10	26	11
Total		1.00	9	42	111	49	69	299	744	339	2	11	30	13
4048	**Total: Assessed portions of Pannonian Basin Province**													
Oil Fields	1	1.00	153	339	631	359	132	344	790	387	5	13	32	15
Gas Fields	6						1,556	3,563	6,582	3,756	39	103	221	113
Total		1.00	153	339	631	359	1,688	3,907	7,372	4,143	43	116	253	128

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