Chapter R4

REGION 4: EUROPE—ASSESSMENT SUMMARY

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INTRODUCTION

For the purposes of the current USGS World Energy Project Assessment, Europe (Region 4) is considered to include the onshore and offshore areas of Europe exclusive of the former Soviet Union and Turkey. With the exception of the Ukrainian part of the Carpathian Mountains, European countries of the former Soviet Union, including Belarus, Estonia, Latvia, Lithuania, Russia, and Ukraine, are included in Region 1 (Region 1 province map). Resources of the Barents Sea were also assessed as part of Region 1. Greenland was included in North America (Region 5 province map) and is thus not considered here.

Europe was divided into numerous geologic provinces, of which eleven were assessed for undiscovered oil and gas resources (Region 4 province map). The eleven was chosen on the basis of their world ranking in total reserves and cumulative production (Klett and others, 1997) and on the perception of possible future discoveries. These provinces ranged from long-established, historically significant oil and gas areas, such as the Carpathian Basin, to remote areas such as the continental margin of Norway, where an extremely adverse physical environment and sparse data challenge exploration.

Total Petroleum Systems (TPS) were identified in each of these provinces, and assessment units (AU) were defined within each significant TPS. Only those TPS believed to be major contributors to oil and gas resources of the province were evaluated for assessment. Undiscovered resources of oil and gas were estimated in each defined AU (Region 4 Assessment Summary).

Although the geologic history of Europe is complex, and includes rocks that span all ages from Archean to Holocene, significant TPS are concentrated in rocks formed during a few geologic events. Much of what is now Western Europe, excluding most of the Alps, was assembled during the Caledonian (Cambrian-Devonian) accretion of Laurasia. Later, during the Hercynian (Variscan) suturing of Pangaea,

Africa collided with Europe, forming a foldbelt and foreland basin. Terrestrial organic matter accumulated in tropical coal swamps along with Siliciclastic fluvial deposits to form the gas-prone source rocks of the Coal Measures (Ziegler, 1990). Orographic effects of the orogenic belt and continued northward movement of the supercontinent out of the rainy tropics and into the middle latitudes led to the gradual desiccation of the Variscan foreland. At the same time, most of northwestern Europe was experiencing a period of tectonic relaxation, erosion, and planation of relief recorded in the geologic record as a post-Hercynian unconformity. Eolian rocks of the Rotliegend, in which most European natural gas resources are found, and the overlying evaporite deposits of the Zechstein, which provide an effective regional seal for hydrocarbons, accumulated on the principal unconformity. The Coal Measures, the Rotliegend, and the Zechstein together constitute the source rocks, reservoirs, and seals for gas resources of the Anglo-Dutch Basin and Northwest German Basin, provinces 4036 and 4035.

The Mesozoic breakup of Pangaea, the formation of the North Sea Dome, the rifting of the North Sea Graben and subsequent post-rift sag; the opening of the Atlantic and formation of the passive Atlantic margin together set the stage for most of the oil in Europe. In particular, marine waters moving southward from the Boreal Sea filled the North Sea rift and became anoxic in the late Jurassic, leading to deposition of the black shales of the Kimmeridge Clay and other stratigraphically equivalent organic-carbon-rich rocks, which are considered to be the principal source of petroleum in the region.

The final major event responsible for the TPS considered in this assessment was the Alpine collision (Cretaceous-Oligocene) of Europe and Africa, with accompanying post-Alpine rifting and the opening of the Mediterranean. The Alpine orogeny was largely responsible for the subsidence of the North Sea Basin and the North German-Polish platform, as well as the formation of the Carpathian Foreland, the Pannonian Basin, and the basins of the Mediterranean.

TOTAL PETROLEUM SYSTEMS AND ASSESSMENT UNITS

One TPS and three AU were defined in the sedimentary sequences that accumulated in the Carboniferous Variscan foreland of northwest Europe. The single TPS defined for the Anglo-Dutch Basin Province (4036) is named the Carboniferous-Rotliegend TPS (403601) in reference to the predominance of nonmarine organic-carbon-rich Carboniferous strata of the Coal Measures that serve as source rocks, and the excellent eolian and fluvial sandstone reservoirs of the Rotliegend sequences. This TPS is approximately coextensive with the Variscan Foreland that defines the Southern Permian basin, and is included within both the Anglo-Dutch basin province and the Northwest German basin province of this study (Region 4 province map). The geographic area of the Anglo-Dutch Basin (province 4036) has a history of oil production dating to the middle of the 19th century and has been the scene of enormously productive gas development, particularly since the Second World War. The geographic extent of the Carboniferous-Rotliegend TPS is similar to the area referred to as the southern North Sea in previous USGS assessments (Masters and others, 1997). The subdivision of the Carboniferous-Rotliegend TPS into three AU was done mainly because of differences in technology and economics of onshore versus offshore operations. The three AU are the Southern Permian Basin-U.K. Onshore (40360101), the Southern Permian Basin-Europe Onshore (40360102), and the Southern Permian Basin-Offshore (40360103).

One TPS and three AU were also defined in the North Sea Graben Province (4025) (Region 4 province map). The single complex TPS, the Kimmeridgian Shales TPS (402501), refers to the mainly upper Jurassic marine shales of the Kimmeridge Clay and related rocks that are responsible for most petroleum in the northern North Sea Graben Oil and gas accumulations occur in a wide variety of structures and traps including Province. Paleozoic and Mesozoic pre-rift rocks involved in structural blocks, mid Jurassic to earliest Cretaceous rocks that accumulated during rifting (syn-rift sequences), and post-rift sedimentary sections that fill and cover earlier strata and structures.

Nevertheless, the AU were defined geographically, –and named the Central Graben (40250103), the Viking Graben (40250101), and the Moray Firth (40250102).

To the north, two AU were defined and assessed along the Atlantic margin of mid-Norway, the Vestford-Helgeland Province (4017). The first AU includes the area of previous exploration and development in the vicinity of the Halten Terrace and Trondelag Platform and is named the Halten Terrace-Trondelag Platform AU (40170101). The other AU is the adjacent frontier area of the shelf and continental margin, the Mid-Norway Continental Margin AU (40170102). As in the North Sea Graben Province, the mid-Norway area is dominated by a single TPS, the source rock of which is the upper Jurassic anoxic marine shales that accumulated during rifting. In the Vestford-Helgeland Province, these highly organic rich shales are known as the Spekk Formation, and thus the TPS is named Upper Jurassic Spekk (401701).

In southern Europe, two AU were defined within two TPS of the Po Basin Province (4060); one, the Thermal Triassic AU (40600201) in the Triassic marine rocks that accumulated in and adjacent to a carbonate platform during Mesozoic rifting, and a second, the Neogene Flysch Gas AU (40600101) within the Neogene marine flysch section.

In eastern Europe, six AU were defined and five were assessed in the Pannonian Basin Province (4048); the Greater Hungarian Plain Basins AU (40480101); the Mesozoic/Neogene of the Zala-Drava-Sava Basins AU (40480201), the Neogene of the Danube Basin (Danube Basin AU, 40480301), the Neogene of the Transcarpathian Basin (AU 40480401), and the Paleogene of the Hungarian Paleogene Basin (AU 40480601). One composite TPS (Transylvanian Composite, 405701) with one AU was evaluated in the Transylvanian Basin Province (4057). Two TPS and three AU were evaluated in the Carpathian-Balkanian Basin. These are the Moesian Platform AU (40610101), the Romania Flysch Zone (40610201), and the Romania Ploiesti Zone AU (40610202). Three TPS were defined and three

AU were assessed in the North Carpathian Basin Province (4047); one was the Isotopically Light Gas TPS (404701), with the Foreland Basin AU (40470101), a second the Mesozoic/Paleogene Composite TPS (404702) which included the Deformed Belt AU (40470201) contained most rocks of the deformed belt itself, and the third, the Paleozoic Composite TPS (404703) with the Paleozoic Reservoirs AU (40470301) includes all reservoirs of Paleozoic age. Province Basin (4068) was the only province assessed in the Mediterranean Basin (Region 4 province map).

Many interesting, prospective, and historically important oil and gas provinces of Europe, including the Paris Basin, the Vienna Basin, Lower Saxony, and most offshore areas of the Mediterranean Sea, were not considered during this assessment.

RESULTS AND SIGNIFICANCE OF THE ASSESSMENT

Results of the assessment of eleven provinces in Region 4 (Europe) are summarized in a (Region 4 Assessment Summary) for Europe. It is estimated that between 6.4 and 45.4 billion barrels of oil remains undiscovered within the selected provinces of Europe considered in this assessment. Undiscovered gas resources are estimated to range between 44.7 and 733.4 trillion cubic feet (TCF). Natural gas liquids add from 1.6 to 34.2 billion barrels to the undiscovered resources of the selected provinces of Europe. Mean values of estimated undiscovered resources are 22.3 BBO, 312 TCF of natural gas and 13.7 billion barrels of natural gas liquids. Although not directly comparable on a province by province basis with previous USGS world energy assessments, a comparison is instructive. In the last published USGS world energy assessment (Masters and others, 1997), many more European provinces were evaluated, and the Barents Sea in particular was included in Europe. In that earlier assessment, undiscovered resources of oil were estimated to range from 9.3 to 39.7BBO, with a mean of 21.2BBO, a volume remarkably similar to the results of the current assessment. Undiscovered natural gas was estimated in the previous

assessment to range between 125 and 462 TCF, with a mean value of about 260 TCF, a mean volume somewhat smaller than the results of the present assessment.

North Sea

The North Sea is the most significant oil and gas province of Europe, with cumulative production and proved reserves in excess of 77 BBOE. If the gas-prone region of the Anglo Dutch Basin Provinces is included, the North Sea is predominant, with cumulative production and proved reserves of more than 115 BBOE.

In the current assessment, undiscovered oil resources for the North Sea Graben Province are estimated to range from 4.3 to 25.6 BBO, with a mean value of about 13 BBO. It is further estimated that another 11.8 to 75.0 TCF occurs as undiscovered associated and nonassociated natural gas, with a mean estimate of 37.7 TCF. Additional resources include significant quantities of natural gas liquids in both oil and gas accumulations. In the last USGS world assessment (Masters and others, 1997), the "Central North Sea" of the United Kingdom and Norway, which roughly corresponds to the North Sea Graben Province in the present assessment, was estimated to have mean undiscovered oil resources of about 10 BBO. The previous assessment predicted mean undiscovered gas resources of approximately 40 TCF, with a range of 19 to 70 TCF. The mean values of undiscovered resources are thus only a few BOE different (slightly more oil and slightly less gas) than was estimated in the last assessment. Given the intensive exploratory activity in the North Sea in the intervening years, the large volume of assessed undiscovered resources could be considered surprising. Important additional recoverable oil and gas could be added to reserves by growth of existing fields as well.

In the southern Permian basin (parts of the Anglo-Dutch and Northwest German provinces), where natural gas is the predominant hydrocarbon type, and where intensive exploration both onshore and offshore has been going on for almost three

decades, three AU were defined and evaluated. The first two of these, the Southern Permian Basin-U.K. Onshore AU (40360101) and the Southern Permian Basin-Europe Onshore AU (40360102) have been the object of exploration for many decades. Indeed, the enormous Groningen gas field in the Netherlands was the initial impetus for all North Sea exploration and development (Stauble and Milius, 1970). Although undiscovered resources in the onshore part of the United Kingdom are relatively minor, undiscovered resources associated with the Carboniferous-Rotliegend TPS (403601) in the Southern Permian Basin are believed to range from 23 to 148 million barrels of oil, and from 5.0 to 21.6 TCF of natural gas, plus gas associated with undiscovered oil and significant quantities of natural gas liquids. Offshore, undiscovered oil resources are estimated to range from just 13 million barrels to about 133 million barrels. Undiscovered natural gas resources are estimated to range from 2.8 TCF to more than 27.6 TCF, not to mention NGL and associated gas. Thus estimated mean values of undiscovered resources in the onshore and offshore areas of the Anglo Dutch Basin and adjacent parts of the Northwest German Basin provinces are about 144 million barrels of oil and more than 26 TCF of natural gas. These estimates are comparable to those reported by the USGS in 1997 (mean=24 TCF)(Masters and others, 1997), and reflect both remarkable success of explorationists in the southern North Sea area and the increased importance of natural gas recognized in the current World Energy assessment. In addition to these undiscovered resources, significant volumes of gas could be added to reserves as a result of growth in existing fields.

Vestford-Helgeland Province (4017), Norwegian Sea

For this assessment, most of the continental shelf and margin seaward of mid-Norway is in the Vestford-Helgeland Province. The area was divided into AU, both sourced by the upper Jurassic marine Spekk Formation shale. The first, the Halten Terrace-Trondelag Platform AU, includes the explored and developed parts of the Halten Terrace and adjacent areas. This AU was estimated to contain between 1.3 to 13.1 billion barrels of undiscovered oil plus significant amounts of natural gas liquids, and 8.4 to 82.1 TCF of undiscovered nonassociated natural gas, as well as a

similar amount of associated gas in oil fields. We believe that the largest undiscovered oil field remaining to be found in this assessment unit will contain between 300 million barrels of oil to 1.9 BBO. The volume of the largest undiscovered gas field is estimated to be in the range of 1.9 to 11.3 TCF.

The second AU in the Vestford-Helgeland Province includes the frontier areas seaward of and adjacent to the Halten Terrace-Trondelag Platform, and is referred to as the Mid-Norway Continental Margin AU (40170102). This area is thought to be gas prone, given current theories of thermal maturity of Jurassic source rocks in the area. We estimate that this frontier region contains only 31 million to 786 million barrels of undiscovered oil in oil fields (mean=334 MMBO). In contrast, undiscovered gas resources are estimated to range from 1.4 TCF to 269 TCF, with a mean value of 107 TCF, plus minor amounts of gas associated with oil and a large amount of natural gas liquids. The size of the largest undiscovered gas accumulation in the Mid-Norway Continental Margin area is an important issue for analysis of economics in this extremely harsh (for drilling) region and one fraught with uncertainty. Our estimates suggest that the biggest accumulation contains between 4.7 and 93 TCF of natural gas (mean=31.9 TCF). This large range is cautionary, as it illustrates the uncertainty associated with assessment of undiscovered resources in frontier regions. With respect to economically viable exploration and production, the remote parts of the mid-Norway Continental Margin AU are difficult at best, and their development is by no means certain. Nevertheless, the area is highly interesting from the point of view of geologic possibilities for gas accumulations and will no doubt be the subject of further exploration.

To compare the current assessment with the earlier USGS assessment of the Norwegian Sea, one must consider the Vestford-Helgeland province of the current assessment and the Voring, Helgeland, Harstad, and Tromso provinces of the preceding USGS assessment (Masters and others, 1997). The current assessment estimates a mean total of about 6.5 BBO undiscovered, with a range of 1.4 to 13.9 BBO. This estimate reflects the vast area's relatively low potential for undiscovered

oil, and is similar to the estimate (~2.8 BBO) from the assessment of Masters and others, 1997. Gas is a different story, however. The current estimate of 165 TCF, with a range of 13.7 to 395.5 TCF is much greater than the mean value of 28 TCF of undiscovered gas reported in the earlier USGS assessment. The low estimates in the previous assessment probably reflect the perception of economic improbability associated with gas development in this difficult frontier area. Moreover, the earlier USGS assessment was generally limited to offshore areas with water depths of less than 300 m. The extreme parts of the Norwegian shelf evaluated in the current assessment reach water depths of 1000 m or more.

Po Basin (4060)

The first of two AU defined in the Po Basin Province is the Neogene Flysch Gas AU, consisting mainly of gas accumulations believed to be biogenic, as well as lesser amounts of gas believed to be thermogenic or mixed thermogenic and biogenic. In spite of a relatively long history of exploration and production, significant potential exists for further gas exploration in the Po Basin. Undiscovered gas resources were estimated to range between 6.4 and 29.0 TCF, with a mean value of about 16.3 TCF and 34 million barrels of NGL. The largest undiscovered field is believed to be between 491 BCF and 1.8 TCF in volume, indicating significant potential for further economic discoveries within the basin.

In addition to gas in the Neogene Flysch, a second AU, the Meride/Riva di Solto TPS, an oil-prone unit sourced in Triassic rocks and named the Thermal Triassic AU, was estimated to contain between 39 and 916 million barrels of oil. The same AU is thought to contain between 81 BCF and 2.1 TCF of associated natural gas as well as some NGL and a similar amount of gas in gas fields (111 BCF to 2.3 TCF). Mean values of undiscovered oil and gas resources were estimated at 360 MMBO and O.9 TCF, respectively.

In total, we estimate that between 39 and 916 MMBO and between 6.6 and 33.5 TCF of gas remain undiscovered in the Po Basin. These volumes of undiscovered

resources are not directly comparable with the results of the previous USGS assessment (Masters and others, 1997). In that study, the undiscovered gas resources of the Po were reported to be negligible; oil was estimated at 0.9 BB. The greater Adriatic Basin province, which was included in the earlier study, was not assessed as part of the current project.

Eastern Europe

This geologically complex and extensively explored collection of basins includes the Carpathian-Balkanian Basin, the Transylvanian Basin, the Pannonian Basin, and the North Carpathian basin. These were evaluated as twelve AU.

The basins have had significant historical production, which ranks them among those priority basins assessed for this project. In particular, the Carpathian-Balkanian Basin Province (4061), which ranks number 42 in the world (excluding the United States) has reserves plus cumulative production in excess of 7.2 BBOE. The current assessment estimated undiscovered resources in the Carpathian-Balkanian Basin of about 1 BBO and 3.2 TCF of natural gas. In addition, some new reserves can be expected as a result of growth in existing fields. The Transylvanian Basin Province (4057), ranked 56th in the world (exclusive of the United States) has a total of proved reserves and cumulative production slightly in excess of 5 BBOE. Our current estimates of undiscovered resources for the Transylvanian Basin Province range from 460 BCF to 4.5 TCF of natural gas as well as some related natural gas liquids. Likewise, the Pannonian Basin Province (4048) is estimated to contain about 360 MMBO and about 4.1 TCF of undiscovered gas. The North Carpathian Basin Province (4047), ranked 82 in the world, is estimated to contain about 391 MMB of undiscovered oil and 5.0 TCF of undiscovered gas.

In comparison, during the previous USGS world energy assessment (Masters and others, 1997), the entire area of Eastern Europe was estimated to contain and about 2.7 BB of undiscovered oil and about 39 TCF, at the mean level, of undiscovered natural gas. The current assessment estimates a total of about 1.76 BBO and 145.2

TCF of natural gas for the same region. These numbers are not perfectly comparable, but indicate similar views concerning potential for undiscovered resources in Eastern Europe. Potential for growth of reserves in old existing fields is not included in the current assessment.

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