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Geology and Assessment of the Undiscovered, Technically Recoverable Petroleum Resources of Armenia, 2013

Digital Data Series 69–PP

U.S. Department of the Interior
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By T.R. Klett

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Suggested citation:
Klett, T.R., 2016, Geology and assessment of undiscovered, technically recoverable petroleum resources of Armenia, 2013: U.S. Geological Survey Digital Data Series 69–PP, 21 p., http://dx.doi.org/10.3133/ds69PP.

ISSN 2327-638X (online)

Acknowledgments

The authors are grateful for the data and consultation from the Armenia Ministry of Energy and Natural Resources and its agencies. Specific agencies include National Geological Fund and Geological Scientific Institute. We thank Mr. Areg Galstyan (Deputy Minister of Energy and Natural Resources of the Republic of Armenia [RA]), Mr. Hrachik Tsughunyan (Head of Development Department, Ministry of Energy and Natural Resources of RA), Mr. Vardan Vardanyan (Head of Natural Resources Department—Subsoil, Ministry of Energy and Natural Resources of RA), Ms. Victoria Keshishyan (Head of International Economic Cooperation Division, Ministry of Energy and Natural Resources of RA), Mr. Shushanik Kerobyan (Head of Minerals Division, Ministry of Energy and Natural Resources of RA), Ms. Karen Gasparyan (Head of Nature Management Economic Division, Ministry of Energy and Natural Resources of RA), Mr. Gevorg Hovsepyan (Director of National Geological Fund), Mr. Arkady Karakhanyan (Director of Geological Scientific Institute), and Mr. Gourgen Malkhassyan (Geophysicist), Mr. Gaggik Papyan, Mr. Hrachik Chubaryan (Geologist), and Mr. Tim Papworth (Blackstairs Energy Plc., Armenia) were particularly helpful in providing information and insights allowing us to better understand the petroleum geology and unconventional oil and gas resource potential of the basins in Armenia.

The authors are grateful for the coordination and logistical help provided by the U.S. Department of State. Individuals include Ms. Elizabeth Hanny (Economic and Commercial Officer, Embassy of the United States of America, Yerevan, Armenia), Mr. Brian Roraff (Embassy of the United States of America, Yerevan, Armenia), Ms. Megan Bouldin (formerly Economic and Commercial Officer, Embassy of the United States of America, Yerevan, Armenia), Mr. Aleksey Hovakimyan (Economic Specialist, Embassy of the United States of America, Yerevan, Armenia), Ms. Marina Vardanyan (Energy and Water Team Leader, U.S. Agency for International Development, Yerevan, Armenia), Ms. Lilit Antonyan (Administrative Assistant, Political/Economic Section, Embassy of the United States of America, Yerevan, Armenia), Mr. David Stevenson (Acting Political-Economic Section Chief, Embassy of the United States of America, Yerevan, Armenia), and Mr. John Heffern (U.S. Ambassador to Armenia, Embassy of the United States of America, Yerevan, Armenia).

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Conversion Factors

Multiply	By	To obtain
barrel (bbl)	0.1590	cubic meter (m^3)
barrel (bbl)	0.136	metric ton (MT), average gravity
cubic feet (ft^3)	0.02382	cubic meter (m^3)
cubic meter (m^3)	35.3147	cubic feet (ft^3)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square meter (m^2)	10.76	square foot (ft^2)

Geology and Assessment of the Undiscovered, Technically Recoverable Petroleum Resources of Armenia, 2013

By T.R. Klett

Abstract

The U.S. Geological Survey (USGS) assessed the undiscovered, technically recoverable oil and gas resources of Armenia in 2013. A Paleozoic and a Cenozoic total petroleum system (TPS) were identified within the country of Armenia. The postulated petroleum system elements are uncertain, resulting in low geologic probabilities for significant oil and gas resources. Two assessment units (AU) were delineated in each TPS—a Paleozoic-Sourced Conventional Reservoirs AU and a Permian Shale Gas AU in the Paleozoic Composite TPS and a Paleogene-Sourced Conventional Reservoirs AU and a Cenozoic Coalbed Gas AU in the Cenozoic Composite TPS. The TPS elements are largely uncertain and risked, and so only the Paleogene-Sourced Conventional Reservoirs AU was quantitatively assessed because the geologic probability is more than the threshold of 10 percent (that is, the probability of at least one conventional oil or gas accumulation of 5 million barrels of oil equivalent or greater based on postulated petroleum-system elements). The USGS estimated fully risked mean volumes of about 1 million barrels of oil (MMBO), about 6 billion cubic feet of natural gas (BCFG), and less than 1 million barrels of natural gas liquids (MMBNGL).

Introduction

The U.S. Geological Survey (USGS) assessed the undiscovered, technically recoverable oil and gas resources of Armenia in 2013. Two total petroleum systems (TPSs), each having two assessment units (AUs), were identified and delineated. The geology and the postulated TPS elements are uncertain, resulting in low geologic probabilities for significant oil and gas resources. Although all of the AUs were evaluated, only one was quantitatively assessed.

Armenia is a landlocked country located in the Lesser Caucasus Province, between the Black and Caspian Seas (fig. 1). Neighboring countries include Turkey to the west, Georgia to the north, Azerbaijan to the east, Iran to the southeast, and Nakhichevan (part of Azerbaijan) to the south. The country straddles a tectonic plate boundary with the South Armenian block in the south and the Eurasian continental plate to the north. Several geologic intermontane basins containing Paleozoic, Mesozoic, and Cenozoic sedimentary rocks are present. These basins developed during the collision of the Gondwanan South Armenian block with the Eurasian continental plate during the closing of the Tethyan seaways during the Mesozoic (fig. 2).

Tectonostratigraphic Development

The South Armenian block was part of a northern passive margin of Gondwana. Paleozoic rocks include Upper Devonian marine clastic rocks (at least 1,000 meters [m] thick), Lower Carboniferous reef limestones (ranging from 500 to 700 m thick), and Permian platform carbonate rocks. Upper Devonian and Permian rocks could be petroleum source rocks (Sosson and others, 2010). Silurian and Lower and Middle Devonian marine clastic and carbonate rocks crop out in Nakhichevan and are presumed to be present in Armenia (SPT/Partex, written commun., 1995). Middle and Upper Carboniferous rocks are generally absent in Armenia.

The South Armenian block separated from Gondwana during the Permian and drifted northward toward the Eurasian continental plate during the Triassic and Jurassic (SPT/Partex, written commun., 1995). Shallow water limestones, sandstones, and coals were deposited in the Triassic and range from 700 to 900 m thick. During the Jurassic, subduction and back arc rifting (forming the Sevan–Akera intraocean basin and eventually a suture zone) occurred along the Eurasian continental margin (fig. 2; Sosson and others, 2010). Jurassic clastic and volcanic rocks are present in the northern and eastern parts of Armenia in the Somkhet–Karabakh Zone and Kapan Block (Mariposa Petroleum Company, written commun., 1994). Few Jurassic rocks have been identified on the South Armenian block, in the southern part of the country. A large portion of the South Armenian block underwent nondeposition or erosion during the Early Cretaceous (Valanginian and Hauterivian) (Mariposa Petroleum Company, written commun., 1994). Upper Cretaceous sediments include reef-carbonate, clastic, and volcanogenic rocks (SPT/Partex, written commun., 1995). As the South Armenian block approached the Eurasian continental plate during the Late Cretaceous and Paleocene, intraoceanic crust of the Sevan–Akera back arc basin was thrusted over the block resulting in obduction of ophiolites. Three ophiolite belts have been identified in Armenia: Sevan–Akera, Zangezur, and Vedi (SPT/Partex, written commun., 1995).

Figure 1. Map showing location of U.S. Geological Survey delineated geologic provinces of Armenia and surrounding countries that were assessed in this study. Locations of the Araks (2080) and Lesser Caucasus (2081) Provinces are shown by red outlines.

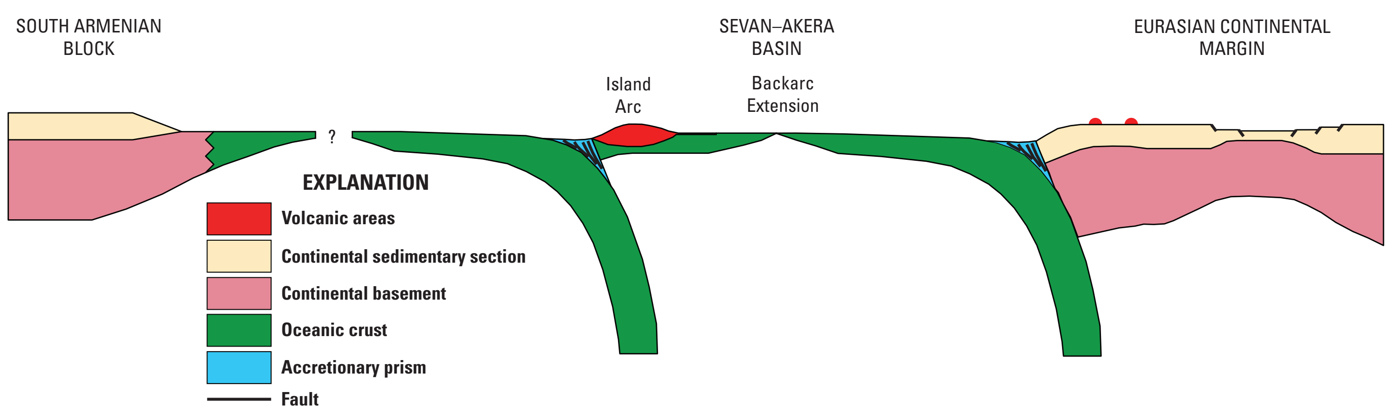

Figure 2. Diagram of a tectonic model of the Lesser Caucasus area before the South Armenian Block–Eurasian Margin collision during the Late Jurassic (about 140 million years ago). Modified from Sosson and others (2010).

Collision of the South Armenian block with the Eurasian continental plate occurred during the Paleocene (Sosson and others, 2010). Paleocene sediments include marine carbonate rocks passing upward into terrigenous clastic rocks deposited as shallow-water turbidites (Mariposa Petroleum Company, written commun., 1994; SPT/Partex, written commun., 1995). Lower Eocene rocks are mainly calcareous, but become more clastic and volcanogenic upward. Middle Eocene rocks are primarily tuffs and tuffaceous sediments. During the late Eocene to Miocene, nearshore marine, paralic, deltaic, and lagoonal conditions existed, depositing red beds, nearshore marine and lacustrine clastic rocks, coal, and evaporites in present-day southern Armenia. Magmatic and volcanic activity has occurred from Eocene to present (Sosson and others, 2010).

Structure

The main tectonic element is the Sevan–Shirak Zone (suture) which separates the Eurasian continental margin to the north and the South Armenian Block to the south (fig. 3, location shown in figure 4). Schematic regional geologic cross sections showing the tectonic elements and generalized rock units are shown in figures 5, 6 and 7.

Eurasian Continental Margin

In the northern part of Armenia, deformed remnants of a back arc basin comprise the Transcaucasus area of the Eurasian continental margin (Sossan and others, 2010).

Bazum and Somkhet–Karabakh Zones

Small tectonic blocks containing Mesozoic sedimentary and volcanogenic rocks, the Bazum Zone and Somkhet–Karabakh Zone, are located north the Sevan–Shirak Zone. The Somkhet–Karabakh Zone is interpreted to be remnants of island arcs (Adamia and others, 1977; Gabrielyan, 1980; Sossan and others, 2010). The Bazum Zone might also be a continuation of this island arc remnant. The Somkhet–Karabakh Zone forms the southern part of the Kura Basin. Both the Somkhet–Karabakh and Bazum Zones contain Triassic and Jurassic igneous and metamorphic rocks (Mariposa Petroleum Company, written commun., 1994) with overlying Middle Jurassic to Cretaceous sedimentary rocks (SPT/Partex, written commun., 1995) (figs. 5 and 6). Structures include reverse faulted blocks and thrust sheets. Both zones were modified by a significant number of igneous intrusions (SPT/Partex, written commun., 1995).

Sevan–Shirak Zone

A deformed belt along the suture zone (the Sevan–Shirak Zone) trends northwest-to-southeast and separates the Somkhet–Karabakh and Bazum Zones to the north from sedimentary basins to the south (figs. 5 and 6). A thick section of Eocene tuffs and volcanics, which can be intensely deformed, covers the belt (SPT/Partex, written commun., 1995).

South Armenian Block

In the Lesser Caucasus of Armenia, some of the intermontane basins (also called depressions hereafter) contain sufficient thicknesses of sedimentary and volcanogenic rocks ranging in age from Paleozoic to Holocene that they could provide viable petroleum systems. The depressions include (1) the Shirak and Sabunchi Depressions along the western border with Turkey, (2) the Central Depression in the central part of Armenia, (3) the Ararat Intermontane Depressions along the southern border with Turkey, and (4) the Jermuk Depression along the eastern border (fig. 4).

Shirak and Sabunchi Depressions

The Shirak and Sabunchi Depressions are part of the Kars Basin in Turkey. A thick section of Eocene to Pliocene volcanogenic and clastic rocks with igneous intrusions was observed in the only two exploratory wells drilled in the Shirak Depression (SPT/Partex, written commun., 1995). Although not penetrated by drilling, Upper Jurassic to Cretaceous rocks might be present in deeper parts of these depressions based on outcrops in the Bazum Zone (Tumanyan, 1986; Mariposa Petroleum Company, written commun., 1994; SPT/Partex, written commun., 1995). However, the Shirak Depression is separated from Bazum Zone by the Tumanian trough and ophiolites at Amasya (suture zone) (Sosson and others, 2010). The Sabunchi Depression is assumed to have stratigraphy similar to that of Shirak, but was likely deposited in a shallower basin.

Central Depression

The Central Depression consists of several smaller depressions separated by structural highs. The major subdepressions are the Sevan, Near Yerevan, and Chatma–Vedi. The Vaiotsdzor area is an extension of the Central Depression. The Aragats volcanic complex is located near the northwestern end of the Central Depression. Numerous oil and gas exploration wells were drilled (figs. 4 and 8).

The Near Yerevan depression (in the middle part of the Central Depression) contains Upper Cretaceous to Neogene marine, continental, and lacustrine clastic rocks overlain by Pliocene to Holocene volcanic rocks (fig. 7). Permian to Lower Cretaceous rocks might be present beneath the Cenozoic section. The Near Yerevan depression, north of the Garni fault zone (fig. 8), contains a complete stratigraphic section of middle Eocene to Holocene clastic and volcanogenic rocks and has undergone a moderate amount of exploration (SPT/Partex, written commun., 1995). Close to the Garni fault zone, in the Garni–Shoraghbyur area, the depression contains

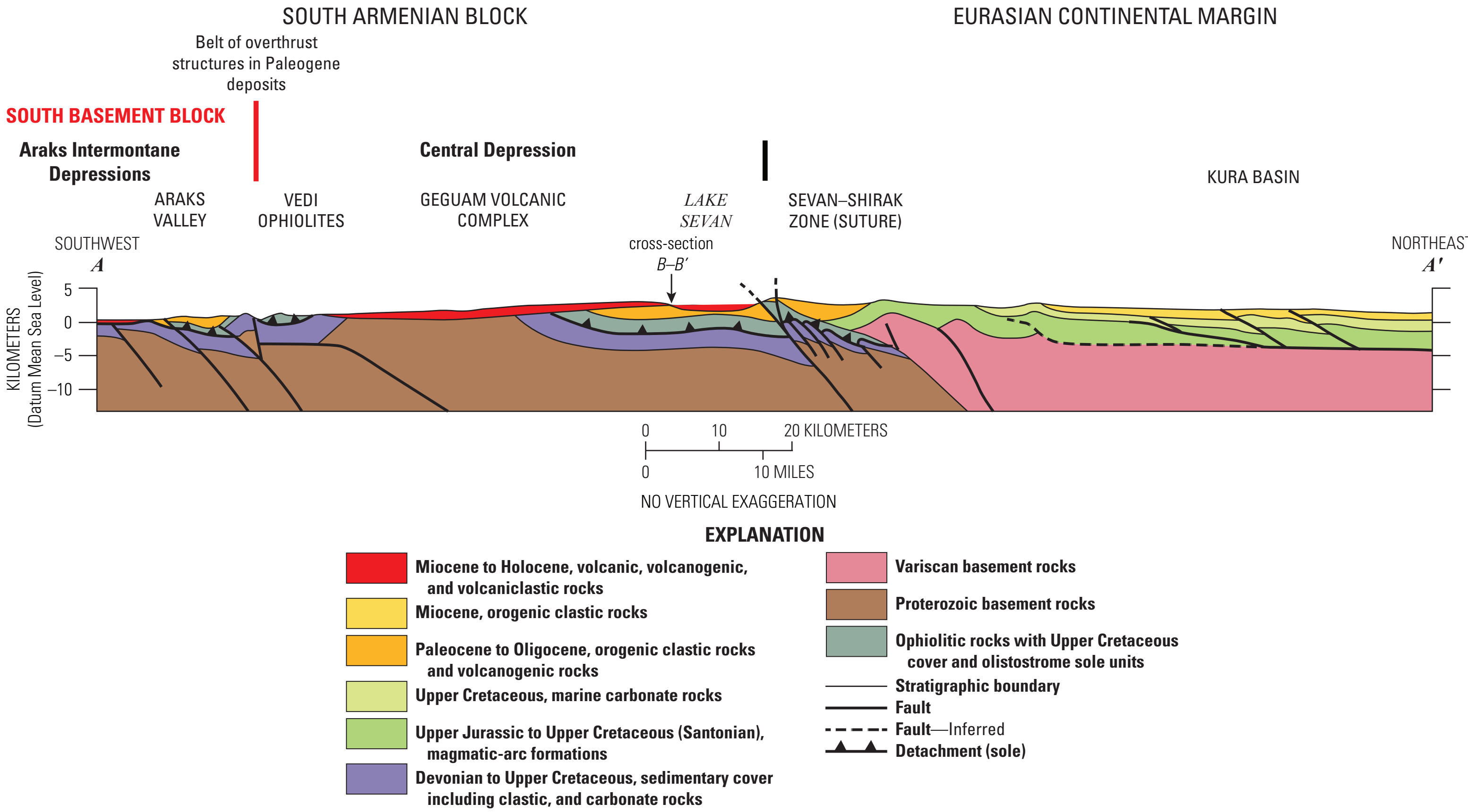

Figure 3. Schematic tectonic geologic cross section (*A–A′*) of Armenia showing major tectonic elements. Location of cross section is shown in figure 4. Modified from Sosson and others (2010).

Figure 4. Map showing major tectonic elements of Armenia, location of cross sections, and known well locations. Tectonic elements from SPT/Partex (written commun., 1995).

Upper Cretaceous to lower Eocene carbonate and clastic rocks and middle Eocene to Oligocene volcaniclastic and clastic rocks. Middle and upper Miocene rocks are absent in the Garni–Shoraghbyur area, presumably by erosion or nondeposition (SPT/Partex, written commun., 1995; Papworth and Aghabalyan, 2002).

To the southeast, the Chatma–Vedi depression contains Permian carbonate rocks overlain by Cenomanian to lower Coniacian carbonate rocks (figs. 7 and 8). Upper Jurassic to Cretaceous Vedi ophiolites were emplaced above the Cretaceous carbonate rocks. Coniacian to Maastrichtian carbonate rocks unconformably overlie the ophiolites, while Paleocene to Eocene gravity debris flow sediments of clastic and carbonate rocks and Pliocene volcanic rocks overlie the Upper Cretaceous carbonate rocks. Oligocene and Miocene rocks are absent (SPT/Partex, written commun., 1995).

The Vaiotsdzor area contains Middle? to Upper Devonian clastic and carbonate rocks (figs. 6 and 8; Sadoyan and Aslanyan, 1981) overlain by Carboniferous? through Triassic carbonate rocks and Middle Jurassic carbonates and mudstone. Upper Cretaceous to Paleocene carbonate and clastic rocks unconformably overlie these rocks. Eocene carbonate (reefs), clastic, volcanic, and volcanogenic rocks are at the top of the section.

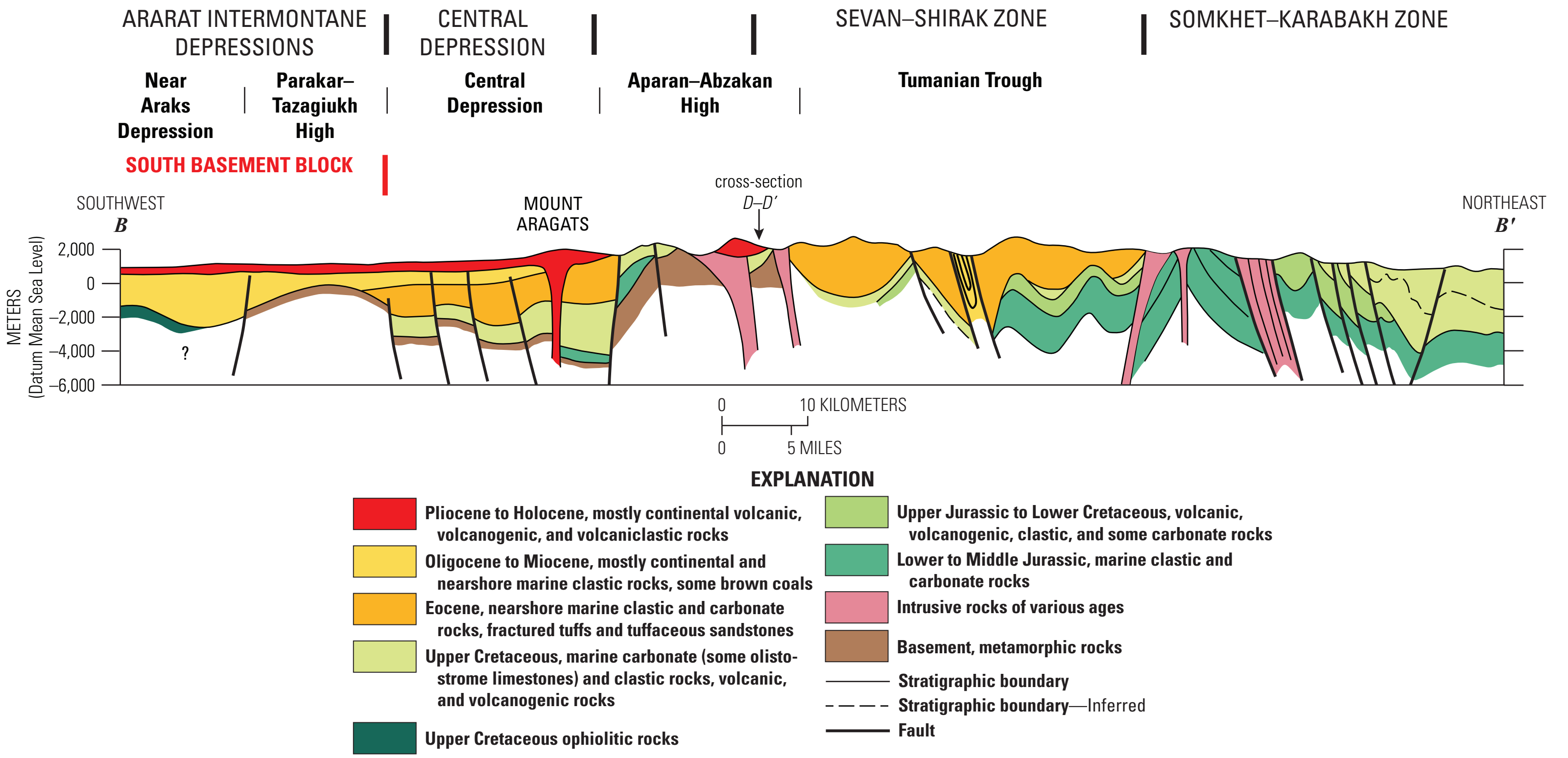

Figure 5. Schematic regional geologic cross section (*B–B′*). Location of cross section is shown in figure 4. Modified from SPT/Partex (written commun., 1995).

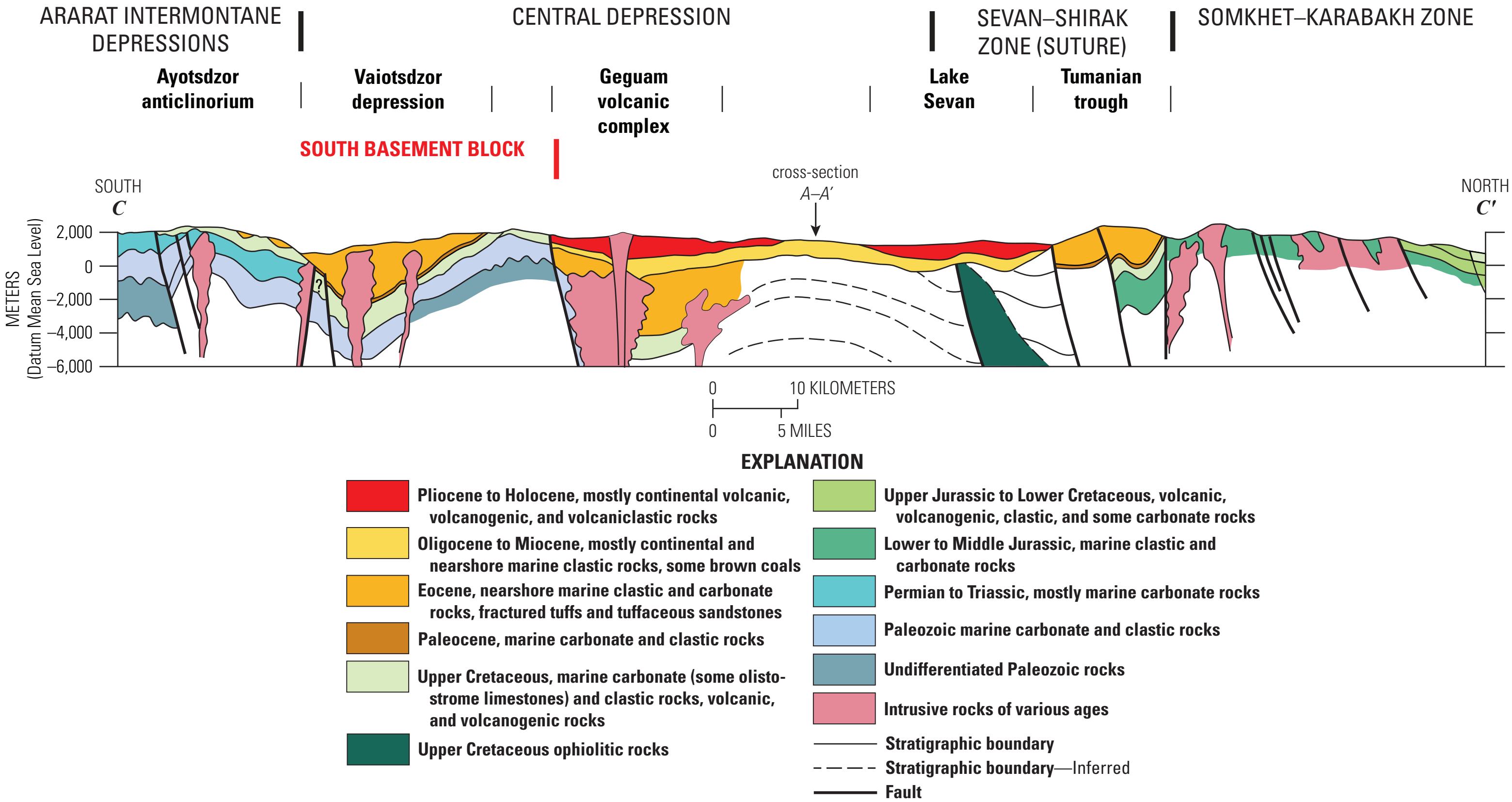

Figure 6. Schematic regional geologic cross section (*C*–*C*′). Location of cross section is shown in figure 4. Modified from SPT/Partex (written commun., 1995).

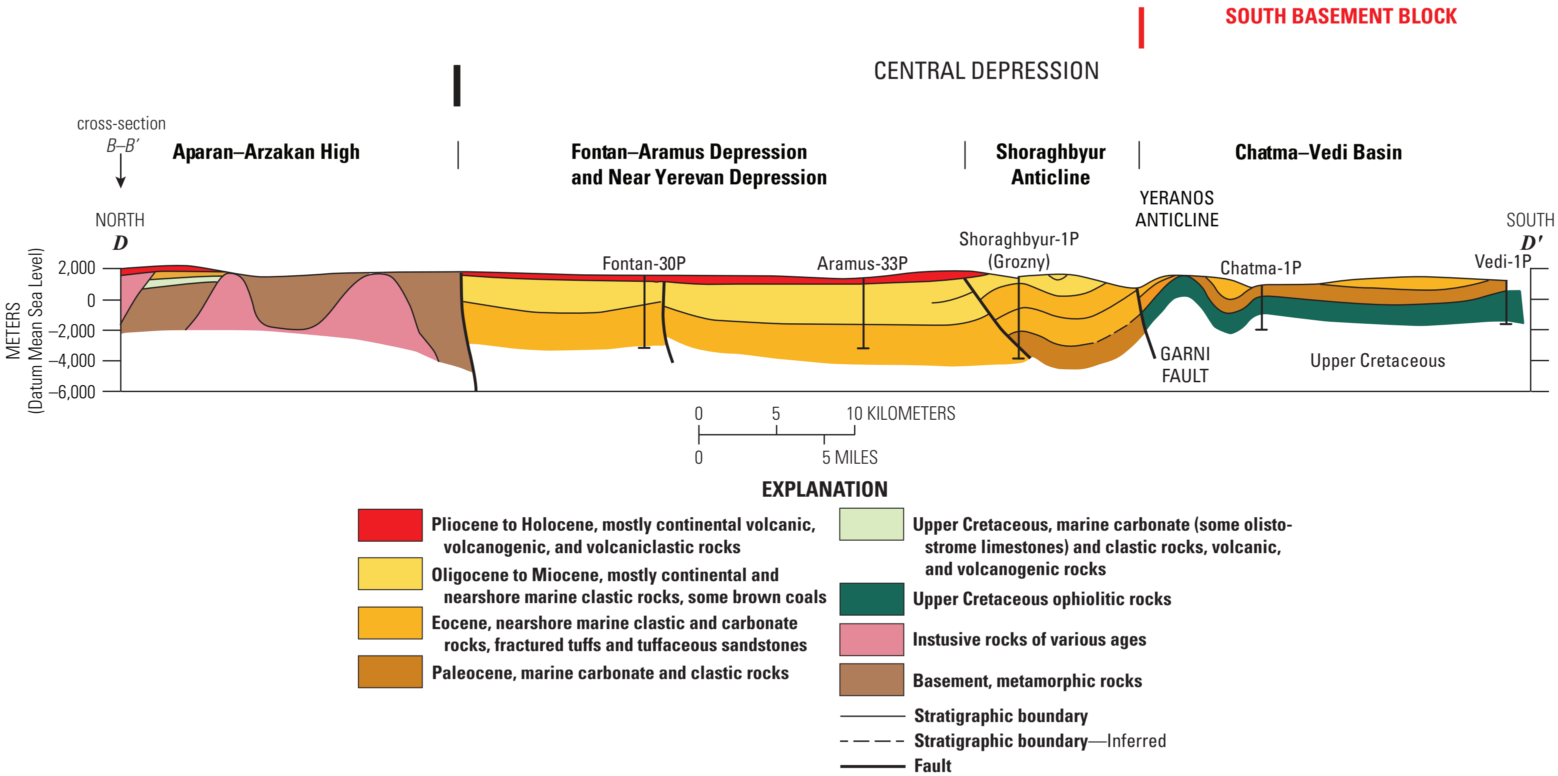

Figure 7. Schematic geologic cross section through the Central Depression (*D*–*D′*). Location of cross section is shown in figure 4. Modified from SPT/Partex (written commun., 1995).

Figure 8. Map showing major basement faults and depressions of Armenia and known well locations. Depression boundaries from SPT/Partex (written commun., 1995) and basement faults modified from Papworth and Aghabalyan (2002). Well names are *A*, Hoktemberyan-1P (Grozny), Hoktemberyan-7P, and Hoktemberyan-13E; *B*, Hoktemberyan-1R; *C*, Hrazdan-14P; *D*, Fontan-30P, *E*, Aramus-33P; *F*, Shoraghbyur-1P (Grozny) and Shoraghbyur-31P; *G*, Azat-1/1A and Garni-1G; *H*, Chatma-1P; *I*, Vedi-1T (also called Karabakhlar-1) and Vedi-17; *J*, Yeranos-1. The south basement block is located south of the southern major fault.

Ararat Intermontane Depressions

The Ararat Intermontane Depressions consist of three smaller depressions separated by structural highs that were formed by Pliocene deformation (fig. 3; SPT/Partex, written commun., 1995). From west to east, these are the Hoktemberyan depression, the Artashat (or Near Araks) depression, and the Surenavan depression. The Hoktemberyan and Artashat Depressions have undergone much exploration and study. The sedimentary sections in these two depressions contain mainly Cenozoic clastic and volcanogenic rocks overlying Upper Cretaceous volcanogenic rocks (ophiolites) or Paleozoic rocks (figs. 5 and 6; SPT/Partex, written commun., 1995; Papworth and Aghablyan, 2002). The Surenavan depression (the smallest of the group) has not been drilled, but a stratigraphy similar to the other two depressions is postulated (SPT/Partex, written commun., 1995).

The Hoktemberyan depression contains ophiolites overlain by middle Eocene to upper Miocene, mainly nearshore marine, continental, and lacustrine clastic rocks. Pliocene to Holocene volcanic rocks and alluvium overlie the Miocene rocks.

The Artashat depression contains possible ophiolites overlain by Upper Cretaceous to upper Miocene rocks, mainly nearshore marine, continental, and lacustrine clastic rocks. Pliocene to Holocene volcanic rocks and alluvium are present at the top of the section. Paleozoic rocks might be present beneath the ophiolite.

The Surenavan depression has not been drilled and the stratigraphy is inferred by outcrops. The stratigraphy is expected to be similar to that of the Artashat sub-basin (SPT/Partex, written commun., 1995). Paleozoic rocks might be present based on exposures and a well drilled across the Araks River in Nakhichevan.

Jermuk Depression

The Jermuk Depression is located along the eastern border with Azerbaijan north of the Meghri Block. It has not been drilled and the subsurface stratigraphy is not well understood. Quaternary basalts cover this depression.

Kapan and Meghri Blocks

Two tectonic elements are located in the southeastern part of the country, the Kapan and Meghri Blocks (fig. 3). The Meghri and Kapan rocks are immediately adjacent to one another, separated by a structural dislocation. The Kapan Block is an area where Jurassic and Cretaceous rocks directly overlay metamorphosed Precambrian to lower Paleozoic basement rocks (Mkrtchyan, 1971) and are overlain by Cenozoic volcanic and volcanogenic rocks cut by igneous intrusions (SPT/Partex, written commun., 1995). The stratigraphy appears similar to and might be associated with the Somkhet–Karabakh Zone. The Meghri Block is a basement high comprising mainly granodiorites and granites with overlying Cenozoic volcanic and volcanogenic rocks (Mkrtchyan, 1971; SPT/Partex, written commun., 1995).

Petroleum Occurrence

More than 200 wells were drilled for oil and gas in Armenia (fig. 8), but no commercial accumulations have been discovered at the time of this report. Several other wells were drilled for stratigraphic studies and coal exploration.

In the Garni–Shoragbyur area of the Central Depression, one oil well (Shoraghbyur-1P Grozny) and several wells with oil and gas shows have been reported (Azat-1/1A and Garni-1G) (figs. 7 and 8; Papworth and Aghabalyan, 2002). A few oil and gas shows were reported in wells along Lake Sevan, as well as some gas seeps. In the Chatma–Vedi and Vaiotsdzor areas (figs. 7 and 8), oil and gas shows were reported in one well (Vedi-1T) and were reported in the drilling fluid of some other wells. Degraded oil (bitumen and seep) is observed in Upper Triassic hard coal in the Jermanis area of the Chatma–Vedi depression.

In the Ararat Intermontane Depressions, primarily in the Hoktemberyan depression, two discovered gas wells (Hoktemberyan-7P and 13E) and several gas shows were reported in other wells (fig. 8). One heavy oil show (Hoktemberyan-1R) and degraded oil have been reported in some wells. Degraded oil (bitumen and in seeps) is observed at the Harsnasar outcrop in the Ararat Intermontane Depressions, near the Vaiotsdzor area in the Central Depression.

The petroleum geology in the Sevan–Shirak and Somkhet–Karabakh Zones was interpreted based on outcrops and a limited number of wells. Oil and gas shows have been reported in some wells and degraded oil (bitumen and asphalt) has been reported in some outcrops. Cenozoic brown coals that are exposed or near the surface in the Bazum and Somkhet–Karabakh Zones could be potential source and reservoir rocks for coalbed gas. In addition, Middle Jurassic hard coals in the Idjevan area of the Somkhet–Karabakh Zone (fig. 8) might be potential source rocks.

In the Kapan and Meghri Blocks, oil shows in the Nor Arevik coal mine area of the Meghri Block (fig. 8) and degraded oil (bitumen) in some shallow boreholes and outcrops were reported.

Total Petroleum Systems and Geologic Models

Undiscovered oil and gas resources were evaluated and assessed in this study on the South Armenian block, south of the suture zone. Two parallel basement blocks within the South Armenian block are identified. The south basement block contains the Ararat Intermontane Depressions and a southern portion of the Central Depression (Chatma–Vedi and Vaiotsdzor areas) (fig. 8). The south basement block is separated from the northern basement block to the north by a major basement fault where overthrust structures are present in Paleogene sediments (fig. 8). The Araks and Lesser Caucasus Province boundary approximately coincides with this fault.

The northern basement block contains the greatest portion of the Central Depression.

Two total petroleum systems (TPSs) were identified in this study: (1) a Paleozoic Composite TPS that comprises the south basement block, including the Ararat Intermontane Depressions and part of the Central Depression, and (2) a Cenozoic Composite TPS that includes most of the Central Depression, as well as the Bazum and Somkhet–Karabakh Zones. Potential coalbed gas resources were identified north of the suture in the Bazum and Somkhet–Karabakh Zones. A lithostratigraphic column, petroleum system events chart showing geologic elements, and major tectonic events for petroleum systems in basins of Armenia are shown in figure 9. Upper Cretaceous and Cenozoic rocks and petroleum shows in both basement blocks (Ararat Intermontane Depressions and Central Depression) are shown in figure 10.

Paleozoic Composite TPS

The Paleozoic Composite TPS lies within the Ararat Intermontane Depressions and the southeastern part of the Central Depression.

Source Rocks

The main potential source rocks include Permian organic-rich limestones, marls, and mudstones. In the Chatma–Vedi subdepression and the Vaiotsdzor area, Permian bituminous marls and shales with no overlying Triassic section were observed in outcrops near the Urts Mountains south of the Central subdepressions. Permian rocks in the Ararat-1 well (penetrated between 817 to 1,500 m) on the Ararat High between the Artashat and Surenavan depressions have total organic carbon contents of up to 1.25 weight percent (1,322 m) and vitrinite reflectance of 1.04 percent at an outcrop in the Chatma–Vedi subdepression. Permian rocks are reported to be thermally late mature to overmature with respect to petroleum generation elsewhere in the TPS (SPT/Partex, written commun., 1995). Although maximum burial is unknown, Permian rocks could have been buried to more than 5 km. Maximum burial is unknown, and this might have occurred during the Cretaceous (pre-Cenozoic), and was subsequently followed by erosion.

Cenomanian to Turonian carbonate rocks could possibly be organic rich. Gas shows in these rocks were observed in the Vedi-1T well (SPT/Partex, written commun., 1995). The report suggested that Turonian carbonate rocks observed in the Chatma–Vedi subdepression (Vedi-1T) could be source rocks in the Ararat Intermontane Depressions.

In the Vaiotsdzor area, Eocene carbonate and clastic rocks may be gas sources. These rocks were observed in the Martiros-2 and 3 wells, however, they were reported to be thermally immature (SPT/Partex, written commun., 1995). In addition, Oligocene mudstones interbedded with and overlying reservoirs (lower and middle Hoktemberyan suite) might be sources of petroleum.

Other source rocks have been proposed but not proven, including possible Silurian to Devonian marine mudstones, Upper Devonian mudstones and bituminous carbonate rocks (Galant, 1986, for example), and Carboniferous bituminous limestones, all of which are exposed in outcrops (Samodurov, 1985; SPT/Partex, written commun., 1995). Gas from Silurian to Devonian carbonate and clastic rocks drilled in Nakhichevan (Dagna well) was analyzed and contains measured hydrocarbon gas as high as 47.5 percent containing about 99 percent methane and some heavier homologs (Galant, 1986), with carbon dioxide and nitrogen.

Reservoir Rocks

Known reservoir rocks are present in Oligocene deltaic sandstones (Hoktemberyan suite). Some gas was produced from these sandstones in the Hoktemberyan depression (SPT/Partex, written commun., 1995). Eocene to Oligocene sandstones and middle Eocene fractured tuffs might provide reservoirs where reservoir quality is sufficient for petroleum accumulation. Other potential reservoir rocks that were suggested include fractured ophiolites (gas show in Hoktemberyan-1P Grozny), Upper Cretaceous to Paleogene turbidite sandstones and fractured limestones, and Triassic limestones and sandstones (SPT/Partex, written commun., 1995). Permian fractured limestones are possible reservoirs and were suggested to be present in the Chatma–Vedi subdepression and Vaiotsdzor area (SPT/Partex, written commun., 1995).

Seal Rocks

Seal rocks are mainly Eocene to Oligocene intraformational mudstones. Cretaceous carbonate rocks and mudstones, and Miocene evaporite rocks are also possible seals.

Traps

Traps include anticlines and potential stratigraphic traps. The anticlines are generally reverse-faulted and thrust-faulted anticlines, which developed during the late Miocene and Pliocene. Timing of petroleum generation from the aforementioned source rocks in relation to trap development is unknown. Petroleum generation possibly occurred before the Cenozoic. Neogene deformation and inversion most likely affected retention of any previously accumulated petroleum.

Cenozoic Composite TPS

The Cenozoic Composite TPS lies within the Central Depression and the Bazum and Somkhet–Karabakh Zones.

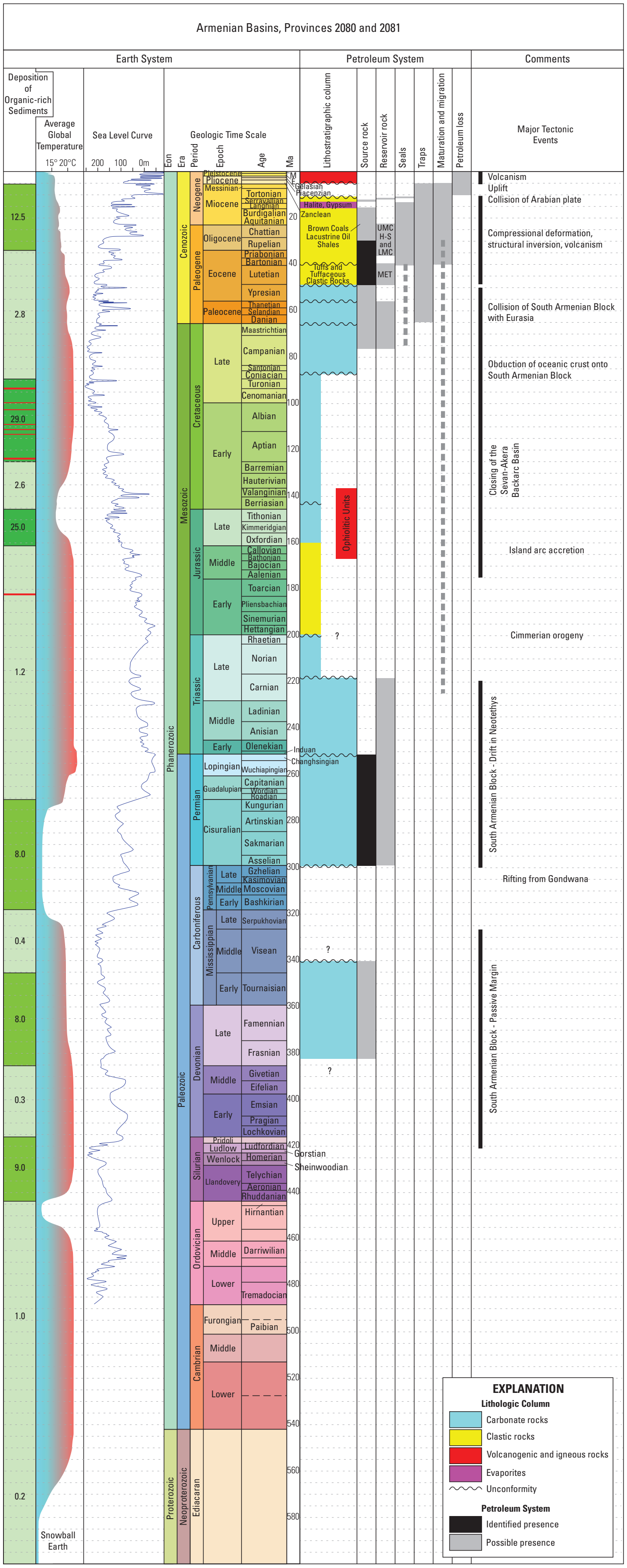

Figure 9. Lithostratigraphic column, petroleum system events chart showing geologic elements, and major tectonic events in basins of Armenia. Data from Mariposa Petroleum Company (written commun.,1994), SPT/Partex (written commun., 1995); Papworth and Aghabalyan (2002); Kazmin and Tikhonova (2006); Sosson and others (2010); Stampfli and Borel (2002). Reference for deposition of organic-rich sediments is Ulmishek and Klemme (1990) (column shows percent of world's total petroleum reserves generated by source rocks, redlines depict oceanic anoxic events); references for average global temperature are Barrett (2003) and Frakes and others (1992); references for Sea level curve are Golonka and Kiessling (2002) and Hardenbol and others (1998); and reference for geologic time scale is Gradstein and others (2004). Geologic chart designed by P.J. McCabe (written commun., 2006). [UMC, Upper Multicolored Suite; H-S, Hoktemberyan and Shoraghbyur Suites; LMC, Lower Multicolored Suite; MET, Middle Eocene tuffs and tuffaceous sandstones] Click on the figure to view full-size high-resolution image.

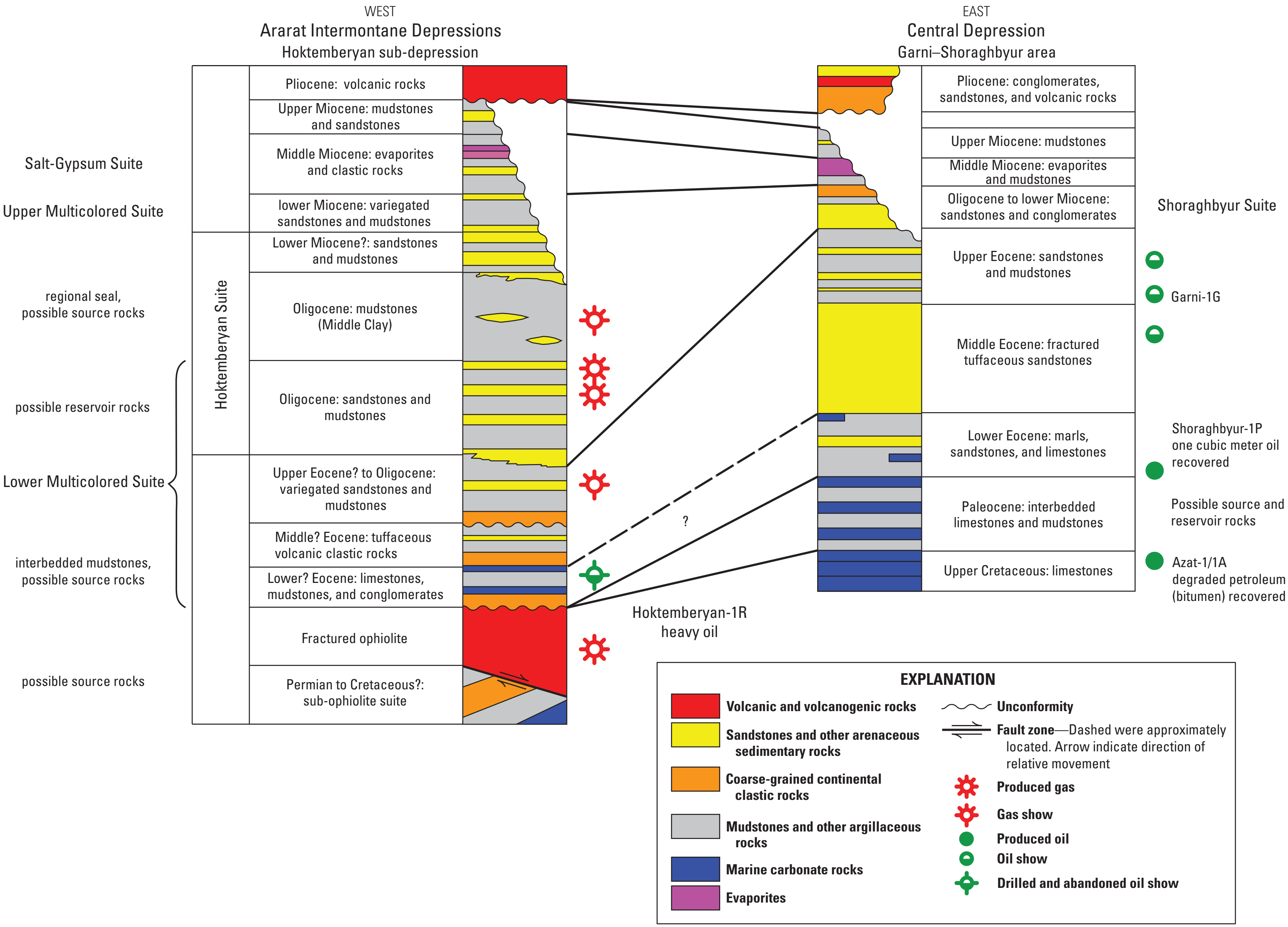

Figure 10. Schematic stratigraphic sections of the Ararat Intermontane Depressions (Hoktemberyan area) and Central Depression (Garni–Shoraghbyur area). Locations are shown in figure 8. Modified from Papworth and Aghablyan (2002).

Source Rocks

The main source rocks are interpreted to be middle Eocene and Oligocene intraformational mudstones (including the marine Shoraghbyur suite). Eocene and Oligocene rocks contain total organic carbon contents up to 3 weight percent, but are typically less than 2 weight percent. These rocks could have become thermally mature with sufficient burial or if subjected to high heat flow. Vitrinite reflectance has been measured as high as 1.04 percent in the Chatma–Vedi subdepression, possibly as a result of high heat flow. Oligocene rocks in Hoktemberyan depression were reported to be thermally immature (SPT/Partex, written commun., 1995).

Oligocene and Miocene lacustrine oil shales, which are stratigraphically equivalent to the Shoraghbyur suite of the Central Depression and the Hoktemberyan and Upper Multicolored Suites of the Hoktemberyan depression (fig. 8), could be oil sources. However, these organic-rich mudstones were reported as thermally immature in the Shoraghbyur-31 and Aramus-33 wells. The oil shales were most likely deposited in isolated basins and probably have limited areal extents (SPT/Partex, written commun., 1995). Oil seeps and oil inclusions were observed in middle Miocene evaporites, but the source of the oil is speculative (Kagramanov and others, 1975; SPT/Partex, written commun., 1995).

Upper Cretaceous rocks and Paleocene intraformational mudstones and marls might have source-rock potential. Gas shows were observed in Paleocene rocks in wells of the Mkhchyan area south of Yerevan (fig. 8; SPT/Partex, written commun., 1995). Degraded oil was observed in Upper Cretaceous clastic and carbonate rocks in the Hrazdan-14P well north of the Garni fault zone. In addition, degraded oil was observed and oil recovered in Shoraghbyur-1P (Grozny) in Paleocene carbonate rocks at the Paleocene–Eocene contact. Upper Cretaceous or Cenozoic rocks may have sourced oil in the Azat-1/1A and Shoraghbyur-1 wells south of the Garni fault zone and perhaps the Yeranos-1 well near Lake Sevan (fig. 8). The proposed source rocks for Azat-1/1A and Shoraghbyur-1 oils are presumed to be similar to those observed near Lake Sevan. Geochemical analysis of the oil indicates that it was generated during the early thermal maturity phase of the source rocks. The oil window is presumed to be between 3 and 5.5 kilometers depth (SPT/Partex, written commun., 1995). A map showing areal distribution of present-day heat flow and corresponding geothermal gradients is shown in figure 11.

Other proposed source rocks in the Central Depression include Eocene tuffaceous, marginally organic rich, sandstone that sometimes contain abundant plant remains (SPT/Partex, written commun., 1995) and middle to upper Miocene mudstones.

Reservoir Rocks

Reservoir rocks include middle Eocene tuffaceous sandstones and fractured tuffs, Paleocene fractured turbidite limestones and sandstones, Eocene to Miocene sandstones (those of the Shoraghbyur and Multicolored suites).

Seal Rocks

Seal rocks include intraformational Paleocene and Eocene to Miocene mudstones and Miocene evaporite rocks.

Traps

Traps could be faulted anticlines formed during the early Pliocene and include structures related to movement and deformation of Miocene evaporite rocks. Timing of petroleum generation from the aforementioned source rocks in relation to trap development is unknown. Burial history based on models presented by SPT/Partex (written commun., 1995) indicates that oil generation could have begun during the Eocene and Oligocene and gas generation during the Miocene and Pliocene. Neogene deformation and inversion most likely negatively affected retention of any previously accumulated petroleum.

Other Total Petroleum Systems

Potential source rocks in the Somkhet–Karabakh Zone could include Aalenian mudstones and Aptian to Albian tuffaceous sandstones containing plant remains. Jurassic to Cretaceous sandstones and limestones sealed by Upper Cretaceous volcanogenic rocks are proposed reservoir and seal rocks. Faults and thrust-faulted anticlines could provide traps (SPT/Partex, written commun., 1995).

Potential source rocks in the Shirak and Sabunchi Depressions might include Upper Cretaceous carbonate rocks that contain some interbedded organic-rich limestones, similar to those observed in the Bazum Zone. Analysis of the Cretaceous rocks, however, indicates that they are not organic rich. In addition, the thermal maturity in the depressions is unknown (SPT/Partex, written commun., 1995). Upper Cretaceous and Paleocene limestones, and Eocene sandstones, sealed by Eocene mudstones are proposed reservoir and seal rocks. Reverse-faulted anticlines are proposed traps (SPT/Partex, written commun., 1995).

Assessment Units

The assessment was based on the postulated presence and viability of petroleum system elements, including: (1) petroleum source rocks (quality, source-rock maturation, generation, and migration), (2) reservoir rocks (depositional environments, stratigraphy, and petrophysical properties), (3) traps (type and formation), and (4) timing considerations. Using this geologic framework, the USGS defined two hypothetical TPSs—the Paleozoic Composite TPS and the Cenozoic Composite TPS. Four assessment units (AUs) consisting of one conventional and one unconventional (shale gas and coalbed gas) in each TPS were evaluated (figs. 12 and 13). The AUs are the Paleogene-Sourced Conventional Reservoirs AU, the

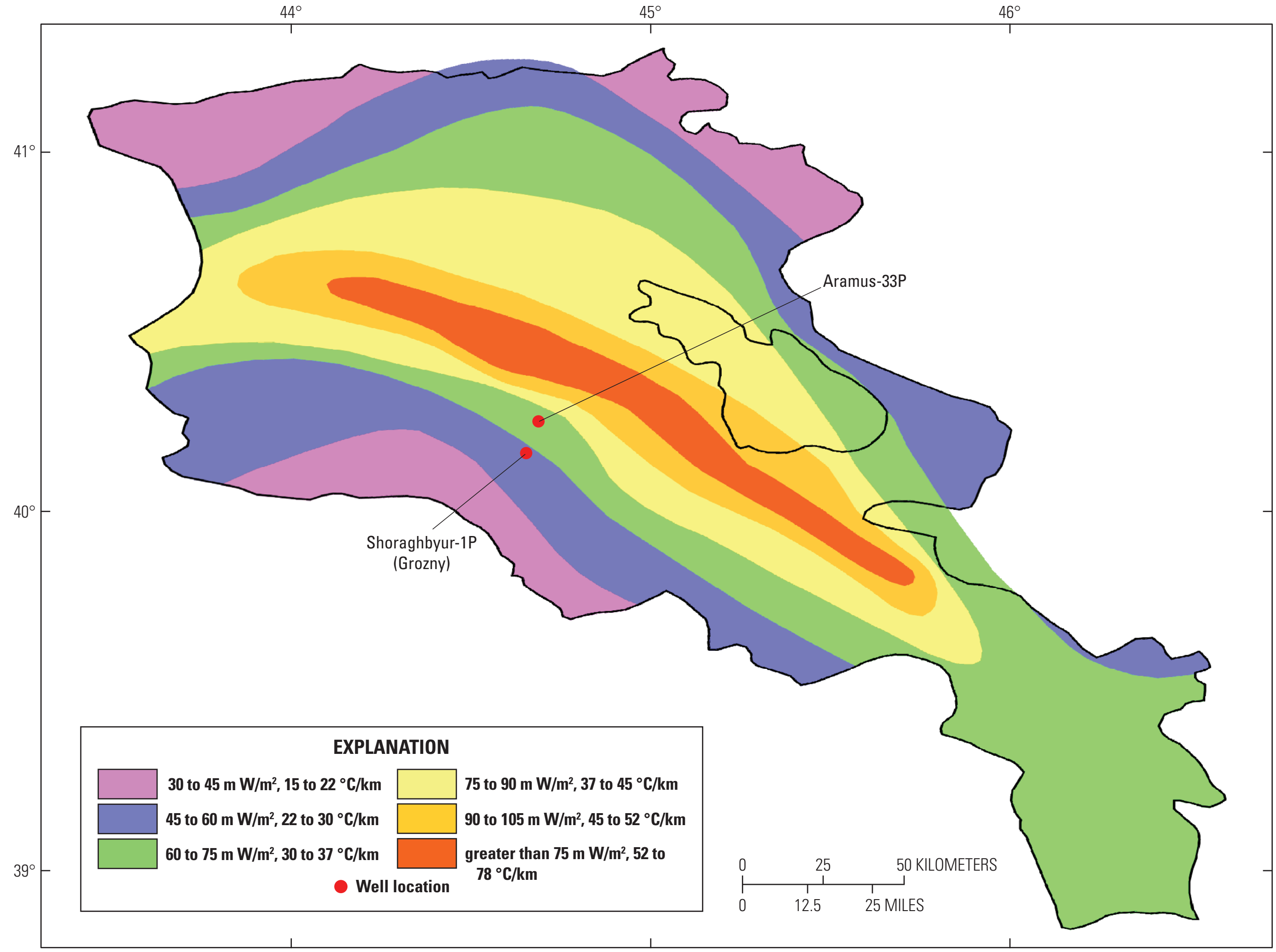

Figure 11. Map showing areal distribution of present-day heat flow and corresponding geothermal gradients. Modified from Vartanyan and Gordienko (1984). Despite being plotted in area 3 (30 to 37 °C/km) the Aramus-33P well has an average geothermal gradient of 20.5 °C/km to 2,380 meters depth and Shoraghbyur-1P (Grozny) well, 25.0 °C/km to 4,488 meters depth (SPT/Partex, written commun., 1995). mW/m^2, milliwatt per square meter; °C/km, degrees Celsius per kilometer.

Paleozoic-Sourced Conventional Reservoirs AU, the Permian Shale Gas AU, and the Cenozoic Coalbed Gas AU. Only the Paleogene-Sourced Conventional Reservoirs AU was quantitatively assessed for potential conventional oil and gas resources because it has a sufficient probability for petroleum resources. This assessed AU focused on the potential for technically recoverable resources in new field discoveries; economic resources were not evaluated. The Paleozoic-Sourced Conventional Reservoirs AU, the Permian Shale Gas AU, and the Cenozoic Coalbed Gas AU were not quantitatively assessed.

The USGS delineated geologic provinces around the world for assessment purposes. The Paleozoic Composite TPS and its AUs are located mainly in the Araks Province (fig. 1). The Cenozoic Composite TPS and its AUs are located mainly in the Lesser Caucasus Province. The geologic provinces, TPSs, and AUs are given codes that are used for data tracking (table 2).

Conventional Assessment Units

USGS assessments estimate the numbers and sizes (recoverable volumes taking into account reserve growth) of undiscovered, conventional crude oil and natural gas accumulations, along with petroleum coproduct ratios and AU probability. In areas that are mature with respect to exploration, these variables can be estimated from exploration-history analysis. In immature areas, analogs with similar geologic characteristics are used for the assessment. Three geologic elements are estimated for the AU probability: (1) charge, (2) adequate reservoir, and (3) seal rocks, and timing of maturation and trap formation. The AU probability is the probability of the existence of one accumulation anywhere in the AU having a size of 0.5 million barrels of oil equivalent (MMBOE, in terms of energy equivalence) or greater. Estimates of undiscovered petroleum resources were calculated by statistically combining

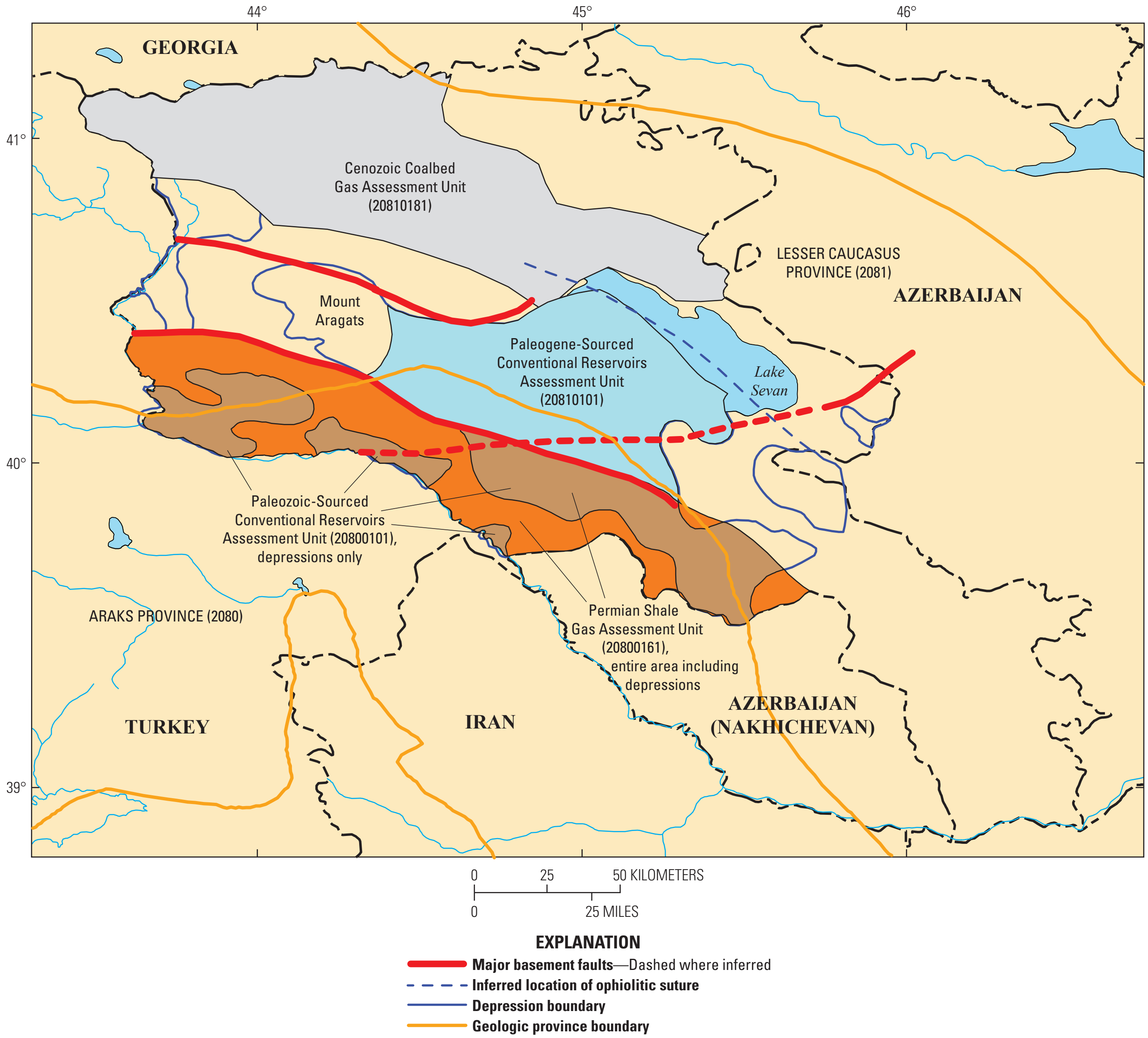

Figure 12. Map showing assessment units delineated on depressions, major basement faults, rock ages, and ophiolitic suture. The Permian Shale Gas Assessment Unit overlies the Paleozoic-Sourced Conventional Reservoirs Assessment Unit.

distributions of the number and sizes of undiscovered accumulations, and the geologic probability. The statistical combination uses Monte Carlo simulation with 50,000 iterations. Calculated resource quantities and the largest accumulation size selected during each iteration are recorded. The results are given as probability distributions. The calculated largest accumulation size distribution is used to calibrate estimates of the practical largest undiscovered accumulation size. The USGS methodology to assess undiscovered, technically recoverable, conventional petroleum resources is described in Schmoker and Klett (2000).

Paleozoic-Sourced Conventional Reservoirs (20800101)

Permian rocks have been proposed to be the source rocks for petroleum in Paleozoic and younger rocks (SPT/Partex, written commun., 1995). Some degraded petroleum was reported in Permian rocks within outcrops and seeps. Only one well was reported to have been drilled in Armenia that penetrated Permian rocks, however, and no shows were reported. An AU was delineated on the south block where Permian rocks have been reported (figs. 6 and 7; SPT/Partex, written commun., 1995, and

Figure 13. Map showing assessment units and areas. Assessment unit areas: km², square kilometers; ac, acres. The Permian Shale Gas AU overlies the Paleozoic-Sourced Conventional Reservoirs Assessment Unit.

lithologic and paleogeographic maps by Mkrtchyan and others, 1974). The AU consists of four areas corresponding to the Arak Depressions, in which sediment thicknesses are sufficient to retain conventional accumulations (fig. 12). Data available for this study, however, do not provide enough information to characterize the required geologic elements sufficiently to provide an AU probability of 0.1 percent or more for assessment. This AU was not quantitatively assessed.

Paleogene-Sourced Conventional Reservoirs (20810101)

Paleogene and possibly Upper Cretaceous rocks have been proposed to be source rocks for petroleum (SPT/Partex, written commun., 1995). Oil and gas shows and degraded petroleum have been reported in some wells. Data available for this study have a high level of uncertainty and a low probability for the existence of the required geologic elements for a TPS and sufficient AU probability for assessment.

The area of the AU that was delineated is approximately 3,700 square kilometers (km^2) (915,000 acres [ac]) and is in the Central Depression (figs. 12 and 13). The Mount Aragats volcanic complex, which is also in the Central Depression, is excluded from the AU (fig. 12). Data used to calculate undiscovered oil and gas resources in the Paleogene-Sourced Conventional Reservoirs AU are shown in table 1.

The median density of undiscovered fields of 0.5 MMBOE and larger for the assessment of this AU were estimated using analogs that include the Assam Basin of India and general fields in forearc basins. A field density of about 1.1 was used in this assessment to calculate the median number of undiscovered fields and 5.3 fields per 1,000 km^2 for the maximum number of undiscovered fields. The calculated numbers of undiscovered fields are 4 and 20, respectively. An estimate was made that one half are oil fields and one half are gas fields. A minimum number of 1 oil field and a minimum number of 1 gas field was assigned for the assessment. Compressional-setting analogs were used for the assessment of the Assam Province. The median density of fields in compressional settings is about 8 fields per 1,000 km^2 (ranging from 0.2 to 75) and in forearc basins, about 6 fields per 1,000 km^2 (ranging from 1.4 to 27). The number of undiscovered fields is conditional on the AU probability of 0.16. If the 3 geologic elements are present, then at least 3 and up to 20 undiscovered fields could be present. Otherwise, no fields would be present in the AU.

Estimated sizes (ultimate recoverable volumes) of undiscovered fields are 0.5 MMBO and 3 BCFG for the minimum; 1.5 MMBO and 9 BCFG for the median; and 25 MMBO and 150 BCFG for the maximum. The conditional mean estimated largest undiscovered field sizes are about 3 MMBO and 19 BCFG.

Because few coproduct data were available for this study, ranges of gas-to-oil ratio and NGL- or liquids- (oil plus NGL)-to-gas ratio were assigned from average values of fields throughout the world. Ranges of American Petroleum Institute (API) gravity and sulfur content of oils, inert gas content, carbon dioxide content, and hydrogen sulfide content in gas were estimated using the few reported data. Drilling depths were estimated based on available geologic cross sections.

The Paleogene-Sourced Conventional Reservoirs AU is located entirely with the borders of Armenia. The AU resides in both the Lesser Caucasus and Araks Provinces, most of the area (75 percent) in the Lesser Caucasus Province.

Unconventional Assessment Units

Unconventional (continuous) reservoirs include shale gas, continuous oil (shale, chalk, and so on), tight sandstone gas, and coalbed gas. Oil and gas accumulations contained in these reservoirs are not buoyant on water; they are regional in extent, typically have abnormal reservoir pressures (either high or low), and reside in rocks having unfavorable reservoir properties whereby stimulation is required for production (fractures provide access to matrix storage). Almost all wells drilled into unconventional reservoirs show a presence of oil or gas, although the wells might not be economical to produce.

Several types of geologic and geochemical data are used to identify and delineate potential unconventional reservoirs. These reservoirs can be better identified and delineated with increasing amounts of data, resulting in better assessments of undiscovered unconventional oil and gas resources, but often data are limited. The assessment method is an integration of geologic, geochemical, and engineering data used to estimate ranges of particular variables that define the unit

Table 1. Input data used for the assessment.

Assessment unit name and code	**Paleogene-Sourced Conventional Reservoirs, Assessment Unit 20810101**			
Assessment unit area (km^2)	3,703			
Assessment unit probability				
Charge	0.2			
Rocks	1			
Timing	0.8			
Total probability	0.16			
Number of undiscovered fields	Minimum	Median	Maximum	Lognormal distributions
Oil	1	2	10	
Gas	1	2	10	
Sizes of undiscovered fields	Minimum	Median	Maximum	Lognormal distributions
Oil	0.5	1.5	25	
Gas	3	9	150	
Coproduct ratios	Minimum	Median	Maximum	Lognormal distributions
Gas-to-oil ratio in oil fields	100	1,000	20,000	
Natural gas liquids-to-oil ratio in oil fields	5	25	85	
Liquids (Oil plus natural gas liquids)-to-gas ratio in gas fields	5	25	75	

being assessed, the AU. An AU is a package of reservoir rock (having area and thickness) that has the potential to contain oil and gas resources.

Variables used for the quantitative assessment of unconventional resources in a given AU include the productive area of the accumulation, the percentage of the assessment unit that is untested, the percentage of the untested assessment unit area that is in sweet spots, the untested area, the drainage area of wells drilled, the estimated ultimate recovery (EUR) of wells, and the future success ratio. Minimum, central tendency, and maximum parameters are estimated and triangular distributions assigned to each, except the EUR parameters. EUR parameters are minimum, median, and maximum to which shifted, truncated lognormal probability distributions are assigned. The distributions of each variable are used in Monte Carlo simulation for the calculation of a distribution of undiscovered, unconventional oil and gas resources. The USGS methodology to assess undiscovered, technically recoverable, unconventional petroleum resources is described in Charpentier and Cook (2011).

Detailed assessments of every potential unconventional reservoir in every basin are not feasible. Therefore, unconventional reservoirs were high graded based on geologic attributes in order to prioritize the areas to be assessed and provide the best estimate of unconventional resources at a regional or country level. Sets of criteria were developed for each unconventional reservoir type in order to select rock units that have the greatest potential and least risk of containing undiscovered oil and gas resources. These criteria help to delineate organic-rich marine shales from coaly, carbonaceous shales and sandstones, which are defined by the USGS as tight gas reservoirs. The criteria are based on total organic carbon (TOC) content, net thickness of organic-rich intervals, thermal maturity with respect to oil and gas generation in terms of vitrinite reflectance measurements in oil (Ro) or equivalent, kerogen type, pressure system, and oil- or gas-storage capacity. Except for thermal maturity, the criteria list for shale gas and shale oil is similar.

For each of the AUs, the presence and thickness of organic-rich shales, the thermal windows for oil and gas generation, the kerogen type, and the potential for matrix storage of gas are all subject to significant geologic uncertainty. Engineering and production data from unconventional reservoirs are typically unavailable in areas outside of the United States. Consequently, unconventional accumulations of the United States are used as geologic and engineering analogs in the USGS assessment of these provinces (Charpentier and Cook, 2011). Analog data from U.S. accumulations included EUR distributions, average drainage areas of wells, and ranges of success ratios based on analog wells of the United States. The AUs that fulfill the requirements of the criteria given in the previous section are subject to quantitative assessment.

Permian Shale Gas (20800161)

Permian rocks have been proposed to be sources of petroleum in younger rocks (SPT/Partex, written commun., 1995) and some degraded petroleum was reported from seeps and outcrops. Only one well drilled in Armenia penetrated Permian rocks, however, and no shows were reported. An AU was delineated that contains depressions and uplifts of the south block (figs. 12 and 13). Shale gas reservoirs are self-sealed, therefore, considerable sediment thickness is less of a requisite to retain gas accumulations as opposed to conventional accumulations. Data available for this study do not provide enough information to characterize the required geologic elements that are sufficient to provide an AU probability for assessment. Thus, this AU was not quantitatively assessed.

Cenozoic Coalbed Gas (20810181)

An area that includes known brown coal deposits that are exposed at or near the surface, the Bazum and Somkhet–Karabakh Zones was delineated as an AU (figs. 12 and 13). The AU boundary is based on the extent of Paleogene and Neogene rocks exposed at the surface. Data available for this study do not provide enough information to characterize the required geologic elements that are sufficient to provide an AU probability for assessment. Thus, this AU was not quantitatively assessed.

Resource Summary

Four AUs were delineated entirely within the country of Armenia. In three of these AUs (the Paleozoic-Sourced Conventional Reservoirs AU, the Permian Shale Gas AU, and the Cenozoic Coalbed Gas AU), the postulated petroleum system elements have high levels of uncertainty, resulting in low geologic probabilities, and the AUs were not quantitatively assessed. The TPS elements are also highly uncertain and risked in the Paleogene-Sourced Conventional Reservoirs AU. This AU, however, was quantitatively assessed because the geologic probability of at least one conventional oil or gas accumulation of 0.5 million barrels of oil equivalent or greater based on postulated petroleum-system elements is more than the threshold of 10 percent.

The results of the USGS assessment of undiscovered, technically recoverable conventional petroleum resources of Armenia are listed in table 2. Only the Paleogene-Sourced Conventional Reservoirs AU was quantitatively assessed. With an AU probability of 0.16 (that is, 16 percent), the estimated mean volumes of technically recoverable petroleum resources are 1 MMBO (F95 to F05 range, 0 to 5 MMBO); 6 BCFG (F95 to F05 range, 0 to 41 BCFG) and less than 1 MMBNGL (F95 to F05 range, 0 to 1 MMBNGL). The assessment of undiscovered petroleum resources at the 95th and 50th fractiles is zero and reflects the low geologic AU probability and high levels of geologic uncertainty on petroleum system elements.

Table 2. Assessment results for undiscovered, technically recoverable, petroleum resources in Armenia (Klettandothers, 2014).

[MMBO, million barrels of oil; BCFG, billion feet of gas; MMBNGL, million barrels of natural gas liquids. Results shown are fully risked estimates. For gasfields, all liquidsare included under the natural gas liquids (NGL) category. F95 denotes a 95-percent chance of at least the amount tabulated, F50 denotes a 50-percent chance, and F5 denotes a 5-percent chance. Gray shading indicates not applicable]

Geologic provinces, total petroleum systems, and assessment units (AU)	AU probability	Accumulation type	Total undiscovered resources											
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)			
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Araks Province, 2080; Paleozoic Composite Total Petroleum System, 208001														
Paleozoic-Sourced Conventional Reservoirs AU, 20800101	0.9	Oil	Not quantitatively assessed.											
		Gas												
Permian Shale Gas AU, 20800161		Gas	Not quantitatively assessed.											
Lesser Caucasus Province, 2081; Cenozoic Composite Total Petroleum System, 208101														
Paleogene-Sourced Conventional Reservoirs AU, 20810101	0.16	Oil	0	0	5	1	0	0	8	1	0	0	<1	<1
		Gas					0	0	33	5	0	0	1	<1
Permian Shale Gas AU, 20800161		Gas	Not quantitatively assessed.											
Total unconventional resources			0	0	5	1	0	0	41	6	0	0	1	<1

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Klett—**Geology and Assessment of the Undiscovered, Technically Recoverable Petroleum Resources of America, 2013**—Digital Data Series 69–PP

ISSN 2327-638X (online)
http://dx.doi.org/10.3133/ds69PP