The North Sakhalin Neogene Total Petroleum System of Eastern Russia

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April, 2000

FOREWORD

This report was prepared as part of the World Energy Project of the U.S. Geological Survey. For this project, the world was divided into eight regions and 937 geologic provinces, which were then ranked according to the discovered oil and gas volumes within each (Klett and others, 1997). Next, 76 "priority" provinces (exclusive of the U.S. and chosen for their high ranking) and numerous "boutique" provinces (exclusive of the U.S. and chosen for their anticipated petroleum richness or special regional economic importance) were selected for appraisal of oil and gas resources. The petroleum geology of these priority and boutique provinces is described in this series of reports. The North Sakalin Basin Province ranked 50th in the world, exclusive of the U.S.

The purpose of the World Energy Project is to assess the quantities of oil, gas, and natural gas liquids that have the potential to be added to worldwide reserves within the next 30 years. These volumes either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the AU (variable, but must be at least 1 million barrels of oil equivalent), or they occur as reserve growth of fields already discovered. Assessment results are documented separately from this report.

The ***Total Petroleum System*** (TPS) constitutes the basic geologic unit of the oil and gas assessment. The TPS includes all genetically related petroleum that occurs in shows and accumulations (discovered and undiscovered) that (1) has been generated by a pod or by closely related pods of mature source rock and (2) exists within a limited mappable geologic space, along with the other essential mappable geologic elements (reservoir, seal, and overburden rocks) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum. The ***minimum petroleum system*** is that part of a TPS encompassing discovered shows and accumulations, along with the geologic space in which the various essential elements have been proved by these discoveries.

An ***Assessment Unit*** (AU) is a mappable part of a TPS in which discovered and undiscovered fields constitute a single, relatively homogenous population such that the chosen methodology of resource assessment – based on estimation of the number and

[2] **North Sakhalin Neogene** Total Petroleum System (#132201), North Sakhalin Island area of eastern Russia, North Sakhalin Basin Province (#1322), Former Soviet Union (Region 1)

sizes of undiscovered fields – is applicable. A TPS could equate to a single AU, or it can be subdivided into two or more AU if each AU is sufficiently homogeneous – in terms of geology, exploration considerations, and risk – to assess individually. AU are considered *established* if they contain more than 13 fields greater than the minimum established size, *frontier* if they contain 1-13 fields, and *hypothetical* if they contain no fields.

A graphical depiction of the elements of a TPS is provided in the form of an events chart that shows the times of (1) deposition of essential rock units, (2) trap formation, (3) generation, migration, and accumulation of hydrocarbons, and (4) preservation of hydrocarbons.

A numeric code identifies each region, province, TPS, and AU; these codes are uniform throughout the project and will identify the same type of entity in any of the publications. The code is as follows**:**

The code is as follows:	Example
Region, single digit	**3**
Province, three digits to the right of region code	3**162**
TPS, two digits to the right of province code	3162**05**
AU, two digits to the right of petroleum system code	316205**04**

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

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

Figures in this report that show boundaries of the TPS, AU, and pods of active source rocks were compiled using geographic information system (GIS) software. Political boundaries and cartographic representations were taken, with permission, from Environmental Systems Research Institute's ArcWorld 1:3 million digital coverage (1992). They have no political significance and are displayed for general reference only. Oil and gas field centerpoints, shown on these figures, are reproduced, with permission, from Petroconsultants (1996).

ABSTRACT

The North Sakhalin Basin Province of eastern Russia contains one Total Petroleum System (TPS) – North Sakhalin Neogene – with more than 6 BBOE known, ultimately recoverable petroleum (61% gas, 36% oil, 3% condensate). Tertiary rocks in the basin were deposited by the prograding paleo-Amur River system. Marine to continental, Middle to Upper Miocene shale to coaly shale source rocks charged marine to continental Middle Miocene to Pliocene sandstone reservoir rocks in Late Miocene to Pliocene time. Fractured, self-sourced, Upper Oligocene to Lower Miocene siliceous shales also produce hydrocarbons. Geologic history is that of a Mesozoic Asian passive continental margin that was transformed into an active accretionary Tertiary margin and Cenozoic fold belt by the collision of India with Eurasia and by the subduction of Pacific Ocean crustal

plates under the Asian continent. The area is characterized by extensional, compressional and wrench structural features that comprise most known traps.

INTRODUCTION

The North Sakhalin Basin Province was an active Tertiary margin and Cenozoic fold belt characterized by repeated wrench movements and both compressional and extensional structural features. It contains one major TPS called North Sakhalin Neogene, with Neogene shale and siliceous-shale source rocks and Neogene sandstone and fractured siliceous-shale reservoir rocks.

References listed in this report include a limited selection of those most recent and most pertinent to this document. Not all are specifically cited in the text. Russian translations are referenced according to the translation date, and many such maps and illustrations are lacking in needed detail, explanation or location. The literature commonly contains multiple spellings for names and features within Russian provinces. The stratigraphic equivalents chart is composited from multiple references to approximately equate the range of stratigraphic nomenclature in use. It is not intended to be precise with respect to absolute geologic age.

PROVINCE GEOLOGY

Province Boundary and Geographic Setting

Sakhalin Island is part of the northwestern Pacific rim, adjacent to the southeasternmost coast of mainland Russia, directly north of Japan's Hokkaido Island, and between the Sea of Okhotsk and the Tatar Strait (fig. 1). The North Sakhalin Basin geologic province includes much of the northern half of the island plus northwestern (Baykalo-Pomor syncline) and northeastern (North Sakhalin and Pogranichnyy grabens) offshore areas (red outline on fig. 1). The 84,000-sq-km province area (72% offshore, 28% onshore) is within latitude 47.5° to 55.5° N. and longitude 140° to 146° E. Southwest of the province are the onshore East and West Sakhalin uplifts, the offshore Tatar Strait and Terpeniya Bay Basins, and the Sikhote-Alin Folded Region of the Russian mainland. East of the province is the offshore Deryugin Basin.

Geologic Setting

Until the end of the Early Cretaceous Neocomian Epoch, the area adjacent to where the North Sakhalin Basin would develop was an offshore, eastern passive continental margin of the Bureinsk massif located on the Asian continent (Parfenov and Natal'in, 1985). Aptian to Paleogene plate collision resulted in subduction of oceanic crust from an eastern direction; the creation and subsequent consolidation of the Sikhote-Alin volcanic arc and its forearc and backarc basins (west of Sakhalin Island); and the accretion of sedimentary wedges that would form the core of Sakhalin Island.

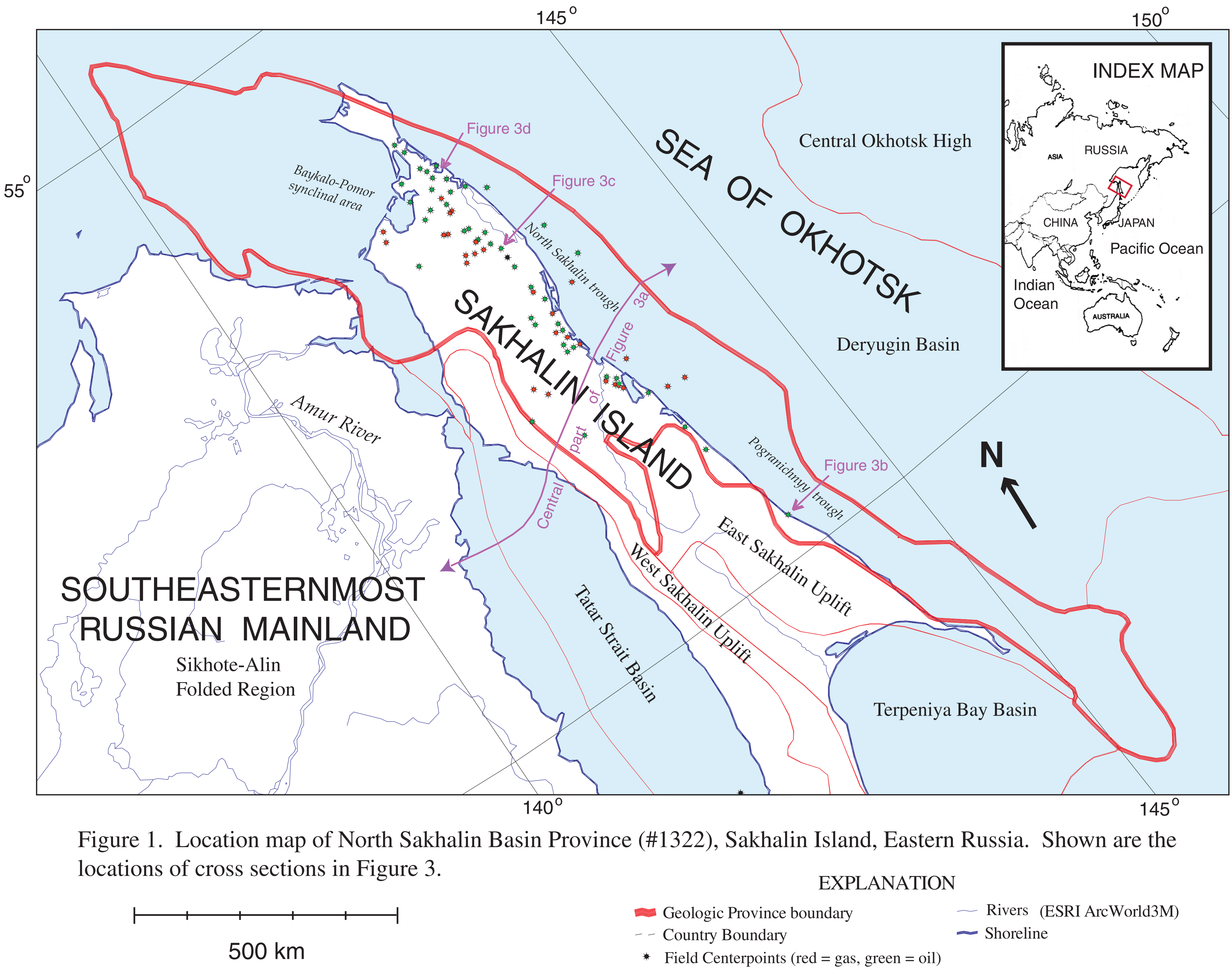


Figure 1. Location map of North Sakhalin Basin Province (#1322), Sakhalin Island, Eastern Russia. Shown are the locations of cross sections in Figure 3.

North Sakhalin Basin is a deep (to 8 km), Tertiary strike-slip downwarp associated with the major, north-south trending Hokkaido-Sakhalin-Kashevarov en echelon dextral shear system (Mochalov, 1983; Worrall and others, 1996). The basin is filled with Paleocene and post-Paleocene siliciclastic marine sediments and eastward-prograding deltaic deposits of the paleo-Amur River (figs. 1 and 2).

Sakhalin Island and most of the North Sakhalin Basin unconformably overlie Cretaceous to Paleocene deformed and metamorphosed accretionary rocks of a complex continental suture (figs. 2 and 3a), including flysch, blueschists, melange and ophiolites. In westerly and northerly directions, approximate age-equivalent paleo-Amur strata are underlain by partly conformable Cretaceous to Paleocene flysch and forearc strata and by volcanic and intrusive rocks that crop out locally on western Sakhalin Island and on the Russian mainland. East of the suture zone (east of Sakhalin Island and under the Okhotsk Sea), Eocene to Recent strata are underlain by acoustically distinct basement rocks of the Okhotsk crustal block that collided with the Bureinsk massif.

NE-SW trending normal faults (Eocene to Early Miocene transtension) and slightly younger, NW-SE trending en echelon thrusts and folds (Late Miocene and Pliocene transpression) complement the major N-S vertical dextral shear faults of North Sakhalin Basin (figs. 3b, 3c and 3d). Most known hydrocarbon accumulations along the East Sakhalin shear zone of the island's eastern side are associated with these structural features, especially those of compressional origin .

Early Tertiary transtension provided necessary accommodation space for deltaic progradation from the paleo-Amur River and its distributaries. Depositional rates were as high as 500-800 meters per million years (Nikolayev and Kleshchev, 1984; Tull, 1997). Continued wrench movement likely contributed to the strike (N-S) dispersal of sediments. Late Pliocene tectonism and orogenic inversion resulted in significant geologically recent folding, in modification and rupturing of pre-existing structures, and in uplift of the western and some central regions while other areas were subsiding (Mochalov, 1983; Tull, 1997). Offshore regions were less tectonically deformed than those onshore. Pliocene tectonism resulted in local onshore erosion of as much as 3.5 km and largely created the physiographic configuration of the province today. The Pleistocene Epoch was characterized by extension and transtension, which served to breach traps that contained accumulated hydrocarbons.

The North Sakhalin Basin's overall structural configuration is compatible with modeled stress fields and complex strain signatures resulting from the collision of India and Eurasia, in which sinistral and dextral wrench systems act as regional conjugate shear sets (Worrall and others, 1996). Major sinistral shear systems are just north of the North Sakhalin Basin Province, and some dextral systems experienced sinistral movement in their past. Tectonism can be related to intermittent magmatic movements in the crust and mantle (Sychev and others, 1986) and to crustal microplate drift in the northwestern Pacific Ocean. Present thermal phenomena, mud volcanoes, and seismic activity are evidence of active movement on many faults.

Figure 2. Stratigraphic equivalents chart for the siliciclastic North Sakhalin Basin province.

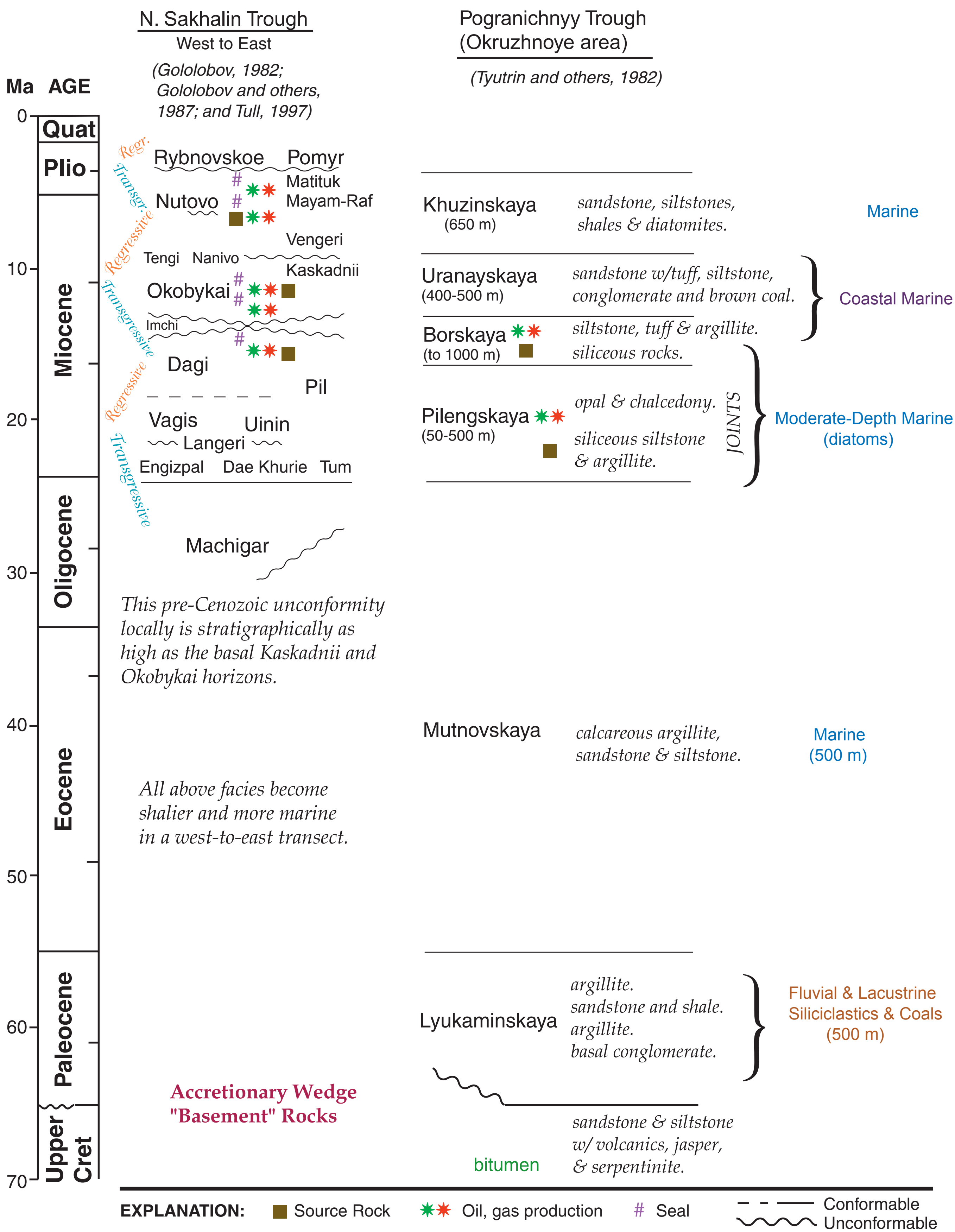


Figure 3a. W-E regional structural cross section of the Sakhalin area (after Worrall and others, 1996). Location shown on Figure 1.

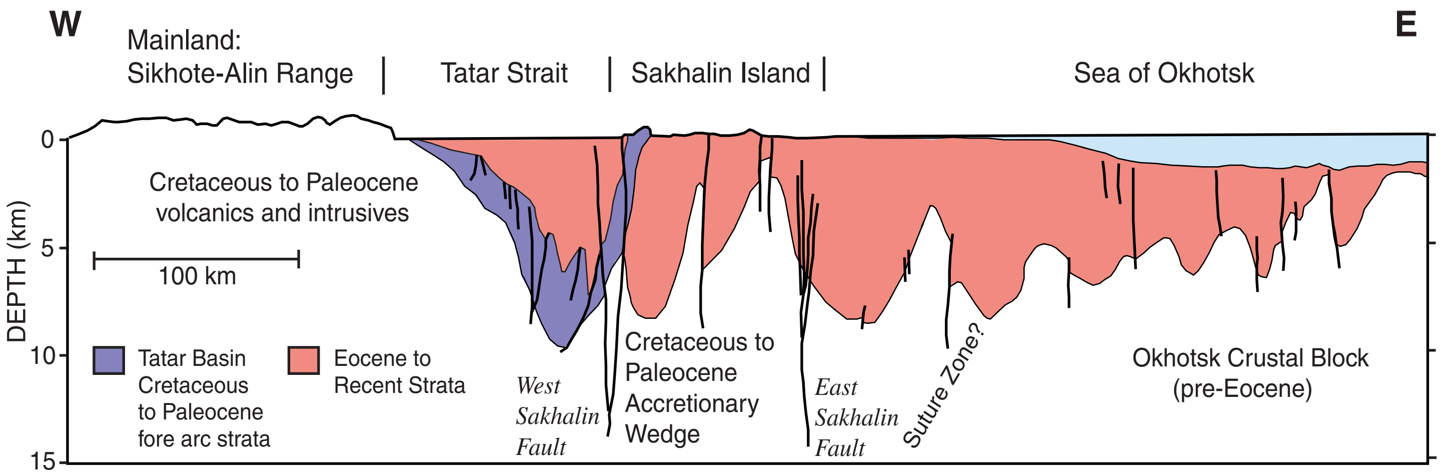
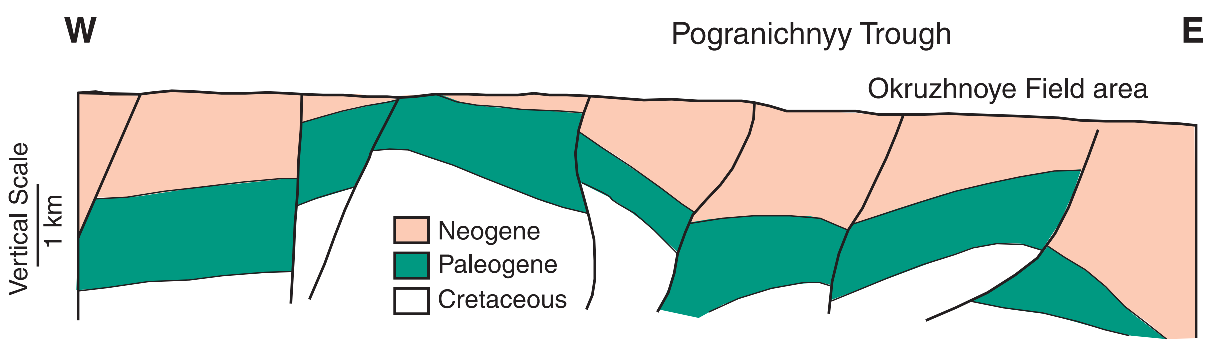
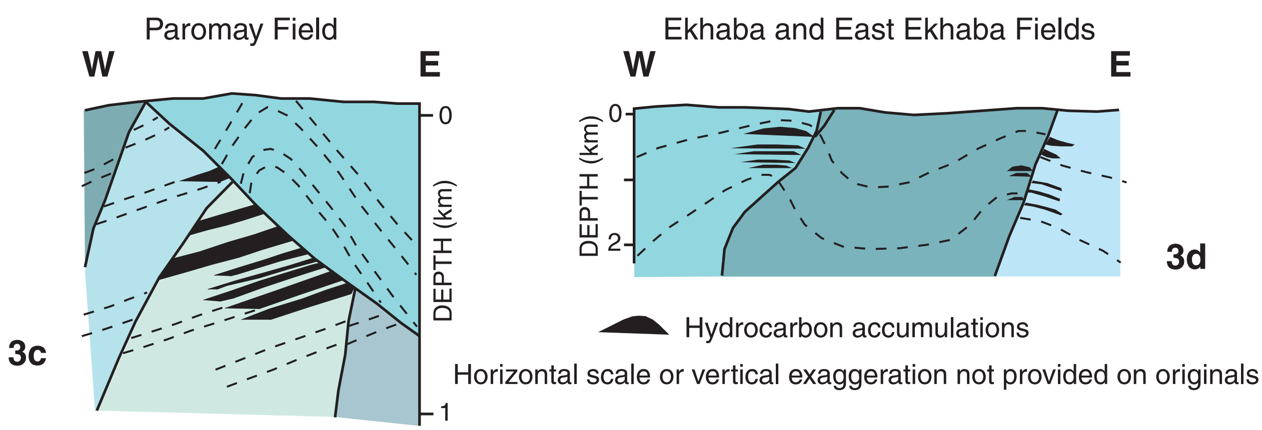


Figure 3b. W-E detailed structural cross section of southernmost production at coast (after Tyutrin and others, 1982). Location shown on Figure 1.



Horizontal scale or vertical exaggeration not provided on original

Figures 3c and 3d. W-E detailed structural cross sections of two northern onshore fields (after Rozhdestvenskiy, 1975). Locations shown on Figure 1.



Horizontal scale or vertical exaggeration not provided on originals

Exploration and Discovery History

Petroconsultants (1996) document a field-discovery history over the years 1923 to 1992 (table 1, fig. 4). Six onshore fields were discovered from 1923 to 1935 in the North Sakhalin trough (northeastern part of the island, fig. 1) – including the Okha, Katangli, and Ekhabi complexes, which are among the top twenty fields of the province in terms of recoverable reserves. A more regular annual pattern of onshore drilling, with resulting discoveries, began in 1947. Numbers of annual onshore-field discoveries peaked in the 1960s, and most onshore development has been conducted by Sakhalinmoreneftegaz, a Russian state-run enterprise.

Offshore fields were discovered beginning in the 1970s. The Pogranichnyy trough (east of the central part of the island, fig. 1) was first explored by deep drilling from 1971 to 1975, and southernmost Okruzhnoye field within that trough was discovered in 1972. Offshore exploration and development occurred jointly with Japan between 1976 and 1982 and included discovery of the Chaivo and Odoptu fields, 2^{nd} and 4^{th} largest in terms of province reserves. Largest reserve volumes were added by field discoveries from about 1976 to 1986. The six largest fields (five of which are offshore) were discovered since 1975, but the next three largest fields (all onshore) are among the earliest discoveries made prior to 1936. Potential significant Eastern Asian markets for Sakhalin oil and gas include Japan, Korea and China.

All existing offshore fields are in water depths of less than 100 m. Ice conditions in the Sea of Okhotsk have challenged both exploration and development efforts. Typical 2-m-thick ice floes can move at speeds of 1 m/sec, and ice routinely scours the sea bottom.

PETROLEUM AND SOURCE ROCK

Geographic and Stratigraphic Occurrence

The North Sakhalin Basin Province has 32 onshore gas fields, 29 onshore oil fields, five offshore gas fields, and two offshore oil fields (table 1). Another two gas fields and three oil fields straddle the coastline. Offshore fields are larger both in closure areas and in petroleum volumes (table 2) than fields onshore. Onshore seeps are common along the trends of the major north-south faults, and production occurs to depths exceeding 4,000 m. Producible hydrocarbons or hydrocarbon shows are in more than 30 stratigraphic zones (Silverman, 1990) of Tertiary sandstones and fractured siliceous shales, and in pre-Tertiary serpentinites that are unconformably juxtaposed with Tertiary source rocks.

Table 1. List of fields in North Sakhalin Neogene total petroleum system.
(data from Petroconsultants, 1996; O=oil, G=gas, C=condensate)

Field Name	Commodity	Discovery	Location
Aban	G	1962	On
Arkutun-Dagi	GCO	1989	Off
Askasay Sredniy	O	1983	On
Astrakhanovskoye	GC	1973	On/Off
Baykal' Vostochnyy	OG	1989	On/Off
Berezovskoye (Sakhalin)	OG	1967	On
Boatasino Severnoye	G	1967	On
Chaivo-More	GCO	1979	Off
Dagi Nizhnyeye	GCO	1981	On
Dagi Vostochnoye	GO	1970	On
Dagi Yuzhnoye	OG	1980	On
Ekhabi	OG	1933	On
Ekhabi Vostochnoye	OG	1935	On
Erri	G	1953	On
Erri Zapadnoye	G	1962	On
Evay Nizhniy	GCO	1984	On
Evay Vostochnyy	OG	1984	On
Gilyako-Abunan	GO	1950	On
Glukharka Severnaya	G	1963	On
Goromay	O	1975	On
Gyrgylan'i	G	1966	On
Imchin	G	1964	On
Imchin Severnoye	G	1967	On
Katangli	O	1928	On
Katangli Zapadnyy	GO	1966	On
Katangli-Lysaya Sopka	O	1928	On
Katangli-Uyglekuty	OG	1928	On
Kaygan Vostochnyy	O	1991	On
Keniga Yuzhnaya	G	1964	On
Kirinskoye (Sakhalin)	GC	1992	Off
Kolendo	OG	1961	On
Kolendo Severnoye	OG	1963	On
Krapivnen (Krapivnenskoye)	GO	1965	On
Kydylan'i	GO	1961	On
Lun (Lunskoye)	GCO	1984	Off
Mirzoyev	GCO	1984	On
Mongi	OGC	1975	On
Moroshkinskoye	O	1965	On
Mostovoye	G	1971	On
Mukhto	OG	1959	On
Nabil'	OG	1975	On/Off
Nekrasovka	GCO	1957	On
Nel'ma	OG	1964	On
Nizhnyy Paromayskoye	O		On
Nogliki	O	1956	On
Odoptu	G	1955	On
Odoptu-More	OGC	1977	Off
Okha Severnaya	OG	1967	On
Okha Tsentral'naya	OG	1923	On
Okha Yuzhnaya	GO	1947	On
Okruzhnoye	OG	1972	On/Off
Osinovskoye (Sakhalin)	G	1973	On
Paromay	OG	1949	On
Pil'tun	OG	1953	On
Pil'tun-Astokh	OGC	1986	Off
Polyarnen	OG	1984	On
Pribrezhnoye (Sakhalin)	GO	1964	On
Sabo	GO	1952	On
Sabo Maloye	GCO	1958	On
Sabo Zapadnyy	OG	1961	On
Shkhunnoye	GO	1964	On
Tatam Verkhne	O	1991	On
Tatam Zapadnoye	GC	1987	On
Tungor (Tungorskoye)	GCO	1958	On
Ufskoye	OG	1984	On
Ust'-Evay	GC	1986	On
Ust'-Tomi	GC	1981	On/Off
Ust-Boatasino	O	1968	On
Uzlovo	GC	1969	On
Val Yuzhnyy	O	1974	On
Venin	GC	1985	Off
Verkhne-Nysh	GC	1990	On
Volchinka	GO	1963	On

Figure 4. Field Discovery History for the North Sakhalin Basin Province

(data from Petroconsultants, 1996; four largest fields noted)

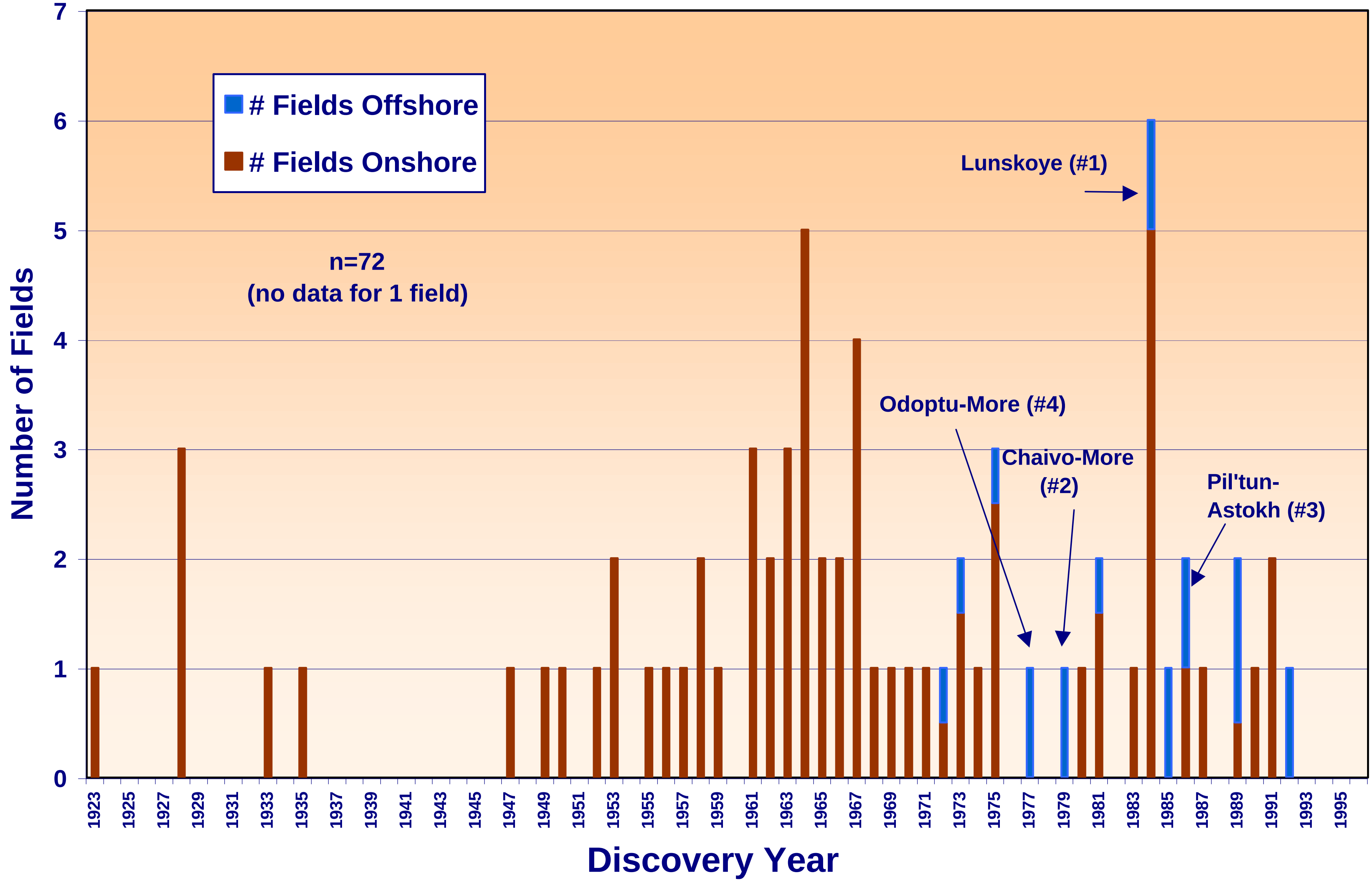


Table 2. Comparison of field-size statistics for onshore and offshore fields in the North Sakhalin Basin (data derived from Petroconsultants, 1996). *approximations ("close to"). (MMBOE, million barrels of oil equivalent)

Location	**Total Recoverable (MMBOE)**	Median **(MMBOE)**	Mean **(MMBOE)**	Minimum **(MMBOE)**	Maximum **(MMBOE)**
Offshore Gas (n=5)	2800*	181	562	10*	1700*
Offshore Oil (n=2)	1400*	713	713	630*	800*
Onshore Gas (n=32)	650*	8	20	<1*	100*
Onshore Oil (n=29)	1100*	2	37	<1*	200*
On/Off Gas (n=2)	40*	19	19	10*	30*
On/Off Oil (n=3)	70*	33	22	<1*	35*

Source rocks are Middle to Upper Miocene alluvial, deltaic and prodeltaic marine shales, coaly shales and coals, which range from oil- to gas-prone, and Upper Oligocene(?) to Lower Miocene deep marine, diatomaceous, oil-prone shales (fig. 5). The formations in which the source-rock shales occur are hundreds of meters thick. Effective source rocks are somewhat less abundant in the more western, sand-rich facies of each formation, and overall source rock character changes from mostly gas-prone in the western onshore regions to oil-prone in eastern offshore areas (Huizinga and others, 1997).

Geochemistry

North Sakhalin crude oils are generally low in sulfur and paraffin, but high in resins. API gravities reported by Petroconsultants (1996) for oils and condensates in all fields range from 18°-62°. Low gas-oil ratios (GOR) and biodegradation are common because of the abundant seeps, and many fields need steam, gas and water injection for optimal recovery. Most of the Miocene to Oligocene source rocks have type II to type III organic matter, with total organic carbon (TOC) content ranging from <1 to 5 wt % (Mavrinski and Koblov, 1993; Khvedchuk, 1993).

Some published literature attributes significant hydrocarbon reserves to the deep-marine siliceous-shale source rocks. For example, Kodina and others (1989) discuss the isotopic similarity of Lower and Middle Miocene oils ($\delta^{13}C$ = -25.2 to -25.8 $^{o}/_{oo}$) to Lower Miocene bitumen extracts ($\delta^{13}C$ = -26.4 to –23.9 $^{o}/_{oo}$), and state that they both exhibit characteristics compatible with deep-marine diatomaceous oozes and siliceous source rocks.

Others believe that petroleum in the northern part of the province is sourced by the older, Upper Oligocene to Lower Miocene proximal-to-distal deltaic shales (rather than anoxic, deep-marine siliceous source rocks), based on biomarker, isotopic and chemometric oil-source correlations (Peters and others, 1997 (abstract only)).

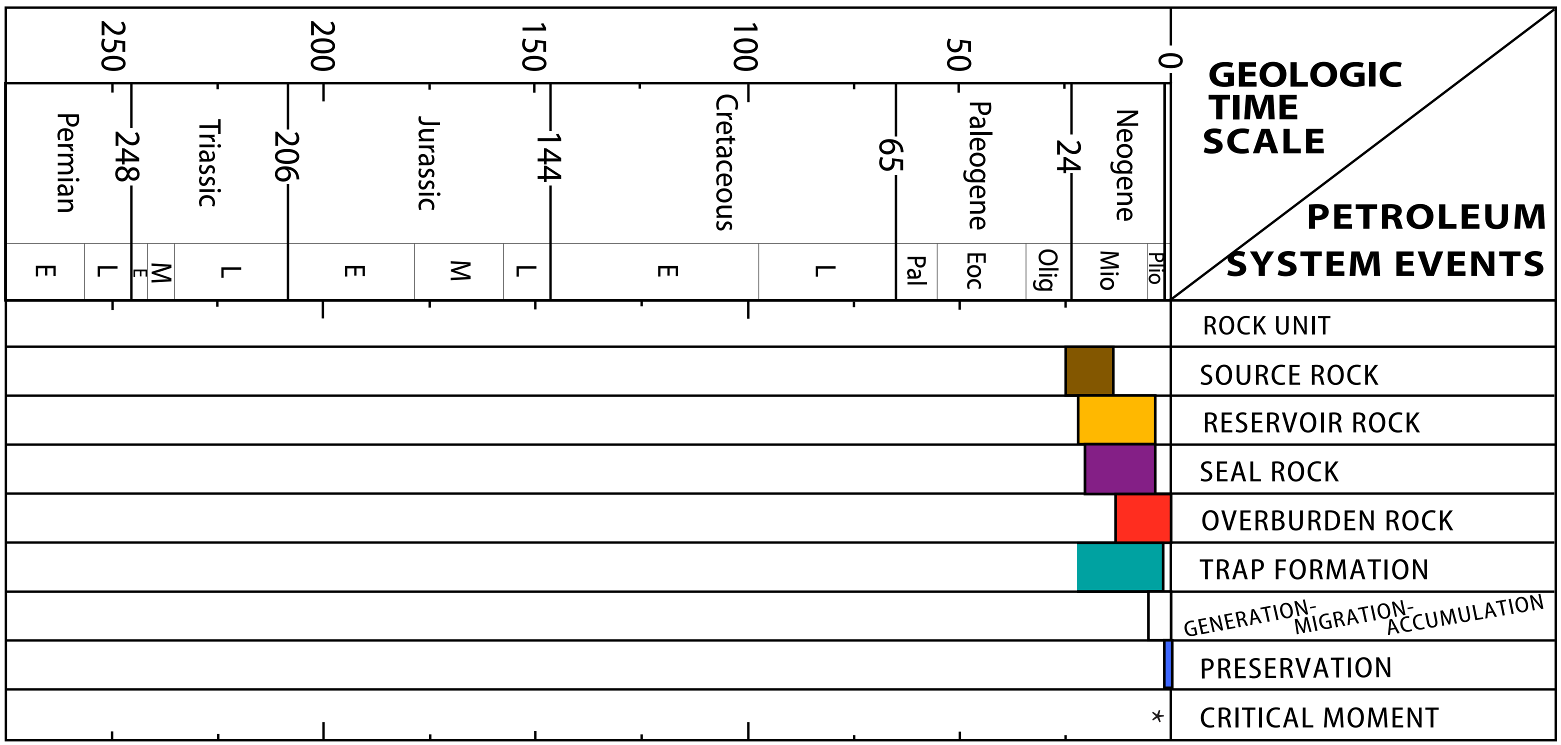
Figure 5. Total Petroleum System Events Chart

Province Name: North Sakhalin Basin

TPS Name: North Sakhalin Neogene

Author(s): S.J. Lindquist

Date: June, 1999



Variable proportions of humic and sapropelic organic matter in the source rocks – related both to age and to paleogeographic setting (marine to continental) – result in differences in petroleum geochemical character, including normal sterane (C_{27}, C_{28}, C_{29}) ratios, cyclohexane to cyclopentane (ch:cp) ratios, and pristane-phytane (pr:ph) ratios, according to Popovich and Kravchenko, 1995, and Tull, 1997. These researchers believe that the northern part of the province is dominantly sourced by Middle to Upper Miocene shales (largely sapropelic), with petroleum characterized by subequal normal sterane content, ch:cp of 0.26-1.28, and pr:ph of 1.1-2. In contrast, they assert that central and southern parts of the province are sourced primarily by uppermost Oligocene and Lower to Middle Miocene (mostly humic) siliceous shales, with the petroleum characterized by C_{29} dominance, ch:cp > 1.5, and pr:ph of 1.13-2.61.

Oil from the fractured, siliceous reservoirs in Okruzhnoye field (Pogranichnyy trough coastline) is characterized as low density (0.8 grams/cubic centimeter), high resin (20%), low-sulfur (0.26%), and low-paraffin (1.8%) (Tyutrin and others, 1982). The associated gas is typically 70-91% methane.

Gas data from Kalendo and Tungor fields (onshore northeastern Sakhalin Island) show methane ranging from 78-97%, C_{2+} ranging from 2-7%, CO_2 ranging from <1-15%, He ranging from 10-26 ppm, and N_2 at <1% (Kamenskiy and others, 1975).

Total Petroleum System Size

The North Sakhalin Neogene TPS contains 6.1 BBOE (billion barrels of oil equivalent) known ultimately recoverable reserves, 13% of which was produced through 1995 (Petroconsultants, 1996). Thirty-six percent of the reserves are oil (35% produced), 61% are gas (<1% produced) and 3% are condensate (2.5% produced). The largest oil field is nearly 800 MMBO (million barrels of oil) (offshore) (table 2), with known sizes of *all* oil fields having a mean of 90 MMBO and a median of 9 MMBO. The largest gas field is approximately 10 TCF (trillion cubic feet) (nearly 1700 MMBOE; offshore) (table 2), with known sizes of *all* gas fields having a mean of 456 BCF (billion cubic feet) (76 MMBOE) and a median of 18 BCF (3 MMBOE). The smallest field that has been produced is onshore and contains only a few hundred thousand barrels of ultimately recoverable oil.

BURIAL, MATURATION, AND MIGRATION

Neogene and Pleistocene siliciclastic overburden on the source rocks (fig. 5) locally can exceed 6 km in thickness, and it generally changes from more marine to more terrigenous in character upward and westward. Present geothermal gradients across the North Sakhalin Basin Province range from approximately 24° to 50° C/km (1.3°-2.7° F/100 ft) (Mavrinski and Koblov, 1993; Khvedchuk, 1993), and heat flow is irregular along the major fault zones (Kononov and others, 1991). The oil and gas window falls within 2.5 to 4 km depths currently, and peak generation, maturation and migration was likely in

Late Miocene to Pliocene time (although local generation could have begun as early as Middle Miocene) (Mochalov, 1983; Silverman, 1990).

Migration paths include short to moderate lateral distances and significant vertical distances along faults, particularly along the major regional shears. Pleistocene leakage along these faults, especially from onshore accumulations, has resulted in many of those traps being underfilled relative to their spill points. Easternmost offshore basinal areas in the province expelled hydrocarbons westward and contributed to creating local overpressures.

TRAP STYLE AND DEVELOPMENT

Trap types in the most explored North Sakhalin trough (northernmost part of the east portion of the island and its adjacent offshore, fig. 1) – are Neogene in age and are known to consist of anticlines, complexly faulted anticlines, and fault traps with significant stratigraphic, truncational, and hydrodynamic components and complications (figs. 3b, 3c, and 3d).

Large, low-amplitude structural closures began to form in Early Miocene time, and more intense syn-sedimentary folding had occurred by the end of Middle Miocene time (fig. 5). The overall basin axis shifted progressively eastward throughout the Tertiary Period (Mochalov, 1983, 1985). Late Pliocene high-amplitude folding and inversion and later Pleistocene extension resulted in local loss of trap integrity and the redistribution or leakage of generated hydrocarbons. Thus, many onshore traps are not filled to spill point, but anticlines reportedly are less faulted in eastern offshore regions.

The northeastern part of the province is characterized by local overpressures (20% above normal; Tull, 1997) and by hydrodynamic impact, particularly in eastern areas where coastal or marine sandstones have a lithologic transition into offshore shales. This combination of phenomena causes oil-water contacts dip significantly westward in several fields.

North Sakhalin fault displacements range from tens to thousands of meters vertically and horizontally. Structural closures are characterized by areas of 5-300 km^2 and amplitudes of 80-600 m (Mavrinski and Koblov, 1993; Nikolayev, 1983). Some of the best anticlinal traps are reported to be associated with intersections of faults (Saprygin and others, 1978).

The Baykalo-Pomor synclinal area (offshore and onshore) on the northwest side of Sakhalin Island (fig. 1) was in existence by Middle Miocene time, and it contains eight major anticlinal zones and numerous folds with maximum dimensions of 30 km in length, six km in width, and 600 m in amplitude (Mustafin, 1983). Further Neogene structural deformation was contemporaneous with sedimentation. The structural closures are complicated by strike-slip (both dextral and sinistral) faults, with lateral displacements to 30 km, and by normal faults. There are no published penetrations in the offshore portions of the Baykalo-Pomor syncline, and less is known about the existence or extent of folds offshore.

The Pogranichnyy trough (south-central part of the east portion of the island and its adjacent offshore, fig. 1) has little published information, except for the Okruzhnoye field area at the coastline where traps consist of multi-directional block faults and thrusts (Silverman, 1990). Extension of paleo-Amur deltaic facies into the Pogranichnyy trough is questionable.

RESERVOIR ROCK

Identification and Description

North Sakhalin reservoir rocks are mostly Neogene in age (figs. 2 and 5). Middle Miocene to Pliocene reservoir sandstones are continental to marine in origin, with the most recognized names being Dagi, Okobykai, and Nutovo. Their source rocks are laterally equivalent shale facies and perhaps underlying organic-rich siliceous rocks. Self-sourced Upper Oligocene to Lower Miocene fractured, siliceous-shale reservoir rocks (comparable to Monterey Formation of California) include the names Pilengskaya and Borskaya. These Neogene reservoirs produce at depths ranging from approximately 25 to 4150 meters within the province (Petroconsultants, 1996).

All Tertiary formations generally are more shale-rich and more marine in origin to the east. Reservoir sandstones and pay zones are commonly stacked. For example, East Ekhaba field (northern coastal area, schematically shown on fig. 3d) contains 18 hanging wall and 20 footwall Miocene sandstone pay zones (Nikolayev, 2000). Producing sandstones range from laterally continuous (shallow-marine deposits) to highly discontinuous (channel deposits), with maximum individual thicknesses as great as tens of meters, but more typically several meters. East Ekhaba channel sandstones trend east-west and are 0.1 to 0.4 km wide. At Mongi field (central coastal area), offshore-bar reservoir sandstones have maximum dimensions of 3.6 km by 14 km (Gololobov and others, 1983).

Many sandstone reservoirs associated with this active Tertiary margin are mineralogically immature. Hanging-wall sandstones from multiple formations in the East Ekhaba field are fine to medium grained, with 30-45% quartz, 15-57% feldspar and 10-27% rock fragments (Nikolayev, 2000). Okobykai and Dagi sandstone reservoir rocks in the Gilyako-Abunan field (northern onshore area) contain frameworks of quartz, feldspar and chert, with cements of chlorite, kaolinite, carbonate, and quartz (Kuklich and others, 1984). Common montmorillonite clays convert to illite and mica with increased depth of burial.

Fractured siliceous shales that form the “silicite” reservoirs have been described for Okruzhnoye field (Yurochko, 1982; Danchenko and Chochiya, 1983), which also produces from younger Miocene sandstones and contains a 600-m oil column. Many silicites formed from globules of oversaturated gels during gas-hydrothermal stages of subaqueous volcanic activity. The Pilengskaya formation at Okruzhnoye field is 100-500 m of siliceous and clay-siliceous rocks. It contains montmorillonite and illite clay, tuffaceous pyroclastic or terrigenous quartz and feldspar, and authigenic silica as globules, with lesser amounts of pyrite, siderite, calcite and glauconite. Much of the silica was derived organically from diatoms and sponge spicules. Pilengskaya silicites include opoka or opoka-like rocks (cristobalite globules with <1 to 4 micron pores, 50% of formation), chalcedonite (chalcedony with pores <1 micron, 5-10% of formation), siliceous argillites (cristobalite and opal with pores < 1 micron, 35-40% of formation), and some diatomites. All silicites contain both tectonic and diagenetic joints.

Underexplored reservoir rocks in the North Sakhalin Basin Province are eastern (offshore) Miocene sandstones of deep-marine origin, fractured siliceous shales, and pre-Tertiary serpentinites.

Reservoir Properties

North Sakhalin Miocene sandstone reservoirs have an average of 22% porosity (range 7-35%) and an average of 247 md permeability (range 0.01-4200 md). These data are derived from Petroconsultants (1996).

Reservoir quality figures have been published for several fields producing from Miocene sandstone reservoirs. East Ekhaba field sandstones have 14-36% porosity in the hanging wall, and even “better” reservoir properties in the footwall (Nikolayev, 2000). Mongi field reservoir sandstones are characterized by 20-25% porosity and 3 darcies permeability (Gololobov and others, 1983). Gilyako-Abunan field has porosities up to 40% and permeabilities up to one darcy at less than 1500 meters paleodepth, but at 3500-4000 meters paleodepth, porosity is less than 10% and permeability less than one millidarcy (Kuklich and others, 1984).

The fractured siliceous shale (silicite) reservoir rocks can have “interglobular” porosity ranging from 3-27% , but matrix permeabilities commonly are < 0.01 md (Saprygin and others, 1978; Margulis, 1996).

SEAL ROCK

Numerous and excellent local and regional, vertical and lateral seals exist in Miocene and Pliocene deltaic and marine shales (fig. 5), typically at least tens to many hundreds of meters thick (Nikolayev, 1983; Kononov and others, 1991; Bogdanchikov and Stytsenko, 1995). Adequate shale seals are more rare in the western, more sand-rich facies of each formation. The province and TPS also are characterized by abundant and imperfect vertical and lateral fault seals where sandstones and shales are in juxtaposition. Reverse (compressional) faults commonly are better seals than normal (extensional) faults. Offshore areas probably contain more numerous and better shale seals and fewer fault seals than regions onshore.

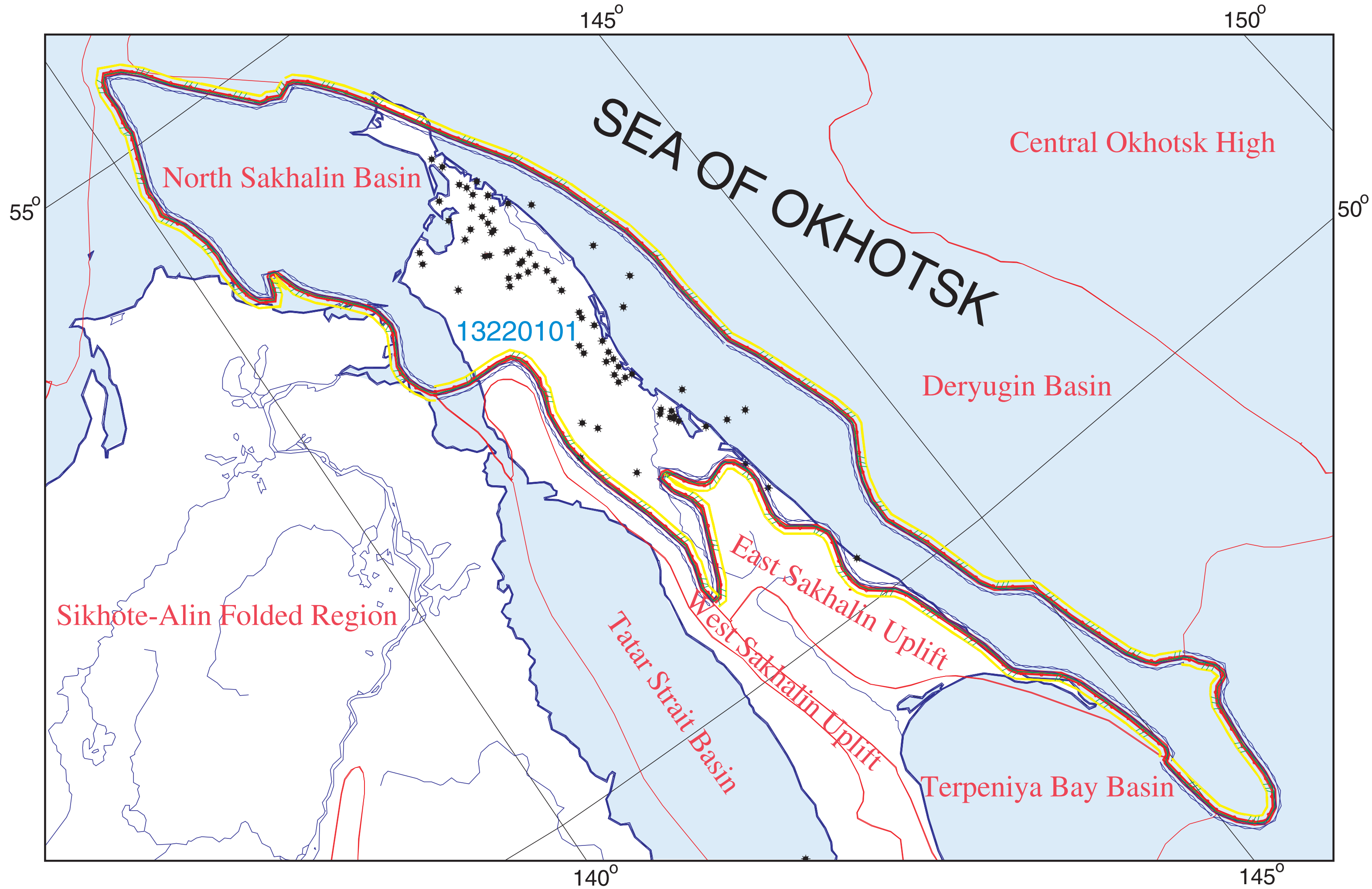


Figure 6. Coincident total petroleum system (North Sakhalin Neogene #132201) and singular assessment unit (Onshore and Offshore Northeastern Shelf #13220101) of North Sakhalin Basin Province #1322.

EXPLANATION

- Rivers and lakes
- Shoreline
- Geologic province boundary
- Country boundary
- Field location
- 13220101 Assessment region outline and code
- Minimum petroleum system outline
- Total petroleum system outline
- Pods of active source rock (tics on side of presence)

ASSESSMENT UNITS (AU)

The North Sakhalin Neogene gas-dominated TPS contains one established AU, *Onshore and Offshore Northeastern Shelf #13220101*, approximately 84,000 sq km in area and 72% in offshore areas (fig. 6). More future gas resources are expected than oil resources because the northern and northwestern offshore areas likely are dominated with gas-prone source rocks and many eastern offshore oil-prone source rocks are deeply buried. Eastern offshore regions will be less intensely deformed than those onshore. The fractured siliceous-rocks reservoirs are expected to be mostly oil-producing in both onshore and offshore locales.

Future fields will be in Middle Miocene to Pliocene sandstone reservoir rocks and in self-sourced Upper Oligocene to Lower Miocene fractured siliceous deposits comparable to the Monterey Formation of California. Some future reserves might be from pre-Cenozoic basement rocks that are unconformably overlain locally by Tertiary source rocks. Hydrocarbons will be found in anticlines, fault traps and stratigraphic traps. The expected total drill depth is approximately 3500 m for future oil fields and 6000 m for future gas fields. Future gas fields are expected to outnumber future oil fields by a 2:1 ratio. Province water depths do not exceed 200 m. No reserve growth factor is used in the assessment.

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