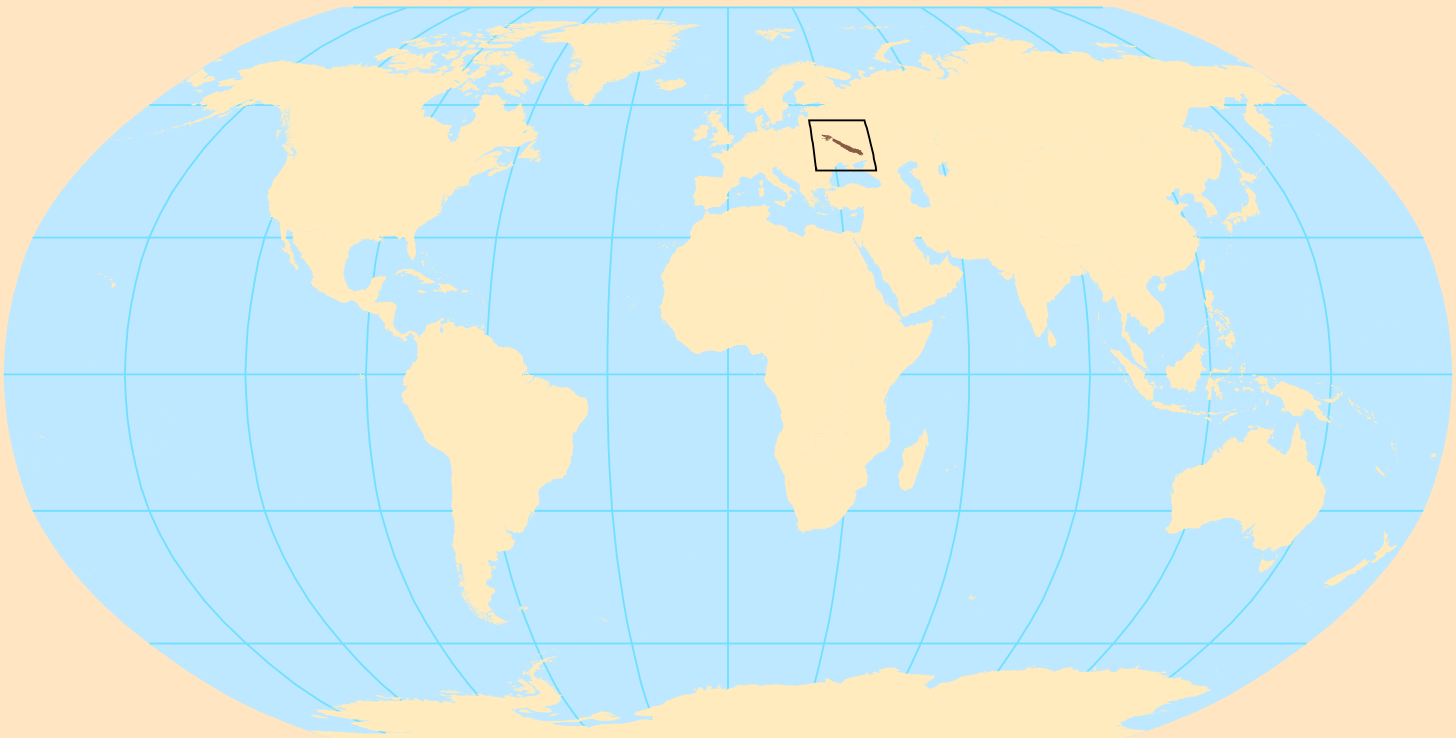
science for a changing world

Global Mineral Resource Assessment

Geology and Undiscovered Resource Assessment of the Potash-Bearing Pripyat and Dnieper-Donets Basins, Belarus and Ukraine



Scientific Investigations Report 2010–5090–BB

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

This page intentionally left blank

Global Mineral Resource Assessment

Michael L. Zientek, Jane M. Hammarstrom, and Kathleen M. Johnson, editors

Geology and Undiscovered Resource Assessment of the Potash-Bearing Pripyat and Dnieper-Donets Basins, Belarus and Ukraine

By Mark D. Cocker, Greta J. Orris, and Pamela Dunlap, with contributions from Bruce R. Lipin, Steve Ludington, Robert J. Ryan, Mirosław Słowakiewicz, Gregory T. Spanski, Jeff Wynn, and Chao Yang

Scientific Investigations Report 2010–5090–BB

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

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

U.S. Geological Survey, Reston, Virginia: 2017

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov/.

Suggested citation:
Cocker, M.D., Orris, G.J., and Dunlap, Pamela, with contributions from Lipin, B.R., Ludington, Steve, Ryan, R.J., Słowakiewicz, Mirosław, Spanski, G.T., Wynn, Jeff, and Yang, Chao, 2017, Geology and undiscovered resource assessment of the potash-bearing Pripyat and Dnieper-Donets Basins, Belarus and Ukraine: U.S. Geological Survey Scientific Investigations Report 2010–5090–BB, 116 p., and spatial data, https://doi.org/10.3133/sir20105090BB.

ISSN 2328-0328 (online)

Acknowledgments

This publication represents the work of the authors, assisted by an assessment oversight committee, technical reviewers, GIS specialists, and figure preparers, as well as others familiar with stratabound and halokinetic potash-bearing salt deposits. The authors are grateful to Michael Zientek and Jane Hammarstrom of the USGS who provided scientific and logistical guidance through the late stages of the USGS global potash assessment.

Bruce Lipin (USGS), Greg Spanski (USGS), Steve Ludington (USGS), Chao Yang (Saskatchewan Geological Survey), Mirosław Słowakiewicz (Polish Geological Institute), and Robert J. Ryan (Nova Scotia Department of Natural Resources) participated in the three-part assessment of the halokinetic structures in the Dnieper-Donets Basin. Chao Yang, Mirosław Słowakiewicz, and Robert J. Ryan also provided insights into potash deposits in their respective countries.

USGS colleagues Michael Zientek, Steve Box, Rob Robinson, and Cliff Taylor served as an assessment oversight committee to evaluate the assessment results for tract 150haK0042b prior to final manuscript preparation. Cliff Taylor (USGS) and Brad Van Gosen (USGS) reviewed early versions of the Pripyat tract and of the assessment of tract 150haK0042b. Steve Box (USGS) and Tim Klett (USGS) reviewed the entire manuscript. Pamela Cossette (USGS) reviewed the GIS portion of the manuscript. Kathleen Johnson and Michael Zientek served as the series editors and reviewed and edited the entire manuscript prior to publication.

Deborah Briggs and Leila Gass assisted in georeferencing and digitizing of maps and drill holes and preparation of GIS shapefiles and geodatabases. Jim Bliss provided guidance in the use and interpretation of statistical results. Deborah Briggs, Leila Gass, Robert Miller, Connie Dicken, Hannah Campbell, Drew Luders, Michael Landkammer, Logan Matti, J.R. Bell, Joe Miles, Heather Parks, and Kassandra Lindsey assisted in preparation of figures

This page intentionally left blank

Contents

Contents—Continued

Contents—Continued

Figures

Figures—Continued

Tables

Tables—Continued

Conversion Factors

[Inch/pound to International System of Units]

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
ounce, troy (troy oz)	31.015	gram (g)
ounce, troy (troy oz)	0.0000311	megagram (Mg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

Conversion Factors—Continued

[International System of Units to inch/pound]

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
gram (g)	0.03215	ounce, troy (troy oz)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Abbreviations

Bt	billion metric tons
GIS	geographic information system
g/t	grams per metric ton
kt	thousand metric tons
Ma	million years before present
Mt	million metric tons
m.y.	million years
t	metric ton (ton) or megagram (Mg)
USGS	United States Geological Survey

Geology and Undiscovered Resource Assessment of the Potash-Bearing Pripyat and Dnieper-Donets Basins, Belarus and Ukraine

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap,[1] with contributions from Bruce R. Lipin,[2] Steve Ludington,[3] Robert J. Ryan,[4] Mirosław Słowakiewicz,[5] Gregory T. Spanski,[6] Jeff Wynn,[7] and Chao Yang[8]

Abstract

Undiscovered potash resources in the Pripyat Basin, Belarus, and Dnieper-Donets Basin, Ukraine, were assessed as part of a global mineral resource assessment led by the U.S. Geological Survey (USGS). The Pripyat Basin (in Belarus) and the Dnieper-Donets Basin (in Ukraine and southern Belarus) host stratabound and halokinetic Upper Devonian (Frasnian and Famennian) and Permian (Cisuralian) potash-bearing salt. The evaporite basins formed in the Donbass-Pripyat Rift, a Neoproterozoic continental rift structure that was reactivated during the Late Devonian and was flooded by seawater. Though the rift was divided, in part by volcanic deposits, into the separate Pripyat and Dnieper-Donets Basins, both basins contain similar potash-bearing evaporite sequences. An Early Permian (Cisuralian) sag basin formed over the rift structure and was also inundated by seawater resulting in another sequence of evaporite deposition. Halokinetic activity initiated by basement faulting during the Devonian continued at least into the Permian and influenced potash salt deposition and structural evolution of potash-bearing salt in both basins.

Within these basins, four areas (permissive tracts) that permit the presence of undiscovered potash deposits were defined by using geological criteria. Three tracts are permissive for stratabound potash-bearing deposits and include Famennian (Upper Devonian) salt in the Pripyat Basin, and Famennian and Cisuralian (lower Permian) salt in the Dnieper-Donets Basin. In addition, a tract was delineated for halokinetic potash-bearing Famennian salt in the Dnieper-Donets Basin.

The Pripyat Basin is the third largest source of potash in the world, producing 6.4 million metric tons of potassium chloride (KCl) (the equivalent of about 4.0 million metric tons of potassium oxide or K_2O) in 2012. Potash production began in 1963 in the Starobin #1 mine, near the town of Starobin, Belarus, in the northwestern corner of the basin. Potash is currently produced from six potash mines in the Starobin area. Published reserves in the Pripyat Basin area are about 7.3 billion metric tons of potash ore (about 1.3 billion metric tons of K_2O) mostly from potash-bearing salt horizons in the Starobin and Petrikov mine areas. The 15,160-square-kilometer area of the Pripyat Basin underlain by Famennian potash-bearing salt contains as many as 60 known potash-bearing salt horizons. Rough estimates of the total mineral endowment associated with stratabound Famennian salt horizons in the Pripyat Basin range from 80 to 200 billion metric tons of potash-bearing salt that could contain 15 to 30 billion metric tons of K_2O.

Parameters (including the number of economic potash horizons, grades, and depths) for these estimates are not published so the estimates are not easily confirmed. Historically, reserves have been estimated above a depth of 1,200 meters (m) (approximately the depths of conventional underground mining). Additional undiscovered K_2O resources could be significantly greater in the remainder of the Fammenian salt depending on the extents and grades of the 60 identified potash horizons above the USGS assessment depth of 3,000 m in the remainder of the tract. Increasing ambient temperatures with increasing depths in the eastern parts of the Pripyat Basin may require a solution mining process which is aided by higher temperatures.

No resource or reserve data have been published and little is known about stratabound Famennian and Frasnian salt in the Dnieper-Donets Basin. These Upper Devonian salt units dip to the southeast and extend to depths of 15–19 kilometers (km) or greater. The tract of stratabound Famennian salt that lies above a depth of 3 km, the depth above which potash is

---

[1]U.S. Geological Survey, Tucson, Arizona, United States.

[2]U.S. Geological Survey, Reston, Virginia, United States.

[3]U.S. Geological Survey, Menlo Park, California, United States.

[4]Nova Scotia Department of Natural Resources, Halifax, Nova Scotia, Canada.

[5]Polish Geological Institute, Warsaw, Poland.

[6]U.S. Geological Survey, Denver, Colorado, United States.

[7]U.S. Geological Survey, Vancouver, Washington, United States.

[8]Saskatchewan Geological Survey, Regina, Saskatchewan, Canada.

technically recoverable by solution mining, underlies an area of about 15,600 square kilometers (km^2). If Upper Devonian salt units in the Dnieper-Donets Basin contain potash-bearing strata similar to salt of the same age in the Pripyat Basin, then the stratabound Famennian tract in the Dnieper-Donets Basin could contain significant undiscovered potash resources.

The Cisuralian evaporite sequence in the Dnieper-Donets Basin consists of 10 evaporite cycles with the upper 3 cycles containing potash-bearing salt (mainly as sylvite and carnallite) in several subbasins and polyhalite in the sulfate bearing parts of the identified tract. The area of the Cisuralian tract is 62,700 km^2. Potash-bearing cycles are as much as 40 m thick. One subbasin is reported to contain 794 million metric tons of “raw or crude” potash-bearing salt which could contain 50 to 150 million metric tons of K_2O, depending on the grade. Undiscovered potash resources in the remainder of this permissive tract may be significantly greater. Depths to the Permian salt range from less than 100 to about 1,500 m.

Undiscovered resources of halokinetic potash-bearing salt in the Dnieper-Donets Basin were assessed quantitatively for this study by using the standard USGS three-part form of mineral resource assessment (Singer, 2007a; Singer and Menzie, 2010). Delineation of the permissive tract was based on distributions of mapped halokinetic salt structures. This tract contains at least 248 diapiric salt structures with a total area of 7,840 km^2 that occupies approximately 8 percent of the basin area. The vertical extent of these salt structures is hundreds of meters to several kilometers. This assessment estimated that a total mean of 11 undiscovered deposits contain an arithmetic mean estimate of about 840 million metric tons of K_2O in the halokinetic salt structures of the Dnieper-Donets Basin for which the probabilistic estimate was made.

Chapter 1. Introduction

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

The Pripyat Basin in Belarus and the Dnieper-Donets Basin in Ukraine and southern Belarus (fig. 1–1) host stratabound and halokinetic Upper Devonian (Frasnian and Famennian) and Permian (Cisuralian) potash-bearing salt. Belarus is the world's third largest producer of potash with 16 percent of world potash production (Foreign Policy and Security Research Center, 2011). From 1967 to 2003, total potash production from Famennian stratabound potash-bearing salt in Belarus exceeded 1 billion metric tons (Bt). In 2012, six mines in Belarus produced 8.8 million metric tons (Mt) of potassium salts annually and planned to expand production to 15 Mt by 2020 (Truscott, 2011; Cocker and Orris, 2013). Although drill holes have intersected potash-bearing salt units of the same age in the adjacent Dnieper-Donets Basin, no potash resources have been identified. No information is available regarding possible recovery of byproduct potash from the salt mines in Ukraine.

Potash resources of the Pripyat and Dnieper-Donets Basins were assessed as part of a U.S. Geological Survey-led global mineral resource assessment of undiscovered resources of potash, copper, and platinum-group elements (Schulz and Briskey, 2003; Hammarstrom and others, 2010). The purposes of the assessment are to (1) delineate permissive areas (tracts) for undiscovered potash-bearing salt deposits at a scale of 1:1,000,000, (2) provide a database of known potash-bearing salt occurrences, and (3) evaluate available data to assess amounts of undiscovered potash resources in the permissive tracts. This assessment includes a qualitative discussion of the undiscovered potash resource potential of both basins as well as a quantitative assessment for halokinetic potash-bearing salt deposits in the Dnieper-Donets Basin.

This study was done by the U.S. Geological Survey (USGS) in collaboration with geologists from the Polish Geological Institute, the Nova Scotia Department of Natural Resources, and Saskatchewan Ministry of Energy and Resources. A potash assessment workshop held in Tucson, Arizona, in May 2009 included an overview of the geology of the study area, discussions on potash-bearing salts within the Pripyat and Dnieper-Donets Basins, selection of appropriate mineral deposit models, and delineation of permissive tracts. Four tracts were identified that contain potash-bearing salt: (1) Permian (Cisuralian) stratabound potash-bearing salt in the Dnieper-Donets Basin, (2) Upper Devonian stratabound potash-bearing salt in the Dnieper-Donets Basin, (3) Upper Devonian stratabound potash-bearing salt in the Pripyat Basin, and (4) Upper Devonian halokinetic potash-bearing salt in the Dnieper-Donets Basin. Summaries of the mineral deposit models for stratabound and halokinetic potash-bearing salts are included in this report as appendixes A and B, respectively. During the 2009 assessment meeting, the amount of undiscovered potash in halokinetic potash-bearing salt structures in the Dnieper-Donets Basin was estimated quantitatively. Preliminary results from the 2009 workshops were updated and refined after formal reviews.

Structure of this Report

This report discusses the structural development of the Pripyat and Dnieper-Donets Basins, the Devonian and Permian stratigraphy of the potash-bearing salt units, and secondary dissolution and structural effects on the potash-bearing salt. Individual tracts are discussed in the following order: (1) stratabound Cisuralian Dnieper-Donets Basin, (2) stratabound Upper Devonian Dnieper-Donets Basin, (3) stratabound Upper Devonian Pripyat Basin, and (4) halokinetic Upper Devonian Dnieper-Donets Basin. Each tract description includes a discussion of the development of potash-bearing salt, followed by an assessment of undiscovered potash resources. The first three tracts were assessed qualitatively, and the halokinetic Upper Devonian Dnieper-Donets Basin tract was assessed quantitatively. The appendixes contain descriptive models of stratabound and halokinetic potash-bearing salt (appendixes A and B); data for a grade and tonnage model for halokinetic potash deposits (appendix C); a glossary of terms used in descriptions of evaporitic salt (appendix D); names, locations, and sizes of halokinetic salt structures in the Dnieper-Donets Basin (appendix E); a list of halite occurrences in the study area (appendix F); a brief description of the spatial databases included in this publication (appendix G); and biographical information for the members of the assessment team (appendix H).

[1]U.S. Geological Survey, Tucson, Arizona, United States.

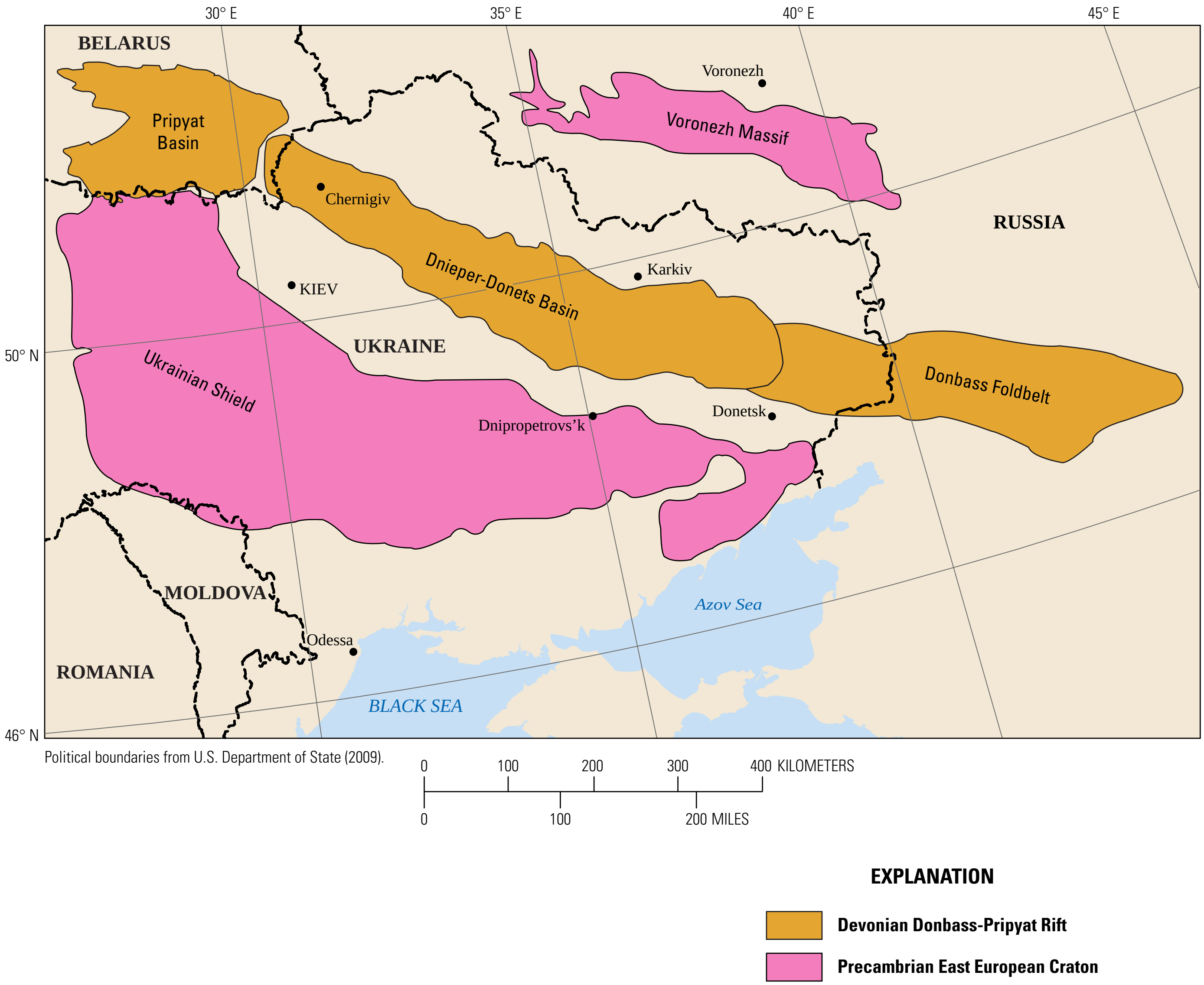


Figure 1–1. Map showing locations of the Pripyat and Dnieper-Donets Basins, the Donbass Foldbelt, and surrounding major structural elements (modified from Stephenson and others, 2006).

Potash

Potash denotes a variety of mined and manufactured salts (table 1–1), all of which contain the element potassium in water-soluble form (Jasinski, 2015a). Potassium is an essential nutrient for plants, animals, and humans, and has no known substitutes; 90–95 percent of potash is used for fertilizer (Prud'homme and Krukowski, 2006; Jasinski, 2015a). Potash is a nonrenewable resource, and the only economic sources are potassium-bearing brines or geologic salt deposits. Industry uses the term "potash" to refer to potassium chloride as well as potassium sulfate, nitrate, and oxide (Neuendorf and others, 2005). The principal products of potash mining are potassium chloride (KCl), which is referred to as "muriate of potash" or "MOP" and potassium sulfate (K_2SO_4), which is referred to as "sulfate of potash" or "SOP."

Potash deposits are accumulations of potassium chloride and potassium sulfate evaporite minerals intimately associated with halite and related basin-wide evaporites. Most potash-bearing salt deposits form by evaporation of large volumes of seawater in hydrographically restricted or isolated basins under hyperarid conditions (Warren, 2006, 2010; Kendall, 2010). Hyperarid climatic conditions promote high evaporation and salt precipitation rates, resulting in hypersaline conditions and eventual deposition of potash and magnesium salts. Potash-bearing salt deposits are classified into two end-member deposit types: (1) stratabound potash-bearing salt deposits (appendix A) characterized by relatively flat-lying, undeformed potash-enriched beds, 1 centimeter (cm) to ~10 meters (m) thick, that can extend for tens to hundreds of kilometers within a basin; and (2) halokinetic potash-bearing salt deposits (appendix B) that originally

Table 1–1. Potash ore minerals and ore materials from Orris and others (2014).

[Composition formulas from Back and Mandarino (2008); potassium content and specific gravity from Harben and Kužvart (1996) and Anthony and others (1997, 2003); <, less than]

Mineral or material	Composition	Potassium oxide (K_2O) (percent)	Specific gravity (metric tons/ cubic meter)
Primary potash minerals			
Carnallite	$KMgCl_3 \cdot 6H_2O$	16.9	1.60
Kainite	$MgSO_4 \cdot KCl \cdot 3H_2O$	19.3	2.10
Langbeinite	$K_2Mg_2(SO_4)_3$	22.7	2.83
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$	15.6	2.77
Sylvite	KCl	63.2	2.00
Primary potash ore materials			
Carnallitite	Mix of halite and carnallite	As much as 15	Variable
Hartsalz	Mix of sylvite, halite, anhydrite, and kieserite	Typically <15	Variable
Sylvinite	Mix of sylvite and halite	Typically <25	Variable
Accessory potassium minerals			
Aphthitalite (glaserite)	$(K,Na)_3Na(SO_4)_2$	42.5	2.69
Arcanite	K_2SO_4	54.1	2.66
Douglasite	$K_2Fe^{2+}Cl_4 \cdot 2H_2O$	30.2	2.16
Leonite	$K_2Mg(SO_4)_2 \cdot 4H_2O$	25.7	2.20
Niter (saltpeter)	KNO_3	44.0	2.1
Picromerite (schönite)	$K_2Mg(SO_4)_2 \cdot 6H_2O$	23.4	2.03
Rinneite	$K_3NaFe^{2+}Cl_6$	34.5	2.35
Syngenite	$K_2Ca(SO_4)_2 \cdot H_2O$	28.7	2.58
Accessory non-potassium minerals			
Anhydrite	$CaSO_4$	0	2.98
Bischofite	$MgCl \cdot 6H_2O$	0	1.59
Blödite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$	0	2.23
Dolomite	$CaMg(CO_3)_2$	0	2.86
Epsomite	$MgSO_4 \cdot 7H_2O$	0	1.68
Gypsum	$CaSO_4 \cdot 2H_2O$	0	2.30
Halite	NaCl	0	2.17
Hexahydrite	$MgSO_4 \cdot 6H_2O$	0	1.76
Kieserite	$MgSO_4 \cdot H_2O$	0	2.57
Löweite	$Na_{12}Mg_7(SO_4)_{13} \cdot 15H_2O$	0	2.36–2.42
Tachyhydrite	$CaMgCl_6 \cdot 12H_2O$	0	1.67
Vanthoffite	$Na_6Mg(SO_4)_4$	0	2.69

formed as stratabound potash-bearing salt deposits and subsequently were altered by salt tectonics (halokinesis), changing the lateral continuity, geometry, size, and structural position of the potash-bearing salt.

In 2015, world potash production was about 38.8 Mt of K_2O equivalent (Jasinski, 2016). Canada was the largest producer of potash (9.5 Mt K_2O equivalent in 2013), followed by Russia, Belarus, China, Germany, Israel, and Jordan (Jasinski, 2015b; fig. 1–2). Eight of the 12 major potash-producing countries produced 1 Mt or more in 2014; production from other countries was less than 1 Mt (Jasinski, 2015b).

Recent compilations of global stratabound and halokinetic salt deposits (Orris and others, 2013, 2014) provide geologic data regarding deposits located in the major potash-producing countries as well as in other countries which may become important potash sources in the future. A surge in potash prices during the early part of the 21st century spurred a period of renewed exploration for potash deposits throughout the world and expansion of existing mine capacity or related potash-bearing salt, including those found in the Pripyat Basin (Cocker and Orris, 2013).

Considerations for Users of this Assessment

Ideally, assessments are done on a recurring basis, at a variety of scales, because the availability of data changes over time. This report represents a synthesis of current, readily available information, as of November 2012. The assessment is based on descriptive and grade-tonnage data contained in published mineral deposit models (table 6–2). These data represent the most reliable values available for potash found in the deposit type(s) considered by the assessment and for which data were available when the model was constructed.

The economic viability of any mineral deposit depends on a variety of factors, many of which vary with time. This caveat applies to deposits used to construct grade-tonnage models, as well as to undiscovered deposits, so care must be exercised when using the results of this assessment to answer economic questions. If discovered, deposits may not be developed immediately or ever. Furthermore, estimates in this assessment are in-place resources and (or) numbers of deposits that are likely to exist, not necessarily those likely to be discovered (Singer and Menzie, 2010). Prospects, revealed by past or current exploration efforts, may become deposits through further drilling and characterization. These potential deposits are treated here as undiscovered deposits, albeit ones with a high degree of certainty of existence.

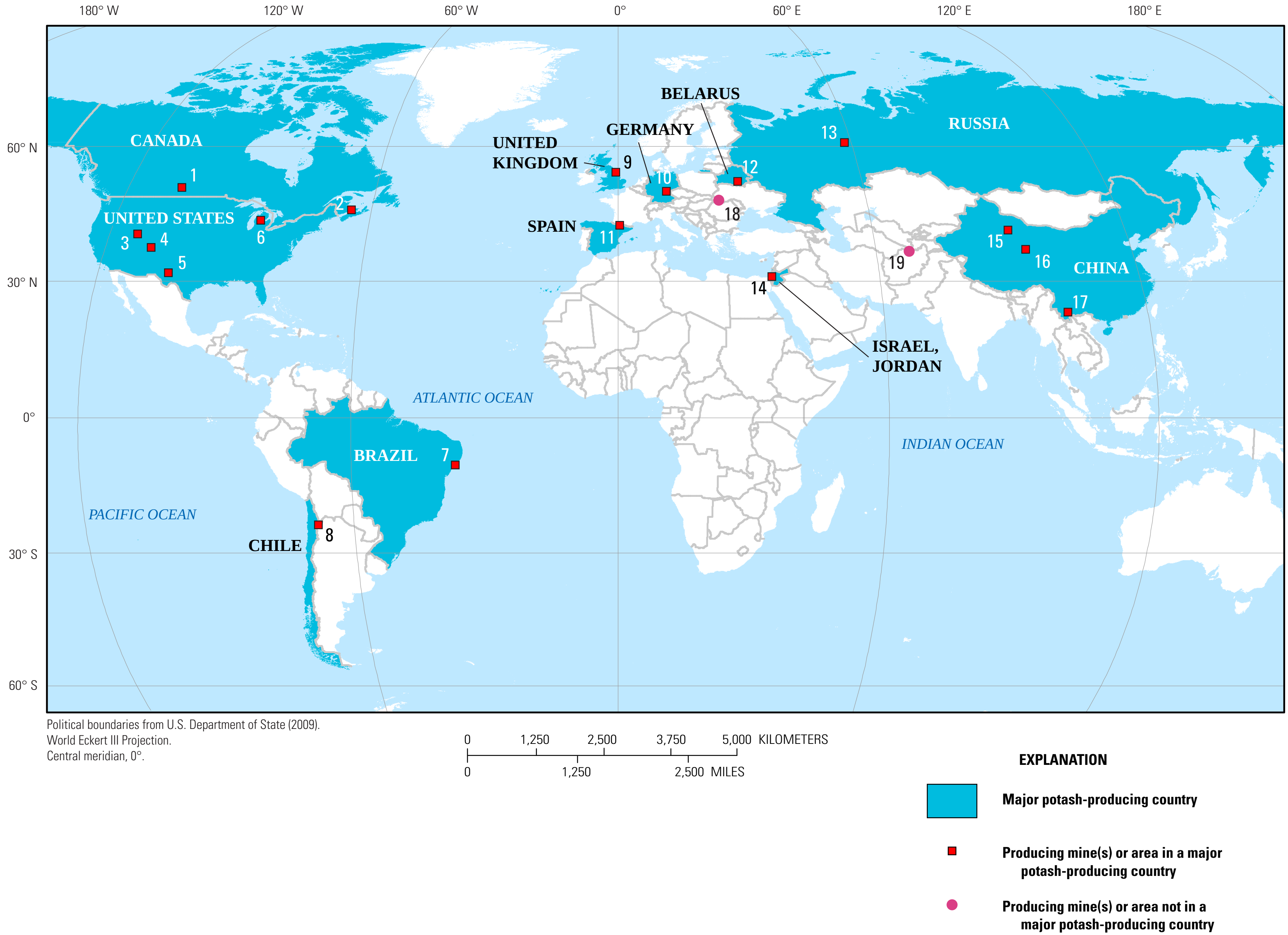
The mineral industry typically explores for extensions of identified resources, as well as for undiscovered deposits. Extensions of identified resources are not explicitly estimated in this assessment. This assessment considers the potential for undiscovered deposits within 3 kilometers (km) of the surface. Potash, if ever exposed at the surface, has normally been long since lost to dissolution and (or) erosion. Higher grade deposits may be exploited at greater depths than lower grade deposits. Solution mining allows for extraction of lower grades of potash at greater depths and has been more commonly considered for development of new mines than in the past. Exploration for, and possible exploitation of, these deeper deposits may be so expensive that they may not be discovered in the near term except incidentally during oil and gas exploration. If discovered, costs or extreme geological conditions to mine a deeply buried potash deposit may prohibit its development into a mine, given current or anticipated commodity prices, potential markets and transportation distances, and technology.

Permissive tracts are identified on the basis of geology, irrespective of political boundaries. Tracts in this assessment cross political boundaries. The tracts are constructed at a scale of 1:1,000,000 and are not intended for use at larger scales.

Terminology

Several factors were encountered during this assessment of potash in the Pripyat and Dnieper-Donets Basins that are common in areas where the main information sources are published in Russian. These factors include (1) poor to nonexistent locational data for geologic maps and drill holes, including such items as north arrows, scale bars, and location maps; (2) lack of detailed drill logs and drill-hole locations; (3) stratigraphic terminology in eastern Europe that is not compatible with that of western Europe or the

Figure 1–2. On opposite page (p. 7). Map from Orris and others (2014) showing active potash mines or producing areas. Sites in the top 12 potash-producing countries, as listed in the USGS Mineral Commodity Summaries 2015 (Jasinski, 2015b), are shown as numbered red boxes. The potash-producing areas in these countries are (1) Elk Point, Saskatchewan, Canada; (2) Penobsquis-Piccadilly, New Brunswick, Canada; (3) Bonneville brines, Utah, USA; (4) Moab mine, Utah, USA; (5) Carlsbad district, New Mexico, USA; (6) Michigan basin brines, USA; (7) Taquari-Vassouras, Sergipe, Brazil; (8) Salar de Atacama, Chile; (9) Boulby mine, United Kingdom; (10) Zechstein basin potash mines, Germany; (11) Navarra and Cardona, Spain; (12) Pripyat Basin, Belarus; (13) Bereznicki and Solikamsk mines, Russia; (14) Dead Sea brine operations, Jordan and Israel; (15) Lop Nur brine, Xinjiang, China; (16) Qaidam basin brine operations, Qinghai, China; and (17) Mengyejing district, Yunnan, China. Numbered pink circles identify active potash mines or producing areas outside the top 12 potash-producing countries. These locations are (18) Carpathian region, Ukraine, and (19) Tyubegatan, Uzbekistan.


180° W
120° W
60° W
0°
60° E
120° E
180° E
60° N
30° N
0°
30° S
60° S
CANADA
UNITED STATES
BRAZIL
CHILE
UNITED KINGDOM
GERMANY
BELARUS
RUSSIA
SPAIN
ISRAEL, JORDAN
CHINA
ATLANTIC OCEAN
PACIFIC OCEAN
INDIAN OCEAN
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
Political boundaries from U.S. Department of State (2009).
World Eckert III Projection.
Central meridian, 0°.
0 1,250 2,500 3,750 5,000 KILOMETERS
0 1,250 2,500 MILES
EXPLANATION
Major potash-producing country
Producing mine(s) or area in a major potash-producing country
Producing mine(s) or area not in a major potash-producing country

Americas; (4) variations or inconsistencies in stratigraphic definitions (including such terms as horizon, suite, sequence, and formation) between various authors and in single publications by the same author from at least as early as 1967 to the present; and (5) variations in naming of geologic features which could refer to one or more than one feature (such as the halokinetic structures). Because of our unfamiliarity with some Russian geological concepts, some ambiguities could not be resolved. As a result, for this report we used either the original terminology or our best interpretations of the original investigations based on our experience in this study area and in other potash-bearing salt basins, as reported by Orris and others (2013, 2014).

A number of terms that are used to describe potash-bearing salt deposits are in common usage in Europe or are described by European authors. These terms may refer to particular types of potash occurrences or deposits. Alteration of these terms would change their meanings or result in awkward terminology that does not adequately describe a feature. The authors thought it was most appropriate to continue using the same terminology employed in the descriptions of the potash and salt deposits and evaporite stratigraphy. Terms such as "cycles," "horizons," and particularly those related to halokinesis, are defined in the glossary (appendix D).

Potash-bearing stratabound salt depositional sequences or layers are referred to in the Pripyat Basin and other potash salt basins around the world as "horizons" (Eroshina, 1981; Eroshina and Obrovets, 1983; Garetsky and others, 1984; Zharkov, 1984). In the Pripyat Basin, the earliest known potash-bearing horizons were designated as horizon I, horizon II, horizon III, and horizon IV numbered from shallowest to deepest. At least 60 layers of potash are known at present, and all are labeled as horizons (Eroshina, 1981; Eroshina and Obrovets, 1983; Garetsky and others, 1984; Zharkov, 1984).

This report uses stratigraphic age terminology as presented in the International Stratigraphic Chart (International Commission on Stratigraphy, 2011). As a result, all references to lower Permian are noted in this report as Cisuralian.

The Soviet Stratigraphic Code includes the term "suite" for a local stratigraphic unit that is characterized by specific lithological facies or petrographic features (Zhamoida, 1984). Gladenkov (2007) indicated that a suite differs from a formation (a lithostratigraphic unit), because a suite is defined by additional data such as paleontology, magnetic reversals, and geochemistry, and ideally has isochronous boundaries rather than diachronous boundaries for formations. The term "suite" is used extensively when Cisuralian stratigraphy in the Dnieper-Donets Basin is described in chapter 3.

Political Boundaries

Political boundaries used in this report are, in accord with U.S. Government policy, the small-scale digital international boundaries (SSIB) provided by the U.S. Department of State (U.S. Department of State, 2009). In various parts of the world, some political boundaries are in dispute. The use of the boundaries certified by the U.S. Department of State does not imply that the USGS advocates or has an interest in the outcome of any international boundary disputes.

Chapter 2. Geologic Overview of the Pripyat and Dnieper-Donets Basins and the Donbass-Pripyat Rift

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

Introduction

This section provides an overview of the geologic features of the Pripyat and Dnieper-Donets Basins (fig. 1–1) and the Donbass-Pripyat Rift (fig. 2–1), how they evolved, and how their evolution influenced the evolution of evaporite and potash deposits. Despite being separate basins through much of their evolution, the tectonics, stratigraphy, and evaporites of these basins are very similar and can be discussed as one system with minor variations. Sedimentary deposition in basins like these is commonly divided into pre-rift, syn-rift, and post-rift phases, and this discussion follows that order.

Salt structures in the Pripyat and Dnieper-Donets Basins have been explored by drilling and seismic surveys seeking oil and gas in structural and sedimentary traps. Many of these traps are related to salt tectonics or seals (Clarke, 1987; Chekunov and others, 1993; Ulmishek and others, 1994; Ulmishek, 2001). Parts of the Dnieper-Donets Basin deeper than the salt structures have not been drilled (Ulmishek and others, 1994; Stova and Stephenson, 2003).

Devonian and younger sedimentary rocks within the Pripyat Basin are as much as 4 km thick. Within the Dnieper-Donets Basin, Devonian and younger sedimentary rocks are generally 5–6 km thick (Ulmishek and others, 1994) but increase to 15–19 km thick in the southeastern part of the basin (Stova and Stephenson, 2003).

Basin Tectonics, Structure, and Architecture

Pre-Rift

The Donbass-Pripyat Rift formed during the Devonian, exploiting a Riphean (Meso- to Neoproterozoic, 1,400–850 million years before present [Ma]) aulacogen that follows the Sarmatian-Turan lineament (fig. 2–1; Aizberg and others, 2004). During the Meso- to Neoproterozoic, the rift system opened northwestward into the continent as a transform fault (Chekunov and others, 1992; Aizberg and others, 2004).

The Sarmatian-Turan lineament may have developed as the Paleotethyan mid-ocean ridge approached the Eurasian continental margin. The Riphean aulacogen extends about 2,600 km (fig. 2–1) from Belarus through Ukraine, Russia, and Kazakhstan, and into Turkmenistan (Oczlon, 2006). The Riphean aulacogen split the Sarmatia portion of the East European Craton into the Voronezh Massif to the northeast and the Ukrainian Shield to the southwest (Ulmishek and others, 1994; Bogdanova and others, 1996; Stovba and Stephenson, 2003; Oczlon, 2006).

The northern (Baranovichsko-Astrakhan) and southern (Pripyatsko-Manych) rift boundary faults, the Bragin-Loev High, and the Polessian Saddle (fig. 2–2) mark the current, preserved depositional limits of the Pripyat Basin (Zharkov, 1984). The Polessian Saddle separates the Pripyat Basin from the Poljassk-Brest Basin (Garetsky and others, 1984, 2004) located to the west (fig. 2–1).

Middle Devonian pre-rift sedimentary rocks in the Dnieper-Donets Basin consist of a sand-shale sequence deposited in small isolated troughs. In the Pripyat Basin, deposition of clastic rocks of similar age was followed by Middle to Upper Devonian carbonate rocks. Pre-rift sediment thickness in the Dnieper-Donets Basin was as much as 100 m, and in the Pripyat Basin, sediment thickness was as much as 425 m (Aizberg and others, 2004).

Syn-Rift

During the Middle and Late Devonian, rifting was renewed along the Samartian-Turan continental rift system as the Donbass-Pripyat Rift. Initial rifting of the Pripyat part of the rift began prior to the Middle Frasnian (369 Ma), but most rifting occurred during the Late Devonian (367–364 Ma) (Kuznir and others, 1996). Although main rifting in the Pripyat Basin began slightly later than in the Dnieper-Donets Basin, it ended at the same time that rifting in the Dnieper-Donets Basin ended, at the Devonian-Carboniferous boundary (Aizberg and others, 2004). Additional basin-extension-related faults are shown in basin cross sections (fig. 2–3). More than 66 percent of basin extension of both basins occurred over more than 5 million years (m.y.). The period of most rapid extension coincides with the period of most active volcanism (Kuznir and others, 1996).

[1]U.S. Geological Survey, Tucson, Arizona, United States.

Figure 2–1. Map showing the location of the late (middle?) Proterozoic Sarmatian-Turan continental rift system, the precursor to the Donbass-Pripyat Rift, and major eastern European regional structural features (modified from Sliaupa and others, 2006).

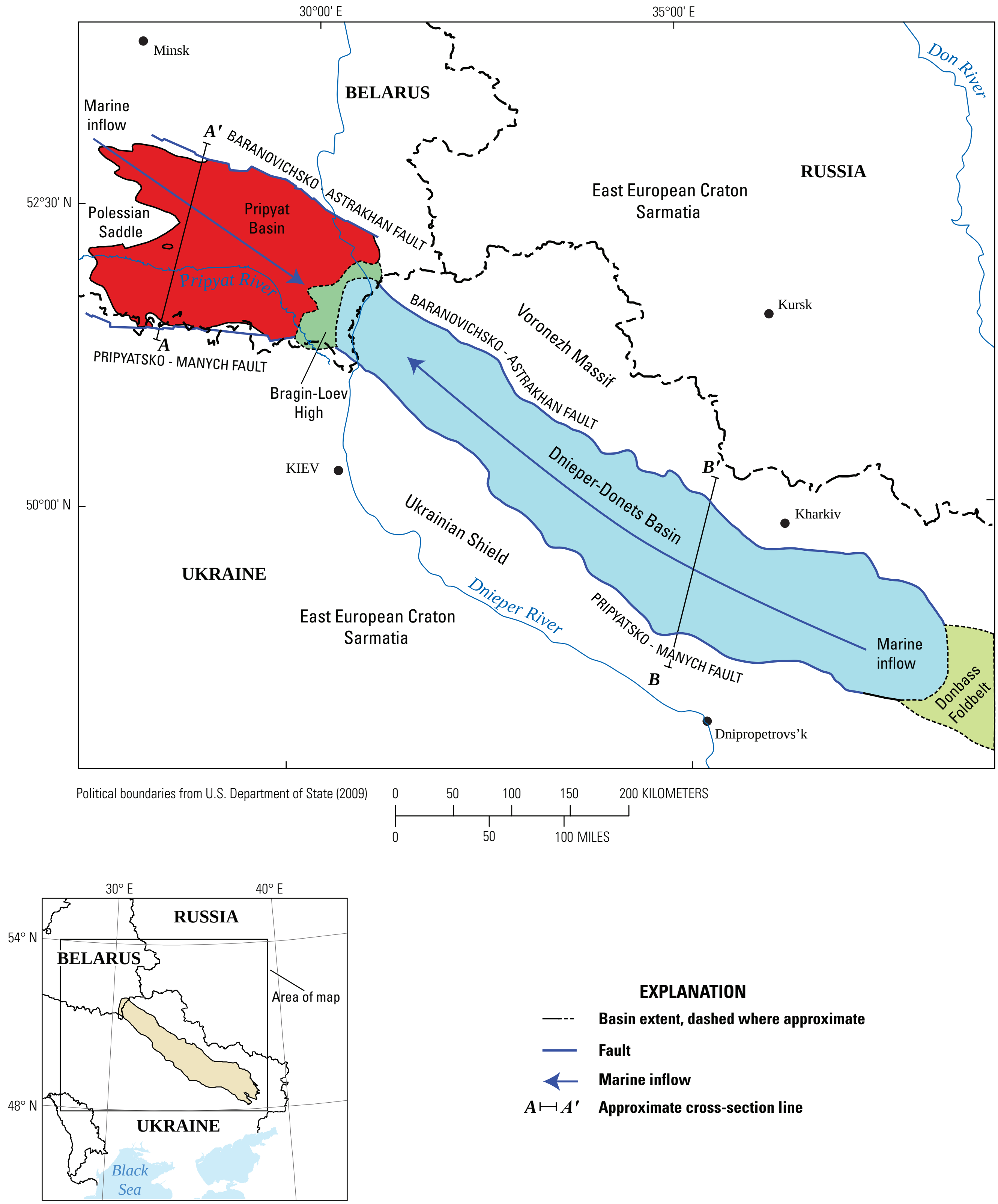


Figure 2–2. Map showing major structural elements of the Donbass-Pripyat Rift and surrounding areas. During the early part of the Late Devonian, marine waters may have entered the Pripyat Basin from the west-northwest and northwest, and the Dnieper-Donets Basin from the southeast with perhaps marine flow across the Bragin-Loev High. However, the principal direction of flow is presumed to be from the Podlasie-Brest Basin, located to the northwest of the Pripyat Basin (fig. 2–1).

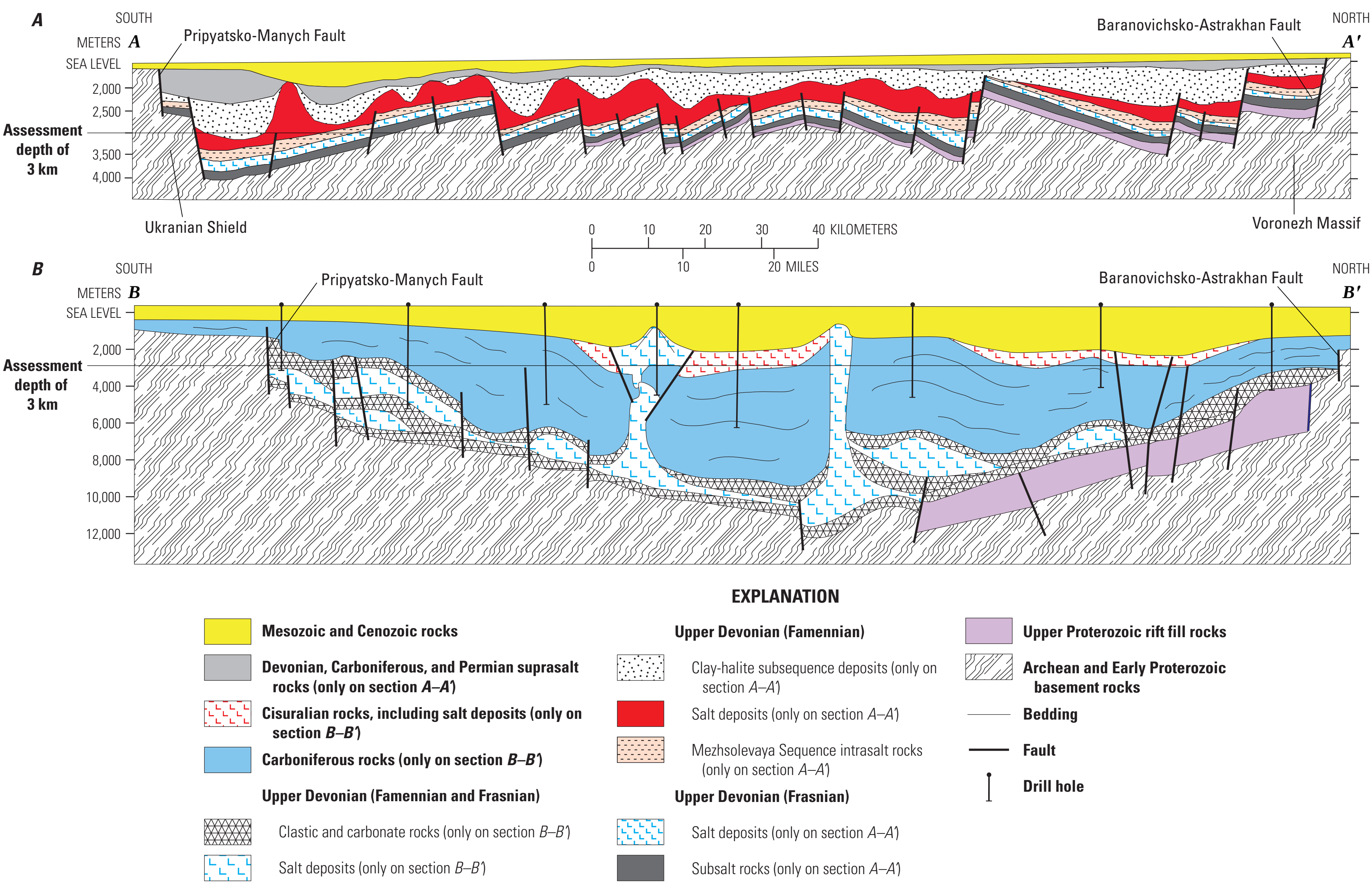


Figure 2–3. Geologic cross sections of the Pripyat and Dnieper-Donets Basins (modified from Garetsky and others, 2004). *A*, Generalized cross section (*A*–*A*′) of the Pripyat Basin. *B*, Generalized cross section (*B*–*B*′) of the Dnieper-Donets Basin.

Upper crustal extension across the Dnieper-Donets part of the rift zone may be about 5–10 km, and total extension of the Pripyat part of the rift zone is about 11–14 km. The rift is 70–150 km wide. Maximum subsidence rates were 175–433 m/m.y. in the late Frasnian and 784–1,293 m/m.y. in the Famennian (Aizberg and others, 2004). The deepest part of combined Pripyat and Dnieper-Donets Basins is in the southeastern end of the Dnieper-Donets Basin and is at least 10–15 km deep (Ulmishek, 1994). Periodic magmatism and crustal attenuation, and ultimately crustal extension along the Donbass-Pripyat Rift, may be related to underlying mantle plumes (Wilson and Lyashkevich, 1996).

Border faults of the Donbass-Pripyat Rift include the Baranovichsko-Astrakhan Fault on the northeast side and the Pripyatsko-Manych Fault on the southwest side (figs. 2–2, 2–3). These border faults appear to be continuous adjacent to the Dnieper-Donets part of the rift (Kityk, 1970) but are broken into segments by numerous cross-faults in the Pripyat part of the rift (Garetsky, 1979, 1982; Korenevskiy, 1990; Makhnach and others, 2002).

A number of major and minor axial rift faults occupy interior parts of the rift and greatly influenced halokinesis in both basins. Garetsky (1979, 2004) shows an extensive fault system oriented principally west-northwest to east-west in the Pripyat Basin (fig. 2–3*A*). A few crosscutting structures oriented northeast-southwest are also present. Halokinetic activity in the Devonian salts was initiated by reactivation of axial rift faults (Kityk, 1970). Numerous other faults displace salt formations and overlying suprasalt units in both basins (Kityk, 1970; Garetsky, 1979; Garetsky and others, 1982). Some of these faults are related to recurring movement of underlying rift structures and others are related to recurring halokinetic activity (Garetsky and others, 2004).

Segmentation of the Donbass-Pripyat Rift into the Pripyat and Dnieper-Donets Basins and the Donbass Foldbelt is related to crosscutting pre-Riphean transverse faults that were reactivated during Phanerozoic evolution of the rift system (Chekunov and others, 1992). The Bragin-Loev High (fig. 2–2) is a Late Devonian uplift and volcanic center (Yakushkin, 1964; Aizberg and others, 2001) that developed over one of these crosscutting faults and separated the Dnieper-Donets and Pripyat Basins. The Bragin-Loev High is composed of a thick sequence of Late Devonian alkaline-ultrabasic and alkaline-basaltic volcanic rocks (Garetsky and others, 1984).

Volcanism was centered on the Bragin-Loev High and diminished to the northwest in the Pripyat Basin and to the southeast in the Dnieper-Donets Basin (Yakushkin, 1964; Aizberg and others, 2001). Late Frasnian igneous rocks in the Dnieper-Donets Basin consist of 100–900 m of basalts, pyroclastic rocks, and alkali-ultramafic breccias and agglomerates. During the Late Devonian, igneous activity was marked by basaltic, trachytic, and rhyolitic lavas accompanied by dolerite dikes and small gabbro-dolerite stocks (Wilson and Lyashkevich, 1996). Pre-existing crosscutting basement structures, major rift-bounding faults, and axial rift faults all played major roles in channeling magmas into the Pripyat and Dnieper-Donets Basins (Wilson and Lyashkevich, 1996). Igneous activity in the Dnieper-Donets Basin is indicated in the stratigraphic section (fig. 2–4) for that basin, but details regarding igneous rock compositions and their distribution in that basin are unknown.

The Bragin-Loev High restricted flow of marine fluids between the Pripyat and Dnieper-Donets Basins. Syn-rift sedimentation in the Dnieper-Donets Basin consisted initially of 250 m of volcanic and carbonate rocks overlain by 500 m of volcaniclastic rocks (fig. 2–4). In the Pripyat Basin, as much as 320 m of a sulfate-bearing dolomite-limestone-marl sequence was deposited (fig. 2–4) along with rocks of an alkaline ultramafic-alkali basalt sequence (Aizberg and others, 2004). During the Late Devonian, Frasnian and Famennian potash-bearing evaporite sequences and additional volcanic rocks were deposited in both basins. Evaporite sedimentation in both basins occurred at the same time and is believed to have been similar in composition and style (fig. 2–4). Devonian to Carboniferous sedimentary rocks are mainly shallow marine; however, lagoonal and terrestrial facies are also present.

During and subsequent to deposition of Frasnian and Famennian salt-bearing sequences, continued adjustments along axial rift faults initiated halokinesis in the Pripyat and Dnieper-Donets Basins. Within the Pripyat Basin, a number of synclines and anticlines developed within Famennian salt as a result of upward movement of both Frasnian and Famennian salt.

Volcanic rocks, including tuffs, flows, and diabase intrusions, are similar in composition to Late Devonian alkaline-ultrabasic and alkaline-basaltic volcanic rocks of the Bragin-Loev High and are locally interbedded with Upper Devonian evaporite, clastic, and carbonate rocks (Garetsky and others, 1984; Hryniv and others, 2007). These volcanic rocks are abundant near the Bragin-Loev High and Donbass-Pripyat Rift border faults. How these volcanic rocks affected potash-bearing salt units is unknown.

To the southeast, the Donbass Foldbelt part of the Donbass-Pripyat Rift (figs. 1–1, 2–1) contains mainly terrestrial clastic rift sedimentary rocks, including numerous coal beds (Ulmishek and others, 1994). These rocks were structurally inverted, folded, and thrust northward during the end of the Permian. No marine evaporite rocks are reported for this area.

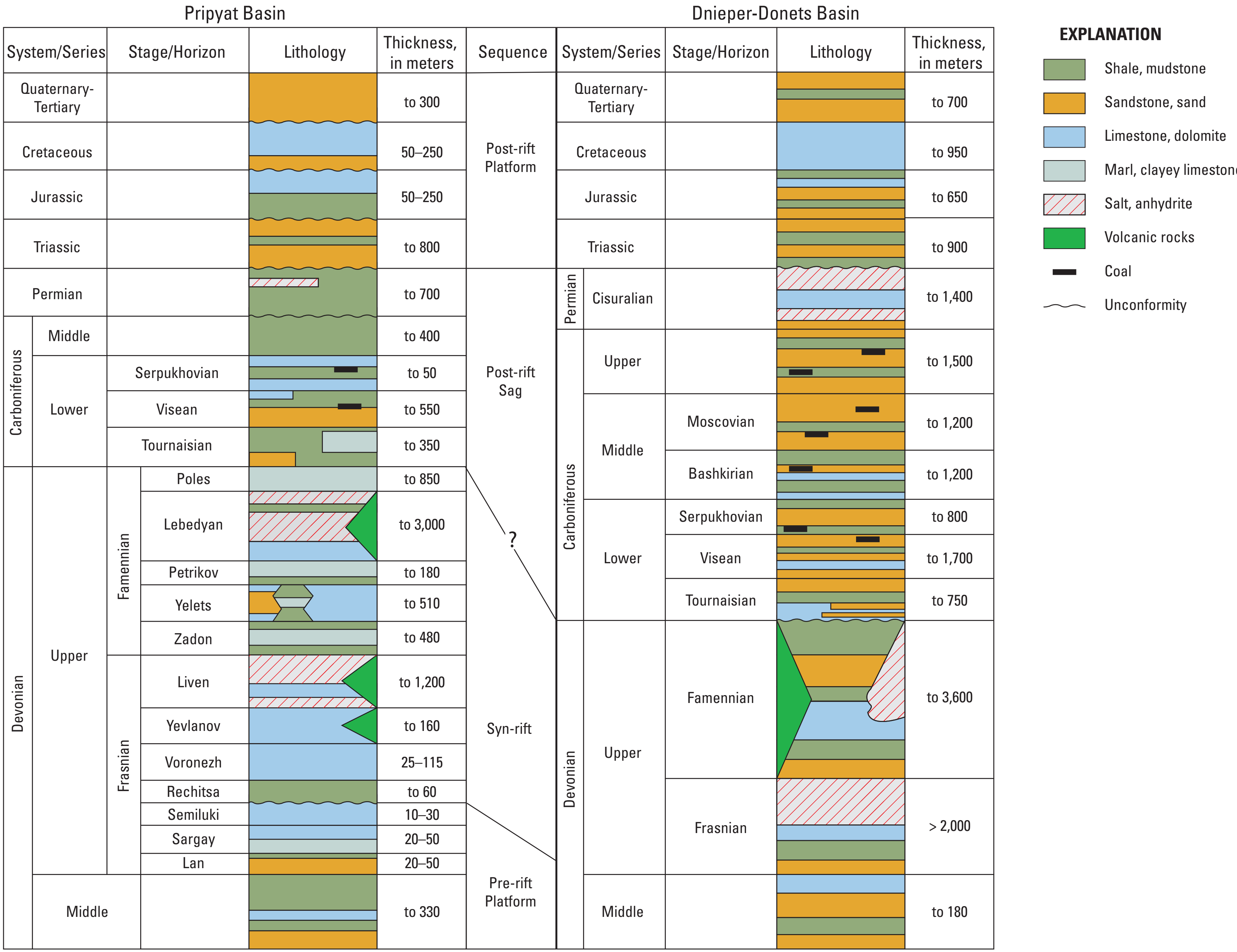


Figure 2–4. Correlation of major stratigraphic units deposited during evolution of the Donbass-Pripyat Rift, showing the location of major halite-bearing units within the Dnieper-Donets and Pripyat Basins (modified from Ulmishek and others, 1994; and Ulmishek, 2001).

Post-Rift

Rifting continued for several million years after the main Late Devonian rifting in the Dnieper-Donets Basin. Rifting ceased by the Cisuralian (early Permian). During the Carboniferous and Permian, the rift and surrounding areas developed into a post-rift sag (intracratonic) basin. This subsidence is attributed to crustal attenuation centered on the rift (Wilson and Lyashkevich, 1996). Continental crust thinned to 30–35 km within the axial part of the Dnieper-Donets section compared with 40–45 km along the flanks of the rift. Whereas Devonian rift width was about 110 km, Carboniferous to Permian sag basin width was at least 320 km based on Kovalevym and others' (1965) map of pre-Mesozoic rocks in the eastern end of the Dnieper-Donets Basin. The subsidence rate is estimated to have been 75–350 m/m.y.

Post-rift sedimentary rocks include Carboniferous to Permian clastic and coal-bearing sequences, as well as Cisuralian evaporite rocks (fig. 2–4). Permian strata include continental to lagoonal facies rocks. Clastic and carbonate rocks are generally concentrated near the rift margins with evaporite strata concentrated within the central part of the basin.

Permian sedimentation in both basins was modified by concordant and discordant salt structures (fig. 2–3). Salt structures that were intruded at or near the Permian surface formed intrabasin highs that influenced sedimentation patterns and types during the Permian. As a result, subbasins formed, each displaying unique internal zoning patterns from clastic sediments to evaporites.

Tectonic and magmatic activity continued episodically during and after Carboniferous and Permian sedimentation. Major structural reactivation continued along rift-related faults into the Cenozoic. This renewed faulting continued to affect salt structures by reactivating their vertical movement (fig. 2–3). Smycznik and others (2006) notes that smaller faults, about 60–100 m in displacement, are present in the Starobin potash deposits in the Pripyat Basin. Magmatic activity continued into the Late Jurassic (Wilson and Lyashkevich, 1996). Igneous rocks that include volcanic ash and tuffaceous rocks are present in the Dnieper-Donets Basin (Aizberg and others, 2004).

This page intentionally left blank

Chapter 3. Evaporite Stratigraphy and Potash-Bearing Strata

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

Potash-bearing salt strata were deposited during evaporation of marine water in the Pripyat and Dnieper-Donets Basins. In both basins, these strata include upper Frasnian, upper Famennian, and Cisuralian potash-bearing salt (fig. 2–4). In available literature, descriptions of upper Frasnian and upper Famennian strata are mainly from the Pripyat Basin, and those of Cisuralian strata are from the Dnieper-Donets Basin. Published descriptions of Upper Devonian and Cisuralian stratigraphy contain numerous unresolvable ambiguities and contradictions; this report includes the best available information.

Upper Devonian (Frasnian and Famennian)

Upper Frasnian and upper Famennian salt-bearing formations are best described for the Pripyat Basin, in part, because potash-bearing salt has been mined in the Pripyat Basin. Salt-bearing units are at shallower depths in the Pripyat Basin than in the Dnieper-Donets Basin, and drilling and geophysical data characterizing the subsurface are more abundant for the Pripyat Basin. In the Dnieper-Donets Basin, upper Frasnian and upper Famennian salts are generally mapped as Devonian salt in the salt structures (Kityk, 1970). During the assessment, we assumed that stratigraphy of Devonian evaporite units in the Dnieper-Donets Basin is generally the same as the Pripyat Basin based on information provided by Ulmishek (2000) and Ulmishek and others (1994), and as shown in figure 2–4.

Present thickness of stratabound Devonian salt in the Pripyat Basin averages about 1,400 m (Zharkov, 1984). Because of halokinesis and depth to Devonian salt-bearing strata in the Dnieper-Donets Basin, present and original thicknesses of source Devonian salt beds are difficult to determine. In the Dnieper-Donets Basin, estimates of original thickness of Devonian salt-bearing strata range from 1 (Kityk, 1970) to about 3 km (Zharkov, 1984; Aizberg and others, 2004).

Volume estimates for Devonian salt in these basins are also varied. Garetsky and others (1984) estimated the volume of Famennian salt in the Pripyat Basin to be 31,100 cubic kilometers (km^3). In contrast, Zharkov (1984) estimated the volume of all Devonian salt in the Pripyat Basin to be 28,400 km^3. The volume of Devonian salt in the Dnieper-Donets Basin was estimated to be about 40,000 km^3 (Zharkov, 1984).

Frasnian Salt (Lower Salt)

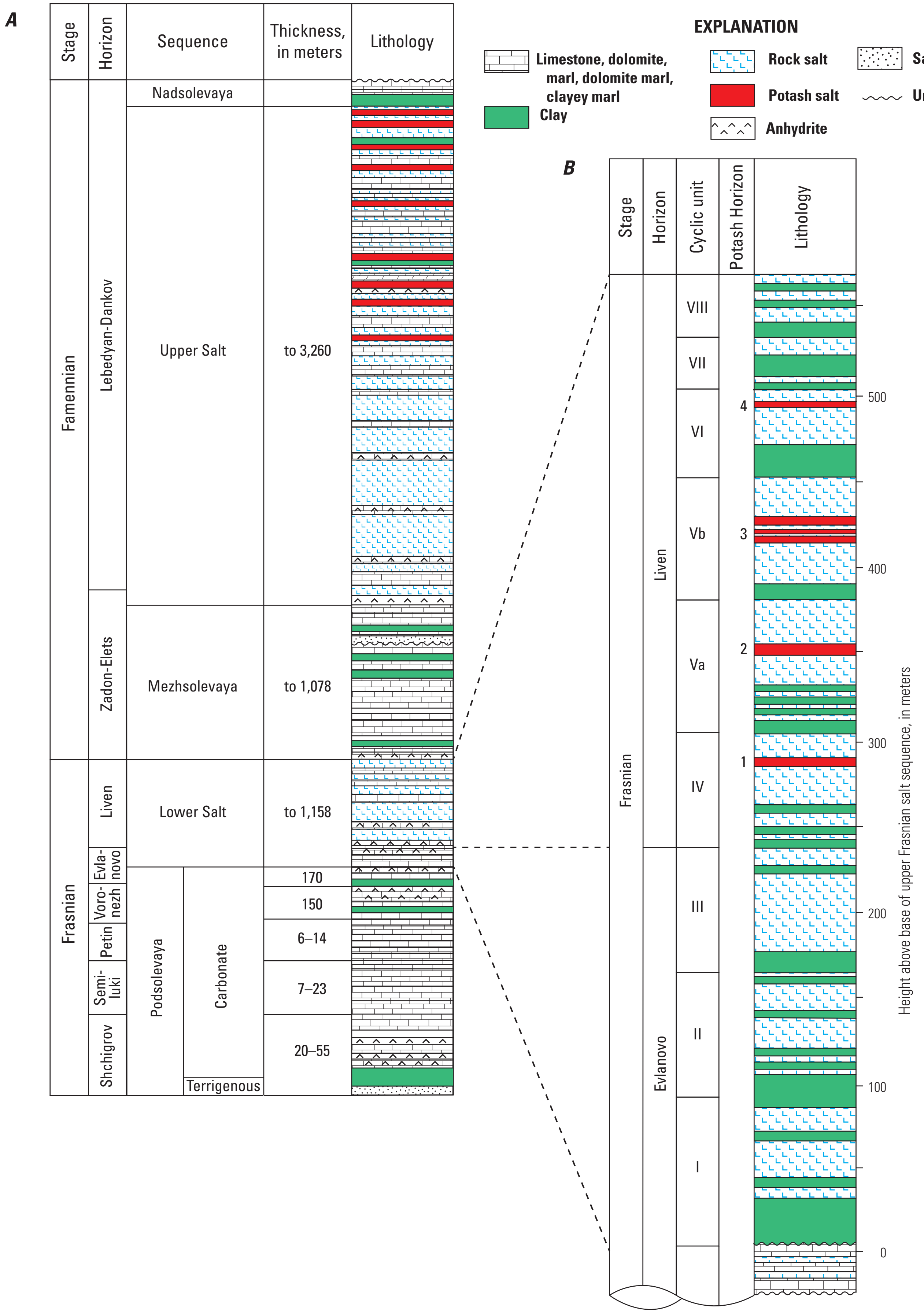
In the Pripyat Basin, the Frasnian is divided into an older Podsolevaya sequence and a younger Lower Salt sequence (fig. 3–1). Stratigraphy of the Frasnian Podsolevaya sequence is depicted in apparently greater detail in figure 3–1 by Zharkov (1984) than in later figures included in Ulmishek and others (1994) that are modified as figure 2–4. The Podsolevaya (meaning below salt) sequence consists of the Lan, Sargay (Shchigrov), Semiluki, Rechitsa (Petin), Voronezh, and Yevlanov (Elanovo) stages or horizons (figs. 2–4, 3–1).

Estimates of depth to the Frasnian salt unit in the Pripyat Basin include 1,040–4,250 m (Konishchev and Kovkhuto, 2011); 2,250 to more than 4,126 m (Zharkov, 1984); 2,175–4,126 m (Garetsky and others, 1984); and 2–4 km (Wysocki and others, 2005). The areal extent of the Frasnian salt is estimated to be about 20,000 km^2 (Zharkov, 1984). Salt constitutes about 45–52 percent of the Frasnian salt-bearing strata (Zharkov, 1984; Konishchev and Kovkhuto, 2011), and Zharkov (1984) calculated a volume of 5,000 km^3 for this salt.

The Frasnian Lower Salt sequence has received relatively little attention, because more viable potash-bearing salt lies at shallower levels in the Famennian Upper Salt sequence. Descriptions of lithologies and thicknesses differ between the various authors noted in this section, and these differences may significantly affect our understanding of the halokinetic evolution of these units and the effect of the Frasnian Lower Salt lithologies on the overlying potash-bearing stratigraphy.

The Podsolevaya sequence consists mainly of limestone, dolomite, and marl, with interbedded clay and anhydrite at the base and top, and is as much as 400 m thick. The Lower Salt sequence consists mainly of salt with interbedded limestone and anhydrite. The Lower Salt sequence may range in thickness from 95 (Konishchev and Kovkhuto, 2011) to more than 700 m (Wysocki and others, 2005) and may be as thick as 1,200 m (Konishchev and Kovkhuto, 2011) or 1,500 m (Zharkov, 1984). Average thickness of the salt sequence is reported to be 500 m (Zharkov, 1984).

[1]U.S. Geological Survey, Tucson, Arizona, United States.


A
Stage
Horizon
Sequence
Thickness, in meters
Lithology
Famennian
Lebedyan-Dankov
Zadon-Elets
Nadsolevaya
Upper Salt
to 3,260
Mezhsolevaya
to 1,078
Frasnian
Liven
Evla-novo
Voro-nezh
Petin
Semi-luki
Shchigrov
Lower Salt
to 1,158
Podsolevaya
Carbonate
Terrigenous
170
150
6–14
7–23
20–55
EXPLANATION
Limestone, dolomite, marl, dolomite marl, clayey marl
Clay
Rock salt
Potash salt
Anhydrite
Sandstone
Unconformity
B
Stage
Horizon
Cyclic unit
Potash Horizon
Lithology
Frasnian
Liven
Evlanovo
VIII
VII
VI
Vb
Va
IV
III
II
I
4
3
2
1
500
400
300
200
100
0
Height above base of upper Frasnian salt sequence, in meters

Evaporite lithologies described by Zharkov (1984) include eight evaporite cycles (fig. 3–1) in the Lower Salt, referred to as “rhythm units” in older Russian publications (Zharkov, 1984). These evaporite cycles consist mainly of repeating sequences of salt, anhydrite, clayey carbonate rock, dolomite, limestone, and marl (Eroshina, 1981; Eroshina and Obrovets, 1983). Zharkov (1984) reports that rock salt thickness in these cycles may be 5–100 m, and interbedded non-saliferous rocks are 2–40 m thick. Konishchev and Kovkhuto (2011) describe the salt layers as 1–15 m thick and the interbedded non-saliferous rocks as 7–8 m thick. Along the basin margins, volcanic rocks, sandstones, and breccia conglomerate may be interbedded with the evaporite cycles (Zharkov, 1984).

Four potash-bearing horizons occur within evaporite cycles IV, V, and VI (Zharkov, 1984). These potash horizons (fig. 3–1) range in thickness from several centimeters to 5 m. Potash minerals are mainly sylvite (KCl) with some carnallite ($KMgCl_3 \cdot 6H_2O$) (Wysocki and others, 2005). Eroshina and Obrovets (1983) noted that one potash horizon contains 20.8–38.4 percent K_2O. Approximate extents of the various salt and potash units are shown in Eroshina and Kislik (1980) and Zharkov (1984). Zharkov (1984) calculated the extents of these potash horizons to range from 130 to 1,450 square kilometers (km^2).

As described later in this chapter and in chapter 4, Frasnian salt lithologies have been deformed by halokinesis and intruded into overlying Famennian salt and potash as well as much younger Permian evaporite lithologies. Because of the different structural and soluble behavior of the interlayered salt, carbonate, and sulfate rocks, potash potential of the Frasnian stratigraphy in the halokinetic structures described later in this report and appendix B is difficult to assess.

Mezhsolevaya Sequence

The Mezhsolevaya (meaning “between salt”) sequence lies between the Lower and Upper Salt sequences, and is assigned to the Zadon and Yelets (Elets) horizons of the Famennian (fig. 3–1). The Mezhsolevaya sequence consists of interbedded argillaceous rocks, marl, limestone, dolomite, anhydrite, mudstone, sandstone, and tuff (Zharkov, 1984). Sequence thickness ranges from 30–100 m in the northwest to 300–500 m in the center and to more than 1,000 m in the northern part of the basin.

Figure 3–1. On opposite page (p. 19). Upper Devonian stratigraphy of the Pripyat Basin (modified from Zharkov, 1984). *A*, Composite section showing Frasnian and Famennian rocks. *B*, Detailed stratigraphy of Frasnian Lower Salt sequence.

Famennian Salt (Upper Salt)

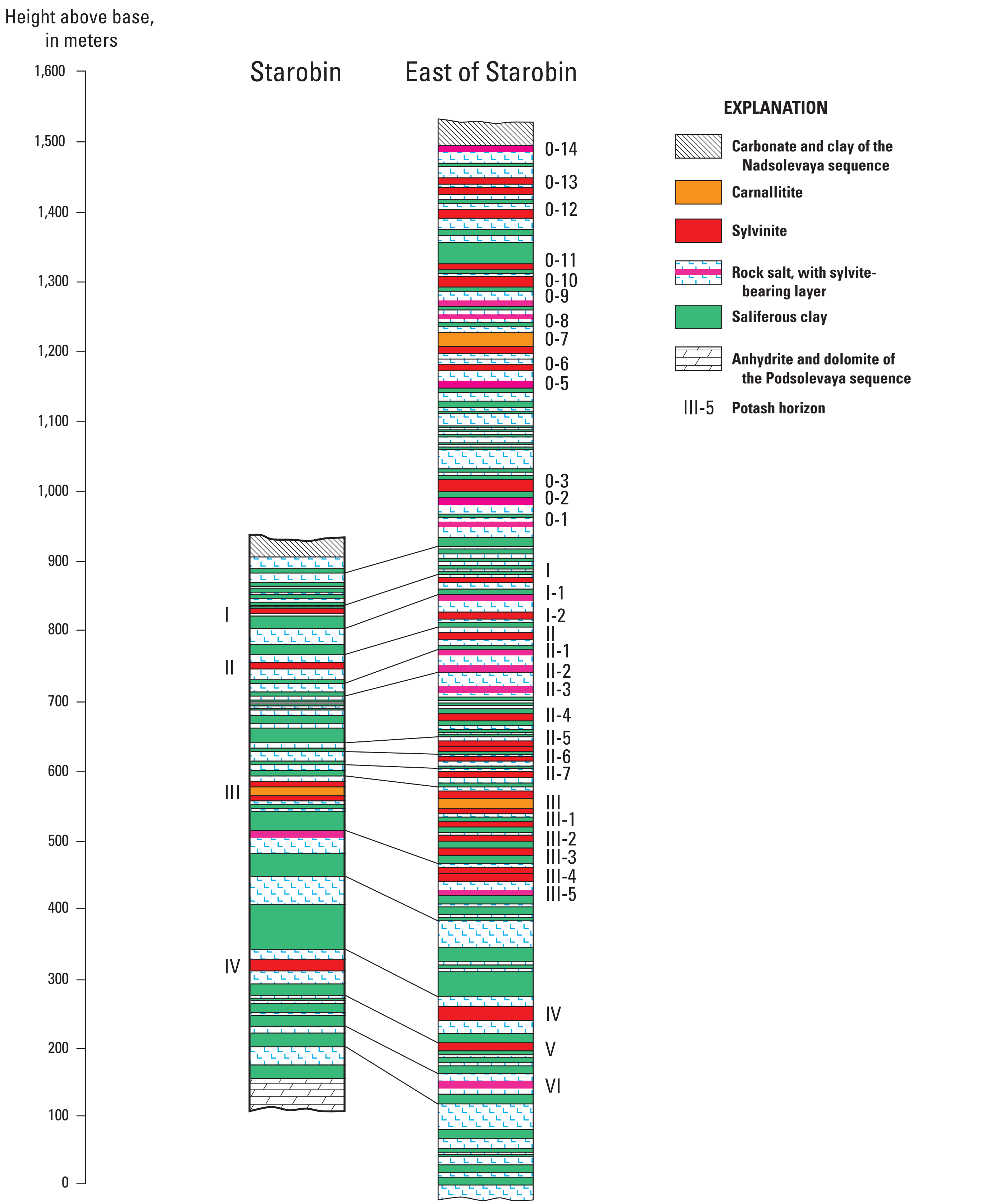
The Famennian Upper Salt sequence (figs. 2–4, 3–1, 3–2) is as much as 3,260 m thick and averages 1,500 m thick in the Pripyat Basin. The Upper Salt sequence underlies about 23,200–26,000 km^2 (Lupinovich, 1971; Garetsky and others, 1984; Zharkov, 1984) of the Pripyat Basin.

Within the Upper Salt sequence, two subformations are distinguished: a lower salt and an upper potassium-bearing salt. The lower salt subformation averages 600 m thick and consists mainly of halite. The upper potassium-bearing salt subformation averages 980 m thick with an estimated volume of 18,700 km^3 (Garetsky and others, 1984). Anhydrite-dolomitic, clayey-sulfate-carbonaceous, argillic-arenaceous, and volcanogenic strata occur along the margins of the basin.

In the northwestern, northern, and northeastern part of the Pripyat Basin, sulfate-bearing clays and marls were deposited instead of salt-bearing strata. Clayey, arenaceous sediments occur along the edges of the basin to the south, southeast, and southwest (Garetsky and others, 1984). Lupinovich (1971) suggested that the Upper Devonian salt units originally extended north and south of their present extent in the Pripyat Basin but have been subsequently removed.

In the Starobin (Soligorsk) mine area (figs. 3–2, 3–3, 3–4), four potash-bearing horizons are recognized in the Famennian salt formation. The number of potash-bearing horizons increases to the east (figs. 3–2, 3–4*B*), and at least 60 horizons have been documented east of the Starobin mine area (Korenevskiy, 1989). In the northwestern part of the basin, including the Starobin mine area, these potash-bearing horizons occupy a west-northwest-striking syncline formed by deformation of older Frasnian and lower Famennian salt (fig. 2–3*A*). The potash-bearing horizons dip 2–3 degrees to the southeast. The southern limb of the syncline dips 1–3 degrees to the south, and the northern limb dips as much as 5 degrees to the north (Smycznik and others, 2006). Reported K_2O grades, thicknesses, depths, and insoluble contents of each of the four potash-bearing horizons vary in the vicinity of the Starobin mines (table 3–1). Individual horizons may range from 0.15 to 40 m in thickness. Depths to the Starobin horizons range from 350 to 1,335 m. Thickness of the potash-bearing Famennian salt formation at Starobin averages 550–800 m (Garetsky and others, 1984) but may be as thick as 1,200 m farther east and southeast in the Pripyat Basin (Zharkov, 1984). The total combined thickness of potassium-bearing horizons is about 100 m in the Starobin mines (Garetsky and others, 1984).

In a composite section for salt sequences east of the Starobin mine complex (fig. 3–2), the Famennian salt is shown directly overlying a portion of the Podsolevaya sequence instead of the Mezhsolevaya or Lower Salt sequences (fig. 3–1). This discrepancy may result from (a) a misinterpretation of the age of this interval during early investigations of the Pripyat Basin (Garetsky and others,


Height above base, in meters
1,600
1,500
1,400
1,300
1,200
1,100
1,000
900
800
700
600
500
400
300
200
100
0
Starobin
East of Starobin
I
II
III
IV
0-14
0-13
0-12
0-11
0-10
0-9
0-8
0-7
0-6
0-5
0-3
0-2
0-1
I
I-1
I-2
II
II-1
II-2
II-3
II-4
II-5
II-6
II-7
III
III-1
III-2
III-3
III-4
III-5
IV
V
VI
EXPLANATION
Carbonate and clay of the Nadsolevaya sequence
Carnallitite
Sylvinite
Rock salt, with sylvite-bearing layer
Saliferous clay
Anhydrite and dolomite of the Podsolevaya sequence
III-5 Potash horizon

1984; Zharkov, 1984), (b) erosion or dissolution of the Mezhsolevaya or Lower Salt sequences, or (c) non-deposition of the Mezhsolevaya or Lower Salt sequences.

Figure 2–3*A* shows how Famennian salt formation thickness varies locally within the Pripyat Basin because of secondary structural factors. Similar variations would be expected in the Dnieper-Donets Basin, but these variations, as shown in figure 2–3*B*, are not well documented at the scale of that figure. The thickest salt is in part related to halokinetic flowage over basement faulting.

Additional potash horizons, east of the Starobin mine area and above horizon I, are designated as O-1, O-2, and so forth (fig. 3–2). Additional potash horizons roughly equivalent to horizons I, II, and III are designated in a similar manner, as shown in figure 3–2. Little information is available regarding these additional horizons.

In the Starobin mines area, horizon I is 1.3–8.1 m thick with 11.4–18.94 percent K_2O (table 3–1). Depths to this horizon range from 350 to 726 m. The amount of insoluble minerals averages 13 percent. Production from horizon I began in 2003 (Dakuko, 2003).

Early studies (Zharkov, 1984) suggested that horizon II ranges in thickness from 1 to 4.6 m with a K_2O content of 13.3–20.2 percent (table 3–1). More recent publications indicate that this second horizon is 2–2.9 m thick. This horizon consists of two sylvinite beds or seams 0.7–1.2 m thick separated by rock salt 0.5–0.9 m thick (Smycznik and others, 2006). Grades of these sylvinite beds range from 13.3 to 20.2 percent K_2O. The content of magnesium chloride ($MgCl_2$) is 0.14 percent and indicates a low amount of carnallite. Depths range from 350 to 1,000 m. This potash horizon contains 51 halite and sylvinite-halite layers that are 0.5–8 cm thick. Clay laminae cover some halite layers and 8 clay layers, 0.5–3 cm thick, are in this horizon (Wysocki and others, 2006). Clay layers increase in frequency as depth in the section decreases. These thin layers indicate salinity fluctuations, perhaps in a relatively shallow brine pool that was decimeters to a meter deep. Periodic influx of higher salinity brines alternating with fresher water is suggested by Wysocki and others (2006). Aeolian deposition of clay particles may have occurred during periods of increased aridity (Wysocki and others, 2006). The content of insoluble minerals ranges from 5 to 6.4 percent (table 3–1). Photos of potash-bearing strata in the Starobin mines on the Belarusian Potash Company Web site (2011c) show numerous halite, sylvinite-halite, and clay layers about centimeters thick. These cyclic units record halite to sylvinite to clay transitions. Kislik and Lupinovich (1968) relate halite-sylvinite-clay cycles of this scale to annual sedimentation cycles. Distortion of these cycles may partly result from conversion of primary carnallite to secondary sylvite and a consequent volume reduction.

Garetsky and others (1984) distinguish two types of sylvinite: (1) Starobin-type which is colored red, and (2) Petrikov-type which is light colored, white, and motley with blue halite. Starobin-type sylvinite is laminated and banded with grain sizes ranging from less than 1 mm to as much as 10 mm (microgranular to coarse grained). Petrikov-type sylvinite is indistinctly stratified, has an irregular texture, and has a grain size of 3–10 mm (medium to coarse grained).

Horizon III averages 21 m in thickness but may be as thick as 38.6 m in the Starobin area (table 3–1). Average K_2O contents of 12.6–18.39 percent are reported for this horizon and depths range from 350 to 1,200 m. Insoluble minerals range from 6.5 to 18.47 percent. The $MgCl_2$ content is 0.4 percent, indicating a low amount of carnallite in the sylvinite layers (Lupinovich and others, 1968). Horizons II and III consist of two sylvinite layers separated by a sylvinite-poor, argillaceous, carnallitic salt.

Horizon IV is 1.66–40 m thick and has a K_2O content of 9.5–15.5 percent (table 3–1). Depths to this horizon are 600–1,335 m. The content of insoluble minerals may range from 2.49 to 25 percent but averages 12 percent. In the vicinity of Petrikov, the IV-p horizon has a high KCl content (more than 30 percent) and a low insoluble content, but has a high $MgCl_2$ content (carnallitic) (Garetsky and others, 1984).

Horizons II and III have been the preferred mining horizons in the Starobin mines, because they have higher K_2O grades and lower insoluble contents than the other horizons. Horizon III has been nearly depleted in the older Starobin mines. The number of horizons considered to be economic in other deposits varies (Garetsky and others, 1984) and may now be different from the early 1980s because of increased world demand for potash and improved mining methods (table 3–2).

Within the Pripyat Basin, bedded Famennian salt ranges in thickness from 0 to 320 m over the tops of salt structures and appears to thicken on the flanks of salt structures (Vysotskiy and others, 1981). Potash-bearing layers within the Famennian salt appear to decrease in thickness near salt structures and no potash-bearing layers extend over the structures (Vysotskiy and others, 1981). Halite is the only reported salt within the salt structures (Hryniv and others, 2007), but it is unclear whether the salt is Famennian or Frasnian. Also, it is not documented whether all 138 salt structures contain only halite, or, how deep exploration drilling may have investigated salt structure interiors. Recrystallization of salt and deposition of secondary sulfides, oxides, and silicates may indicate hydrothermal activity in the Famennian salt (Hryniv and others, 2007), which may be related to heat flow associated with the Donbass-Pripyat Rift or nearby intrusions.

Figure 3–2. On opposite page (p. 20). Detailed stratigraphy of Famennian potash-bearing sections in the Starobin mine area and farther east in the Pripyat Basin (modified from Lupinovich and others, 1968; Zharkov, 1984). Location of eastern section is not documented.

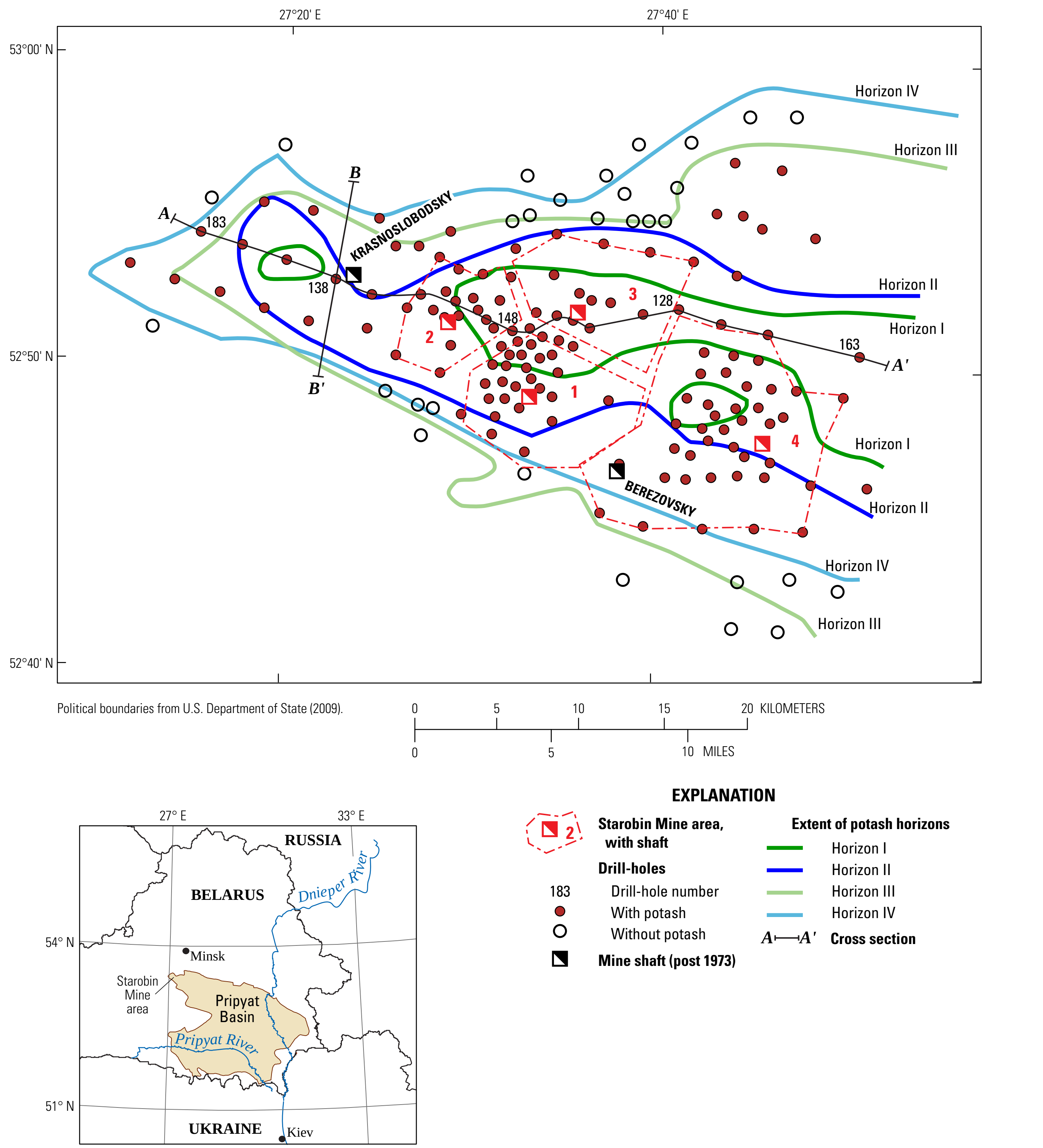


Figure 3–3. Map of the Starobin mine area showing locations (as of 1973) of mine fields, outlines of mining horizons, cross sections, drill holes, and mine shafts (modified from Rayevskiy and Fiveg, 1973). Locations of newer mines, Krasnoslobodsky and Berezovsky, are also shown.

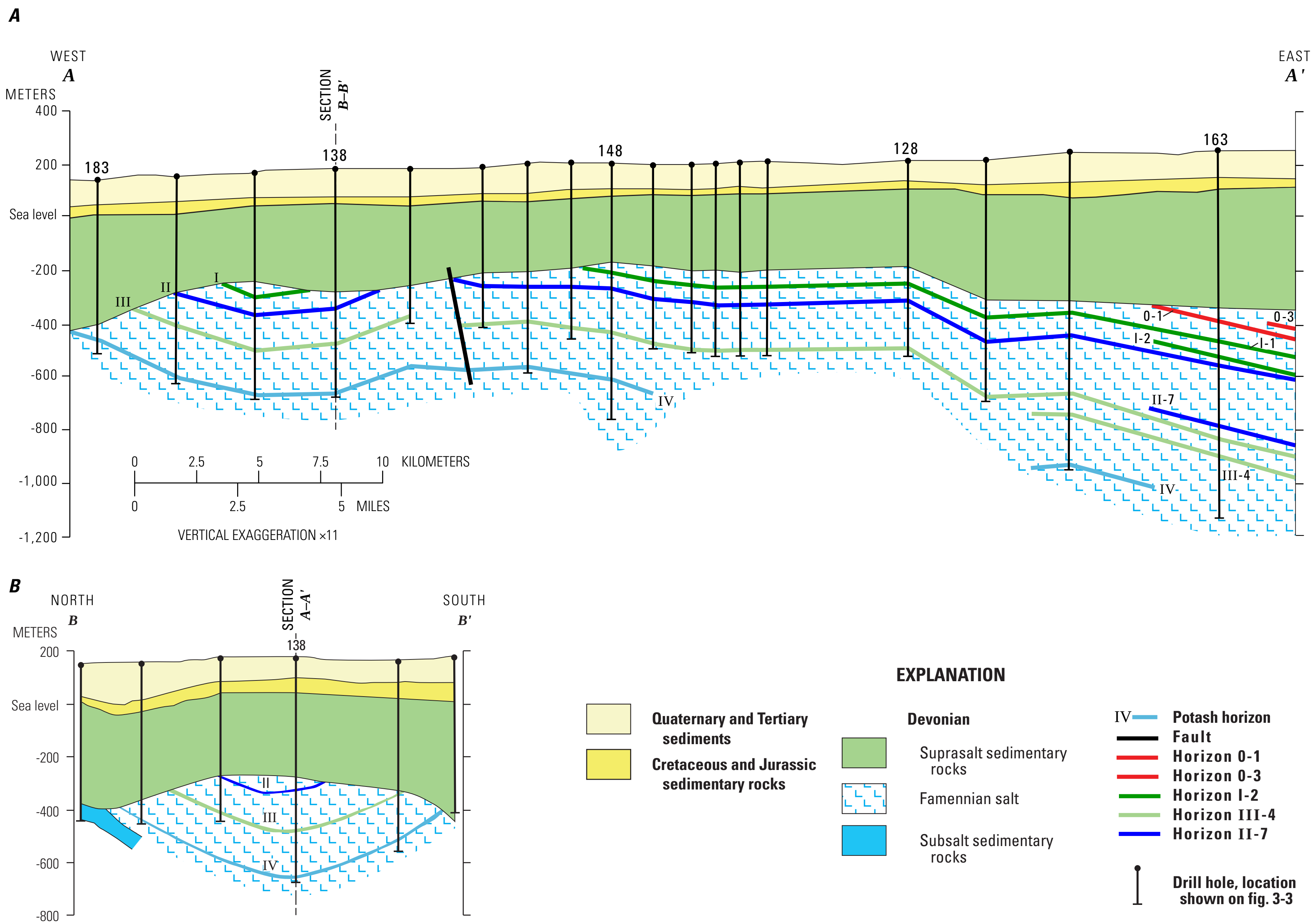


Figure 3–4. Cross sections through the Starobin mine area. *A*, Section *A–A′* (modified from Rayevskiy and Fiveg, 1973). *B*, Section *B–B′* (modified from Garetsky and others, 1982).

Table 3–1. Physical characteristics of the Famennian potash horizons in the Starobin (Soligorsk) mines, Pripyat Basin, Belarus.

[avg., average; n.d., no data]

	K_2O (percent)	Thickness (meters)	Depth (meters)	Insolubles (percent)	References
Horizon I	n.d.	1.3–8.1	352–726	n.d.	Lupinovich and others (1968); Lupinovich (1971)
	n.d.	n.d.	n.d.	n.d.	Korenevsky (1973)
	13.22–18.94	3–6	364–728	12.0–28.66	Garetsky and others (1982)
	14.5	n.d.	n.d.	12–35 (avg. 13)	British Sulphur Corporation Limited (1975, 1984)
	n.d.	n.d.	n.d.	n.d.	Harben and Kužvart (1996)
	14.5	n.d.	n.d.	13	Garrett (1996)
	11.4	2–7	350–620	n.d.	Troitsky and others (1998)
	n.d.	n.d.	n.d.	n.d.	Smycznik and others (2006)
Horizon II	17.9	1–4.4	369–818	6.4	Lupinovich and others (1968); Lupinovich (1971)
	17.84	2.05	n.d.	6.09	Korenevskiy (1973)
	17.88	1.8–4.38	382–1,000	6.4	Garetsky and others (1982)
	17.7	1.8–4.4	350–620	5	British Sulphur Corporation Limited (1975, 1984)
	17.7	2–4.6	385–678	n.d.	Harben and Kužvart (1996)
	17.7	1.8–4.4	350–620	5	Garrett (1996)
	17.1–20.2	1–4	370–700	n.d.	Troitsky and others (1998)
	13.3–17.1	2–2.9	370–700	n.d.	Smycznik and others (2006)
Horizon III	13.4	5–27.9	354–1,075	6.5	Lupinovich and others (1968); Lupinovich (1971)
	18.39	3.54	n.d.	18.47	Korenevskiy (1973)
	13.4	0.15–1.6	451–1,200	n.d.	Garetsky and others (1982)
	13.4–16.4	6.8–38.6 (avg. 21)	350–1,200	9	British Sulphur Corporation Limited (1975, 1984)
	13.4–16.4	n.d.	556–853	n.d.	Harben and Kužvart (1996)
	13.4–16.4	6.8–38.6	510–780	9	Garrett (1996)
	[1]15.8–20.8	4.5	350–1,200	n.d.	Troitsky and others (1998)
	12.6–16.4	4.0–4.8	350–900	n.d.	Smycznik and others (2006)
Horizon IV	n.d.	1.66–40	604–1,335	n.d.	Lupinovich and others (1968); Lupinovich (1971)
	n.d.	n.d.	n.d.	n.d.	Korenevskiy (1973)
	10.6–15.5	1.59–3.79	1,200	2.49–9.42	Garetsky and others (1982)
	12.6	n.d.	n.d.	8–25 (avg. 12)	British Sulphur Corporation Limited (1975, 1984)
	n.d.	n.d.	n.d.	n.d.	Harben and Kužvart (1996)
	12.6	n.d.	n.d.	12	Garrett (1996)
	9.5–12	25–35	600–1,335	n.d.	Troitsky and others (1998)
	n.d.	n.d.	n.d.	n.d.	Smycznik and others (2006)

Table 3–2. Deposits and economic potash horizons within the Pripyat Basin, Belarus, based on early 1980s data.

[Garetsky and others, 1984). Production from horizon I at Starobin began in 2003 (Dakuko, 2003)]

Deposit	Potash horizons
Starobin (Soligorsk)	II and III
Petrikov	IV-p
Shestovichy	I-p, II-p, O-2-p
Zhitkovichy	I-p, II-p, O-2-p
Kopatkevichy	IV-p
Smolovo	III
Oktyabrsk (October)	O-8 and O-9

Secondary Geologic Effects on Potash-Bearing Strata

Dissolution Effects on Devonian and Permian Salt Formations

Salts are highly soluble and susceptible to the effects of water from the time they are precipitated through progressive burial. Because potash salts are more soluble than halite, changes in mineralogy and mineral textures occur whenever a less saline, hydrous pore fluid or brine comes into contact with potash salts. Water may include the brine from which the evaporite rocks were precipitated, which is no longer in equilibrium with the precipitated salts. Surface water may include freshwater from surface runoff or rainfall, or a new influx of seawater. Evaporites may react with near-surface brines that penetrate porous salts soon after burial. Even long after burial, evaporites may be dissolved or altered by descending formation waters or brines. In addition, brines may form from dewatering of hydrous minerals such as gypsum and upward migration of these dewatering brines. Faults or joints that extend upward through subsalt rocks may provide pathways for circulating groundwater and brines.

Interaction with fluids may result in alteration, recrystallization, or dissolution of salt (Borchert and Muir, 1964; Schwerdtner, 1964; Linn and Adams, 1966; Jones and Madsen, 1968; McIntosh and Wardlaw, 1968; Wardlaw, 1968; Kislik, 1970; Fusezy, 1982; Hite, 1982; Korenevskiy, 1989; Warren, 2010). These processes may affect thickness, mineralogy, grade, and distribution of salt and potash-bearing salt. Features related to water and brine that should be expected in the potash-bearing salt within the Pripyat and Dnieper-Donets Basins include

1. subrosion or groundwater dissolution along the top and sides of a salt unit,
2. interaction of less saline surface waters soon after salt deposition,
3. karst development in overlying carbonate rocks during periods of exposure,
4. downward movement of brines, and
5. upwelling of brines during dewatering of underlying sediments (Holter, 1969; Baar, 1972, 1974; Boys, 1990; Wittrup and Keyser, 1990).

Dissolution by Surface Water or Brine

Some relatively small dissolution areas at the top of salt layers are attributed to surface erosion by fresher or less saline water subsequent to salt deposition (Baar, 1972, 1974; Boys, 1990) and may be referred to as “washouts” or “washout anomalies.” Washout anomalies are associated with intraformational erosional “channels” in which potash minerals, such as carnallite or sylvite, were locally dissolved and subsequently replaced by halite. In the Elk Point Basin in Saskatchewan, Canada, halite in washout anomalies consists of euhedral to subhedral, medium to large (0.5–1.0 cm) grains within a groundmass of smaller intermixed halite and clay-sized insoluble minerals (Boys, 1990). Clay intraclasts as large as 1.0 cm may be present, and clay is typically concentrated at the top and base of the altered zone. These dissolution features are probably present in the potash-bearing horizons of the Pripyat and Dnieper-Donets Basins and may represent the relatively small, secondary pockets of halite in the Famennian potash-bearing salt in the Pripyat Basin described by Kislik (1970, 1971). Effects of washout anomalies on potash grades and tonnages are relatively small in the Elk Point Basin in Saskatchewan, Canada (Boys, 1990), and are expected to be relatively small in the Pripyat and Dnieper-Donets Basins.

Subrosion or Subsurface Dissolution

Subrosion is a process by which underground salt is dissolved where it contacts less saline groundwater. Salt dissolution may occur along the upper and lower boundaries of a salt bed or formation. Subrosion may result in broadly irregular surfaces on the tops of salt sections, thinning or removal of salt, and in some places, removal of potash horizons. An impermeable layer of salt above economic potash-bearing strata protects the more soluble potash from dissolution and may be referred to as the “salt back.” Subrosion may occur along the edges of an evaporite basin where the local dip of the layers allows water access to soluble rocks, along the top or base of an evaporite body or along tectonic structures (for example, faults) (Rauche and Van der Klauw, 2007; Rauche, 2011).

Some effects of subrosion are suggested by Korenevskiy (1989) who notes that potash horizons have been removed along the western margin of the Starobin deposit, probably meaning the westernmost part of the potash horizons and the younger potash horizons have been removed (fig. 3–4). In the Starobin deposit area, potash horizons are successively absent from the top toward lower horizons; potash-bearing salt gives way to clay-carbonate rocks with halite interlayers and eventually to halopelitic rocks with increasing calcium sulfate content, which are less soluble materials than salt and potash-bearing salt (Korenevskiy, 1989). The effects of subrosion can be observed in the sections shown in figure 3–4, where suprasalt rock overlies the Famennian salt and potash layers. The upper parts of the Famennian salt were removed by extensive subrosion and suprasalt rocks were laid down on the salt.

Subrosion may affect other parts of the Pripyat Basin as well as the Dnieper-Donets Basin, particularly along updip edges of inclined strata and basin margins. Subrosion effects observed in salt diapirs are discussed in more detail in chapter 4. Cap rocks, which generally consist of insoluble material such as gypsum, carbonate, and clay in the form of a solution breccia, and occur along the sides of the diapirs and the top of the source salt, also result from subrosion.

Embayments resulting from subrosion can be a significant factor in the preservation of potash-bearing salt deposits. Apparent embayments of the Famennian stratabound potash-bearing salt (fig. 3–5) in the Pripyat Basin may partially result from subrosion. Subrosion of more soluble potash salts may be developed adjacent to salt structures, also.

Karst Structures

Dissolution and collapse features form by caving of overlying rocks into dissolution voids. As overlying rocks collapse into voids, fractures propagate into overlying strata and provide additional pathways for groundwater. Because karst structures commonly provide groundwater pathways for modern aquifers, they are potentially major flood hazards for underground mines. Garetsky and others (1984) noted (but did not discuss in detail) dissolution cavities in Famennian potash-bearing salt in the Starobin mine area of the Pripyat Basin.

Alteration Related to Ascending and Descending Brines

Interaction of upwelling or downward-moving brines is well documented in the alteration of primary carnallite ($KMgCl_3 \cdot 6H_2O$) to sylvite (KCl), or, less commonly, to other potassium chloride or potassium sulfate minerals (Kühn, 1955; Borchert and Muir, 1964; Schwerdtner, 1964; Wardlaw, 1968; Hite and Japakasetr, 1979; Hite, 1982; Korenevskiy, 1989). The relative distribution of sylvite and carnallite is of great importance to potash exploration and mining as well as in grade and tonnage calculations.

In the Pripyat Basin, a small amount of carnallite has replaced sylvite in the upper part of the Famennian III horizon. This replacement is developed in the upper parts of the lower sylvinite layer of that horizon and is spatially associated with subsidence troughs in that layer. Secondary carnallite has also been attributed to upwelling magnesium-bearing brines (Garetsky and others, 1984).

The distribution of sylvite and carnallite, shown on a sketch map of the northwestern part of the Pripyat Basin (Obrovets and others, 1990), appears to correlate with position within large-scale synclines oriented northwest-southeast to east-west, such as the one running through the Starobin area (fig. 3–6). Korenevskiy (1973, 1990) noted that carnallite is better developed in the axial part of these synclines (fig. 3–4*B*), indicating that carnallite has been preferentially leached on the updip flanks of synclines, leaving sylvite-enriched areas.

In the Cisuralian salts of the Dnieper-Donets Basin, carnallite, kieserite, sylvite are present in a number of potash-bearing horizons. The areal and vertical extent of carnallite with respect to kieserite and sylvite could not be determined from available information.

Barren Areas Resulting from Upwelling Brines (Leach Anomalies or Salt Horses)

Leach anomalies consist of halite beds barren of potash minerals and represent postdepositional replacement of sylvite or carnallite by euhedral to subhedral halite. These barren areas, referred to as “salt horses,” are within potash horizons where potash minerals have been dissolved by less saline brines rising from deeper levels in an evaporite basin (Linn and Adams, 1966; Jones and Madsen, 1968; McIntosh and Wardlaw, 1968; Korenevskiy, 1989). This type of potash dissolution is noted in studies of all mined potash deposits (Korenevskiy, 1989).

Kislik (1970) and Korenevskiy (1989) describe two types of depletion zones in horizon II of the Starobin #1 mine; they are also reported in horizon III of Starobin #1 mine and horizon II of the Starobin #2 mine. Horizon II contains two sylvinite layers 80–110 cm thick separated by rock salt 30–55 cm thick. Smaller depletion zones, which occur in the lower sylvinites, are usually 10–50 m in length, but may be as much as 70 m in length. Depletion zones are elliptical, extend west-southwest to east-southeast within a given layer, and commonly occur as part of a string of multiple depletion areas. In these depletion zones, sylvinite was removed, the layer decreased in thickness, and the rock above the sylvinite sagged into the area formerly occupied by sylvinite.

Larger depletion zones are 100–400 m long with an area as large as 0.12 km^2 (Kislik, 1970; Korenevskiy, 1989). These zones are round or elliptical and occur with two sets of faults: those which strike east-northeast to east-southeast and those which strike more northeasterly. Depletion zones are more widely developed in the lower sylvinite layer than in the upper layer, forming dome-like zones of depletion in horizon III. Features labeled by Russian authors as “swelling mounds” of halite form gentle anticlinal folds, as much as 10 m long and 50 cm high in the centers of these depletion zones. A sketch map of horizon III shows concentric zones of magnesium chloride ($MgC1_2$) that are 5–10 times lower than normal concentrations and concentrations of sylvite and carnallite ranging from total absence or sporadic appearance to depletion zones locally as much as 5–8 percent of the horizon III area (Vysotskiy and others, 1990). The zones of greatest depletion are around the basin edges and are adjacent to a series of faults that crosscut the Pripyat Basin. Depletion affects all four potash horizons, and widths of depletion zones range from 0.5 to 1.5 km. Kislik (1970) and Korenevskiy (1989) suggest that depletion zones in horizon II may have affected 15–20 percent of its area.

Kislik (1970), Korenevskiy (1989), Vysotskiy and others (1990), and Kutyrlo and others (2008) suggest that brines not in equilibrium with sylvite rose along faults and dissolved sylvinite, leaving recrystallized halite. Descriptions and origins of these depletion zones are similar to those of the salt horses or leach anomalies described by Boys (1990), Linn and Adams (1966), Jones and Madsen (1968), and McIntosh and Wardlaw (1968) in other stratabound potash-bearing salt deposits (appendix A).

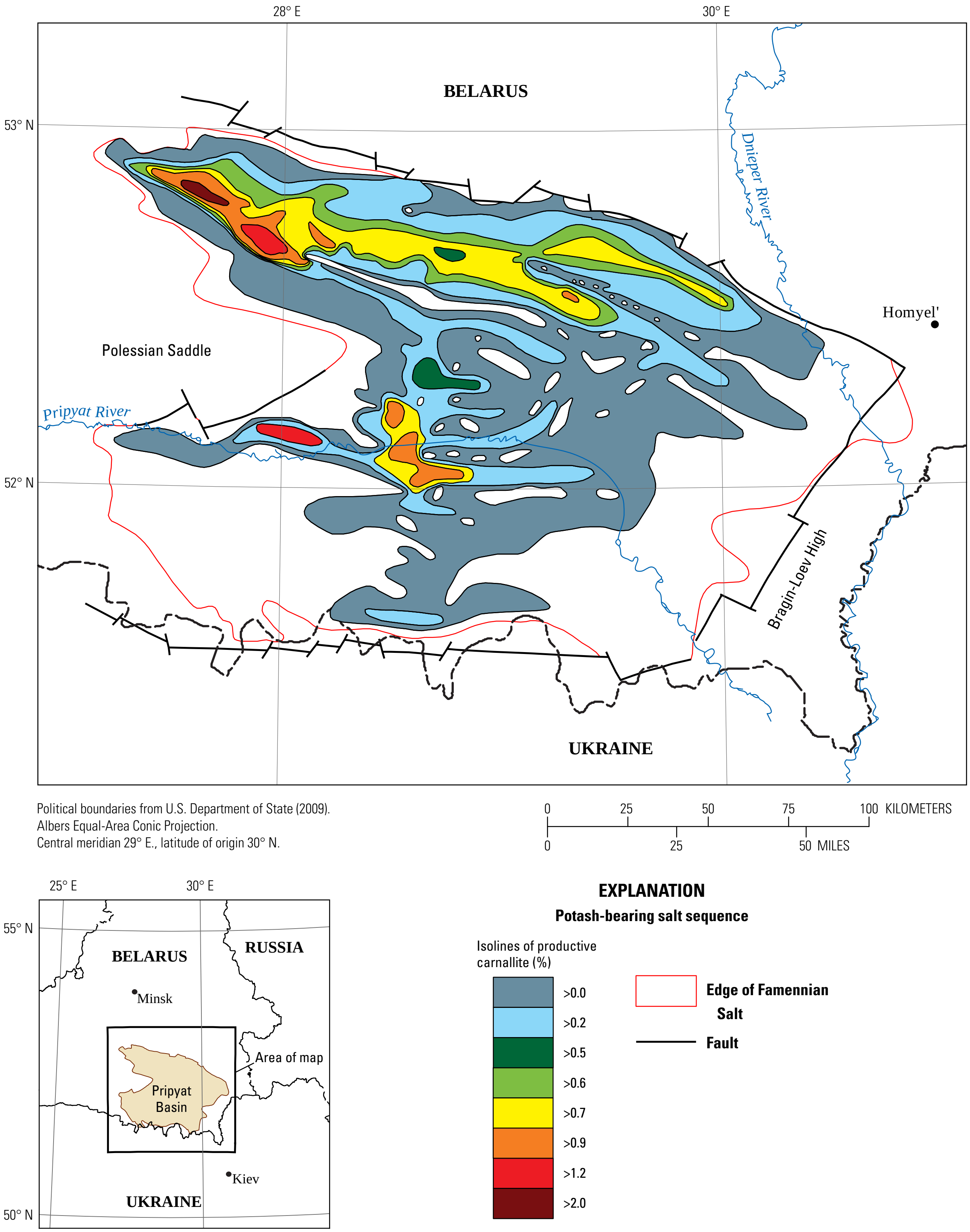


Figure 3–5. Map showing concentration of carnallite in Famennian potash-bearing salt in the Pripyat Basin and some basin marginal faults (modified from Korenevskiy and Shamakhov, 1990). Outer edge of plotted isolines marks maximum extent of credible potassium horizons.

The extent of potash salt dissolution was described for only a small area in the northwestern corner of the stratabound potash-bearing salt in the Pripyat Basin. Salt anomalies that include the various dissolution features described previously can occupy 4 to more than 40 percent of a mineralized area in stratabound potash horizons and deposits (Linn and Adams, 1966; Baar, 1972, 1974; Boys, 1990; Kopnin, 1995, Stirrett and Gebhardt, 2011; appendix A). Anomaly sizes vary relative to total potash-mineralized area depending on the factors that created the anomalies.

The locations of dissolution features are crucial to resource estimation and mine planning (appendix A). Modern three-dimensional seismic surveys provide better information about shape and location of dissolution features than older two-dimensional surveys (Gendzwill, 1978; Stirrett and Gebhardt, 2011).

Thermal Metamorphism and Hydrothermal Alteration

Intrusive and extrusive volcanic activity occurred in the Pripyat and Dnieper-Donets Basins, particularly in the vicinity of the Bragin-Loev High and near the rift boundary faults. Hydrothermal effects on the salt include formation of secondary sulfides. Basalt dikes may alter carnallite to sylvite or totally destroy potassium salts in the vicinity of the intrusions (Beer, 1996; Hoppe, 1960). Sulfur associated with intrusions may react with carnallite to form potassium sulfates such as kainite and langbeinite and perhaps kieserite (Knipping, 1991). These igneous rocks or their effects have not been noted in Pripyat Basin mine workings, but they may be present in other parts of the Pripyat and Dnieper-Donets Basins.

Paleogeography and Formation of the Upper Devonian Salt Formations

During the early part of the Late Devonian, marine waters likely entered the Pripyat Basin from the west-northwest and northwest, and the Dnieper-Donets Basin (fig. 2–2) from the southeast (Kityk and Galbuda, 1981; Vysotskiy and others, 1988; Petrychenko and Peryt, 2004). During later part of the Late Devonian, marine inflow into the Pripyat Basin may have been through the Podlasie-Brest Basin (fig. 2–1) and across what is now the Polessian Saddle (Aizberg and others, 2004). Marine water may have entered the Dnieper-Donets Basin from the west-northwest through a narrow passage in volcanic rocks of the Bragin-Loev High (Kityk and Galbuda, 1981; Protasevich, 1990) or from the Paleo-Asian Ocean in the Transcaspian region to the southeast (Aizberg and others, 2004). Kityk and Galbuda (1981) depict a narrow, restricted passage between the two basins during the Late Devonian, and Protasevich (1990) discusses some intermittent opening and closing of such a passage that, in part, caused increased salinity and potash precipitation. Some tectonically controlled restrictions may relate to development of the Donbass Foldbelt to the southeast. Despite uncertainties in inflow directions of seawater into these two basins, salt and potash-bearing salt are roughly simultaneous (fig. 2–4) and of similar origin (Kityk and Galbuda, 1981; Protasevich, 1990; Aizberg and others, 2004).

Salt volumes, estimated at 40,000 km^3 in the Dnieper-Donets Basin and 28,400–31,100 km^3 in the Pripyat Basin (Zharkov, 1984; Garetsky and others, 1984), would have required a considerable input of highly saline marine water. Considering the relatively small amount of carbonate rocks and sulfates as gypsum or anhydrite in either basin, it may be assumed that these rock types were deposited outside the current extent of these basins (see the general zoning pattern of evaporite depositional systems in appendix A), and that the waters that entered these basins were enriched in salts to the extent that the main evaporites were halite and carnallite, and perhaps sylvite. Protasevich (1990) suggests that the areal extent of progressively younger potash-bearing salt horizons decreased as evaporation areas decreased. Unfortunately, no figures are available to determine the extent and volumes of these younger potash horizons.

Upper Devonian salt was derived from sodium-potassium-magnesium-calcium-chloride (Na-K-Mg-Ca-Cl)-type seawater with a potassium-magnesium ion ratio ($K+/Mg^{2+}$) close to that of modern seawater (Petrichencko and Peryt, 1989). Fluid inclusions indicate that temperatures for halite precipitation in the Devonian did not exceed 43 °C. During formation of (secondary?) sylvite, temperatures increased to 60–65 °C. These subsequent higher temperatures may be related to volcanism and generally increased geothermal temperatures in the active rift environment in which the Pripyat and Dnieper-Donets Basins were developing (Yakushkin, 1964; Kityk, 1970; Aizberg and others, 2001).

Because of variable estimates on original thicknesses of Upper Devonian salt strata in the Pripyat and Dnieper-Donets Basins, estimates of duration of salt deposition vary widely. With halite accumulation rates at 5–150 m per thousand years (Becker and Bechstädt, 2006) and an adequate supply of brine, a minimum salt thickness of 1,000 m could be deposited in as few as 6,000 years or as many as 200,000 years. With a maximum salt thickness of 3,000 m, salt accumulation could last 20,000–1,500,000 years. Because salt thicknesses in the Pripyat Basin are better estimated at about 1,500 m, a range between 10,000 and 300,000 years is the most likely duration of salt deposition. These ages should be viewed as estimates given the wide variation in estimated salt thicknesses.

Much has been written about the structural evolution of the Pripyat and Dnieper-Donets Basins, but very little has been written about genesis and evolution of the salt and potash-bearing salt. This lack of discussion regarding the formation of the evaporite deposits probably results from the lack of detailed mineralogical and geochemical information about the numerous medium- and small-scale evaporite cycles and the overall evaporite basin system.

Cisuralian Evaporite Stratigraphy and Potash-Bearing Strata

Cisuralian Salt

Cisuralian evaporite rocks were mainly deposited in the Dnieper-Donets Basin and descriptions of the stratigraphy are from that basin. Descriptions of Cisuralian stratigraphy in the Dnieper-Donets Basin are quite varied, and, at times, seem to contradict unit labels and unit thicknesses.

Cisuralian stratigraphy comprises the Kartamyshskaya, Nikitovskaya, Slavyansk, and Kramatosk Formations (Korenevskiy and others, 1968; Vysotskiy and others, 1988). Cisuralian sedimentary rocks attain a maximum thickness of 2.5–2.7 km (Korenevskiy and Bobrov, 1968; Korenevskiy and others, 1968). The Kartamyshskaya Formation consists of reddish argillite-clay deposits and subordinate interlayered sandstone, gray clay, and dolomite. The thickness of this formation ranges from 10–30 m to 600–1,200 m. The Nikitovskaya Formation is 10–300 m thick (Hryniv and others, 2007) and consists of red clay, anhydrite, carbonate rock, argillite, anhydrite, and halite. Halite layers range in thickness from 40 to 80 m (Vysotskiy and others, 1988). The Slavyansk Formation consists of anhydrite, halite, dolomite, limestone, gypsum, and red argillite (fig. 3–6). Thickness of this formation ranges from 14–100 m in the northwestern part of the basin to 600–900 m in the southeast (Korenevskiy and others, 1968; Kovalevych and others, 2002; Hryniv and others, 2007).

According to Korenevskiy (1990), the Kramatorsk Formation contains ten evaporite cycles and is the only Cisuralian unit that contains potash. The lower (Asselian) part of this formation, which is as much as 1,000 m thick, contains no potash. Each cycle consists of argillite, carbonate rock, and anhydrite, and is capped by halite. This lower part of this formation probably includes the lithologies t1 and t2 shown in figure 3–6. The upper (Sakmarian) part of the formation is as much as 700 m thick and contains three evaporite cycles, each of which contains at least one potash-bearing bed. This upper part of the formation is probably represented by the lithologies shown as t3, t4, t5, and t6 in figure 3–6.

Korenevskiy and others (1968), Galitskiy (1972), Vysotskiy and others (1988), and Hryniv and others (2007) describe the Kramatorsk Formation as containing five potash-bearing horizons (t1, t2, t3, t4, t5) that are each as much as 30 m thick (fig. 3–6). These potash horizons appear to be mineralogically and stratigraphically equivalent to the two potash layers in cycle 8, the two potash layers in cycle 9,

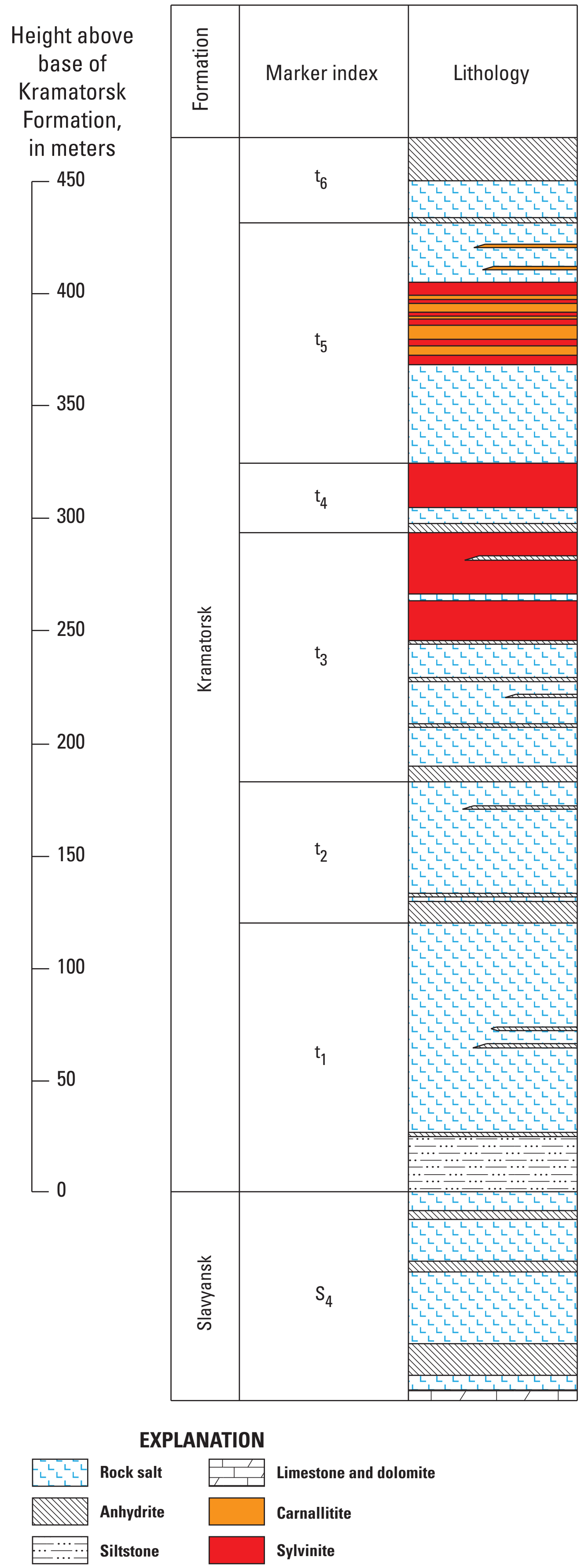


Figure 3–6. Detailed stratigraphy of Cisuralian salt of the Slavyansk and Kramatorsk Formations, measured in the Bakmutskya Subbasin of the Dnieper-Donets Basin (modified from Korenevskiy and others, 1968).

plus the single potash layer in cycle 10 (supposedly equivalent to the two potash layers in t3, the one in t4, and the remainder in t5). Korenevskiy and others (1968) and Vysotskiy and others (1988) describe the potash-bearing layers t1 to t5 in detail. Only a few potash grades and stratigraphic sections are included in these publications, and the locations of drill holes that contain potash are not provided (Korenevskiy and others, 1968; Vysotskiy and others, 1988; Korenevskiy, 1990; and Hryniv and others, 2007).

The descriptions of the evaporite cycles provided in Korenevskiy (1990) do not correspond to those shown in figure 3–6, which is modified from Korenevskiy and others (1968). According to Korenevskiy (1990), the lowermost cycle (cycle 8) contains a basal kieserite-carnallite bed, with local kainite and bischofite layers and an upper sylvinite layer. In peripheral parts of the Dnieper-Donets Basin, this cycle contains two polyhalite-bearing layers which are stratigraphic equivalents of the basal kieserite-carnallite and the sylvinite beds. Two sylvinite-bearing layers occur within cycle 9. The tenth cycle contains a sylvite-carnallite horizon. Five intervals, each 2–4 m thick, occur in the Mashivka area and contain carnallite in the lower layers and sylvite in the upper layers. At Svyatohirs’k, this cycle contains sylvite-kieserite-langbeinite hartsalz. Borates that include colemanite, ascharite, and sulfoborite occur within the kieserite-carnallite-bearing layers in cycles 8 and 10. Bischofite-bearing layers contain as much as 0.53 percent bromine. Korenevskiy (1990) also noted that potassium salt saturation of the Kramatorsk suite generally ranges from 4 to 6 percent, but is locally as much as 12 percent.

Petrographic studies of drill core indicate that carnallite initially precipitated from seawater. Sylvite formed from postsedimentation alteration of carnallite by brines saturated with $MgCl_2$ (Korenevskiy and others, 1968; Vysotskiy and others, 1988; and Korenevskiy, 1990).

A schematic map of Cisuralian lithofacies in the Dnieper-Donets Basin (fig. 3–7) shows a roughly concentric zonation of evaporites and evaporite-related deposits from peripheral sandstones, clays, carbonate, and sulfate rocks to salt to potassium salts in the interior part of the basin. Polyhalite layers occur in peripheral parts of the Dnieper-Donets Basin (Korenevskiy, 1990) and are not shown on the map.

Sedimentation during the Permian was modified by a series of northwest-trending concordant and discordant salt structures containing mainly Upper Devonian salt. Potash deposition was concentrated in the Pereyaslovka-Ivangorodekaya, Shilovskaya, Stepkovsko-Gusarovskaya, Srebnenskaya, Bakhmutskaya, Zhdanovskaya, Krotenkovsko-Grigorovskaya, and Kalmius-Toretskaya Subbasins that developed as second order depressions between the Devonian salt diapirs and domes (figs. 3–7, 3–8). Erosion of exposed diapirs contributed sodium, chlorine, and potassium to basinal waters, increased the salinity of subbasin brines, and facilitated precipitation of salt and potash-bearing salts during the Permian (Petrychenko and Peryt, 2004; Vysotskiy and others, 2004).

Within the Pripyat Basin, evaporites were deposited in the center of the basin during the Cisuralian. Vysotskiy and others (2004) equate the Svaboda Suite (Formation) in the Pripyat Basin with the Kramatorsk Suite (Formation) in the Dnieper-Donets Basin. The lower subsuite of the Svaboda Formation contains salt with interbeds of red claystone and K-Mg and magnesium-sulfate salts (Vysotskiy and others, 2004). As in the Dnieper-Donets Basin, Upper Devonian diapiric salt structures modified the Pripyat Basin into a series of small subbasins in which the evaporite facies were deposited. A map of the evaporite facies shows most of the evaporites to be sulfates (gypsum and anhydrite) with a small area of potash-bearing salt and halite (Vysotskiy and others, 2004). The Permian potash-bearing salt has dimensions estimated to be 8 by 15 km. The potash-bearing strata consist of two beds containing potassium-magnesium salts. The lower bed is 3–9 m thick, and the upper bed is 7.5–25.5 m thick (Wysocki and others, 2005). As in the Dnieper-Donets Basin, Devonian diapirs breached the surface of the Pripyat Basin and contributed sodium, chlorine, and potassium to the basinal brines (Vysotskiy and others, 2004).

Paleogeography

During the Permian, seawater traveled from the Nordic Sea area (fig. 3–9) through the Eastern European Basin, into the Pricaspian Basin, and northwestward through a strait along the northern edge of the Donbass portion of the Donbass-Pripyat Rift into the Dnieper-Donets and Pripyat Basins (Korenevskiy and others, 1968; Zharkov, 1984; Vysotskiy and others, 1988; Korenevskiy and Shamakhov, 1990). Features such as reef complexes, topographic sills or highs, or basin narrows which might have restricted the inflow of marine water into either the Dnieper-Donets or Pripyat Basins were not noted in publications, but an apparently narrow marine strait along the north side of the Donbass Foldbelt may have restricted flow of saline water to the northwest. Seawater traveling 3,000–4,000 km from the Nordic Sea into the Dnieper-Donets and Pripyat Basins was probably subjected to evaporation, salinity increase, and evaporite precipitation throughout the length of this major seaway.

Seawater Composition and Temperatures

Cisuralian salt deposits in the Dnieper-Donets Basin were derived from solutions containing sodium-potassium-magnesium-chloride-sulfate (Na-K-Mg-Cl-SO_4) seawater (Kovalevych and others, 1998, 2002). The sulfate (SO_4^{-2}) ion content of seawater in the Permian was lower than that of modern seawater (Kovalevych and others, 1998, 2002).

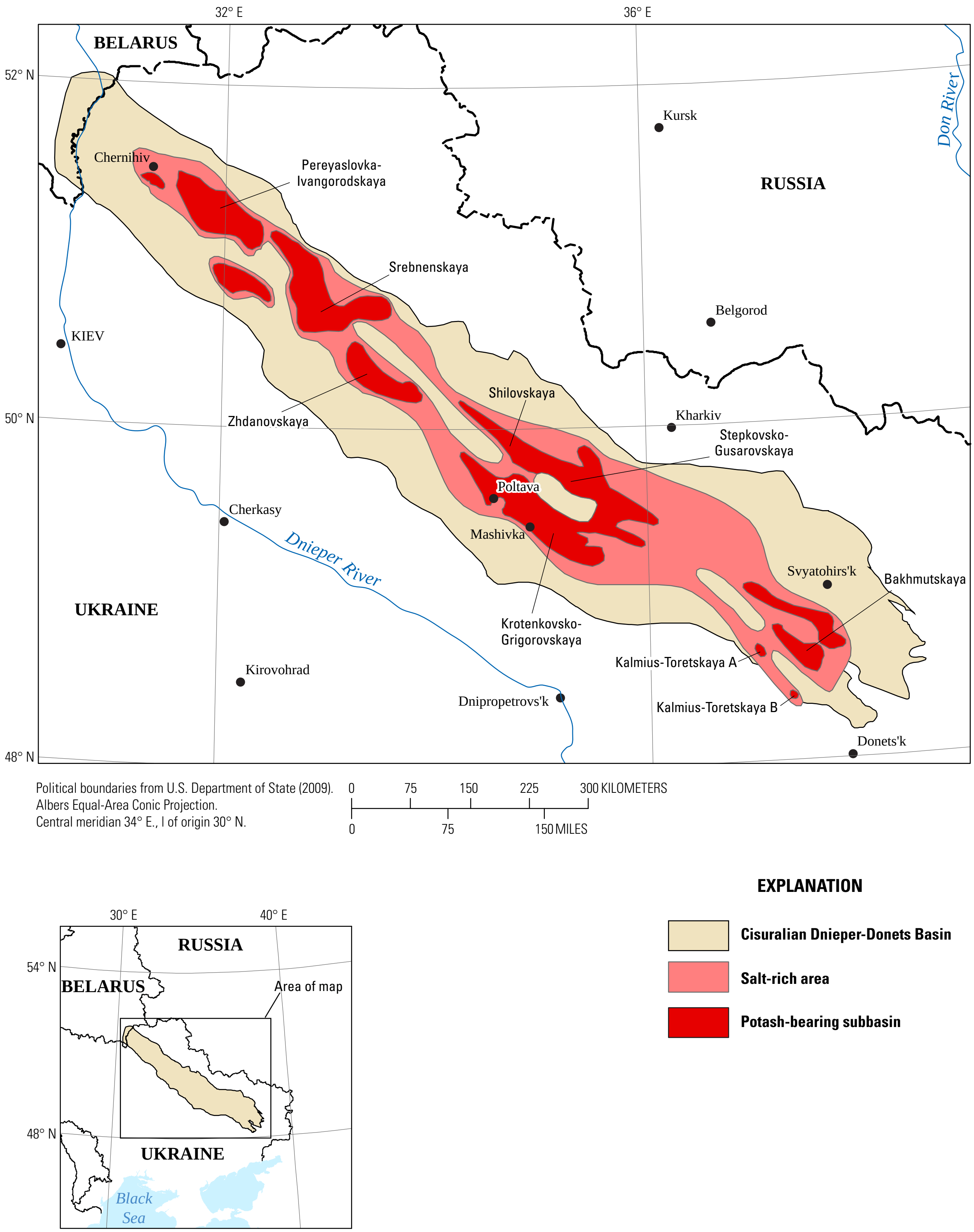


Figure 3–7. Map showing distribution of potash-bearing subbasins and halite-rich areas within Cisuralian rocks of the Dnieper-Donets Basin. Figure modified from Korenevskiy and others (1968) by using information from Vysotskiy and others (1988), Korenevskiy (1990), and Hryniv and others (2007).

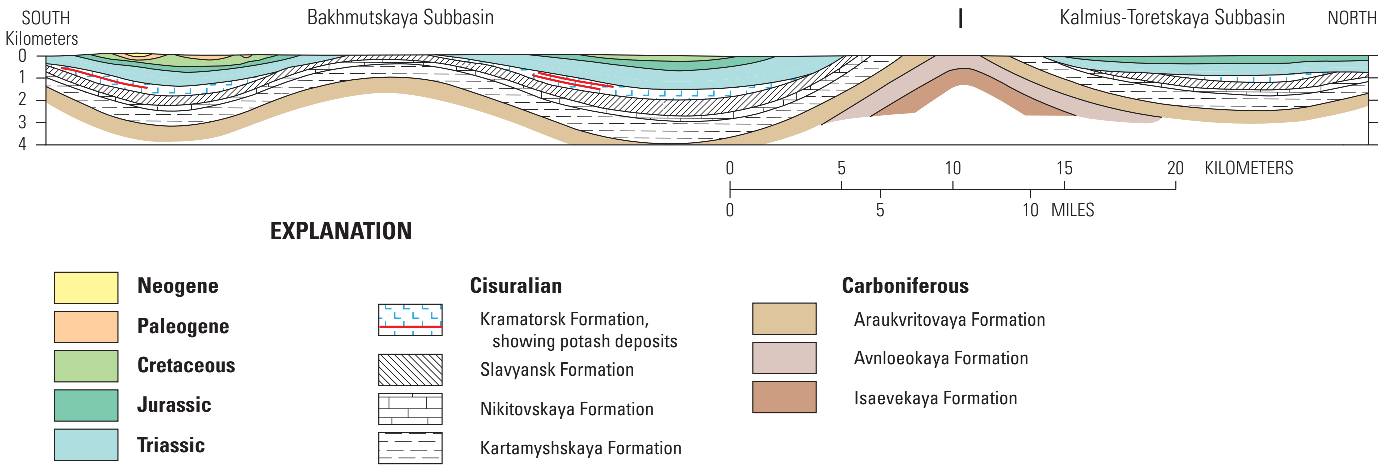


Figure 3–8. Schematic cross section through the Bakhmutskaya and Kalmius-Toretskaya Subbasins (boundary shown by thick vertical black line), southeastern Dnieper-Donets Basin. These and other Permian subbasins formed in response to episodic upward movement of Devonian salt diapirs (modified from Korenevskiy and others, 1968).

Temperatures of brines from which salts were deposited appear to have increased from 43 °C to about 83 °C, and the brine became more saline over time (Petrychenko, 1988). Fluid inclusions indicate that temperatures for halite precipitation in the Devonian and Permian did not exceed 43 °C. Temperatures increased to 60–65 °C in the sylvinite stage in the Devonian. In the Cisuralian, temperatures for carnallite deposition were as much as 78–83 °C and 65–83 °C for bischofite deposition (Petrychenko, 1988). These temperatures are similar to those obtained by Lowenstein and Spencer (1990) and Borchert and Muir (1964) for sylvite and carnallite in the Permian Carlsbad and Zechstein Basins. Zambito and Benison (2013) document temperature variations of more than 30 °C in halite in Permian ephemeral lakes, with maximum temperatures of more than 70 °C. Tabor (2013) noted that these extreme, above average temperatures may have been possible in the Permian. Diagenetic transformation temperatures in Permian salt were 45–55 °C and in Permian potash-bearing rocks temperatures were 75–82 °C (Petrychenko, 1988).

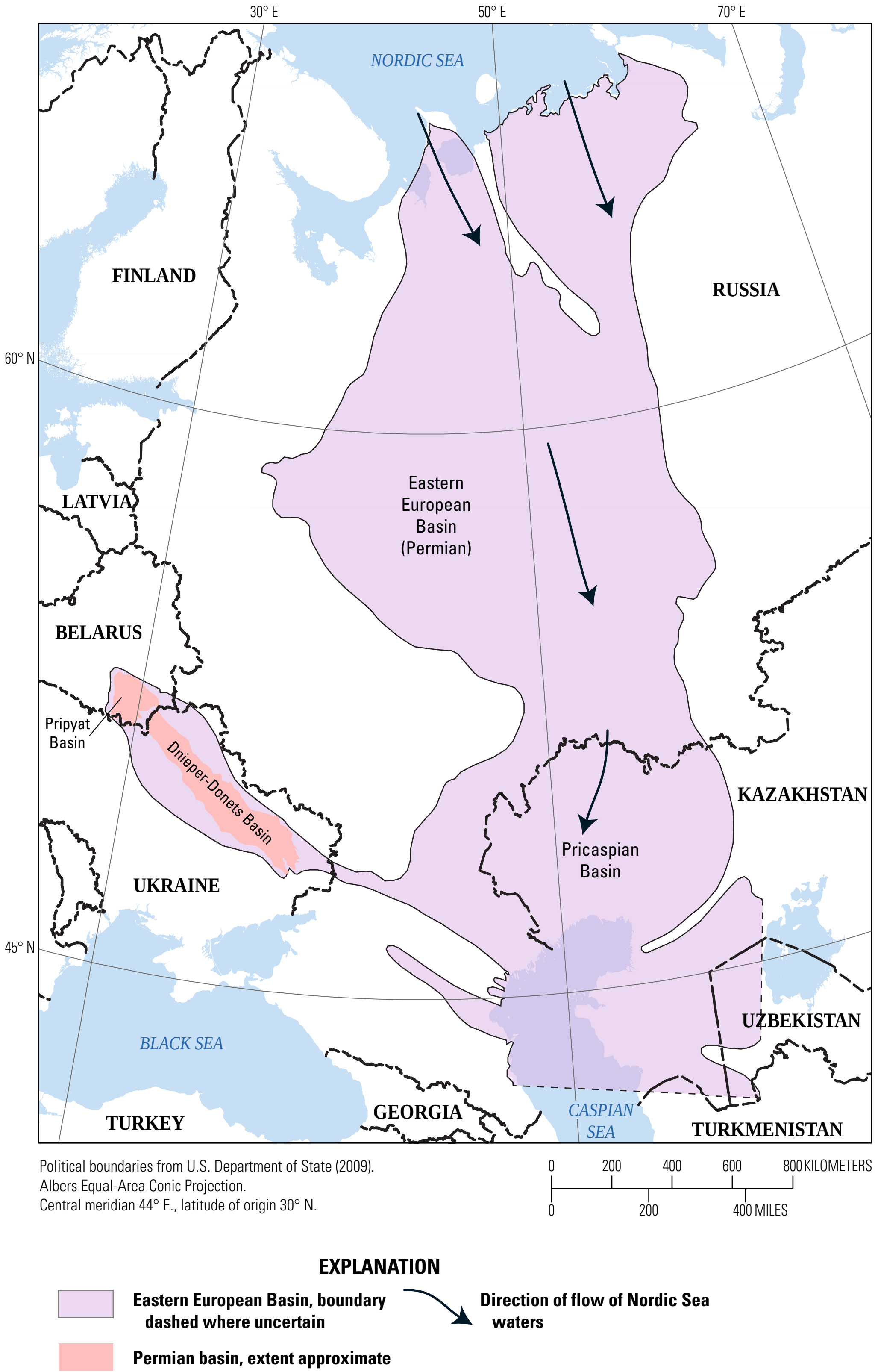


Figure 3–9. Paleogeographic map showing possible inflow path of marine water from the Nordic Sea to the Dnieper-Donets and Pripyat Basins during the Permian (modified from Zharkov, 1984).

This page intentionally left blank

Chapter 4. Development of Halokinetic Salt Structures

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

The Pripyat and the Dnieper-Donets Basins are characterized by numerous salt structures formed by halokinesis (fig. 4–1). These halokinetic salt structures have had important effects on the accessibility and homogeneity of salt and potash-bearing salt (appendix B) in these basins. Halokinetic movement of potash-bearing salt to near-surface levels offers the possibility of relatively low-cost mining from surface facilities. On the other hand, it also offers the possibility of destruction of potentially mineable deposits through dissolution of potash salts interacting with groundwater (Cocker and Orris, 2010). Such cases may exist in the Dnieper-Donets Basin where the sources for Upper Devonian salt layers are deeply buried, and diapirs bring salts toward the surface.

Representative cross sections of salt structures in the Dnieper-Donets Basin are shown in figure 4–2. Although these cross sections show no internal features in the salt structures, stratigraphy involving Frasnian, Famennian, and perhaps Cisuralian structures is expected to be as complex as stratigraphy in the German part of the Zechstein Basin, as shown in Gimm (1968).

Salt and potash-bearing salt initially deposited as a stratabound layer or layers in an evaporite basin are susceptible to diagenetic and postdepositional physical and chemical changes (appendixes A and B). Salt will flow plastically at elevated temperature and pressure but maintains its original density and will deform and flow generally upward. Plastic salt flow may be initiated by basement or other faulting, asymmetric sediment loading or unloading, or by lateral tectonic stresses. Salt deformation may result in disruption of salt layers and layering as well as vertical and lateral displacement of the salt from its original depositional position. Vertical displacement from a source salt layer may be about a few hundred meters to several tens of kilometers.

Many salt structures begin to form soon after burial of the salt source, probably because of syndepositional faulting or basin subsidence (Stovba and Stephenson, 2003; Warren, 2006). Development of axial rift faults in basement rocks within the Pripyat and Dnieper-Donets Basins (fig. 2–3) initiated and localized halokinesis (Kityk, 1970; Garetsky, 1979), and the salt structures or diapirs are aligned along these axial rift faults (fig. 4–1). Episodic movement related to various Devonian to early Tertiary regional tectonic events (Kityk, 1970; Stovba and Stephenson, 2003) along these basement faults caused repeated periods of diapir growth (fig. 4–3). This relation of halokinesis to basement structures is well documented in the Zechstein (Coward and Stewart, 1995; Warren, 2008) and Gulf of Mexico Basins (Paulson, 1970). Korenevskiy (1973) noted that diapirs in the Dnieper-Donets Basin contain lower and upper Frasnian salt and upper Famennian salt. Frasnian salt intruded through overlying Famennian salt. In some cases, Devonian salt continued to intrude upward through Permian salt (fig. 4–2*C*). Because three major salt units are involved in halokinesis in these basins, and because of the episodic nature of salt movement, the main periods of halokinesis could not be determined with the available information.

At least 249 salt diapirs (fig. 4–1) are known in the Dnieper-Donets Basin (Klimenko, 1957; Kityk, 1970), and they occupy about 8 percent of the basin area. The two main discordant Devonian salt structures in the Dnieper-Donets Basin are (1) columnar diapirs, and (2) diapirs with overhanging tops (fig. 4–2). During the Cisuralian, Devonian salt may have been extruded to form the overhanging diapirs (Stovba and Stephenson, 2003). The height of salt structures can reach 7–11 km above the top of the Upper Devonian source salt layer (fig. 2–3*B*). Lateral distances between salt structures (diapirs and domes) are typically 5–15 km. Many salt structures are located 40–1,000 m below the present surface (Hryniv and others, 2007); deeper salt structures may be 6–7 km below the surface (Ulmishek, 2001).

Garetsky (1982) mapped 138 diapirs (fig. 4–1) in the Pripyat Basin. The few cross sections of the upper parts of these diapirs show no potash-bearing layers and the text does not indicate their presence. Because the salt is probably Frasnian, potash-bearing layers should be expected in these diapirs, perhaps at deeper levels than shown in the cross sections. These diapers cover a total area of 2,972 km^2 which is equal to about 11 percent of the about 26,000 km^2 underlain by Famennian salt in the basin.

---

[1]U.S. Geological Survey, Tucson, Arizona, United States.

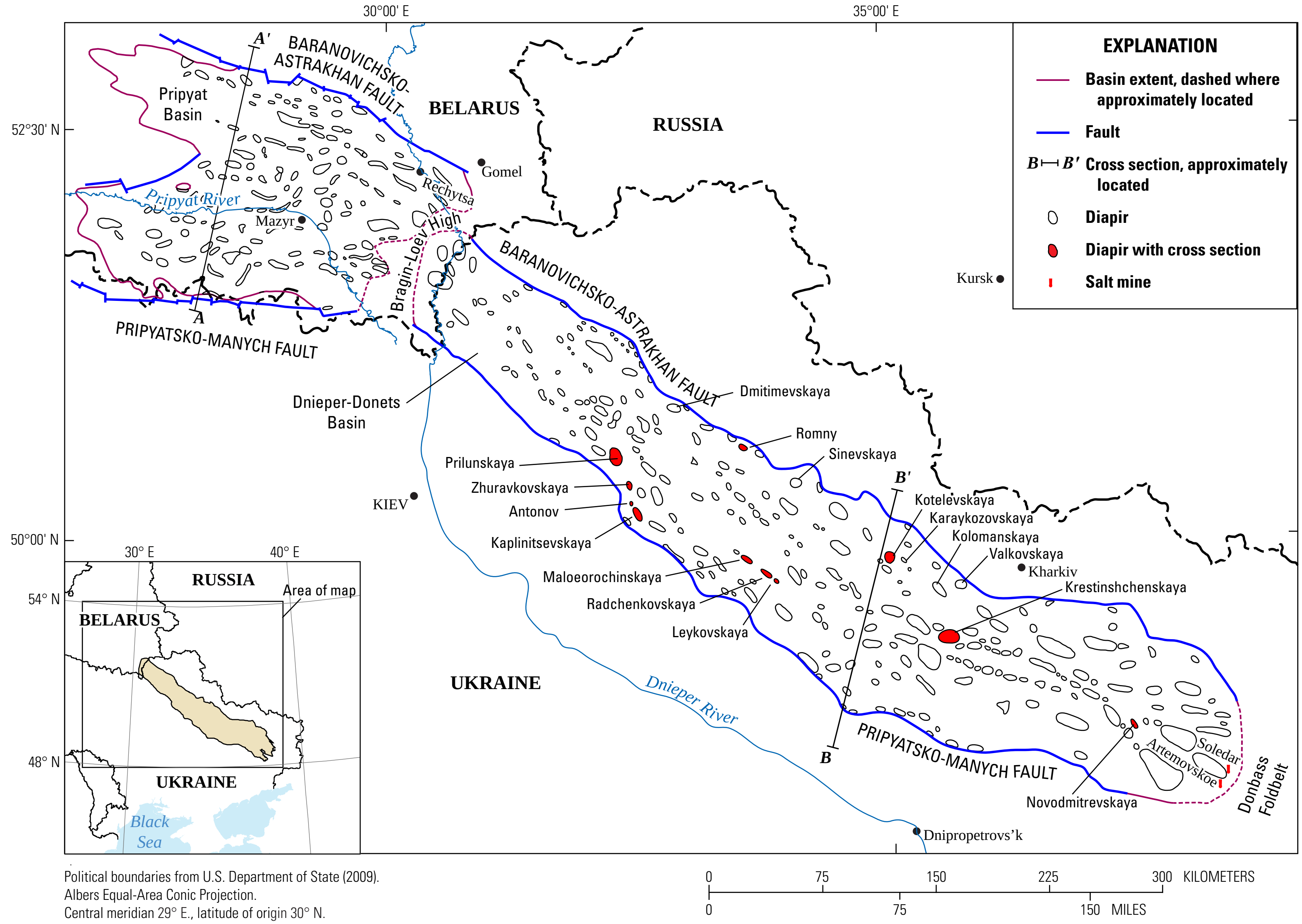
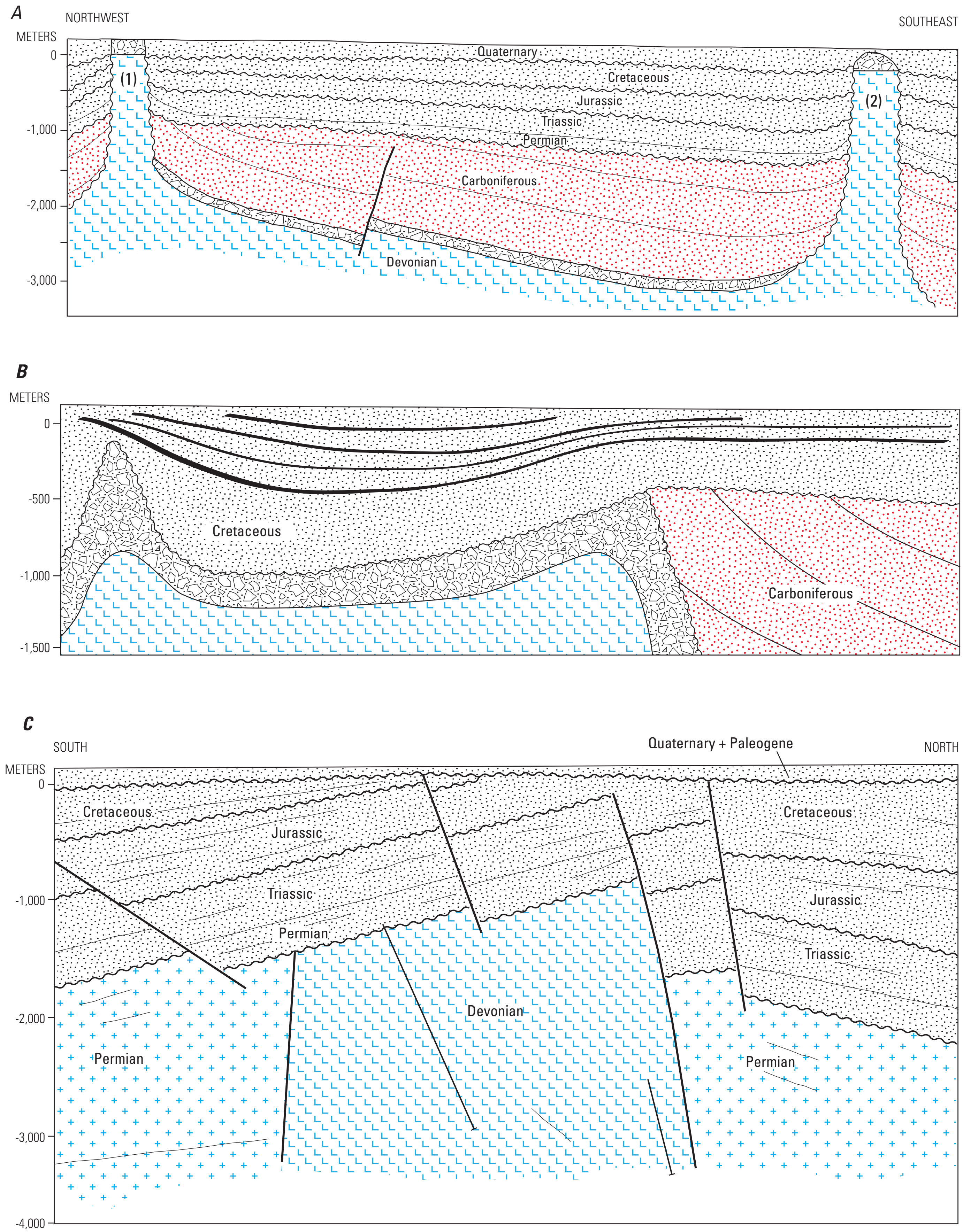
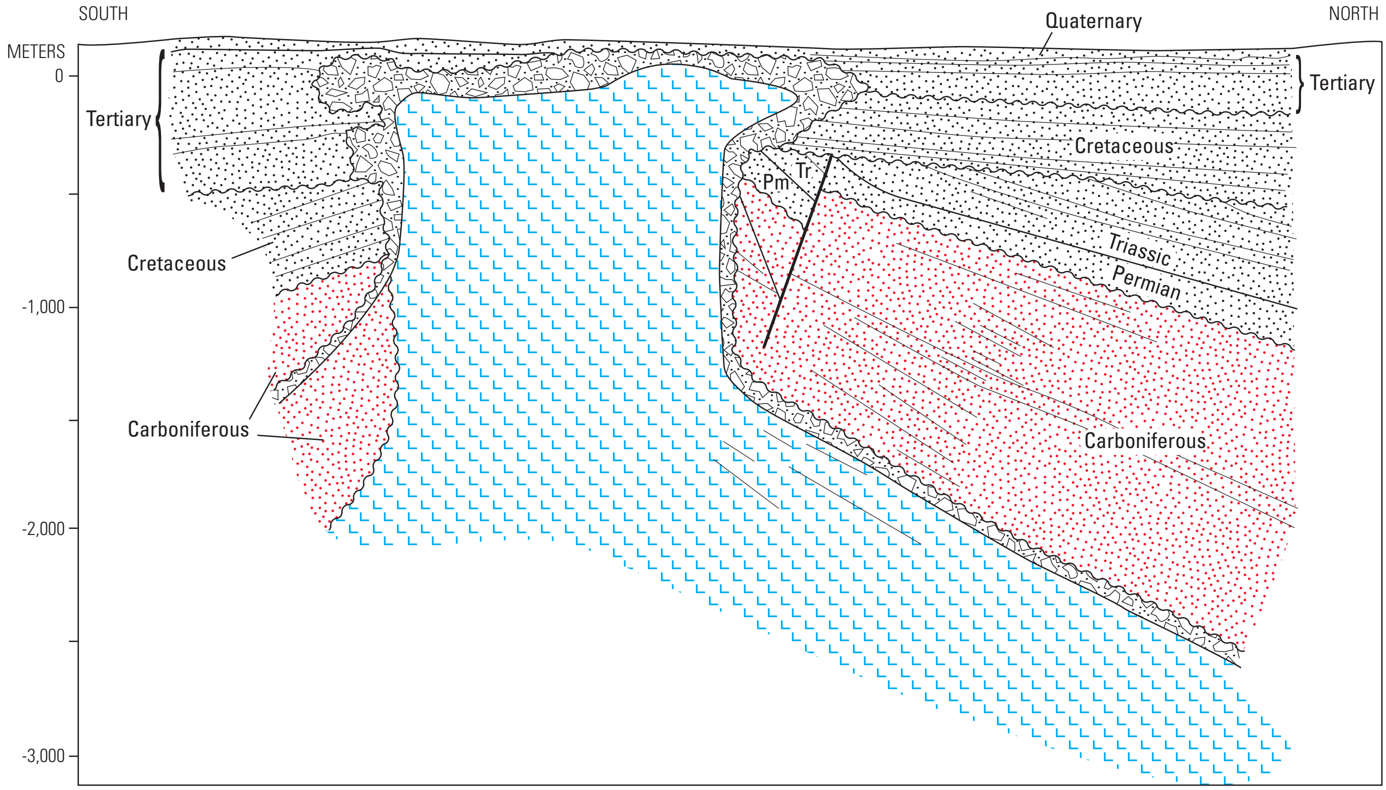


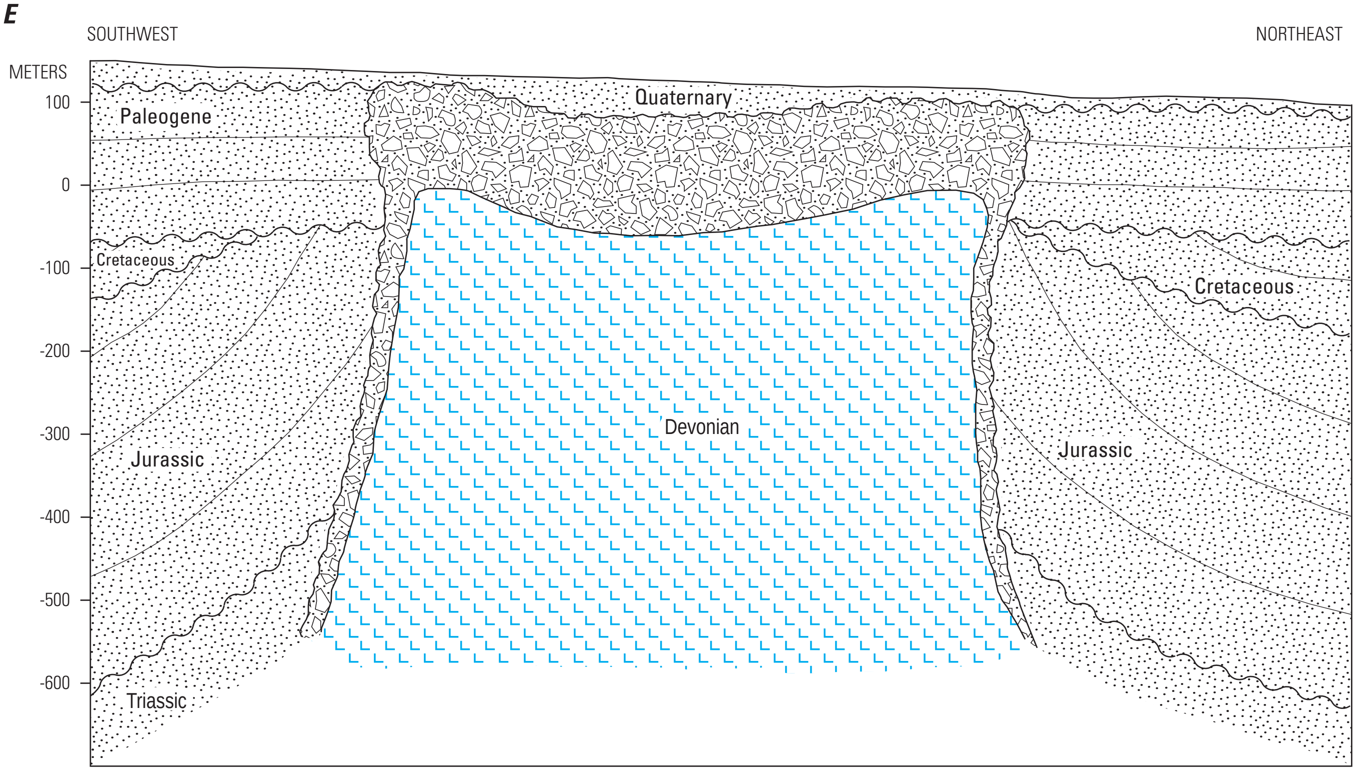
Figure 4–1. Map showing extent of Famennian salt and salt structures (diapirs) in the Pripyat and Dnieper-Donets Basins. Salt structures in the Pripyat Basin modified from Garetsky and others (1982); structures in the Dnieper-Donets Basin modified from Klimenko (1957) and Kityk (1970). Cross-section lines locate sections illustrated in fig. 2–3.


A
NORTHWEST
SOUTHEAST
METERS
0
-1,000
-2,000
-3,000
Quaternary
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
Devonian
(1)
(2)
B
METERS
0
-500
-1,000
-1,500
Cretaceous
Carboniferous
C
SOUTH
NORTH
Quaternary + Paleogene
METERS
0
-1,000
-2,000
-3,000
-4,000
Cretaceous
Jurassic
Triassic
Permian
Devonian
Cretaceous
Jurassic
Triassic
Permian
Permian

D


SOUTH
NORTH
METERS
0
-1,000
-2,000
-3,000
Quaternary
Tertiary
Tertiary
Cretaceous
Cretaceous
Tr
Pm
Triassic
Permian
Carboniferous
Carboniferous

E


SOUTHWEST
NORTHEAST
METERS
100
0
-100
-200
-300
-400
-500
-600
Quaternary
Paleogene
Cretaceous
Cretaceous
Devonian
Jurassic
Jurassic
Triassic

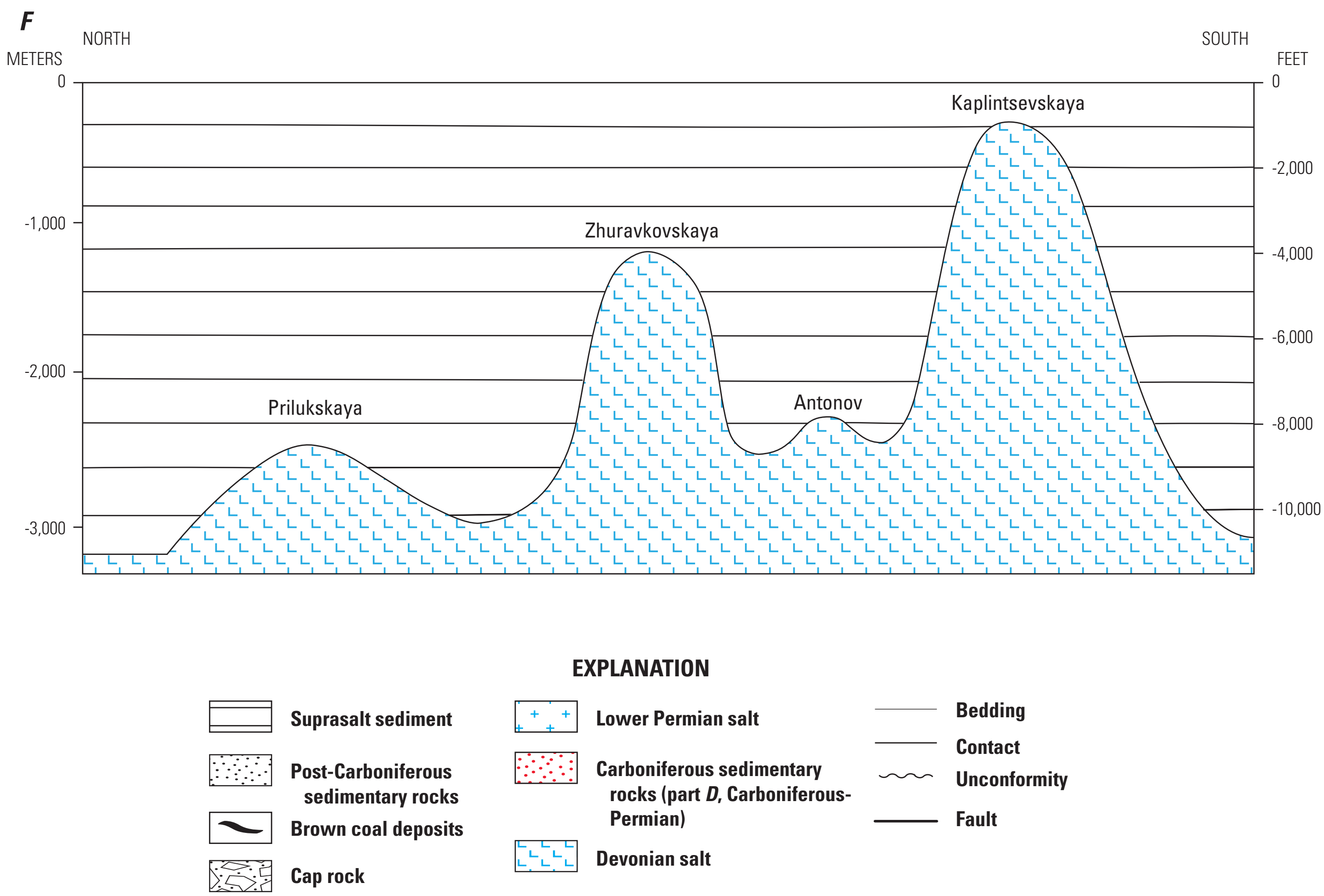


Figure 4–2. Illustrative cross sections through salt structures in the Dnieper-Donets Basin (modified from Kityk, 1970). Locations shown on fig. 4–1. Vertical exaggeration unknown. *A*, The Leykovskaya (1) and Maloeorochinskaya (2) salt structures **(p. 37)**; *B*, the Novodmitrievskaya salt structure, showing a sag basin formed by dissolution of the upper part of the salt diapir **(p. 37)**; *C*, the Krestinshchenskaya salt structure, an example of a diapir bounded by normal faults **(p. 37)**; *D*, the Romenskaya salt structure, which may have reached the surface and spread laterally **(p. 38)**; *E*, the Radchenkovskaya salt structure, which may have reached the surface but has been subjected to extensive dissolution that formed an insoluble cap rock **(p. 38)**; *F*, longitudinal cross section through the Prilunskaya, Zharavkoyskaya, Antonov, and Kaplinitsevekaya salt structures, which form a salt ridge in which the diapirs reached a variety of heights.

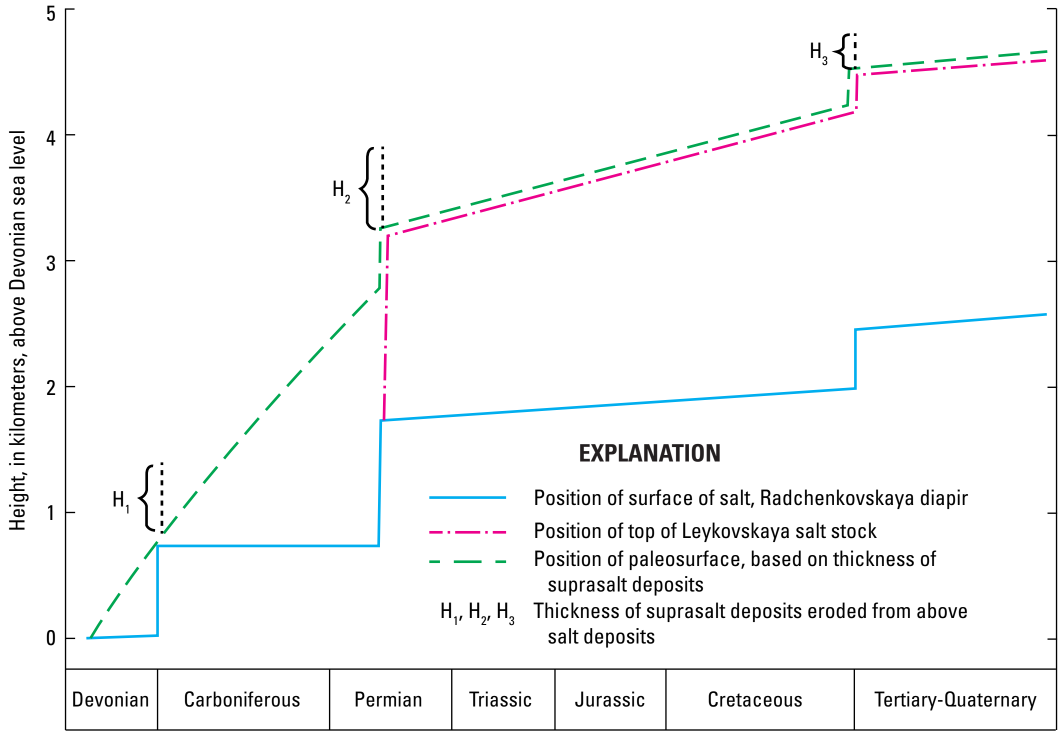


Figure 4–3. Diagram illustrating episodic upward movement of the Radchenkovskaya and Maloeorochinskaya diapirs in the Dnieper-Donets Basin (modified from Kityk, 1970); locations shown on fig. 4–1. Episodic movement was probably controlled by repeated basement faulting.

Table 4–1. Diapir sizes in basins with halokinetic structures worldwide compared with the Dnieper-Donets and Pripyat Basins.

[km, kilometer; km^2, square kilometer; worldwide includes the Dnieper-Donets and Pripyat Basins, Ukraine and Belarus; Zechstein Basin, northern Europe; and Qom-Great Kavir Basin, Yazd, and Hormuz Basins, Iran; n.d., no data]

Basin	Number of diapirs	Mean (km^2)	Standard deviation (km^2)	Median (km^2)	Average salt thickness (km)	Depth to top of salt (km)
Worldwide	926	17	3.16	16.22	n.d.	n.d.
Dnieper-Donets and Pripyat	486	18	2.4	17.78	1–3	~0.3–15
Dnieper-Donets	248	20	2.51	18.2	1–3	0.3–3
Pripyat	138	16	2.19	16.98	1.4	~2.5–15

As salt diapirs near the paleosurface, they are subjected to ground and surface water dissolution (Kityk, 1970). Undissolved parts of the diapirs consist of blocks of suprasalt sedimentary rock entrained in the salt; other less soluble evaporite rocks such as anhydrite, gypsum, and carbonate rocks form cap rocks on these diapirs (fig. 4–2). Depressions or sags may form above shallowly emplaced diapirs as salt is dissolved and may fill with younger sedimentary rocks.

Salt diapirs in the Dnieper-Donets and Pripyat Basins are similar in size to salt diapirs worldwide (table 4–1 and fig. 4–4) despite differences in basin age, salt thickness, and depths to salt. The size distributions are lognormal and worldwide mean and median sizes are essentially the same (appendix B).

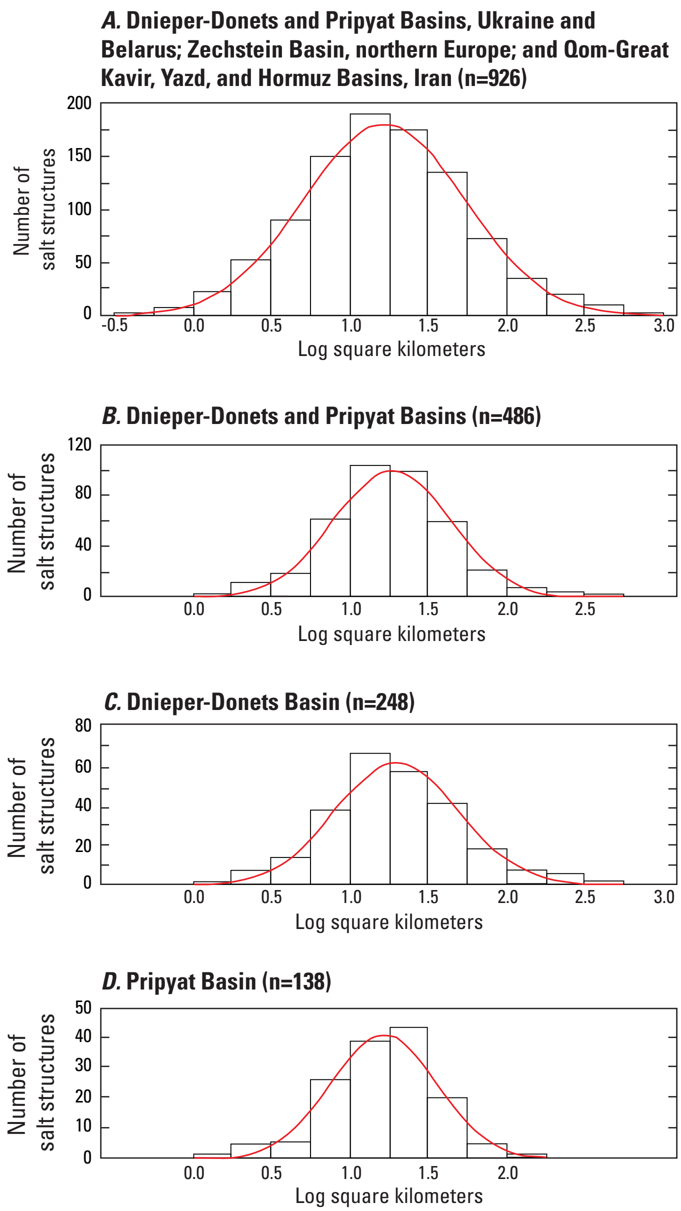


Figure 4–4. Frequency distribution of salt structure sizes for basins with halokinetic structures worldwide compared with the Dnieper-Donets and Pripyat Basins. Red line shows fitted normal curve.

Chapter 5. Assessing Undiscovered Potash Resources

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

Assessment of undiscovered potash resources requires identification and delineation of tracts (areas) that are permissive for mineral deposits. Identification and delineation of assessment tracts requires (1) knowledge of the probable extent of the host rocks, (2) establishment of a maximum assessment depth, (3) identification of known resources, (4) identification of known occurrences, and (5) characterization of geologic factors affecting grade and tonnage.

The Assessment Process

The goal of the USGS potash study of the Pripyat and Dnieper-Donets Basins is to estimate undiscovered potash (as K_2O) resources, where "undiscovered resources" are operationally defined as those resources that do not meet the criteria for reserves or indicated and inferred resources. This section describes the steps in estimation of undiscovered K_2O within permissive tracts delineated by the USGS potash assessment team.

Because of postmineralization tectonics and subsequent salt movement, some original stratabound potash-bearing salt in the Pripyat and Dnieper-Donets Basins has been mobilized into halokinetic potash-bearing salt structures, and these two styles of potash-bearing salt have separate deposit models (appendixes A, B). Four tracts were identified; three contain stratabound salt, and one contains halokinetic salt.

At the assessment meeting in May 2009, more data were available for the halokinetic tract (tract 150haK0042b), and the assessment team decided to perform a probabilistic quantitative assessment of that tract. Data were insufficient for probabilistic quantitative assessments of the other tracts (tracts 150sbK0042a, 150sbK0042c, and 150sbK0043).

The Three-Part Assessment Method

Quantitative estimates for undiscovered halokinetic potash-bearing resources in tract 150haK0042b tract were made using the three-part assessment methodology of Singer (Singer, 1993, 2007a,b; Singer and Menzie, 2005, 2010). In this method, an expert panel compares known deposits and permissive geology with the halokinetic potash-bearing salt deposit model, estimates the number of undiscovered deposits remaining in the tract, and then uses Monte Carlo simulation to combine a grade-tonnage model with the estimated number of deposits to arrive at a tonnage distribution for undiscovered potash resources.

The three-part assessment consists of

1. development of descriptive and grade-tonnage models appropriate to the deposit type and area being assessed,
2. delineation of areas (tracts) where undiscovered deposits of the sizes and grades described in the grade-tonnage models might occur, and
3. estimation of the number of undiscovered deposits (Singer, 2007a).

Information Used to Assess the Tracts

The first step in the assessment process was data collection and analysis. Based on those data, information used to delineate and assess the tracts includes

1. type or form of potash-bearing salt, whether stratabound or halokinetic;
2. depth of potash-bearing salt;
3. presence of thick salt strata, usually greater than 100 m (Harben and Kužvart, 1996);
4. presence of potash mineralized areas, occurrences, and deposits; and
5. extent of salt or potash-bearing salt.

Tracts underlain by salt or potash-bearing salt are summarized in table 5–1.

[1]U.S. Geological Survey, Tucson, Arizona, United States.

Assessment Depth

The assessment depth for potash resources is limited to 3 km, the depth above which potash may be recovered using solution mining techniques. Solution mines at Hersey, Michigan, and Veendam, Netherlands, extract dissolved potassium from sylvite or carnallite at depths approaching 2,000 m, and some solution mining of salts to form storage caverns may exceed 2,000 m. Maximum assessment depth includes the deepest active mining. Also, most assessment data could not be interpolated at a scale finer than 1-km intervals. It should be noted that China has experimented with using high-pressure multistage pumps to attempt solution mining at depths of 3,000 m, but results were limited at those depths (Shun, 1993). The actual economic and physical depth limit of potash probably lies between 2 and 3 km.

Known Resources of Potash

For the purposes of this report, there is an operational definition of "known" potash deposits and (or) resources. A known resource for potash at a given location (usually a deposit, lease, or permit area) consists of known or estimated grade and tonnage of all production and all known in-place resources. Resources include proven, probable, recoverable, measured, indicated, and inferred reserves and resources.

Data Availability for Permissive Tracts of the Pripyat and Dnieper-Donets Basins

This study involved the English translation of more than 30 Russian language articles or books, 23 of which are included as references; others were deemed to be either of little value or the translations were not of sufficient quality to be cited. These 23 references included more than 1,600 pages of text, maps, and tables. The few English language

Table 5–1. Age and area of delineated tracts.

[km^2, square kilometer]

Tract ID	Basin	Age	Area (km^2)
150sbK0042a	Dnieper-Donets	Cisuralian	63,700
150haK0042b	Dnieper-Donets	Upper Devonian	7,840
150sbK0042c	Dnieper-Donets	Upper Devonian	15,600
150sbK0043	Pripyat	Upper Devonian	15,500

publications are commonly journal publications or abstracts, which lack necessary geological details. In addition, a number of relevant Polish and German language articles and books were translated. Because most of the published information is in Russian, some details regarding deposit and basin geology may have been missed or misunderstood. Principal sources of information for all of the permissive tracts are contained in table 5–2.

The lack of geographic references on many published Pripyat and Dnieper-Donets Basin sketch maps of evaporite and volcanic rocks, structure maps, and other geologic maps makes those maps and their features impossible to locate and establish good locations and scales. Where possible, maps that had geographic locations were digitally georeferenced, and their features were digitized. Of the maps that could be georeferenced, maps of the same areas from different sources could not be consistently matched, and as a result, map features may not be consistently matched. An example of this would be where salt structures on one map lie within the basin or permissive tract, but when plotted from another map, they lie outside of the basin or permissive tract. Greater reliance was placed on maps that could be georeferenced consistently. Some generalizations were required when data on other maps could not be used. Some summary drill-hole data are available, but some drill-hole locations are lacking, or drill holes were located only on less reliable maps.

Table 5–2. Principal information sources for the Pripyat and Dnieper-Donets Basins, Belarus and Ukraine.

Theme	Source name or title	Scale	Citation
Geology	Mineragenetic map of the Russian Federation and adjacent states.	1:2,500,000	Rundkvist (2001)
	Figure 34. The diagram of the layout of salt raising in the Dnieper-Donets depression.	Approximately 1:2,000,000	Kityk (1970)
	Potash-bearing basins of the world.		Vysotskiy and others (1988)
	Evaporites of Ukraine: A review.		Hyrniv and others (2007)
	An atlas of the geology and mineral deposits of the Ukraine.	1:5,000,000	Galitskiy (2007)
	Geological map of the USSR, sheet M-37 Kharkov, Map of the pre-Mesozoic rocks.	1:1,000,000	Kovalevym and others (1965)
	Schematic map of the thickness of the Upper Famennian salt formation, figure 9.	n.d.	Garetsky and others (1984)
Mineral occurrences	Figure 2. Structure of the first potash horizon.	n.d.	Eroshina and Kislik (1980)
	Figure 1. Schematic map of potentially productive potash deposits in potassium-bearing Upper Famennian subformation of the Pripyat Basin.	n.d.	Korenevskiy and Shamakhov (1990)
	Figure 37. Schematic lithofacies map of the Lower Permian deposits of the Dnieper-Donets depression and northwestern outskirts of Donbass.	n.d.	Vysotskiy and others (1988)
	Figure 34. The diagram of the layout of salt diapirs in the Dnieper-Donets depression.	Approximately 1:2,000,000	Kityk (1970)
Subsurface geology	Figure 43. Composite section of Devonian salt deposits of Pripyat Depression.	n.d.	Zharkov (1984)
	Figure 44. Composite section of lower (Upper Frasnian) salt sequence.	n.d.	Zharkov (1984)
	Figure 47. Structure of upper salt sequence in northwestern Pripyat Depression.	n.d.	Zharkov (1984)
	Figure 48. Correlation of composite sections of potash member in different parts of western Pripyat Depression.	n.d.	Zharkov (1984)
	Figure 45a-d. Thicknesses of salt units and distribution of related potash horizons of lower salt sequence in Pripyat Depression.	n.d.	Zharkov (1984)
	Figure 49. Distribution of Devonian salt strata in Dnieper-Donets Depression.	n.d.	Zharkov (1984)
	Thicknesses of salt units and distribution of 1st potash horizon in lower salt sequence.	n.d.	Eroshina and Kislik (1980)
	Thicknesses of salt units and distribution of 2nd potash horizon in lower salt sequence.	n.d.	Eroshina and Kislik (1980)
	Thicknesses of salt units and distribution of 3rd potash horizon in lower salt sequence.	n.d.	Eroshina and Kislik (1980)
	Thicknesses of salt units and distribution of 4th potash horizon in lower salt sequence.	n.d.	Eroshina and Kislik (1980)
	Long-sections and cross sections of the basins.	n.d.	Ulmishek and others (1994)
	Cross sections, and structure contour maps mainly of individual diapirs.	n.d.	Vysotskiy and others (1988); Kityk (1970)
	Figure 12 Geological section of the north-western part of the Starobin deposit.	n.d.	Garetsky and others (1984)
Geophysics	Sketch seismic-geologic sections.	n.d.	Kityk (1970)
Exploration	n.d.	n.d.	Garetsky and others (1982, 1984)
	n.d.	n.d.	Truscott (2011)
	n.d.	n.d.	Foreign Policy and Security Research Center (2011)

This page intentionally left blank

Chapter 6. Qualitative Assessment of Tract 150sbK0042a, Permian (Cisuralian) Evaporites—Dnieper-Donets Basin, Belarus and Ukraine

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

Tract 150sbK0042a outlines a permissive area for Cisuralian stratabound potash-bearing salt that is present throughout the Dnieper-Donets Basin (fig. 6–1). This is a qualitative assessment because of the general lack of geologic data. As noted in chapter 3, available descriptions of Cisuralian stratigraphy have numerous ambiguities and contradictions.

Delineation of the Permissive Tract

The permissive tract boundary (fig. 6–1) was defined by using several sources. The Geological Map of the USSR, sheet M-37 Kharkov, Map of the pre-Mesozoic rocks (Kovalevym and others, 1965) was used to define the southeastern part of the tract. The outline is based on the mapped extent of Permian units in the subsurface as depicted on the geologic map of Kovalevym and others (1965). A similar map adjoining sheet M-37 to include Permian strata to the northwest was not available. For the remainder of the tract to the northwest, the extent of the Upper Devonian Dnieper-Donets Basin, as defined by border faults of the rift from a georeferenced map of the Dnieper-Donets Basin (Kityk, 1970), was used in conjunction with the distribution of evaporite facies as depicted in a sketch map by Vysotskiy and others (1988). The outline of this Devonian part of the basin corresponded reasonably well with the southeastern Permian part of the basin. The resulting tract outline includes all of the various Permian evaporite facies mapped by Vysotskiy and others (1988).

Although the sketch map by Vysotskiy and others (1988) shows the distribution of potash-bearing subbasins (fig. 3–7), it was not used to delineate the tract for several reasons: (1) precise georeferencing of the map could not be achieved; (2) the borders of the Permian basin were imprecise on the sketch map; (3) imprecise borders suggest that potash extent was also not accurate; and (4) the scale of the sketch map did not approach that of Kityk's 1:2,000,000-scale map (Kityk, 1970). The outline of the Devonian part of the basin also includes potash extent and the rest of the evaporite facies on the map by Vysotskiy and others (1988). Because polyhalite was noted beyond potash areas in the sulfate parts of the basin, the remaining Permian evaporite facies (shown by Vysotskiy and others, 1988) was included, also. The area of this permissive tract was not modified by Upper Devonian halokinetic salt structures of tract 150sbK0042b.

Assessment Depth

Cisuralian salt is believed to be above the 3-km depth limit.

Known Potash Resources

Known potash resources within the Permian (Cisuralian) tract (150sbK0042a) are listed in table 6–1. A tonnage is reported for the Bakhmutskaya Subbasin, but no potash grades are available. Because drill-hole intercepts range from 6.98 to 18.9 percent K_2O, it might be reasonable to expect that potash grades for this subbasin lie somewhere in that range.

Potash Occurrences

Potash in Cisuralian salt is reported in 12 drill holes and 8 subbasins (figs. 3–7, 6–1) within the Dnieper-Donets Basin (table 6–2). Descriptions of these potash occurrences are inconsistent regarding details of depths, thicknesses, and grades. Reported data may have come from different petroleum exploration programs rather than from potash exploration.

Exploration and Development Overview

Exploration for potash in this tract is unknown beyond that published in Korenevskiy and others (1968) and Vysotskiy and others (1988).

[1]U.S. Geological Survey, Tucson, Arizona, United States.

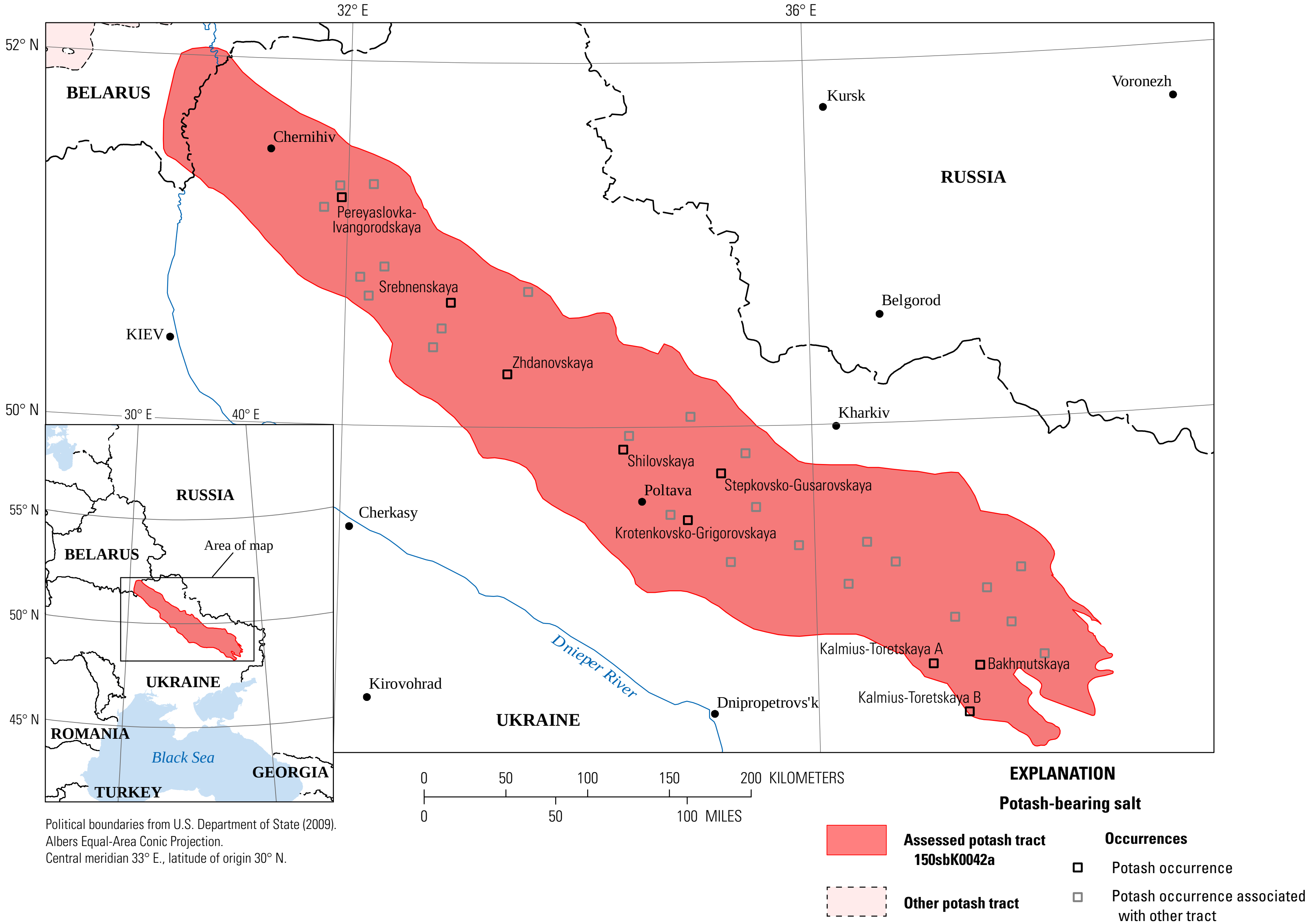


Figure 6–1. Map showing extent of tract 150sbK0042a, Permian (Cisuralian) evaporites—Dnieper-Donets Basin, Belarus and Ukraine. Known potash occurrences also shown.

Table 6–1. Known resources of potash within tract 150sbK0042a, Permian (Cisuralian) evaporites—Dnieper-Donets Basin, Belarus and Ukraine.

[See figure 3–7 for subbasin location. Bt, billion metric tons; m, meter; n.d., no data]

Resource name	Tonnage (Bt, in place)	Grade (percent K_2O)	Contained K_2O (Bt)	Reference
Bakhmutskaya Subbasin (specific location within basin not known)	0.794 (to a depth of 1,200 m)	n.d.	n.d.	Korenevskiy and others (1968); Vysotskiy and others (1988)

Table 6–2. Known occurrences of Cisuralian stratabound potash-bearing salt within tract 150sbK0042a, Permian (Cisuralian) evaporites—Dnieper-Donets Basin, Belarus and Ukraine.

[Subbasin locations are approximate centers of areas shown on figure 3–7. n.d., no data; m, meter]

Name	Latitude	Longitude	Comments	Reference
SKV 137	n.d.	n.d.	Kieserite, sylvite, langbeinite, polyhalite	Korenevskiy and others (1968)
SKV 6950	n.d.	n.d.	Sylvite, carnallite; 13.5–18.9 percent K_2O over 5 m	Korenevskiy and others (1968)
SKV 76	n.d.	n.d.	Sylvite, carnallite	Korenevskiy and others (1968)
SKV 6809	n.d.	n.d.	Sylvite, carnallite; 13.79 percent K_2O over 0.3 m	Korenevskiy and others (1968)
SKV 6901	n.d.	n.d.	Sylvite; 10.37 percent K_2O (interval unknown)	Vysotskiy and others (1988)
SKV 204	n.d.	n.d.	Carnallite, kieserite; 17.56 percent K_2O over 6 m	Korenevskiy and others (1968)
SKV 1-r	n.d.	n.d.	Sylvite	Korenevskiy and others (1968)
SKV 4-r	n.d.	n.d.	Polyhalite	Korenevskiy and others (1968)
SKV 3-r	n.d.	n.d.	Polyhalite	Korenevskiy and others (1968)
SKV 5-r	n.d.	n.d.	Sylvite	Korenevskiy and others (1968)
SKV 6-r	n.d.	n.d.	Polyhalite, kieserite	Korenevskiy and others (1968)
SKV 203	n.d.	n.d.	Kieserite, carnallite; 6.98 percent K_2O over 6 m	Korenevskiy and others (1968)
Bakhmutskaya Subbasin	48.6494	37.3419	n.d.	Vysotskiy and others (1988)
Kalmius-Toretskaya Subbasin	48.6683	36.9578	n.d.	Vysotskiy and others (1988)
Krotenkovsko-Grigorovskaya Subbasin	49.489	34.9344	n.d.	Vysotskiy and others (1988)
Pereyaslovka-Ivangorodekaya Subbasin	51.2487	31.943	n.d.	Vysotskiy and others (1988)
Shilovskaya Subbasin	49.8795	34.393	n.d.	Vysotskiy and others (1988)
Srebnenskaya Subbasin	50.6812	32.9111	n.d.	Vysotskiy and others (1988)
Stepkovsko-Gusarovskaya Subbasin	49.7437	35.2213	n.d.	Vysotskiy and others (1988)
Zhdanovskaya Subbasin	50.2923	33.4029	n.d.	Vysotskiy and others (1988)

Salt resources have been developed from at least five underground mines in the Dnieper-Donets Basin (Yermakov and Galushko, 2002). It is not known if any potash is produced from these mines. Annual production of salt from 2000 to 2002 was 2.008, 1.969, and 0.870 Mt, respectively (Yermakov and Galushko, 2002). Sample depths of 44–89 m in the Artemivsk Sverdlov Mine, Artemivsk Mine 3, and Artemivsk Volodarsk Mine suggests these mines are rather shallow (Kovalevych and others, 2002). These mines are probably in the vicinity of or part of the Artemovskoe and Soledar salt mines shown in figure 4–1.

Qualitative Assessment

The permissive tract consists of the total possible extent of Cisuralian rocks of the Dnieper-Donets Basin, including eight potash-bearing subbasins (table 6–2, fig. 3–7). Potash is documented in five horizons as much as 40 m thick each. Potash minerals include sylvite, carnallite, langbeinite, kainite, and polyhalite. Except for the few available drill holes with grade data (table 6–2), potash grades of individual subbasins or potash horizons are not known. Vysotskiy and others (1988) estimated potash resources in part of the Bakhmutskaya Subbasin to be 794 Mt of “raw or crude” salts to a depth of 1,200 m. Depending on the grade, this amount of mineralized rock could contain 50 to 150 metric tons of K_2O. The area of the Bakhmutskaya Subbasin is estimated to be 440 km^2 and has a maximum thickness of 40 m. The total area of the subbasins shown to contain potash (Vysotskiy and others, 1988) is about 10,450 km^2.

Chapter 7. Qualitative Assessment of Tract 150sbK0042c, Upper Devonian (mainly Famennian) Stratabound Potash-Bearing Salt—Dnieper-Donets Basin, Belarus and Ukraine

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

Tract 150sbK0042c outlines a permissive area for Upper Devonian (mainly Famennian) stratabound potash-bearing salt that is present above a depth of 3 km in the Dnieper-Donets Basin (fig. 7–1). Because of the lack of information regarding this salt unit, this assessment is qualitative. Of the four tracts in this report, this tract has the least available information but may have the greatest potential because stratigraphy is similar to potash-producing salt in the Pripyat Basin (fig. 2–4).

Delineation of the Permissive Tract

The Dnieper-Donets Basin is underlain by Upper Devonian salt. Strata dip from northwest to southeast, and the tract includes the northwestern part of Upper Devonian salt. This tract is permissive for bedded, stratabound potash-bearing salt, based on the available geology.

The northeastern boundary fault of the Donbass-Pripyat rift is the Baranovichsko-Astrakhan Fault, and the southwestern boundary fault is the Pripyatsko-Manych Fault; both were located using a georeferenced map of salt diapirs in the Dnieper-Donets Basin (Kityk, 1970). The northwestern boundary was extended by including a georeferenced map of salt diapirs from Klimenko (1957). The precise northwestern boundary could not be determined from available maps; instead, it is approximated from subsurface Devonian effusive volcanic rocks of the Bragin-Loev High. The southeastern end of the tract was located approximately at the 3-km depth limit by using a longitudinal cross section of the Dnieper-Donets Basin (Ulmishek and others, 1994). The tract was further modified by removing areas occupied by salt structures in tract 150sbK0042b.

Delineating the southeastern end of this tract was difficult because of the lack of detailed geology regarding the stratabound salt. No maps depicting depths to the top of the Upper Devonian salts were found. The vertical and horizontal scales of the Dnieper-Donets Basin in figure 2–3*A*, *B*, could cause significant variation in the location of the southeastern end of the tract. The upper surface of the stratabound salt appears to continue to dip southeast at an undetermined angle (Ulmishek, 1994); the depths to this salt in the southeastern part of the basin may be about 10–15 km.

Assessment Depth

The tract is defined by the stratabound Upper Devonian (undifferentiated) salt above the 3-km depth limit.

Known Potash Resources

Potash resources or occurrences are not known for this tract.

Exploration and Development Overview

Exploration activities for potash in this tract are unknown.

Qualitative Assessment

The presence of several potash-bearing strata in halokinetic salt structures derived from salt of this tract indicates that stratabound potash could be present in this tract. The extent and grade of potash is unknown. However, based on the quantitative assessment of halokinetic salt structures derived from salt units in this tract (see chapter 9), the possibility exists for the presence of substantial tonnages of potash.

[1]U.S. Geological Survey, Tucson, Arizona, United States.

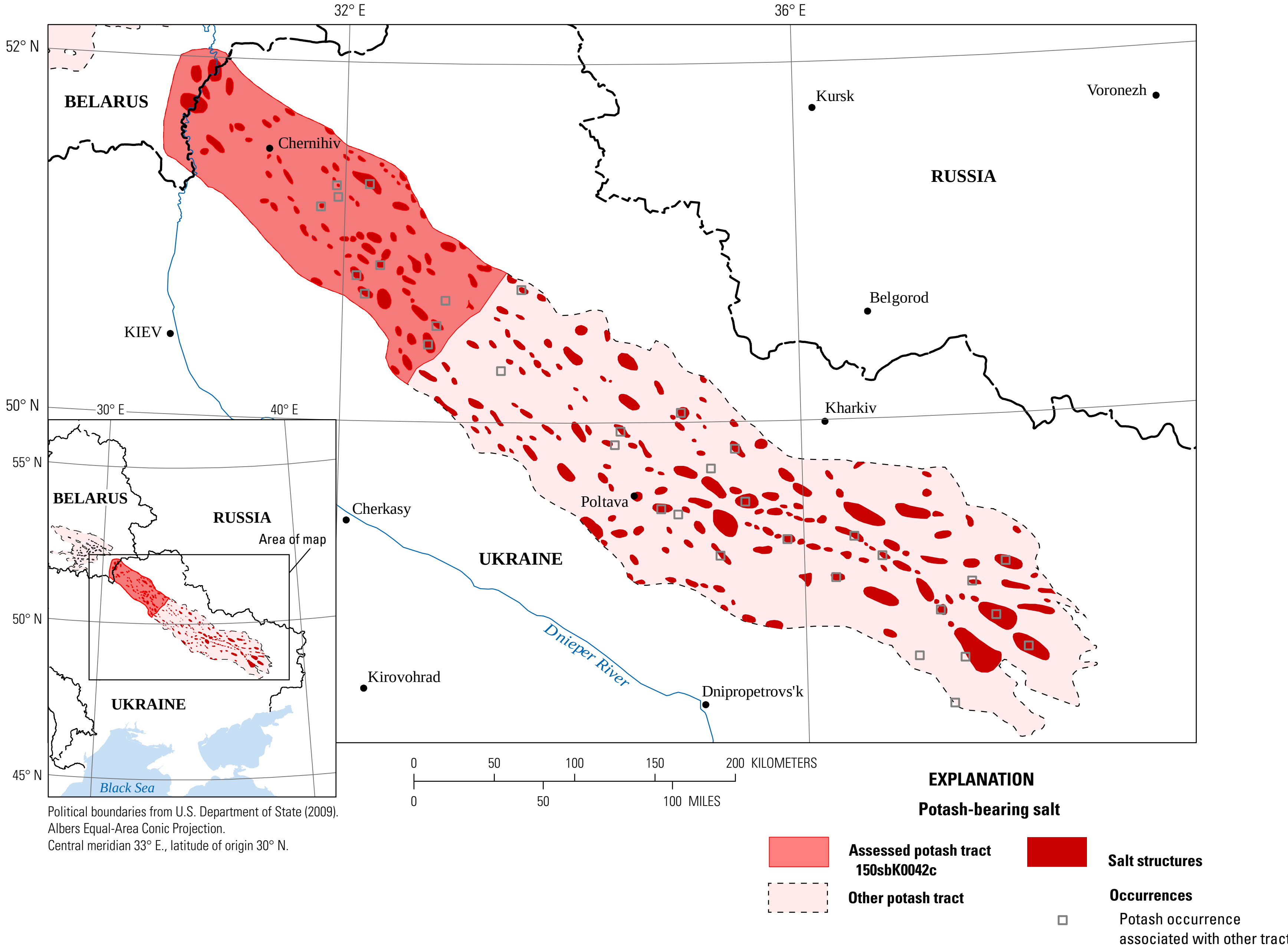


Figure 7–1. Map showing extent of tract 150sbK0042c, Upper Devonian (mainly Famennian) stratabound potash-bearing salt—Dnieper-Donets Basin, Belarus and Ukraine. Also shown are Upper Devonian halokinetic salt structures that constitute tract 150haK0042b.

Chapter 8. Qualitative Assessment of Tract 150sbK0043, Upper Devonian (Famennian) Stratabound Potash-Bearing Salt—Pripyat Basin, Belarus

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

Tract 150sbK0043 defines a permissive area for stratabound potash-bearing salt in the Pripyat Basin (fig. 8–1). Most of the permissive area is believed to be above a depth of 3 km.

Delineation of the Permissive Tract

The permissive tract lies within the Pripyat Basin which occupies the northwestern part of the Donbass-Pripyat Rift. The basin is bounded on the north by a series of normal faults called the Baranovichsko-Astrakhan Fault and on the south by a series of normal faults called the Pripyatsko-Manych Fault (figs. 2–2, 2–3). On the east side, the Pripyat Basin is separated from the Dnieper-Donets Basin by volcanic rocks of the Bragin-Loev High. The western edge is separated from the Podlasie-Brest Basin by the Polessian Saddle (Garetsky and others, 1984, 2004). These borders represent the preserved depositional limits of the evaporite basin (Zharkov, 1984).

The permissive tract is defined by the extent of Famennian subsurface potash-bearing strata within the Pripyat Basin as reported by Korenevskiy and Shamakhov (1990). As shown by Korenevskiy and Shamakhov, potash-bearing strata cover a large part of the Pripyat Basin. The extent of individual horizons may not be as great as that shown by the tract outline (fig. 8–1). Voids or embayments within or along the edges of the permissive tract generally coincide with salt structures. Several cross sections (Vysotskiy and others, 1981) of salt structures depict the potash-bearing strata as not being present over or immediately adjacent to the salt structures.

Assessment Depth

Most stratabound Famennian salt in the Pripyat Basin is above the 3-km depth limit. Most Frasnian salt is below this depth, with the exception of salt in diapirs.

Known Potash Resources

Belaruskali is the sole potash mining company in Belarus. It operates six mines in the vicinity of Soligorsk (fig. 3–4) that access three of the four main potash horizons. The Starobin #1, #2, #3, and #4, Krasnoslobodsky, and Berezovsky mines (table 8–1) have been developed sequentially since 1963 in the westernmost and shallowest part of the Pripyat Basin. Expected capacity for Krasnoslobodsky is 3 Mt per year by 2012, and for Berezovsky, capacity is expected to be 6 Mt per year by 2015 (Truscott, 2011). All of these mines are essentially adjacent to each other, with the mines accessing different potash horizons.

Most current development is in and around current mine infrastructure in the Starobin mines area. Recently, high potash prices, increasing demand, and impending depletion of reserves in the first Starobin mines have encouraged further mining expansion. The Nezhinsky and Darasinsky mines are scheduled to be developed by the end of 2020 (Truscott, 2011; Foreign Policy and Security Research Center, 2011). Petrikov (the Petrikoskoye field) appears to be the next area to be developed (Truscott, 2011).

Obtaining reliable or recent reserve estimates for parts or all of the Pripyat Basin has been difficult. Recent literature with new data regarding production or reserves is not available. Most estimates were published in the 1980s, and recently published information, which have no attributed data, appear to be data reproduced from the 1980s. In many instances, it isn't clear what is being reported.

As of January 1, 2009, the balance reserves (categories A+B+C1+C2[2]) for potash-bearing salt were 7.9 Bt of mineralized material with a grade of 18 percent K_2O (Unukovich and Ansohko, 2012; table 8–1; figs. 8–1 and 8–2).

---

[1]U.S. Geological Survey, Tucson, Arizona, United States.

[2]Reserves in the Russian scheme of ore classification (Henley, 2004; Arden and Tverdov, 2014). Under optimal conditions, category A represents production reserves, B represents blocked out ore panels, and C1 represents ore estimated in a completed feasibility study. However, A and B may also be measured resources, and C1 may be composed of measured and indicated resources. Category C2 spans the boundary of indicated to inferred reserves and resources.

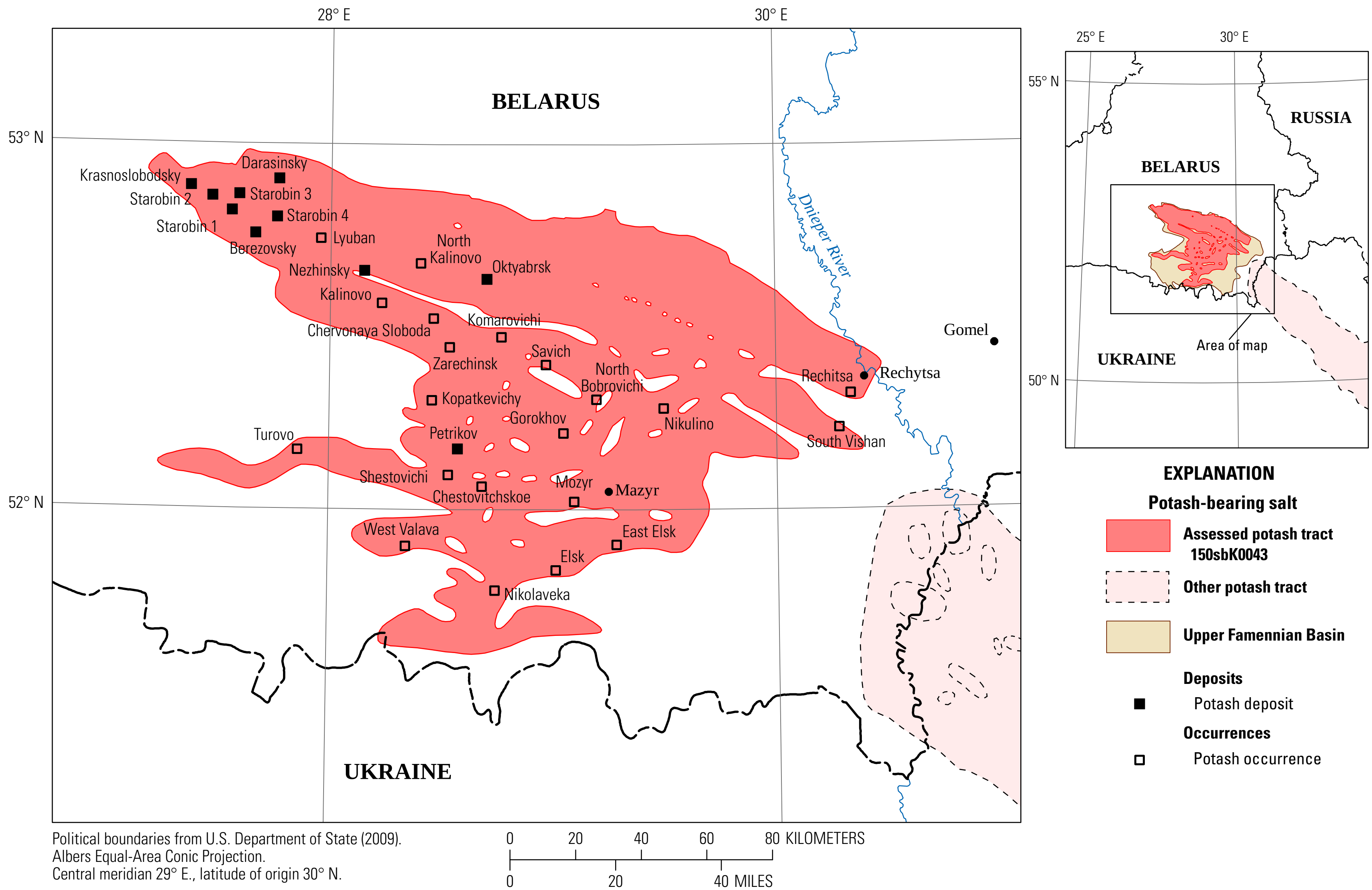


Figure 8–1. Map showing extent of tract 150sbK0043, Upper Devonian (Famennian) stratabound potash-bearing salt—Pripyat Basin, Belarus, and known potash deposits and occurrences.

Table 8–1. Known resources of potash within tract 150sbK0043, Upper Devonian (Famennian) stratabound potash-bearing salt—Pripyat Basin, Belarus.

[Most reported grades and tonnages reflect only 1 or 2 of the possible mineable potash horizons in an area (see table 3–5). Mt, million metric tons; n.d., no data]

Site name	Latitude	Longitude	Tonnage (Mt, in place)	Grade (percent K_2O)	Contained K_2O (Mt)	Resource notes	Reference
Starobin deposit and its extensions, Minsk region							
Berezovsky (Berezovskiy)	52.7578	27.676	n.d.	n.d.	240	n.d.	Truscott (2011); Foreign Policy and Security Research Center (2011)
			247.5	n.d.	n.d.	n.d.	Geonews (2011); Belaruskali (2017a)
Darasinsky	52.9	27.78	n.d.	n.d.	n.d.	n.d.	Truscott (2011); Foreign Policy and Security Research Center (2011)
			180	n.d.	n.d.	n.d.	Geonews (2011); Interfax (2014)
Nezhinsky (Nezhinskiy)	52.6529	28.1601	n.d.	n.d.	n.d.	n.d.	Truscott (2011); Foreign Policy and Security Research Center (2011)
			311.3	n.d.	n.d.	Approved reserves of potash industrial categories	Belarus News (2011)
			375	n.d.	n.d.	Industrial reserves	Geonews (2011)
Krasnoslobodsky (Krasnoslobodskogo)	52.8809	27.3803	345.00	14.9	51.4	Balance reserves; January 1, 2005	Levanevskogo (2006); Smycznik and others (2006); Foreign Policy and Security Research Center (2011); Truscott (2011)
			346.62	n.d.	n.d.	Reserves of potash ore	Kurkachi (2012)
Starobin	52.7833	27.7667	2,655	n.d.	n.d.	Reserves (A+B+C1); January 1, 2000	Smycznik and others (2006)
Subtotal, Starobin and extensions	n.d.	n.d.	3,804.12	n.d.	n.d.	n.d.	n.d.
Starobin area, Minsk region							
Starobin mine fields	n.d.	n.d.	4,600	n.d.	n.d.	Balance reserves; January 1, 1969	Korulin (1976)
JSC Belarusakali mine fields	n.d.	n.d.	~4,000	n.d.	n.d.	Balance reserves	Belaruskali (2017b)
Additional data on Starobin, Minsk region							
Starobin	52.7833	27.7667	4,420	15.2	670	Reserves (A+B+C1+C2)	Garetsky and others (1982)
	52.7833	27.7667	5,330	15	800	n.d.	Troitsky and others (1998)
Additional data on Starobin area, Minsk region							
Starobin mine fields, horizons II and III	52.7833	27.7667	3,956	15.5	612	Reserves (A+B+C1+C2)	Garetsky and others (1984)

Table 8-1. Known resources of potash within tract 150sbK0043, Upper Devonian (Famennian) stratabound potash-bearing salt—Pripyat Basin, Belarus.—Continued

Site name	Latitude	Longitude	Tonnage (Mt, in place)	Grade (percent K_2O)	Contained K_2O (Mt)	Resource notes	Reference
Additional data on Starobin area, Minsk region—Continued							
Starobin area outside of the mine fields, horizons II and III	52.7833	27.7667	3,245	15.9	517	Reserves (A+B+C1+C2)	Garetsky and others (1984)
Starobin area, total for horizons II and III	52.7833	27.7667	7,200	15.7	1,130	Reserves (A+B+C1+C2)	Garetsky and others (1984)
Starobin area (total)	52.7833	27.7667	7,900–8,500	n.d.	n.d.	n.d.	British Sulphur Corporation Limited (1984)
Deposit on mineralized trend east of Starobin, Gomel region							
Oktyabrsk (Oktyabr'sk)	52.6550	28.9976	1,500	23	345	n.d.	Garetsky and others (1984)
Smolovo	52.6236	28.4579	1,300	n.d.	n.d.	n.d.	Garetsky and others (1984)
Petrikov deposit and its extensions, Gomel region							
Petrikov	52.1690	28.4993	1,064	22	236	Indicated reserves (A+B+C1)	Ministry of Economy of the Republic of Belarus (2011)
Petrikov	52.1690	28.4993	825	22	179	Indicated reserves (C2)	Ministry of Economy of the Republic of Belarus (2011)
Petrikov (total)	52.1690	28.4993	1,989	21	415	Indicated reserves (A+B+C1+C2)	Ministry of Economy of the Republic of Belarus (2011)
Kopatkevichy (Kopatkevichskiy, Kopatkevichi, Kopatkevichey)	52.3168	28.6437	1,200	24.6	295	n.d.	Garetsky and others (1984)
Zhitkovichy (Zhitkovichi, Žytkavičy, Žytkavicki)	52.13966	28.0095	1,900	16.8	276	n.d.	Garetsky and others (1984)
Estimate for Pripyat Basin, Belarus, 2009							
Belarus (total)	n.d.	n.d.	5,397.3	17	916.1	Balance reserves (A+B+C1); January 1, 2009	Unukovich and Ansohko (2012)
	n.d.	n.d.	2,509.9	20	496	Balance reserves (C2); January 1, 2009	Unukovich and Ansohko (2012)
	n.d.	n.d.	7,907.2	18	1,412.1	Balance reserves (A+B+C1+C2); January 1, 2009	Unukovich and Ansohko (2012)
Estimate for Pripyat Basin, Belarus, 2012							
Belarus (total)	n.d.	n.d.	5,931.4	n.d.	n.d.	Balance reserves (A+B+C1); January 1, 2012	Rusy (2013)
	n.d.	n.d.	7,277.8	18	1318.1	Reserves, January 1, 2012	Rusy (2013)

Table 8–2. Known occurrences of potash within tract 150sbK0043, Upper Devonian (Famennian) stratabound potash-bearing salt—Pripyat Basin, Belarus.

[Mt, million metric tons; n.d., no data]

Occurrence name	Latitude	Longitude	Reference
Chervonaya Sloboda	52.5237	28.4651	Eroshina and Kislik (1980)
East Elsk	51.7901	29.2856	Eroshina and Kislik (1980)
Elsk	51.8013	29.0364	Eroshina and Kislik (1980)
Gorokhov	52.2101	29.0476	Eroshina and Kislik (1980)
Kalinovo	52.5657	28.2327	Eroshina and Kislik (1980)
Komarovichi	52.4733	28.7703	Eroshina and Kislik, 1980
Lyuban	52.7421	27.9639	Eroshina and Kislik (1980)
Mozyr	52.0225	29.0951	Eroshina and Kislik (1980)
Nikolaveka	51.7789	28.7423	Eroshina and Kislik (1980)
Nikulino	52.2773	29.4872	Eroshina and Kislik (1980)
North Bobrovichi	52.3025	29.196	Eroshina and Kislik (1980)
North Kalinovo	52.6749	28.4063	Eroshina and Kislik (1980)
Rechitsa	52.2745	30.2628	Eroshina and Kislik (1980)
Savich	52.3977	28.9692	Eroshina and Kislik (1980)
Shestovichi	52.0953	28.5323	Eroshina and Kislik (1980)
South Vishan	52.6021	30.2628	Eroshina and Kislik (1980)
Turovo	52.1625	27.8687	Eroshina and Kislik (1980)
West Valava	51.7929	28.3531	Eroshina and Kislik (1980)
Zarechinsk	52.4453	28.5379	Eroshina and Kislik (1980)

This corresponds to 1.4 Bt of K_2O-equivalent material. Most reserves are associated with mine fields near Starobin (Starobin 1 through 4, Berezovsky, Darasinsky, Krasnoslobodsky, and Nezhinsky). In 2017, balance reserves were approximately 4 Bt of potash-bearing salt for this area (Belaruskali, 2017b). The next largest reserve is associated with the Petrikov deposit; in 2011, reserves in categories A+B+C1+C2 were 2 Bt of mineralized material with a grade of 21 percent K_2O (Ministry of Economy of the Republic of Belarus, 2011). Substantial reserves have also been estimated at Kopatkevichy, Oktyabr’sk, and Smolovo.

During the 1990s, potash production from the Starobin mines accounted for nearly half the total production in the Commonwealth of Independent States (CIS). Dakuko (2003) reported that, as of August 29, 2003, 1 Bt of potash ore had been hoisted from the Starobin mines during the time of operation. Truscott (2011) and Foreign Policy and Security Research Center (2011) reported that overall capacities will increase with the addition of two new mines, probably Krasnoslobodsky and Berezovsky. Three additional mines are expected to be developed during this decade.

Known Potash Occurrences

A number of potash occurrences are noted in the literature (table 8–2), but little detailed information is available. These occurrences are believed to be areas, so the locational data should be considered approximate. Only a few occurrences have reported grades and tonnages.

Exploration and Development Overview

Potash development in Belarus has changed significantly since the Soviet Union dissolved in the 1990s. Potash production in the former Soviet Union was initially developed to meet the internal market, and exports played only a minor role. In 1988, only 1.5 Mt of K_2O were exported. When the Soviet Union was dissolved, capacity utilization plunged to less than 40 percent. The closest external markets for potash were in western Europe, but a united German potash industry controlled that market. The potash industry faced additional problems that included undeveloped logistical infrastructure and insufficient specialized rail cars as well as a narrow product variety, an insufficient quality of goods, and a changing regulatory regime (Lomakin, 2003; Cocker and Orris, 2013).

Infrastructure development has been widespread. In 1988, the only port with a specialized potash terminal was at Ventspils, Latvia, on the Baltic Sea. By 2003, capacity increased at Ventspils, and terminals and storage facilities were constructed at the Black Sea port of Nikolaev, Ukraine; the Baltic Sea ports of St. Petersburg, Russia, and Klaipeda, Lithuania; and the Pacific Ocean port of Vostochny, Russia (Lomakin, 2003; Cocker and Orris, 2013). Belaruskali has acquired new, advanced hopper cars for its products.

Before 1991, most potash production was for consumption in the Soviet Union, and quantity rather than quality was the principal incentive for potash production. Consistent product quality was necessary to meet demands of countries with different climates than the domestic market. Foreign customers' preferences for product color, granularity, and other characteristics required an increased variety of product types (Lomakin, 2003; Cocker and Orris, 2013).

International sales of potash by Belaruskali were also hindered by European Union regulations which limited the amount of externally supplied materials by imposing anti-dumping duties on potash (Lomakin, 2003; Cocker and Orris, 2013). Beginning in July, 2011, the European Union allowed duty-free export volumes of 700,000 t of potash (KCl) to Europe with an anti-dumping duty of 27.5 percent if that quota is exceeded (Belarusian Potash Company, 2011a).

Since that time, potash production capacity and exports have grown considerably, and Belaruskali now exports potash to India, China, Latin America, eastern Europe, and North America (Belaruskali, 2011). Global market share of Belaruskali is 16 percent (Foreign Policy and Security Research Center, 2011). In 2012, Belaruskali will have a potash fertilizer output capacity of 10.3 Mt (Foreign Policy and Security Research Center, 2011). Projected new mines are expected to increase potash output through 2020.

Countries that must import large quantities of potash products, such as China and India, have recently been trying to acquire interests in Belaruskali. However, Belaruskali is looking for investment capital to further develop resources through new mines. Up until 2012, Belaruskali was part of the joint stock company Belarusian Potash Company, which was jointly owned by Belaruskali (45 percent), Uralkali (50 percent), and the State Association of Belarusian Railways (5 percent) (Belarusian Potash Company, 2011b). During 2013, Uralkali decided to break with Belaruskali and sell larger amounts of potash to China. This move had an adverse effect on potash markets, particularly in Europe and Asia, by putting downward pressure on the price of potash which plunged to about $300/metric ton.

No detailed information regarding exploration efforts is available. It can be assumed that much of the basin has been explored at least on a reconnaissance scale, and a number of areas have been investigated in more detail since the initial discovery of economic potash deposits.

Mining of stratabound, potash-bearing salt is relatively straightforward in the Pripyat Basin because of the characteristics of stratabound salt deposits (appendix A). Potash is recovered from conventional underground hard-rock mines. Underground mining in the Starobin mines at Belarus includes the potash horizons II and III at depths of 400–700 m and 500–700 m, respectively (Tomchin and Mackie, 1999). Early mining of horizon II attempted to increase the extraction ratio which was as low as 32 percent and overall losses in the range of 65–70 percent. Early mining operations attempted to increase the efficiency of recovery through the use of as many as 30 variations of room-and-pillar systems (Dakuko, 2003). In 1967, the dimensions of rooms in horizons II and III were 200 m by 8 m by 2.5 m with pillars 6 m wide in the upper horizon and 200 m by 8 m by 4.5 m with pillars 10 m wide in the lower horizon (British Sulphur Corporation Limited, 1975). Since 1969, geological and engineering studies have allowed greater flexibility in extraction and greater protection from flooding in the Belarus mines. Extraction on horizon II is now accomplished using four shearer machines working in tandem. On the third level, new mining machines were developed, and the present ore extraction is by the pillar and longwall method and allowing roof collapse. Longwalls are 150–350 m, and this allows extraction of 70 percent of the ore (Dakuko, 2003). Solution mining does not appear to be in the foreseeable future for the Pripyat Basin potash.

Qualitative Assessment

Stratabound potash-bearing salt deposits are an important world potash resource because they commonly comprise continuous, structurally and mineralogically simple strata in sedimentary basins that form large-tonnage ore bodies. As a result, stratabound potash-bearing salt deposits are generally less expensive to develop and more economically viable than halokinetic potash-bearing salt deposits. Significant resources have been identified for the stratabound Fammenian potash-bearing salt that occurs in the Pripyat Basin in tract 150sbK0043 and substantial amounts of undiscovered resource are likely to be present. Balance reserves of the Starobin deposit, as of January 1, 1969, were 4.6 billion metric tons of potash-bearing salts (Korulin, 1976). As of 2012, reserves of potash-bearing salts in Belarus were 7,277.8 Bt (1,381.1 Bt of contained K_2O). As of January 1, 2012, balance reserves (in mineral inventory categories A+B+C1) were 5,931,384,000 metric tons (Rusy, 2013). Published reports suggest that the mined layers are open at depth.

The mineral inventory numbers summarized in table 8–1 and in the previous paragraph are based on detailed exploration and mine operations data (Arden and Tverdov, 2014). Categories A, B, and C1 are explored reserves with different levels of confidence and category C2 is for reserves that have not been evaluated to determine if they can be extracted economically. Balance reserves meet predetermined criteria for economically justifiable extraction and have been approved by a government committee to be included in the balance books of mineral reserves for planning purposes. Industrial reserves are balance reserves that have been adjusted for operational losses.

In addition to balance and industrial reserves, some reserve numbers reported in literature must represent rough estimates based on preliminary exploration. For example, reserves reported for the Starobin and Petrikov areas in table 8–1 are about 6 Bt of potash-bearing salt. In contrast, Export.By (2011) reported reserves of 42 Bt of potash-bearing salt (or approximately 7 Bt K_2O) for the same areas. In other examples for the entire Pripyat Basin, projected reserves were estimated at 45 Bt of potash-bearing salt (Korulin, 1976). About 30 years later, total inferred resources in the Pripyat Basin were estimated to be about 80 Bt of potash-bearing salt (Peschenko and Mychko, 2008). If we assume an overall grade of 19 percent K_2O for the 80 Bt estimate, then inferred K_2O resources would be about 15 Bt. Garetsky and others (2004) say that total ore reserves in the Pripyat Basin are about 200 million metric tons of potash-bearing salt (30 billion metric tons K_2O). There is no information that supports how these large mineral inventory estimates were generated.

Larger estimates may have included greater depths and more potash-bearing salt horizons, and (or) larger areas. Historically, reserves were estimated to depths of about 1,200 m (Garetsky and others, 1982). The depth to potash-bearing salt horizons increases from the west where mines have been developed. In the mine areas, the potash-bearing salt horizons are approximately 500–1,200 m below the surface (fig. 3–4). As depth increases, so does rock temperature (Zui, 2015). Increasing geothermal temperatures, in part associated with thinned crust in the Donbass-Pripyat Rift, and deformation of salt with increasing depths and pressures limits where potash can be developed by using conventional underground mining methods. However, solution mining, which is not currently applied in Belarus, is facilitated by higher geothermal temperatures such as in deeper parts of the Elk Point Basin in Saskatchewan and in the Michigan Basin in Michigan, U.S.A. (Cocker and others, 2016). Solution mining in the Michigan Basin has recovered potash from depths of approximately 2,500 m (Cocker and others, 2016). Estimated depths to Fammenian salts in tract 150sbK0043 shown in figure 8–1 (Garetsky and others, 2004) would allow for potash recovery by way of current solution mining techniques. Extension of the permissive tract 150sbK0043 to depths of 3,000 m would increase the undiscovered K_2O resource estimate.

In the Starobin mine area, mineral inventory is reported for only the 4 potash-bearing units that are mined (figs. 3–2, 3–3, 3–4). In the Petrikov deposit, mining focuses only on potash salt horizon IV-п that occurs at depths of 516 to 1,386 m (Barbikov and others, 2016). Garetsky and others (2004) mention that 62 potash-bearing salt horizons have been discovered in the Pripyat Basin that are 0.5 to 40 m thick and occur at depths of 350 to 4,026 m. Increasing the number of potentially mineable potash horizons would increase the undiscovered K_2O resource estimate.

If potash-bearing salt units are continuous across parts of the Pripyat Basin, then the effect on undiscovered resource potential should be enormous. Published maps of exploration and development results illustrate where undiscovered resources are likely located (fig. 8–2). The best potential areas for undiscovered resources are in extensions to areas where mineral inventory has been reported, such as the Starobin, Petrikov, Kopatkevichy, and Oktyabr’sk areas (Garetsky, 1984, and Khorenevskiy, 1990a). Recent mineral inventory information summarized in table 8–1 and development history are consistent with production of resource by mining in the Starobin area that is offset by addition of new mineral inventory around the original mining area—Berezovsky, Darasinsky, Krasnoslobodsky, and Nezhinsky (Cocker and Orris, 2013; Cocker and others, 2016). The Starobin mining area and its extensions occur along the western third of a 2,600 km^2 elliptical area of mineralized rock (fig. 8–2) that coincides with a synclinal structure depicted in part in figure 3–4*B*. Potash-bearing salt horizons continue eastsoutheastward from the Starobin area but will be deeper and probably hotter than in the Starobin mine area (Zui, 2015). Approximately 90 km southeast of the Starobin mine area, potash-bearing salt deposits of Petrikov and Kopatkevichy occur in the center of another area of mineralized rock that covers roughly 1,500 km^2. Undiscovered resources are also likely in this area, but with the same caveats—the potash horizons will be deeper and possibly hotter.

Several factors limit the potential for undiscovered potash in the Pripyat Basin. Unlike stratabound deposits in the Prairie Evaporite in Elk Point Basin, Saskatchewan (Holter, 1969; Fuzesy, 1982; Yang and others, 2009), potash-bearing salt units in Pripyat Basin are disrupted by salt tectonics, particularly in the eastern part of the basin (Garetsky and others, 1982, 1984, 2004; Ulmishek and others, 1994). The irregular shape of the tract and salt tectonics reflect west-northwesterly trending basement faults developed along or near these structures. This affects mineralization continuity and may have promoted dissolution of potash-bearing salt units, particularly near the salt structures.

In chapter 3 (this report), depletion zones (areas of either total or partial potash removal by secondary brines) were estimated to be locally as much as 5–8 percent of the area in horizon III (Vysotskiy and others, 1990) and 15–20 percent of the area in horizon II (Kislik, 1970; Korenevskiy, 1989) in the Starobin mines. The Famennian potash horizons are at the shallowest part of the Pripyat Basin in the Starobin mine area and could be assumed to have been more exposed to shallow, near-surface brines than potash in the remaining, deeper parts of the basin. If we assume that depletion is somewhere between these estimates, perhaps about 10–15 percent, then approximately 1 to 2 Bt of potash (as K_2O) could be subtracted from the 15 Bt resource based on tonnages reported by Peschenko and Mychko (2008).

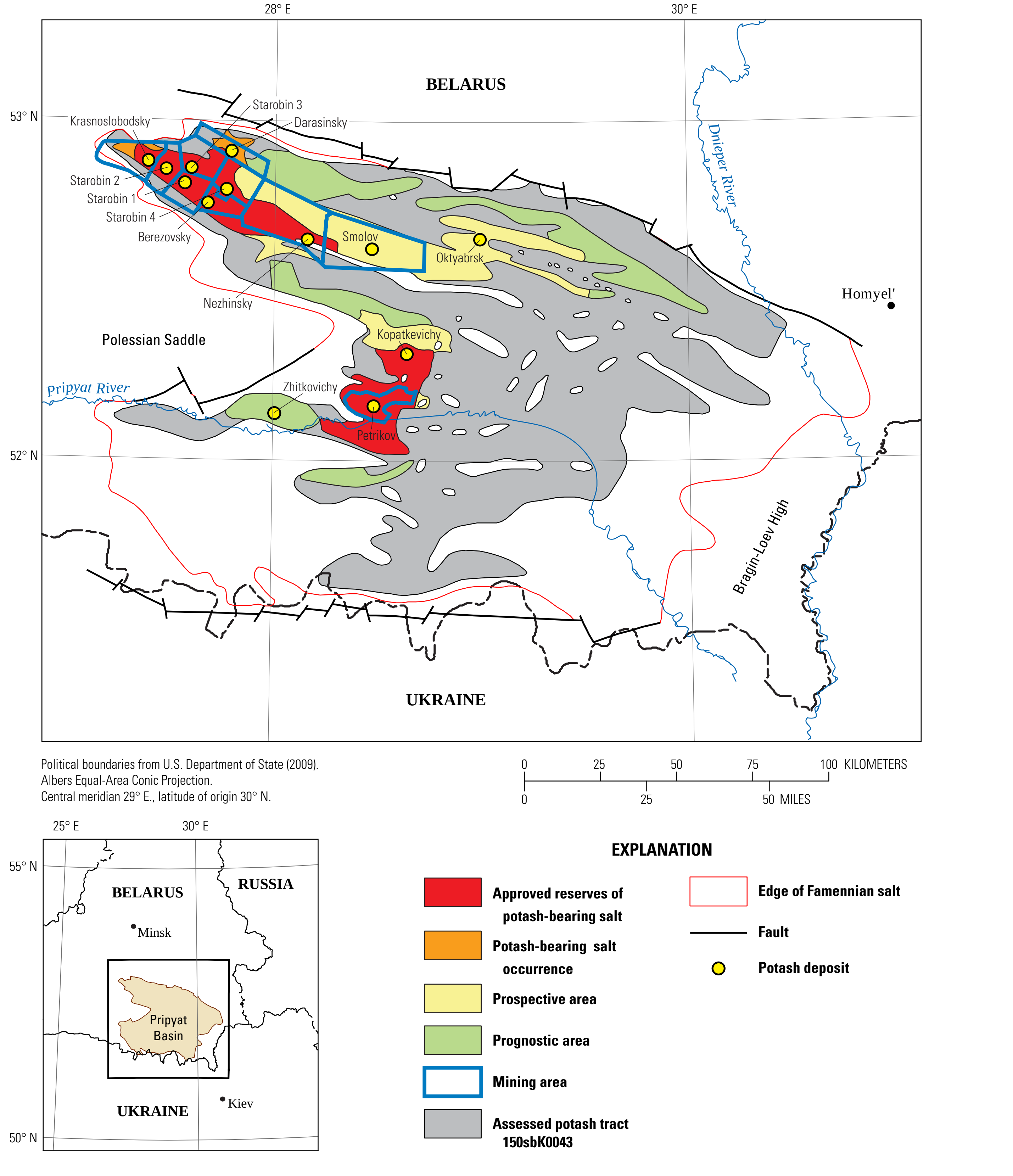


Figure 8-2. Map showing mining, mineral reserve, and resource areas superimposed on permissive tract 150sbK0043, Upper Devonian (Famennian) stratabound potash-bearing salt—Pripyat Basin, Belarus. Areas with approved reserves of potash-bearing salts have undergone detailed exploration and (or) mine development. Prospective areas have been characterized by using a wide-spaced grid of drill holes. Prognostic areas have been explored by using geophysical surveys and isolated drill holes. Mineral inventory information for the potash deposits is summarized in table 8–1. Modified from Korenevskiy and Shamakhov (1990). Mining areas are modified from Barbikov and others (2016), Belaruskali (2017a), and Petrova and others (2012).

Chapter 9. Quantitative Assessment of Tract 150haK0042b, Upper Devonian Potash-Bearing Evaporites in Halokinetic Structures—Dnieper-Donets Basin, Ukraine and Belarus

By Mark D. Cocker,[1] Pamela Dunlap,[1] Bruce R. Lipin,[2] Steve Ludington,[3] Greta J. Orris,[1] Robert J. Ryan,[4] Mirosław Słowakiewicz,[5] Gregory T. Spanski,[6] Jeff Wynn,[7] and Chao Yang[8]

Introduction

Tract 150hsK0042b defines a permissive area for undiscovered potash resources associated with halokinetic salt structures in the Dnieper-Donets Basin, Ukraine and Belarus (fig. 9–1). The time period for the assessment was the first half of 2009. A quantitative assessment meeting was held in Tucson, Arizona, during the first week of May 2009. Participants included the author and coauthors for this assessment (appendix H).

Geologic Features Assessed

The geologic features assessed are potassium salts within halokinetic salt structures in the Dnieper-Donets Basin expected above a depth of 3 km.

Methodology and Models

The assessment of undiscovered resources in tract 150haK0042b is based on the descriptive model of halokinetic potash-bearing salt (appendix B). The assessment applied the USGS three-part assessment methodology (Singer, 1993; Singer and Menzie, 2005, 2010).

Delineation of the Permissive Tract

The permissive tract (fig. 9–1) lies within the Dnieper-Donets Basin which occupies the central part of the Donbass-Pripyat Rift (fig. 2–2). The Donbass-Pripyat Rift continues to the northwest and southeast of the Dnieper-Donets Basin. The Dnieper-Donets Basin is confined at the northwestern end by Devonian volcanic rocks of the Bragin-Loev High and at the southeastern end by non-evaporite-bearing rocks of the Donbass Foldbelt (fig. 2–2). The northeastern boundary fault of the Donbass-Pripyat rift is the Baranovichsko-Astrakhan Fault, and the southwestern boundary fault is the Pripyatsko-Manych Fault (fig. 2–3).

The permissive tract is defined by the areal extent of salt diapirs within the Dnieper-Donets Basin. Salt diapirs were digitized from georeferenced maps of salt diapirs in the Dnieper-Donets Basin (Klimenko, 1957; Kityk, 1970). All diapirs shown in this tract lie within the boundaries of the area underlain by salt as depicted on the Mineragenetic Map of Russian Federation and Adjacent States (Rundkvist, 2001). This permissive tract is further defined by the Upper Devonian potash in the adjacent Pripyat Basin and the presence of salt of the same age in the Dnieper-Donets Basin (Kityk, 1970). The generalized stratigraphy of the Dnieper-Donets and Pripyat Basins (fig. 2–4) shows the relation of the Upper Devonian salt to the structural development of these basins and the relative thickness of bedded salt in each basin. Although information regarding depths to the tops of the diapirs is limited, Kityk (1970) and Ulmishek and others (1994) show a few of these diapirs in cross sections (fig. 4–2) and all are above a depth of 3 km.

Summary of Tract Geology

Basin tectonics, structures, stratigraphy, salt and potash stratigraphy, and description of the halokinetic structures are presented in chapters 2 and 3. Very little has been published on potash and salt stratigraphy, mineralogy, and grade within the halokinetic structures of the Dnieper-Donets Basin. Information based on better-known potash and salt in the Pripyat Basin was used in this assessment to better understand the geology and potash potential of this tract.

[1]U.S. Geological Survey, Tucson, Arizona, United States.

[2]U.S. Geological Survey, Reston, Virginia, United States.

[3]U.S. Geological Survey, Menlo Park, California, United States.

[4]Nova Scotia Department of Natural Resources, Halifax, Nova Scotia, Canada.

[5]Polish Geological Institute, Warsaw, Poland.

[6]U.S. Geological Survey, Denver, Colorado, United States.

[7]U.S. Geological Survey, Vancouver, Washington, United States.

[8]Saskatchewan Geological Survey, Regina, Saskatachewan, Canada.

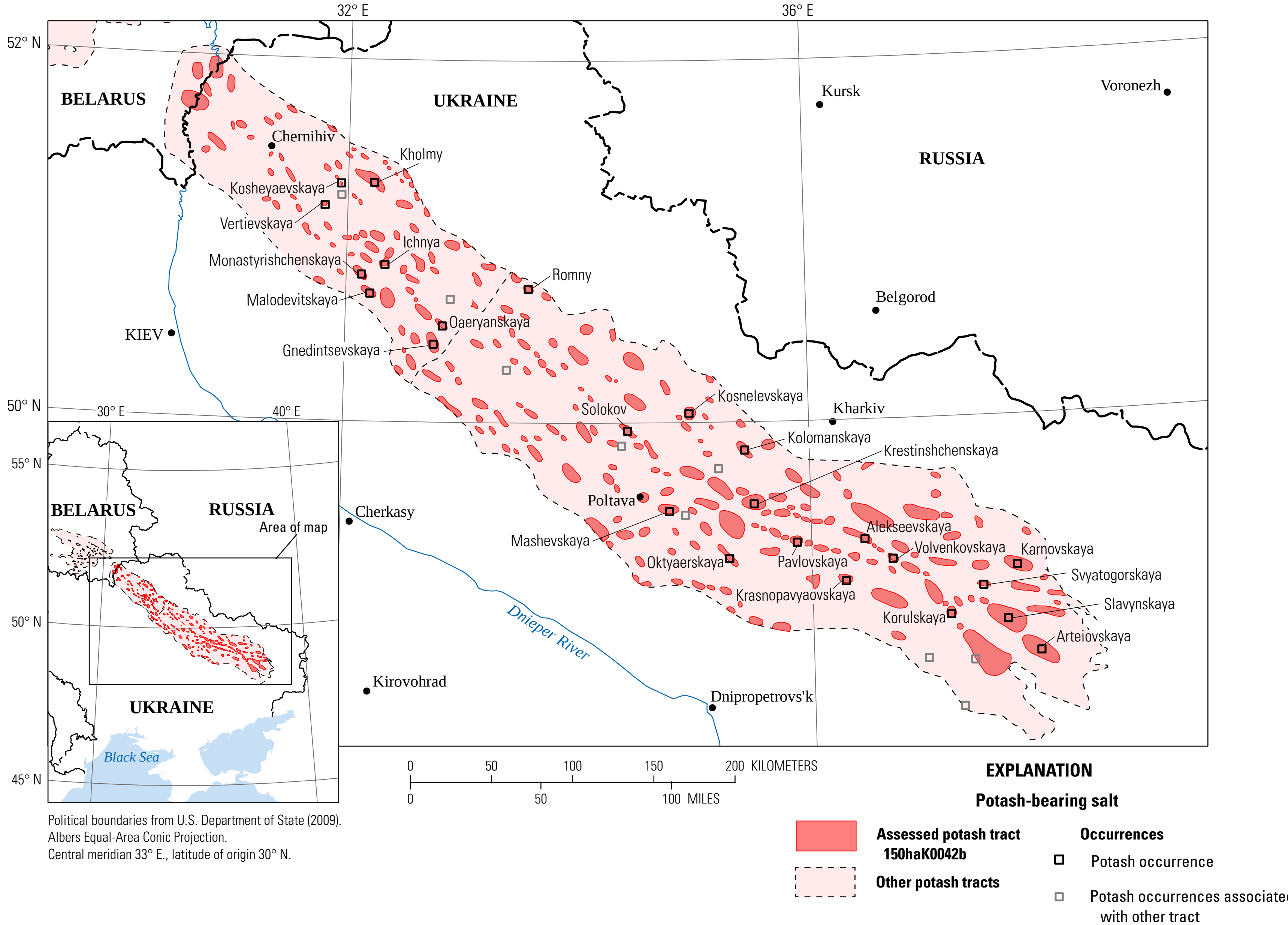


Figure 9–1. Map showing extent of tract 150haK0042b, Upper Devonian potash-bearing evaporites in halokinetic structures—Dnieper-Donets Basin, Ukraine and Belarus, and known potash deposits and occurrences.

Known Deposits and Occurrences of Potash

No Upper Devonian potash deposits within the Dnieper-Donets Basin have been developed or explored to the extent that grade and tonnage information is available. Because there are no published descriptions of potash resources that include grade and tonnage data, all potash occurrences are treated as undiscovered resources.

Twenty-four occurrences of potash are noted in drill holes that intersected salt structures in this tract (table 9–1). In the Romenskaya (Romny) diapir (figs. 4–1, 4–2), drilling intersected both Frasnian and Famennian salt units (Hryniv and others, 2007) plus two strongly deformed potash-bearing horizons of unreported ages, both containing sylvite and halite. No maps or cross sections show the internal structures or potash layers in these structures. Pre-deformation horizon thicknesses were 4 m for the upper horizon and 18 m for the lower horizon. (Hryniv and others, 2007). The grades of potash intercepts range from 15 to 21 percent K_2O (Korenevskiy and others, 1968). In addition to the potash occurrences and drill holes noted in table 9–1, Khrushchov and others (1974) suggested that the Dmitirnevskaya, Sinevskiy, Karaykozovskaya, Kolontaevskaya, and Valkovskaya diapirs (fig. 4–1) potentially contain potash.

Table 9–1. Known occurrences and drill holes with potash within Upper Devonian (Famennian and Frasnian) salt diapirs in tract 150haK0042b, Upper Devonian potash-bearing evaporites in halokinetic structures—Dnieper-Donets Basin, Ukraine and Belarus.

[n.d., no data]

Occurrence name	Latitude	Longitude	Potash grade (percent K_2O)	Reference
Alekseevskaya	36.4491	49.3438	n.d.	Korenevskiy and others (1968)
Arteiovskaya	37.8888	48.6895	n.d.	Korenevskiy and others (1968)
Gnedintsevskaya	32.764	50.4408	n.d.	Korenevskiy and others (1968)
Ichnya (Ichnyanskaya)	32.3345	50.8753	n.d.	Korenevskiy and others (1968)
Karnovskaya	37.7368	49.1665	n.d.	Korenevskiy and others (1968)
Kholmy (Kholmskaya)	51.3193	32.2306	n.d.	Kityk (1970); Petrychenko and Peryt (2004)
Kolomanskaya	35.442	49.847	n.d.	Korenevskiy and others (1968)
Korulskaya	37.1577	48.9157	n.d.	Korenevskiy and others (1968)
Kosheyaevskaya	31.9348	51.3096	n.d.	Korenevskiy and others (1968)
Kosnelevskaya	34.9813	50.0521	n.d.	Korenevskiy and others (1968)
Krasnopavyaovskaya	36.277	49.1216	n.d.	Korenevskiy and others (1968)
Krestinshchenskaya	35.5203	49.5545	n.d.	Korenevskiy and others (1968)
Malodevitskaya	32.1986	50.7174	n.d.	Korenevskiy and others (1968)
Mashevskaya	34.7899	49.5241	n.d.	Korenevskiy and others (1968)
Monastyrishchenskaya	32.1205	50.8195	n.d.	Korenevskiy and others (1968)
Oktyaerskaya	35.291	49.2614	n.d.	Korenevskiy and others (1968)
Oaeryanskaya	32.8365	50.5431	n.d.	Korenevskiy and others (1968)
Pavlovskaya	35.8713	49.3398	n.d.	Korenevskiy and others (1968)
Romny (Romenskaya)	50.7402	33.5888	15–21	Kityk (1970); Korenevskiy and others (1968)
Slavynskaya	37.63	48.8722	n.d.	Korenevskiy and others (1968)
Solokov (Solokovskaya)	49.8795	34.393	n.d.	Kityk (1970); Petrychenko and Peryt (2004)
Svyatogorskaya	37.4419	49.0632	n.d.	Korenevskiy and others (1968)
Vertievskaya	31.7942	51.1931	n.d.	Korenevskiy and others (1968)
Volvenkovskaya	36.6827	49.2301	n.d.	Korenevskiy and others (1968)

Exploration and Development Overview

Recent exploration history is unknown. Ukraine obtains most of its potash from either Belarus or Russia, so there has been little past incentive to develop a potash mine industry.

Data Availability

Most reports and maps describing this basin and its salt and potash occurrences are Russian studies that focused on petroleum potential of the salt structures. Information on the basin was influenced by interest in the hydrocarbon potential of the basin and its tectonic evolution. Because much of the older (Upper Devonian) salt lies at depth, and younger sedimentary rocks and sediments cover this older salt, available geologic maps were not useful for the assessment.

The main data sources are listed in table 6–2, and additional data sources are listed in the References Cited.

Grade and Tonnage Model Selection

Grade and tonnage models are used in conjunction with descriptive models to define what is meant by the term "deposit" in terms of size and grade. These models are used to determine the number of known deposits and to estimate the number of undiscovered deposits during the assessment process. A descriptive model for halokinetic-potash-bearing salt was based on these types of deposits in a wide variety of salt basins throughout the world (appendix B). The halokinetic salt model was chosen for this assessment, because a number of these structures contained potash-bearing salt of potentially mineable thickness and grade, and most were of sufficient size to contain a mineable tonnage of potash. In addition, Devonian salt structures were mainly above the maximum assessment depth of 3 km. Individual diapiric structures in the Dnieper-Donets Basin could be defined with reasonable accuracy, and the halokinetic tract was defined on the basis of the location or presence of these salt structures and the known occurrences of potash.

The three-part form of assessment described by Singer (1993) and Singer and Menzie (2005, 2010) was used to estimate undiscovered potash resources in halokinetic structures located within the Dnieper-Donets Basin. In this method, an expert panel compared known occurrences and permissive geology with the deposit model for halokinetic potash-bearing salt, estimated the number of undiscovered deposits in the tract, and then used a Monte Carlo simulation to combine a grade-tonnage model with the estimated number of deposits to arrive at a tonnage distribution for undiscovered potash resources; in the case of potash this is the remaining in-place K_2O value.

The assessment team (appendix H) consisted of three international experts and five USGS experts, plus a USGS facilitator who was experienced in mineral resource assessments and had a broad understanding of evaporite potash deposits. During the workshop, the team used a preliminary grade-tonnage model that was similar but not quite identical to the final model. The mean and median were similar, but the number of very large and very small deposits was slightly less. The final model (appendix C, summarized in table 9–2) was used to calculate the results presented here.

Each halokinetic structure in this assessment can be viewed as being permissive for potash-bearing salt deposits. This does not mean that potash is necessarily present in every or any individual structure. The distribution of both Frasnian and Famennian potash as it was deposited in the Dnieper-Donets Basin in the Late Devonian is the primary factor controlling which halokinetic structures could be potash-bearing, and in the case of this basin, the original distribution of potash has not been defined.

Table 9–2. Summary statistics for grade and tonnage model for halokinetic potash-bearing salt deposits.

[Mt, million metric tons]

	Distribution	Number of deposits	Mean	Quantiles		
				90	50 (median)	10
Tonnage (Mt)	Lognormal	25	343.4	39.4	152.9	1,153
Grade (percent K_2O)	Normal	25	16.5	9.2	15.8	24.7

Estimation Process and Rationale for the Number of Undiscovered Deposits

The assessment team used the potash-bearing halokinetic salt structure model (appendix B) and the grade-tonnage model (Orris, 1992) for halokinetic salt structures when making their estimates. In addition, the assessment team considered the following factors when making their estimates:

1. The Dnieper-Donets Basin contains three major salt horizons: one Cisuralian horizon and two Upper Devonian horizons.
2. Ages of salt and sylvite in a few diapirs are shown as undifferentiated Devonian, which could include Famennian and (or) Frasnian. Ages of salt in most diapirs in this tract are not found in literature.
3. In the adjacent Pripyat Basin, both Famennian and Frasnian salt units contain multiple potash-bearing strata. The upper Famennian salt unit contains the presently economic potash horizons, because depth to them is considerably less than depth to salt in the Frasnian unit.
4. Famennian salt within the Pripyat Basin contains large potash reserves.
5. Marine water exchange between these basins was restricted by volcanic rocks of the Bragin-Loev High, which may have influenced potash deposition in the Dnieper-Donets Basin.
6. At least 248 diapiric salt structures are located within the Dnieper-Donets Basin.
7. Twenty-four potash occurrences are noted in literature on this tract but have little or no detailed geologic information.
8. At least two potash horizons, 4 and 18 m thick and containing reported sylvite, were drilled in the Romenskaya (also known as Romny) diapir (table 9–1).
9. Diapir sections depicted in the literature were all above 3 km depth.
10. No Devonian diapir-hosted salt is currently mined for potash within this basin.
11. Exploration for potash within salt diapirs in the Dnieper-Donets Basin appears to have been limited because of established potash production from (a) Starobin mines in the Pripyat Basin, Belarus; (b) the Stebnyk, Kalush, and other deposits in the Carpathian Basin, western Ukraine; and (c) the Solikamsk and Bereznicki mines in the Solikamsk Basin, Russia, which can provide relatively cheap potash to Ukraine. A similar explanation has been espoused for lack of potash development in Poland (Czapowski and Bukowski, 2009).
12. Exploration of salt diapirs has focused on oil and gas rather than potash or salt.
13. Details of drill results on potash occurrences are unpublished.
14. Much of the literature is in Russian, and some details or interpretations may have been obscured or lost as a result of translations.

A summary of how these factors were considered by the assessment team is shown in table 9–3.

After reviewing estimated numbers of undiscovered deposits for each percentile category, the assessment team observed that estimates for the 90th percentile range from 2 to 5 with half of estimates being 2 deposits. Following this analysis, the consensus estimate was 3 deposits. Although estimates for the 50th percentile ranged from 4 to 8 deposits, the group consensus raised the estimate to 8 deposits because of the large number (n=248) of salt structures assessed. Estimates of the number of deposits in the 10th percentile ranged from 10 to 70 deposits with most estimates in the range of 18 to 23 deposits. Group consensus raised the estimate to 23 deposits, because of the large number (n=248) of salt structures assessed (table 9–4).

Table 9–3. Factors considered by the assessment team and the degree to which they may have influenced assessments.

[Factors listed by numbers in this table are given in the text.]

Factor	Positive	Negative	Speculative
1	×		
2	×		
3	×		
4	×		
5		×	
6	×		
7		×	
8	×		
9	×		
10		×	
11			×
12			×
13		×	
14		×	

Table 9–4. Probabilistic assessment for tract 150haK0042b—Upper Devonian potash-bearing evaporites in halokinetic structures, Dnieper-Donets Basin, Ukraine and Belarus.

[N_{XX}, Estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; tract area (km^2), area of permissive tract in square kilometers; deposit density, the total number of deposits per km^2. N_{und}, s, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Consensus undiscovered deposit estimates					Summary statistics					Tract area (km^2)	Deposit density (N_{total}/km^2)
N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}		
3	8	23	23	23	11	7.4	68	0	11	7,840	0.0014

	Estimated number of undiscovered deposits		
	N_{90}	N_{50}	N_{10}
Estimator 1	2	5	20
Estimator 2	5	5	10
Estimator 3	2	5	20
Estimator 4	2	4	15
Estimator 5	4	5	15
Estimator 6	3	8	70
Estimator 7	2	6	20
Estimator 8	5	8	18
Consensus	3	8	23

Quantitative Simulation Results and Discussion

Undiscovered resources for the tract were estimated by combining consensus estimates for numbers of undiscovered halokinetic potash-bearing salt deposits with the halokinetic potash-bearing salt grade and tonnage model using the economic minerals resource simulator (EMINERS) program (Bawiec and Spanski, 2012). Selected output parameters are reported in table 9–5. The cumulative frequency plot of Monte Carlo simulation results (fig. 9–2) shows estimated resource volumes associated with cumulative probabilities of occurrence, as well as the mean, for potash and for total mineralized rock.

At the time of the assessment, certain assumptions were made that could affect assessment results. We did not know the extent of the stratabound potash-mineralized areas versus the nonmineralized areas from which the halokinetic salt was derived. Therefore, we assumed that the number of diapirs reflected the number of opportunities for a potash deposit to be present in those structures. However, potash occurrences within diapirs represent potash-bearing strata brought to higher structural levels from the underlying salt source layer. The probability of potash in diapirs should therefore depend on the original distribution of potash-bearing strata within a basin. As shown in figure 3–5, Famennian potash is not uniformly distributed in the Pripyat Basin and is not likely to be uniformly distributed in the Dnieper-Donets Basin. A few simple examples may illustrate how potash distribution would affect the probability of diapirs to contain a potash deposit. If potash deposition extended across a basin, then the probability would approach 100 percent. If potash deposition were concentrated in one half of a basin, then the probability that diapirs would contain a deposit or occurrence would be 50 percent for the basin as a whole. Also, the probability of other diapirs containing a deposit in the vicinity of a known occurrence or deposit should be higher than for diapirs farther from those with known potash-bearing strata. In the case of the Pripyat Basin, salt diapirs within the Famennian stratabound potash might be expected to have a higher probability of containing a potash deposit or occurrence. In addition, the salt which forms the major part of a diapir may be sourced from an underlying salt unit which contains no potash. In a basin such as the Dnieper-Donets Basin with very little known potash in the salt structures, the estimates for the number of deposits could not be refined by available data.

Other, secondary factors such as subrosion and salt horses or replacement zones may also affect presence or mineralogy of potash in the source layer from which a diapir arises and may affect the presence of potash or the grade of potash in a salt structure (appendixes A and B). Replacement of lower grade minerals such as carnallite with sylvite either in the source layer or later in the salt structure would significantly affect grade and tonnage calculations in the assessment. Because halokinetic, potash-bearing salt deposits may have a mixture of potash minerals, some potential variation in a deposit is captured in the grade-tonnage model during the deposit simulation process.

Table 9–5. Results of Monte Carlo simulations of undiscovered resources for tract 150haK0042b, Upper Devonian potash-bearing evaporites in halokinetic structures—Dnieper-Donets Basin, Ukraine and Belarus.

[Mt, million metric tons]

Material	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Potash (Mt)	40	120	700	1,800	2,100	840	0.42	0.03
Rock (Mt)	220	640	3,600	9,100	11,000	4,300	0.43	0.03

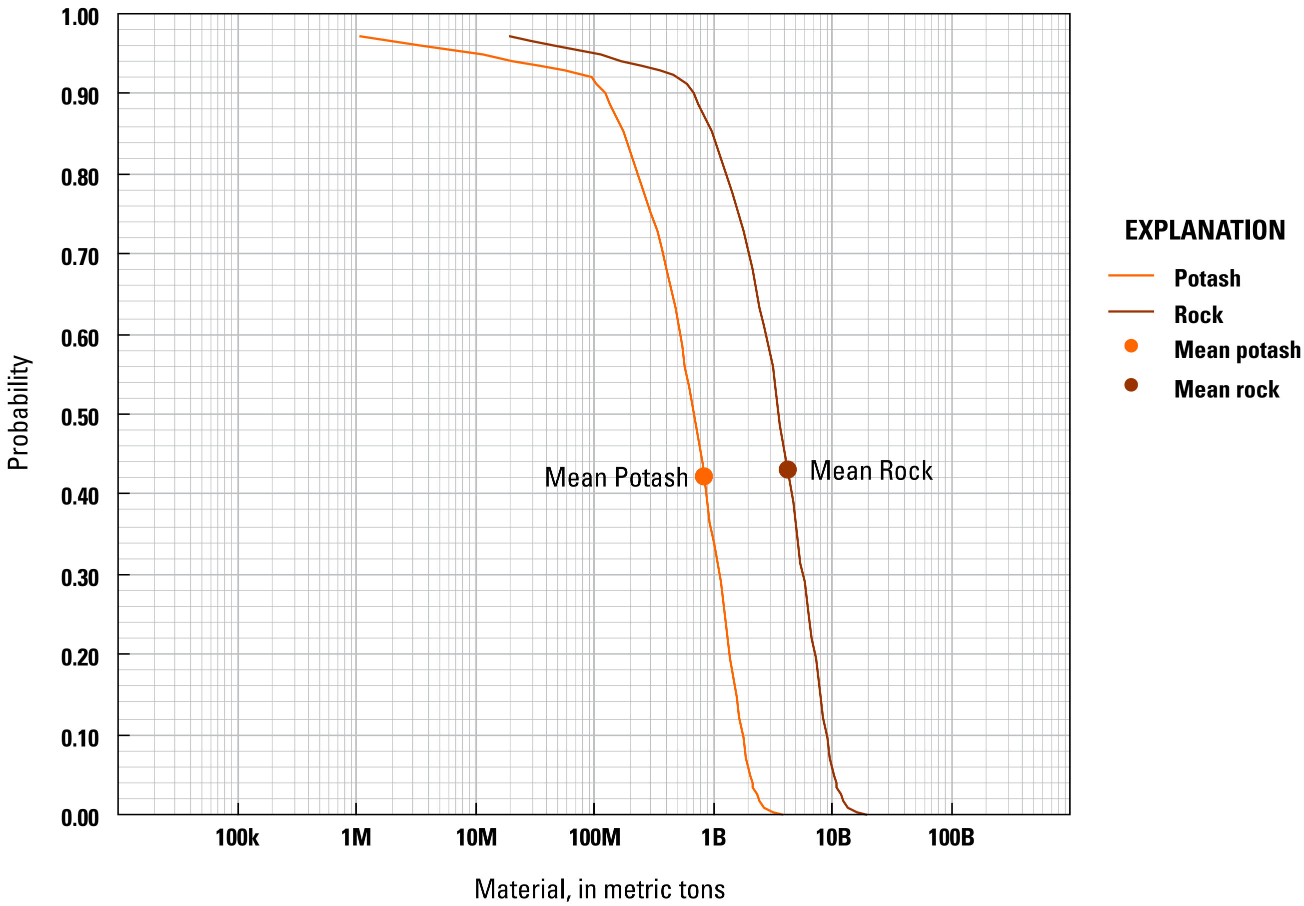


Figure 9–2. Cumulative frequency plot showing results of a Monte Carlo computer simulation of undiscovered resources in tract 150haK0042b, Upper Devonian potash-bearing evaporites in halokinetic structures—Dnieper-Donets Basin, Ukraine and Belarus. k=thousands, M=millions, B=billions.

This page intentionally left blank

Chapter 10. Outlook for Potash Development within the Pripyat and Dnieper-Donets Basins

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

Groundwater Conditions That May Affect Potash Development in the Pripyat and Dnieper-Donets Basins

Salt dissolution areas related to karst structures and subrosion are generally not suitable for mining, because they commonly contain water undersaturated with respect to salt and potash and are open to aquifers that can flood a mine and dissolve the salt and potash. Mining operations avoid larger salt dissolution anomalies associated with karst structures and areas of excessive subrosion (Jones and Prugger, 1982; Boys, 1990; Gendzwill and Martin, 1996; Choteau and others, 1997). Mining operations continue through smaller anomalies and those that include salt horses and washout anomalies (Baar, 1972, 1974; Boys, 1990). Shaft sinking, drilling, and mining are carefully planned to avoid jeopardizing the integrity of the salt containing potash-bearing units.

In the Pripyat Basin, aquifers are present in Quaternary, Neogene, Paleogene, Cretaceous, and Jurassic rocks overlying the upper part of the Famennian salt (Garetsky and others, 1982). Salt back thickness (appendix D) is not specifically referred to in the literature, but Garetsky and others (1982) noted the presence of an impermeable gypsum layer 20–60 m thick which lies above the salt. This gypsum layer serves a similar purpose as a salt back and may represent insoluble material left by subrosion of the top of the salt (fig. 3–4).

Offsets in the potash horizons result from faulting. Major structures account for division of potash horizons into the various minefields in the Starobin area (fig. 3–3). Large and small structures may provide groundwater communication from overlying aquifers and pose mine flooding hazards (Garetsky and others, 1984).

Potash Development in the Pripyat Basin

The Pripyat Basin in Belarus has favorable conditions to develop additional undiscovered potash resources, including

1. relatively simple stratabound potash-bearing salt stratigraphy that is traceable over tens of kilometers;
2. apparently continuous potash-bearing strata;
3. simple potash ore mineralogy consisting mainly of sylvite, carnallite, and halite;
4. apparently consistent medium grade of potash;
5. minor amounts of insoluble minerals in the potash;
6. large expanses of sylvite;
7. generally undeformed potash-bearing salt;
8. large K_2O tonnages;
9. few areas affected by salt dissolution;
10. extensive seismic coverage for detection of salt dissolution anomalies;
11. improved transportation infrastructure;
12. established water and utility infrastructure;
13. large and experienced workforce; and
14. favorable government attitudes toward potash development.

Unfavorable conditions for developing additional potash resources in the Pripyat Basin include

1. overlying high-pressure aquifers that pose a flooding threat during mine development and operations;
2. land-locked country dependent on transportation, port, and storage facilities in other countries;
3. long transportation distances to end users;
4. transportation involves extensive, relatively high-cost rail;
5. transportation facilities, and electrical and gas utilities are dependent on other countries; and
6. high costs of new mine development.

[1]U.S. Geological Survey, Tucson, Arizona, United States.

Potash Development in the Dnieper-Donets Basin

In the Dnieper-Donets Basin, conditions are more favorable for development of potash resources in the stratabound Cisuralian part of the basin than in the Upper Devonian halokinetic salt structures and stratabound salt. These conditions include

1. apparent large lateral extent of potash-bearing salt layers,
2. relatively shallow depth to the potash-bearing salt,
3. large K_2O tonnages (possible),
4. large and experienced workforce in Ukraine’s salt mines,
5. relatively simple stratabound potash-bearing salt stratigraphy, and
6. generally undeformed potash-bearing salt.

Other conditions listed as favorable for the Pripyat Basin are unknown for the Dnieper-Donets Basin.

Chapter 11. Summary

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

This report contains modern descriptions of geology of potash deposits and potential resources in Upper Devonian stratabound potash-bearing salt in the Pripyat Basin and in Upper Devonian and Cisuralian stratabound potash-bearing salt in the Dnieper-Donets Basin, as well as a quantitative estimate of Upper Devonian halokinetic salt structures in the Dnieper-Donets Basin. These potential potash resources are described in the context of the evolution of the Donbass-Pripyat Rift and the Pripyat and Dnieper-Donets Basins.

The Pripyat Basin is currently the third largest source of potash production in the world and has the potential for hosting additional large potash resources. Sixteen percent of world potash production comes from four mines in this basin, which have operated for more than 40 years, and two new mines opened over the past 4 years. Continued optimism about potash demand has led to further exploration and plans for an additional three mine projects to become operational by the end of 2020. Total production from the Starobin mines complex from 1963 to 2003 reached 1 Bt of potash, and there are estimated reserves of about 1.3 Bt of K_2O from the Starobin mines and other areas proposed for development. In Belarus, potash has been mined by conventional underground mining techniques.

Potash-bearing salt occurs in Frasnian and Famennian sedimentary rocks of the Pripyat Basin, but most Frasnian salt is below the assessment depth of 3 km. Most of the potash occurs as sylvite with apparently small amounts of carnallite. Economic potash-bearing strata in the northwestern part of the basin occurs in four horizons, with horizons II and III currently in production. Much of horizon III has been mined out in the Starobin mines. Published reserves in the Pripyat Basin area are about 7.3 Bt of potash ore (about 1.3 Bt of K_2O) mostly from potash-bearing salt horizons in the Starobin and Petrikov mine areas. Rough estimates of the total mineral endowment associated with stratabound Famennian salt horizons in the Pripyat Basin range from 80 to 200 Bt of potash-bearing salt that could contain 15 to 30 Bt of K_2O. Parameters (including number of economic potash horizons, grades, and depths) for these estimates are not published so they are not easily authenticated. Historically, reserves have been estimated above a depth of 1,200 m (approximately the depths of conventional underground mining). Additional undiscovered K_2O resources could be significantly greater in the remainder of the Fammenian salt depending on the extents and grades of the 60 identified potash horizons above the USGS assessment depth of 3,000 m in the remainder of the tract. Increasing ambient temperatures with increasing depths in the eastern parts of the Pripyat Basin may require a solution mining process which is aided by higher temperatures.

The Pripyat Basin has favorable conditions for development of additional undiscovered potash resources. Principal advantages include the characteristics of stratabound type potash mineral deposits, an already established infrastructure, and the Belarus government’s favorable attitude toward potash mining. Major disadvantages include Belarus’ dependence on other countries for utilities necessary for mining operations, and lengthy and costly transportation to world markets.

The Dnieper-Donets Basin, mainly in Ukraine, has few of the advantages attributed to the Pripyat Basin, which lies entirely in Belarus, and most of the disadvantages. The lack of an established potash industry in the Dnieper-Donets Basin would tend to hinder potash exploration in this basin. Poorly described potash resources are recognized in the Cisuralian stratabound salt. Similarities with the Upper Devonian salt in the Pripyat Basin and much thicker salt in this basin might suggest that similar or larger potash resources may exist in the Dnieper-Donets Basin.

Stratabound Upper Devonian salt may be above a depth of 3 km in the northwestern part of the Dnieper-Donets Basin, but increasing depths to the southeast put much of this potential resource beyond depths currently considered to be minable. Very little has been published about this salt unit, and no information, except for the presence of potash in some of the diapirs in the halokinetic tract, was found regarding potash occurrences or detailed stratigraphy of this tract’s salt.

At least 248 salt diapirs bring Upper Devonian salt above the 3-km depth limit in the Dnieper-Donets Basin and many are apparently quite close to the surface. A few drill holes into some of these salt structures encountered Upper Devonian potash horizons. Very little information regarding the internal stratigraphy and potash occurrences appears to be documented for these structures. A quantitative assessment in May 2009 produced a mean estimate of 11 undiscovered deposits in these diapirs, with a combined resource of 840 Mt of K_2O.

---

[1]U.S. Geological Survey, Tucson, Arizona, United States.

In the Cisuralian tract (150sbK0042a) in the Dnieper-Donets Basin, an estimate of potash resources in one subbasin (with an area of 440 km^2) was 794 Mt of "raw or crude" potash-bearing salt which could contain 50 to 150 Mt of K_2O, depending on the grade. Significant tonnages of undiscovered K_2O resources may be present in the other subbasins which have a combined area of about 10,450 km^2 and as polyhalite in the sulfate-rich parts of this tract. Because depths to the Permian salt are relatively shallow, ranging from less than 100 m to about 1,500 m, conditions are more favorable for development of potash resources in the stratabound Cisuralian part of the basin than in the Upper Devonian halokinetic salt structures and stratabound salt. Advantages include potentially low-cost mining of known stratabound potash-bearing salt at relatively shallow depths than in potentially structurally complex diapirs.

Assessment of potash resources in these basins would benefit from database improvements. Detailed drill-hole data, seismic studies, better geologic maps of the basins, and better location references would increase the confidence of an investigation of undiscovered potash resources.

Assessments of potash resources in the Pripyat and Dnieper-Donets Basins have yielded important contributions to the understanding of global potash resources. This report contains a compilation of information describing Upper Devonian salts in the Pripyat and Dnieper-Donets Basins and Cisuralian salt in the Dnieper-Donets Basin, an interpretation of the evolution of the evaporite and potash mineralization, descriptions of development of halokinetic structures, assessments of undiscovered potash resources in these salt units, and analysis of potential for development of these undiscovered resources.

Finally, this report offers an updated and expanded compilation and interpretation of the geology and extent of known potash occurrences and deposits in the Pripyat and Dnieper-Donets Basins, providing more information than was available in either the older Russian language scientific literature or in recent press releases from Belarus or the Belarussian Potash Company. The information compiled and understanding gained in producing this report can facilitate increased understanding of other stratabound and halokinetic potash-bearing salt basins.

References Cited

Aizberg, R.Y., Beskopylny, V.N., Starchik, T.A., and Tsekoyea, T.K., 2001, Late Devonian magmatism in the Pripyat paleorift—A geodynamic model: Geological Quarterly, v. 45, no. 4, p. 349–358.

Aizberg, R.E., Garetsky, R.G., and Starchik, T.A., 2004, Correlation of Late Paleozoic tectonic events in basins at the southwestern margin of the East European Craton and in surrounding structures: Geotectonics, v. 38, no. 1, p. 51–62.

Arden, H., and Tverdov, A., 2014, Resource and reserve valuation practices in countries forming the Russian Commonwealth of Independent States, *in* Mineral resource and ore reserve estimation—The AusIMM guide to good practice: The Australasian Institute of Mining and Metallurgy Monograph 30, p. 825–834.

Baar, C.A., 1972, Actual geological problems in Saskatchewan potash mining: Saskatoon, Saskatchewan Research Council, Engineering Division Report E72–18, 50 p., and 37 figs.

Baar, C.A., 1974, Geological problems in Saskatchewan potash mining due to peculiar conditions during deposition of potash beds, *in* Coogan, A.H., ed., Fourth Symposium on Salt: Cleveland, Ohio, Northern Ohio Geological Society, p. 101–118.

Barbikov, D.V., Grechko, A.M., Savchenko, V.V., Zlebova, A.E., Kurlovich, D.M., and Sauchy, S.F., 2016, An Environmental Impact Assessment of the underground operations at the designed Petrikov potash mine, Belarus: Environmental & Socio-economic Studies, v. 4, no. 2, p. 1–8.

Bawiec, W.J., and Spanski, G.T., 2012, Quick-start guide for version 3.0 of EMINERS—Economic Mineral Resource Simulator: U.S. Geological Survey Open-File Report 2009–1057, 26 p., http://pubs.usgs.gov/of/2009/1057. [This report supplements USGS OFR 2004–1344.]

Becker, Frank, and Bechstädt, Thilo, 2006, Sequence stratigraphy of a carbonate-evaporite succession (Zechstein 1, Hessian Basin, Germany): Sedimentology, v. 53, p. 1083–1120.

Beer, W.W., 1996, Kalilagerstätten in Deutschland [Potash deposits in Germany]: Kali und Steinsalz, v. 12, no. 1, p. 18–30.

Belarus News, 2011, Geologi zavershili detal’nuyu razvedku Nezhinskogo uchastka Starobinskogo mestorozhdeniya kaliynykh soley [Geologists have completed detailed exploration Nezhinsky site Starobin potassium salt deposit]: Belarus News, Belarusian Telegraph Agency Web page, accessed February 10, 2017, at http://www.belta.by/economics/view/geologi-zavershili-detalnuju-razvedku-nezhinskogo-uchastka-starobinskogo-mestorozhdenija-kalijnyh-solej-123429-2011.

Belarusian Potash Company, 2011a, EU Anti-dumping measures against Belarusian Potash Company’s shareholders expire, news release dated 7/20/11: Minsk, Belarus, Belarusian Potash Company Web page, accessed February 15, 2012, at http://belpc.by/en/presscenter/news/83.htnl?page=2.

Belarusian Potash Company, 2011b, Corporate profile: Minsk, Belarus, Belarusian Potash Company Web page, accessed February 15, 2012, at http://belpc.by/en/about/.

Belarusian Potash Company, 2011c, Press-kit: Minsk, Belarus, Belarusian Potash Company Web page, accessed August 15, 2011, at http://belpc.by/en/press-kit /presscenter.

Belaruskali, 2011, Belaruskali Joint Stock Company: Web page, accessed January 5, 2012, at http://www.kali.by.

Belaruskali, 2017a, Production units: Belaruskali Joint Stock Company web page, accessed February 10, 2017, at http://kali.by/en/production/main_production/Production%20units/.

Belaruskali, 2017b, Production: Belaruskali Joint Stock Company web page, accessed February 10, 2017, at http://kali.by/en/production/.

Bogdanova, S.V., Pashkevich, I.K., Gorbatschev, R., and Orlyuk, M.I., 1996, Riphean rifting and major Palaeoproterozoic crustal boundaries in the basement of the East European Craton—Geology and geophysics: Tectonophysics, v. 268, p. 1–21.

Borchert, H., and Muir, R.O., 1964, Salt deposits—The origin, metamorphism and deformation of evaporites: New York, D. Van Nostrand Co., Ltd., 338 p.

Boys, C., 1990, The geology of potash deposits at PCS Cory Mine, Saskatchewan: Saskatoon, Saskatchewan, Canada, University of Saskatchewan, unpublished Master’s thesis, 225 p.

British Sulphur Corporation Limited, 1975, World survey of potash resources (2d ed.): London, British Sulphur Corporation Limited, 148 p.

British Sulphur Corporation Limited, 1984, World survey of potash resources (4th ed.): London, British Sulphur Corporation Limited, 145 p.

Chekunov, A.V., Garvish, V.K., Kutas, R.I., and Ryabchun, L.I., 1992, Dnieper-Donets paleorift: Tectonophysics, v. 208, p. 257–272.

Chekunov, A.V., Kaluzhnaya, L.T., and Ryabchun, L.I., 1993, The Dnieper-Donets paleorift, Ukraine—Deep structures and hydrocarbon accumulations: Journal of Petroleum Geology, v. 16, no. 2, p. 183–196.

Choteau, M., Phillips, G., and Prugger, A., 1997, Mapping and monitoring soft rock mining, *in* Gubins, A.G., ed., Geophysics and geochemistry at the Millennium; Proceedings of Exploration 97, Fourth Decennial International Conference on Mineral Exploration: Toronto, Prospectors and Developers Association of Canada, p. 927–940.

Clarke, J.W., 1987, Dnieper-Pripyat oil-gas province, U.S.S.R.: U.S. Geological Survey Open-File Report 87–288, 25 p.

Cocker, M.D., and Orris, G.J., 2010, Effects of halokinesis on the economic viability of potash-bearing salt deposits: 46th Annual Forum on the Geology of the Industrial Minerals, Harrisburg, Pennsylvania: Pennsylvania Geological Survey, p. 8.

Cocker, M.D., and Orris, G.J., 2013, World potash developments, *in*, Conway, F.M., ed., Proceedings of the 48th Annual Forum on the Geology of Industrial Minerals, Phoenix, Arizona, April 30–May 4, 2012, Arizona Geological Survey Special Paper #9, Chapter 1, p. 1–16.

Cocker, M.D., Orris, G.J., and Wynn, Jeff, 2016, U.S. Geological Survey assessment of global potash production and resources—A significant advancement for global development and a sustainable future, *in* Wessel, G.R., and Greenberg, J.K., eds., Geoscience for the public good and global development—Toward a sustainable future: Geological Society of America Special Paper 520, p. 1–10, doi:10.1130/2016.2520(10).

Coward, M.P., and Stewart, S., 1995, Salt-influenced structures in the Mesozoic-Tertiary cover of the southern North Sea, U.K., *in* Jackson, M.P.A., Roberts, D.G., and Snelson, S., eds., Salt tectonics, a global perspective: American Association Petroleum Geologists Memoir 65, p. 225–250.

Czapowski, G., and Bukowski, K., 2009, Zloza soli w Polsce – stan aktualny I perspektywy zagospodarowania [Salt deposits in Poland—Current state and management perspectives]: Przeglad Geologiczny, v. 57, no. 9, p. 798–811.

Dakuko, N., 2003, Technical and technological development of PA Belaruskali: St. Petersburg, Russia, 2003 IFA Production and International Trade Conference and Regional Conference for Eastern Europe and Central Asia, 10 p.

Eroshina, D.M., 1981, Pozdnefranskiy etap solenakopleniya v Pripyatskoy vpadine [Late Frasnian stage of salt accumulation in the Pripyat Depression], *in* Yanshin, A.L., and Zharkov, M.A., eds., Stroyeniye i usloviya obrazovaniya solenosnykh formatsiy [The structure and formation conditions of salt-bearing horizons]: Novosibirsk, Izd. Nauka, Sibirsk. Otdel., USSR, p. 82–91.

Eroshina, D.M., and Kislik, V.Z., 1980, Ob usloviyakh formirovaniya kaliynykh soley verkhnefranskoy solenosnoy formatsii Pripyatskoy vpadiny [Depositional environments of potash salts of the Upper Frasnian salt formation in the Pripyat Depression]: Sovetskaya Geologiya, v. 10, p. 43–50.

Eroshina, D.M., and Obrovets, S.M., 1983, Petrografiya i veshchestvennyy sostav porod pervogo kaliynogo gorizonta verkhefranskoy solenosnoy formatsii [Petrography and composition of rocks of the first potash horizon in the salt formation of the upper Frasnian]: Doklady Akademii Nauk, BSSR, v. 27, no. 4, p. 355–358.

Export.By, 2011, Mineral resources and fossils: Minsk, Belarus, Export.by Web page, accessed January 4, 2012, at http://export.by/en/bel_info/o_belarusi/obschaya_informaciyafc5/geograficheskaya_spr_d1a6/poleznie_iskopaemiec8a.html.

Foreign Policy and Security Research Center, 2011, Belaruskali commissions second priority complex at Krasnoslobodsky mine: Minsk, Belarus, Foreign Policy and Security Research Center Web page, accessed January 4, 2012, at http://forsecurity.org/belaruskali-commissions-second-priority-complex-krasnoslobodsky-mine.

Fuzesy, A., 1982, Potash in Saskatchewan: Saskatchewan Geological Survey Report 181, 44 p.

Galitskiy, I.V., 1972, Cyclicity of saliferous deposits of Lower Permian Kramatorsk suite of Dnieper-Donets depression, *in* Kaleda, G.A., ed., Lithology and paleogeography of Paleozoic deposits of Russian platform: Nauka, Moscow, p. 249–255.

Galitskiy, L.S., 2007, An atlas of the geology and mineral deposits of the Ukraine (scale 1:5,000,000): Toronto, University of Toronto Press, 168 p.

Garetsky, R.G., 1979, Tektonika Pripyatskogo Progiba [Tectonics of the Pripyat trough]: Minsk, Nauka i Tekhnika Publ., 174 p.

Garetsky, R.G., Aisberg, R.E., Starchik, R.E., 2004, Pripyat Trough—Tectonics, geodynamics, and evolution: Russian Journal of Earth Sciences, v. 6, no. 3, p. 217–250.

Garetsky, R.G., Kichkina, M.S., Kruchek, S.A., Makhnach, A.S., Pap, A.M., Urjev, I.I., Khonich, P.Z., Vysotskiy, E.A., Zingerman, A.Ya., Zykov, I.A., Kislik, V.Z., Narodetskaya, A.D., Petrova, N.S., Sedun, E.V., and Fomina, V.D., 1984, Byelorussian Soviet Socialist Republic, *in* Garetsky, R.G., Ilkevich, G.I., Kislik, V.Z., Kuznetsov, V.A., Levkov, E.A., Matveev, A.V., Makhnach, A.S., Pavlov, Yu.I., Pap, A.M., Urjev, I.I., and Khomich, P.Z., eds., International Geological Congress XXVII Session Excursions—024 Glacial deposits of Byelorussia, 15 Byelorussian potassium-bearing basin Guidebook: Minsk, Nauka Tekhnika, 75 p.

Garetsky, R.G., Kislik, V.Z., Vysotskiy, E.A., Eroshina, D.M., Petrov, N.S., Obrovets, S.M., Sedun, E.V., and Protasevich, B.A., 1982, Devonskiye solenosnyye formatsii Pripyatskogo progiba [The Devonian saliferous formations of the Pripyat Basin]: Minsk, Izd. Nauka Tek., USSR, SSR, 207 p.

Garrett, D.E., 1996, Potash—Deposits, processing, properties and uses: New York, Chapman and Hall, 734 p.

Gendzwill, D.J., 1978, Winnipegosis mounds and Prairie Formation of Saskatchewan-seismic survey: American Association of Petroleum Geologists Bulletin, v. 62, no. 1, p. 73–86.

Gendzwill, D.J., and Martin, N., 1996, Flooding and loss of the Patience Lake potash mine: CIM Bulletin, v. 89, no. 1000, p. 62–73.

Geonews, 2011, Belarus’. “Belarus’kaliy” v 2015 godu nameren uvelichit’ dobychu rudy na chetvert’ [Belarus. “Belaruskali” in 2015 plans to increase extraction of ore by a quarter]: Geonews web page, accessed February 10, 2017, at http://geonews.com.ua/news/detail/belarus-belaruskalij-v-2015-godu-42171.

Gimm, Werner, 1968, Kali- und Steinsalzbergbau; band 1, Aufschluss und Abbau von Kali- und Steinsalzlagerstätten [Potash and rock salt mining, vol. 1, Exploration and exploitation of potash and rock salt deposits]: Leipzig, VEB Deutscher Verlag für Grundstoffindustrie, 600 p.

Gladenkov, Y.B., 2007, The new Russian Stratigraphic Code and some problems of stratigraphic classification: Stratigraphy, v. 4, nos. 2–3, p. 169–172.

Hammarstrom, J.M., Robinson, G.R., Jr., Ludington, Steve, Gray, Floyd, Drenth, B.J., Cendejas-Cruz, Francisco, Espinosa, Enrique, Pérez-Segura, Efrén, Valencia-Moreno, Martín, Rodríguez-Castañeda, José Luis, Vásquez-Mendoza, Rigoberto, and Zürcher, Lukas, 2010, Porphyry copper assessment of Mexico: U.S. Geological Survey Scientific Investigations Report 2010–5090–A, 176 p., http://pubs.usgs.gov/sir/2010/5090/a/.

Harben, P.W., and Kužvart, M., 1996, Industrial minerals—A global geology: London, Industrial Minerals Information Ltd., 462 p.

Henley, S., 2004, Russian mineral reporting: Mining Journal, August 20, 2004, p. 18–21.

Hite, R.J., 1982, Progress report on the potash deposits of the Khorat Plateau, Thailand, U.S. Geological Survey Open-File Report 82–1096, 70 p.

Hite, R.J., and Japakasetr, T., 1979, Potash deposits of Khorat Plateau, Thailand and Laos: Economic Geology, v. 74, no. 2, p. 448–458.

Holter, M.E., 1969, The Middle Devonian Prairie Evaporite of Saskatchewan: Saskatchewan Department of Mineral Resources Report 123, 134 p.

Hoppe, Walter, 1960, Die Kali- und Steinsalzlagerstätten des Zechsteins in der Deutschen Demokratischen Republik [The potassium and rock salt deposits of the Zechstein in the German Democratic Republic]: Berlin, Freiberger Forschungsheft, 169 p.

Hryniv, S.P., Dolishniy, B.V., Khmelevska, O.V., Poberezhskyy, A.V., and Vovnyuk, S.V., 2007, Evaporites of Ukraine—A review, *in* Schreiber, B.C., Lugli, S., and Babel, M., eds., Evaporites through space and time: Geological Society of London Special Publication 285, p. 309–334.

Interfax, 2014, “Belarus’kaliy” vvel v stroy vtoruyu ochered’ Berezovskogo rudnika [“Belaruskali” has put into operation the second stage of Berezovsky mine]: Interfax web page, accessed February 10, 2017, at http://www.interfax.by/news/belarus/1146217.

International Commission on Stratigraphy, 2011, International stratigraphic chart: International Commission on Stratigraphy Web page, accessed February 21, 2012, at http://www.stratigraphy.org/.

Jackson, M.P.A., 1995, Retrospective salt tectonics, *in* Jackson, M.P.A., Roberts, D.G., Snelson, S., eds., Salt Tectonics—A Global Perspective: American Association of Petroleum Geologists Memoir, v. 65, p. 1–28.

Jasinski, S.M., 2015a, Potash [advance release], *in* Metals and minerals: U.S. Geological Survey Minerals Yearbook 2013, v. I, p. 58.0–58.6, http://minerals.usgs.gov/minerals/pubs/commodity/potash/myb1-2013-potas.pdf.

Jasinski, S.M., 2015b, Potash: U.S. Geological Survey Mineral Commodity Summaries 2015, p. 122–123, http://minerals.usgs.gov/minerals/pubs/commodity/potash/mcs-2015-potas.pdf.

Jasinski, S.M., 2016, Potash: U.S. Geological Survey Mineral Commodity Summaries 2015, p. 128–129, http://minerals.usgs.gov/minerals/pubs/commodity/potash/mcs-2016-potas.pdf.

Jones, C.L., and Madsen, B.M., 1968, Evaporite geology of Fifth ore zone Carlsbad District, Southeastern New Mexico: U.S. Geological Survey Bulletin 1252–B, 27 p.

Jones, P.R., and Prugger, F.F., 1982, Underground mining in Saskatchewan potash: Mining Engineering, v. 34, p. 1677–1683.

Kendall, A.C., 2010, Marine evaporites, *in* James, N.P., and Dalrymple, R.W., eds., Facies models 4: Geological Association of Canada GEOtext 6, p. 505–540.

Khrushchov, D.P., Grabyanskaya, N.N., Grabyanskiy, V.V., Levenshteyn, M.M., Edel'shteyn, A.M., Yudel'son, A.A., Korenevskiy, S.M., Bobrov, V.P., Sushchuk, Ye G., and Kovalenko, D.N., 1974, Osadochnyye i osadochno-vulkanogennyye formatsii Dneprovsko-Donetskoy vpadiny i Donbassa [Sedimentary and sedimentary-volcanic formations of the Dnieper-Donets and Donets basins], *in* Tkachuk, L.G., ed., Prognoz mestorozhdeniy poleznykh iskopayemykh v osadochnykh formatsiyakh Ukrainy: Kiev, Naukova Dumka, p. 75–85.

Kislik, V.Z., 1970, Vtorichnyye gnezdovidnyye obrazovaniya galita i sil'vina v kaliynykh gorizontakh Starobinskogo mestorozhdeniya [Secondary pockets of development of halite and sylvite in potassium horizons of the Starobin deposits], *in* Litologiya, geokhimiya i poleznyye iskopayemyye Belorussii i Pribaltiki, USSR [Lithology, geochemistry and mineral resources of Belarus and the Baltic States, Soviet Union]: Minsk, Minist. Geol., Inst. Geol. Nauk, p. 290–296.

Kislik, V.Z., 1971, Postsedimentatsionnyye izmeneniya v kaliynykh gorizontakh Starobinskogo mestorozhdeniya [Postsedimentary changes in potassium-bearing strata of the Starobin deposit], *in* Ivanov, A.A., Krasilnikova, N.A., and Otreshko, A.I., eds., Problemy prognoza, poiskov i razvedki mestorozhdenii gornokhimicheskogo syria SSSR [The problems of prediction, prospecting and exploration of mining chemical raw materials of the USSR]: Moscow, Nedra, p. 209–218.

Kislik, V.Z., and Lupinovich, J.J., 1968, Ũber den Jahresrhythmus der sedimentation der sylvinite in der Starobinsker lagerstätte [The annual sedimentation rhythm of the sylvinite in the Starobin deposit]: Deutsche Gesellschaft für Geologische Wissenschaften, Berlin, Reihe B, Mineralogische Lagerstättenforsch., v. 13, no. 5, p. 616.

Kityk, V.I., 1970, Solianaia tektonika Dneprovsksko-Donetskoi vpadiny [Salt tectonics of the Dnieper-Donets depression]: Kiev, Ukraine Academy of the Institute of Geology and Geochemistry, 201 p.

Kityk, V.Z., and Gabulda, N.I., 1981, Paleogeografiya periodov devonskogo solenakopleniya v Dneprovsko-Donetskoy vpadine [Paleogeography of periods of Devonian salt accumulation in the Dnieper-Donets Basin], *in* Yanshin, A.L., and Zharkov, M.A., eds., Stroyeniye i usloviya obrazovaniya solenosnykh formatsiy [The structure and formation conditions of salt-bearing horizons]: Novosibirsk, Izd. Nauka, Sibirsk. Otdel., USSR, p. 74–82.

Klimenko, V.Y., 1957, Struktura Dneprovsko-Donetskoi vpadiny, usloviya ee formirovaniya i zakonomernosti obrazovaniya i razmeshcheniya v nei mestorozhdenii nefti i gaza [Structure of Dnieper-Donets Depression, condition for its shaping and laws governing formation and arrangement of oil and gas layers]: Kiev, Akad. Nauk Ukrain. SSR, Inst. Geol. Nauk, 104 p.

Knipping, B., 1991, Basaltische Gesteine in Zechstein evaporiten [Basaltic rocks in Zechstein evaporites]: Zentralblatt fur Geologie und Palaontologie, v. 1, p. 1149–1163.

Konishchev, V.S., and Kovkhuto, A.M., 2011, Saliferous formations of the Pripyat Trough as host rocks for construction of underground storages [abs.]: Polish Salt conference 2011, XVI, p. 81–82.

Kopnin, V.I., 1995, Halite anomalies in potash-bearing beds in the southern part of the Verkhnekama potash salt deposit—Structure and genesis: Lithology and Mineral Resources, v. 30, no. 5, p. 453–464.

Korenevskiy, S.M., 1973, Kompleks poleznykh iskopayemykh galogennykh formatsiy [Complex mineral deposits of halide-bearing formations]: Moscow, Nedra, 300 p.

Korenevskiy, S.M., 1989, Substitution and depletion zones of potash and potassium-magnesium salt deposits: Lithology and Mineral Resources, v. 24, no. 1, p. 50–63.

Korenevskiy, S.M., 1990, Lithotypes of potassium-bearing formations: Lithology and Mineral Resources, v. 25, no. 2, p. 99–106.

Korenevskiy, S.M., and Bobrov, V.P., 1968, Nikitovskaya svita nizhnepermskoy galogennoy formatsii Dneprovsko-Donetskoy vpadiny i Donetskogo basseyna [The Nikitova suite (lower Permian evaporites) of the Dnieper-Donets basin and the Donets basin]: Bulleten Moskovskogo obshchestva ispytatele prirody, Otdel. geologicheskiy, v. 43, no. 2, p. 57–73.

Korenevskiy, S.M., Bobrov, V.P., Supronyuk, C.C., and Khrushchov, D.P., 1968, Galogennye formatsii severo-zapadnogo Donbassa I Dneprovsko-Donetskoi vpadiny i ikh kalienosnost [Salt formations in the northwestern Donbass and Dnieper-Donets depression and their potash deposits]: Moscow, Nedra, 240 p.

Korenevskiy, S.M., and Shamakhov, V.A., 1990, Kaliyenasyshchennost' razreza, Kaliyenosnost' i udel'naya produktivnost' verkhnefamenskoy Kaliyenosnoy subformatsii pripyatskoy vpadiny [Potassium-bearing section and potassium-bearing specific productivity of upper Famennian potassium-bearing subformations in the Pripyat trough], *in* Petrychenko, O.I., ed., Geologiya i geokhimiya solenosnykh otozhenii neftegazonosnich provinpii [Geology and geochemistry of salt-bearing deposits of oil-and-gas content province]: Kiev, Naukova Dumka, p. 70–85.

Korulin, D.M., 1976, Geologiya i poleznyye iskopayemyye Belorussii [Geology and mineral resources of Belarus]: Minsk, Vysheyshaya School, 160 p.

Kovalevych, V.M., Peryt, T.M., Carmona, V., Sydor, D.V., Vovnyuk, S.V., and Halas, S., 2002, Evolution of Permian water—Evidence from fluid inclusions in halite: Neues Jahrbuch für Mineralogie Abhandlungen, v. 178, p. 27–62.

Kovalevych, V.M., Peryt, T.M., and Petrychenko, O.I., 1998, Secular variation in seawater chemistry during the Phanerozoic as indicated in brine inclusions in halite: Journal of Geology, v. 106, p. 695–712.

Kovalevym, B.S., Utekhinym, D.N., and Dubinskim, A.Y., 1965, Geological map of the USSR, sheet M-37 Kharkov, Map of the pre-Mesozoic rocks: Leningrad, State Geological Committee of the USSR, VSEGEI, scale 1:1,000,000. [In Russian.]

Kühn, R., 1955, Über den Bromgehalt von Salzgesteinen, insbesondere die quantitative Ableitung des Bromgehaltes nichtprimärer Hartsalze oder Sylvinite aus Carnallit [About the bromine content of salt rocks, in particular the quantitative derivation of the bromine content is not of primary hard salts or sylvite from carnallite]: Kali und Steinsalz, v. 1, no. 9, p. 3–16.

Kurkachi, Sergey, 2012, Belarus'kaliy nachinayet glavnuyu novostroyku strany—Chyrvonaslabodski shakhtu [Belaruskali begins a major new building of the country - Chyrvonaslabodski mine]: News and history of Belarus web page, accessed February 10, 2017, at http://belhist.ru/2012/07/belaruskalij-nachinaet-glavnuju-novostrojku-strany/.

Kutyrlo, W., Warnel, J., and Trefilawa, W., 2008, Geneza zaburzeń budowy geologicznej w horyzontach przemyslowych starobińskiego zloza soli potasowych (Bialorus) [Genesis of geological complications in industrial horizons of the Starobin potash deposit (Belarus)]: Gospodarka Surowcami Mineralnymi, v. 24, no. 3/2, p. 289–298.

Kuznir, N.J., Kovkhuto, A., and Stephenson, R.A., 1996, Syn-rift evolution of the Pripyat Trough—Constraints from structural and stratigraphic modeling: Tectonophysics, v. 268, p. 221–236.

Levanevskogo, Valeria, ed., 2006, Postanovleniye Soveta Ministrov Respubliki Belarus' ot 13.09.2006 No. 1206 "O Programme razvitiya otkrytogo aktsionernogo obshchestva `Belarus'kaliy' do 2012 goda" [Republic of Belarus Council of Ministers on 13.09.2006 number 1206 "On the Program of the Open Joint Stock Company `Belaruskali' until 2012"]: Law Legislation Republic of Belarus web page, accessed February 10, 2017, at http://www.levonevski.net/pravo/norm2013/num31/d31660.html.

Linn, K.O., and Adams, S.S., 1966, Barren halite zones in potash deposits, Carlsbad, New Mexico, *in* Rau, J.L., ed., Second Symposium on Salt: Cleveland, Ohio, Northern Ohio Geological Society, p. 59–69.

Lomakin, A.G., 2003, Present condition and outlook for potash deliveries from Russia and Belarus—Production, logistics, markets: 2003 IFA Production and International trade conference and regional conference for Eastern Europe and Central Asia, St. Petersburg, Russia, September 22–26, 2003, 7 p., 15 slides.

Lowenstein, T.K., and Spencer, R.J., 1990, Syndepositional origin of potash evaporites—Petrographic and fluid inclusion evidence: American Journal of Science, v. 290, p. 1–42.

Lupinovich, Yu.I., 1971, Galogennaya formatsiya Pripyatskoy vpadiny i perspektivy yeye kaliyenosnosti [Halogenic formations in the Pripyat Basin and prospects for potassium], *in* Ivanov, A.A., Krasilnikova, N.A., and Ozreshko, A.I., eds., Problemy prognoza, poiskov i razvedki mestorozhdeniy gornokhimicheskogo syr'ya SSSR [The problems of prediction, prospecting and exploration of mining chemical raw materials of the USSR]: Moscow, Nedra, p. 174–184.

Lupinovich, Yu.I., Kislik, V.Z., Zelentsov, I.I., Eroshina, D.M., 1968, Novye dannyye o kaliyenosnosti famenskoy solenosnoy tolshchi Pripyatskoy vpadiny [New data on potassium content of the Famennian salt-bearing sequence in the Pripet depression]: Sovetskaya Geologiya, v. 6, p. 23–35.

Makhnach, A.A., Kuleshov, V.N., Pokrovskii, B.G., Gulis, L.F., Mikhailov, N.D., and Kolosov, I.L., 2002, Isotopic composition of oxygen and carbon and formation temperature of accessory minerals from evaporitic sediments in the Pripyat Trough: Lithology and Mineral Resources, v. 37, no. 6, p. 536–545.

McIntosh, R.A., and Wardlaw, N.C., 1968, Barren halite bodies in the sylvinite mining zone at Esterhazy, Saskatchewan: Canadian Journal of Earth Sciences, v. 5, p. 1221–1238.

Mayrhofer, H., 1983, World reserves of mineable potash salts based on structural analysis: Sixth International Symposium on Salt, v. 1, p. 141–160.

Ministry of Economy of the Republic of Belarus, 2011, Investment project—Commercial development of the Petrikov deposit of potash salts together with building up of ore mining and dressing complex: Ministry of Economy of the Republic of Belarus website, accessed February 10, 2017, at http://www.economy.gov.by/nfiles/001519_998661_PROJECT_Petrikov_deposit_potash_14102011.pdf.

Neuendorf, K.K.E., Mehl, Jr., J.P., and Jackson, J.A., 2005, Glossary of Geology (5th ed.): Alexandria, Virginia, American Geological Institute, 799 p., http://www.agiweb.org/pubs/glossary/.

Obrovets, S.M., Vysotskiy, E.A., and Kislik, V.Z., 1990, Litologo-fatsial'noye rayonirovaniye kaliyenosnoy subformatsii Pripyatskogo progiba. Lithofacial regionalization of potash-bearing subformations of Pripet Basin, *in* Merzlyakov, G.A., and Zharkov, M.A., eds., Usloviya obrazovaniya mestorozhdenii kaliinykh solei [The conditions of the formation of potash salt deposits]: Novosibirsk, Izdatel'stvo Nauka, p. 125–132.

Oczlon, M.S., 2006, Terrane map of Europe (1st ed.): Heidelberg, Germany, Gaea Heidelbergensis, v. 15, 1 sheet, scale 1:5,000,000.

Orris, G.J., 1992, Preliminary grade and tonnage model of potash-bearing bedded salt, *in* Orris, G.J., and Bliss, J.D., eds., Industrial mineral deposit models—Grade and tonnage models: U.S. Geological Survey Open-File Report 92–437, p. 50–52.

Orris, G.J., Dunlap, P., Cocker, M.D., Wynn, J.C., 2013, Challenges and approaches to assessing industrial minerals—The USGS global potash assessment databases [abs.]: Geological Society of America 125th Annual Meeting, Abstracts with Programs, v. 45, no. 7, p. 560.

Orris, G.J., Cocker, M.D., Dunlap, P., Wynn, Jeff, Spanski, G.T., Briggs, D.A., and Gass, L., with contributions from Bliss, J.D., Bolm, K.S., Yang, C., Lipin, B.R., Ludington, S., Miller, R.J., and Słowakiewicz, M., 2014, Potash—A global overview of evaporite-related potash resources, including spatial databases of deposits, occurrences, and permissive tracts: U.S. Geological Survey Scientific Investigations Report 2010–5090–S, 76 p., and spatial data, http://dx.doi.org/10.3133/sir20105090S.

Paulson, Jr., O.L., 1970, Wrench faulting as a trigger mechanism for interior salt ridges of Mississippi, *in* Rau, J.L., and Dellwig, L.F., eds., Third Symposium on Salt: Cleveland, Ohio, Northern Ohio Geological Society, p. 283–285.

Peschenko, A.D., and Mychko, D.I., 2008, Resursy i perspektivy ispol’zovaniya kamennoy i kaliynykh soley Belarusi [Resources and prospects of Belarusian potash and rock salt]: Chemistry—Teaching problems, no. 3, 2008, p. 5–14.

Petrova, N.S., Bakhmutskaya, L.V., and Zhuravskaya, A.M., Assessments of the sylvinite ore dressability at the Starobin potassium salt deposit: Geology, Geophysics, and Environment, v. 38, p. 93–97.

Petrychenko, O.Y., and Peryt, T.M., 1989, Composition of brines in the Late Devonian evaporite basin of the Pripyat Trough (Belarus): Biuletyn Panstwowego Instytutu Geologicznego, v. 387, p. 54–55.

Petrychenko, O.I., 1988, Physico-chemical conditions of sedimentation in the evaporite paleobasins: Naukova Dumka, Kiev (Russian).

Petrychenko, O.Y., and Peryt, T.M., 2004, Geochemical conditions of deposition in the Upper Devonian Prypiac' and Dnipro-Donets evaporite basins (Belarus and Ukraine): The Journal of Geology, v. 112, p. 577–592.

Protasevich, B.A., 1990, Paleotektonicheskaya obstanovka i kharaakter kaliyenakopleniya vo vremya obrazovaniya kaliyenosnoy subformatsii Pripyatskogo progiba [Paleotectonic situation and characteristics of potassium accumulation at the time of potash formation in Pripet Basin], *in* Merzlyakov, G.A., and Zharkov, M.A., eds., Usloviya obrazovaniya mestorozhdenii kaliinykh solei [The conditions of the formation of potash salt deposits]: Novosibirsk, Izdatel'stvo Nauka, p. 138–144.

Prud’homme, Michel, and Krukowski, S.K., 2006, Potash, *in* Kogel, J.E., Trivedi, N.C., Barker, J.M., and Krukowski, S.K., eds., Industrial Minerals and Rocks, 7th edition: Littleton, Colorado, Society for Mining, Metallurgy, and Exploration, Inc., p. 723–741.

Rauche, H., and Van der Klauw, S., 2007, Resource estimate for the Makola exploration permit area, Kouilou Region, Republic of Congo; Technical report prepared for MagMinerals Inc.: Erfurt, Germany, ERCOPSPLAN Ingenieurgesellxchaft, 130 p. [plus appendixes.]

Rauche, H., 2011, Technical report and resource report for the Danakhil potash deposit, Afar State, State/Ethiopia: Erfurt, Germany, ERCOPSPLAN Ingenieurgesellschaft, 128 p. [plus appendixes.]

Rayevskiy, V.I., and Fiveg, M.P., 1973, Mestorozhdeniya kaliynykh soley SSSR; metody ikh poiskov I razvedki [Deposits of potassium salts in the USSR; methods of exploration and surveying]: Leningrad, Izd. Nedra, Otd., USSR, 344 p.

Rundkvist, D.V., ed., 2001, Mineragenetic map of Russian Federation and adjacent states (within the boundaries of former USSR), with contributions from Kraush, M.A., Gavrilov, V.K., and Portnov, A.M.: Ministry of Natural Resources of Russian Federation, State Research and Development Enterprise “AEROGEOLOGIA,” 1 map on 18 sheets, scale 1:2,500,000.

Rusy, M.I., 2013, Strategiya razvitiya geologicheskoy otrasli i intensifikatsii osvoyeniya mineral’no-syr’yevoy bazy

Respubliki Belarus’ do 2025 goda [The development strategy of the geological industry and the intensification of the development of mineral resources base of the Republic of Belarus until 2025]: Ministry of Natural Resources and Environmental Protection of the Republic of Belarus, 41 p., accessed February 7, 2017, at http://www.minpriroda.gov.by/uploads/files/000724_477221_strategia_geologia.doc.

Schulz, K.J., and Briskey, J.A., 2003, The Global Mineral Resource Assessment Project: U.S. Geological Survey Fact Sheet 053–03, accessed February 2, 2011, at http://pubs.usgs.gov/fs/fs053-03/.

Schwerdtner, W.M., 1964, Genesis of potash rocks in Middle Devonian Prairie Evaporite Formation of Saskatchewan: American Association of Petroleum Geologists Bulletin, v. 48, no. 7, p. 1108–1115.

Shun, X.S., 1993, Study on solution mining technology for 3000 m deep wells, *in* Kakihana, H., Hardy, Jr., H.R., Hoshi, T., and Toyokura, K., eds., Seventh Symposium on Salt, volume 1: New York, Elsevier, p. 339–345.

Singer, D.A., 1993, Basic concepts in three-part quantitative assessments of undiscovered mineral resources: Nonrenewable Resources, v. 2, no. 2, p. 69–81.

Singer, D.A., 2007a, Short course introduction to quantitative mineral resource assessments: U.S. Geological Survey Open-File Report 2007–1434, accessed May 15, 2009, at http://pubs.usgs.gov/of/2007/1434/.

Singer, D.A., 2007b, Estimating amounts of undiscovered resources, *in* Briskey, J.A., and Schulz, K.J., eds., Proceedings for a workshop on deposit modeling, mineral resource assessment, and their role in sustainable development, 31st International Geological Congress, Rio de Janeiro, Brazil, August 18–19, 2000: U.S. Geological Survey Circular 1294, p. 79–84, at http://pubs.usgs.gov/circ/2007/1294/.

Singer, D.A., and Menzie, W.D., 2005, Statistical guides to estimating the number of undiscovered mineral deposits—an example with porphyry copper deposits, *in* Cheng, Qiuming, and Bonham-Carter, Graeme, eds., Proceedings of IAMG—The annual conference of the International Association for Mathematical Geology: Toronto, Canada, Geomatics Research Laboratory, York University, p. 1028–1033.

Singer, D.A., and Menzie, W.D., 2010, Quantitative mineral resource assessment—An integrated approach: New York, Oxford University Press, 219 p.

Sliaupa, A., Fokin, P., Lazauskiene, and Stephenson, R.A., 2006, The Vendian-Early Paleozoic sedimentary basins of the East European Craton, *in* Gee, D.G., and Stephenson, R.A., eds. European lithosphere dynamics: Geological Society of London Memoir 32, p. 449–462.

Smycznik, A., Wysocki, E., Machnacz, A., Kruczek, S., and Gulis, L., 2006, Starobin potash salt deposit—Geology, exploitation, methods and perspectives: XI International Symposium on Salt “Quo Vadis Sal,” Polish Salt Mining Association, p. 81–82.

Stirrett, T.A., and Gebhardt, E., 2011, Technical summary report for 2011 Encanto Potash, Inc. potash resource assessment for Muskowekwan First Nations Home Reserve, Saskatchewan, Canada: Saskatoon, Saskatchewan, North Rim Exploration Ltd., 393 p., http://www.sedar.com.

Stephenson, R.A., Yegorova, T., Brunet, M.F., Stovba, S., Wilson, M., Starostenko, V., Saintot, A., Kusznir, N., 2006, Late Palaeozoic intra- and pericratonic basins on the East European Craton and its margins, *in* Gee, D.G., and Stephenson, R.A., eds., European Lithosphere Dynamics: Geological Society of London Memoir 32, 463–479.

Stovba, S.M., and Stephenson, R.A., 2003, Style and timing of salt tectonics in the Dnieper-Donets Basin (Ukraine)—Implications for triggering and driving mechanisms of salt movement in sedimentary basins: Marine and Petroleum Geology, v. 19, p. 1169–1189.

Tabor, N.J., 2013, Wastelands of tropical Pangea—High heat in the Permian: Geology, v. 41, no. 5, p. 623–624.

Tomchin, L.I., and Mackie, K., 1999, Potash mining in Belarus: International Mining and Minerals, v. 2, no. 24, p. 328–332.

Troitsky, V., Petrov, I., and Grishaev, S., 1998, Industrial minerals of the CIS: Worcester Park, Surrey, England, Industrial Minerals Information Ltd., 135 p.

Truscott, B., 2011, Potash companies appear intent on pushing the capacity envelope: Investor Intel Web site, accessed January 4, 2012, at http://www.potashblog.com/2011/12/capacity-concerns-will-no-doubt-continue-to-weigh-on-the-potash-sector-given-the-number-of-greenfield-projects-and-brownfiel.html#tp.

Ulmishek, G.F., 2001, Petroleum geology and resources of the Dnieper-Donets Basin, Ukraine and Russia: U.S. Geological Survey Bulletin 2201–E, 14 p.

Ulmishek, G.F., Bogino, V.A., Keller, M.B., and Poznyakevich, Z.L., 1994, Structure, stratigraphy, and petroleum geology of the Pripyat and Dnieper-Donets Basins, Belarus and Ukraine, *in* Landon, S.M., ed., Interior rift basins: American Association of Petroleum Geologists Memoir 59, p. 125–156.

Unukovich, Anatoly, and Anoshko, Jadwiga, 2012, Geologo-ekonomicheskaya otsenka mestorozhdeniy poleznykh iskopayemykh Belarusi [Geological and economic evaluation of mineral deposits in Belarus]: Minsk, Belarusian Navuka, 456 p.

Yermakov, V., and Galushko, S., 2002, Iodized salt situational analysis in Ukraine: Kiev, United Nations Children's Fund (UNICEF), 34 p.

U.S. Department of State, 2009, Small-scale digital international land boundaries (SSIB)—Lines, edition 10, and polygons, beta edition 1, in Boundaries and sovereignty encyclopedia (B.A.S.E.): U.S. Department of State, Office of the Geographer and Global Issues.

Vysotskiy, E.A., Kislik, V.Z., and Proasevich, B.A., 1981, O paleotecktonicheskoy obstanovke nakopleniya kaliynykh soley v famenskiy vek v Pripyatskom progiba [The paleotectonic setting of potash salt accumulation during the Famennian Epoch in the Pripyat Basin], *in* Yanshin, A.L., and Zharkov, M.A., eds., Stroyeniye I usloviya formirovaniya mestorozhdeniy kaliynykh soley [The structure and formation conditions of potash salt deposits]: Novosibirsk, Izd. Nauka, Sbirdk. Otel., USSR, p. 67–73.

Vysotskiy, E.A., Kislik, V.Z., Sedun, E.V., and Vishnevskiy, V.N., 1990, Zony zameshcheniya v III kaliynom gorizonte Krasnoslobodskogo uchastka i kriterii ikh prognozirovaniya [Potash localization zone in Krasnoslobodsk Mine and its exploration criteria], *in* Merzlyakov, G.A., and Zharkov, M.A., eds., Usloviya obrazovaniya mestorozhdenii kaliinykh solei [The conditions of the formation of potash salt deposits]: Novosibirsk, Izdatel'stvo Nauka, p. 132–138.

Vysotskiy, E.A., Garetsky, R.G., and Kislik, V.Z., 1988, Kalienosnye basseiny mira [Potassium-bearing basins of the world]: Minsk, Izd. Nauka i Tekh, Byelorussian SSR, 387 p.

Vysotskiy, E.A., Makhnach, A.A., Peryt, T.M., and Kruchek, S.A., 2004, Marine and continental Lower Permian evaporites of the Prypiac' Trough (Belarus): Sedimentary Geology, v. 172, p. 211–222.

Vysotskiy, E.A., Petrova, N.S., Dashkevich, V.P., Plutenko, V.S., and Linnik, I.A., 2001, Geological structure and conditions of formation of the Oktyabrsky potash salt deposit in the Pripyat trough [in Russian]: LITASFERA (Lithosphere), v. 2, no. 15, p. 52–64.

Wardlaw, N.C., 1968, Carnallite-sylvite relationships in the Middle Devonian Prairie Evaporite Formation, Saskatchewan: Geological Society of America Bulletin, v. 79, p. 1273–1294.

Warren, J.K., 2006, Evaporites—Sediments, resources and hydrocarbons: Berlin, Springer-Verlag, 1035 p.

Warren, J.K., 2008, Salt as sediment in the Central European Basin system as seen from a deep time perspective, *in* Littke, Ralf, Bayer, Ulf, and Gajewski, Dirk, eds., Dynamics of complex intracontinental basins: Berlin, Springer-Verlag, p. 249–276.

Warren, J.K., 2010, Evaporites through time—Tectonic, climatic, and eustatic controls in marine and nonmarine deposits: Earth-Science Reviews, v. 98, nos. 3–4, p. 217–268.

Wilson, M., and Lyashkevich, Z.M., 1996, Magmatism and the geodynamics of rifting of the Pripyat-Dnieper-Donets rift, East European Platform: Tectonophysics, v. 268, p. 65–81.

Wittrup, M.B., and Keyser, T.K., 1990, The petrogenesis of brines in Devonian potash deposits of western Canada: Chemical Geology, v. 82, p. 103–128.

Wysocki, E., Machnacz, A., Kruczek, S., and Gulis, L., 2005, Stages of Paleozoic potash deposits formation in the Pripyat Trough (Belarus): X International Symposium on Salt "Quo Vadis Sal," Polish Salt Mining Association p. 85–86.

Wysocki, E., Machnacz, A., Kruczek, S., Gulis, L., Czapowski, G., Tomassi-Morawiec, H., Bornemann, O., and Schramm, M., 2006, Characteristics and genesis of the Upper Devonian potash deposit in the Prypec Basin (Soligorsk Area, Belarus)—Preliminary report: XI International Symposium on Salt "Quo Vadis Sal", Polish Salt Mining Association, p. 67–68.

Yakushkin, I.V., 1964, Tectonic structure of the Pripyat Trough: International Geology Review, v. 6, no. 1, p. 58–67.

Yang, C., Jensen, G., and Berenyi, J., 2009, The stratigraphic framework of the potash-rich members of the Middle Devonian upper Prairie Evaporite Formation, Saskatchewan, in Summary of Investigations 2009 Volume 1: Saskatchewan Geological Survey Miscellaneous Report 2009–4.1, Paper A-4, 28 p.

Zambito, J.J., IV, and Benison, K.C., 2013, Extreme high temperatures and paleoclimate trends recorded in Permian ephemeral lake halite: Geology, v. 41, p. 587–590.

Zhamoida, A.I., 1984, Comparing the Soviet stratigraphic code with the international guide: Episodes, v. 7, no. 1, p. 9–11.

Zharkov, M.A., 1984, Paleozoic salt bearing formations of the world: New York, Springer-Verlag, 427 p.

Zui, V.I., 2015, Geothermal resources, country update for Belarus: Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015, 14 p., accessed February 3, 2017, at https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/01022.pdf.

Appendixes A–H

Appendix A. Summary Descriptive Model of Stratabound Potash-Bearing Salt Deposits

By Mark D. Cocker[1] and Greta J. Orris[1]

Introduction

Stratabound potash-bearing salt is associated with thick sections of evaporitic salt (halite) that form laterally continuous strata in marine evaporite basins. Deposits are extremely soluble and are easily altered or destroyed over geologic time. Stratabound potash deposits range in size from several tens of millions to more than 30 Bt of potassium oxide (K_2O). Most of the world's potash resources are associated with this deposit type.

Representative Deposits

Examples of stratabound potash-bearing salt deposits include those in the Givetian (Middle Devonian) Elk Point Basin in Canada, the Frasnian and Famennian (Upper Devonian) Pripyat Basin in Belarus, and the Lopingian (upper Permian) Solikamsk Basin in Russia (fig. A–1). Some larger basins, such as the Lopingian Zechstein Basin in Europe (fig. A–1, location 4) and the Central Asia Salt Basin (fig. A–1, location 9), contain potash-bearing salt in both stratabound and halokinetic (appendix B) forms.

Brief Description

Synonyms

Synonyms for stratabound potash-bearing salt deposits include potash deposits, potash-bearing salt deposits, bedded potash, and marine potash.

Principal Commodities and Byproducts

The principal products of potash mining are potassium chloride (KCl), which is referred to as muriate of potash (MOP), and potassium sulfate (K_2SO_4), which is referred to as sulfate of potash (SOP). Where carnallite ($KMgCl_3 \cdot 6H_2O$) constitutes a major part of a deposit, magnesium may be recovered. The main byproduct commodity is halite or rock salt.

[1]U.S. Geological Survey, Tucson, Arizona, United States.

Relative Importance of the Deposit Type

Stratabound potash-bearing salt deposits may contain billions to trillions of tons of mineralized rock and are amenable to relatively low-cost, bulk underground mining methods. Approximately 75 percent of the world's potash production is from stratabound potash-bearing salt deposits, and more than 25 percent of that production is from the Middle Devonian Prairie Evaporite Formation of the Elk Point Basin in Saskatchewan, Canada.

Global Distribution

The largest and economically most important deposits of potash are found in North America, Europe, and Asia. Newly explored deposits in Africa and South America are increasingly important.

Associated/Related Deposit Types

Stratabound potash-bearing salt deposits are associated with stratabound and bedded gypsum, anhydrite, halite, and sulfur deposits (Long, 1992). Halokinetic potash-bearing salt deposits (see appendix B, this report) originally formed in the same manner as stratabound deposits, but deformation of salt resulted in grade and tonnage differences between these two end member deposit types. Stratabound and halokinetic potash-bearing salt may occur concurrently in some larger basins.

Descriptive and Genetic Synopsis

Potash-bearing salt is a chemically deposited sedimentary rock made up of fine- to coarse-grained, potassium- and magnesium-chloride and sulfate minerals intergrown with halite. Beds of laterally continuous stratabound potash-bearing salt occur within thick sections of halite-dominant evaporite deposits. Potash-bearing strata range from centimeters to meters in thickness, and potash-bearing intervals may consist of one bed or numerous thin layers.

These deposits are commonly attributed to evaporation of large volumes of seawater in hydrographically restricted or isolated basins under hyperarid climatic conditions (Warren, 2006, 2010; Kendall, 2010). Progressive evaporation of saline water (usually seawater) and salt precipitation contribute to

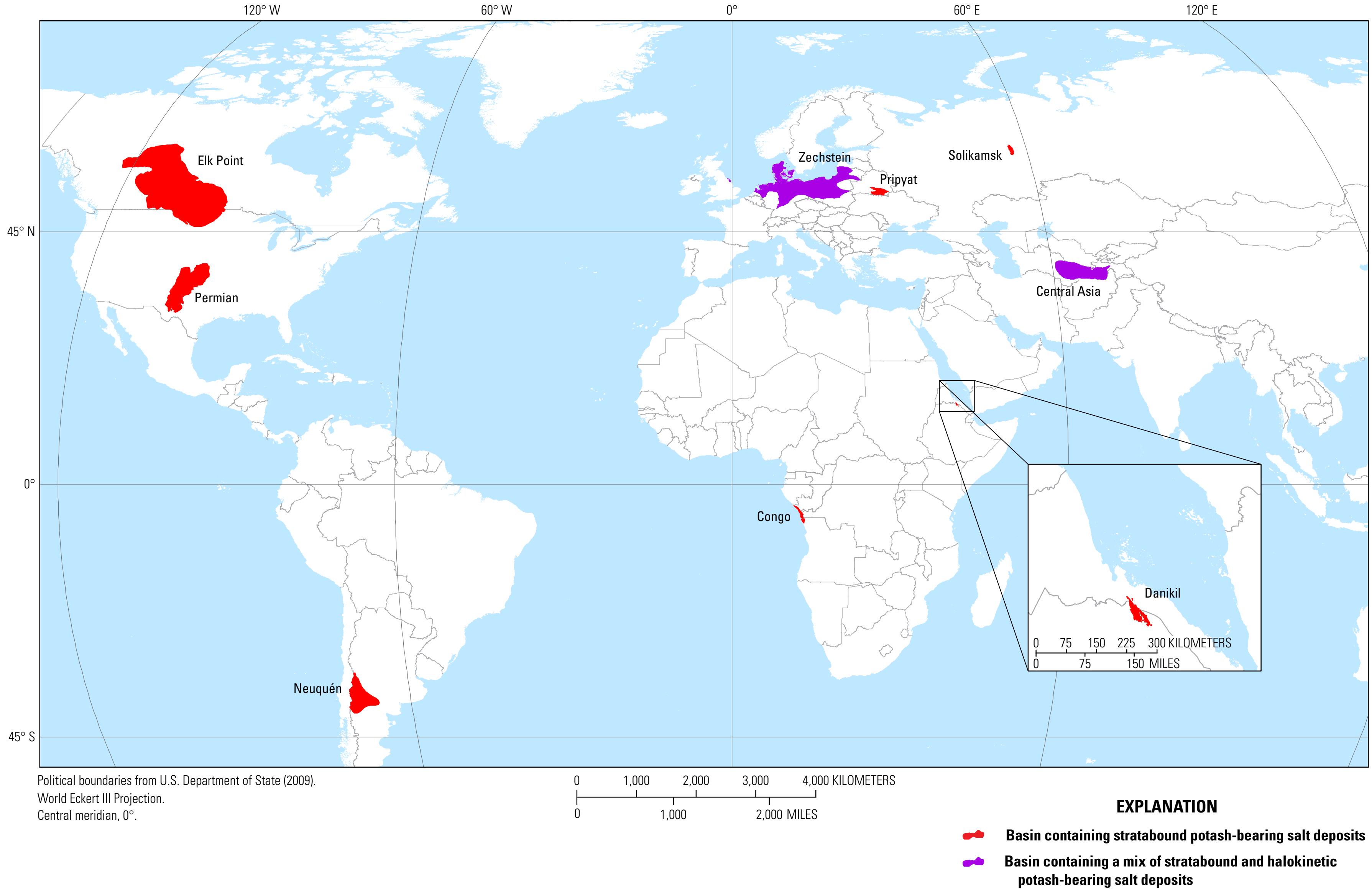


Figure A–1. Map showing locations of basins containing stratabound potash-bearing salt deposits and those containing a mix of stratabound and halokinetic potash-bearing salt deposits (from Orris and others, 2014).

increasingly hypersaline conditions, formation of bitterns, and eventual deposition of potassium- and magnesium-bearing minerals. Multiple episodes of saline water inflow result in cyclic deposition of potash minerals and yield deposits that are many tens of meters thick.

Permissive Tract Delineation

The fundamental geologic feature for delineation of tracts permissive for stratabound potash-bearing salt is an evaporite-bearing sedimentary basin that contains halite-dominated areas and evidence that evaporation reached the bittern stage. Evidence of potash mineralization includes reports of the presence of sylvite, carnallite, polyhalite, or other potassium saline minerals, or indirect evidence from downhole geophysical surveys.

Permissive tracts are outlined by selecting basins with known evaporites, restricting tract boundaries to areas likely underlain by salt at depths of 3 km or less, and if possible, using drill hole or other information to limit tracts to areas underlain by potash-bearing salt. Halite-rich layers are preferably many tens to hundreds of meters thick and (or) areally extensive.

Regional Geologic Attributes

Tectonic Setting of Basin

Stratabound potash-bearing salt is found in sedimentary basins that formed in regions of arid climate. Tectonic plate interactions that formed basins located between 15° and 45° north and south of the equator were likely places for stratabound potash-bearing salt deposition. Deposits have been described in continental and oceanic rift basins, foreland basins, intracontinental sag basins, and in transform basins that are products of the breakup (or failed breakup) of continents, convergence or collision of continental plates, or intraplate thinning and weakening (Warren, 2010). Basin type is less critical than climatic conditions at the time of deposition. Hot, hyperarid climatic conditions are necessary to form brines from saline waters and deposit evaporites. These conditions may result from global scale atmospheric wind circulation patterns (Warren, 2010). Many of the world's deserts are near latitudes of 30° N and 30° S, which correspond to the boundary between atmospheric circulation cells.

Depositional Systems

In an evaporite basin, near-shore, shallow clastic facies rocks grade to carbonate-, then sulfate-, then halide-rich rocks towards the central part of a basin or parts more distal from the point of seawater influx. Central parts of an evaporite basin may have facies representing shallow water to deep water (Schmalz, 1969; Warren, 2006; Kendall, 2010). The resulting stratigraphic sequence begins with minor clastic red beds, followed by carbonate rocks, anhydrite or gypsum, salt, and ends with potash-bearing salt. Multiple episodes of evaporite mineral precipitation may be recorded in cyclic sequences of rock layers, with individual cyclic units from a few centimeters to hundreds of meters thick.

Age Range and Age-Related Features

Potash-bearing salt deposits are found in Neoproterozoic or younger basins (Zharkov, 1984, 2005; Goncharenko, 2006; Kovalevych and others, 2006; Warren, 2006, 2008). Half of the world's known potash-containing basins are Middle and Late Devonian, Permian, or Paleogene-Neogene (Goncharenko, 2006).

Differences in deposit mineralogy likely reflect temporal changes in global seawater chemistry. During the Phanerozic, marine brine chemistry appears to have oscillated between Na-K-Mg-Ca-Cl and Na-K-Mg-Cl-SO_4 types (Hardie, 1990, 1996; Holland and others, 1996; Horita and others, 2002; Kovalevych and others, 1998; Ries, 2010; Warren, 2006). Magnesium sulfate-poor deposits dominated by sylvite and carnallite are derived from the Na-K-Mg-Ca-Cl brines. Magnesium-rich sulfate type deposits, with variable amounts of K- and Mg-sulfate minerals, may form from Na-K-Mg-Cl-SO_4 brines. Local environmental conditions may be significant factors in basin brine geochemistry.

Local Geologic Attributes and Deposit Characteristics

Host Rocks

Host rocks are evaporitic sedimentary rocks, such as rock salt, sylvinite, carnallitite, kainitite, hartsalz, anhydrite, and gypsum. Mineralized rock strata consist of potash salt minerals, including chlorides, sulfates, and halite, in evaporite sequences.

Deposit Characteristics

Deposit Form and Dimensions

Stratabound potash-bearing salt deposits are composed of one or more layers or beds of potash-bearing salt. The beds or layers or groups of layers are commonly laterally continuous across large areas of a basin. Individual potash beds or layers range in thickness from less than a meter to several tens of meters, to almost a hundred meters (rare). A sequence of potash-bearing salt beds may range from tens of meters to a few hundred meters thick. The areal extent of potash mineralization is ultimately limited by basin size at time of deposition. Typical volumes of stratabound potash-bearing salt can be hundreds to thousands of cubic kilometers.

Mineralogy

Ore Mineralogy

Primary ore minerals include sylvite, carnallite, kainite, polyhalite, and langbeinite (table A–1). These minerals are most commonly found as intergrowths with halite.

Ore Assemblages

Dominant ore assemblages contain sylvite and halite with minor (less than 6 weight percent) carnallite or carnallite plus halite with negligible amounts of sylvite. Some deposits may contain ore assemblages of kainite, langbeinite, polyhalite, kieserite, and (or) bischofite mixed with halite and gypsum or anhydrite.

Gangue Mineralogy

Gangue minerals include halite, clay minerals, dolomite, anhydrite, gypsum, bischofite, epsomite, tachyhydrite, leonite, blödite, hexahydrite, vanthoffite, löweite, aphthitalite, picromerite, and borate minerals (table A–1). Sonnenfeld (1991) noted the presence of halloysites, kaolinite, iron-chlorite, magnesium-chlorites, montmorillonite, palygorskite, illite, sepiolite, and muscovite in evaporite basins.

Primary mineral zoning may consist of an outer or stratigraphically lower zone dominated by sulfates such as anhydrite or gypsum, changing to a halite-dominated zone, and culminating with an inner or upper zone containing halite plus potassium chloride or potassium sulfate minerals. Under certain conditions at the end of an evaporation sequence, some other bittern minerals such as tachyhydrite or bischofite may also be present and preserved. These minerals are highly soluble and are commonly no longer present in most of these deposits.

Effects of Alteration

Potash-bearing salt is highly soluble and susceptible to alteration, recrystallization, and dissolution by surface water, less saline brine, and groundwater (Warren, 2010).

Table A–1. Ore minerals and common accessory and gangue minerals in stratabound potash-bearing salt deposits.

[From Orris and others (2014). Composition formulas from Back and Mandarino (2008)]

Ore minerals	Composition	Other minerals	Composition
Carnallite	$KMgCl_3 \cdot 6H_2O$	Aphthitalite	$(K,Na)_3Na(SO_4)_2$
Kainite	$MgSO_4 \cdot KCl \cdot 3H_2O$	Anhydrite	$CaSO_4$
Langbeinite	$K_2Mg_2(SO_4)_3$	Bischofite	$MgCl \cdot 6H_2O$
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$	Blödite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$
Sylvite	KCl	Boracite	$Mg_7B_7O_{13}Cl$
		Dolomite	$CaMg(CO_3)_2$
		Epsomite	$MgSO_4 \cdot 7H_2O$
		Gypsum	$CaSO_4 \cdot 2H_2O$
		Halloysite	$Al_2Si_2O_5(OH)_4$
		Halite	NaCl
		Hexahydrite	$MgSO_4 \cdot 6H_2O$
		Kaolinite	$MgSO_4 \cdot H_2O$
		Kieserite	$MgSO_4 \cdot H_2O$
		Kurnakovite	$K_2Mg(SO_4)_2 \cdot 4H_2O$
		Leonite	$Na_{12}Mg_7(SO_4)_{13} \cdot 15H_2O$
		Löweite	$(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$
		Lüneburgite	$Mg_3B_2(PO_4)_2(OH)_6 \cdot 6H_2O$
		Montmorillonite	$(Mg,Al)_2Si_4O_{10}(OH) \cdot 4H_2O$
		Palygorskite	$K_2Mg(SO_4)_2 \cdot 6H_2O$
		Picromerite	$Mg_4Si_6O_{15}(OH)_2 \cdot 6H_2O$
		Sepiolite	$CaMgCl_6 \cdot 12H_2O$
		Tachyhydrite	$Na_6Mg(SO_4)_4$
		Vanthoffite	$Na_6Mg(SO_4)_4$
		Volkovskite	$KCa_4B_{22}O_{32}(OH)_{10}Cl \cdot 4H_2O$

Groundwater dissolution can modify the mineralogy, layering, grain size, or porosity, or it can totally destroy a deposit. Increased pressure and temperature related to burial metamorphism can also lead to recrystallization and destruction of primary textures and changes in grain size.

Exploration Guides

Geochemical Signature(s)

In many primary deposits, brines in boreholes may be anomalous in potassium, sodium, magnesium, bromine, chlorine, and sulfur (Rogers, 2011). Exceptionally saline wells and saline spring water are indicative of an evaporite sequence and have historically led to discoveries of concealed salt and potash deposits.

Bromine content of halite increases as brine salinity increases; bromine profiles show increasing-upwards trends in unaltered evaporite cycles. Residual brines at this stage may contain hundreds of parts per million bromine, and about a thousand parts per million or more bromine during precipitation of potash minerals, although reported values are typically much lower because of dilution and dissolution, diagenesis, and brine fluctuations (Webb and Stewart, 2011).

Geophysical Signature(s)

Radiometric signatures

High gamma radiation signatures from the natural isotope potassium-40 (K^{40}) are used to map potassium content of salt in downhole geophysical surveys (Garrett, 1996).

Seismic signatures

Reflection seismic methods are used to delineate salt structures and layers (Fox, 1987; Simeonova and Iasky, 2005).

Other Exploration Guides

Except for drilling confirmation of potash, there are few sure indications of the presence of potash-bearing salt. Thick sections of halite, usually greater than 100 m, are believed to be necessary prior to potash deposition (Harben and Kužvart, 1996), and this could be used in conjunction with other data to identify or rank potash potential of basins with little exploration history.

Typical Grade and Tonnage

Average reported potash grades in explored deposits of this type may range from 5.3 percent to 38 percent K_2O (de Ruiter, 1979; Kumar and Bakliwal, 2005). Most reported grades in operating mines range from 11 to 25 percent K_2O. In general, the lowest average grade that is currently being mined is in the range of 8–10 percent K_2O, with the lowest associated cutoff grade below 4 percent K_2O.

The minimum thickness of a potash layer that is being mined is about 1 m. In Saskatchewan, minimal mining thicknesses range from 2.44 to 3.35 m because of the mining equipment used and the thickness of the highest grade ore in different mines (Moore and others, 2010a,b,c,d, 2011).

Reported tonnages for potash deposits range from a few tens of millions to 30 Bt (British Sulphur Corporation Limited, 1984; Hardy and others, 2009). Reported tonnages since 2000 for greenfield potash projects that reported NI 43-101-compatible reserves and resources largely exceed 500 Mt, and commonly, 1 Bt, of potash ore (Rauche and van der Klauw, 2009, 2012; South Boulder Mines, 2012; BHP Billiton, 2010; Western Potash, 2010).

References Cited

Back, Malcolm, and Mandarino, J.A., 2008, Fleischers glossary of mineral species 2008: Mineralogical Record, Inc., 346 p.

BHP Billiton, 2010, BHP Billiton announces mineral resource estimate for its Jansen potash project: BHP Billiton news release, June 7, 2010, 2 p., accessed June 26, 2010, at http://www.bhpbilliton.com/bb/investorsMedia/news/2010/.

British Sulphur Corporation Limited, 1984, World survey of potash resources (4th ed.): London, British Sulphur Corporation Limited, 145 p.

de Ruiter, P.A.C., 1979, The Gabon and Congo Basins salt deposits: Economic Geology, v. 74, no. 2, p. 419–431.

Fox, James, 1987, Seismic interpretation in salt-controlled basins: The Leading Edge, v. 6, no. 3, p. 11–18.

Garrett, D.E., 1996, Potash—Deposits, processing, properties and uses: New York, Chapman & Hall, 734 p.

Goncharenko, O.P., 2006, Potassic salts in Phanerozoic evaporite basins and specific features of salt deposition at the final stages of halogenesis: Lithology and Mineral Resources, v. 41, no. 4, p. 378–388.

Harben, P.W., and Kužvart, M., 1996, Industrial minerals—A global geology: London, Industrial Minerals Information Ltd., 462 p.

Hardie, L.A., 1990, The roles of rifting and hydrothermal $CaCl_2$ brines in the origin of potash evaporites—An hypothesis: American Journal of Science, v. 290, no. 1, p. 43–106.

Hardie, L.A., 1996, Secular variation in seawater chemistry—An explanation for the coupled secular variation in the mineralogies of marine limestones and potash evaporites over the past 600 m.y.: Geology, v. 24, p. 279–283.

Hardy, M., Halabura, S.P., and Shewfelt, D., 2009, Technical Report—2009 potash resource assessment for Subsurface Mineral Permit KP 289, Saskatchewan: Agapito Associates, Inc., North Rim Exploration Ltd., 163 p.

Holland, H.D., Horita, Juske, and Seyfried, W.E., Jr., 1996, On the secular variation in the composition of marine potash evaporates: Geology, v. 24, no. 11, p. 993–996.

Horita, Juske, Zimmerman, Heide, and Holland, H.D., 2002, Chemical evolution of seawater during the Phanerozoic—Implications from the record of marine evaporites: Geochimica et Cosmochimica Acta, v. 66, no. 21, p. 3733–3756.

Kendall, A.C., 2010, Marine evaporites, *in* James, N.P., and Dalrymple, R.W., eds., Facies models 4: Geological Association of Canada, GEOtext 6, p. 505–540.

Kovalevych, V.M., Peryt, T.M., and Petrychenko, O.Y., 1998, Secular variation in seawater chemistry during the Phanerozoic as indicated by brine inclusions in halite: Journal of Geology, v. 106, p. 695–712.

Kovalevych, V.M., Marshall, T., Peryt, T.M., Petrychenko, O.Y., and Zhukova, S.A., 2006, Chemical composition of seawater in Neoproterozoic—Results of fluid inclusion study of halite from Salt Range (Pakistan) and Amadeus Basin (Australia): Precambrian Research, v. 144, p. 39–51.

Kumar, V., and Bakliwal, P.C., 2005, Potash in India: Geological Survey of India Miscellaneous Publication 65, 131 p.

Long, K.R., 1992, Descriptive model of stratabound sulfur and contained-sulfur model of stratabound sulfur: U.S. Geological Survey Open-File Report 92–0705, 8 p.

Moore, G., Danyluk, T.K., Franklin, B., Prugger, A., and Vander Most, A., 2010a, National Instrument 43–101 technical report on Allan potash deposit (KL–112R), Saskatchewan, Canada: Saskatoon, Sask., Potash Corporation of Saskatchewan Inc., 62 p.

Moore, G., Danyluk, T.K., Franklin, B., Prugger, A., and Vander Most, A., 2010b, National Instrument 43–101 technical report on Cory potash deposit (KL–103R), Saskatchewan, Canada: Saskatoon, Sask., Potash Corporation of Saskatchewan Inc., 63 p.

Moore, G., Danyluk, T.K., Franklin, B., Prugger, A., and Vander Most, A., 2010c, National Instrument 43–101 technical report on Lanigan potash deposit (KLSA–001), Saskatchewan, Canada: Saskatoon, Sask., Potash Corporation of Saskatchewan Inc., 65 p.

Moore, G., Danyluk, T.K., Franklin, B., Prugger, A., and Vander Most, A., 2010d, National Instrument 43–101 technical report on Rocanville potash deposit (KLSA–002), Saskatchewan, Canada: Saskatoon, Sask., Potash Corporation of Saskatchewan Inc., 68 p.

Moore, Garth, Danyluk, T.K., Franklin, Bob, Prugger, Arnfinn, and Vander Most, Anastasia, 2011, National Instrument 43–101 technical report on Rocanville potash deposit (KLSA–002) Saskatchewan, Canada: Saskatoon, Sask. Potash Corporation of Saskatchewan, Inc., 68 p.

Rauche, Henry, and van der Klauw, S.N.G.C., 2009, Updated reserve and resource estimate for MagMinerals Kouilou potash project, Republic of Congo: Technical report prepared for MagMinerals Inc., 209 p., accessed August 15, 2011, at http://www.magindustries.com/cmsdocs/Technical%20Reports/08-016_NI-43-101_Updated_Reserve-Report_June_2009_rev01.pdf.

Rauche, Henry, and Van der Klauw, S.N.G.C., 2012, Preliminary economic assessment, sylvinite mining in the Danakhil potash deposit, Afar State, Ethiopia—Preliminary economic assessment study: Erfurt, Germany, ERCOPSPLAN Ingenieurgesellschaft, 131 p. [plus appendixes.]

Ries, J.B., 2010, Review—Geological and experimental evidence for secular variation in seawater Mg/Ca (calcite-aragonite seas) and its effect on marine biological calcification: Biogeosciences, v. 7, p. 2795–2849.

Rogers, M.C., 2011, Saskatchewan descriptive mineral deposit models: Saskatchewan Ministry of Energy and Resources Open File Report 2011–57, 112 p.

Schmalz, R.F., 1969, Deep-water evaporite deposition—A genetic model: American Association of Petroleum Geologists Bulletin, v. 53, no. 4, p. 798–823.

Simeonova, A.P., and Iasky, R.P., 2005, Seismic mapping, salt deformation, and hydrocarbon potential of the central western Officer Basin, Western Australia: Western Australia Geological Survey Report 98, 49 p., plus appendixes.

Sonnenfeld, P., 1991, Evaporite basin analysis, *in* Force, E.R., Eidel, J.J., and Maynard, J.B., Sedimentary and diagenetic mineral deposits—A basin analysis approach to exploration: Reviews in Economic Geology Volume 5, p. 159–169.

South Boulder Mines, 2012, Colluli potash project: Web site, accessed April 17, 2012, at http://www.southbouldermines.com.au/projects/colluli-potash-project/.

U.S. Department of State, 2009, Small-scale digital international land boundaries (SSIB)—Lines, edition 10, and polygons, beta edition 1, *in* Boundaries and Sovereignty Encyclopedia (B.A.S.E.): U.S. Department of State, Office of the Geographer and Global Issues.

Warren, J.K., 2006, Evaporites—Sediments, resources and hydrocarbons: Berlin, Springer-Verlag, 1,035 p.

Warren, J.K., 2008, Salt as sediment in the Central European Basin system as seen from a deep time perspective, *in* Littke, Ralf, Bayer, Ulf, and Gajewski, Dirk, eds., Dynamics of complex intracontinental basins: Berlin, Springer-Verlag, p. 249–276.

Warren, J.K., 2010, Evaporites through time—Tectonic, climatic, and eustatic controls in marine and nonmarine deposits: Earth-Science Reviews, v. 98, issues 3–4, February 2010, p. 217–268.

Webb, T.C., and Stewart, H.J., 2011, Bromine as an indicator of potash mineralization in Carboniferous marine evaporites, Sackville Subbasin, southeastern New Brunswick: New Brunswick Department of Natural Resources, Lands, Minerals and Petroleum Division Mineral Resource Report 2011-1, 40 p.

Western Potash, 2010, Western Potash Corp. updates measured and indicated potash resource to 174 million tonnes: Western Potash Corp Web page, accessed July 5, 2010, at http://www.westernpotash.com/.

Zharkov, M.A., 1984, Paleozoic salt bearing formations of the world: New York, Springer-Verlag, 427 p.

Zharkov, M.A., 2005, Evolyutsiya evaporitov v dokembrii v svyazi s preobrazovaniyami biosfery i khimicheskogo sostava mirovogo okeana; Stat'ya 1, Evapority arkheya i rannego proterozoya [Evolution of Precambrian evaporites, transformation of biosphere and the world oceans' chemical composition—Paper 1, Archean and Paleoproterozoic evaporites]: Stratigrafiya, Geologicheskaya Korrelyatsiya, v. 13, no. 2, p. 19–29.

Appendix B. Summary Descriptive Model of Halokinetic Potash-Bearing Salt Deposits

By Mark D. Cocker[1] and Greta J. Orris[1]

Introduction

Halokinetic potash-bearing salt occurs in salt structures developed from stratabound potash-bearing salt deposits where differential loading by thick overlying sediments initiated and drove upward movement of low density potash-bearing salt. The original stratabound salt beds are disrupted during halokinesis, resulting in complexly deformed lenses and beds of potash-bearing salt. Potash deposits within salt structures range in size from 1 to more than 1,000 Mt. Most mined halokinetic potash deposits are from 50 to several hundred million metric tons in size.

Representative Deposits

Some of the best known halokinetic potash-bearing salt deposits occur in the evaporites of the Lopingian (upper Permian) Zechstein Basin of Germany, Poland, The Netherlands, and Denmark; the Cisuralian (lower Permian) Pricaspian Basin of Kazakhstan and Russia; the Middle Pennsylvanian of the Paradox Basin in the United States; and the Miocene Carpathian Basin of Romania and Ukraine (fig. B–1). Some larger basins, such as the Zechstein Basin (fig. B–1, location 2) and the Central Asia Salt Basin (fig. B–1, location 7) contain potash-bearing salt in both halokinetic and stratabound (appendix A) forms.

Brief Description

Synonyms

Synonyms for this type of deposit include potash deposits, potash-bearing salt deposits, diapiric potash, marine potash, and halokinetic potash-bearing salt deposits.

Principal Commodities and Byproducts

The principal products of potash mining are potassium chloride (KCl), which is referred to as muriate of potash (MOP), and potassium sulfate (K_2SO_4), which is referred to as sulfate of potash (SOP). Where carnallite ($KMgCl_3 \cdot 6H_2O$) constitutes a major portion of a deposit, magnesium may be recovered. The main byproduct commodity is halite or salt.

Relative Importance of the Deposit Type

An estimated 10–15 percent of the world's potash production is from halokinetic potash-bearing salt deposits.

Global Distribution

The largest known deposits are found in Europe and Central Asia.

Associated/Related Deposit Types

Some salt structures may contain associated gypsum, sulfur, iodine, bromine, or borate deposits (Long, 1992; Raup, 1991). Salt structures and associated fault-related features commonly form hydrocarbon traps (Long, 1992; Kyle and Posey, 1991). Because stratabound potash-bearing salt deposits have not suffered the deformation characteristic of halokinetic potash-bearing salt deposits, there are important differences in grades and tonnages between these two end-member deposit types. Stratabound and halokinetic potash-bearing salt may both occur in some larger basins.

Descriptive and Genetic Synopsis

Halokinetic potash-bearing salt deposits are the layers or beds of stratabound potash-bearing salt deposits that have moved by plastic flow into a salt structure along with the enclosing sedimentary rock, most of which is salt. The internal structure of the salt layers, and hence the potash-bearing salt layers, can be simple to complex, and the original continuity and thickness of the potash-rich layers may be altered considerably by internal deformation.

Structural deformation of low-density salt may be related to differential loading or unloading of the sedimentary sequence and local or regional tectonic activity. Halokinetic salt structures are generally developed in tectonically active salt basins such as rift or foreland basins.

[1]U.S. Geological Survey, Tucson, Arizona, United States.

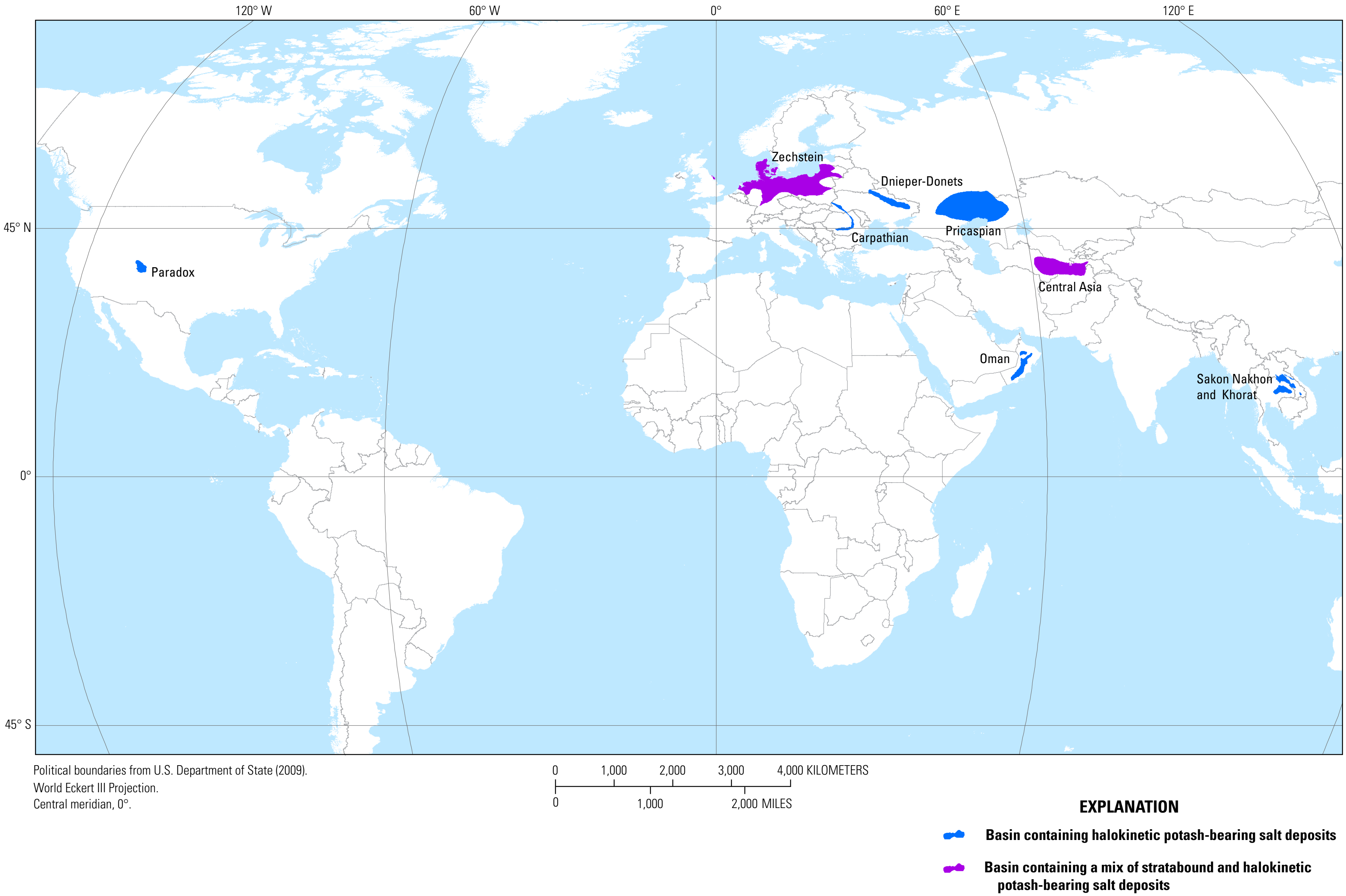


Figure B–1. Map showing locations of basins containing halokinetic potash-bearing salt deposits and those containing a mix of stratabound and halokinetic potash-bearing salt deposits (from Orris and others, 2014).

Permissive Tract Delineation

The fundamental unit for delineation of tracts permissive for potash-bearing bedded salt is an evaporite-bearing sedimentary basin that contains halite-dominated areas and evidence that evaporation reached the bittern stage. Evidence of potash mineralization includes reports of the presence of sylvite, carnallite, polyhalite, other potassium saline minerals, or indirect evidence from downhole geophysical surveys.

Permissive tracts for halokinetic potash-bearing salt deposits are outlined by (1) selecting basins with known halokinetic salt; (2) restricting tract boundaries to areas likely underlain by halokinetic salt at depths of 3 km or less; (3) if possible, using drill hole or other information to limit tracts to areas underlain by potash-bearing salt, and (4) delineating specific salt structures likely to contain potash-bearing salt.

Regional Geologic Attributes

Halokinesis is most common in continental and oceanic rift basins, foreland basins, convergent basins, and transform basins where lateral compression or extension is active. Halokinesis may be initiated by such factors as (1) differential loading through rapid deposition of thick, overlying clastic sediments; (2) differential unloading resulting from listric block faulting during extensional rifting; (3) differential erosion of overlying sedimentary rocks; (4) rift basement block faulting; and (5) compressional or extensional regional tectonic activity (Al-Zoubi and ten Brink, 2001; Amor, 1999; Jarhani and others, 2007; Kityk, 1970).

Depositional Systems

In an evaporite basin, near-shore, shallow, clastic facies rocks grade to carbonate-, then sulfate-, then halide-rich rocks towards the deeper, central parts of a basin. Central parts of an evaporite basin may have facies representing shallow to deep water (Warren, 2006; Kendall, 2010; Schmalz, 1969). The resulting stratigraphic sequence begins with minor clastic red beds, followed by carbonate rocks, anhydrite or gypsum, and salt, and ends with potash-bearing salt. Multiple episodes of evaporite mineral precipitation may be recorded in cyclic sequences of rock layers, with individual cyclic units ranging in thickness from a few centimeters to hundreds of meters. During halokinesis, original depositional layering is partly to wholly disrupted by plastic flow, which may result in complex folding, discontinuous mineralization, or even loss of mineralization.

Age Range and Age-Related Features

Potash-bearing salt deposits are found in Neoproterozoic or younger basins (Zharkov, 1984, 2005; Goncharenko, 2006; Kovalevych and others, 2006; Warren, 2006, 2008). Half the world's known potash-containing basins are Middle and Late Devonian, Permian, or Paleogene-Neogene (Goncharenko, 2006).

Differences in deposit mineralogy likely reflect temporal changes in global seawater chemistry. During the Phanerozic, marine brine chemistry oscillated between Na-K-Mg-Ca-Cl and Na-K-Mg-Cl-SO_4 types (Hardie, 1990, 1996; Holland and others, 1996; Kovalevych and others, 1998; Horita and others, 2002; Warren, 2006; Ries, 2010). Magnesium sulfate-poor deposits dominated by sylvite and carnallite are derived from the Na-K-Mg-Ca-Cl brines. Magnesium-rich sulfate type deposits, with variable amounts of K- and Mg-sulfate minerals, may form from Na-K-Mg-Cl-SO_4 brines. Local environmental conditions may be a significant factor in basin brine geochemistry.

Local Geologic Attributes and Deposit Characteristics

Host Rocks

Host rocks are evaporitic sedimentary rocks, such as rock salt, sylvinite, carnallitite, kainitite, hartsalz, anhydrite, and gypsum. Diapiric structures pierce overlying sediments, so any younger, originally overlying sedimentary rocks may appear to host the salt and potash mineralization.

Impacts of Local Structures

Halokinetic salt structures are commonly aligned over basement faults.

Deposit Characteristics

Deposit Form and Dimensions

The areal extent of salt diapirs ranges from a few to several hundred square kilometers. With a vertical extent ranging from a few hundred meters to more than 10 km, salt volumes of diapirs are about tens to hundreds of cubic kilometers. Potash forms only a small portion of an individual salt diapir.

Mineralogy

Ore Mineralogy

Primary ore minerals include sylvite, carnallite, kainite, polyhalite, and langbeinite (table B–1). These minerals most commonly are found as intergrowths with halite.

Ore Assemblages

The dominant ore assemblages contain sylvite and halite with minor (less than 6 weight percent) carnallite or carnallite plus halite and negligible amounts of sylvite. Some deposits may contain ore assemblages of kainite, langbeinite, polyhalite, kieserite, and (or) bischofite mixed with halite and gypsum or anhydrite.

Gangue Mineralogy

Gangue minerals include halite, clay minerals, dolomite, anhydrite, gypsum, bischofite, epsomite, tachyhydrite, leonite, blödite, hexahydrite, vanthoffite, löweite, aphthitalite, picromerite, and borate minerals (table B–1). Sonnenfeld (1991) noted the presence of halloysites, kaolinite, iron-chlorite, magnesium-chlorites, montmorillonite, palygorskite, illite, sepiolite, and muscovite in evaporite basins.

Primary mineral zoning may consist of an outer or stratigraphically lower zone dominated by sulfates such as anhydrite or gypsum, changing to a halite-dominated zone, and culminating with an inner or upper zone containing halite plus potassium chloride or potassium sulfate minerals. Under certain conditions at the end of an evaporation sequence, some other bittern minerals, such as tachyhydrite or bischofite, may also be present and preserved. These minerals are highly soluble and are commonly no longer present in most of these deposits.

Table B–1. Ore minerals and common accessory and gangue minerals in halokinetic potash-bearing salt deposits.

[From Orris and others (2014). Composition formulas from Back and Mandarino (2008)]

Ore minerals	Composition	Other minerals	Composition
Carnallite	$KMgCl_3 \bullet 6H_2O$	Aphthitalite	$(K,Na)_3Na(SO_4)_2$
Kainite	$MgSO_4 \bullet KCl \bullet 3H_2O$	Anhydrite	$CaSO_4$
Langbeinite	$K_2Mg_2(SO_4)_3$	Bischofite	$MgCl \bullet 6H_2O$
Polyhalite	$K_2Ca_2Mg(SO_4)_4 \bullet 2H_2O$	Blödite	$Na_2Mg(SO_4)_2 \bullet 4H_2O$
Sylvite	KCl	Boracite	$Mg_7B_7O_{13}Cl$
		Dolomite	$CaMg(CO_3)_2$
		Epsomite	$MgSO_4 \bullet 7H_2O$
		Gypsum	$CaSO_4 \bullet 2H_2O$
		Halloysite	$Al_2Si_2O_5(OH)_4$
		Halite	NaCl
		Hexahydrite	$MgSO_4 \bullet 6H_2O$
		Hydroboracite	$CaMgB_6O_8(OH)_6 \bullet 3H_2O$
		Inderite	$Al_2Si_2O_5(OH)_4$
		Kaolinite	$MgSO_4 \bullet H_2O$
		Kaolinite	$MgSO_4 \bullet H_2O$
		Kieserite	$MgSO_4 \bullet H_2O$
		Kurnakovite	$K_2Mg(SO_4)_2 \bullet 4H_2O$
		Leonite	$Na_{12}Mg_7(SO_4)_{13} \bullet 15H_2O$
		Löweite	$(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2 \bullet nH_2O$
		Lüneburgite	$Mg_3B_2(PO_4)_2(OH)_6 \bullet 6H_2O$
		Montmorillonite	$(Mg,Al)_2Si_4O_{10}(OH) \bullet 4H_2O$
		Palygorskite	$K_2Mg(SO_4)_2 \bullet 6H_2O$
		Picromerite	$Mg_4Si_6O_{15}(OH)_2 \bullet 6H_2O$
		Sepiolite	$CaMgCl_6 \bullet 12H_2O$
		Tachyhydrite	$Na_6Mg(SO_4)_4$
		Vanthoffite	$Na_6Mg(SO_4)_4$
		Volkovskite	$KCa_4B_{22}O_{32}(OH)_{10}Cl \bullet 4H_2O$

Mineral Zoning

Secondary zoning due to alteration may be pronounced along the flanks and apexes of salt structures.

Ore Controls

Ore controls peculiar to potash-bearing halokinetic salt structures include (1) zones of primary and secondary potash mineralization, (2) internal structure of salt structures that affects thickness and location of potash beds, and (3) depth to potash ore. Halokinesis may bring potash-bearing salt to shallower depths where they are more amenable to mining.

Effects of Alteration

As they rise to the surface, halokinetic potash-bearing salt structures interact with less saline brine and groundwater. Surface and groundwater may partially dissolve carnallite, removing magnesium chloride and leaving potassium chloride to form sylvite. In the upper portion of a salt structure, dissolution of salt minerals leaves insoluble materials such as gypsum, anhydrite, and clay that form a cap rock that may be may be on the order of tens to a thousand meters thick (Warren, 2006).

Halokinesis can bring potash-bearing salt to the earth's surface or close to it, exposing the salt to surface weathering. In areas of extreme aridity, such as the Middle East, surface weathering is minimal, and salt and potash-bearing salt can exist on the surface.

Exploration Guides

Geochemical Signatures

Primary indicator elements of potash mineralization in rocks and groundwater include potassium, sodium, magnesium, bromine, chlorine, and sulfur as sulfate (Rogers, 2011). Exceptionally saline wells and saline spring water may indicate an evaporite sequence at depth, and have historically led to discoveries of concealed salt and potash deposits.

Geophysical Signatures

Seismic, gravity, and downhole gamma radiation surveys may be useful in delineation of potash-bearing salt. The velocity contrast between salt and most other sedimentary rocks is sufficient that reflection seismic methods are used extensively to delineate salt structures and beds (Ratcliff and others, 1992; Ezersky, 2005). Salt is less dense than most enclosing sediments, so gravity surveys work well to identify and define salt structures (Benassi and others, 2006; Nettleton, 1968). High gamma radiation from the natural isotope K^{40} provides a measure of the potassium content of salt in drill-hole logs (Garrett, 1996). In underground mines, ground penetrating radar may be used to define the structure of the salt diapir (Behlau and Minzerzahn, 2001; Kovin, 2011).

Geomorphic and Physiographic Features

Near-surface diapirs may be expressed as domal or collapse structures that are roughly circular topographic highs or lows. Lakes may form at the crest of near-surface salt structures owing to dissolution of underlying evaporites.

Other Exploration Guides

The most readily detectable features of concealed salt structures that may contain potash include saline wells and springs. Except for drilling confirmation of potash, there are few sure indications of the presence of potash-bearing salt. Thick sections of halite, usually greater than 100 m, are believed to be necessary prior to potash deposition (Harben and Kužvart, 1996), and this feature could be used in conjunction with other data to identify or rank the potash potential of basins with little exploration history.

Typical Grade and Tonnage

Tonnages of these deposits are smaller on average than stratabound potash-bearing salt deposits. However, some of the deposits have reported resources of as much 6–10 Bt in some unusually large and complex salt structures. Grades are highly variable, but commonly average less than 20 percent K_2O.

References Cited

Al-Zoubi, Abdallah, and ten Brink, U.S., 2001, Salt diapirs in the Dead Sea basin and their relationship to Quaternary extensional tectonics: Marine and Petroleum Geology, v. 18, no. 7, p. 779–797.

Amor, H., 1999, Halokinesis and structural evolution of the major features in eastern and southern Tunisian Atlas: Tectonophysics, v. 306, no. 1, p. 79–95.

Back, Malcolm, and Mandarino, J.A., 2008, Fleischers glossary of mineral species 2008: Mineralogical Record, Inc., 346 p.

Behlau, J., and Minzerzahn, G., 2001, Geological and tectonic investigations in the former Morsleben salt mine (Germany) as a basis for the safety assessment of a radioactive waste repository: Engineering Geology, v. 61, p. 83–97.

Benassi, R., Jallouli, C., Hammami, M., and Turki, M.M., 2006, The structure of Jebel El Mourra, Tunisia—A diapiric structure causing a positive gravity anomaly: Terra Nova, v. 18, p. 432–439.

Ezersky, M., 2005, The seismic velocities of the Dead Sea salt applied to the sinkhole problem: Journal of Applied Geophysics, v. 58, no. 1, p. 45–58.

Garrett, D.E., 1996, Potash—Deposits, processing, properties and uses: New York, Chapman & Hall, 734 p.

Goncharenko, O.P., 2006, Potassic salts in Phanerozoic evaporite basins and specific features of salt deposition at the final stages of halogenesis: Lithology and Mineral Resources, v. 41, no. 4, p. 378–388.

Harben, P.W., and Kužvart, M., 1996, Industrial minerals—A global geology: London, Industrial Minerals Information Ltd., 462 p.

Hardie, L.A., 1990, The roles of rifting and hydrothermal $CaCl_2$ brines in the origin of potash evaporites—An hypothesis: American Journal of Science, v. 290, no. 1, p. 43–106.

Hardie, L.A., 1996, Secular variation in seawater chemistry—An explanation for the coupled secular variation in the mineralogies of marine limestones and potash evaporites over the past 600 m.y.: Geology, v. 24, p. 279–283.

Holland, H.D., Horita, Juske, and Seyfried, W.E., Jr., 1996, On the secular variation in the composition of marine potash evaporates: Geology, v. 24, no. 11, p. 993–996.

Horita, Juske, Zimmerman, Heide, and Holland, H.D., 2002, Chemical evolution of seawater during the Phanerozoic—Implications from the record of marine evaporites: Geochimica et Cosmochimica Acta, v. 66, no. 21, p. 3733–3756.

Jarhani, S., Callot, J.-P., Frizon de Lamotte, D., Letouzey, J., and Leturmy, P., 2007, The salt diapirs of the eastern Fars Province (Zagros, Iran)—A brief outline of their past and present, *in* Lacombe, O., Lavé, J., Roure, F., and Vergés, J., eds., Thrust belts and foreland basins: Berlin, Springer, p. 289–308.

Kendall, A.C., 2010, Marine evaporites, *in* James, N.P., and Dalrymple, R.W., eds., Facies models 4: Geological Association of Canada, GEOtext 6, p. 505–540.

Kityk, V.I., 1970, Solianaia tektonika Dneprovskso-Donetskoi vpadiny [Salt tectonics of the Dnieper-Donets Depression]: Kiev, Akad. Nauk Ukrain. SSR, Inst. Geol. Nauk, 201 p.

Kovalevych, V.M., Marshall, T., Peryt, T.M., Petrychenko, O.Y., and Zhukova, S.A., 2006, Chemical composition of seawater in Neoproterozoic—Results of fluid inclusion study of halite from Salt Range (Pakistan) and Amadeus Basin (Australia): Precambrian Research, v. 144, p. 39–51.

Kovalevych, V.M., Peryt, T.M., and Petrychenko, O.Y., 1998, Secular variation in seawater chemistry during the Phanerozoic as indicated by brine inclusions in halite: Journal of Geology, v. 106, p. 695–712.

Kovin, O., 2011, Mapping of evaporite deformation in a potash mine using ground penetration radar—Upper Kama deposit, Russia: Journal of Applied Geophysics, v. 74, p. 131–141.

Kyle, J.R., and Posey, H.H., 1991, Halokinesis, cap rock development, and salt dome mineral resources, *in* Melvin, J.L., ed., Evaporites, petroleum and mineral resources: New York, Elsevier, p. 413–474.

Long, K.R., 1992, Descriptive model of salt-dome sulfur and contained-sulfur model for salt-dome sulfur: U.S. Geological Survey Open-File Report 92–403, 8 p.

Nettleton, L.L., 1968, Gravity anomalies over salt diapirs, northern Spain, *in* Mattox, R.B., Holser, W.T., Odé, H., McIntire, W.L., Short, N.M., Taylor, R.E., and Van Siclen, D.C., eds., Saline deposits: Geological Society of America Special Paper 88, p. 75–82.

Ratcliff, D.W., Gray, S.H., and Whitmore, N.D., Jr., 1992, Seismic imaging of salt structures in the Gulf of Mexico: The Leading Edge, v. 11, p. 15–31.

Raup, O.B., 1991, Descriptive model of salt domes; Deposit subtype—Diapiric salt structures, *in* Orris, G.J., and Bliss, J.D., Some industrial mineral deposit models—Descriptive deposit models: U.S. Geological Survey Open-File Report 91–11A, 73 p.

Ries, J.B., 2010, Review—Geological and experimental evidence for secular variation in seawater Mg/Ca (calcite-aragonite seas) and its effect on marine biological calcification: Biogeosciences, v. 7, p. 2795–2849.

Rogers, M.C., 2011, Saskatchewan descriptive mineral deposit models: Saskatchewan Ministry of Energy and Resources Open File Report 2011–57, 112 p.

Schmalz, R.F., 1969, Deep-water evaporite deposition—A genetic model: American Association of Petroleum Geologists Bulletin, v. 53, no. 4, p. 798–823.

Sonnenfeld, P., 1991, Evaporite basin analysis, *in* Force, E.R., Eidel, J.J., and Maynard, J.B., Sedimentary and diagenetic mineral deposits—A basin analysis approach to exploration: Reviews in Economic Geology Volume 5, p. 159–169.

U.S. Department of State, 2009, Small-scale digital international land boundaries (SSIB)—Lines, edition 10, and polygons, beta edition 1, *in* Boundaries and Sovereignty Encyclopedia (B.A.S.E.): U.S. Department of State, Office of the Geographer and Global Issues.

Warren, J.K., 2006, Evaporites—Sediments, resources and hydrocarbons: Berlin, Springer-Verlag, 1035 p.

Warren, J.K., 2008, Salt as sediment in the Central European Basin system as seen from a deep time perspective, *in* Littke, Ralf, Bayer, Ulf, and Gajewski, Dirk, eds., Dynamics of Complex Intracontinental Basins: Berlin, Springer-Verlag, p. 249–276.

Zharkov, M.A., 1984, Paleozoic salt bearing formations of the world: New York, Springer-Verlag, 427 p.

Zharkov, M.A., 2005, Evolyutsiya evaporitov v dokembrii v svyazi s preobrazovaniyami biosfery i khimicheskogo sostava mirovogo okeana; Stat'ya 1, Evapority arkheya i rannego proterozoya [Evolution of Precambrian evaporites, transformation of biosphere and the world oceans' chemical composition—Paper 1, Archean and Paleoproterozoic evaporites]: Stratigrafiya, Geologicheskaya Korrelyatsiya, v. 13, no. 2, p. 19–29.

Appendix C. Grade and Tonnage Data for Potash-Bearing Halokinetic Salt Structures

Table C–1. Grade and tonnage data for potash-bearing halokinetic salt structures.

[Mt, million metric tons; %, percent. See appendix A for additional information and references]

Deposit name	Basin	Country	Grade (% K_2O)	Tonnage (Mt)	Age	References
Clover Hill	Maritimes	Canada	28	224	Early Mississippian (Tournasian)	Gardiner (1990)
Millstream	Maritimes	Canada	20.6	[1]256	Early Mississippian (Tournasian)	Webb (2009)
Penobsquis-Picadilly	Maritimes	Canada	24.18	1,093	Early Mississippian (Tournasian)	Moore and others (2008)
Friedenshall-Bernburg	Zechstein	Germany	9.6	24	Kazanian to Tatarian (Late Permian)	Beer (1996); British Sulphur Corporation Limited (1966); U.S. Office of Military Government for Germany (1945)
Niedersachen-Riedal	Zechstein	Germany	13.4	50	Kazanian to Tatarian (Late Permian)	Beer (1996); British Sulphur Corporation Limited (1966, 1975, 1979, 1984); U.S. Office of Military Government for Germany (1945)
Ronnenberg-Hansa	Zechstein	Germany	13.3	54	Kazanian to Tatarian (Late Permian)	Beer (1996); British Sulphur Corporation Limited (1966, 1975, 1979); U.S. Office of Military Government for Germany (1945)
Salzdetfurth	Zechstein	Germany	14.6	88	Kazanian to Tatarian (Late Permian)	Beer (1996); British Sulphur Corporation Limited (1966, 1975, 1979, 1984); U.S. Office of Military Government for Germany (1945)
Siegfried-Giesen	Zechstein	Germany	12.2	51.6	Kazanian to Tatarian (Late Permian)	Beer (1996); British Sulphur Corporation Limited (1966, 1975, 1979, 1984); U.S. Office of Military Government for Germany (1945)
Stassfurt	Zechstein	Germany	8.3	105	Kazanian to Tatarian (Late Permian)	Beer (1996)
Inder—Areas III, IV	Pricaspian	Kazakhstan	18.6	125	Kungurian (Early Permian)	Diarov and others (1983)
Inder—Area XI	Pricaspian	Kazakhstan	14.5	23	Kungurian (Early Permian)	Diarov and others (1983)
Inder—Deposit 99	Pricaspian	Kazakhstan	9.7	153	Kungurian (Early Permian)	Diarov and others (1983)
Inder—Dzhien-Kazgantau	Pricaspian	Kazakhstan	14.35	71	Kungurian (Early Permian)	Diarov and others (1983)
Inder—North area	Pricaspian	Kazakhstan	17.5	186	Kungurian (Early Permian)	Diarov and others (1983)
Zhilian	Cisuralian	Kazakhstan	10.5	382	Kungurian (Early Permian)	Makarov (1981)
Klodawa	Zechstein	Poland	8.5	72	Kazanian to Tatarian (Late Permian)	Czaposki and Bukowski (2009)

Table C–1. Grade and tonnage data for potash-bearing halokinetic salt structures.—Continued

Deposit name	Basin	Country	Grade (% K_2O)	Tonnage (Mt)	Age	References
Elton—North area	Pricaspian	Russia	19.2	1,372	Kungurian (Early Permian)	Svidzinskiy and others (1982)
Elton—Ulagan	Pricaspian	Russia	21.9	1,906	Kungurian (Early Permian)	Svidzinskiy and others (1982)
Cardona	Ebro/Catalan	Spain	15	665	Late Eocene to Early Oligocene	British Sulphur Corporation Limited (1966, 1979, 1984); Rios (1968); Vázquez Guzmán (1989)
Llobregat	Ebro/Catalan	Spain	15.8	137	Late Eocene to Early Oligocene	British Sulphur Corporation Limited (1966, 1984); Ramirez Ortega (1986); Rios (1968); Vázquez Guzmán (1989)
Suria	Ebro/Catalan	Spain	15.8	186	Late Eocene to Early Oligocene	British Sulphur Corporation Limited (1966, 1984); Ramirez Ortega (1986); Rios (1968); Vázquez Guzmán (1989)
Somboon	Sakon Nakhon	Thailand	23.5	225	Late Cretaceous	Industrial Minerals (2002)
Udon (North)	Sakon Nakhon	Thailand	17.16	665	Late Cretaceous	Lomas (2002)
Cane Creek	Paradox	United States	25	209	Middle Pennsylvanian (Desmoinesian)	British Sulphur Corporation Limited (1984)
Salt Valley Anticline	Paradox	United States	18	[2]952	Middle Pennsylvanian (Desmoinesian)	Hite (1976); Hite and Lohman (1973)

[1]Deposit may not be fully explored.

[2]Geologic estimate.

References Cited

Beer, W.W., 1996, Kalilagerstätten in Deutschland [Potash deposits in Germany]: Kali und Steinsalz, v. 12, no. 1, p. 18–30.

British Sulphur Corporation Limited, 1966, World survey of potash resources: London, British Sulphur Corporation Limited, 93 p.

British Sulphur Corporation Limited, 1975, World survey of potash resources (2d ed.): London, British Sulphur Corporation Limited, 148 p.

British Sulphur Corporation Limited, 1979, World survey of potash resources (3rd ed.): London, British Sulphur Corporation Limited, 138 p.

British Sulphur Corporation Limited, 1984, World survey of potash resources (4th ed.): London, British Sulphur Corporation Limited, 145 p.

Czapowski, Grzegorz, and Bukowski, Krzysztof, 2009, Zolza soli w Polsce; stan aktualny i perspektywy zagospodarowania [Salt deposits in Poland—Current state and perspectives for management of the resources]: Prezegląd Geologiczny, v. 57, no. 9, p. 798–811.

Diarov, M., Utarbaev, G.S., and Tukhfatov, K.T., 1981, Tipy i nekotoryye zakonomernosti razmeshcheniya zalezhey kaliynykh soley solyanokupol’nykh struktur Prikaspiyskoy vpadiny [Patterns and some distribution mechanisms for potash salt deposits of salt dome structures in the Pricaspian Depression], *in* Yanshin, A.L., and Zharkov, M.A., eds., Stroyeniye i usloviya formirovaniya mestorozhdeniy kaliynykh soley [The structure and formation conditions of potash salt deposits]: Novosibirsk, USSR, Izdaniye Nauka, Sibirskoe Otdelenie, p. 124–126.

Gardiner, C.D., 1990, Canadian Mines Handbook, 1989–1990: Toronto, Northern Miner Press, 608 p.

Hite, R.J., 1976, A potential target for potash solution mining in Cycle 13, Paradox Member, near Moab, Utah: U.S. Geological Survey Open-File Report 76–755, 5 p.

Hite, R.J., and Lohman, S.W., 1973, Geologic appraisal of Paradox basin salt deposits for waste emplacement: U.S. Geological Survey Open-File Report OF 73–114, 75 p.

Industrial Minerals, 2002, Udon Thani potash progress: Industrial Minerals, no. 422, p. 55–56.

Lomas, S., 2002, Technical Report for the Udon North Deposit, Udon Thani Concession, Thailand, prepared for Asia Pacific Potash Corporation: Vancouver, British Columbia, MRDI Canada, variously paged.

Makarov, A.S., 1981, Otsenka perspektiv Kungurskoy solyanoy tolshchi Severnogo Prikaspiya na kaliyno-magniyevyye soli. [Evaluation of the prospects for potash-magnesium salts at the Kungurian salt deposit in the northern Caspian Depression], *in* Yanshin, A.L., and Zharkov, M.A., eds., Stroyeniye i usloviya formirovaniya mestorozhdeniy kaliynykh soley. [The structure and formation conditions of potash salt deposits]: Novosibirsk, USSR, Izdaniye Nauka, Sibirskoe Otdelenie, p. 133–137.

Moore, G.W., Appleyard, Janelle, Danyluk, Terry, Nemeth, Balazs, Prugger, Arnfinn, and Roulston, Brian, 2008, National Instrument 43-101 technical report on Penobsquis & Picadilly potash deposits, King’s County, New Brunswick, Canada: Saskatoon, Saskatchewan, Potash Corporation of Saskatchewan Inc., 83 p.

Ramirez Ortega, A., 1986, The Catalan potash field: Industrial Minerals, no. 230, p. 55–59.

Rios, J.M., 1968, Saline deposits of Spain: Geological Society of America Special Paper 88, p. 59–74.

Svidzinskiy, S.A., Derevyagin, V.S., Vyazovov, V.V., Koval’skii, F.I., and Sedletskaya, N.M., 1982, Kieserite of the Elton deposit and prospects of its commercial exploitation: Lithology and Mineral Resources, v. 17, no. 1, p. 84–90.

U.S. Office of Military Government for Germany, 1945, Report on barite, fluorspar, graphite, potash, pyrite, salt and other miscellaneous non-metallic minerals in Germany: U.S. Office of Military Government for Germany, Economic Division, Industry Branch, Coal and Non-Metallic Mining Section, 28 p.

Vazquez Guzman, F., 1989, Spain, *in* Dunning, F.W., Garrard, P., Haslam, H.W., and Ixer, R.A., eds., Mineral deposits of Europe, v. 4/5; Southwest and eastern Europe, with Iceland: London, Institution of Mining and Metallurgy and Mineralogical Society, p. 105–196.

Webb, T.C., 2009, Potash: New Brunswick Department of Natural Resources Mineral Commodity Profile 4, 8 p.

This page intentionally left blank

Appendix D. Glossary of Terms Used in Description of Evaporites

By Mark D. Cocker[1] and Greta J. Orris[1]

Allochthonous salt Sheetlike salt bodies emplaced at stratigraphic levels above the autochthonous source layer. Allochthonous salt lies on stratigraphically younger strata; theoretically, allochthonous salt could overlie older strata, but such examples have not yet been reported (Jackson and Talbot, 1991).

Autochthonous salt Salt body resting on the original strata or surface on which it accumulated by evaporation (Jackson and Talbot, 1991).

Bittern The bitter liquid remaining after seawater has been concentrated by evaporation until most of the sodium chloride has crystallized out (Neuendorf and others, 2005).

Bittern salts Any of the salts that may be extracted from the bittern of a saltworks or from a comparable natural solution; such as magnesium chloride, magnesium sulfate, bromides, iodides, and calcium chloride (Neuendorf and others, 2005).

Brachyanticline A short, broad anticline (Neuendorf and others, 2005). A short anticlinal fold of layers of rock having an oval map pattern. The layers of rock that form the brachyanticline slope away from the central part of its crest on all sides. A brachyanticline is represented on a geological map in the form of concentric oval rings, with the older rocks located in the center; the rocks become progressively younger toward the periphery (Prokhorov, 1970–1979).

Cap rock [tectonics] In a salt dome, an impervious body of anhydrite and gypsum, with minor calcite and sometimes with sulfur, that overlies a salt body or plug. It probably results from accumulation of less soluble minerals of the salt body during leaching in the course of its ascent (Neuendorf and others, 2005).

Carnallite A primary potash ore mineral, KMgCl3• 6H2O, which also is a source of magnesium in some deposits. Usually occurs as crystalline or granular masses. Mode of occurrence—occurs chiefly as a component of extensive thick sedimentary saline deposits, commonly associated with kieserite, halite, sylvite, and polyhalite (Roberts and others, 1974; Neuendorf and others, 2005).

Carnallitite A rock composed largely of a mixture of carnallite and halite (salt).

Cycle A kind of rhythmicity exhibited in many sedimentary sections owing to regularly alternating beds traceable over long distance, or a repetition of larger units that are referred to as sedimentary sequences or cycles. Rhythmic and cyclic sequences occur worldwide on various scales in presumably every environmental and stratigraphic system (Einsele, 2000).

Dewatering The expulsion of water from sediments during diagenesis or metamorphism. The water may have been present in the form of interstitial pore waters or water bound to hydrous minerals, such as certain clays or gypsum (Friedman and others, 1992, p.11; Neuendorf and others, 2005).

Diapir [structural geology] A dome or anticlinal fold in which the overlying rocks have been ruptured by the squeezing out of plastic core material. Diapirs in sedimentary strata usually contain cores of salt or shale (Neuendorf and others, 2005).

Evaporite A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent. Examples include gypsum, anhydrite, other diverse sulfates, halite (rock salt), primary dolomite, and various nitrates and borates (Neuendorf and others, 2005).

[1]U.S. Geological Survey, Tucson, Arizona, United States.

Gypsum A widely distributed mineral consisting of hydrated calcium sulfate: $CaSO_4 \cdot 2H_2O$. Usually occurs as crystalline masses, fine to coarse granular; fibrous; pulverent; concretionary. Mode of occurrence—abundant and widespread, largest volumes in marine sedimentary (evaporite) deposits. Also occurs in sediments of saline lakes and playas, as efflorescence on certain soils, in the oxidized parts of ore deposits, and in deposits associated with volcanic activity (Roberts and others, 1974). It is the most common sulfate mineral, and is frequently associated with halite and anhydrite in evaporites, forming thick, extensive beds interstratified with limestone, shale, and clay (especially in Permian and Triassic rocks) (Neuendorf and others, 2005). It may alter to anhydrite under burial metamorphic conditions, and release its water of hydration (Adams, 1970).

Halite An abundant evaporite mineral, NaCl, most commonly interbedded or intergrown with various potash minerals. Usually occurs as crystalline masses, granular, and rarely columnar or stalactitic. Mode of occurrence—widespread, chiefly as extensive sedimentary deposits ranging from a few centimeters to more than several thousand meters in thickness; as efflorescence in playa deposits; and as a sublimation product in areas of volcanism (Roberts and others, 1974; Neuendorf and others, 2005).

Halokinesis (1) A class of salt tectonics in which salt flow is powered entirely by gravity in the absence of significant lateral tectonic forces Jackson and Talbot (1991). (2) The deformation of halite by flowage. Mechanisms cited for this process include gravity flow, tectonic thrusting, and diapirism (Kyle and Posey, 1991; Neuendorf and others, 2005).

Hartsalz Hard salt, typically a mixture of sylvite and kieserite, with some anhydrite, found in the Stassfurt salt deposits (U.S. Bureau of Mines, 1996).

Horizon (1) In geology, any given definite position or interval in the stratigraphic column or the scheme of stratigraphic classification. (2) An identifiable rock stratum regionally known to contain or be associated with rock containing valuable minerals (U.S. Bureau of Mines, 1996).

Horse A mining term for a barren mass of country rock occurring within a vein (Neuendorf and others, 2005).

Intracratonic basin A basin formed within the interior region of a continent, away from plate boundaries. It develops where there is subsidence of a portion of a craton, probably due to thermal subsidence of an unsuccessful rift (Neuendorf and others, 2005).

Potash (1) A generic industry term for potassium-bearing salts that includes the commodities potassium chloride, potassium sulfate, potassium nitrate, and potassium oxide; (2) A generic geologic term that mainly includes the minerals sylvite, carnallite, kainite, and langbeinite; (3) A generic geologic term for a sedimentary rock containing significant amounts (commonly more than 20 percent by weight) of soluble, precipitated potassium- and magnesium-chloride and sulfate minerals intermixed or interlayered with halite and other bittern minerals. Variable amounts of insoluble minerals such as gypsum, anhydrite, clay, quartz, and hematite are generally present.

Rim syncline A fold having an arcuate or subcircular axial tract on the outer margin of a salt upwelling. Rim syncline is a nongenetic term, but in the context of salt tectonics a rim syncline typically results from salt withdrawal in the source layer. Peripheral sinks of sediments accumulate within rim synclines (Nettleton, 1968; Jackson and Talbot, 1991; Neuendorf and others, 2005).

Rock salt Coarsely crystalline halite occurring as a massive, fibrous, or granular aggregate, and constituting a nearly pure sedimentary rock that may occur in domes or plugs, or as extensive beds resulting from evaporation of saline water. It is frequently stained by iron or mixed with fine-grained sediments (Neuendorf and others, 2005).

Safety pillar A significant thickness, usually about 150 meters, of salt that is left in place below brine-saturated cap rock and surrounding water-bearing strata to act as a seal in a diapiric salt structure (Heim and Potthoff, 1983).

Saline giant A term used to describe thick, basin-filling evaporite units; synonymous with mega-evaporites. Mineralogies are dominated by halite and (or) anhydrite, along with varying amounts of carbonates and potash salts (Warren, 2006, 2010).

Salt A general term for naturally occurring sodium chloride, NaCl (see rock salt).

Salts (1) A generic term for chemicals classified as chlorides, sulfates, bromides, and iodides; (2) A generic term for minerals classified as chlorides, sulfates, bromides, and iodides. This can include sylvite, carnallite, halite, and other minerals (operational definition; see appendix A for some of these minerals).

Salt anticline (1) A diapiric or piercement structure, like a salt dome, except that the salt core is linear rather than equidimensional, such as the salt anticlines in the Paradox basin of the central Colorado Plateau (Neuendorf and others, 2005); (2) Elongated upwelling of salt having concordant overburden (DeGolyer, 1925; Harrison and Bally, 1988; Jackson and Talbot, 1991).

Salt back A significant thickness of salt above the mining horizon maintained to ensure a water seal between mine openings and overlying strata that contain groundwater. Salt back thickness depends on mining method and nature of water saturation and rock competency in overlying beds (Holter, 1969).

Salt diapir A mass of salt that has flowed ductilely and appears to have discordantly pierced or intruded the overburden. In its broadest sense, "diapir" includes (1) lateral or vertical intrusion of any shape, (2) upwelling of buoyant or non-buoyant rock or magma, or (3) emplacement by passive piercement or by faulting of prekinematic overburden (Mrazec, 1907; Jackson and Talbot, 1991).

Salt dome (1) A diapir or piercement structure with a central, nearly equidimensional salt plug, generally 1 to 2 kilometers (km) or more in diameter, which has risen through enclosing sediments from a mother salt bed (source layer) 5 km to more than 10 km beneath the top of the plug. Many salt plugs have a cap rock of less soluble evaporite minerals, especially anhydrite. Enclosing sediments are commonly turned up and complexly faulted next to a salt plug, and these more permeable beds serve as reservoirs for oil and gas (U.S. Bureau of Mines, 1996); (2) An informal, general term for a domal upwelling comprising a salt core and its envelope of deformed overburden. The salt may or may not be discordant (Harris and Veatch, 1899; Jackson and Talbot, 1991).

Salt glacier Sheetlike extrusion of salt flowing from an exposed diapir and spreading subaqueously or subaerially (Jackson and Talbot, 1991).

Salt horse A dome-shaped barren zone generally consisting of halite that crosscuts potash horizons. Bedding is continuous through the halite, but is thinner than the potash horizons. Halite is believed to have replaced the potash horizon in the salt horse through upward movement of saline brines (Linn and Adams, 1963).

Salt pillow A subcircular upwelling of salt having concordant overburden (Jackson and Talbot, 1991).

Salt plug The salt core of a salt dome. It is nearly equidimensional, about 1–2 km in diameter, and has risen through the enclosing sediments from a mother salt bed (source layer) 5–10 km below (Neuendorf and others, 2005).

Salt solutioning A partial to complete dissolution of salts, commonly resulting in collapse of overlying strata, and is attributed to ascending or descending less saline water or brine (Holter, 1969).

Salt stock (synonym, salt plug) A pluglike salt diapir having subcircular planform. (Trusheim, 1957; Jackson and Talbot, 1991; Neuendorf and others, 2005).

Salt structure A generic term used in petroleum, salt, and other geologic literature to refer to geologic structures formed partly or wholly from the movement and (or) deformation of salt (see halokinesis or salt tectonics); may include salt anticlines, salt diapirs, salt domes, salt pillows, salt stocks, salt plugs, salt walls, and other structures (operational definition).

Salt tectonics (synonym, halotectonics) Any tectonic deformation involving salt, or other evaporites, as a substratum or source layer; including halokinesis (Trusheim, 1957; Jackson and Talbot, 1986, 1991).

Salt wall An elongated upwelling of diapiric (discordant) salt, commonly forming sinuous, parallel rows (Trusheim, 1960; Jackson and Talbot, 1991).

Salt weld Surface or zone joining strata originally separated by autochthonous or allochthonous salt. The weld is a negative salt structure resulting from the complete or nearly complete removal of intervening salt.

The weld can consist of brecciated, insoluble residue containing halite pseudomorphs, or of salt that is too thin to be resolved in reflection-seismic data. The weld is usually, but not always, marked by a structural discordance. Another distinctive feature of welds is a structural inversion above them (Jackson and Talbot, 1991).

Salt withdrawal (synonym, salt expulsion) Mass transfer of salt over time without obvious change in salt area in cross section. Examples include salt migration from the flanks of a salt pillow into its core as it evolves into a diapir or the flow of salt along a salt wall into local culminations that evolve into salt stocks. (Jackson and Talbot, 1991; Neuendorf and others, 2005).

Source layer (synonym, mother salt) Layer supplying salt for the growth of salt structures; the source layer is a particular type of substratum (Jackson and Talbot, 1991).

Stratabound Said of a mineral deposit confined to a single stratigraphic unit (Neuendorf and others, 2005).

Substratum An underlying layer; in salt tectonics, substratum refers to the ductile layer below a brittle overburden and above the subsalt strata or basement. “Substratum” is a term more general than source layer; the substratum may or may not give rise to upwelling structures (Jackson and Talbot, 1991).

Subrosion (synonym, postburial dissolution) The process by which soluble rocks in the underground are dissolved by groundwater or water penetrating from the surface. Subrosion takes place where soluble rocks are not protected by a layer of impermeable rocks (Rauche and van der Klauw, 2011).

Subsalt strata Sedimentary unit immediately underlying salt (Jackson and Talbot, 1991).

Sylvite The mineral sylvite, KCl, is the principal ore mineral of potassium. Usually in crystalline masses, compact to granular, as crusts, and columnar. Mode of occurrence—Occurs chiefly as extensive thick sedimentary deposits, typically associated with halite, gypsum, anhydrite, carnallite, polyhalite, kieserite, and kainite (Roberts and others, 1974; Neuendorf and others, 2005).

Sylvite The mineral sylvite, KCl, is the principal ore mineral of potassium. Usually in crystalline masses, compact to granular, as crusts, and columnar. Mode of occurrence: Occurs chiefly as extensive thick sedimentary deposits, typically associated with halite, gypsum, anhydrite, carnallite, polyhalite, kieserite, and kainite (Roberts and others, 1974; Neuendorf and others, 2005).

Sylvinite A mixture of halite and sylvite, mined as a potash ore; a rock that contains chiefly impure potassium chloride (Neuendorf and others, 2005).

Turtle-structure anticline Mounded strata between salt diapirs having a flat base and rounded crest over a local primary increase in sedimentary thickness; the anticline may or may not be cored by a low salt pillow. There are two possible methods of formation: (1) The turtle structure forms between diapirs whose flanks subside because of regional extension or between salt structures evolving from pillows to diapirs (Trusheim, 1957; Neuendorf and others, 2005); (2) The turtle structure forms by structural inversion of a primary peripheral sink when salt is withdrawn from the margins of the peripheral sink by growing diapirs. The planform of turtle structures is typically highly irregular, depending on the number, location, and relative vigor of the diapirs flanking it (Trusheim, 1960; Jackson and Talbot, 1991).

References Cited

Adams, S.S., 1970, Ore controls, Carlsbad Potash District, Southeast New Mexico, in Rau, J.L., and Dellwig, L.F., Third Symposium on salt, volume 1: Cleveland, Ohio, Northern Ohio Geological Society, p. 246–257.

DeGolyer, E.L., 1925, Discovery of potash salts and fossil algae in Texas salt dome: American Association of Petroleum Geologists Bulletin, v. 9, no. 2, p. 348–349.

Einsele, G., 2000, Sedimentary basins—evolution, facies, and sediment budget: New York, Springer, 792 p.

Friedman, G.M., Sanders, J.E., and Kopaska-merkee, D.C., 1992, Principles of sedimentary deposits—Stratigraphy and sedimentology: New York, MacMillan Publishing Company, 43 p.

Harris, G.D., and Veatch, A.C., 1899, A preliminary report on the geology of Louisiana: Baton Rouge, Geological Survey of Louisiana Report, 324 p.

Harrison, J.C., and Bally, A.W., 1988, Cross sections of the Devonian to Mississippian fold belt on Melville Island, Canadian Arctic Islands: Canadian Society of Petroleum Geologists, v. 36, p. 311–332.

Heim, W.A., and Pothoff, A.H., 1983, Potash mining in steep deposits (salt domes), *in* McKercher, R., ed., Potash ’83: New York, Pergamon Press, p. 79–84.

Holter, M.E., 1969, The Middle Devonian Prairie Evaporite of Saskatchewan: Saskatchewan Department of Mineral Resources Report 123, 134 p.

Jackson, M.P.A., and Talbot, 1986, External shapes, strain rates, and dynamics of salt structures: Geological Society of America Bulletin, v. 97, p. 305–323.

Jackson, M.P.A., and Talbot, C.J., 1991, A glossary of salt tectonics: Texas Bureau of Economic Geology Geological Circular 91-4, 44 p.

Kyle, J.R., and Posey, H.H., 1991, Halokinesis, cap rock development, and salt dome mineral resources, *in* Melvin, J.L., ed., Evaporites, petroleum and mineral resources: New York, Elsevier, p. 413–474.

Linn, K.O., and Adams, S.S., 1963, Barren halite zones in potash deposits, Carlsbad, New Mexico, *in* Rau, J.L., ed., Second Symposium on Salt: Cleveland, OH, Northern Ohio Geological Society, p. 59–69.

Mrazec, L., 1907, Despre cute cu sîmbure de strapungere [On folds with piercing cores]: Romania, Buletinul Societatiide de ştiinţe, v. 16, p. 6–8.

Nettleton, L.L., 1968, Gravity anomalies over salt diapirs, northern Spain, *in* Mattox, R.B., Holser, W.T., Odé, H., McIntire, W.L., Short, N.M., Taylor, R.E., and Van Siclen, D.C., eds., Saline deposits: Geological Society of America Special Paper 88, p. 75–82.

Neuendorf, K.K.E., Mehl, Jr., J.P., and Jackson, J.A., 2005, Glossary of Geology (5th ed.): Alexandria, Virginia, American Geological Institute, 799 p.

Prokhorov, A.M., ed., 1970–1979, The Great Soviet Encyclopedia: New York, Macmillan Inc., 31 volumes and 3 volumes of indexes.

Rauche, H., and van der Klauw, S., 2011, Technical report and resource report for the Danakhil potash deposit, Afar State/Ethiopia: Erfurt, Germany, ERCOPSPLAN Ingenieurgesellschaft, 128 p. [plus appendixes]

Roberts, W.L., Rapp, Jr., G.R., and Weber, Julie, 1974, Encyclopedia of minerals: New York, Van Nostran Reinhold Company, 693 p.

Trusheim, Ferdinand, 1957, Über halokinese und ihre bedeutung für die strukturelle entwicklung Norddeutschlands [On halokinesis and its significance for the structural development of North Germany]: Zeitschrift für Deutsche Geologische Gesellschaft, v. 109, p. 111–151.

Trusheim, Ferdinand, 1960, Mechanism of salt migration in northern Germany: Bulletin of the American Association of Petroleum Geologists, v. 44, no. 9, p. 1519–1540.

U.S. Bureau of Mines, 1996, Dictionary of mining, mineral, and related terms: U.S. Bureau of Mines Report SP-96-1, CD-ROM.

Warren, J.K., 2006, Evaporites—Sediments, resources and hydrocarbons: Berlin, Springer-Verlag, 1,035 p.

Warren, J.K., 2010, Evaporites through time—Tectonic, climatic, and eustatic controls in marine and nonmarine deposits: Earth-Science Reviews, v. 98, no. 3–4, p. 217–26.

Appendix E. Diapiric Salt Structures in the Dnieper-Donets Basin, Ukraine and Belarus

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

This appendix is a compilation of the names and locations of 249 Upper Devonian diapiric salt structures that appear to extend above the 3-km depth limit in the Dnieper-Donets Basin (table E–1). In most descriptions of the salt structures, salt ages are not reported. Most salt structures probably contain Upper Devonian salt, and the salt structures may be Frasnian and (or) Famennian. Some salt structures may contain some Permian salt through entrainment. The latitude and longitude values are the approximate center of each digitized salt structure. Some name misspellings may have happened during translation.

In the accompanying geographic information system (GIS), there are several instances where two spatially close, usually small, diapirs have one reference number as shown by Kityk (1970). They may appear to be duplicates in the GIS but were just assigned the same name as there is a lack of any more detailed information. Similarly, Buromekaya and Ichnya are combined as "Buromekaya and Ichnya" in the GIS, because they are adjacent to each other. Another named diapir, Duvaiskaya, is included in this appendix but not in the GIS. The location in Kityk's figure 34 is represented by a number (233), but no outline of the diapir was drawn on that map. The position included in this table is in the approximate location of the reference number.

No detailed geological maps or topical studies of halite deposits and occurrences were located during this study. The map areas were derived by calculating the areas of the digitized diapirs. Spelling of the salt structure names varies between references and within the same reference.

References Cited

Kityk, V.I., 1970, Solianaia tektonika Dneprovsksko-Donetskoi vpadiny [Salt tectonics of the Dnieper-Donets depression]: Kiev, Ukraine Academy of the Institute of Geology and Geochemistry, 201 p.

Klimenko, V.Y., 1957, Struktura Dneprovsko-Donetskoi vpadiny, usloviya ee formirovaniya i zakonomernosti obrazovaniya i razmeshcheniya v nei mestorozhdenii nefti i gaza [Structure of Dnieper-Donets Depression, condition for its shaping and laws governing formation and arrangement of oil and gas layers]: Kiev, Akad. Nauk Ukrain. SSR, Inst. Geol. Nauk, 104 p.

[1]U.S. Geological Survey, Tucson, Arizona, United States.

Table E–1. Diapiric salt structures in the Dnieper-Donets Basin, Ukraine and Belarus.

[All diapirs are believed to contain Upper Devonian (Famennian, Frasnian, or both) salt. km², square kilometer; n.d., no data]

Diapiric salt structure name	Latitude	Longitude	Area (km²)	Map reference number	Reference
Abazovskaya	34.3528	49.6396	12	164	Kityk (1970)
Adaiovskaya	37.4343	48.9687	15	226	Kityk (1970)
Adamovskaya	32.4698	51.3292	3	37	Kityk (1970)
Alekseevskaya	36.4491	49.3438	69	160	Kityk (1970)
Allekeandrovskaya	31.7673	50.7712	20	54	Kityk (1970)
Anastasevoskaya	33.5614	50.5907	11	85	Kityk (1970)
Andreevskaya	34.8487	49.399	11	187	Kityk (1970)
Andreyashevskaya	33.3587	50.5781	7	86	Kityk (1970)
Anisovskaya	31.4863	51.3491	22	9	Kityk (1970)
Antonov (Antonovskaya)	32.5158	50.3949	5	66	Kityk (1970)
Arteiovskaya	37.8888	48.6895	215	228	Kityk (1970)
Baaakyaeevsiaya	36.9336	49.4698	145	231	Kityk (1970)
Berekskaya	36.9565	49.1307	7	218	Kityk (1970)
Bereziiiskai	31.8414	51.6089	12	14	Kityk (1970)
Blivnetsovskaya	36.7036	48.7954	34	207	Kityk (1970)
Boyarskaya	34.2903	49.3323	12	171	Kityk (1970)
Budeiovskaya	31.3619	51.6692	11	12	Kityk (1970)
Budyshchanskaya	34.54	49.8736	17	141	Kityk (1970)
Buguevskaya	37.3268	48.9845	11	225	Kityk (1970)
Buromekaya	32.3812	50.9327	25	49	Kityk (1970)
Chervoiotsartieanskaya	31.6424	51.0547	20	19	Kityk (1970)
Chervono-Donetskaya	37.1866	49.3346	43	235	Kityk (1970)
Chizhevskaya	33.4524	50.4995	13	87	Kityk (1970)
Chutovskaya	34.9943	49.7228	82	145	Kityk (1970)
Dikanskaya	34.6484	49.8398	34	142	Kityk (1970)
Dmitimevskaya	32.9251	50.9799	42	61	Kityk (1970)
Doroshevskaya	35.0113	49.3234	20	189	Kityk (1970)
Dovzhnkovskaya	30.9621	51.6098	9	4	Kityk (1970)
Droiovskaya	37.9581	48.8982	93	246	Kityk (1970)
Druzhelyubovskaya	37.819	49.343	17	241	Kityk (1970)
Druzhkovsko-Konstantinovskaya	37.4425	48.6734	424	224	Kityk (1970)
Duvaiskaya	37.2896	49.512	n.d.	233	Kityk (1970)
Dyagovskaya	32.0396	51.4979	4	30	Kityk (1970)
Dyubechekaya	30.7197	51.8027	26	1	Kityk (1970)
Efremovskaya	36.1573	49.4424	24	159	Kityk (1970)
Elskaya	30.627	51.9036	54	11	Klimenko (1957)
Fedorovekaya	35.1078	49.4135	38	186	Kityk (1970)
Fomentsevskaya	33.1241	50.6488	9	83	Kityk (1970)
Fvstovtsevskaya	32.586	51.0699	19	43	Kityk (1970)
Gasevkovekaya	33.5196	50.0999	8	111	Kityk (1970)
Gmyryanskaya	32.5	50.8414	18	57	Kityk (1970)
Gnedintsevskaya	32.764	50.4408	66	75	Kityk (1970)
Gnrmanovskaya	31.0352	51.6164	22	3	Kityk (1970)
Golubovskaya	35.31	48.9627	12	180	Kityk (1970)
Grabovskaya	30.9304	51.8412	39	2	Kityk (1970)
Grigorovskaya	31.7348	51.0098	6	20	Kityk (1970)
Ichnya (Ichnyanskaya)	32.3345	50.8753	21	51	Kityk (1970)
Isachkovskaya	33.1784	50.1053	41	100	Kityk (1970)
Iskrovskaya	35.1289	49.8275	14	135	Kityk (1970)
Ivangorodskaya	32.4349	51.0291	15	47	Kityk (1970)
Ivanitskaya	32.5761	50.789	23	59	Kityk (1970)
Ivashkovskaya	31.4823	51.7097	15	13	Kityk (1970)

Table E–1. Diapiric salt structures in the Dnieper-Donets Basin, Ukraine and Belarus.—Continued

Diapiric salt structure name	Latitude	Longitude	Area (km^2)	Map reference number	Reference
Ivavovskaya	31.3117	51.3579	11	10	Kityk (1970)
Kaainovskaya	35.6198	49.4955	15	150	Kityk (1970)
Kachanovskaya	34.5001	50.3412	93	121	Kityk (1970)
Kamyshevakhskaya	37.0165	49.0292	92	219	Kityk (1970)
Kaplinitsevskaya	32.578	50.3301	37	67	Kityk (1970)
Karaykozovskaya	35.1648	49.9735	4	136	Kityk (1970)
Karaykozovskaya	35.1151	50.0322	7	136	Kityk (1970)
Karnovskaya	37.7368	49.1665	115	242	Kityk (1970)
Kartamyshchskaya	36.5275	49.2973	4	213	Kityk (1970)
Kegnchevskaya	35.7768	49.3555	10	195	Kityk (1970)
Kharkovtsevskaya	33.79	50.279	16	91	Kityk (1970)
Khervukhvnskaya	32.918	50.3103	18	76	Kityk (1970)
Khimo-Ryabushinskaya	32.079	51.0124	10	44	Kityk (1970)
Kholmy (Kholmskaya)	32.2014	51.336	109	34	Kityk (1970)
Khomovskaya	32.0399	50.9182	7	56	Kityk (1970)
Khotinovskaya	31.5692	51.1644	10	18	Kityk (1970)
Kibnntsevskaya	33.5607	49.9148	9	102	Kityk (1970)
Knrovskaya	32.3544	51.3992	4	35	Kityk (1970)
Kobzevskaya	35.649	49.2813	48	201	Kityk (1970)
Kolaydnntsevskaya	32.9201	50.0861	48	79	Kityk (1970)
Kolomanskaya	35.442	49.847	51	138	Kityk (1970)
Korobovskaya	36.3162	49.5863	21	210	Kityk (1970)
Korotkovokaya	34.3223	49.8886	20	161	Kityk (1970)
Korulskaya	37.1577	48.9157	32	222	Kityk (1970)
Kosheyaevskaya	31.9348	51.3096	2	27	Kityk (1970)
Kosnelevskaya	31.8961	51.343	3	27	Kityk (1970)
Kotelevskaya	34.9813	50.0521	45	132	Kityk (1970)
Koyanchevskaya	31.3994	51.4433	8	8	Kityk (1970)
Koyanchevskaya	31.3074	51.4593	4	8	Kityk (1970)
Kozevskaya	35.1536	50.1255	11	130	Kityk (1970)
Kpapivnyaiskaya	31.8753	50.9675	6	21	Kityk (1970)
Krasio-Oskolskaya	37.4185	49.1689	49	237	Kityk (1970)
Krasnoaavodskaya	33.3221	50.4381	15	97	Kityk (1970)
Krasnogradskaya	35.5251	49.426	9	192	Kityk (1970)
Krasnokolyadiyaskaya	33.0457	50.9829	10	62	Kityk (1970)
Krasnopavyaovskaya	36.277	49.1216	36	203	Kityk (1970)
Krasnopopovskaya	38.0417	48.9934	28	244	Kityk (1970)
Krasnoselskaya	32.1089	51.2092	6	29	Kityk (1970)
Kreienovskaya	34.8588	49.1227	18	175	Kityk (1970)
Kreshchatiiskaya	31.37	51.1794	15	16	Kityk (1970)
Krestinshchenskaya	35.5203	49.5545	105	148	Kityk (1970)
Kurenskaya	32.6916	51.1583	13	42	Kityk (1970)
Leekovetskaya	32.1349	51.4604	9	32	Kityk (1970)
Lesinovskaya	31.9472	50.8205	8	53	Kityk (1970)
Levevtsovskaya	35.7324	48.8637	46	182	Kityk (1970)
Leyayakovskvya	32.6802	50.6081	50	72	Kityk (1970)
Leykovskaya	33.8998	49.9182	8	114	Kityk (1970)
Lnsogorskaya	32.7448	50.9097	19	60	Kityk (1970)
Loeovenkovskaya	36.5795	49.272	8	214	Kityk (1970)
Loevskaya	30.7916	51.9257	94	15	Klimenko (1957)
Lyubechskaya	30.6129	51.7376	152	16	Klimenko (1957)
Lyutenkovskaya	34.0489	50.1898	5	96	Kityk (1970)
Maksakovskaya	32.3188	51.4308	5	33	Kityk (1970)
Malodevitskaya	32.1986	50.7174	37	55	Kityk (1970)

Table E–1. Diapiric salt structures in the Dnieper-Donets Basin, Ukraine and Belarus.—Continued

Diapiric salt structure name	Latitude	Longitude	Area (km^2)	Map reference number	Reference
Maloeorochinskaya	33.6191	50.0522	26	112	Kityk (1970)
Malopereshchepinskaya	34.585	49.3994	29	170	Kityk (1970)
Maltsevskaya	33.4924	49.8437	5	109	Kityk (1970)
Manokotsyubinskaya	31.1216	51.5467	8	7	Kityk (1970)
Markovian	33.807	50.4453	22	93	Kityk (1970)
Mashevskaya	34.7899	49.5241	58	183	Kityk (1970)
Medvedovskaya	35.7562	49.4929	37	151	Kityk (1970)
Mikhajlovskaya	34.5983	49.1118	14	174	Kityk (1970)
Miroiovskaya	36.0789	49.2923	27	198	Kityk (1970)
Mirolyubovskaya	36.5041	49.2084	16	204	Kityk (1970)
Monastyrishchenskaya	32.1205	50.8195	43	52	Kityk (1970)
Nezhnnskaya	32.001	51.012	13	23	Kityk (1970)
Novodmitrevskaya	37.1091	48.9623	8	221	Kityk (1970)
Novodolazhskaya	35.8588	49.6954	55	157	Kityk (1970)
Novodubrovskaya	38.0469	48.9389	7	245	Kityk (1970)
Novoefremovskaya	36.05	49.4406	16	154	Kityk (1970)
Novogrngorevskaya	34.8155	49.2892	14	188	Kityk (1970)
Novomechebnlovekaya	36.6398	49.0034	159	206	Kityk (1970)
Novonkkolaevskaya	34.5455	49.2361	24	172	Kityk (1970)
Novosanzhaskaya	34.422	49.3835	42	169	Kityk (1970)
Novoselkovskaya	35.0349	49.1017	26	176	Kityk (1970)
Novoselovskaya	37.2167	48.9717	18	220	Kityk (1970)
Novotroitskaya	34.324	50.4881	21	119	Kityk (1970)
Oktyaerskaya	35.291	49.2614	51	190	Kityk (1970)
Olkshevskaya	31.2817	51.2095	12	15	Kityk (1970)
Ombnshekaya	32.2657	51.0237	42	46	Kityk (1970)
Orekhovshchivskaya	33.2892	49.9592	10	106	Kityk (1970)
Ostrovskaya	32.6029	51.2432	9	40	Kityk (1970)
Oaeryanskaya	32.8365	50.5431	24	73	Kityk (1970)
Ovnyanekaya	33.6772	49.917	9	110	Kityk (1970)
Pakchlskaya	30.73	51.4718	15	6	Kityk (1970)
Parafievskaya	32.6352	50.8772	44	58	Kityk (1970)
Paraskoveyskaya	35.9564	49.5203	19	155	Kityk (1970)
Pavlovskaya	35.8713	49.3398	32	196	Kityk (1970)
Perekhodovekaya	31.5153	51.2265	6	17	Kityk (1970)
Perekopovskaya	33.404	50.6281	26	84	Kityk (1970)
Pereshchepniskaya	35.2663	49.0688	24	178	Kityk (1970)
Perevolochnenskaya	32.6136	50.676	4	71	Kityk (1970)
Pesochknnskaya	33.4706	50.3418	12	98	Kityk (1970)
Petrovo-Ronenskaya	33.7139	50.3304	19	90	Kityk (1970)
Petrovskaya	36.8273	49.1689	46	217	Kityk (1970)
Plichevskaya	35.5131	48.8989	34	181	Kityk (1970)
Poanyakovskaya	32.9915	50.2299	12	77	Kityk (1970)
Pogarshchinskaya	33.5551	50.4355	27	88	Kityk (1970)
Poltavaskaya	34.5773	49.5889	31	165	Kityk (1970)
Prilunskaya	32.3625	50.6816	83	64	Kityk (1970)
Proletarskaya	35.141	49.0876	10	177	Kityk (1970)
Protopopovskaya	36.8645	49.2381	12	216	Kityk (1970)
Pvryatnnskaya	32.4721	50.2864	18	68	Kityk (1970)
Radchenkovskaya	33.8071	49.9652	24	113	Kityk (1970)
Radyanekaya	34.0237	50.3717	76	120	Kityk (1970)
Raspashvsvskaya	35.2366	49.6378	112	146	Kityk (1970)
Rchbanskaya	33.7465	50.6995	20	117	Kityk (1970)
Reshetnnkovekaya	34.3582	49.4689	16	168	Kityk (1970)

Table E–1. Diapiric salt structures in the Dnieper-Donets Basin, Ukraine and Belarus.—Continued

Diapiric salt structure name	Latitude	Longitude	Area (km^2)	Map reference number	Reference
Romny (Romenskaya)	33.5906	50.7381	18	116	Kityk (1970)
Romodanovskaya	33.3613	50.0254	30	101	Kityk (1970)
Runovshchanskaya	34.6821	49.7406	13	143	Kityk (1970)
Ryaeukhinskaya	35.9928	49.6101	63	158	Kityk (1970)
Ryealtsevskaya	34.7735	50.1949	31	128	Kityk (1970)
Saatykovo-Deavtskaya	31.8096	51.3938	13	25	Kityk (1970)
Sagaydakskaya	33.9614	49.7231	77	115	Kityk (1970)
Saiarvnskaya	34.0731	49.9517	62	126	Kityk (1970)
Sakhnovshchinskaya	36.0129	49.1156	42	202	Kityk (1970)
Sarskaya	33.9036	50.3146	10	95	Kityk (1970)
Savnntsevskaya	37.1484	49.4502	19	232	Kityk (1970)
Seieatsovskaya	34.2812	49.6936	30	163	Kityk (1970)
Semenovekaya	35.8787	49.4774	8	152	Kityk (1970)
Semnrenkovekaya	34.002	50.0881	8	123	Kityk (1970)
Sevepo-Krestishchenskaya	35.4204	49.6154	27	147	Kityk (1970)
Severo-Dorognnekaya	32.2173	50.9617	35	48	Kityk (1970)
Severo-Golchbovskaya	37.4213	49.4041	24	234	Kityk (1970)
Severo-Volvenkovskaya	36.7469	49.287	51	212	Kityk (1970)
Shapovalovskaya	32.5547	51.3094	7	39	Kityk (1970)
Shchebelinskaya	36.5151	49.4635	207	211	Kityk (1970)
Shchurovskaya	32.5592	50.7245	14	69	Kityk (1970)
Shevchenkovskaya	37.0701	49.6745	15	229	Kityk (1970)
Shevchenkovskaya	33.5805	50.2899	14	99	Kityk (1970)
Sinevskaya	34.0961	50.5182	39	118	Kityk (1970)
Slavynskaya	37.63	48.8722	265	227	Kityk (1970)
Smolyazhskaya	32.0559	51.24	5	28	Kityk (1970)
Sokolovskaya	36.2296	49.6901	18	208	Kityk (1970)
Solokov (Solokovskaya)	34.4496	49.9575	39	140	Kityk (1970)
Solonytskaya	33.1748	50.023	13	105	Kityk (1970)
Sosnovskaya	35.6932	49.3848	26	194	Kityk (1970)
Southern-Pereshchepinskaya	35.3843	48.9913	7	179	Kityk (1970)
Spivakovskaya	37.1018	49.194	56	236	Kityk (1970)
Staroverovskaya	35.7251	49.58	45	149	Kityk (1970)
Starovokrovskaya	36.4836	49.7408	16	209	Kityk (1970)
Stepkovskaya	36.6723	49.1603	11	205	Kityk (1970)
Svnrndovskaya	33.1475	50.436	25	74	Kityk (1970)
Svyatogorskaya	37.4419	49.0632	19	239	Kityk (1970)
Talalaevskaya	33.1425	50.7908	26	80	Kityk (1970)
Tarasovekaya	35.1222	49.5513	60	184	Kityk (1970)
Ternovskaya	37.9495	49.0826	12	243	Kityk (1970)
Tervovshchevskaya	33.1777	49.9604	12	107	Kityk (1970)
Toastsyaesovskaya	31.2786	51.6399	16	11	Kityk (1970)
Torsko-Shandrvgolovskaya	37.7769	49.0348	66	240	Kityk (1970)
Tvanskaya	32.1403	51.032	16	45	Kityk (1970)
Valkovskaya	35.6494	49.8723	41	139	Kityk (1970)
Vantyshevskaya	37.2229	48.8336	11	223	Kityk (1970)
Vayrakskaya	34.3181	49.7577	12	162	Kityk (1970)
Veayaevskaya	36.3591	49.2421	25	200	Kityk (1970)
Vedintsevskaya	30.8247	51.5173	54	5	Kityk (1970)
Velnkobogachaiskaya	33.6553	49.8345	44	104	Kityk (1970)
Velskaya	34.5106	50.1158	81	127	Kityk (1970)
Veneslavovskaya	33.6656	50.3801	7	89	Kityk (1970)
Venikobubiovekaya	33.2438	50.8619	28	81	Kityk (1970)
Venikoeagorovskaya	32.4929	51.2007	38	41	Kityk (1970)

Table E–1. Diapiric salt structures in the Dnieper-Donets Basin, Ukraine and Belarus.—Continued

Diapiric salt structure name	Latitude	Longitude	Area (km^2)	Map reference number	Reference
Verezovskaya	34.9484	49.979	22	133	Kityk (1970)
Vergunekaya	33.4061	49.8617	16	108	Kityk (1970)
Verkhnelannovskaya	35.3284	49.4356	190	191	Kityk (1970)
Vertievskaya	31.7942	51.1931	6	24	Kityk (1970)
Veselovskaya	36.2046	49.2743	12	199	Kityk (1970)
Vladimirovskaya	34.7821	49.7173	8	144	Kityk (1970)
Vlistovskaya	31.9074	51.4104	14	26	Kityk (1970)
Vlivavetovskaya	34.9932	49.5132	15	185	Kityk (1970)
Vogdanovskaya	32.6107	50.4601	28	70	Kityk (1970)
Volvenkovskaya	36.6827	49.2301	19	215	Kityk (1970)
Vorkovskaya	31.9996	51.466	8	31	Kityk (1970)
Vorozenkovskaya	33.4808	50.799	21	82	Kityk (1970)
Vostochio-Poyatavskaya	34.7806	49.6208	31	166	Kityk (1970)
Vostochko-Medvedovskaya	35.8325	49.5215	9	156	Kityk (1970)
Vostochvopavlovskaya	35.9746	49.3216	14	197	Kityk (1970)
Vrigadirovskaya	37.0639	49.571	23	230	Kityk (1970)
Vyazovekaya	35.0716	49.8984	5	134	Kityk (1970)
Vysokoaskaya	35.4173	49.9907	18	137	Kityk (1970)
Vysokovskaya	32.5066	51.3656	14	38	Kityk (1970)
Yadutovskaya	32.4206	51.3674	2	36	Kityk (1970)
Yaroshevskaya	32.7717	50.8385	13	63	Kityk (1970)
Yatsynologovnkovskaya	32.7601	50.2573	39	78	Kityk (1970)
Yuzhno-Dorognnekaya	32.1696	50.9012	23	50	Kityk (1970)
Zachepilovskaya	34.1942	49.4194	96	167	Kityk (1970)
Zaluzhskaya	34.1299	50.136	7	124	Kityk (1970)
Zapadno-Efremovskaya	35.9552	49.4531	12	153	Kityk (1970)
Zapadno-Kotelevskaya	34.89	50.03	8	131	Kityk (1970)
Zapadno-Mikhajlovskaya	34.5112	49.1421	12	173	Kityk (1970)
Zapadno-Nezhinskaya	31.8283	51.0703	14	22	Kityk (1970)
Zapadno-Sosnovskaya	35.5967	49.408	7	193	Kityk (1970)
Zaporozhskaya	35.1584	50.2374	13	129	Kityk (1970)
Zevkovekaya	34.3496	50.2335	3	122	Kityk (1970)
Zevkovekaya	34.2872	50.2484	9	122	Kityk (1970)
Zharzhevskaya	34.1573	49.9614	18	125	Kityk (1970)
Zhuravkovskaya	32.4961	50.5041	17	65	Kityk (1970)
Total number of structures	249				

Appendix F. Additional Halite Deposits and Occurrences in the Pripyat and Dnieper-Donets Basins, Belarus and Ukraine

By Mark D. Cocker,[1] Greta J. Orris,[1] and Pamela Dunlap[1]

Salt occurrences noted in the literature that do not correspond exactly in name or location with the digitized diapirs in appendix E are included in table F–1. Ages of the salt occurrences are uncertain. Most are probably Upper Devonian and may contain Frasnian and (or) Famennian salt. Those listed as Cisuralian are probably that age. These halite occurrences are not depicted in figure 4–1 or in the accompanying GIS. Some occurrence name misspellings may have happened during translation.

[1]U.S. Geological Survey, Tucson, Arizona, United States.

References Cited

Kityk, V.I., 1970, Solianaia tektonika Dneprovskso-Donetskoi vpadiny [Salt tectonics of the Dnieper-Donets depression]: Kiev, Ukraine Academy of the Institute of Geology and Geochemistry, 201 p.

Klimenko, V.Y., 1957, Struktura Dneprovsko-Donetskoi vpadiny, usloviya ee formirovaniya i zakonomernosti obrazovaniya i razmeshcheniya v nei mestorozhdenii nefti i gaza [Structure of Dnieper-Donets Depression, condition for its shaping and laws governing formation and arrangement of oil and gas layers]: Kiev, Akad. Nauk Ukrain. SSR, Inst. Geol. Nauk, 104 p.

Table F–1. Halite deposits and occurrences in the Pripyat and Dnieper-Donets Basins, Belarus and Ukraine.

[All diapirs shown as Devonian(?) are believed to contain Upper Devonian (Famennian, Frasnian, or both) salt; Mt, million metric tons]

Occurrence name	Latitude	Longitude	Age	Comments (grade and tonnage data, if available)	Reference
Akhyrka	50.2987	34.8895	Devonian(?)	—	Orris and Cocker, unpublished data
Artemivs'k	48.5914	37.9962	Cisuralian	Production approximately 2 Mt per year (2000–2001)	Troitsky and others (1998); Yermakov and Galushko (2002)
Borznyanskaya	51.2603	32.3075	Devonian(?)	—	Klimenko (1957)
Budskaya	52.2361	29.3406	Devonian(?)	—	Klimenko (1957)
Chermnukhvnskaya	50.3811	32.897	Devonian(?)	—	Klimenko (1957)
Chunakhovsk	50.3802	34.5689	Devonian(?)	—	Orris and Cocker, unpublished data
Davydovsko-Korenevskaya	52.4417	29.3529	Devonian(?)	—	Klimenko (1957)
Dolzhavskaya	50.1013	34.5786	Devonian(?)	—	Klimenko (1957)
Doroginskaya	50.9508	32.1292	Devonian(?)	—	Klimenko (1957)
Eaoernaya	51.8943	29.1152	Devonian(?)	—	Klimenko (1957)
Elizavetovskaya	49.5094	35.0392	Devonian(?)	—	Klimenko (1957)
Glinsk	50.6459	33.286	Devonian(?)	—	Orris and Cocker, unpublished data
Glnnsko-Rozbyshevskaya	50.448	33.5582	Devonian(?)	—	Klimenko (1957)
Gomel	52.407	30.7621	Devonian(?)	—	Klimenko (1957)
Gulevichskaya	52.1494	29.2539	Devonian(?)	—	Klimenko (1957)
Itsynsko-Rozhnevskaya	50.9037	32.414	Devonian(?)	—	Klimenko (1957)
Kolontaevokaya	49.9626	34.9847	Devonian(?)	—	Klimenko (1957)
Kopagkevnchskaya	52.3079	28.8155	Devonian(?)	—	Klimenko (1957)
Koplincevskoe	50.3727	32.4434	Devonian(?)	—	Rundkvist (2001)
Kramatorskoe	48.9094	37.5049	Cisuralian	—	Rundkvist (2001)
Krasno-partienskaya	50.9582	31.7057	Devonian(?)	—	Klimenko (1957)
Litvnnovskaya	49.7843	35.7302	Devonian(?)	—	Klimenko (1957)
Moeyrskaya	52.0033	29.3678	Devonian(?)	—	Klimenko (1957)
Norovlyanskaya	51.8993	29.5288	Devonian(?)	—	Klimenko (1957)
Novo Senzhary	49.3652	34.3226	Devonian(?)	—	Orris and Cocker, unpublished data
Old Senzharskaya	49.3955	34.3903	Devonian(?)	—	Klimenko (1957)
Olitevskaya	51.2306	31.2971	Devonian(?)	—	Klimenko (1957)
Petrikovskaya	52.1494	28.8007	Devonian(?)	—	Klimenko (1957)
Petrivtsevskaya	49.8561	33.4666	Devonian(?)	—	Klimenko (1957)
Pmtaookaya	49.6035	34.5736	Devonian(?)	—	Klimenko (1957)
Pogovikovskaya	50.3168	32.783	Devonian(?)	—	Klimenko (1957)
Rechitskaya	52.3748	30.1603	Devonian(?)	—	Klimenko (1957)
Rospashnovskaya	49.5342	35.2819	Devonian(?)	—	Klimenko (1957)
Sesnskaya	51.9117	30.6185	Devonian(?)	—	Klimenko (1957)
Shostovichskaya	52.0949	29.0681	Devonian(?)	—	Klimenko (1957)
Slovyansk	48.8706	37.6742	Cisuralian	—	Yermakov and Galushko (2002)
Soledar	48.6803	38.0974	Cisuralian	—	Yermakov and Galushko (2002)
Upper-Lanovskaya	49.4301	35.3488	Devonian(?)	—	Klimenko (1957)
VelikoZagorovskaya	51.191	32.4388	Devonian(?)	—	Klimenko (1957)

Appendix G. Spatial Databases for Resource Assessments of Potash in the Pripyat and Dnieper-Donets Basins, Belarus and Ukraine

By Pamela Dunlap,[1] Deborah A. Briggs,[2] and Leila Glass[1]

Spatially referenced data for the distribution of mineral deposits and potential resource areas of potash are important elements of mineral resource assessments. When combined with a common set of descriptive data and a variety of other types of spatial data, this information can be used to conduct further detailed resource assessments, to understand the likely distribution and availability of potash resources to meet future needs, and to help inform resource policy.

The datasets and documentation presented in this report were developed for use with Esri's ArcGIS 10 software. Geographic information system (GIS) terminology specific to Esri software is used throughout this report; definitions of GIS-related terms and concepts are available online at http://support.esri.com/en/knowledgebase/Gisdictionary/browse (accessed March 20, 2014).

Overview of Spatial Databases

The spatial databases released in this report are listed and briefly described in table G–1. Each spatial database is provided in vector format as a feature class in the Esri File Geodatabase (FGDB) ***DDPripyat.gdb***. The geodatabase is packaged with metadata files in the compressed archive file sir20105090bb_gis.zip, which is available on the Internet at https://doi.org/10.3133/sir20105090BB.

[1]U.S. Geological Survey, Tucson, Arizona, United States.

[2]U.S. Geological Survey, Spokane, Washington, United States.

Permissive areas or tracts are represented by the feature class ***DDP_Tracts***; information about potash deposits and occurrences is provided in the feature class ***DDP_Deposits***, and data for halite occurrences are in ***DDP_Halite***. Extent of Devonian rock salt is provided in the feature class ***DDP_Salt***, and location of faults that, in part, define the basins is in ***DDP_Faults***. The diapiric salt structures that together comprise the Dnieper-Donets halokinetic tract are identified by name in the feature class ***DDP_Diapirs***. Boundaries for countries in the region are in the feature class ***DDP_Countries*** which was extracted from a larger dataset for the world (U.S. Department of State, 2009).

Metadata files provide information about the spatial databases. Metadata in extensible markup language (XML) format are both embedded in each feature class and exported to standalone files, all of which can be read using ArcGIS 10. Metadata are also provided in portable document format (PDF) files.

Reference Cited

U.S. Department of State, 2009, Small-scale digital international land boundaries (SSIB)—Lines, edition 10 and Polygons, beta edition 1: Boundaries and Sovereignty Encyclopedia (B.A.S.E.), U.S. Department of State, Office of the Geographer and Global Issues.

Table G–1. List and description of spatial databases and associated files in compressed archive sir20105090bb_gis.zip.

File name	File description
	Esri file geodatabase (FGDB)
DDPripyat.gdb	The collection of spatial databases, in feature class format, prepared for and used in the mineral resource assessment for undiscovered potash in the Dnieper-Donets and Pripyat basins, Belarus and Ukraine.
FGDB feature classes in the file geodatabase DDPripyat.gdb	
DDP_Countries	Countries in the region.
DDP_Deposits	Potash deposits and occurrences.
DDP_Diapirs	Diapiric salt structures in the Dnieper-Donets basin.
DDP_Faults	Geologic faults.
DDP_Halite	Halite occurrences.
DDP_Salt	Extent of Devonian rock salt.
DDP_Tracts	Potash tracts, with assessment information.
Metadata in Adobe Acrobat Portable Document Format (.pdf)	
DDP_Countries_metadata.pdf	Metadata for countries.
DDP_Deposits_metadata.pdf	Metadata for spatial database for potash deposits and occurrences.
DDP_Diapirs_metadata.pdf	Metadata for diapiric salt structures.
DDP_Faults_metadata.pdf	Metadata for spatial database for faults.
DDP_Halite_metadata.pdf	Metadata for spatial database for halite occurrences.
DDP_Salt_metadata.pdf	Metadata for spatial database for extent of rock salt.
DDP_Tracts_metadata.pdf	Metadata for spatial database of permissive tracts.
Metadata exported to standalone extensible markup language (.xml) format files	
DDP_COUNTRIES_METADATA_XML.xml	Metadata for countries.
DDP_DEPOSITS_METADATA_XML.xml	Metadata for spatial database for potash deposits and occurrences.
DDP_DIAPIRS_METADATA_XML.xml	Metadata for diapiric salt structures.
DDP_FAULTS_METADATA_XML.xml	Metadata for spatial database for faults.
DDP_HALITE_METADATA_XML.xml	Metadata for spatial database for halite occurrences.
DDP_SALT_METADATA_XML.xml	Metadata for spatial database for extent of rock salt.
DDP_TRACTS_METADATA_XML.xml	Metadata for spatial database of permissive tracts.

Appendix H. The Assessment Team

Mark D. Cocker, Ph.D., PG, is a research geologist with the USGS in Tucson, Arizona. His background is in global potash assessment, lateritic, supergene rare earth elements, precious and base metals in the western US, industrial minerals in Georgia, and hydrocarbon exploration in Alaska. His work has involved field mapping, drilling, geochemical sampling, petrography, geophysical surveys, and GIS mapping and analysis. He has authored over 170 papers, abstracts, maps, and digital publications. He has been a member of several mineral resource assessment teams.

Greta J. Orris, Ph.D., is a research geologist with the USGS in Tucson, Arizona. She specializes in industrial minerals and in tools and methodologies for quantitative assessment of these and other minerals, and conducts research in mineral economics. She has served as a leader of mineral resource assessment teams evaluating a wide range of commodities in North and South America, Europe, Asia, and Africa.

Pamela Dunlap, M.S., is a geologist with the USGS in Tucson, Arizona. She worked as an exploration geologist for several mining companies in Nevada, Montana, Idaho, and Washington and also as a research geologist for various state geological surveys (Idaho, Montana, and Washington) prior to joining the USGS in 1992. She has done mineral-resource assessment work in Idaho (phosphate) and Montana (oil shale) under contract to the USGS. She has prepared many geologic map and mineral-resource assessment products in a GIS while with the USGS.

Bruce Lipin, Ph.D., is a research geologist with the USGS in Reston, Virginia. He is a specialist in ultramafic rocks and their mineral resources, and mineral resource assessments.

Steve Ludington, Ph.D., is a research geologist with the USGS in Menlo Park, California. He worked as an exploration geologist in Colorado, New Mexico, and Arizona before joining the USGS in 1974. His work with the USGS has included regional geologic studies, metallogenic and geochemical studies, wilderness studies, and mineral-resource assessments. Ludington has done mineral-resource assessment work in the United States, Costa Rica, Bolivia, Mongolia, Afghanistan, and Mexico and was a coordinator for the 1998 USGS National Mineral Resource Assessment.

Robert J. Ryan, Ph.D., is a geologist and section leader with the Nova Scotia Department of Natural Resources, Halifax, Nova Scotia, Canada.

Miroslaw Słowakiewicz, Ph.D., is a sedimentary geologist with the Polish Geological Institute, Warsaw, Poland.

Gregory T. Spanski, Ph.D., is a geologist with the USGS in Denver, Colorado. He is a mineral resource specialist for Africa, and a former university professor.

Jeff Wynn, Ph.D., is a research geophysicist with the USGS in Vancouver, Washington. He has authored over 220 books, papers, and maps in geophysics, mineral resource assessments, astrophysics, and ocean engineering. He authored the first three-dimensional geologic map, and the first age-correlated mineral resource assessment of southern Venezuela. He has served as a US diplomat and USGS mission chief in Venezuela and Saudi Arabia, and as USGS chief scientist for volcano hazards. He holds three patents in mineral exploration technology and deep ocean geophysical mapping.

Chao Yang, Ph.D., is a senior oil and gas and evaporite geologist with Saskatchewan Energy and Resources, Regina, Saskatchewan, Canada.

Menlo Park Publishing Service Center, California
Manuscript approved for publication, June 21, 2017
Edited by Sarah E. Nagorsen
Layout and design by Sharon L. Wahlstrom

USGS

Cocker and others—**Geology and Undiscovered Resource Assessment of the Potash-Bearing Pripyat and Dnieper-Donets Basins, Belarus and Ukraine**—Scientific Investigations Report 2010–5090–BB

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20105090BB