Potential Underground Gas Storage Reservoirs in Latvia

Limez

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POTENTIAL UNDERGROUND GAS STORAGE RESERVOIRS IN LATVIA

by

Santis Limezs

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
April 1997
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Thanks also go to Linda Harrison for her support and assistance which greatly contributed in the completion of this work.

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Santis Limezs
POTENTIAL UNDERGROUND GAS STORAGE RESERVOIRS IN LATVIA

Santis Limezs, M.S.

Western Michigan University, 1997

The Baltic state of Latvia, produces no natural gas; all natural gas consumed is imported. In order to address future gas needs in Latvia, this study was undertaken to provide geological background and select sites with the best gas storage potential and reduce costs of more detailed field analyses in the next phase of gas storage development. Russia is the sole natural gas supplier and delivers the gas to Latvia via transmission pipelines. The Inchukalns underground gas storage field is the only underground gas storage field in the Baltic states. Although this structure accommodates current needs, projections show additional storage will be required within ten years. The Geological Survey of Latvia has identified more than ten additional geologic structures similar to Inchukalns. This study has analyzed geological characteristics, including reservoir structure, thickness and reservoir property data in five of these structures--Dobele, North Blidene, Amata, Ligatne and North Ligatne. The study proves the suitable geological conditions in all of the studied structures. Economic considerations favor development of the Ligatne structure, but availability of geologic data and large volume potential suggests better utilization of the Dobele structure.
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CHAPTER I
INTRODUCTION

This study was undertaken to evaluate the geological characteristics of regional structures, reservoir rocks, and sealing units which may be potential underground storage sites for natural gas in Latvia. While present storage sites can supply sufficient gas for Latvia’s current consumption, projections show additional capacity will be required within ten years.

The Inchukalns underground gas storage field is the only underground gas storage field in the Baltic States (Latvia, Lithuania, and Estonia). Inchukalns, presently providing storage for Latvia, Estonia, and parts of Russia, has a total reservoir storage capacity of 4.05 BCM (billion cubic meters) with a working gas capacity of 2.12 BCM. Latvia’s gas consumption alone was 1.2 BCM in 1996. The Geological Service of Latvia has identified more than 10 additional structures similar to Inchukalns with cumulative gas storage potential of 50 BCM. This report analyzes five of these structures--Dobele, North Blīdene, Amata, Līgatne and North Līgatne.

The main market which would be served by additional underground gas storage reservoirs in Latvia is the Baltic Region (Latvia, Lithuania, Estonia, Kaliningrad, Northwest Russia). This area is served by a pipeline distribution system which is an infrastructure remnant of the Soviet Union. Russia is presently the sole
source of natural gas supply in the Baltic Region. Gazprom, the successor to the Soviet Ministry of Gas, contracts more than 90% of the gas produced in Russia and controls all of the high-pressure transmission lines. Russia has been able to maintain its production rates over the past five years by increasing its exports and has maintained gas reserves by the development of new fields.

Northern Lights gas pipeline system, originating in the Urengoy-Yamburg natural gas fields in Western Siberia, carries all the natural gas to Latvia. There are no immediate economically viable options to acquire natural gas from alternative sources. Natural gas is provided directly by the pipeline grid stemming from the Northern Lights pipeline feeding the Inchukalns gas storage field. As the economies of the Baltics area recover and grow, the natural gas system will again be stressed, particularly in the winter months. As a consequence additional year-round gas storage will be necessary for continued economic development.

Geological Aspects of Underground Gas Storage

Underground reservoirs are geological structures that have porous rock or sediment media with some degree of permeability. Porosity allows natural gas to be contained within the medium. Permeability allows the gas to move from point to point within the medium. Impermeable sealing layers overlay the porous media thus providing containment of interstitial fluids. The overlying sealing unit is usually curved or dome-shaped preventing the underlying gas from rising to the ground
The curvature of these sealing units prevents the lateral movement or escape of gas from the confining structure.

In some cases, a geologic fault may have produced a vertical or lateral shift along one or more sides of the gas reservoir to provide a lateral seal. The bottom of the porous medium reservoir unit may be sealed by impermeable rock, or by water.

The greater the porosity of a given medium, the more gas can be contained in a unit volume of the medium. Porosity is represented as a percentage of total unit volume and may vary from zero to some higher number. Porosities may vary from point to point, and generally would have to be above 15% to be considered useful for natural gas injection and storage.

Gas permeability is the ability of gas to flow through a medium with a given pressure drop. The greater the permeability, the greater the flow volume for any given pressure drop. Because the flow of a fluid in a permeable medium requires a pressure gradient, the pressure in a reservoir, that is being produced, will vary within the reservoir. Permeability may vary widely from zero to several thousands millidarcies (mD). Very low permeability can seal off portions of a reservoir and variations in permeability can cause an unequal distribution of pressure throughout the field.

Underground reservoirs may be classified in two general types: volumetric reservoirs and water-drive reservoirs. The volumetric type is sealed on all sides by impermeable rock and maintains constant shape and size. The water drive reservoir is sealed on the top and sides by impermeable rock, but the porosity below the gas-filled
zone is filled with water. As gas is injected into a water-drive reservoir, water is pushed out.

Most gas storage fields are created in depleted oil fields, because those structures generally have structural integrity. Also, injection of gas in a known oil reservoir will increase oil production because gas is miscible within the oil and will "strip-out" the oil as the gas is produced. However, gas deliverability rates from depleted oil fields may be lower than from aquifers.

Gas storage is also created in depleted gas fields. These fields also have structural integrity and some gas is already in place. However, production data obtained during the gas production phase of the field may not be accurate for the gas storage phase. For example, water encroachment during virgin gas withdrawal might have altered minerals present in pores and "clogged" some of the pore throats. Such processes would decrease the injection/withdrawal rates in the reservoir when gas is re-injected for storage.

An ideal gas storage field will have the capability of receiving injected gas at high rates. Ideally, when gas is injected into a reservoir filled with water, the gas would displace the water and maintain a level, horizontal gas-water interface contact. If this is the case, gas can be injected at a high rate. Unfortunately, gas has a tendency to override the water and travel along the top surface of the reservoir. This can result in a gas-water interface which is highly sloped and runs down-structure.

In the study region, (Figures 1 and 2) all existing gas storage fields are created in water-drive aquifers.
Figure 1. Map of Baltics Region, Study Area, Potential Storage Sites and Gas Transmission Pipelines.
Regional Potential for Underground Gas Storage

At present there is no natural gas production from gas fields in the Baltic region and nearby districts of Russia. All the gas consumed in the area is delivered via gas transmission pipelines (Figure 1) from eastern Russia and western Siberia.

Because the gas fields are so far away, transmission costs are high and supply is sometimes uncertain. Therefore local underground reservoirs are used to balance large seasonal fluctuations in gas consumption. The best substrate for such underground reservoirs are porous, highly permeable sedimentary rocks such as sandstones and limestones.

Figure 2. Baltics Region Showing Major Structural Provinces.
Geologically, the study area occupies part of the Russian or East European Platform. Paleozoic sediments fill depressions in the Precambrian basement. Consequently, sediment thicknesses vary from 0 to 2000-3000 m.

Paleozoic strata are unmetamorphosed and often poorly lithified. For instance, blue Cambrian clays are almost indistinguishable from blue Quaternary clays, although more consolidated.

Part of northwest Russia (west of Moscow and south of St. Petersburg) and all of Estonia (Figure 2) are located on the Baltic Shield or on its slopes. Because of very thin sedimentary rock cover, gas storage development has limited potential here. Currently there are two operating underground gas storage fields. The Nevskoe gas storage reservoir was created in a low amplitude (10 m) structural trap. The Gatchina gas storage is in a thin, stratigraphically trapped, horizontal aquifer.

Although the rest of Northwest Russia east of the Baltic States has thick sedimentary rock deposits, the lack of good reservoir/seal sequences preclude gas storage opportunities.

Studies carried out in Estonia from 1975 to 1978 discovered several potentially useful structures for gas storage. One such structure is the Meremjae structure in southeast Estonia with structural closure at -400 m, an areal extent of 6x4 km, and amplitude above the closure contour of 40 m. This structure was evaluated for exploration drilling using single-fold reflection seismic data.

Underground gas storage was also proposed in the Gdov Formation sandstones of Vendian age in Estonia with a capacity of 1 BCM (Лаврентьева,
In addition, studies carried out during 1971 in the central part of Lithuania discovered low amplitude structures in the Gdov Formation in Vendian age rocks. For example, the East Ukmerge structure in Lithuania has an areal extent at the closure elevation of (-555m) 4 by 3.5 km and amplitude above closure contour of 8 m. Calculated potential storage volume would be about 0.7 to 0.8 BCM.

Thicker, larger sedimentary sections are present in Latvia and regions to the south. Brangulis, Freimanis, and others (1981) compiled and analyzed available geologic data in the Baltic region to determine specific areas with adequate geological conditions for underground gas storage or industrial wastewater disposal. They described geological information about local structures, discussed reservoir properties and seal integrity, and gave recommendations for further research (Brangulis, Freimanis и др., 1981). Their work suggested Lower Ordovician to Cambrian sandstones in Latvia (Figure 2) were the best prospects for storage reservoir and recommended the Dobele structure as the next exploration target for test drilling.

History of Related Geological Research in the Region

Relevant geologic information about Latvia has been obtained during the past forty years as a result of several applied activities:
1. Major exploration for hydrocarbon reservoirs. Initiated in the 1960s, this search led to the discovery of an oil field in Cambrian sandstones in the Kuldiga structure in Kurzeme, Latvia.

2. Study for industrial wastewater disposal in deep formations. Numerous wells were drilled near Riga, Olaine, Ventspils, Krāslava, Malta, Puikule and Nagli, between 1972 to 1978 to delineate reservoirs suitable for industrial wastewater disposal. Extensive single-fold seismic reflection surveys and hydrogeological analyses were also performed in these regions (Башкин, 1975; Науменко, 1980; Сокуренко, Григоренко, 1977; Григоренко, 1978).

3. Search for mineral waters. Groundwater from Cambrian sediments have high concentrations of chloride, sulfate, bromine and other dissolved minerals. This water is being used both for medicinal purposes and commercial sale. Exploration wells were drilled in Gaiļezers, Valmiera, Piltene, Ķemeri, Liepāja, Jaunķemeri and Mežciems, and other locations in search of this resource.

4. Underground gas storage site selection. The first exploration for geological structures suitable for underground gas storage in Latvia was done by a Soviet operation "Спецгеофизика" (Specgeophysica) in 1961. As a result of this reconnaissance, and more detailed geophysical investigations, the following structures were discovered to have a vertical displacement on the top of the basement--Ergli, Ogre, Malpils and Inčukalns (herein referred to as Inchukalns) (Лукашева и др., 1961).
This study initiated development of the Inchukalns Underground Gas Storage Field. The initial target reservoir was in the Devonian, but drilling results showed that there was no closure at the Devonian level, so a deeper Cambrian reservoir was proposed as an alternative.

Results from these applied studies have been compiled into numerous publications and reports discussing regional reservoir properties, lithostratigraphy, paleogeography, and regional facies correlation. Several maps have also been published: (a) lithopaleogeographic map with a scale of 1:1,500,00 (1979); (b) paleotectonic map with a scale of 1:1,000,000 (1976-1980); and (c) structural map with a scale of 1:500,000 (1982).

In the early nineties, the lithological characteristics of Cambrian reservoir rocks and Ordovician sealing units were studied by Zābele and Sprīnge (1992). This work concluded that the most favorable conditions for underground gas storage development are along the Rīga-Pskov fault zone in the region of the Bīriņi and Dzērbene deep wells, and that the Dobele structure is probably the most prospective site in the western part of Latvia, because of its reservoir properties and structural configuration.
CHAPTER II

GEOLOGIC INFORMATION

Well Data

Extensive analytical studies were performed by scientists on the collected data from test wells drilled and sampled in many areas of Latvia. Wells were drilled by the government of the Soviet Union, and usually were part of some larger scientific or political program. Well reports available at the State Geological Survey of Latvia are extensive volumes (see column headed Stock # in Table 1) with very detailed historical and site analyses, mud logging data, core descriptions, chemical analyses and petrophysical test results (Tables 1 and 2).

Table 1 lists various electrical logs (E-logs) which are available for most wells. E-logs performed with Russian logging tools were generally less precise than similar logs run with logging tools from French and U.S. companies due to the lack of tool centering. Typical well log suites include gamma ray log; neutron-gamma ray log; spontaneous potential; caliper; laterolog; and sometimes temperature measurements. Sonic logs were introduced just recently, and a consequence are not available for the study area. Data quality varies greatly and depends on subjective errors, tool precision, and calibration.
Table 1

General Well Data, Coring, Logging

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**ABBREVIATIONS:**
- **ND**: No data
- **Core recovery (m)**:
  - **Tot**: For Cambrian and Ordovician intervals together
  - **Res**: In the main reservoir interval - Deimena/Cirma and Kallavere formations
- **Logging**:
  - **GR**: Gamma ray
  - **RL**: Resistivity log
  - **NGR**: Neutron gamma ray
  - **CL**: Caliper
  - **T**: Thermometer

**Geological Survey of Latvia does not have information about these wells.**
**Drilling was performed by Belarus geologists and data could be purchased from them.**
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**ABBREVIATIONS:**

**Analysis qty:**

Tot For Cambrian and Ordovician intervals together

Geological Survey of Latvia does not have information about these wells.

Drilling was performed by Belorus geologists and data could be purchased from them.
Seismic Data

Several types and formats of seismic data (Table 3) have been acquired in Latvia. The total length of seismic profiles in Latvia is 6,927 km, consisting of 5,788 km single-fold reflection seismic (MOB) and 1,139 km common depth point reflection seismic (МОГТ). This kind of survey was performed only in southwest Latvia, and on the Inchukalns structure.

Table 3

Translations of Commonly Used Russian Abbreviations for Geophysical Survey Methods

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<th>TYPE OF SURVEY</th>
<th>ABBREVIATION IN RUSSIAN (LATIN PRONUNCIATION)</th>
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<td>Single-fold seismic reflection</td>
<td>MOB (MOV)</td>
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<td>Common depth point seismic reflection</td>
<td>MOГТ (MOGT)</td>
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<td>Refraction profiling</td>
<td>КМПВ (KMPV)</td>
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<td>Local refraction measurements</td>
<td>РНП (RNP)</td>
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<tr>
<td>Telluric method</td>
<td>ТЗ (TZ)</td>
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Most of the seismic surveys (5,389 km) were done by a Soviet Government trust “Спецгеофизика” (SpecGeophysica), but 1,538 km were done by the Geological Survey of Latvia.

Information about seismic data relevant to the study area is presented in Table 4.
The majority of surveys are compiled from single-fold seismic reflection data. These were recorded on paper with analog photographic methods. An example of the available seismic data record from the Dobele region is shown in Figure 3. Magnetic (analog) tape recording was used only in recent years on the Dobele structure, but there is no information about the availability or quality of the stored data. It seems unlikely that tapes will be in readable condition after years of storage. Paper copies

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from other surveys are not organized, and there was no information available about their completeness and condition.

Information presented on structural maps (Maps 8, 10 and 12) was compiled as of the date of seismic interpretation (1959-1973). The maps represent digitized copies of the hand-drawn maps that were attached to original seismic survey party reports.
Because high resolution seismic survey technology was not available at the time of data acquisition and interpretation (1959 to 1973), it was common practice to identify a regional argillaceous clay reflector in the Lower Ordovician, and then "deepen" it to map the top of the Cambrian. Regional geologic data and control from well logs support the validity of this approach. Quality of interpretation is largely dependent on the density of seismic profile coverage, and the availability of well control at the time of survey. Precision of seismic data is dependent on several subjective factors including, but not limited to
density of survey profile lines, field registration errors, and local geological conditions. Statistical analyses correlating seismic interpretations with later-drilled wells is the only objective source on interpretation accuracy. Drilling results generally confirmed the structural configurations derived from the seismic map data. Vertical interpretation error for the Dobele and Blidene region is probably less than 25 meters and dependent on the above-mentioned factors.

Refraction profiling surveys were used to detect the top of the basement consisting of igneous or metamorphic rocks. The thickness of Cambrian sedimentary formations were then added to map the top of the Cambrian. The thickness of the Cambrian is not as uniform in the region as is the isopach thickness from the Ordovician reflector to the top of the Cambrian. Refraction profiling surveys, together with local refraction measurements and telluric methods, are the only sources of geophysical information about the Ligatne, N. Ligatne and Amata structures. These geophysical methods are far less precise than data acquired from seismic reflection surveys. The density of profile lines and the number of measurement sites in the region are insufficient to provide good interpretations. There is no statistical information available regarding correlation of these data with well drilling data which would be the only valid comparison. Vertical interpretation error may reach as much as 50 meters.
Magnetic Survey

The onshore territory of Latvia has been mapped in 1: 500,000 scale with aerial magnetic surveys and gravity by the Soviet trust “Спецгеофизика” (Specgeophysica). More detailed surveys were performed in regions outside of the study area--mostly offshore.
CHAPTER III

GENERAL REGIONAL GEOLOGY

The typical sequence of rocks encountered in the subsurface of Latvia has been primarily documented by well drilling and coring. This is because most units do not outcrop within the country.

The basement rocks consist of a diverse variety of Archean and Proterozoic igneous and metamorphic rocks. Sedimentary rock cover above this crystalline basement consists of Vendian, Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian, Triassic, Jurassic and Quaternary sediments. Jurassic, Triassic, Permian and Carboniferous formations are present only in southwest Latvia.

The most suitable formations for underground gas storage are Cambrian-Lower Ordovician sandstones which have a thick and integral seal composed of clays and dense limestones. Subsea elevations of the top of the Cambrian increase from less than 600 m in northeastern part of the study region to approximately 1600 m in the southwest (Figure 4 and Map 1). Stratigraphy of the reservoir rocks changes within the study region. For this study, detailed discussion will cover only the stratigraphy of Vendian, Cambrian, and Ordovician rocks. Figure 5 shows the stratigraphic scheme used in Latvia.
Figure 4. Top of the Cambrian Reservoir Structural Map.
Figure 5. Stratigraphy of Vendian and Cambrian Rocks in Latvia\(^1\).

\(^1\) 1993; Менс, Бергстрём, Лендион, 1987; Каталог стратотипов, 1992).
Vendian and Cambrian Stratigraphy

Vendian rocks contain Zuras and Krāslava strata, Gdov, Kotlin and Voronka Formations. Vendian sediments are present mostly in the eastern part of Latvia, where formations younger than the Gdov Formation belong to facies deposited in the westernmost part of the large Moscow Syncline.

Zuras Strata--occur in northwest Kurzeme. These strata consist of two sequence types--volcanogenic and clastic. Total thickness does not exceed 30 m.

Kraslava Strata--occur only in southeast Latvia. These are up to 82 m thick strata consisting of red-brown, poorly sorted, sandy-siltstones with vulcanogenic tuff.

Gdov Formation--present in eastern Latvia. These are poorly sorted micaceous and feldspathic sandstones and iron-rich siltstones. Thicknesses are up to 64m.

Kotlin Formation--present in eastern Latvia as fine layered clays above the Gdov Formation. The top of the formation has dessication fractures which could suggest subareal exposure. Thicknesses are up to 60 m.

Voronka Formation--present in eastern Latvia as poorly sorted, weakly-cemented, silty, quartzose and feldspathic sandstones with kaolinitic clay and gravel interlayers. Formation thickness is up to 33 m and its areal extent is slightly smaller than that of the Gdov and Kotlin Formations.

Cambrian rocks in Latvia consist of Lontova, Ovisi, Ventava, Tebra, Deimena Formations and Cirma Strata. The Lontova Formation sediments accumulated as part of sediment sequences deposited in the Moscow basin. Later a change in structural
configuration of the Eastern European plate occurred, subareally exposing is area of Latvia. A new transgression from the area of the Baltic syncline advanced from the northwest and west producing greater sediment thicknesses in the Dobele and North Blīdene regions compared with Līgatne region. This new transgression resulted in deposition of the Ovīši Formation and younger sediments.

During Ventava Formation deposition, a basin in the northwest covered an area overlapping the Dobele and Blīdene structures and allowing deposition of silt-clay sediments exceeding 10 m. The Līgatne region on the northeast was most likely subareally exposed at this time.

With Tebra sedimentation, the basin extended over all of Latvia, resulting in deposition of a shallow marine sand-silt-clay sequence in the Dobele and Blīdene regions; whereas the Līgatne region, at the margin of the basin, received deposition of predominantly sandy sediments. Regression at the end of Tebra time interrupted deposition in the eastern part of Latvia producing an unconformity.

A new transgression then encroached from the west and southwest which deposited the Deimena Formation sandstones. At this time, shallow basin covered all of the territory of Latvia accumulating mostly relict and recycled sandy sediments. Wells drilled in the easternmost part of the Dobele and Blīdene structures provide data that supports a distinction between the Tebra and Deimena Formations. However, further to the east, sandstones from both formations merge together. The Cirma Strata represent lateral facies equivalents of the Deimena and Tebra Formations in eastern and central Latvia (Figures 6, 7 and 8).
Figure 6. Index Map of Cross Sections.
Figure 7. Cross Section A-A’
Figure 8. Cross Section B-B'. 
The following is a detailed description of sediment types (with formational names) in the Cambrian sequence:

Lontova Formation--consists of gray-blue clays with gravel, sandstone, and siltstone interlayers in the lower part. The upper part consists of clays. These units are present in eastern Latvia on top of Vendian sediments. The maximum thickness of the Lontova Formation is up to 75 m.

Oviši (Ovishi) Formation--consists of sandstones, siltstones, and clays with thin conglomerate interlayers. These sediments are present in northwest Kurzeme overlying basement rocks or Zuru strata. Maximum thickness is 60 m.

Ventava Formation--consists of three units. The lowest unit consists of clays with silty clay and sandstone interlayers. Saka, the middle unit is composed of white, fine- to medium-grained sandstones and coarse siltstones. The upper unit is made of shaly-siltstones with sandstone and silty-clay interlayers. The Ventava Formation is present in most of the Kurzeme Peninsula with a thickness of up to 56 m.

Tebra Formation--composed mostly of bioturbated, silty clays and siltstones. Typically the base of the formation has some iron-oolite interlayers. The upper part consists of interlayered quartz sandstones, siltstones, and clays. These sediments are present in western Latvia and range from 32 to 91 m thick.

Deimena Formation--consists of fine- to medium-grained quartz sandstones and coarse siltstones with local, lenticular interlayers of clay. Siltstones and clays constitute less than 25-30% of the total thickness. Clays are sometimes argillicous,
but mostly silty. The Deimena Formation is separated from the Tebra Formation in the Kurzeme Peninsula. Formation thickness ranges from 32 to 84 m.

Cirma Strata—transgressively cover Lontova clays in eastern Latvia and overlie basement rocks in central Latvia (Figures 7 and 8), these consist of the Deimena and Tebra Formations facies analogues. Sediments are identical to the Deimena Formation sandstones, obscuring the distinction of separate Deimena and Tebra Formations in central Latvia.

Ordovician Stratigraphy

Ordovician sediments are represented by two facies types which were first characterized in the Baltic region by Mjannils (Mяаниль, 1966). Both types have distinct lithologies and fossils as a result of their paleogeographic location in Early Ordovician time. The western facies zone is the Sweden-Latvia assemblage type.

Eastern Latvia and north Kurzeme constitute the eastern facies zone called the Baltic assemblage type. In general, Ordovician sediments consist of clays, limestone, and marl with minor siltstone and sandstone interlayers. Because the sealing properties of the Ordovician rocks are critical for this project, discussion will concentrate on the Pakertort, Varangu, Latorp, Volkhov, Kunda, and Azeri regional horizons in Lower Ordovician (Table 5).
Table 5

Stratigraphy of the Ordovician in Latvia

<table>
<thead>
<tr>
<th>Sub system</th>
<th>Series</th>
<th>Regional Stage (Horizon)</th>
<th>Western Latvia, Central Latvia</th>
<th>Southeastern Latvia</th>
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<tr>
<td>Upper</td>
<td>Ashgill</td>
<td>Porkuni</td>
<td>Saldus</td>
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<td>Lower</td>
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<td>Llandeilo</td>
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<td>Kunda</td>
<td>Baldone</td>
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<td>Arenig</td>
<td>Volkhov</td>
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<td>Latorp</td>
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<td>Tremadoc</td>
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<td>Pakerort</td>
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Pakertorta horizon--consists mostly of poorly sorted quartz sandstones, which commonly contain brachiopod fossils (*Obolus* sp.) and occasional clays. The Pakertorta horizon is locally present in Latvia and transgressively overlies the Cambrian Deimena Formation and Cirma Strata. The thickness of this unit is usually 0.1-0.3 m to 1 m with maximum thickness reaching 6 m in central and northeast Latvia.

Varrangu horizon--is present in the central part of the Jelgava depression, which developed locally on the Middle Latvian monocline during Ordovician time (Figure 9). The horizon consists of blue-gray clays with maximum thicknesses up to 11 m.

Latorp horizon--sediments are found throughout Latvia. The maximum thickness of 38 m is reached in the Jelgava depression where deposits consist of green-gray and reddish argillaceous clays. Outside of the Jelgava depression, this horizon is represented by a 0.1-0.3 m-thick glauconite-rich sandstone layer.

Volkhov horizon--consists of reddish brown clay-marl, which can be up to 32.5 m thick in central Latvia. However, it changes laterally into a dense, dolomite-rich limestone, ranging in formation thickness from about 2 m outside of the Jelgava depression.

Kunda horizon--carbonates are present in all of Latvia as a green-gray marl and reddish brown limestone ranging in thickness from about two meters in northern and eastern Latvia to 39 m in the Sturi well in central Latvia.
Figure 9. Map of Regional Structures in Latvia.
Azeri horizon--shows a facies relationships with the Kunda horizon and is found throughout Latvia as a 2-4 meter-thick layer of reddish brown limestone.

More detailed information about stratigraphy is available in numerous publications (Брангулис., 1985,1989; Ульст, Гайлите, Яковлева, 1982; Гайлите, Рыбинкова, Ульст, 1867; Гайлите, Ульст, Яковлева, 1987; Савваитова, 1977).

Structural Geology

Latvia is situated in the southwestern part of the Eastern European Plate. Igneous and metamorphic basement rocks are heavily faulted. The main structural features in Latvia are the Baltic Syncline, Latvia Saddle, and the southern slope of the Baltic Shield. (Figure 9).

The Baltic Syncline is located in western and central Latvia. To the east it borders the Latvia Saddle which comprises most of eastern Latvia. The Latvia Saddle separates two major depressions—the Baltic and Moscow synclines. To the north, the Latvia Saddle borders the Baltic Shield which unlies Estonia. The Latvia Saddle has a northeast to southwest orientation with dimensions of 300km by 200km.

Within the Baltic Syncline are several smaller structures. These are the Dundega Monocline, the Liepāja Depression, the West Kurzeme Anticline, the East Kurzeme Step, the South Latvia Step, the Middle Latvia Monocline and the Limbaži Step. Our interest is concentrated on the Saldus-Slokas and Inchukalns Fractured Zones which have numerous associated anticlinal structures (Геологическое строение, 1979; Тектоника Прибалтики, 1979). The Latvia Saddle also includes
several sub-regional size structures such as the Ergļu Anticline, the Gulbene Depression, and the Daugavpils Monocline (Геологическое строение, 1979; Теология Прибалтики, 1979; Проблемы унаследованности, 1979). The Valmiera-Lokno Anticline is a part of the southern slope of the Baltic Shield. (Figure 9).

Depth to the top of the basement increases in the southwestern direction, from 300 m subsea in the Valmiera-Lokno Anticline to 1900 m subsea in the Pape-Bārta Trough in the Baltic Syncline. The Baltic Syncline has a more complete depositional sequence compared to the Latvia Saddle and Baltic Shield slope. The thickness of sedimentary rock cover decreases to the north and northeast.

The following structural complexes have been defined based on geologic time and the regional depositional sequence boundaries found in Latvia: Baikalian, Caledonian, Hercynian and Alpine. Only the Baikalian and Caledonian complexes contain sediments of interest for this study. The Hercynian and Alpine complexes will not be discussed here.

Baikalian--Vendian-Lower Cambrian complex consists of poorly sorted sandstone-siltstone deposited during Vendian time and clay-rich Kotlin and Lontova Formations. The Baikalian structural stage is present only in eastern Latvia and locally in northwestern Kurzeme. A maximum thickness of 300 m is found in southeastern Latvia.

Caledonian--Lower Cambrian to Lower Devonian time sediments are composed of elasic Cambrian rocks, clay-carbonates and carbonate Ordovician and
Silurian rocks, and clastic rocks of the Lower Devonian Gargždu Formation. Lower and upper boundaries of this sedimentary complex are represented by a regional erosional unconformity.

The structural configuration of the Caledonian complex generally replicates that of the basement rocks, with all of the regional structures and most local structures present. Sedimentary rock layers are frequently cut by faults propagating from igneous and metamorphic basement rocks. This sediment complex in Latvia increases in thickness from 200 m to 1000 m towards the southwest.

Faults

Fault systems are classified on the basis of time of formation and lateral extent. These supra-regional, regional and local fault systems are also described and qualified by the physical propagation of fault planes as: (a) pre-platform faults which have formed in basement rocks and do not penetrate the sedimentary rocks, and (b) platform faults with fault planes reaching into sedimentary rock formations.

Most of these faults are considered to be normal faults. Thrust faults are less common, or not recognized due to lack of sufficient information about fault dip angles and plunge directions. Some faults also show multiple reactivations. At the time regional seismic surveys were performed, it was commonly assumed that all faults were vertical in a platform setting.
Approximately 60% of the faults occur in the Baikalian and Caledonian complexes. The vertical separation of strata along the foot wall and hanging wall in Caledonian faults ranges from a few meters to 600 meters. Maximum separation values are present in the Liepāja-Rīga-Pskov Fault zone. About 30% of faults reach into Hercynian Complex sediments and only a few of them continue into the Alpine Complex. Faults in the Hercynian Complex typically have very little displacement or appear as fault-drag folds. More detailed descriptions and analyses of faults are compiled in several publications (Тектоническая карта, 1980; Геологическое строение, 1979; Тектоника Прибалтики, 1979).

Local Structures

At least 60 local anticlinal structures are known in Latvia. About 20 of these are represented as local highs on the Cambrian surface within the study area (Figure 4 and Map 1). Most of these highs are genetically associated with fault systems in the basement rocks. These structures are mostly asymmetrical anticlines or domes, usually associated with buttresses and up-lifted fault walls. Often these structures resemble non-cylindrical folds with axes parallel to the main fault, complicated by numerous dislocations cutting the faulted side flank of the anticline. Amplitude above the closure contour in these structures varies from a few meters to more than 100 meters.

These structures have developed as a result of tectonic movement during Vendian, Early Cambrian, Silurian, Early Devonian and Jurassic ages. Most intense
activation and structural development occurred during Late Cambrian-Early Ordovician and Late Silurian-Early Devonian. The majority of the Caledonian complex structures have similar structural configurations in formations from Cambrian to Silurian age.

A few local structures continued development through the Hercynian complex and the amplitude above the closure contour decreases from the Caledonian to Hercynian even if the structural configuration is retained. (Геологическое строение, 1979; Тектоника Прибалтики, 1979).

Hydrogeology

The Baltic aquifer underlies all of Latvia. The aquifer itself is subdivided into two hydrogeologic zones based on their structural and depositional origin. The lower zone consists of Baikalian and Caledonian complex sediments, whereas the upper zone encompasses sediments of Hercynian and Alpine complexes and Quaternary drift sediments.

The upper zone consists of numerous groundwater-saturated sedimentary rock horizons separated by impermeable sediments. Regionally the most important ones are the Lower and Mid-Devonian groundwater horizons separated by an impermeable mid-Devonian Narva Formation aquatard.

The Arukila-Burnieku (Middle Devonian) groundwater horizon does not have a regionally continuous or thick sealing formation. The Gargzdu-Keferu-Parnu (Lower to Middle Devonian) groundwater horizon in Latvia is located in the zone of
active water flow and exchange between the surface and subsurface, and thus is not suitable for underground gas storage.

Groundwater chemistry and dissolved solids in the upper zone depend upon the distance from surface-water infiltration source area. Movement of water in formations is predominantly horizontal from the infiltration source to discharge areas. There is a distinct vertical hydrodynamic and hydrochemical zonation. The Gargzdu-Ķemeru-Parnu horizon can be used to test sealing integrity for underground gas storage created in the Cambrian reservoir.

The lower hydrogeologic zone can be further subdivided into Vendian and Cambrian-Ordovician groundwater horizons, separated by Kotlin and Lontov Formation clays. The lower hydrogeologic zone is overlain by an aquaclude of Ordovician-Silurian clays and carbonates.

This hydrogeologic zone consists of sediments that are cut by a series of regional fault blocks with vertical displacements of hundreds of metres. As a result, faults frequently become an impermeable barrier for lateral groundwater movement. The faulted blocks may receive water from different infiltration source areas and have differences in formation pressure. This results in Cambrian groundwater having dissolved solids of more than 100 grams/liter at relatively shallow depths of 500 - 700 metres subsea.

Vendian clastic formations are less suitable for underground gas storage development because they occur only locally in the eastern part of Latvia at depths from 600 to 1138 meters subsea.
The Pakerorta groundwater horizon (Cambrian and Lower Ordovician), consisting mainly of sandstones, is the main potential candidate for underground gas storage development. It is present throughout Latvia. In western Latvia, it is split into two separate zones corresponding to the Lower-Cambrian Ovīšu and Ventava Formations and Middle-Cambrian Deimena Formation. These horizons are separated by less permeable rocks of the Tebra Formation (Lower-Middle Cambrian time). To the east both horizons merge and form one groundwater aquifer.

Water-saturated rocks are generally sandstones and siltstones with clay and less frequently with gravel interlayers. Sandstones are mainly fine to medium grain size with different degrees of cementation which determines overall reservoir properties and performance.

According to Freimanis and Skrupstele (Брангулицс, Фриманис, 1981), dissolved solids are about 10 grams per liter in northern Latvia, but increase to 110 grams per liter in the Latvia Saddle and reach maximum values of 136 grams per liter in the Baltic Syncline. This increase in dissolved solids correlates with a decrease in Na/Cl ratio from 1.0 to 0.46, an increase in bromide (Br) concentration from 12 to 500 milligrams per liter, and a decrease in Cl-Br ratio indicating a stagnant water system in the deepest parts of this structure.

The predominant dissolved minerals in deep groundwater are sodium or sodium-calcium chloride. More calcium-rich waters are typical for the deepest parts of the Baltic Syncline where salinities are highest. Nitrogen is the main dissolved gas in this groundwater.
Static water levels in the Cambrian-Ordovician groundwater horizon had original pressures high enough to lift water in wells to elevations ranging from -37 meters subsea to +98 meters above sea level. Maximum debit values are present on the aquifer margins where reservoir properties such as permeability are somewhat higher.

The water temperatures of the Cambrian-Ordovician groundwater zone range from 15°C to 65°C. There are two elevated thermal water zones in the Eleja and Nidasciems regions with maximum temperatures of 55°C to 65°C.

Because of hydrogeologic and reservoir properties of the Cambrian-Ordovician groundwater zone in Latvia, Freimanis (Брангулис, Фрейманис, 1981) suggested it was the most favorable aquifer for underground gas storage development.

Deimena-Cirma-Pakertorta Reservoir Properties

This reservoir is present in all the study area, but consists of the Cirma Strata in central and eastern Latvia and the Deimena Formation in the western part. In central Latvia, where the clayey facies disappears, sediments in the Deimena and Tebra formations are identical, obscuring the distinction of between the two. To the east from this line (Figure 10 and Map 2), the corresponding sediments are called Cirma Strata. This explains the increase in reservoir thickness from 9-12 m in southeastern and northeastern Latvia to 104 m in central Latvia (the Jūrmala-R4 well) (Figure 9).
Figure 10. Isopach Map of the Cambrian Reservoir.
The Pakertorta Formation comprises a very small part of the reservoir (commonly less than 0.5 m) and has a stratigraphic difference only because of its younger age (Ordovician) and Obolus sp. fossils.

Reservoir property test results for the reservoir comprised by the Deimena Formation, Cirma Strata and Pakertorta Formation (further called the Cambrian reservoir) are available from locations throughout Latvia. However, data coverage varies and the majority of analyses were performed in Ventspils, Jūrmala, Olaine and Rīga regions.

Porosity and permeability data can be grouped into several classes for this reservoir interval. Figure 11 shows the proportion of samples with permeability and porosity values in these class ranges. Average porosity is similar for all classes, however permeability varies greatly and is the basis for class distinctions.

Sandstones with permeability higher than 1000 mD constitute only 1.5% of the total number of analyses, and appear to be sporadically distributed. Porosity ranges from 15% to 24% with average of 20%. High permeability values are likely associated with fractures in the sandstone.

Most widespread are sandstones with a permeability range from 500 to 1000 mD. They make up 42% of analyses. Porosity in this group ranges from 17% to 28% with an average value above 20%. In the study area, these well-sorted, fine-grained quartz sandstones with little cementation are present in the upper and middle parts of the Kurzeme cross sections, the upper 20-40 m in the Rīga-Jūrmala region, and the central part of the reservoir in the Bīriņi-Inchukalns-Nītaure region. Sediments with
these properties are also occasionally present in the lower or middle parts of the reservoir as 20-40 m-thick layers. Higher than average porosity is encountered in the Snēpele, Bauska and Oltuži wells where it ranges from 26% -28%.

The Cambrian reservoir sandstones belong to the intergranular, pore reservoir class with occasional fracture enhancement. Statistics are available for 1270 samples from this reservoir (Zābele and Sprinģe, 1992).

![Figure 11. Percent of Samples in Each Permeability Class.](image)

The second most widespread sediments have permeabilities from 100 to 500 mD. This group comprises 34% of total analyses. Average porosity is 17% but deviations from average are substantial, with some locations at only 10-15% whereas
others are as high as 24-26%. This type of sediment is common in northern Kurzeme and eastern Latvia.

Sediments with low permeability ranges from 10-100 mD, represent 7% of analyses and are found in the south-central part of Latvia, Ragaciems, Madona and Nagli. Porosity for these rocks range from 2% to 20%, with an average of 16%.

Only 6.5% of the samples have a permeability range of 1-10 mD. Studies show that low-permeability sediments (1-10mD) have a porosity range of 10% to 20%, with average of 16-18%. Interlayers of these rocks form 3 to 15m thick layers in the Jūrmala-Olaine region and the Dzērbene-100 well.

Nine percent of all tested samples in the Cambrian reservoir sandstones indicate permeability less than 1 mD. Porosity for these layers is 1% to 15%. These are almost impermeable layers which are present in all Cambrian cross sections in Latvia, but their total thickness in the overall reservoir is insignificant. Usually they appear as interlayers 0.1 to 1 m thick. Thicker units of 4 -13 m are present in the Slampe and Olaine-Jūrmala-Rīga region. Sediments with low porosity and high gas permeability are present in south-central part of Latvia.

Reservoir rocks of the Cambrian Cirma Strata and Deimena Formation and the Lower Ordovician Pakertorta horizon consist of light-colored, fine- to medium-grained, massive quartz sandstones (Figure 12).

Here permeability is very good and ranges from 10 to 1000 mD with open porosity of 15-25%. Layers of coarse siltstone are present in the reservoir as several-meters-thick interlayers with reservoir properties close to that of sandstone. Clayey
siltstones and clays are present as lenticular laterally discontinuous beds and as interlayers rarely exceeding 0.1 m. In general, 13.5% of analyses indicate rocks with poor reservoir qualities with permeability less than 10 mD. However, the net thickness of good quality reservoir rocks is close to the gross thickness indicated in Figure 10 and is not being seriously affected by the extent of low permeability lenticular beds. Nevertheless, these layers can and do cause a reservoir management problem by acting as an internal seal for vertical migration within the reservoir.

Figure 12. Sandstone Sample From the Dobele-92 Well at 1457.0 m Subsea Depth.
Core recovery was difficult in many of these wells due to poor sandstone cementation. At the time of drilling, there was no technology available to perform porosity and permeability analyses on loose, weakly-cemented sandstones.

Lower Ordovician Reservoir Seal

Ordovician sediments are present throughout Latvia, but are represented by a lower clayey member and an upper carbonate member, which represent different depositional environments during the Early Ordovician. The Cambrian sandstone reservoir has a regional seal of complex sequences of interlayered clayey-carbonate and carbonate rocks. The seal consists of sediments from the Varangu, Latorpa, Volhov, Kunda and Azeri horizons. The gross thickness of sealing formations varies with maximum values of 80 to 110 m in the Jelgava Depression and decreasing gradually to 10 - 20 m outside the depression in northern Kurzeme and eastern Latvia (Figure 13 and Map 4).

The basal part of the seal consists mostly of clays (Map 5). The clay layer is present only in western and central Latvia, where in the Jelgava Depression it reaches a maximum thickness of 40-50 m. Varangu and Latorp horizon clays were not found in wells drilled in northern Kurzeme and southeastern Latvia.

The clays are greenish-gray, gray or reddish-brown with high carbonate content, 5-10% silt fraction and 78-90% of total insoluble-solid content (Figure 14).
Figure 13. Isopach Map of the Ordovician Seal.
Clay minerals include illite (average 82%), kaolinite (up to 16%) and chlorite (8-11%). Carbonate minerals are generally calcite and dolomite. All Lower Ordovician clays have primary porosity of 6% to 19%. Gas permeability is very low, ranging from 0.00089 mD to 0.002 mD. No secondary porosity or micro-fractures have been found in the clayey formations. Very low values for gas permeability are typical for clays in all of the region. The clays are considered the main seal for the underlying sandstone reservoir (Zābele and Springle, 1992).

The upper carbonate seal member consists of limestones and marl. The western facies zone consists mainly of marl, which changes to limestone as these
facies interfinger with sediments of the eastern facies zone. The carbonate part of the seal is present throughout Latvia. The maximum carbonate thickness is in the Jelgava Depression (50-70 m), but thickness decreases rapidly outside the depression to 20-25 m. This part of the seal corresponds to the Volhov, Kunda and Azeri horizons (Table 5). Sealing properties of these carbonate lithologies are very good. Marls in western Latvia have gas permeability values less than 0.024 mD, and the limestones are equally impermeable (0.001-0.12 mD). However, in regional fault zone areas, limestones are slightly fractured and gas permeability increases to 0.1-0.2 mD. In the eastern facies zone, the carbonate part of the seal consists of 7 to 25 m of limestone with very low permeability values of 0.033-0.56 mD.
CHAPTER IV

GEOLOGIC AND RESERVOIR DESCRIPTIONS OF INDIVIDUAL STRUCTURES

Inchukalns Structure and Gas Storage Field

The first explorations for geological structures suitable for underground gas storage in Latvia were performed by “Спецгеофизика” (Specgeophysica) in 1961. As a result of reconnaissance and more detailed geophysical investigations, the following structures were discovered to have displacement on the top of the basement: Ergļu, Ogres, Mālpils and Inchukalns (Лукашева и др., 1961). The Inchukalns structure located in central Latvia, 7 km west of Sigulda, was chosen for further development. Initially 39 wells were drilled. The Cambrian reservoir was developed after drilling showed that the Devonian reservoir did not have sufficient closure. Most of the exploration and development of this structure was done by drilling. By 1968, the final report containing analyses of 86 samples from the Cambrian and Ordovician was completed and gas storage development began.

Geological, hydrogeological and hydrochemical properties for the Inchukalns structure were described by Artyomenko (Артоменко, 1969). Regional reservoir properties were later assessed by Semyonov (Семонов, 1973) when he was studying hydrogeological methods for underground gas storage creation in aquifers.
The Inchukalns structure is represented by a northeast-oriented anticline located on the southeastern, uplifted side of the Inchukalns Fault (Maps 5 and 6). The anticline hinge is subparallel to the fault line. The highest point of the anticline is at 620 m subsea on the top of the Cambrian reservoir. The structure’s area here is approximately 9 km by 2 km with 80 m amplitude. This structure began to form at the end of the Caledonian tectonic cycle and continued into the Devonian. Amplitude at the Devonian level decreases to 10 m.

There are a total of 180 wells drilled in the vicinity of the Inchukalns gas storage field (1995 data). Table 6 shows the different functions for these wells.

Table 6

Functions of the Wells in the Inchukalns Underground Gas Storage Field

<table>
<thead>
<tr>
<th>Number of Wells</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>93</td>
<td>Gas injection and withdrawal</td>
</tr>
<tr>
<td>44</td>
<td>Monitoring</td>
</tr>
<tr>
<td>23</td>
<td>Monitoring in overlaying aquifers</td>
</tr>
</tbody>
</table>

The 23 monitoring wells in the overlying Devonian, Silurian and Ordovician strata were drilled to detect possible leakage from the reservoir. Until recently there was no detailed seismic information available for the Inchukalns structure. Extensive common-depth-point seismic surveys (MOGT) performed in 1994 (Map 6) proved
that the structure is more complex than it was perceived from original well data interpretation in 1985 (Map 5). The 1985 map shows that most of the 180 wells were already in place, but information derived from the well data was not sufficient to interpret structural details.

In general, gas storage in this field has been managed as two separate reservoirs in the central part (Figure 15). Low permeability interlayers divide the upper unit (33 m) from the lower unit (10 m). Locally, lenses of low permeability sediments required the advanced gas storage management technique of injecting and withdrawing gas at different levels. Of the 93 working wells, 55 were completed in the upper unit, 23 in the middle of the reservoir and 15 in the lower unit.

From 1968 to the end of 1995, 28,034 MCM of gas have been injected and 25,479.9 MCM have been withdrawn (Figure 16 and Table 7). Gas volume in the reservoir before withdrawal in 1995 was calculated at 4048.1 MCM. According to A/S Latvijas Gāze data the total gas volume currently in storage is 4011.7 MCM, which indicates a volume loss of 36.4 MCM, 0.9% of total storage volume, over a 27-year period. The areal extent of gas occupying the structure is nearly 2000 hectares.

2 Four of these wells are in the downdropped northwest side of the fault, and 37 are on the southwest side.
Figure 15. Schematic Southwest-Northeast Cross Section of the Inchukalns Gas Storage Field.
Figure 16. Historic Gas Volume Dynamics in the Inchukalns Gas Storage Field.
## Table 7

Historic Gas Volume Data on the Inchukalns Gas Storage Field

<table>
<thead>
<tr>
<th>Year</th>
<th>Injected gas volume</th>
<th>Withdrawn gas volume</th>
<th>Calculated gas volume in reservoir before withdrawal</th>
<th>A/S Latvijas Gaze data for gas volume in reservoir before withdrawal</th>
<th>Volume difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>MCM</td>
<td>MCM</td>
<td>MCM</td>
<td>MCM</td>
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<td>1375.9</td>
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<td>1979</td>
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<td>1980</td>
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<td>1147.2</td>
<td>2080.0</td>
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<td>1983</td>
<td>1214.0</td>
<td>1198.9</td>
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<td>1984</td>
<td>1203.1</td>
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<td>1205.8</td>
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<td>24.7</td>
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</table>
Table 7--Continued

<table>
<thead>
<tr>
<th>Year</th>
<th>Injected gas volume</th>
<th>Withdrawn gas volume</th>
<th>Calculated gas volume in reservoir before withdrawal</th>
<th>A/S Latvijas Gaze data for gas volume in reservoir before withdrawal</th>
<th>Volume difference</th>
</tr>
</thead>
<tbody>
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<td>MCM</td>
<td>MCM</td>
<td>MCM</td>
<td>MCM</td>
<td>MCM</td>
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<td>1175.4</td>
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<td>3400.1</td>
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<td>1989</td>
<td>1900.0</td>
<td>1443.5</td>
<td>3621.6</td>
<td>3591.1</td>
<td>30.5</td>
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<tr>
<td>1990</td>
<td>1839.5</td>
<td>1815.9</td>
<td>4017.6</td>
<td>3985.2</td>
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<td>1991</td>
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<td>1830.9</td>
<td>4009.1</td>
<td>3976.1</td>
<td>33.0</td>
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<td>1992</td>
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<td>1254.1</td>
<td>3825.1</td>
<td>3791.1</td>
<td>34.0</td>
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<td>1993</td>
<td>1351.7</td>
<td>1172.1</td>
<td>3922.7</td>
<td>3887.7</td>
<td>35.0</td>
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<td>1994</td>
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<td>1387.7</td>
<td>4075.0</td>
<td>4038.5</td>
<td>36.5</td>
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<tr>
<td>1995</td>
<td>1360.8</td>
<td>1493.4</td>
<td>4048.1</td>
<td>4011.70</td>
<td>36.4</td>
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<tr>
<td>Total*</td>
<td>28034.6</td>
<td>25479.9</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
</tbody>
</table>

* The difference between cumulative injected and withdrawn gas volume is 2554.7 MCM.

** Calculated values for gas volume in reservoir before withdrawal and data submitted by A/S Latvijas Gaze indicate a difference of 36.4 MCM, which corresponds to 0.9% of total gas storage volume.
Calculations are based on the equation $Q = V \cdot h \cdot f \cdot \alpha \cdot m \cdot Kr \cdot Pnrr$, where:

- $Q$ = gas volume
- $V$ = area of the gas saturated part
- $h$ = net reservoir thickness
- $f$ = temperature adjustment coefficient
- $\alpha$ = compensation coefficient to comply with the Boyle’s law.
- $m$ = porosity
- $Kr$ = gas saturation
- $Pnrr$ = reservoir pressure

Geologists at the Inchukalns gas storage field have monitored observation wells on both sides of the fault system for 30 years. The hydrodynamic data from the wells ( #14, #16, #54, #53, #52, #7, #13 in Map 6 ) indicate that the fault system is not impermeable and formation pressure in juxtaposed fault blocks reacts to withdrawal and injection of gas in the main reservoir.

However, Map 6 shows locations where gas is contained at the fault system. This could suggest either lack of sufficient data for the area or perhaps juxtaposed impermeable strata outside the upper part of the fault-contained volume.

According to A/S Latvijas Gāze data, monitoring wells have not shown any leakage of gas into formations above the storage zone or into the Devonian aquifer and it is believed that contained gas does not reach the fault system.

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3 Based on formula published by М.А. Жданов “Недра” 1967.
The average porosity values are quite similar in both operating units of the field--20.1% in the upper unit and 21.7% in the lower unit (A/S Latvijas Gāze data). Gas permeability ranges from 6.2 to 4154.5 mD, where the lowest values correspond to low permeability interlayers. Average gas permeability for the Inchukalns structure is 460 mD according to Brangulis (Брангулис А.П., 1985.).

Dobele Structure

The Dobele structure is located in western Latvia 10 km east from Dobele city. It is 5 to 7 km south of the Iecava-Liepāja gas transmission pipeline with a 500 mm diameter. The surface location of the structure is in a forested and agricultural area, which can be easily accessed by roads.

The primary controlling fault for the Dobele structure is a part of the Saldus-Sloka Fault Zone (Кореневский, Болотов, 1970; Брангулис, Брио, 1979). Geological explorations of the Dobele structure were started by the Soviet operation “Союзбургаз” (Soyuzburgaz) in 1972. The structure was discovered by interpretation of seismic reflection profiles of the Ordovician seismic marker and top of the basement reflector.

Semyonov and Freimanis (Семонов, Фрейманис, 1974) analyzed a Middle Cambrian aquifer in the Dobele structure to assess hydrogeological and geological properties for creation of an underground gas storage field. Research data from the Dobele structure performed in later years is available in several reports as part of a major study to evaluate gas storage feasibility here (Бутковский, 1982, 1990;
Бондаренко и др., 1988; Бондаренко, Миронюк, 1990). The study was never completed, however, and the location of most of the original information is unknown.

Average porosity for Cambrian sandstones and siltstones at this structure is 23% to 25.8% with gas permeability ranges of 425 - 725 mD. As shown in Table 8, there is significant variability in porosity and permeability, which is a result of highly variable clay content.

Table 8

Examples of Porosity and Permeability Values from the Dobele-91 Well

<table>
<thead>
<tr>
<th>Well Name and Sample #</th>
<th>Depth (m)</th>
<th>Open porosity (%)</th>
<th>Horizontal Gas Permeability (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dobele-91 (38°)</td>
<td>920.0</td>
<td>8.85</td>
<td>0.1305</td>
</tr>
<tr>
<td>Dobele-91 (39°)</td>
<td>928.5</td>
<td>7.97</td>
<td>0.0890</td>
</tr>
<tr>
<td>Dobele-91 (40°)</td>
<td>935.0</td>
<td>5.85</td>
<td>0.1025</td>
</tr>
<tr>
<td>Dobele-91 (40°)</td>
<td>940.0</td>
<td>7.41</td>
<td>0.0834</td>
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<td>Dobele-91 (40°)</td>
<td>945.0</td>
<td>7.10</td>
<td>0.0785</td>
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<td>949.8</td>
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<td>0.1171</td>
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<td>0.1295</td>
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<td>0.5270</td>
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<td>607.0000</td>
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<td>Dobele-91 (49°)</td>
<td>1104.8</td>
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<td>7.0000</td>
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<td>Dobele-91 (49°)</td>
<td>1123.0</td>
<td>28.30</td>
<td>12.2800</td>
</tr>
</tbody>
</table>

The Dobele structure is a northeast-oriented anticline delimited on the southeast by the Dobele-Babite Fault (Map 7 and 8). The structure at Cambrian level is about 15 km long and 6 km wide. The highest point on the basement structure is -1040 m subsea. Amplitude on top of the Ordovician is 116 m. In the Hercynian
Complex strata, the amplitude of the structure decreases. The structure developed in Early to Middle Cambrian time, but had most actively grown at the end of the Caledonian cycle. There are 22 wells drilled on the structure and in the nearby vicinity. Unfortunately, information about 13 of the most recently drilled wells (1988-1990) is stored in Belarus. Core samples, hydraulic test results and all other relevant information from these wells has not been made available to the State Geological Survey of Latvia.

The map of the Ordovician seismic reflector prepared in this study, based on seismic data (Map 7), provides reference points for the top of the Cambrian reservoir map. Based on this work, the actual structure at Cambrian level is significantly smaller than had previously been commonly thought. This structure is generally described as having the closure contour at -1075 m or -1100 m subsea on the top of the Cambrian reservoir. However, data from Map 8 suggest the closure contour at fault plane of -975 m subsea. The amplitude of the structure above the contact with the fault zone is not 90 m but only 25 m. A similar reduction is true for the structure’s areal extent. Instead of 69 square km at -1075 m contour, the area would be about 4 square km at -975 m contour. The isopach thickness of the Cambrian reservoir in this area ranges from 31 to 40 m (Map 2).

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4 Belarus geologists had undertaken an extensive drilling/testing program of the Dobele structure for underground gas storage from 1988 to 1990. Then the Soviet Union collapsed and funding was terminated. Now most of this data is housed in Belarus.
At least 42 km of single-fold seismic profile lines cross the Dobele structure. These seismic surveys were done in 1971-1972 (Table 4). The density of the survey lines provides good, basic coverage (Maps 7 and 8).

North Blīdene Structure

The North Blīdene structure is located in western Latvia, 10 kilometers southeast from Saldus city. This structure is located adjacent to the Saldus-Sloka Fault zone. The surface location of the structure is in a forested and agricultural area, which can be easily accessed by roads. This structure was first delineated in the Ordovician strata by single-fold seismic reflection surveys performed from 1959 to 1961 (Table 4). A total of more than 29 km of seismic lines cross the structure (Maps 9 and 10).

The top of the basement is generally reflected in the structure in the Ordovician. This structure is located on the northern, uplifted side of the Liepāja-Saldus Fault and belongs to a group of structures called The Saldus-Sloka Fractured Zone of Anticlines (Figure 9). The structure itself is an anticline with two domes, possibly separated by a fault. Structural development began in the Middle to Late Cambrian and continued throughout Caledonian time. The domes measure 3.5 x 3 km and 9 x 2.5 km at -950 m subsea contour and the amplitude above the closure contour on the Ordovician surface is 50 m. The structure's highest point on the basement surface is -1020 m subsea. The structure continues upward into the
Hercynian Complex and can be traced on the Middle Devonian Narva horizon surface.

Well Blidene-5, which penetrates one of the domes, did not recover any core from the Cambrian sediments. According to e-log data, reservoir rocks have a thickness of 31 m in this well. In the Stūri-8 well, 5 km southeast from the structure, two samples were tested for reservoir properties. Porosity was 29.4% and 28.1% and gas permeability was 829 and 854 mD.

Amata, Ligatne and North Ligatne Structures

The Amata structure is located in central Latvia, 15 km southeast of Cēsis. The surface location is in an easily accessible forested area. This structure belongs to the Inchukalns Fault Zone Anticline Group and is confined by the Inchukalns fault on the north side and may be influenced by the Central Baltic and East Baltic pre-platform faults on the western and eastern sides. The approximate size of the structure is 5 km x 5 km with a maximum of 50 m amplitude on the top of the basement rocks. (Map 11).

The Ligatne structure is located in central Latvia, 10 km southwest of the city of Cēsis. The Northeastern part of this structure is located within the Gauja National Park. The park boundary runs along the highway and this portion of the National Park has a limited set of restrictions. Most importantly, the Ligatne structure is situated directly beneath the Rīga-Inchukalns-Pskov high capacity (700 mm) gas transmission pipeline.
The Līgatne structure is confined by the Inchukalns Fault Zone on the north and may be influenced by the regional West-Baltic pre-platform fault from the west. Based on available data, exact location of the faults is impossible, due to the low resolution of geophysical surveys. The structure was mapped after seismic refraction profiling on the top of the basement rocks in 1963 (Table 4). The confining fault system is located on the northern side of the anticline (Map 11).

The highest point on the top of the basement is at 650 m subsea (Map 11). The structure is 8km x 5km with an amplitude of 70m. The strata within the Līgatne structure show movement in both Caledonian and Hercynian sediments. Amplitude on the top of the Šventoja horizon in the Devonian is 15 to 20 m.

The North Līgatne structure is located in central Latvia, 12 km west from Cēsis. The surface location is partially within the Gauja National Park wetlands. This structure is also associated with the Inchukalns Fault Zone. It was discovered in 1963 by seismic refraction profiling on the top of the basement rocks (Table 4). The structure is represented by an anticline on the top of the basement (Map 11), in the Caledonian cycle sediments. This structure is bordered by the Cēsis-Sloka fault system on the north side and by the Inchukalns Fault on the south. The structure has a northeastern orientation with an areal size of 8 km x 2.5 km and amplitude of 70 m at the top of the basement rocks. The highest point on the basement is at 700 m subsea.

Refraction profiling surveys together with local refraction measurements and telluric methods are the sole sources of geophysical information about the Līgatne, N. Līgatne and Amata structures. These geophysical methods are less precise than
seismic reflection surveys. These surveys were able to detect the top of the basement igneous and metamorphic rocks. Estimated thickness of Cambrian formations were then added to create a synthetic map for the top of the Cambrian (Map 12).

Density of profile lines and number of measurement locations in the area (Maps 11 and 12) are insufficient to provide for good data interpretation. Additionally, there are no wells on these structures to provide drilling data. Estimated interpretation error could be as much as 50 meters. The Kārļi well, located near the Līgatne structure was not cored. The Inchukalns gas storage field and the Līči and Čīrulīši wells are the closest well group where analyses have been performed. It is likely that reservoir properties in these structures may be close to those in the Inchukalns gas storage structure sandstones and siltstones. The porosity ranges from 8.8% to 31.8% (average 19.2%) and gas permeability from 6.2 to 4154.5 mD (average 460 mD). Twelve samples from the Līči/Čīrulīši wells show porosity from 15.8% to 31.5%, with an average of 25.7%. Gas permeability is 552 to 702 mD.

The North Līgatne and Līgatne structures are located within the Gauja National Park.
CHAPTER V

CONCLUSIONS

There are excellent reservoir rocks and structural traps well-suited to underground gas storage in Latvia. The one existing gas storage field, Inchukalns, has been operating since 1968, and can be used as a model for understanding subsurface geology, stratigraphy and structures. Its performance as a reservoir can also serve to indicate engineering characteristics of these reservoirs.

Structures in two geographic regions of Latvia were analyzed for future storage potential:

1. Dobele and North Blīdene structures in west Latvia, associated with the Saldus-Sloka Fault Zone.

The best data coverage including wells drilled and samples analysed is from the Dobele structure. The reservoir rock there is 30-40 m thick and has sufficient porosity and permeability. Data confirm the existence of geological structure and sealing units. The structure map prepared in this study, based on seismic data for the Ordovician reflector (Map 11), provides data for the top of the Cambrian reservoir map (Map 12).

The analyses of fault position on the structure suggests, that the usable structure volume at Cambrian level is significantly smaller than had commonly been
thought. The amplitude of the structure above contact with the fault zone is not 90 m but only 25 m. Similar reduction is true for the structure’s areal extent. Instead of 69 square km at -1075 m contour, the area would be about 4 square km at -975 m contour.

The major unknown variable of concern here is the sealing capacity of the structure-boundary fault. The Inchukalns gas storage field shows that volume used for gas storage is larger than the actual volume above the fault and structure contact.

Additional studies would be required to determine the reservoir volume under the sealed trap. The recommended step is to purchase the hydrodynamic test analyses from Belorus geologists in order to obtain fault system property data. Then the decision could be made about whether to proceed with more expensive high resolution seismic programs.

The North Blidene structure consists of two separate domes. The domes measure 3.5 x 3 km and 9 x 2.5 km at -950 m subsea contour and the amplitude above the closure contour on the Ordovician surface is 50 m. There is very little information about reservoir properties in this structure—the reservoir thickness is 30 m; and, in a well 5 km southeast from the structure, porosity value ranges from two samples are 29.4 % and 28.1% and gas permeability is 829 and 854 mD. It is likely that similar reservoir properties are also present in the structure. The sealing properties increase regionally to the west. However, detailed seismic survey may reveal a complicated fault system in these two domes and the distant location from existing pipelines discourage its development at this time.
2. The Līgatne, North Līgatne and Amata structures are located in north central Latvia and associated with the Inchukalns Fault Zone. There is no direct well data available to develop a geologic cross section or to analyze reservoir properties in these structures. The only well in the region, the Kārļi well, is located near the Līgatne structure and it has not been cored. Regional properties of the strata are based on data collected from Čirulīši, Liči, Bīriņi wells and the Inchukalns Gas Storage Field. The Līgatne and North Līgatne structures are located within the Gauja National Park. The Riga-Inchukalns-Pskov 700-mm gas transmission pipeline is located directly over the Līgatne structure, which makes it a very attractive target for development. Lack of direct data and high quality geophysical surveys limit comparison with regional data and the Inchukalns structure.

Sedimentologic and stratigraphic properties of the Cambrian sandstone units changes from east to west in Latvia. In general, the western part of the study region has more homogeneous sandstones, whereas in the eastern part, Cirma Formation sandstones have more lenticular interlayers of clay and silt. Sandstones in the western part are predominantly fine-grained; whereas in the eastern part, they are medium-grained and poorly sorted. Reservoir thickness in both regions is within the range of 30 to 50 m.

Reservoir properties are similar in both regions. It appears from regional well data that the Līgatne region could have slightly higher values. In general, average porosity ranges from 15% to 20 %.
The sealing formations are more continuous in the western part of study region where thick layers of Ordovician clay overlain by marl were deposited in the deepest parts of the basin. Sealing units in the eastern part were deposited closer to the basin edge and the clay layers are not so thick.

The Dobele and N. Blidene structures have larger potential volumes than the Līgatne, North Līgatne and Amata structures. All the structures are associated with faults in a manner similar to the Inchukalns structure. Examination of detailed seismic surveys of 1994 shows that interpretation of the Inchukalns structure is significantly different in structural configuration from previous descriptions. More detailed seismic surveys would likely show a more complex fault system in all studied structures. Specific recommendations for gas storage should be made only after more detailed seismic surveys confirm structural configurations.

This study was undertaken to estimate the geological potential of underground gas storage in Latvia. It confirms the existence of essential geological criteria—reservoir properties, structure and seal integrity. Currently, data available support recommendation of only the Dobele structure for possible development. However, the storage volume is uncertain here and development of this structure will require a future investment in both geological research as well as additional pipeline construction.

The next most likely candidate is the Ligatne structure. Detailed seismic studies and drilling of several wells are required to make a recommendation about the geology of this structure. However, it has the potential for only moderate storage
volume, and is strategically located under an existing high-volume gas transmission pipeline. Other structures need further geologic and geophysical investigation before they can be effectively evaluated for storage potential.
BIBLIOGRAPHY

Published


Брангулис А.П., (1985). Венч и кембрий Латвии. Рига


Брангулис А. и др., (1989). Стратотипические и опорные разрезы венда, кембрия и ордовика Латвии. Рига, Зинатне

Гайлике Л., Рыбинкова М., Ульст Р., (1967). Стратиграфия, фауна и условия образования силурийских пород Средней Прибалтики. Рига, Зинатне

Гайлике Л., Ульст Р., Яковлева В., (1987). Стратотипические и типовые разрезы силура Латвии. Рига, Зинатне

Геологическое строение и полезные ископаемые Латвии, (1979). Рига, Зинатне

Грунты, (1982). Методы лабораторного определения гранулометрического (зернового) и микроагрегатного состава ГОСТ 12536-79. Издательство стандартов

Девон и карбон Прибалтики, (1981). Рига, Зинатне

Каталог стратотипов венда и кембрия Прибалтики, (1992). Сост. К.Менс. Таллин


Мяннель П.М., (1966). История развития Балтийского бассейна в ордовике. Таллин


Палеогеография и литология венда и кембрия запада Восточно-Европейской платформы, (1980). Москва

Проблемы унаследованности тектонических структур в Прибалтике и Белоруссии, (1979). Таллин
Региональная тектоника Белоруссии и Прибалтики, (1977). Минск, Наука и техника

Савваитова Л. (1977). Фамен Прибалтики. Рига, Зинатне

Семенов О.Г., Фрейманис А. А., (1974). Геологические и гидрохимические условия создания подземного хранилища газа в среднекембрийском горизонте Добельской структуры. Геология и разведка газовых и газоконденсатных месторождений, вып. 10, Москва

Стратиграфия верхнедокембрийских и кембрийских отложений запада Восточно-Европейской платформы, (1979). Москва, Наука

Тектоника Прибалтики, (1979). Под ред. П.И.Сувейздиа, Вильнюс

Тектоническая карта республик Советской Прибалтики, (1980). Масштаб 1:500 000. Объяснительная записка. Ленинград, Недра

Тектоническая терминология Белоруссии и Прибалтики, (1978), Т.1. Минск, Наука и техника.

Тектоническая терминология Белоруссии и Прибалтики, (1979), Т. 2. Локальные структуры. Минск, Наука и техника.

Ульст Р.Ж., Гайлите Л.К., Яковлева В.И., (1982). Ордовик Латвии. Рига

Ханин А.А., (1969). Породы коллекторы нефти и газа и их изучение. Москва

Geological Survey of Latvia Proprietary Information


Башкин В.В., (1975). Геологические и гидрогеологические материалы для рассмотрения вопроса о допустимости сброса промышленных сточных вод Инчуканской СПХТ в пласт-коллектор кембрия через две поглощающие скважины. Рига


Брангулис А.П., Фрейманис А.А. и др., (1981). Геолого-структурная оценка осадочного чехла Прибалтики с целью определения возможностей создания подземных хранилищ газа и захоронения промышленных сточных вод. Рига

Бутковский Ю.М., (1982). Анализ и обобщение материалов буровых работ по подземному хранению газа в Белоруссии и Латвии. Отчет Западной тематической партии по теме 3-81-82. Москва

Бутковский Ю.М., (1990). Результаты поискового бурения на Добельской площади. Отчет Западной камерально-тематической партии. Москва

Григоренко А.А., (1978). Поиски горизонтов в нижнепалеозойских отложениях для захоронения сернокислого гудрона, не поддающегося отчистке, в р-не Инчукалиса. Рига

Кожемякина И.А., Степанян Э.А., (1962). Геологический отчет. Перспективы создания ПХ естественного газа в районе г.г. Вильнюса и Каунаса. Москва

Кожемякина И.А., Пальцева К.Ф. и др., (1971). Отчет о результатах комплексной обработки материалов структурного, разведочного бурения и гидродинамических исследований, проводившихся на Укмьярской площади (работы связаны с созданием ПХГ в Лит.ССР). Москва

Кожемякина И.А., Пальцева К.Ф. и др., (1973). Оценка геологических условий создания подземного хранилища газа вдоль трассы проектируемого газопровода Каунас-Калининград. Москва
Лаврентьева С.А., Костякова Я.В. и др., (1976). Отчет о работах, выполненных Ленинградской электrorазведочной партией № 2-75 на территории Юго-Восток Эст. ССР в 1975 г. Ленинград

Лукашева А.В. и др., (1961). О работе Рижской сейсмической партии № 3159 и Латвийской электrorазведочной партии № 21-59. Рига

Лукашева А.В. и др., (1961-2). Отчет о работах Рижской сейсмической партии № 3-60 Латвийской ССР. Рига

Наumenko E.P., Наumenko L.P., (1980). Предварительная разведка кембрийского горизонта для захоронения промстоков не поддающихся очистке в п-не г. Вентсунис. Рига

Пальцева К.Ф., Кожемякина И.А. и др., (1976). Оценка геологических условий подземных хранилищ газа вдоль трассы газопровода Паневежис-Клайпеда. Москва

Пальцева К.Ф., Кожемякина И.А., Савчук И.В., (1977). Отчет о результатах структурного бурения, проводившегося на Веприйской площади в Лит. ССР для целей подземного хранения газа. Москва

Пензина В.Н., Парвиайнен Л.Н., Штейнман М.В., (1977). Отчет о сейсморазведочных работах МПВ, выполненных Ленинградской с.п. № 20-76 на территории Псковской обл. РСФСР и Эст. ССР. Ленинград

Пензина В.Н., Парвиайнен Л.Н., (1979). Отчет о результатах поисково-рекогносцировочных работ МПВ на Эливетерской площади в 1978 г. Ленинград

Семенов О.Г., (1973). Методы и практика применения гидрогеологических исследований при создании ПХГ в водоносных пластах. Диссертация на соискание ученой степени кандидата геол.-мин. наук. Москва

Сокуренко А.А., Григоренко А.А., (1977). Предварительная разведка кембрийского горизонта для захоронения промстоков не поддающихся очистке в п-не г. Олайне. Рига

Станкевич А.И., Макарова Г.Ф. и др., (1968). Отчет по обработке материалов разведочного бурения и гидрогеологических исследований на Инчукалнной площади. Рига
Федоров В.В., Иванова О.Н., Беляев В.С., (1992). Оценка возможностей создания системы подземных хранилищ газа в Латвийской Республике. Рига