Bulletin of the Geological Society of Finland, Vol. 98, 2026, pp 5–35 https://doi.org/10.17741/bgsf/98.1.001

Economic potential for iron ores in the Precambrian basement of Latvia

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Abstract

Increasing demand for both critical and noncritical metals (Fe, Mn, Co, etc.) needed for e.g. renewable energy projects result in growing exploration interest in areas regarded traditionally as uninteresting for mining sector. Latvia located in the north-western part of the East European platform is one such area that has not been considered historically as a target area for ore exploration, mainly because of the thick (250–1900 m) sedimentary rock cover that overlies Precambrian rocks. Also, geological information about the area is not widely available, and there are no summaries of historical discoveries. In this paper we review geophysical (magnetic and gravity field measurements, seismic and electrical resistivity survey) and drill-core data sets (39 boreholes) that reveal information about the Precambrian basement of Latvia and its ore potential. We describe the methods that were used to obtain these data sets and provide an assessment of the precision and reliability of these data sets. We conclude that many geophysical measurements, that have been conducted in Latvia, can only be used to identify areas of interest. For modelling purposes new measurements must be performed. Thirteen of the magnetic anomalies have been verified by boreholes, most of which confirmed the presence of iron occurrences. The Staicele and Gārsene magnetic anomalies were studied in the most detail, because they likely contain the highest-grade iron occurrences.

Keywords: metals; Precambrian rocks; magnetic field anomaly; critical minerals; Baltica paleocontinent

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Editorial handling: Alexander Slabunov (email: slabunov@krc.karelia.ru)

1. Introduction

In our quest to reach the green energy transition, as well as to continue the development of various technological solutions, we are faced with increasing demand for raw minerals (IEA, 2022; Grohol & Veeh 2023). In order to fulfil our goals in the area of renewable energy sources, we must devote significant resources to building new wind farms, solar parks, geothermal energy plants, etc. (Hund et al. 2020; IEA 2022; Grohol & Veeh 2023). This in turn means that there will be an increasing demand not only for the critical raw minerals (CRMs) but also for the base metals that are needed for building such infrastructure. By looking at different scenarios that describe the future demand for raw minerals, we see that even the modest forecasts indicate that raw mineral resources will run out rather soon, if discoveries of new deposits are not made (Hund et al. 2020).

The Baltic States, which are located in the north-western part of the Eastern-European platform (Fig. 1a), have not historically been considered as a potential target area for mineral exploration, mainly because of the thick sedimentary siliciclastic and carbonate rock cover that overlies the Precambrian rocks. Additionally, geological information about the area is not widely available, and in many instances, there are no summaries of the historical discoveries. As a result, potentially interested parties would need to spend a substantial resources going through historical reports that in many instances are available only in paper format.

The first information about the Precambrian basement of Latvia was obtained during oil and gas exploration campaigns in the late 1940s. Geophysical survey methods were used to pinpoint the locations of the boreholes. These boreholes were drilled until they reached the Precambrian basement. The first such borehole was drilled near the city of Daugavpils in south-eastern Latvia from 1947 to 1949 (Vetrennikov 1996). Early work on the Precambrian geology of Latvia based on bedrock samples obtained rocks during oil exploration and geological mapping was summarised by Bogatikov & Birkis (1973).

Early studies of the crystalline basement of Latvia by Luncs, Ozoliņa and Bogdanova resulted in the first map of the Precambrian basement of Latvia (Luncs & Ozoliņa 1971). A few years later the second interpretation of the Precambrian basement of Latvia was published by Birkis (1975), which was produced with less complexity in accordance with the very limited physical borehole material and regional geophysics. Until that time, most boreholes were drilled in the western part of Latvia, and in most cases penetrated less than 30 m into the Precambrian basement below the sedimentary cover. Nonetheless, three of these boreholes were drilled into the Staicele and Strenči magnetic anomalies, two major geophysical features in the Latvian basement that are disussed in this paper (Fig. 1a).

Later studies on the Precambrian basement of Latvia focused on iron formations, but also a new map was compiled mainly based on magnetic interpretation. Iron ore potential was evaluated using numerical methods and based on analogy with better known deposits in Belarus. (Vetrennikov 1996)

In this paper, we aim to review geophysical and drill-core data sets that reveal information about the Precambrian basement of Latvia and potential metavolcanic and/or metasedimentary iron, manganese, cobalt, and other metal occurrences in it. We describe the methods that were used to obtain these data sets, as well providing an assessment of the precision and reliability of these data sets.

2. Geological settings

Latvia's bedrock divides into two parts – the Precambrian basement, and the Phanerozoic sedimentary rock succession. The sedimentary cover is 250–600 meters thick in the north-east and more than 1900 m in the south-west (Brangulis et al. 1998) (Fig. 1b).

The Precambrian basement was formed between 1.9 and 1.5 Ga and belongs to the Fennoscandian crustal block of the East European Craton and is

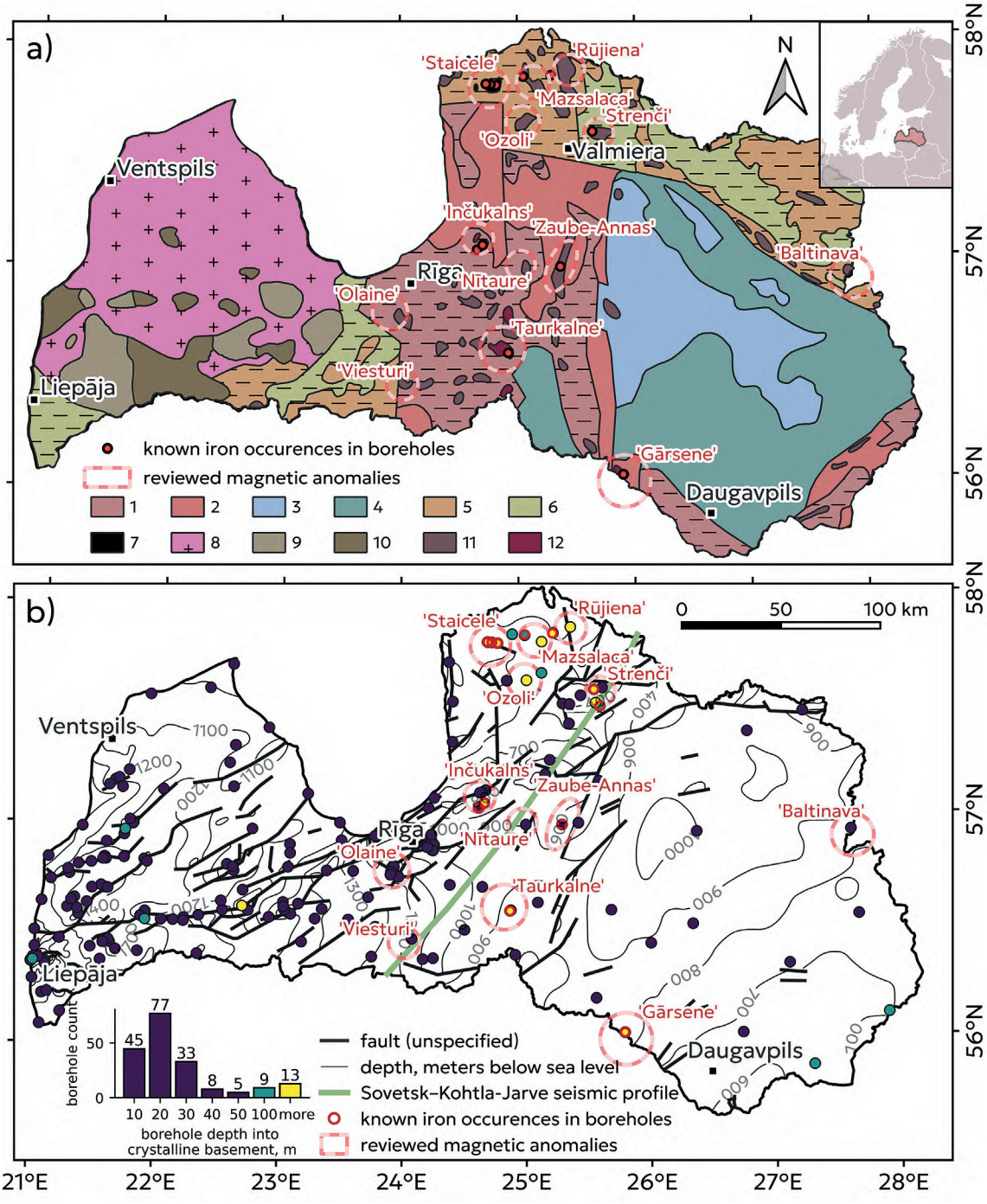


Figure 1. a) Lithological map of the the crystalline basement of Latvia modified after Birķis (1975) with the locations of the reviewed magnetic anomalies circled and known iron occurences in boreholes as verified in later studies. 1: Ca-rich amphibolite, 2: Ca-poor biotite-feldspar gneiss, 3: biotite granitic gneiss and gneiss, 4: biotite gneissgranite and migmatite, 5: Ca-rich hypersthene-plagioclase schist and gneiss, 6: Ca-poor hypersthene-feldspar schist and gneiss, 7: clinopyroxene schist and magnetite quartzite, 8: rapakivi granite, 9: gabbronorite and troctolite, 10: anorthosite and troctolite, 11: magnetic anomalies, presumably mafic igneous rocks or amphibolites, 12: magnetic anomalies of unclear composition, partly magnetite quartzites and ferruginous mafic rocks, b) the depth to the surface of the Precambrian basement surface with boreholes that have reached it, categorised according to the drilled depth into the basement.

considered as a continuation of the Fennoscandian shield beneath the Phanerozoic sedimentary cover (Bogdanova et al. 2008; Bogdanova et al. 2015). Crust formation began in the Paleoproterozoic during the assembly of the Columbia/Nuna supercontinent (Mansfeld 2001; Torsvik & Cocks 2005; Bogdanova et al. 2008; Li et al. 2008), and, just like the outcropping basement in Sweden and Finland, the Precambrian basement rocks in Latvia show a complicated geological history dominated by magmatism and high-grade metamorphism.

According to the tectonic model of Bogdanova et al. (2015), the territory of Latvia at around 1.9 Ga was part of the Livonia megadomain, which together with the Bergslagen megadomain formed a microcontinent. The accretion of neighbouring microcontinents occurred during the Svecofennian orogen at 1.87–1.75 Ga, either in a master subduction zone or as multiple subductions and collisions. The complicated tectonic processes resulted in heterogeneous mixture of metasedimentary and metavolcanic rocks metamorphosed in amphibolite and granulite facies, i.e. quartzites, amphibolites, schists and gneisses, and even migmatites (Birķis 1975) (Fig. 1a). Out of the magmatic intrusions dotting the Precambrian basement one granodiorite has been dated to 1.81 Ga (Bogdanova et al. 2015). Some of the metamorphic rocks are interpreted to be iron formations (Vetrennikov 1996), which are similar to the Bergslagen iron-oxide ores of various origins, although with lesser amounts of sulfides (Jansson 2011).

After the Svecofennian orogeny, possibly due to far-field effects of orogenic processes, a major AMCG (anorthosite-mangerite-charnockite-granite) magmatism event occurred at 1.59–1.56 Ga formed the Kurzeme (formerly Riga) batholith in western Latvia (Bogdanova et al. 2008; Skridlaite et al. 2014) covering approximately 40 000 sq. km. Most of this batholith consists of rapakivi granite, but the southernmost part is mostly made up of mafic and even ultramafic rocks such as gabbros, troctolites and anorthosites (Birķis 1975) (Fig. 1a).

The deep structure of the crust has been studied along the Sovetsk–Kohtla-Järve seismic refraction profile, which crosses central Latvia roughly in a north-south direction (Akundinov et al. 1994). Based on gravity field measurements the Moho surface is at a depth between 45 and 48.5 km (Zandersons & Karušs 2026). Similarly, as in the rest of the Eastern Europe, the Precambrian rocks form distinct blocks (Bogdanova et al. 2015). Seismic data show that these blocks are separated by deep-seated faults that are oriented approximately northwest-southeast and appear to be restricted to the basement (Fig. 1b). Excluding the Leba Ridge-Riga-Pskov fault zone, which is younger than Proterozoic and crosses Latvia as numerous long faults in NE–SW direction (Fig. 1b), the topography of the Precambrian bedrock surface does not show any prominent steps (Tuuling 2019).

Since the late Neoproterozoic, Latvia has experienced relatively stable conditions as it is located almost in the middle of the Baltica palaeocontinent (Cocks & Torsvik, 2005; Torsvik & Cocks 2005; Nance et al. 2014). Ediacaran to Jurassic deposits are the dominant part of the sedimentary rock succession. They are mainly siliciclastic and carbonate sedimentary rocks, which formed in seas, river deltas and estuaries. The sedimentary cover is deformed via numerous faults, most of which are oriented in the NE-SW direction. The uppermost part of the sedimentary cover is made of Quaternary deposits, which formed during the last glaciation and the Holocene.

3. Available historical data

3.1. Geophysical data

Throughout the last century in the territory of Latvia various geophysical methods have been used for geological exploration. Here we present short summary of those measurements. More detailed information can be found in Appendix B.

Magnetic field mapping has been conducted since the beginning of the 20th century. The entire territory of Latvia has not been mapped at a single resolution and the scales of the surveys vary from 1:200 000 to 1:50 000 (Appendix C). Wider areas

were covered with aeromagnetic surveys while at some locations also ground surveys were conducted. During the surveys different types of total field measurement devices were used. Reported precisions vary from 2 to 25 nT. The spatial precision of these measurements is relatively low. Raw data that could be used to apply the corrections now are unavailable.

Gravity field mapping was conducted with different goals and resolutions. The whole country is covered with gravity field measurements in the scale 1:200 000, coinciding with the grid spacing of approximately 2–3 km (Kaminskis 2010). It was reported that the uncertainty of these measurements is 0.4-0.5 mGal. From the 1950s to the 1970s, also gravity profiles for the mapping of buried pre-Quaternary river valleys were made as a part of geological mapping at scales of 1:200,000 and 1:50,000. In 1986, ground-based gravity field mapping at the scale 1:50,000 was conducted in order to study possible valuable resources in the Precambrian basement (Vetrenikov et al. 1986). The gravity measurement points were collected on profile lines spaced 500 meters apart with 250 meter distance between measurements with a precision of 0.1 mGal.

More recent gravity field measurements were conducted by the Geodetic Survey of Latvia (LGS) and the State Land Service between 1998 and 2011 (Zandersons & Karušs 2020). In total, 4886 relative measurements were conducted in an irregular grid with an average distance between points of 3 km. The standard error of those measurements is about ±0.055 mGal.

Seismic surveys (reflection and refraction) have been made to map local structures, as well as to create country-wide structural maps. Most of the profiles are located in the western part of the country, as part of oil exploration works (Brangulis 2002). Individual profiles were several hundreds of metres long, with a sensor spacing of 5 m. The explosions usually were set 300 m apart. Sometimes it is reported that explosives were placed in the boreholes at a depth of 10 m (Mironov et al. 1973; Vetrennikov et al. 1982).

Most of the seismic profiles in Latvia were recorded from 1959 to 1972 and are available and stored in LEGMC (Latvian Environment, Geology and Meteorology centre) in paper format only. The overall quality, as well as the preservation of these data sets, is rather poor. In most cases, it would be complicated to re-interpret the data. Even more problematic is that some parts of the original data are lost. Only a small part of the profiles is available in digital format.

Electrical resistivity measurements were conducted to gain insight into the structure of the Precambrian basement before a significant amount of the seismic data and the magnetic field data were gathered across Latvia (1947–1973, Appendix B). Vertical electrical profiling (VEP) was used with a maximum AB spread reaching 20 km. Non-polarised electrodes, steel electrodes (1.5 m long) and brass electrodes, were used for the measurements.

Around the middle of the last century, the magnetotelluric method was used to determine the electrical conductivity of deeper sedimentary rock layers, as well as to map the surface of the Precambrian basement in Latvia (Mironov et al. 1973). In most cases, there was one observation point for every 50-70 km^2. Measurements were done with a JPL-57 device, using time intervals from 8 s to 2.5 h. For geological purposes, mainly intervals of 10-35 s were used (Jankin et al. 1975). Correlations with boreholes indicated that the uncertainty of the depth of the Precambrian basement does not exceed 50 m.

Since 1959, borehole geophysical logging has been conducted for 189 boreholes that reach the Precambrian basement. For all of those boreholes, gamma logging, neutron logging, cavernometry, inclinometry and electric logging were performed. The electric potential was measured using a Zond MEP device with zinc brooms and a zinc shield (Vetrennikov et al. 1982, 1986; Baulins et al. 1995). For some borehole temperature measurements, acoustic cementometry, induction logging and neutron-gamma logging were done (Vetrennikov et al. 1982, 1986).

For 53 boreholes, including the boreholes in the Gārsene and Strenči magnetic anomalies (Fig. 1b), vertical seismic profiling was done. Explosives

with weights from 0.4-1.2 kg were used as a source in shallow boreholes with casing (Vetrennikov et al. 1982, 1986).

For boreholes drilled in the five most prominent magnetic anomalies, the total magnetic field intensity and magnetic susceptibility were measured. (Vetrennikov et al. 1982, 1986).

Most frequently, gamma logging, neutron logging, cavernometry, inclinometry and electric logging data are digitised and stored at LEGMC. However, more specific data, such as magnetic field parameters, are available only in paper format, and in this case, the values of the recorded measurements are quite often unreadable.

3.2. Boreholes reaching the Precambrian basement

The first boreholes to reach the Precambrian basement in Latvia were drilled from 1948-1954, in the central part of Latvia. Until 1978, the drilling was connected to geological mapping at the scale 1:200,000. Deep boreholes were drilled in order to test oil-bearing structures, find mineral waters, thermal anomalies and to study structures for the deposition of contaminated waste and underground natural gas storage, as well as to confirm the sources of observed geophysical anomalies. Most of the boreholes penetrated less than 25 m into the Precambrian basement (Fig. 1b). Drilling in northern Latvia near the town of Staicele confirmed that some of the local magnetic anomalies (Fig. 1b) are caused by iron occurrences (Bičko et al. 1967).

From 1976-1982, detailed aeromagnetic, ground magnetic, gravity and seismic surveys were conducted in eastern Latvia. Boreholes reaching the Precambrian basement were drilled as part of this work, and they resulted in the discovery of the Gārsene iron-rich formations (see Chapter 4.12.). Similarly, the Inčukalns iron-bearing quartzites were found (Chapter 4.6.), and a more detailed survey of the Staicele iron-rich occurrences (Chapter 4.1.) was conducted (Vetrennikov et al. 1982). Later more boreholes were drilled in northern Latvia, where the Precambrian basement appears at the shallowest depth as part of the study of the iron occurrences in Precambrian rocks (Vetrennikov et al. 1986).

Up to date 207 boreholes that reach the crystalline basement have been drilled. Additionally, two boreholes were drilled in the economic zone of Latvia in the Baltic Sea. Large majority of them were drilled from 1960 to 1990, and do not penetrate deeper than 30 m into the Precambrian basement (Fig. 1b). Excluding one, all of the 14 boreholes extending more than 100 m in the basement have been drilled in or near identified magnetic field anomalies (Figs. 2, 3, 5, 6).

3.3. Petrophysical data

Petrophysical sampling and laboratory analyses were conducted for the boreholes drilled to find the iron formations, i.e. the ones drilled into Staicele, Strenči, Mazsalaca, Rūjiena, Inčukalns, Zaube-Annas, Taurkalne and Gārsene anomalies (Vetrennikov et al. 1982) (Figs. 4, 6, 7; Chapter 4). Drill core samples for laboratory analyses were taken with a spacing of 1 m on average. From these samples the density, susceptibility, remanent magnetisation, electrical resistivity, electrical polarisation and Vp speed were measured (Vetrennikov et al. 1982, 1986). In the laboratory, the electrical resistivity was measured using an ESK-1 device with four electrodes and an estimated precision of +/-20%. The polarisation was measured using V Komarov's core holder and VP-94 and ESK-1 devices, with an estimated precision of +/-5%. The Vp speed was measured with a UZIS-LETI device, with an estimated precision of +/-5%. The magnetic properties of sedimentary rocks were determined using an IMV-2 kappameter, while for the measurements of remanent magnetization, an MA-21 astatic magnetometer was used. The estimated precision was +/-10% (Vetrennikov et al., 1982).

The magnetisation direction of the iron occurrences was determined by comparing the orientation of the magnetic anomalies and the direction of the Earth's magnetic field at the time.

3.4. Geochemical studies

Available chemical analysis data are presented in two literature sources (Vetrennikov et al. 1984; Vetrennikov 1991), with the latter essentially duplicating the information from the earlier publication. The analysis of iron-bearing and barren rocks from the Gārsene, Staicele, and other targets were conducted between 1981 and 1983 at the chemical-analytical laboratory of the Far Eastern Geological Institute (FEGI) of the Far Eastern Scientific Center of the USSR Academy of Sciences in Vladivostok. Sampling interval for the 200 g samples was 1 m on average, but no detailed description of the analytical methodology or the equipment used was provided.

The semi-quantitative spectral methods involving microprobe analysis were used to detect trace elements in individual mineral grains from the Staicele deposit. These analyses were carried out at the Central Laboratory of the Production Geological Association "Primorgeologiya" in Vladivostok.

Additionally, earlier data are available from X-ray diffraction analyses of pyroxene and garnet mineral grains from the first drilled borehole 2, with interpretations conducted by geologist Luncs in 1979. More recent data obtained using X-ray diffraction methods during Vetrennikov's active research period (1981–1984) were acquired in the laboratories of VSEGEI in Moscow.

When compared to modern analyses most of the historical data, especially concerning trace elements, show significant discrepancies due to the lower analytical precision available at the time. Moreover, the specific analytical methods used in the 1980s remain unknown. For these two reasons, the chemical analysis data is presented in this article in limited amount (see Chapter 4.1, 4.6, 4.8, and 4.12).

4. Iron occurrences related to magnetic anomalies

In this review we concentrate on the anomalies considered significant in the last summary by Vetrennikov (1996), who regarded local magnetic anomalies as potential indicators of iron and titanium ores. Criteria of defining ore- and non-ore rocks were not described in the publication. He classified the magnetic anomalies based on magnetization intensity using the formula derived from Zander et al. (1967).

Out of the 168 observed anomalies 17 were classified as very high. At least one borehole has been drilled only into 16 of the anomalies (Fig. 2). Further detailed descriptions are given for these 16 anomalies.

Most of the drilled anomalies are also crossed by seismic survey profiles. Due to the poor quality of the old data and its availability only in paper format they only show the upper boundary of the Precambrian basement and a few reflections in the Phanerozoic sedimentary rock cover. They do not give any additional information on the structure of the Precambrian basement, but together with lithological and palaeontological data help to date the fault movement, which mainly took place in the Ordovician to Early Devonian (Tuuling 2019).

4.1. Staicele magnetic anomaly

The complex Staicele magnetic anomaly is characterised by five concentric anomalies with a very high magnetic intensity – up to 8400 nT (Fig. 3). This configuration and the high intensity are somewhat similar to the Jõhvi magnetic anomaly in northern Estonia (Plado et al. 2020), although the Precambrian basement rocks in Staicele lie at a depth that is three times greater than in Jõhvi. Four of the five high-intensity magnetic features are clumped together, while one of them is 6 km away from the others. However, the longer-wavelength background anomaly of approximately 1000 nT, which surrounds them and possibly originates from a deeper source, seems to indicate that all five of

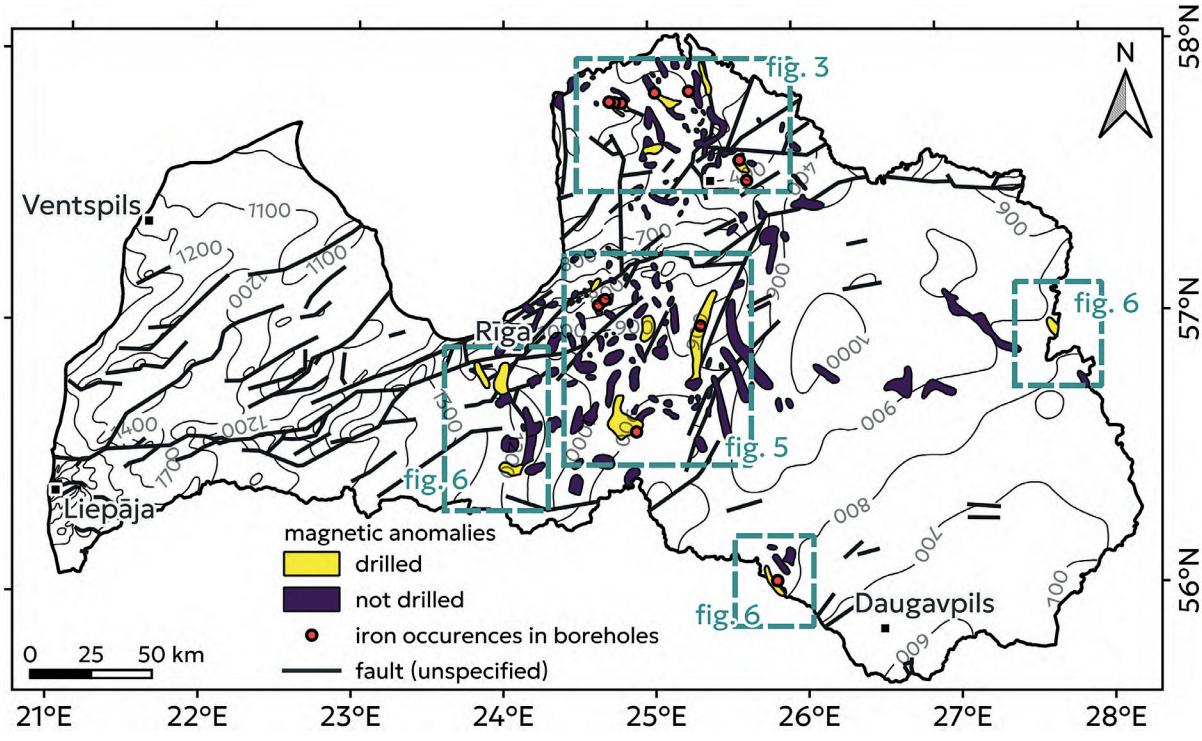


Figure 2. Identified magnetic anomalies in Central and Eastern Latvia according to Vetrennikov (1996). The Precambrian basement depth map is in the background. Dashed lines present the boundaries of the magnetic maps in the following figures.

these 'peaks' are related. A more detailed ground survey, albeit covering only half of the prospective territory (Vetrennikov et al. 1986), also shows additional smaller round features near the main anomaly peaks. The single fault running through the middle of the anomaly separates the most intense magnetic peak from the others.

The overall depth of the Precambrian basement in the Staicele magnetic anomaly area is close to 600 m. The surface of the basement in this area is relatively simple, with just one fault crossing the middle of the area. The vertical displacement of the fault is approximately 40 m. Four boreholes were drilled into the Staicele magnetic anomaly in 1967, 1982, and 1986 extending 26.5, 427.5, 400 and 200 m into the Precambrian basement (Vetrennikov et al. 1982, 1986).

Vetrennikov et al. (1982) described the iron-rich formations as being composed of granitised and migmatised plagiogneisses and iron-bearing quartzites. Iron-bearing rocks prevail in the lower and upper parts of the drill cores representing the Precambrian basement, but iron-poor rocks dominate the middle part. Thicknesses of the units are given below as the real thickness, taking into account the steep dip angle of these units. According to observations of the Staicele-1 drillcore, the dip angle of the metamorphic rock foliations is 70-90°, but the dip azimuth is not known. The evaluated thicknesses are based on the quantitative analysis of magnetometric data on the magnetic anomalies (Vetrennikov et al. 1982, 1986).

The lower iron-enriched part (Vetrennikov et al. 1982) is represented in borehole 4 (Fig. 3). It consists of biotite-pyroxene, hornblende-pyroxene plagiogneisses, silicate-magnetite quartzites and iron-enriched granulites. The thickness of the lower iron-enriched part in the section is 80.8 m, but its evaluated total thickness is 1200 m. The middle iron-poor part is represented in borehole

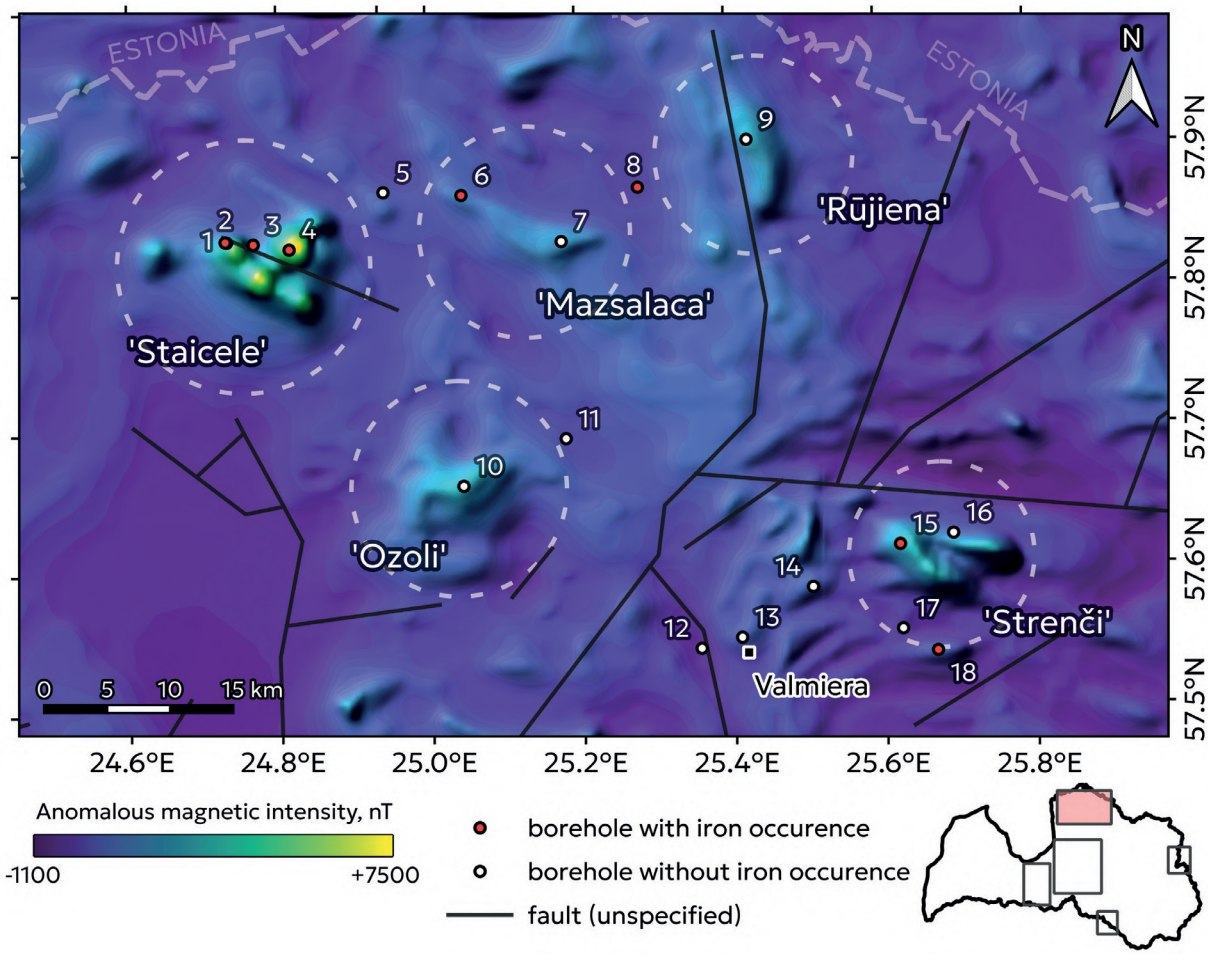


Figure 3. Anomalous magnetic intensity map of the northern Latvia region with reviewed magnetic anomalies circled with a dashed line. Boreholes are numbered according to Appendix A. Location of the region is shown in the inset map. Aeromagnetic maps and borehole locations from (Fursovs & Jevdokimova 1963; Lapina et al. 1967).

3 (not the complete thickness). It is composed of biotite-hypersthene and hornblende-hypersthene gneisses with a smaller amount of magnetite-garnet quartzites, biotite gneisses and amphibolites. The thickness of the middle iron-poor part in the section is 155 m, but its evaluated total thickness is 1300 m. The upper iron-enriched part (Vetrenikov et al. 1982) is exposed in boreholes 1 and 2. It is made of biotite-garnet and biotite-hypersthene gneisses, garnet-magnetite and pyroxene-garnet-magnetite quartzites, and in rare cases, amphibolites. The thickness of the upper miron-enriched part in the section is 102.5 m, but the evaluated total thickness is 1200 m. The evaluated total thickness of the entire Staicele iron-bearing formation is 3700 m (Vetrennikov et al. 1986).

The main iron mineral is magnetite, and its grain size varies from 0.1 to 0.6 mm. The iron-bearing formations of the Staicele site were interpreted as metavolcanic (basalt-andesite-liparite) rocks, partly also metapelite to metasandstone rocks (Vetrennikov 1996).

In recent studies of the borehole 1 drillcore material it was found out that the iron-rich metamorphic rocks are layered, consisting of alternating magnetite, quartz, garnet and pyroxene rich laminas (Fig. 4). Based on the rhythmically laminated structure the rocks are interpreted as

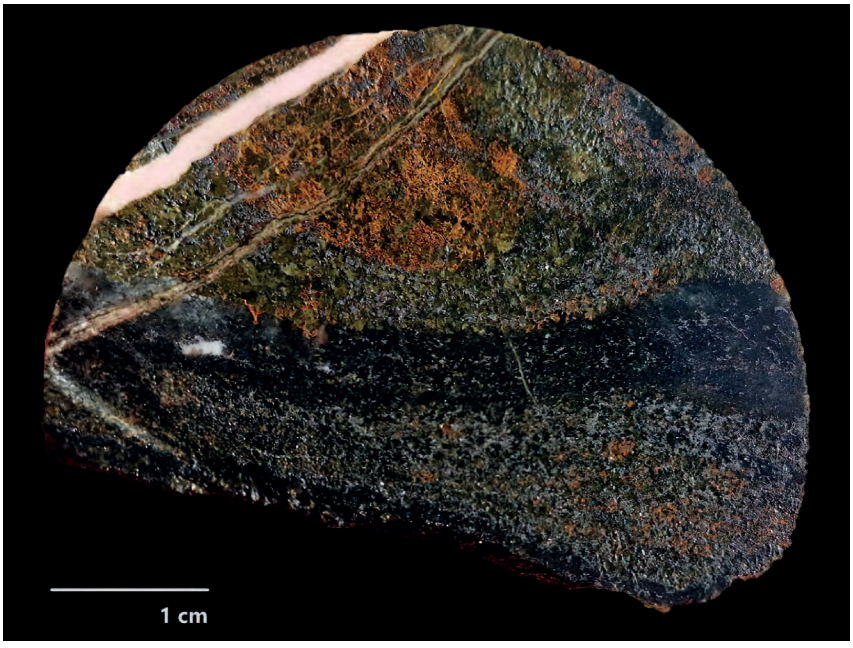


Figure 4. Staicele iron-rich rock sample from borehole 1, 1102-1104 m interval. The dark layers consist mainly of quartz (greyish black), garnet (orange) and pyroxene group minerals (green). The light-grey layers and grains with a metalic lustre are magnetite.

banded iron formations (Vorobjovs & Stinkulis 2024).

The chemical analysis data for the Staicele magnetic anomaly (Vetrennikov 1991) indicate that the in various rock types, including both the iron-poor and iron-enriched ones, the content of Fe_2O_3 is 3.47–36.24 wt.%, FeO 2.14–10.09 wt.%, and MnO 0.4–8.45 w%. New data of SEM with EDX spectroscopy, energy-dispersive XRF, ICP-MS, and laser-induced breakdown spectroscopy (LIBS) analyses indicate that magnetite from the Staicele site contains in average 3.1 wt.% of MnO. Manganese content in the garnets (mainly almandine-spessartine series with dominant spessartine component) reaches 22.10 wt.% (Vorobjovs & Stinkulis 2024).

4.2. Strenči magnetic anomaly

The elongated Strenči magnetic anomaly has three more or less connected magnetic peaks, which have similar intensities of up to 3200 nT (Fig. 3). To the west and south, it is surrounded by numerous curved and fragmented magnetic features generating a quite complex scene. The ground survey partially covering the Strenči magnetic anomaly reveals an even more complex pattern (Vetrennikov et al. 1986). A noteworthy feature is the magnetic low north of the main positive anomaly, which drops down to –1100 nT and coincides with an E-W trending fault.

The depth of the Precambrian basement surface gradually increases from 350 m in the northern part of the anomaly to 400 m in the southern part. There are several faults few kilometres north of the anomaly, but there are no faults that directly crosscut the magnetic anomaly.

Most of the boreholes extend only 7.8-55 m into the Precambrian basement, with the exception of boreholes 15 and 17 (318 m, 149 m) (Vetrennikov et al. 1982, 1986). Drill cores contain mainly iron-poor rocks: biotite-garnet and biotite-hypersthene gneisses, amphibolites, granites, granodiorites, migmatites and migmatites-charnockites. Magnetite-enriched rocks were found only in boreholes 15 and 18. Magnetite-bearing gneisses and granites are present in borehole 18; however, high magnetite amounts were not found (Vetrennikov et al. 1986).

Borehole 15 uncovered 101.4 m of basement rocks (Vetrennikov et al. 1982) represented by

pyroxene, pyroxene-biotite gneisses, amphibolites and charnockite-migmatites. Magnetite and unspecified sulphide concentrations were distinguished in several parts of the section, but higher concentrations were observed only in two 3 and 12 meters long intervals. The metamorphic rocks from the Strenči anomaly were interpreted as mafic metavolcanic (Vetrennikov 1996).

Interpretations of observed magnetic field intensities on the surface and in the boreholes (horizontal anomaly) point to the presence of iron occurrences in the area, but with the exception of iron occurrences in boreholes 15 and 18 they have not been verified by drilling.

4.3. Mazsalaca magnetic anomaly

The Mazsalaca magnetic anomaly is one of the less prominent anomalies in which boreholes were drilled (Fig. 3). The anomaly is elongated in the NNW-SSE direction, and based on ground survey measurements the maximum magnetic intensity reaches over 2000 nT. The shape and direction of the anomaly seem to follow a regional linear trend.

Information on the depth of the Precambrian basement in the area was obtained via several seismic profiles located in the southern part of the area. The surface of the basement in the area is relatively simple. No faults were detected, and the overall depth of the basement surface is close to 690 m. Total of three boreholes have been drilled into the Mazsalaca magnetic anomaly in 1986 extending, 51, 61 and 179.3 m into the basement (Vetrennikov et al. 1986; Appendix A).

Intrusive igneous rocks were identified in the territory of the anomaly, based on data from boreholes 6 and 7. Magnetite-bearing rocks are documented from borehole 6. They include biotite-hornblende granodiorites and gabbro with magnetite in significant quantities (up to 20% in some intervals) and scattered pyrite. Fractured rocks are present in some intervals. Biotite-hornblende granodiorites lacking magnetite are present in borehole 7.

4.4. Rūjiena magnetic anomaly

Similarly to the nearby Mazsalaca anomaly, the Rūjiena magnetic anomaly follows a more regional directional pattern, yet the latter is oriented in an almost N-S direction (Fig. 3). The magnetic intensity of the main, kidney-shaped positive anomaly reaches over 2500 nT. Similarly shaped, but weaker linear anomalies with intensities <2000 nT are located west of the main anomaly.

Information on the depth of the Precambrian basement in the area was obtained via several seismic profiles located in its southern part, as well as two boreholes. A major fault oriented in the N-S direction and coinciding with a linear magnetic low runs west of the Rūjiena magnetic anomaly. West of the fault the depth of the Precambrian basement is ~650 m and east of it ~580 m. Two boreholes drilled into the Rūjiena magnetic anomaly in 1986 extend 139.3 and 149 m into the basement (Vetrennikov et al. 1986).

Iron-enriched rocks have not been encountered in the Rūjiena anomaly. Plagiogranite-gneisses, granite-gneisses, biotite-amphibole gneisses and granites dominate in borehole 8. Intrusive rocks represented by alternating biotite-hornblende and garnet-biotite-hornblende granodiorites are identified in borehole 9. A fluorite vein zone in the intrusive rocks is identified at a depth of about 660 m (Vetrennikov et al. 1986). The contents and probable economic value of fluorite was not evaluated in previous studies.

4.5. Ozoli magnetic anomaly

The prominent Ozoli magnetic anomaly is surrounded by several smaller magnetic lows and a large magnetic low area to the west (Fig. 3). The anomaly has an almost cone-shaped main peak of 2600 nT and a broad base. A couple of interpreted faults run south of it.

Information regarding the depth of the Precambrian basement in the area was obtained via several seismic profiles located across the area. The surface of the basement around the area is relatively

simple. No faults were detected, and the overall depth of the basement surface is close to 720 m. Two boreholes have been drilled into the Ozoli magnetic anomaly in 1986. Boreholes uncovered 52.4 and 271 m of Precambrian basement (Vetrennikov et al. 1986).

Borehole 11 intersects biotite-hornblende gneisses, amphibolites and biotite granites, with no iron occurrences (Vetrennikov et al. 1986). Borehole 10 intersects iron-bearing metamorphic rocks for 271 m, with true thickness of 82.5 m. These rocks are represented by intensively granitised (in places partially melted) rocks such as sillimanite-biotite-garnet and biotite-diopside-garnet gneisses and amphibolites; in one interval, magnetite-hornblende-biotite gneisses are also present. Magnetite grains are present in places (Vetrennikov et al. 1986).

4.6. Inčukalns magnetic anomaly

The Inčukalns magnetic anomaly consists of two compact separate main magnetic features with magnetic intensity >4600 nT (Fig. 5). The northern anomaly is elongated, runs NE-SW and is parallel to a major fault, while the southern anomaly is more rounded and has a flatter peak. There seems to be a linear feature of medium magnetic intensity running from the northern anomaly in the SW direction, which also coincides with the major fault. The vicinity of the Inčukalns magnetic anomaly seems to be dotted with a few point-like magnetic features and some similar high-intensity anomalies to the north.

The surface of the Precambrian basement in the area is complex. Close to the northern boundary of the magnetic anomaly, there is a major fault in the Precambrian basement with vertical displacement of more than 100 m. The depth of the basement surface across the main part of the anomaly is around 800 m, while on the northern edge on the opposite side of the fault, it is around 900 m.

As the boreholes 19 and 20 were drilled to evaluate the possibility of establishing waste dump for acid tar in the overlaying Cambrian rocks they penetrate only 6.9 and 23 m, respectively, into the Precambrian basement. A description of the core is available only for borehole 20. In the northern part of the territory, underground gas storage development in the Cambrian rocks was evaluated. Therefore, 23 boreholes crossing the Cambrian rocks and reaching the Precambrian basement were drilled in the northern part of the survey area (Stankevic et al. 1968). As the goal for the survey was not related to the basement, the boreholes extend only 14–18 m into the basement rocks and only rudimentary description of them is available. Problems with aligning coordinates of the boreholes on the map were encountered, thus they are not included in this review. Borehole 21 was drilled in 1982 during the study focused on iron ores in the Precambrian basement (Vetrennikov et al. 1982) and extends 290.9 m into it.

Borehole 21 uncovers metamorphic rocks, which were subdivided into lower iron-poor, middle iron-bearing (low iron content) and upper iron-poor parts (Vetrenikov et al. 1982). The lower, minimum 21.5 m thick iron-poor part is composed of garnet-hypersthene-biotite gneisses, amphibolites, and migmatites. The 58.2 m thick middle iron-bearing part consists of silicate-magnetite quartzites, enderbite-migmatites, granite-migmatites and amphibolites. This part in general has a relatively low iron content. The thickness of upper iron-poor part is 39.0 m and it is composed of amphibolites, amphibolite-migmatites, hypersthene-biotite-cummingtonite gneisses and hypersthene-biotite quartzites. Borehole 20 uncovers biotite and biotite-hornblende gneisses containing magnetite, apatite, garnet and zircon as accessory minerals (Grigorenko 1978). Iron occurrences were not found in the 23 boreholes that reached the Precambrian basement in the underground gas storage exploration area, but magnetite and titanomagnetite were documented as accessory minerals in biotite and hornblende gneisses (Stankevic et al. 1968).

Chemical analytical data for the metamorphic rocks from the Inčukalns anomaly (Vetrennikov 1991) indicate that in various rock types, including both the iron-poor and iron-enriched ones, the content of Fe_2O_3 is 4.12–21.08 w%, FeO 6.3–11.64 w%, and MnO 0.06–1.31 w%.

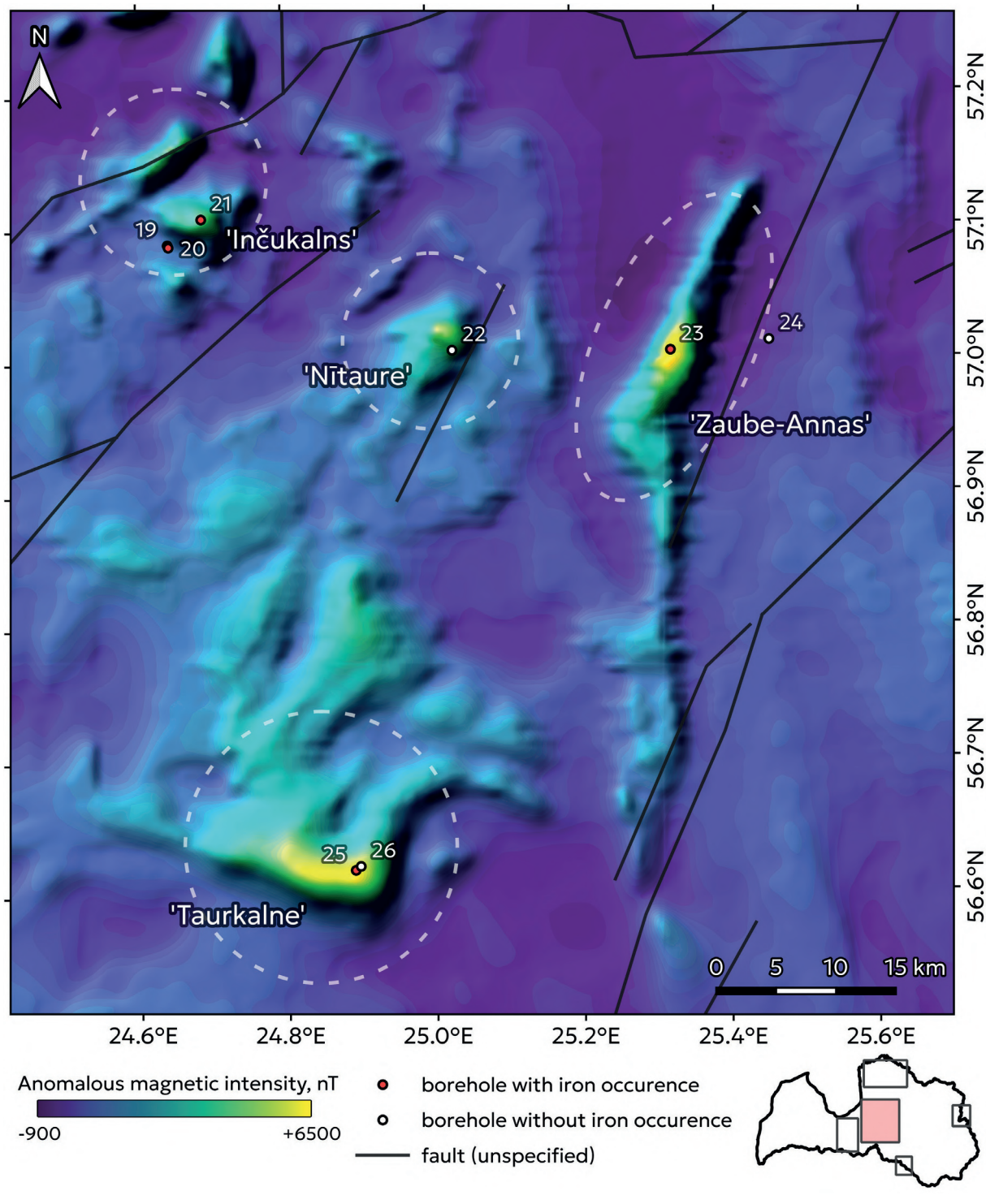


Figure 5. Anomalous magnetic intensity map of the Central Latvia region with the reviewed magnetic anomalies circled with a dashed line. Boreholes used for the review are numbered according to Appendix A. Location of the region is shown in the inset map. Please note that the significant distortion of anomalies (most evident as E–W directed ridge-like features across the linear Zaube-Annas anomaly) is caused by uncorrected original data. Aeromagnetic maps and borehole locations from (Fursovs & Jevdokimova 1963; Lapina et al. 1967; Vetrennikov et al. 1982; Mjasņikovs et al. 1987).

4.7. Taurkalne magnetic anomaly

The Taurkalne magnetic anomaly is one of the largest and most intense magnetic anomalies characterised by a distinct and sharp 'corner', made even more prominent by the magnetic low immediately to the SE of it (Fig. 5). The main magnetic peak is elongated in the E-W direction and reaches an intensity of 6400 nT. To the north, it seems to be connected or is a part of very conspicuous curved magnetic features, which gradually diminish to the east. Despite the high contrast between the Taurkalne magnetic anomaly and the surrounding magnetic low, no faults seem to be identified in the historical studies.

Information about the depth of the Precambrian basement in the area around the Taurkalne anomaly is scarce. Only one NW-SE oriented seismic profile crosses the area. The depth of the basement surface is approximately 900 m in the area. Two boreholes have been drilled into the Taurkalne magnetic anomaly in 1974 and 1986, extending 50 and 207.7 m into the Precambrian basement (Vetrennikov et al. 1976, 1986).

Both boreholes intersect rocks similar to the iron-bearing amphibolite beds of the Inčukalns anomaly (Chapter 5.6), but it is unclear if Vetrennikov et al. (1976, 1986) intended to correlate the units from these two locations. The Precambrian part of the borehole 25 (Vetrennikov et al. 1986) consists of amphibole gneisses and amphibolites with interlayers of garnet-diopside-hypersthene iron-bearing quartzites (lower part, 105.2 m thick in the section) and biotite gneisses, which in places contain magnetite grains (upper part, 101 m thick in the section). In borehole 26, the Precambrian basement is represented by quartzite-like gneisses, which in places have granite veins. The total thickness of the Inčukalns series in the Taurkalne anomaly was evaluated as 5000 m (Vetrennikov et al. 1986).

4.8. Zaube-Annas magnetic anomaly

The prominent linear, more than 80 km long, approximately N-S oriented, Zaube-Annas magnetic anomaly has a maximum intensity of more than 6500 nT (Fig. 5). The northern part of the magnetic anomaly trends NNE and coincides with the follow the direction of a nearby fault, but the direction changes to an almost straight N-S orientation south of the main magnetic peak. The linearity and intensity of the magnetic anomaly are emphasised by the distinct magnetic low (up to –800 nT) on both sides. The anomaly weakens toward south but the Gārsene anomaly in on the border between Latvia and Lithuania (Fig. 6b) can be seen as its continuation.

The overall depth of the Precambrian basement in the area is close to 900 m. The surface of the basement throughout the territory is relatively simple with one fault running parallel to the anomaly. Two boreholes have been drilled in the vicinity of the Zaube-Annas magnetic anomaly in 1970 and 1983, the latter one drilled directly in the anomaly (Mironov et al. 1973; Vetrennikov et al. 1986).

Borehole 24 transected 28 m of rocks not enriched in Fe; amphibolites and biotite-amphibole gneisses (Mironov et al. 1973). Thus, the borehole did not intersect the rocks causing the anomaly. Borehole 23 penetrated 33.8 m of granitic biotite migmatites, iron-bearing plagiogranites, biotite-hornblende plagiogranites and banded iron-bearing migmatites with abundant hematite inclusions, as well as quartz-magnetite rocks with coarse-grained magnetite in the form of belts and lenses. Vetrenikov et al. (1986) suggested that the observed rocks can be correlated with those of the Gārsene magnetic anomaly. Chemical analyses of the Zaube-Annas rocks (Vetrennikov 1991) indicate that in quartz-magnetite lithologies the average content of Fe_2O_3 is 26.08 wt.%, FeO 12.48 wt.%, and MnO 0.52 wt.%.

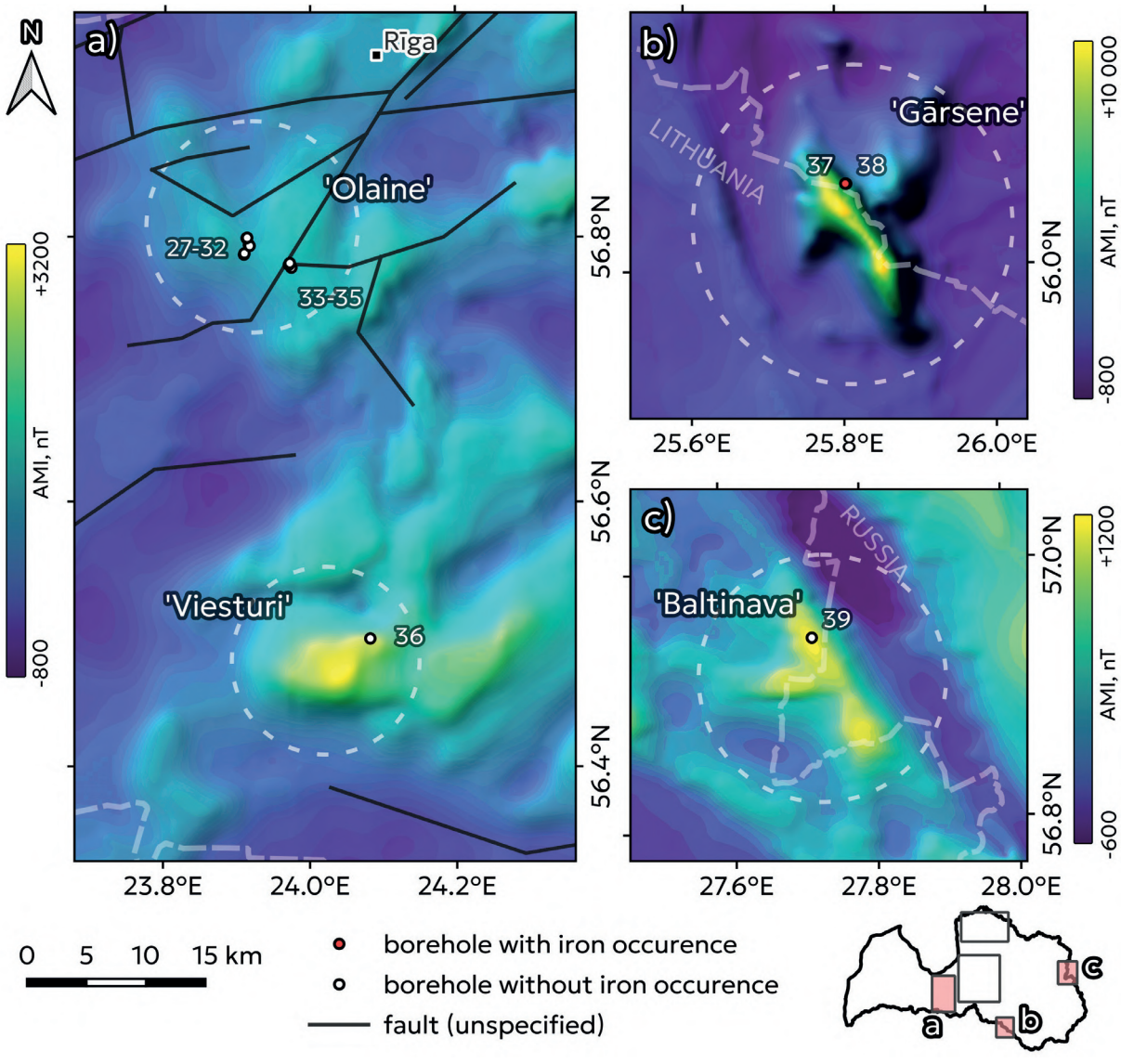


Figure 6. Anomalous magnetic intensity maps of several separated regions, see inset for locations. Note the different scales of anomalous magnetic intensity (AMI) of each figure. Reviewed magnetic anomalies are circled with a dashed line. Boreholes used for the review are numbered according to Appendix A. Aeromagnetic maps and borehole locations from (Fursovs & Jevdokimova 1963; Sokurenko 1976; Vetrennikov et al. 1982; Mjasņikovs et al. 1987).

4.9. Nītaure magnetic anomaly

The Nītaure magnetic anomaly is oblong, elongated in NE-SW direction and, although less distinct than other anomalies in the region, reaches magnetic intensity of more than 5200 nT (Fig. 5). There is a noticeable E-W linear feature extending out from the magnetic peak on its westside, but this could be at least partly caused by the lack of data corrections. There is a NE-SW-oriented fault running close to the SE side of the anomaly, and this may be correlated with the magnetic low there.

Based on one E-W oriented seismic profile and one borehole drilled the depth of the Precambrian basement in the area is close to 1 km. A major fault oriented in the NNE-SSW direction runs along the

eastern side of the Nītaure magnetic anomaly. The vertical displacement of the fault is close to 15 m.

Borehole 22 was drilled 9.15 m in the Precambrian basement in 1970 as a part of a general geological survey of Latvia. The basement consists rocks not enriched in Fe: plagioclase amphibolites and biotite-amphibole gneisses, with pink garnet grains in places.

4.10. Olaine magnetic anomaly

The Olaine anomaly is a weak and broad magnetic feature coinciding with a fault, which was the drilling target (Fig. 6a). Locally the magnetic intensity reaches over 1300 nT, but is mainly <1000 nT. The magnetic anomaly might correlate with the fault network in the area. The Olaine and neighbouring Viesturi anomalies are the westernmost magnetic anomalies in Central Latvia related to the metamorphic part of the Precambrian basement – farther west lies the igneous Kurzeme batholith.

The surface of the Precambrian basement is approximately 1250 m and complicate by several major faults revealed by a seismic survey (1971-1976). The vertical displacement along these faults ranges from 10 m to 70 m. During 1973, 1974 and 1977, nine boreholes reaching the Precambrian basement were drilled in order to test the storage potential of the Cambrian rocks for chemical waste. As basement rocks were not the goal of the survey, there was little attention paid to them in reporting and also the depth of penetration into the basement was low (14-18 m). Rock in all boreholes is reported as: grey, fine-grained biotite granite-gneiss (Sokurenko & Grigorenko 1977).

4.11. Viesturi magnetic anomaly

The Viesturi magnetic anomaly is a slightly elongated and almost conical magnetic feature reaching an intensity of over 3200 nT (Fig. 6a). It has a short 'magnetic protrusion' off to the eastern side, which has been the target of drilling. The anomaly has quite steep gradient to the south but extends to NE as a broader anomalous zone with undulating magnetic intensity, that seems to be separated from the Olaine magnetic anomaly by a magnetic low (Fig. 6a).

Based on one NNW-SSE striking seismic profile and the one borehole (36) drilled in the area the depth of the Precambrian basement is close to 1200 m. Its surface in the area is relatively simple and no faults were detected. The borehole log is not available.

4.12. Gārsene magnetic anomaly

The Gārsene magnetic anomaly is a prominent linear magnetic feature crossing the boundary between Latvia and Lithuania in NW-SE direction (Fig. 6b). The anomaly has an intensity of over 10,000 nT, which amounts to approximately 20% of the Earth's magnetic field intensity in this region. A less intense, elongated magnetic feature oriented in the N-S direction lies to the NE of the main anomaly. Parallel weaker linear magnetic anomaly running approximately 9 km to the west of the Gārsene magnetic anomaly is possibly continuation of the Zaube-Annas magnetic anomaly.

Based on one N-S oriented seismic profile, the depth of the Precambrian basement in the area is slightly more than 800 m. No major faults were detected in this area. Two boreholes were drilled in order to identify the source of the magnetic anomaly (Vetrennikov et al. 1982). Borehole 38 was planned based on magnetic ground survey, but it did not transect magnetic rocks in the Precambrian basement. In-situ magnetic field measurements in the borehole (horizontal and vertical anomaly) however indicated the presence of strongly magnetic rocks in the vicinity of the borehole. Borehole 37 drilled 84 m south-east of borehole 38 verified this interpretation.

The Gārsene iron-bearing metamorphic rocks consists of amphibole-biotite, biotite and pyroxene-biotite gneisses in addition to migmatites and iron-rich quartzites (Vetrennikov et al. 1982). Rocks poor in Fe are represented in the lower and upper parts, but Fe-rich rocks occur in the middle of the drilled

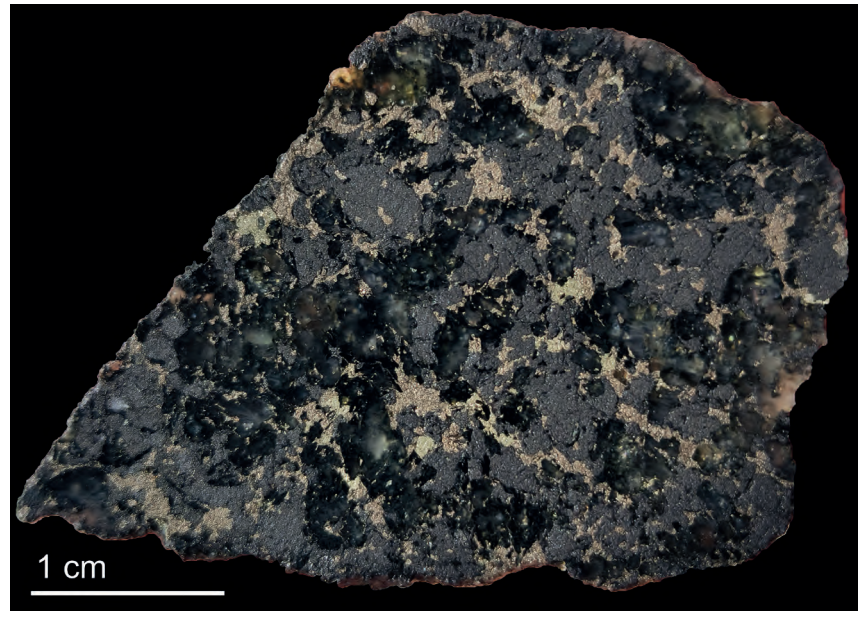


Figure 7. Gārsene iron-rich rock sample from borehole 37, interval 1102–1105 m. Grey, metallic, is magnetite; dark grey is quartz; yellowish, metallic are sulphides – mostly pyrrhotite with some rarer and lighter pyrite grains.

basement interval. The lower non-ferruginous part is dominated by plagioclase gneisses and migmatites, and more rarely granites. The 36.9 m thick middle part is composed of iron-rich rocks with a quartz-biotite-amphibole-magnetite mineral assemblage and various proportions of these minerals. Among these, magnetite quartzites have the highest iron contents. The upper non-ferruginous part is represented by alternating gneisses and migmatites. The thickness of the metamorphic rock formations drilled at Gārsene is 225.9 m (Vetrennikov et al. 1982).

Based on our observations from drill core 37 the layering in the Gārsene anomaly is less prominent, distorted, than in Staicele. Sulphide mineralisation (Fig. 7) is more common than in the Staicele site. It is suggested that the ores of the Gārsene deposit were highly altered by metamorphism, when magnetite and quartz grains formed larger aggregates and enriched the ores (Vorobjovs & Stinkulis 2024).

Observed magnetic field intensities on the surface and in the boreholes (horizontal anomaly) suggest the existence of additional iron-enriched rocks east and south-west of the borehole 37.

Chemical analytical data for the Gārsene magnetic anomaly indicate that in various rock types, the following compositional ranges: Fe_2O_3 is 2.43–52.15 wt.%, FeO 1.98–23.97 wt.%, and MnO 0.01–0.05 wt are present. In magnetite and sulphide-magnetite-bearing rocks a high content of Co (0.7 w%) is noted (Vetrennikov 1991).

4.13. Baltinava magnetic anomaly

The Baltinava magnetic anomaly is situated in the easternmost part of Latvia (Fig. 6c). Although the anomalies magnetic intensity reaches only slightly above 1200 nT it forms a prominent anomaly due to being located in region lacking other magnetic features. The NW-SE oriented main anomaly is linear and connected to E-W directed "branch". Linear magnetic low with an intensity of –700 nT runs parallel to the positive magnetic anomaly.

Based on the one E-W oriented seismic profile and one borehole 39 (Jankin et al., 1975) the depth of the Precambrian basement is around 900 m in the area. No major faults were detected in this seismic profile. The borehole was drilled 23 m into the basement consisting of migmatized gneisses.

5. Discussion

5.1. Dominant rock types and the degree of metamorphism

Based on previous publications, reports and geological reports (Vetrennikov et al. 1982, 1984, 1986; Vetrennikov 1991) and examination of available core (Vorobjovs & Stinkulis 2024) high-grade metamorphic rocks are dominant in all studied magnetic anomalies. The Staicele and Gārsene anomalies are the best studied as there are detailed descriptions (Vetrennikov et al. 1982, 1986) and the core material is available, including the iron-rich rocks in boreholes 1 and 37.

Wall rocks of the Staicele type iron-bearing formations (Vetrennikov et al. 1982) are granitised and migmatised biotite, hornblende, pyroxene, and garnet plagiogneisses. The observed iron-rich rocks are silicate-magnetite quartzites and magnetite granulites, garnet-magnetite and pyroxene-garnet-magnetite quartzites. The layered rocks of the Staicele type iron-bearing formations, consisting of alternating magnetite, quartz, garnet and pyroxene rich laminae, are interpreted as banded iron formations (Vorobjovs & Stinkulis 2024).

In Gārsene type formations (Vetrennikov et al. 1982, 1986) the wall rocks are amphibole-biotite, biotite, pyroxene-biotite gneisses and migmatites, more rarely granites. Iron-bearing rocks are magnetite quartzites and iron-richest ones are quartz-biotite-amphibole-magnetite rocks, displaying various proportions of these minerals. The iron-rich rocks of the Gārsene type are highly altered, when metamorphic processes have caused formation of larger aggregates of magnetite and quartz grains, and enrichment of the rocks in iron. Sulphide minerals are more common in Gārsene type formations than in the Staicele type formations (Vorobjovs & Stinkulis 2024).

Metamorphic rocks are dominant in all studied magnetic anomalies, excluding the Mazsalaca anomaly where magnetite-rich and sulphide-bearing biotite-hornblende granodiorites and gabbro prevail. Garnet-biotite-hornblende granodiorites (with fluorite vein zone) are also common in the nearby Rūjiena anomaly.

There is quite a great variety or metamorphic and igneous rock types in the studied magnetic anomalies, for example, granites, granodiorites, amphibolites and charnockite-migmatites are present in the Strenči anomaly. However, schists or other low-grade metamorphic rocks were not described in any borehole in the anomalies. Also, no volcanic or sub-volcanic igneous rocks were found in the anomalies. All these data well correspond to the interpretation (Bogdanova et al. 2015) that the high-degree amphibolite- and granulite-facies metamorphism formed the rocks of the magnetic anomalies discussed here.

5.2. Crustal evolution and formation of iron ores in the Proterozoic

Almost all magnetic anomalies discussed here are situated in the territory of the Latvian-East Lithuanian tectonic domain with exception of the Baltinava and a few other anomalies located more to the East – in the Latgalia domain (sensu Bogdanova et al. 2015). The Latvian-East Lithuanian tectonic domain mainly contains metasedimentary and metavolcanic rocks of amphibolite to granulite metamorphic facies. The Latgalia domain is dominated by metamorphic rocks of granulite facies (Bogdanova et al. 2015). Both these domains can be correlated with the Bergslagen region in Sweden (Sundblad et al. 2021), where diverse ore types are mined and the Proterozoic rocks are exposed and well-studied. Based on this geological continuation there are basis for exploration of similar resources in the Baltic States. The rocks, which form the anomalies, were involved in the formation of the Fennoscandian crust before 1.9-1.75 Ga (Bogdanova et al. 2008, 2015; Sundblad et al. 2021).

The iron deposits at least partly have formed as ferruginous and silicate sedimentary rocks that can be regarded as banded iron formations typical for the Palaeoproterozoic (e.g., Aftabi et

al. 2021). We suggest this based on observations of abundant iron and silicate mineral lamination in drill cores. The Proterozoic iron formations of Latvia presumably were once a part of c.a. 1.9 billion years old sedimentary and volcanic rock successions (Bogdanova et al. 2015), which afterwards were subjected to considerable high-grade metamorphic changes. Detailed studies of the origin and alteration of the iron formations of Latvia are necessary. Based on wide-scale correlations (Bogdanova et al. 2015; Sundblad et al. 2021) and the occurrences of magnetite in many boreholes into the magnetic anomalies in Latvia, there are good prospects to find additional iron-rich formations. Complex folding and faulting are difficult to interpret due to the paucity of boreholes and ambiguous geophysical data. Probably there are also iron-bearing formations of primary intrusive origin, which were documented in Mazsalaca and Rūjiena anomalies (Vetrennikov et al., 1986). Further geophysical and geological studies of these rocks are also considered.

5.3. Evaluation of existing data on the metal occurrences in the magnetic anomalies

Among the most promising resources of Latvia's Precambrian basement found within magnetic anomalies, iron stands out, along with two other metals that are included in the list of critical raw materials for the European Union — manganese, since 2023, and cobalt, which has been one of the critical raw materials for the EU since 2017 (IEA 2022).

Staicele and Gārsene sites are the most thoroughly explored iron-rich metamorphic rock occurrences in Latvia in terms of drilling. According to available data, the iron-bearing rocks of these sites are quartzites with magnetite content comparable with other iron-ore deposits, e.g. metamorphosed BIFs, Northern Province, South Africa (Du Plessis et al. 1997) with average contents of iron 20–47 %. The data of chemical analyses of 1980s, which are of limited reliability, indicate that magnetite-bearing rocks from the Staicele deposit contain 46–52 % Fe_3O_4, with elevated manganese content (Segliņš et al. 2013). These are low-grade iron ores, containing less than 60 % Fe (Hagemann et al. 2016). Based on geophysical data it was estimated that the Staicele ore body extends to a depth of more than 4 km, and within the entire ore field of Staicele anomaly, the prospective ore bodies contain approximately 2.9 billion tonnes of iron ore (Vetrennikov 1991).

The iron-bearing rocks of the Gārsene site were classified as rich ores (Segliņš et al. 2013). The total iron content varies from 20 to 64 wt.% Fe, mainly corresponding to low-grade ores, but reaching the contents (>60 % Fe) of high-grade ores (Hagemann et al. 2016). In addition, approximately 75% of iron ore has an average iron content of around 45 wt% Fe (Vetrennikov 1991). Based mainly on geophysical data, it was suggested that the iron-bearing layers can be traced to a depth of more than 4.5 km (Segliņš et al. 2013), and the estimated ore resources to a depth of 1.5 km are approximately 2 billion tons (Brangulis & Straume 1984).

The magnetic anomalies considered to be most promising for future exploration include Zaube-Annas, Taurkalne (Birzgale), and Inčukalns ones. For these sites it is even more complicated to evaluate the potential ore quality and distribution. The main reason for the problems is that drill holes often missed the iron formations, resulting in very low ferruginous quartzite content in the drill core. However, Vetrennikov (1991) estimated that the iron fomations in Gārsene and Zaube-Annas areas extend 12 km along the strike of the anomaly and are up to 1.6 km wide.

Based on previous studies (e.g. Vetrennikov 1991) and new drill core mineralogical-petrographic research (Vorobjovs & Stinkulis 2024), it is worth noting that the iron-bearing rocks uncovered in Latvia are composed entirely of magnetite quartzites, occasionally containing hematite in accessory amounts. This feature of the ores favors future prospects, as it enables a simpler and more cost-effective method of extracting magnetite concentrate from the ore, using only grinding and magnetic separation (Mesquita et al. 2025).

As for manganese, in previous studies elevated concentrations were found only in the Staicele anomaly (Vetrennikov 1991). Recent studies confirm this information, and in magnetite from Staicele the average content of MnO is 3.1 wt.% (Vorobjovs & Stinkulis 2024;

Ganeev et al. 2024). Manganese is concentrated in garnet in the form of a spessartine component. In some samples the manganese content in garnet grains reaches 22.1 wt% (Vorobjovs & Stinkulis 2024).

The use of iron-bearing rocks from the Staicele deposit as manganese ores is likely impractical due to the uneconomical extraction of manganese from silicates (Bale 2018). However, the aforementioned manganese present in magnetite–jacobsite series (Vorobjovs & Stinkulis 2024) could potentially be used as a natural alloying element in the production of manganese steels. As an example, a similar situation with elevated manganese content in the iron ores from the Berslagen ore field, such as the Dannemora deposit (Åberg 2015), allowed for the direct production of high-quality steel with an increased manganese content (up to 5%) without artificial alloying.

There are also prospects of cobalt: as according to estimates by semi-quantitative chemical analysis in 1980s, the magnetite-rich rocks in the Gārsene anomaly contain 0.1–0.7 wt.% Co (Vetrennikov 1991). These data require verification.

All the iron occurrences in the Precambrian basement of Latvia occur deeper than 600 meters. Minimum depth of the iron occurrences is 688 m in Staicele and 945 m in Gārsene (Vetrennikov 1991). Due to thickness of the sedimentary series only underground mining could be considered in Latvia. Although iron ores mainly are exploited from large open pit mines, in some cases, such as Kiruna (Sweden), Dagu Mounain (China), Kryvyi Rih (Ukraine), underground mining has proven to economically feasible (Yang et al. 2014; Fan et al. 2018; Pysmennyi et al. 2020). In the Kryvyi Rih iron ore basin the ores are exploited in underground mines reaching even the depth of 1350 m (Pysmennyi et al. 2020).

The estimates of metal contents and resources done in 1980s and 1990s cannot be taken as reliable ones, due to quality of the analyses and out-dated, in some cases even unclear, methodology. However, they indicate significant ore potential and need basis for further studies of the legacy core material, e.g. mineralogy, -petrography and chemical analyses. Also, new magnetic and gravity surveys are needed to more reliably model the distribution of metal enriched rocks. Only after such further studies it is possible to estimate if extraction of iron-bearing rocks from the Precambrian basement of Latvia is a viable option.

6. Conclusion

Major geophysical measurement campaigns have been conducted in Latvia, but these measurements can mostly be used only to identify areas of further research of iron-rich formations. Due to their limitations the historical data sets cannot be used for the detailed inversion modelling of the anomalies. The gravity field measurements, obtained from a country-wide survey conducted over the last 20 years, can be mentioned as the only exception.

Thirteen magnetic anomalies were tested with drilling, which in most cases verified iron enriched rocks as the source of the anomaly. Iron enriched formations were classified based on mineralogical and petrographic studies. Metasedimentary and metavolcanic rocks are the main iron-rich formations, but in some case igneous intrusive rocks host iron as well. In several anomalies, however, the drilling did not intersect high grade iron formations. For several anomalies the total thickness of the iron formations and the amount of resources were tentatively estimated using the borehole and magnetic data. Based mainly on the high intensity of magnetic anomalies, the Staicele and Gārsene ones were studied in the most detail, because they likely contain the highest-grade iron formations. However, the interpretations of the total thickness and resources of the iron ores were mainly based on historical magnetic measurement data. These interpretations far exceed the thicknesses and distribution trends of iron formations proved by boreholes. These discrepancies are further

emphasised by largely outdated correlations of iron-bearing metamorphic rocks with objects located in remote regions.

Based on the data of geophysical, mineralogical and petrographic, as well as geochemical studies, the Proterozoic iron-bearing formations in the Precambrian basement of Latvia contain low-grade to high-grade iron ores, prospective for further detailed studies and economic evaluation.

Acknowledgements

This work was supported by the Latvian Science Foundation project grant "Ore potential of metal-bearing crystalline basement rocks of central and eastern Latvia". Project No. lzp-2023/1-0278). We thank the reviewers for the constructive comments and corrections that improved the quality of the manuscript.

Authorship contribution statement

J. Karušs – writing, editing, conceptualization; Ģ. Stinkulis – writing, editing; M. Brants – data curation, writing, visualisation; D. Vorobjovs – data curation, writing, visualisation; V. Zandersons – data curation, writing, visualisation

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Appendix A

Information on the boreholes.

Borehole No.	Original name of the borehole	Figure	Total length (m)	Length in crystalline basement (m)	Main rock type	Indi-cations of Fe (Yes/ no)
1	Staicele-1	4	1115.5	427.5	gneiss, ferruginous quartzite	Yes
2	Staicele-4	4	714.5	26.5	gneiss, ferruginous quartzite	Yes
3	Staicele GK-1KS	4	1130	402	gneiss	Yes
4	Vīķi GK-2P	4	975.2	245.2	plagiogneiss, quartzite, ferruginous granulite	Yes
5	Mazsalaca-9P	4	755	61	granodiorite	No
6	Mazsalaca-GK-10K	4	748	51	granodiorites and gabbro	Yes
7	Mazsalaca-GK-4P	4	862.8	179.3	granodiorite	No
8	Rūjiena GK-5PR	4	788.3	139.3	plagiogranite-gneiss, granite-gneiss, gneiss, and granite	No
9	Rūjiena GK-6P	4	733	149	granodiorite	No
10	Ozoli-GK-7P	4	990	271	granitised gneiss, amphibolite	Yes
11	Matīši GK-8K	4	762.5	56.5	gneiss, amphibolite. granite	No
12	Valmiera-GK-13K	4	618	49	gneiss, amphibolite, granite, granodiorite, migmatite, migmatites-charnockites.	No
13	Valmiera-7	4	414	16.5	the same as in 12	No
14	Valmiera-GK-11K	4	437	44	the same as in 12	No
15	Strenči-3	4	700	318	the same as in 12	Yes
16	Strenči-8	4	395.8	7.8	the same as in 12	No
17	Valmiera-GK-12PR	4	602	149	the same as in 12	No
18	Trikāta-GK-14K	4	531	55	gneiss, granite	Yes
19	P-43	5	894	6.9	unknown	unknown
20	N-43	5	912	23	gneiss	Yes

Borehole No.	Original name of the borehole	Figure	Total length (m)	Length in crystalline basement (m)	Main rock type	Indi-cations of Fe (Yes/ no)
21	Inčukalns 2P	5	1180.9	290.9	gneiss, quartzite, migmatite, amphibolite	Yes
22	Nītaure-58	5	991.7	10.7	amphibolite, gneiss	No
23	Zaube-Annas GK-15P	5	1112.9	33.9	migmatite, plagiogranite, quartz-magnetite gneiss	Yes
24	Šķaune-Ļauļēni 25(26)	5	1005.3	28.3	amphibolite, gneiss	No
25	Jaunjelgava-GK-16P	5	1133.2	207.7	gneiss, amphibolite, ferruginous quartzite	Yes
26	Taurkalne-1	5	974	49	gneiss	No
27	Olaine R-52	6a	1261	14	gneiss	No
28	Olaine N-52	6a	1258.3	14.3	gneiss	No
29	Olaine N-51	6a	1261.7	14.7	gneiss	No
30	Olaine R-51	6a	1260.4	13.4	gneiss	No
31	Olaine P-39	6a	1263	2	gneiss	No
32	Olaine D-1	6a	1271	19	gneiss	No
33	Olaine N-50	6a	1271	14	gneiss	No
34	Olaine R-50	6a	1264	3	gneiss	No
35	Olaine D-4	6a	1215	17	gneiss	No
36	Lāči-3	6a	1203	16	unknown	unknown
37	Gārsene 2A	6b	1215.2	270.1	gneiss, migmatite, ferruginous quartzite, magnetite-dominated gneiss	Yes
38	Gārsene 2	6b	1225.4	281.1	gneiss, migmatite, ferruginous quartzite, magnetite-dominated gneiss	Yes
39	Baltinava-17	6c	965	23	Migmatised gneiss	No

Appendix B

Magnetic field data

Magnetic field mapping of Latvia has been conducted since the beginning of the 20th century. In the 1950s, aeromagnetic mapping at the scale 1:200,000 was conducted for the entire territory of Latvia (Vetrennikov et al. 1986). The flight height for those surveys varied from 80 to 300 m. Average distance between the flight lines was approximately 2 km. Measurements were conducted with AJM-49 magnetometers. The precision of these data sets was reported to be around 25 nT. The data were used mostly for deep geological mapping. The data sets were used as the basis for the construction of all deep geological structure and composition maps of the area, as well as to map high-amplitude magnetic anomalies. As at later times, higher-resolution mapping was conducted, these data are relevant only in a few areas – mostly small areas close to the border.

From 1965 to 1973 a magnetic field survey at the scale 1:100,000 targeted magnetic anomalies detected in the previous survey, including the one located near the city of Staicele (Bičko et al. 1967). In the case of the Staicele area, the measurements were conducted with an M-18 relative magnetometer. Absolute values were not calculated, and diurnal variations were not applied, as there was no magnetometer that could be used as a base station. A more precise map of the Zaube-Annas magnetic anomaly at the scale 1:50,000 was created during geological mapping of the anomaly at the scale 1:200,000 (Mironov et al. 1973). The same M-18 relative magnetometer and two M-27 devices were used, and a base station was applied for diurnal variations.

From the late 1960s to the 1980s, in many parts of the country aeromagnetic survey was conducted at the scale of 1:50,000. However, the equipment and methods used differed from survey to survey, and therefore merging of the obtained data sets is complicated. For example, in 1978, during a study focused on the iron ores in the Precambrian basement (Vetrennikov et al. 1982), an aeromagnetic survey using a Geometrix G-801 magnetometer was conducted in the eastern part of Latvia. An IL-14 airplane was used; the flying height was 100 m and the line spacing was 500 m. The locations of the profiles were determined using photographic references taken during the flight. Tie lines were used for the determination of the consistency of the measurements. It is reported that the uncertainty of the measurements is 2 nT. However, the generated magnetic maps lack appropriate data corrections, resulting in significant distortions of the drawn contour lines (Fig. 5). Unfortunately, no raw data that could be used to apply the corrections are available. This means that the magnetic data covering almost 1/3 of Latvia are not usable at the provided detailed scale of 1:50,000, but they can be used for regional analysis at larger scales.

A similar survey was conducted a decade later for the western and south-eastern part of Latvia (Mjasņikovs et al. 1987). Flights were conducted with an AN-2 airplane. A magnetometer was towed 40 m behind the airplane, and the distance between the flight lines was 500 m. Tie lines were placed approximately 5–8 km apart. The flight height was 130 m with a reported error of 10%. Spatial referencing was accomplished using photographic references every 3.5 km. MM 305 quantum aeromagnetometer was used. The precision for this device was reported to be 5.4 nT. M-33 quantum magnetometer was used as the base station. Magnetic anomaly maps were created by subtracting the normal magnetic field derived from several observatories across the former Soviet Union, as well as northern Europe. In some cases, magnetic mapping at the scale 1:50,000 was conducted in order to find suitable structures for the disposal of industrial waste near the cities of Riga and Liepāja. The magnetic map sheets in these surveys are segmented using several uncommon formats, and, due to the secrecy of the time, they lack clear indications of precise coordinates.

Especially problematic is the case of the most intense magnetic anomaly – the Gārsene anomaly. This anomaly lies on the border between Latvia and Lithuania; resulting in nomenclature and projection

used for the map sheets differing across the border. Evidently, this has caused noticeable confusion even among the original cartographers, as there are many positioning inconsistencies, i.e. some villages and roads are not aligned between overlapping sheets, the map sheet schematics contradict themselves, etc., severely degrading the credibility of the magnetic data at the original scale of 1:50,000.

During a study focused on the iron ores in the Precambrian basement of Central Latvia (Vetrennikov et al. 1982), a land-based magnetic survey was conducted to precisely determine the maxima of magnetic anomalies using an M-27 magnetometer. For small areas around the detected magnetic field maxima, the measurements were performed on a 50 x 100 m grid, and in some places they were performed in even more detail. It was determined that the uncertainty was 10 nT. Additionally, during this study magnetic profiles were surveyed for calculations and the characterisation of the magnetic anomalies and the iron-bearing bodies linked to them. A distance of 100 m between measurements was used. A drift of 0 point was determined using control point measurements. For the diurnal correction of the profile, the data recorded at the base station with a magnetometer of the same model (M-27) were used. The determined uncertainty of the measurements was 8 nT.

The ground survey at the scale 1:50,000 (Vetrennikov et al. 1986) focusing on the more intense magnetic anomalies, e.g. Staicele and Strenči anomalies in northern Latvia, was planned quite oddly. Only few of the anomalies were completely covered with measurements, and there are no appropriate buffer zones measured for modelling purposes.

Summarising the available information regarding magnetic field anomalies across the country, it is evident that a significant number of measurements have been conducted up to the present. The precision of the spatial referencing of those measurements is relatively low. For example, the spatial referencing for aeromagnetic surveys was done using aero-photographs. Also, the exact coordinates of the aerial and land-based measurements are only available as points on paper maps with rather poor precision and quality. Similarly, the precision of magnetic field measurements does not meet the modern standards.

Gravity field data

The first gravity field measurements in Latvia were conducted in the 1930s (Bičko et al. 1967). Since then gravity field surveys were conducted with different goals and resolutions.

One of the first gravity field data sets was collected in 1958-1965 at the scale of 1:200,000, with the goal of studying the main tectonic structures of the Baltic region, as well as testing the possibilities of mapping local structures, e.g. buried pre-Quaternary river valleys (Bičko et al. 1967; Vetrennikov et al. 1982; Astašenko et al. 1986). The measurements were conducted on a 2 x 4 km grid (Zandersons & Karušs, 2020). The data were collected using GAK-3M, GAK-4M and GVP gravimeters. It was reported that the uncertainty of these measurements is 0.4-0.5 mGal.

Up until 1961, the collected gravity field measurements were used for the construction of a gravity field map at the scale 1:200,000 by A Faitelson (Vetrennikov et al. 1982). It was claimed that the precision of the measurements is 0.26 mGal.

In 1986, ground-based gravity field mapping over a ~1700 square kilometer area in Northern Latvia (only partially covering the Staicele and Strenči magnetic anomaly areas) at the scale of 1:50,000 was conducted to study possible ore resources in the Precambrian basement (Vetrennikov et al. 1986). The applied line spacing was 500 meters and point spacing along the lines 250 meters, reported precision was 0.1 mGal. In order to tie the measurements to absolute field values, a reference grid was created using an absolute reference point at Spilve Airport in Riga (approximately 100 km away from the survey area). The reference grid precision was assessed to be 0.02 mGal. The locations of the points were determined using topographic 1:25,000-scale maps, while the

height was determined using height levelling. The assessed horizontal uncertainty was 25 m (0.024 mGal), while the vertical uncertainty was 10.7 cm (0.02 mGal). Gravity measurements were conducted over approximately the same profile lines that were used for magnetic field measurements. Similar gravity profiles were collected a few years earlier (in 1982) during the study focused on iron ores in the Precambrian basement (Vetrenikov et al. 1982). The gravity measurements were performed using a GP/K2 gravimeter, with a reported uncertainty of 0.06 mGal.

From the 1950s to the 1970s, gravity profiles for the mapping of buried pre-Quaternary river valleys were made as a part of geological mapping at scales of 1:200,000 and 1:50,000. The distance between the profiles was usually set as 1-3 km. The measurements along the profile were usually conducted every 100 m and occasionally every 50 m. During these surveys, GAK-PT, GAK-PTM, GAK-7T, GP/K2 and Delta-2 gravimeters were used. The standard error of the measurements was 0.07-0.11 mGal. The intensity of the observed anomalies was from 0.3 to 1 mGal (Vetrenikov et al. 1982).

If we exclude the profiles, more than 12,000 gravity measurements over the entire territory of Latvia, spaced on an irregular grid with 2-3 km between points, were collected during the last century. All the data have been digitised and recalculated to the IGSN71 reference by J. Kaminskis (Zandersons & Karušs 2020).

More recent gravity field measurements were conducted by the Geodetic Survey of Latvia (LGS) and the State Land Service between 1998 and 2011 (Zandersons & Karušs 2020). The gravity measurements were carried out using Scintrex CG-3 and Scintrex CG-5 gravimeters. In total, 4886 relative measurements were conducted in an irregular grid with an average distance between points of 3 km. Most of the measurement points are in the western and central parts of Latvia, while the point network in the east is less dense. The standard error of those measurements is about ±0.055 mGal.

Currently, new relative gravity data are being gathered over the land and sea areas of Latvia by the LGS. Sea gravity measurements are done using ZLS D13 gravimeters stabilised on a balancing platform and referenced to the IGSN71 using ground control points in Liepāja, Vaiņode and Rucava. Multiple profiles cover Latvia's territorial waters, excluding the Irbe Strait and Gulf of Riga. The spacing between the profiles varies from 5 to 10 km, while the standard error of measurements, determined from profile crossings, is 0.1 mGal (LGS senior specialist V. Zuševics, personal communication).

Current LGS land surveys use Scintrex CG-5 gravimeters, placed on a regular 4 x 4 km grid over the entire country. The goal of the current gravity measurements is to fill the gap in the eastern part of the country, as well as to validate the campaign of 1998-2011, as some gravity points from this campaign are flagged as erroneous (LGS senior specialist Zuševics, personal communication). Over 600 new measurements were made in 2022 and 2023 and the work continues (Zuševics 2024). The standard error determined for the newest land measurements is ±0.04 mGal.

If we compare the measurements of the 20th century with the ones obtained during the last 20 years, there are crucial differences in the measurement quality. The quality differences of various Soviet-era campaigns severely limit their usability as a single data set. Additionally, for most of the 20th century measurements, only map or digital map data are available, and single points suffer from location errors, which reduces the measurement accuracy even further. A difference of around 26 to 29 mGal can be observed between the 1:50,000-scale measurement campaign (20th century) and the modern LGS measurements in northern Latvia (Zandersons et al. 2018). However, some of the historical data can be used for modern mapping purposes. For example, after performing quality control on the points from the 1:200,000-scale geological mapping, they were successfully used to create a new regional gravity anomaly map for Latvia (Zandersons & Karušs 2020). Nevertheless, the old data should be, if possible, used only as trend indicators, not as absolute values.

Seismic survey data

Seismic surveys have been made in Latvia to map local structures, as well as to create country-wide structural maps. Most of the profiles are located in the western part of the country and surveyed during oil exploration (Brangulis 2002). Most of the seismic profiles in Latvia were recorded from 1959 to 1972.

Some studies focused on regional-scale structures. For example, seismic reflection exploration was conducted in 1958 in the southern part of Latvia, with the goal of mapping the surface of the Ordovician sedimentary rocks (Vetrennikov et al. 1982). This surface is the most prominent reflector in seismic cross-sections across Latvia and in many instances is used as a starting point for data interpretation. Similarly, in 1962, a seismic refraction survey was used to map the surface of the Precambrian basement across the whole country. In the following years, more detailed local surveys were conducted in many places. For example, in 1975, a seismic reflection survey was used to map the sedimentary rock cover, as well as the surface of the Precambrian basement, around the city of Limbaži (Vetrennikov et al. 1986).

Similar methods were used in the above mentioned surveys. The seismic reflection surveys were conducted in profiles that had a spacing from 10 km to several tens of kilometres. Each individual profile was 575 m long, with a sensor spacing of 5 m. Explosions were triggered at the middle points of the lines. Profiles were attached one to another at the ends. The stacking of six sensors was used, and as a result 25-m-long groups of sensors were stacked together. The explosions were set 300 m apart.

Sometimes it is reported that explosives were placed in the boreholes at a depth of 10 m. In most such cases, cast trotile with a weight of 2.5 kg was used, while sometimes pressed trotile with a weight of 400 g was used. In other cases, it is reported that either 5.2 kg of explosive material was placed in a 12-m-deep borehole, or a group of 5-6 boreholes was used, with 0.8 kg of explosive placed in each of them (Mironov et al. 1973; Vetrennikov et al. 1982). Litolo-trotile with a weight of 2.6 kg was used as well.

For data recording, the SMP-24 and POISK-1-48-MOV-OV stations were used. The exact locations of the survey lines were determined using geodetic levelling measurements. The precision of the determined locations was assessed as +/-25 m, while the vertical precision was assessed as 1.5 m (Mironov et al. 1973; Vetrennikov et al. 1982).

A large amount of effort was devoted to mapping local structures. The Inčukalns structure is one of the most densely seismically profiled areas. In the early 1960s, seismic reflection and refraction methods were used to study this structure as a potential natural gas storage location. Several additional structures were discovered near the main structure in these studies. A seismic refraction survey was conducted at the Inčukalns structure in 1979. At the same time, some surveys, for example, the seismic refraction survey in the vicinity of Valmiera in 1974, were conducted to map the tectonic faults (Vetrennikov et al. 1982).

Most of the recorded profiles are available and stored in LEGMC (Latvian Environment, Geology and Meteorology centre) in paper format only. The overall quality, as well as the preservation of these data sets, is rather poor. In most cases, it would be complicated to re-interpret the data. Even more problematic is that some parts of the original data are lost. Only a small part of the profiles is available in digital format.

Electrical resistivity measurements

Electrical resistivity measurements were conducted to gain insight into the structure of the Precambrian basement before a significant amount of the seismic data and the magnetic field data were gathered across Latvia. The first electrical resistivity measurements in the eastern part of Latvia were conducted in 1947 near the city of Pļaviņas. Vertical electrical profiling (VEP) was conducted with a maximum AB spread of 12-16 km. There was one measurement point in every 5 km^2 area (Vetrennikov et al. 1982). During the survey, the resistivity profiles were also compiled by using measurement points with a spacing of 3 km. As a result, a structural map of the Precambrian

basement and resistivity profiles along the surveyed profiles were constructed.

Similarly, in 1952, VEP with a maximum AB spread of 16-26 km was conducted around the city of Bauska. In this case, there was one measurement point for every 10 km2 area (Mironov et al. 1973). As a result, a structural map of the Precambrian basement of the survey area with a scale of 1:100,000 was constructed.

In some cases, measurements were done only to construct a resistivity profile. For example, in 1950, VEP with a maximum AB spread of 16 km was used to construct a resistivity profile between the cities of Pļaviņas and Biržai. Measurements along the profile were done every 2-10 km. In 1951, VEP was done in a line between the cities of Rīga and Jēkabpils. In this case, the maximum AB reached 10-20 km and the distance between measurement points was 3-5 km (Mironov et al. 1973). The results of these measurements were used to construct a map of the surface of the Precambrian basement. Since 1961, VEP has been regularly used in geological mapping, mainly for studying the sedimentary rock cover of Latvia.

Similar equipment, such as EP-1 and ESk-1 units, non-polarised electrodes, steel electrodes (1.5 m long) and brass electrodes, was used for the measurements. A 69-GRMC-6 battery was used as a source. The generator-group ERGG-60 was applied for larger offsets (Mironov et al. 1973).

Around the middle of the last century, the magnetotelluric method was used to determine the electrical conductivity of deeper sedimentary rock layers, as well as to map the surface of the Precambrian basement in Latvia (Mironov et al. 1973). In most cases, there was one observation point for every 50-70 km2. Measurements were done with a JPL-57 device, using time intervals from 8 s to 2.5 h. For geological purposes, mainly intervals of 10-35 s were used (Jankin et al. 1975). Correlations with boreholes indicated that the uncertainty of the depth of the Precambrian basement does not exceed 50 m.

Borehole geophysical logging

Since 1959, borehole geophysical logging has been conducted for 189 boreholes reaching the Precambrian basement. For all of those boreholes, gamma logging was done using a DRST-3 device, and neutron logging and cavernometry were performed. Inclinometry was conducted using an IG-50 device. Electric logging was done using A2M0, 25N and 25A devices. The electric potential was measured using a Zond MEP device with zinc brooms and a zinc shield (Vetrennikov et al. 1982, 1986; Baulins et al. 1995).

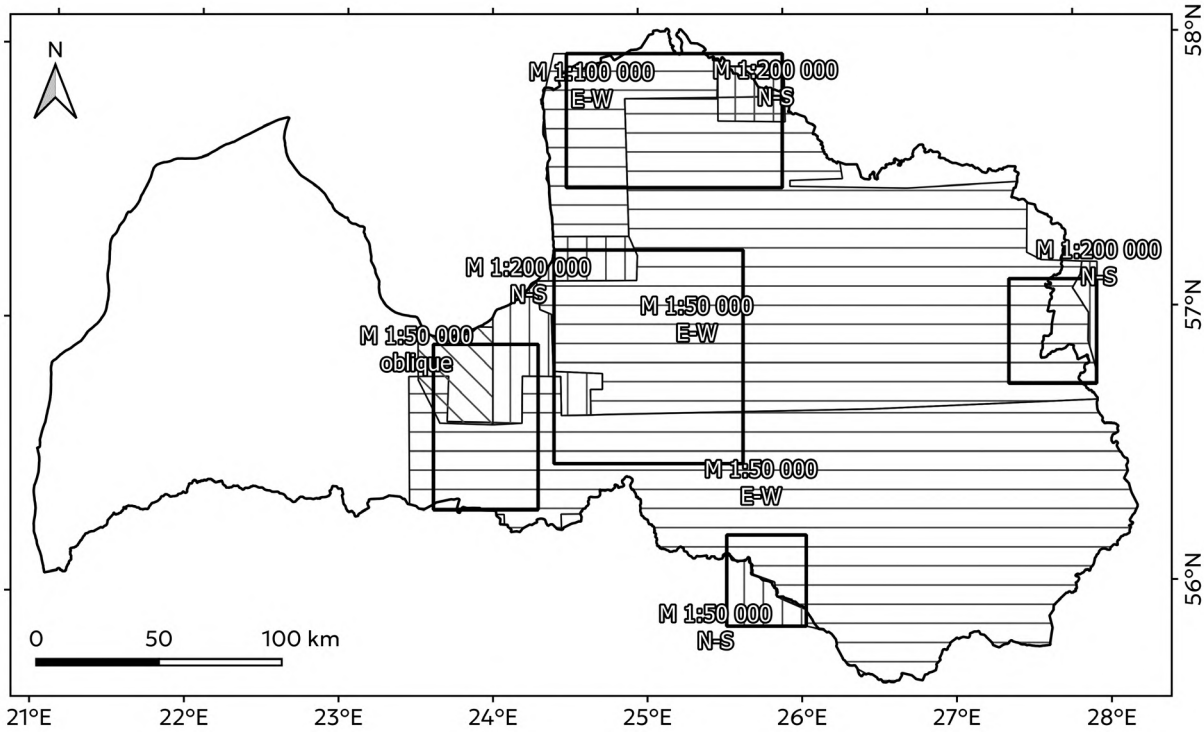
For some borehole temperature measurements, acoustic cementometry, induction logging and neutron-gamma logging were done. Measurements were made using the AKCL-7 and AEKS-1500 logging stations (Vetrennikov et al. 1982, 1986).

For 53 boreholes, including the boreholes in the Gārsene and Strenči magnetic anomalies, vertical seismic profiling was done with the POISK-1-24-MOV and SMP-24 stations. Explosives with weights from 0.4-1.2 kg were used as a source in shallow boreholes with casing (Vetrennikov et al. 1982, 1986).

For boreholes drilled in the five most prominent magnetic anomalies (Vetrenikov et al. 1986), magnetic field parameters were also measured using a TSMK-30 magnetometer. The total magnetic field intensity and magnetic susceptibility were measured. The device was linked to absolute field measurements by taking readings of the magnetic field ~40 m away from the borehole using the same device. Also, the three axis components of the magnetic field were measured. The resolution is reported in units of nT/cm of the paper that was used for data recording (Vetrennikov et al. 1982, 1986).

It is stated that during the measurements, the factory settings of the devices were used and that everything was done according to the instructions (Vetrennikov et al. 1982, 1986).

Appendix C



Aeromagnetic survey coverage of the studied area.

For boreholes that were drilled in magnetic anomalies, the samples for laboratory analysis were taken with a spacing of 1 m on average. The density, magnetic properties (susceptibility and remanent magnetisation), electrical resistivity, electrical polarisation and Vp speed were measured, and chemical analyses were done for the Precambrian rock samples (Vetrennikov et al. 1982, 1986).

Most frequently, gamma logging, neutron logging, cavernometry, inclinometry and electric logging data are digitised and stored in LAS format at LEGMC. However, more specific data, such as magnetic field parameters, are available only in paper format, and in this case, the values of the recorded measurements are quite often unreadable.