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# Critical Raw Materials Potential in the **Netherlands' Subsurface**

**Identifying mineral occurrences hosting critical raw materials in** response to the European Union's Critical Raw Materials Act of 2024

NMO 2025 R11414
8 July 2025

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|---|---|
| Classification report | NMO Public |
| Report Number | NMO 2025 R11414 |
| Number of pages | 74 (excl. front and back cover) |
| Number of appendices | 0 |

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# Summary

This report evaluates the potential for mineral occurrences hosting critical raw materials (CRM) in the Netherlands' subsurface. The study responds to the European Union's 2024 Critical Raw Materials Act (CRMA, 2024), which requires each member state to present a "national exploration program" outlining an inventory of existing CRM resources and a plan to understand the potential for additional CRM resources in the Netherlands.

In late 2022, the Netherlands established the National Raw Materials Strategy (NGS) and, in 2025, opened the Netherlands Material Observatory (NMO). The NMO will meet the objectives and requirements set by the National Raw Materials Strategy (NGS) and the European Critical Raw Materials Act (CRMA) regarding research and information sharing on critical raw materials. The NMO's main tasks are to collect, manage, and provide data, information, and knowledge about CRM and their supply chains.

With a detailed understanding of the geology of the Dutch subsurface, as provided by the Dutch Geological Survey (GDN), it is clear that the Netherlands is generally not assumed to hold significant potential for CRM resources. However, resources of high-purity silica sand, magnesium salt, and coal, which are potential sources of three CRMs, silicon metal, magnesium metal, and coking coal, respectively, have been known and developed for several decades. Several other mineral systems that occur or are likely to occur in the Dutch subsurface have not received appropriate attention to understand their CRM potential.

This first national exploration program focuses on six themes, categorized by mineral systems, in which inherent CRM potential warrants further investigation. Each theme is subdivided into known or probable mineral occurrences and potentially economically interesting deposits. The six themes guiding the national exploration program are:

1) **Mineral Sands**: Heavy minerals in coastal and fluvial sediments, containing valuable elements like niobium, tantalum, titanium, tungsten, and rare earth elements.
2) **Iron, Manganese, and Phosphorus Concretions**: Historical small-scale mining of phosphorite, iron ore, and manganese soils, with potential for further investigation.
3) **Waters & Brines**: Deep subsurface brines containing elevated concentrations of elements like lithium, strontium, magnesium, and boron, with potential for direct CRM extraction.
4) **Sulphides**: Known occurrences of zinc and lead sulphides in South Limburg and East Gelderland, with potential for associated CRM like gallium, germanium, and bismuth.
5) **Mined Deposits**: Existing extraction of magnesium salt and silica sand present a potential opportunity for producing metallic magnesium and silicon, respectively. Historically mined coal resources remain to be assessed for their coking-coal potential.
6) **Industrial & Municipal Waste Products**: Recovery of CRM from residual waste products, such as steel slags and bottom ashes from municipal waste incineration, which are used as aggregate.

Historically, raw materials production in the Netherlands has focused on energy sources (peat, coal, oil, gas) and building materials (limestone, gravel, sand, clay). Identified CRM candidates include known resources of silica sand, metallurgical coal, and magnesium salt. The report provides an overview of resources, current extraction levels, and potential future production.

While standalone primary CRM production in the Netherlands is unlikely to occur in the future, opportunities are being explored to extract CRM in conjunction with existing subsurface activities, such as the production of water, energy, and other raw materials. The economic viability and development potential will be classified according to the United Nations Framework Classification for Resources. The raw-materials sector is a mature commercial industry driven by value creation along the entire supply chain. Economic considerations, legal frameworks, and environmental and social impacts must be carefully managed, especially when potentially viable sites of future CRM production in the Netherlands would emerge.

The report concludes that while the Netherlands' subsurface has limited potential for standalone CRM production, there are opportunities for co-production with existing activities. A thorough review and analysis of existing data will form a solid foundation for further research and technological innovation, which are essential to fully assess the CRM potential in the Netherlands.

Relevant research activities are suggested for each of the six exploration themes. These activities collectively aim to enhance the understanding of CRM mineral systems in relation to Dutch geology and to establish an advanced view on CRM potential in the Netherlands. The suggested activities include: growing the knowledge base through the progressive compilation and assessment of geochemical and geophysical databases relevant to CRM mineral systems, acquiring additional analytical and surveying data to fill spatial data gaps and increase data density with a CRM focus, and reviewing innovative extraction methods to assess the feasibility of sustainable extraction practices. Where CRM potential is identified, based on published data, this will be shared at a European level to a centralized database (MIN4EU format), as proposed by the Geological Services for Europe (GSEU) initiative.

# Glossary

## Abbreviations

BRO – Basisregistratie Ondergrond (National Key Registry of the Subsurface)
CRM - Critical raw material(s)
CRMA – Critical Raw Materials Act (2024)
DINO – Data en informatie van de Nederlandse ondergrond (data and information on the Dutch subsurface)
DIS – Delfstoffen Informatiesysteem (Minerals information system)
DLE – Direct lithium extraction
ESG – Environmental, Social and Governance
GDN – Geologische Dienst Nederland (Geological Survey of the Netherlands)
ISR – In-situ recovery
MBW – Mijnbouwwet (Mining Act)
MBB – Mijnbouwbesluit (Mining Decree)
MBR – Mijnbouwregeling (Mining Regulation)
MRE – Mineral Resource Estimate
NGS – Nationale Grondstoffenstrategie (National raw materials strategy)
NMO – Netherlands Materials Observatory
NLOG – Nederlands olie- en gasportaal (Dutch oil and gas portal)
REE – Rare Earth Element(s)
SodM – Staatstoezicht op de Mijnen (State Supervision of Mines)
TNO – Netherlands Organisation for Applied Scientific Research
UNFC – United Nations Framework Classification for Resources
WWTP – Wastewater-treatment plant(s)
XRF - X-ray fluorescence

## Terminology

**Aeolian -** formed or caused by wind.
**Basin (sedimentary) -** a depression filled with sediments.
**Bog iron** - iron ore consisting of hydrated iron oxide minerals, formed in swamps or lakes through the oxidation of iron-rich groundwater.
**Borehole -** a hole drilled in the subsurface to either extract a resource or obtain (geological) information.
**Brine** - highly concentrated solutions of salt in water, often found in deep subsurface formations.
**Cap rock** – an impermeable overlying layer or rock formation that trap resources like oil and gas in a the reservoir.
**Carbonate rock** - sedimentary rocks composed primarily of carbonate minerals, such as limestone and dolomite.
**Carboniferous** – a period in the Palaeozoic era, approximately 358 to 298 million years ago. Known for the formation of coal, oil and gas and the formation of the supercontinent Pangaea.
**Cenozoic** - the current geological era, beginning 66 million years ago, characterized by the dominance of mammals.
**Coking coal -** metallurgical coal, a specific coal grade that can be used to make cokes for steel production.
**Concretions -** a compacted mass, often ovoid or spherical, that has been formed in sedimentary deposits.
**Cretaceous -** a period in the Mesozoic era, approximately 143 to 66 million years ago. Known for the asteroid mass extinction event ending the era of dinosaurs.
**Critical Raw Materials (CRM)** - materials considered essential for the economy and subject to supply risks, as defined by the European Union.
**Depletion -** in the field of geochemistry depletion of an element refers to a removal or declining concentration of that element.
**Deposition** – the accumulation of material through processes in which gravity has overcome the force driving transportation, causing the material to settle. Deposition also refers to the settling of the remains of organisms, or the precipitation of minerals from a saturated fluid.
**Devonian** - a period in the Palaeozoic Era, approximately 419 to 359 million years ago, known for the diversification of fish and the first appearance of amphibians.

**Dinantian** – an epoch, part of the Lower Carboniferous, approximately 359 to 326 million years ago. Known for the formation of carboniferous limestone used as natural stone and raw material for cement.
**Direct lithium extraction (DLE)** - a range of processes for extracting lithium from brines, including ion exchange, selective adsorption, solvent extraction, and membrane technologies.
**Enrichment -** in the field of geochemistry enrichment of an element refers to the addition or increasing concentration of that element.
**Environmental and Planning Act (Omgevingswet)** – Comprehensive set of laws/regulations for spatial planning, the environment, nature, water, and the superficial extraction of minerals (also see Mining Act).
**Erosion -** the removal of rock or sediment by a natural force.
**EuroGeoSurveys (EGS) -** a non-profit organisation representing the Geological Surveys of Europe.
**Extrusive rock -** solidified lava erupted from, or a deposit of rock fragments ejected by, a volcano.
**Fault -** a fracture plane or zone, along which rock masses move relative to each other.
**Feasibility study -** an objective assessment of the project's potential for success in terms of costs required and value to be attained.
**Fluvial -** formed or caused by rivers or streams.
**Formation -** a body of rock with a consistent set of physical characteristics that distinguishes it from adjacent bodies of rock and large enough to be mapped at the surface or traced in the subsurface.
**Geophysical data/survey -** data / data acquisition, usually covering large areas, by means of measuring physical rock properties such as seismic reflectivity, magnetic field, gravity field, gamma radiation, and electrical conductivity.
**Geothermal energy -** heat stored in the subsurface.
**Geothermal brines** - hot, mineral-rich waters found in geothermal reservoirs, potentially containing valuable elements like lithium.
**Glacial -** formed or caused by glaciers, or associated with glaciations.
**Greenfield exploration** - exploration in areas without known mineral resources, targeting large areas to identify potential new deposits.
**Heavy minerals** - minerals with a density greater than 2.9 g/cm³, often found in placer deposits, used as indicators of sediment provenance.
**Holocene** – the current geological epoch, part of the Quaternary, which began approximately 11.700 years ago.
**Hydrothermal alteration -** the chemical change of a rock, caused by reactions with fluids
**Igneous rocks -** rock formed by the cooling and solidification of magma or lava.
**In-situ recovery (ISR)** - a mining process where a solvent is injected into an orebody to dissolve minerals, which are then pumped to the surface for recovery.
**Industrial minerals** – naturally occurring rocks or minerals which are of economic value, excluding energy minerals, metallic minerals (metals) and gemstones.
**Intervention values -** reference values indicating the concentration threshold for soil contamination
**Intrusive rocks/intrusions -** rocks formed by the cooling and solidification of magma in the subsurface.
**Jurassic -** a period in the Mesozoic era, approximately 201 to 143 million years ago. Known for the break-up of the supercontinent Pangaea and life dominated by dinosaurs.
**Kupferschiefer** - a copper-bearing shale formation in Central Europe, part of the Zechstein Group, known for its significant copper and silver deposits.
**Leaching -** the removal or mobilisation of a solute from a substance via dissolution in a liquid, usually acid.
**Namurian** – a NW European stage of the Carboniferous, approximately 331 to 319 million years ago.
**Natural resource -** a natural source of wealth that holds economic interest and potential value.
**Magnesium metal -** pure magnesium metal, obtained from processing magnesium ore and used in lightweight alloys.
**Magnesium salt** - salts containing magnesium, such as carnallite and bischofite, used in various industrial applications.
**Marine - formed in, or associated with,** oceans, seas, or coasts.
**Mesozoic** – a geological era, approximately 252 to 66 million years ago, known for dinosaurs, a hot climate, and the break-up of supercontinent Pangaea.
**Metallurgical coal** - coal used in the production of steel, also known as coking coal.
**Metals -** selection of individual elements in the periodic table that can conduct electricity and heat, can be shaped easily, have a shiny appearance and relatively high melting point.
**Mineral -** a naturally occurring, inorganic element or compound with a specific chemical composition, crystal structure, and physical properties.
**Mineral exploration -** the process of searching for (geological) evidence of commercially viable concentrations of minerals hosted in rocks.
**Mineral resource -** an elevated (anomalous) concentration of one or multiple minerals, containing chemical elements of interest, predominantly metals, which are potentially feasible for extraction from the subsurface.
**Mineral resource estimate -** estimated mineral content, grade, tonnage (volume, and density), and physical properties, based on geological data and knowledge.
**Mineral reserve -** extractable portion of a mineral resource based on a feasibility study.
**Mineral exploration license -** exclusive rights to explore a specified area for minerals. Dutch mineral exploration licenses are granted by the Ministry of Climate Policy and Green Growth.
**Mining Act (Mijnbouwwet)** – comprehensive Dutch legal framework that regulates activities in the deep subsurface, covering the exploration for, and extraction of, hydrocarbons, minerals, and geothermal heat, as well

as the storage of substances. Deep signifies 500 m below the subsurface in case of geothermal energy and 100 m in all other cases.
**Mining license -** the exclusive rights to produce a resource in a specified area as defined by the production plan. Dutch mining licenses are granted by the Ministry of Climate Policy and Green Growth.
**Mineral deposit -** an concentration of a mineral or minerals, often in the form of one or several defined mineral resource bodies, which may be suitable for economic extraction now or in the foreseeable future.
**Mineral occurrence -** a (high) concentration of a mineral that is of economic value, or of scientific or technical interest.
**Mineral sands** - sands containing heavy minerals like ilmenite, rutile, and zircon, containing valuable metals.
**Mineralization -** in economic geology, referring to a zone containing economic minerals that may indicate an orebody.
**Mississippi Valley-type (MVT) deposits** - epigenetic ore deposits formed by the precipitation of minerals from dense brines in carbonate rocks, typically containing lead and zinc.
**Namurian** - a stage in the Carboniferous period, characterized by coal-bearing deposits.
**National Raw Materials Strategy (NGS)** - a strategy developed by the Netherlands to ensure sustainable supplies of critical raw materials.
**Palaeogene** - the first period of the Cenozoic Era, spanning from 66 to 23 million years ago, marked by the dominance of mammals and birds.
**Palaeozoic -** a geological era, approximately 538 to 251 million years ago, known for both the largest increase in biodiversity and the largest extinction event.
**Permian** - the last period of the Palaeozoic Era, approximately 299 to 252 million years ago, known for the formation of the supercontinent Pangaea.
**Phosphorite** - a sedimentary rock containing high concentrations of phosphate minerals, used as a source of phosphorus for fertilizers.
**Precipitation** – (in the context of the present report) the formation of minerals from a solution.
**Quaternary** – the current geological period, part of the Cenozoic era, beginning approximately 2.58 million years ago. Known for recurring glaciations.
**Radiometric data -** data obtained by measuring radiation emitted from radioactive elements in rocks.
**Rare-earth elements -** group of 17 elements in the periodic table called lanthanides. Although relatively plentiful in the Earth's crusts, they appear individually as trace elements
**Rattle stones** – iron-rich concretions from which the core has been detached from the outer shell by desiccation, causing the concretion to 'rattle'.
**Raw material** – basic material used in the production or manufacturing of goods.
**Recovery -** the share of metal contained in an ore (feed) that is recovered from the concentrate. The remaining metals end up in the tailings.
**Reconnaissance survey** - a preliminary survey to detect minerals.
**Silicon metal** – metallurgical-grade silicon refined to semiconductor purity, which is a nearly defect-free, single-crystalline material.
**Silica sand** – high-purity quartz sand used in industrial applications like glassmaking and silicon-metal production.
**Silurian** – a geological period, part of the Palaeozoic era, approximately 443 to 419 million years ago. Known for the emergence of the first extensive terrestrial ecosystems.
**Slag** – non-metallic residue of steelmaking, which can be used to make cement.
**Solution mining** – the production of salt via injection of water in rock salt or salt-bearing rock, dissolving the salt, and pumping the solution to the surface
**Stratigraphy -** the study and description of layered rocks, focusing on their lithology, fossil content, and age.
**Sulphides** - minerals composed of sulphur and one or more metals, often forming valuable ore deposits.
**Tectonic** – related to the structure, motion, and deformation of the earth's crust.
**Trace elements** - elements that are present at very low concentrations in rocks, soils, fluids or organisms.
**Triassic -** a geological period, part of the Mesozoic era, approximately 251 to 201 million years ago. Known for a hot and dry climate and the Triassic-Jurassic extinction event caused by extensive volcanic activity.
**UNFC Classification** - the United Nations Framework Classification for Resources, a system for classifying mineral and energy resources based on their economic viability and development potential.
**Variscan orogeny** - a mountain-building event that occurred during the late Palaeozoic Era, affecting Europe and North America.
**Westphalian -** a regional stage of the Carboniferous, approximately 315 to 307 million years ago, in NW Europe.
**Zechstein Group** - a sequence of Permian age sedimentary rocks in Europe, known for its evaporite deposits, including rock salt and potash, with the Kupferschiefer at its base.

# 1 Introduction

## 1.1 National Exploration Program of the CRMA

Global energy and digital transitions in combination with increasing urbanization are driving the progressive demand for a growing number of raw materials. Articulated by recent geopolitical developments, awareness has arisen in Europe for strategic autonomy and related security of supply of so-called critical raw materials (CRMs), defined as raw materials that are of high economic importance and are subject to increased supply risks. Table 1.1-1 displays the current EU CRM list, as specified in 2023 and presented in the CRM Act (CRMA, 2024).

In the Netherlands, the increased awareness has led to the establishment of the National Raw Materials Strategy (NGS) in 2022. In the European context this has resulted in the development of the CRMA, in force since 2024. According to the Act, member states must present an inventory of CRM resources present in their subsurface and must present a plan to assess the potential for finding more CRM resources within their territories.

> *"To collect and update information on critical raw material deposits, member states must, if necessary, given the geological conditions, establish national mapping programs for the general exploration of critical raw materials and the main minerals with which they are co-extracted." (CRMA, 2024)*

Table 1.1-1. EU list of critical and strategic (bold) raw materials (2023)

| | | |
|---|---|---|
| antimony | **gallium** | phosphate rock |
| arsenic | **germanium** | phosphorus |
| bauxite/alumina/aluminium | hafnium | **platinum group metals** |
| baryte | helium | scandium |
| beryllium | **heavy rare earth elements** | **silicon** metal |
| **bismuth** | **light rare earth elements** | strontium |
| **boron** (metallurgy grade) | **lithium** (battery grade) | tantalum |
| **cobalt** | **magnesium** metal | **titanium** metal |
| coking coal | **manganese** (battery grade) | **tungsten** |
| **copper** | graphite (battery grade) | vanadium |
| feldspar | **nickel** (battery grade) | |
| fluorspar | niobium | |

To address both the NGS and CRMA, the Dutch government has invested in building up and converging expertise about CRM. The Ministry of Economic Affairs initiated the Netherlands Material Observatory (NMO), which was officially established in February 2025. The NMO is embedded within the Geological Survey of the Netherlands (GDN), which in its turn is part of the Netherlands Organisation for Applied Scientific Research (TNO). The NMO's main tasks are to collect, manage, and provide data, information, and knowledge about CRM and their supply chains, and to prepare the national exploration program as set out by the CRMA (2024). This is not the first time that a comprehensive study of mineral potential has been conducted in the Netherlands. A multi-year national effort, exercised from 1903 to 1916, has been documented in detail by Van Waterschoot van der Gracht & Tesch (1918), and was followed by an inventory of surface mineral resources by Koning et al. (1946). The present report provides an overview of existing knowledge and data regarding the CRM potential in the Netherlands, mapping the CRM potential, and providing guidance on possible future research to further determine this potential, as prescribed by the CRMA (2024).

## 1.2 Geographic scope

The CRMA requests all EU member states to deliver a National Exploration Program. A multi-year study has been initiated into the mineral potential of the Netherlands, including the Dutch part of the North Sea and cross-border occurrences where relevant.

## 1.3 GDN knowledge base

The national CRM exploration program is based on an extensive knowledge base of geology and mineral resources in the Netherlands. With a large team of experts and over a century of geological surveying, the GDN hosts vast amounts of data and knowledge of the geology, stratigraphy, and natural resources, as well as expertise in 3D modelling, advice on mining policy and licensing, and execution of research programs on e.g. geo-energy, groundwater, and ground conditions. Subsurface data and subsurface models are managed in and delivered through open-access databases and information systems such as DINO, BRO, (shallow subsurface), NLOG (data subject to the Mining Act), ThermoGIS (geothermal potential), and Delfstoffen Online (surface mineral resources). Being part of TNO, the GDN has a strong network with government, industry, and the scientific community, to the benefit of developing the national exploration program and CRM expertise in general. Regarding the historically known mineral resources in the Netherlands, the GDN has an extensive knowledge base of gravel, sand, clay, limestone, coal, oil, gas, and salt.

In the creation of this national exploration program, an assessment has been conducted of available GDN knowledge relevant to CRM in the Dutch subsurface. External knowledge has been gathered through relevant open-source scientific papers, industry publications and various dialogues with relevant industry stakeholders in the Netherlands, as well as geological surveys and observatories across Europe. These activities have led to the current scope of the national exploration program, in which the CRM potential of the Dutch subsurface will be investigated.

The GDN is also well connected with geological surveys in our neighbouring countries, facilitating potential cross-border cooperation on the suggested research activities in this program. The GDN also actively collaborates with all other EU national geological surveys represented under EuroGeoSurveys and its data and information platform EGDI.

# 1.4 Identification of exploration themes

The probability of discovering a new material CRM resource that is amenable to conventional extraction techniques within the Netherlands is considered extremely low. The knowledge and understanding of the subsurface geology are exceptional and the spatial coverage of borehole and geophysical data is high, implying that if such resource would exist, it would have been discovered by now. As such, conventional approaches to discovering and developing traditional ore deposits are not applicable in the context of the national exploration program. However, there are several possibilities to consider both known and unknown CRM potential in less conventional ways. For example, co-production of CRM with existing or planned activities in the subsurface could be considered. Additionally, advancing technological innovation and novel, low-impact extraction methods could make small, deep, or low-grade mineralization more accessible.

Resources of high-purity silica sand, magnesium salt, and coal, which are theoretically potential sources of silicon metal, magnesium metal, and coking coal, respectively, have been known and developed for several decades. With new technologies demanding more specialised materials as reflected in the current EU CRM list, the geology of the Netherlands requires a renewed investigation through the lens of mineral systems that can potentially host such materials. The following themes of the exploration program have been identified as being most relevant in the context of the Dutch geology and have been categorized along a mineral-systems framework (Table 1.3-1): i) mineral sands, ii) iron, manganese, and phosphorus concretions, iii) waters and brines, iv) sulphides, v) mined deposits, and vi) industrial and municipal waste products.

The themes are further subdivided into known or probable mineral occurrences with potential material interests. They serve as a starting point and a frame of reference for developing relevant research activities, and will be progressively developed as more data and knowledge become available in the implementation of the national exploration program.

Table 1.4-1. Six identified exploration themes

<table>
<tr><th>1. Mineral Sands</th><th>2. Iron, Manganese, and Phosphorus Concretions</th><th>3. Water and Brines</th></tr>
<tr><td>Large volumes of sand have been deposited in the Netherlands throughout the Cenozoic Era, in rivers, along the coast, and throughout the North Sea Basin. The sand locally contains concentrations of heavy minerals. The heavy mineral fraction may contain elevated levels of ilmenite and rutile, columbite-tantalite, monazite, barite, and zircon (i.e. minerals that are host to several CRM).</td><td>Historically, small occurrences of phosphorite, iron ore, and manganese soils were mined from the shallow subsurface in the Eastern Netherlands. Since then, no targeted research has been conducted to assess the potential of additional resources in the region or in similar formations elsewhere in the country.</td><td>Deep subsurface brines may contain elevated concentrations of elements such as strontium and lithium. Furthermore, purification processes of groundwater, surface water, and wastewater may potentially allow for the recovery of selected chemical elements.</td></tr>
<tr><th>4. Sulphides</th><th>5. Mined Deposits</th><th>6. Industrial and Municipal Waste</th></tr>
<tr><td>Sulphide minerals have been reported in South Limburg and in East Gelderland. In addition to lead and zinc, these minerals may contain gallium, germanium, and bismuth. At considerable depth (>700 m), the Kupferschiefer has been reported, a shale layer enriched in copper sulphides, from which copper is being produced in Poland. Exploration drilling has encountered volcanic and intrusive rocks at depth. Any potentially associated mineralisation is yet to be determined.</td><td>Magnesium salt and silica sand are currently being extracted in the Netherlands. While no magnesium metal or silicon metal have been produced from these resources to date, it would be technically feasible to do so. A proportion of the existing coal resources is expected to be of coking-coal quality, which remains to be quantified.</td><td>The Netherlands annually produces considerable amounts of waste and residual products, such as slags, municipal waste-incineration ashes, and construction and demolition waste. While some metals are already being recovered from these materials, the potential for extracting additional CRM could be examined further.</td></tr>
</table>

## 1.5 Development potential and UNFC classification

Economic viability and development potential are classified according to the United Nations Framework Classification for Resources (UNFC). This is a principles-based system in which the products of a resource project are classified on the basis of the three fundamental criteria of environmental-socio-economic viability, technical feasibility, and degree of confidence in the estimate, using a numerical coding system.

The national exploration program is expected to largely confirm the limited potential for finding additional critical raw material resources with reasonable economic viability. Consequently, stand-alone primary critical raw material production in the Netherlands is not anticipated. However, opportunities are being explored to extract CRM in conjunction with existing subsurface activities, such as the production of water, energy, and other raw materials. In this way both the economic viability and the efficiency of subsurface activities are assessed thoroughly, lowering the threshold for the potential economic extraction of CRM.

# 2 Geology of the Netherlands

## 2.1 Overview

The Netherlands is a small, densely populated country located between the North Sea and the elevated regions of Belgium and Germany. Below its mostly flat landscape, the country has a diverse and complex subsurface formed over more than 400 million years of geological history (Fig. 2.1-1). In many areas, over 10 kilometres of mainly siliciclastic sedimentary rocks (marine, fluvial, aeolian, and glacial) have been deposited on top of an unknown crystalline basement. These sediments were deposited in seas or on landmasses influenced by global and regional tectonic processes, changing climate, glaciations, and sea-level variations. Several major unconformities from the late Palaeozoic (~430 Ma) to the Quaternary (2.6 Ma to present) indicate periods of non-deposition and erosion. These unconformities are crucial for dividing the sedimentary units into various lithostratigraphic groups, formations, and members, each with a different thickness, composition, and origin. Throughout geological history, tectonic events have created numerous fault systems that cut through the stratigraphic sequence, resulting in a fragmented distribution of blocks in the deeper subsurface. The generalized stratigraphic section (Fig. 2.1-2) provides an overview of the characteristics of these sedimentary units within the context of tectonic and paleogeographic developments. It offers a geological framework for understanding and predicting the potential presence and location of CRM discussed in this document.

## 2.2 Geological development and stratigraphy

The simplified stratigraphic column of Figure 2.1-2 belies a more complex geological history detailed below. Understanding these stratigraphic successions and their tectonic history is essential for the identification of any mineral systems that could host CRM and other geological resources.

### 2.2.1 Palaeozoic

The oldest sedimentary rocks in the Dutch subsurface date back to the late Silurian and Devonian periods. These rocks, which lie above older metamorphic rocks, consist of claystone, siltstone, sandstone, and carbonates (Banjar and Old Red Group; Fig. 2.1-2). They were deposited in shallow marine and deltaic environments surrounded by mountainous regions like the London-Brabant Massif, which spans the Dutch Belgian border. Although the rocks of the London-Brabant Massif do not surface in the Netherlands, they are found at shallow depths in South Limburg. During the early Carboniferous period, thick carbonate sequences formed near structural highs in shallow marine environments. In the northern offshore areas, these carbonate rocks transition into claystones and sandstones with minor coal seams. Between 326 and 313 million years ago, the Variscan Orogeny led to the creation of a deep basin north of the Ardennes-Ruhr area, where up to 5500 metres of paralic sediments were deposited. This succession includes marine and lacustrine sediments at the base, overlain by coastal-plain and fluvial deposits with coal seams and thin marine layers. The Namurian sediments are the oldest outcropping sediments in the Netherlands, found at the Heimansgroeve in South Limburg. In the eastern Netherlands and adjacent Germany, Westphalian sediments are locally overlain by Stephanian-age sediments (Ziegler, 1990a). Their iron-reddish colour marks the beginning of large-scale aridity characteristic of the subsequent Permian period. The Namurian sediments are host to some reported base metal sulphide occurrences in Southern Limburg and are a subject of follow-up investigations.

During the early Permian period, tectonic uplift caused widespread erosion, creating what is known as the Base Permian Unconformity (Ziegler, 1990a; Fig. 2.1-2). The limited presence of basalts from the Lower Rotliegend Group suggests that this uplift was accompanied by volcanic activity, similar to other parts of western Europe. By the Permian period, all continents had merged into the supercontinent Pangaea, which experienced arid conditions. At the same time, tectonic subsidence led to the formation of a vast east-west trending basin called the Southern Permian Basin (Van Wees et al., 2000; Bouroullec & Geel, 2025).

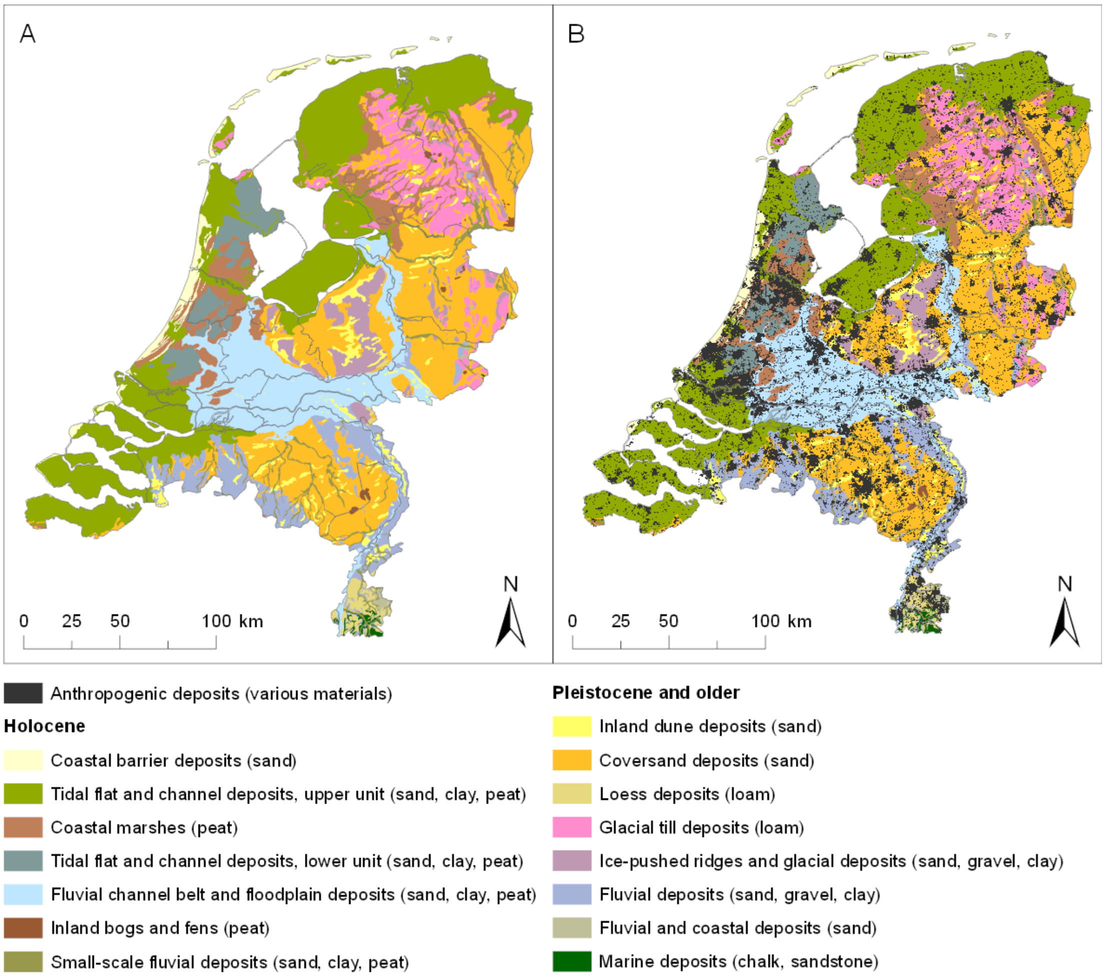


Figure 2.2-1. Geological map of the Netherlands. The map shows the deposits that compose the upper few metres of the subsurface. The map units represent (combinations of) formations, members, and beds. From: Dijkstra et al., 2019.

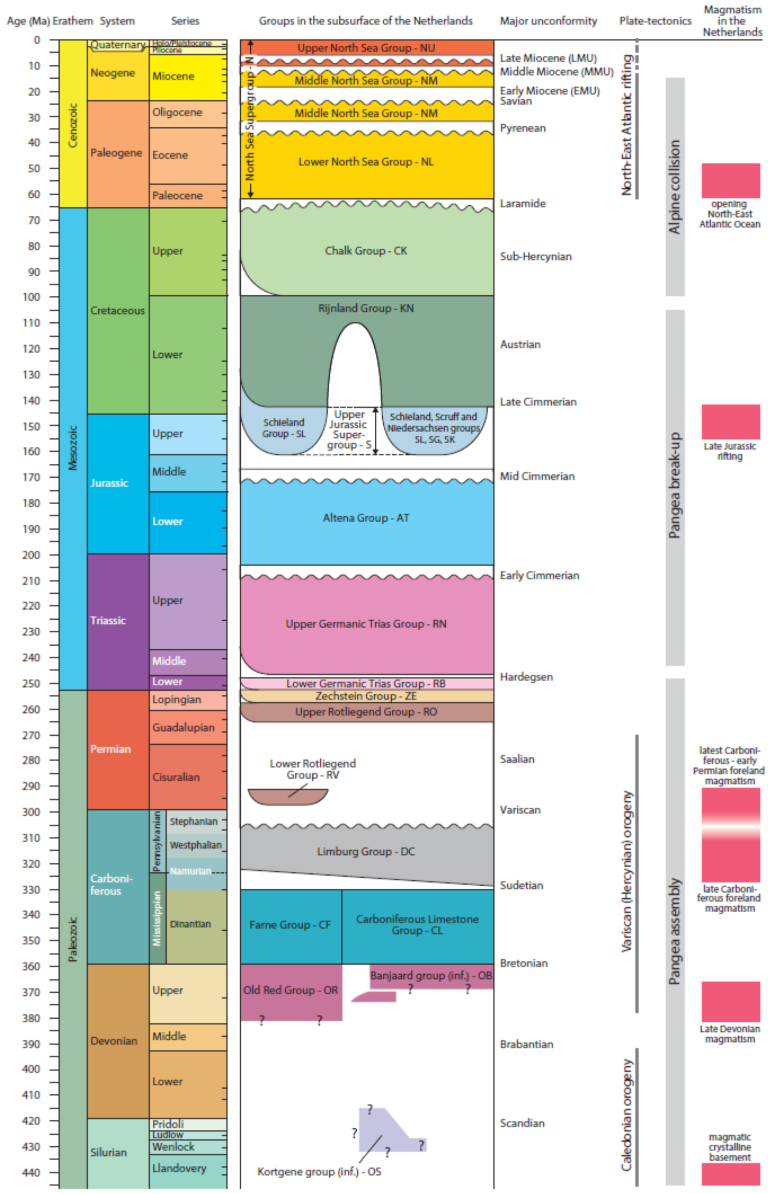


Figure 2.2-2. Generalized Palaeozoic-Cenozoic stratigraphy of the rock succession of the Netherlands. From: De Jager et al., 2025.

Initially, this basin accumulated clastic sediments and some evaporites (like halite) in a desert or playa-lake environment of the Upper Rotliegend Group. As the basin deepened, it was filled with cyclic evaporite sequences deposited in a peri-marine to marine setting. These sequences included carbonate, anhydrite, rock salt, minor amounts of bitter salt, and thin claystone layers within the Zechstein Group (Van den Belt, 2012). After these evaporite sequences were buried, younger tectonic processes and differential loading caused the thick salt layers to flow, forming impressive salt domes (diapirs) and salt ridges, some of which are over 3 kilometres in height. The thick evaporitic Zechstein sequence is the host of known magnesium salt occurrences and can be assessed for additional potential. At the basis of the Zechstein, a narrow shale layer is known to occur with elevated copper values (“the Kupferschiefer”), of which the copper-resource potential in the Netherlands remains to be assessed.

## 2.2.2 Mesozoic

During the Triassic period, the Netherlands experienced mild crustal extension, while other parts of northwestern Europe developed more complex rift systems. These rift systems are significant components of the Arctic-North Atlantic and Tethys-Central Atlantic-Gulf of Mexico rift systems, which contributed to the breakup of Pangaea during the Mesozoic and Cenozoic eras. In the Early Triassic, red-bed sandstones, siltstones, and claystones were deposited in lake and river environments, with some aeolian input forming the Lower Germanic Trias Group. During the Middle and Upper Triassic, a variety of silty claystones, evaporites, carbonates, and sandstones were deposited in alternating shallow marine, inland playa lake, and floodplain settings. In the Early to Middle Jurassic, the region was significantly affected by marine transgression, leading to the deposition of mudstones with occasional siltstone and sandstone successions in open marine basins. These mudstones have high organic-carbon concentrations, with the Posidonia Shale Formation being a particularly important hydrocarbon source rock.

It wasn't until the Late Jurassic period that the Netherlands was significantly impacted by the Atlantic rifting, leading to major tectonic changes. This rifting resulted in the formation of several large fault-bounded rift basins, such as the Dutch Central Graben, the Broad Fourteens Basin, the West Netherlands Basin, the Roer Valley Graben, and the Lower Saxony Basin. These structures generally follow older Palaeozoic trends. This rifting phase also triggered volcanic activity, including the creation of Zuidwal and Mulciber volcanoes, and the formation of related igneous dykes. The igneous activity may have initiated magmatic-hydrothermal activity and associated mineralization.

During the Late Jurassic rift phase, these basins were filled with sediments from the Schieland, Scruff, and Niedersachsen Groups, which consist of claystones with interlayers of carbonates, limestones, coals, and glauconitic sandstones. In the subsequent Early Cretaceous post-rift phase, thermal subsidence caused the basins to deepen further, leading to the deposition of argillaceous and marly sediments with occasional coarse-grained clastic layers. These basin structures played a dominant role in the geological development of the Netherlands throughout the rest of the Mesozoic era and into the Cenozoic era.

By the Late Cretaceous period, compressional forces from the Alpine orogeny began to invert some of the previously formed basins, adding to the structural complexity of the region. This period was also marked by rising global sea levels, as evidenced by younger sediments overlapping older sequences. Eventually, the entire area of the Netherlands was submerged under a shallow sea, leading to extensive marine carbonate deposition (Chalk Group). These carbonates are primarily composed of fine-grained, bioclastic, and marly limestones with chert concretions, as well as local deposits of marls and calcareous claystones. The up to 1500 metres of marine carbonates represent the only significant carbonate unit deposited in the area since the Triassic period.

## 2.2.3 Cenozoic

### 2.2.3.1 Palaeogene and Neogene

In the earliest Cenozoic period (Palaeogene), the Alpine orogeny caused progressive compression, reactivating older structural elements (Michon et al., 2003). This led to basin inversion and erosion of Cretaceous sediments in some areas, while other regions experienced subsidence, accommodating sedimentation in the North Sea Basin. During the Palaeocene and Eocene epochs, the Lower North Sea Group saw the formation of several interbedded layers of carbonate-rich, glauconite-bearing sand, silt, and clay (Landen, Dongen, Tongeren, Rupel, and Veldhoven Formations). These successions resulted from various sedimentation cycles in a marine environment along the edge of the North Sea Basin, where water depths reached up to 500 metres. Some of the clay units contain pyrite, phosphorite nodules, and septarian carbonate concretions. The Rupel Formation (Boom Clay) from this period is particularly important as it acts as a natural barrier to groundwater flow.

In the late Oligocene epoch, the main phase of rifting began behind the Alpine orogeny, leading to the formation of the European Cenozoic Rift System, including the Lower Rhine Graben and the Ruhr Valley Graben (Ziegler, 1994; Ziegler et al., 1995). This rifting caused a significant increase in subsidence rates and the deposition of large amounts of sediments along the margins of the North Sea Basin. The marine sediments from this period mostly consist of glauconite-bearing, fine- to medium-grained sands along the basin margins, and sandy silts and clays in the deeper parts of the Ruhr Valley Graben and North Sea Basin. The fluvial series are composed of medium- and coarse-grained sands. Towards the southeastern margins of the Ruhr Valley Graben, lignite intercalations occur, which are still being mined in Germany today. At the end of the Pliocene epoch, the Baltic River System (Eridanos) deposited sediments in the eastern part of the onshore and offshore sections, as indicated by the shelf, delta, and fluvial sediments of the Peize Formation and its offshore equivalents. River systems like the Baltic River System may have contributed heavy minerals to the sediment deposition, which will be assessed by the program.

#### 2.2.3.2 Quaternary

The shallow subsurface geology of the Netherlands is illustrated by means of four transects that are oriented WSW-ENE or perpendicular to the Quaternary fault lines (Fig. 2.2-1). The transects shows the geological units of the Upper North Sea Group that occur up to a depth of 500m. This stack comprises several formations separated by unconformities that mostly formed as a result of fluvial and glacial erosion events. Towards the end of the Pliocene and the beginning of the Quaternary, the intensity of cold climate phases increased significantly, leading to a strong increase in sediment supply from higher topographic areas to the North Sea Basin. This resulted in the formation of a thick depositional sequence, reaching over 1200 metres in the central parts of the North Sea Basin.

During the first 1.5 million years of the Quaternary, the Baltic River System was the main sediment source for the southern North Sea Basin, filling it with fluvial (Peize Formation) and marine sediments (Maassluis and Yarmouth Roads Formations), causing the basin to shallow. In the last million years, the intensity and duration of cold climatic phases increased, leading to major expansions of the Fennoscandian ice sheet. This caused the Baltic River System to decline, allowing the Rhine-Meuse River System to expand and deposit coarse-grained fluvial sands (Waalre and Sterksel Formations). These sediments are significant construction-sand resources. They also bear heavy minerals containing tantalum, titanium, tungsten, and rare-earth elements (REE).

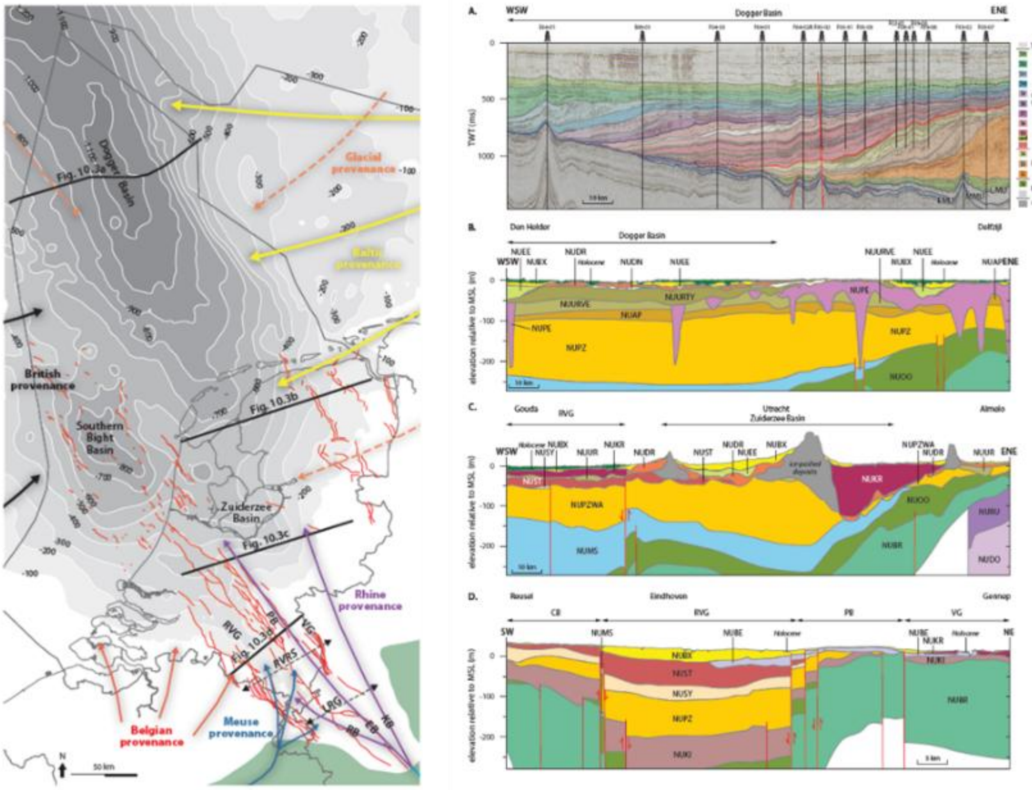


Figure 2.2-3. Left: Depth map of the base of the Quaternary (isolines: depth below MSL) with main tectonic elements, faults (in red), and sediment-transport pathways (arrows). Right: Four sections (a-d, see map) representative of the Quaternary stratigraphic succession of the North Sea region in the on- and offshore areas of the Netherlands. From: Busschers et al., 2025.

During the last 500,000 years of the Quaternary, the Fennoscandian ice sheets repeatedly reached into the North Sea region, covering the northern part of the Netherlands. This resulted in deeply eroded subglacial valleys that were subsequently filled with sand and clay, and ice-pushed ridges like the Veluwe and Utrechtse Heuvelrug. In the last ice age, ice-sheet expansions were confined to the northern Dutch offshore. Coarse-grained sediments from the Rhine, Meuse, and Scheldt rivers were deposited in both the Dutch onshore and offshore regions (Doggerland) during periods of low sea level when the North Sea was dry land. Fluvial sedimentation from these rivers alternated with marine and local aeolian deposits. At the end of the last ice age and the beginning of the Holocene, around 12,000 years ago, the sea level rose, flooding the North Sea Basin. This led to the formation of a complex of peat, marine, and fluvial deposits. Large volumes peat were mined from Roman times up to the mid-20th century, mainly for fuel. In built-up areas, the natural Holocene sequence is overlain by anthropogenic deposits that can reach considerable thicknesses.

# 3 Raw Materials Production

## 3.1 Mineral resource production in the Netherlands

In recent history, raw materials production in the Netherlands has been focused primarily on energy resources such as peat, coal, oil, and gas, as well as construction materials like limestone, gravel, sand, and clay. An overview of current extraction levels of these mineral resources, including those in the North Sea, is provided in Table 3.1-1.

Three CRM candidates have been identified and are being produced in the Netherlands (Table 3.1-2):

1. **Silica sand**: Extracted in South Limburg, this high-purity quartz sand (silicon dioxide) could potentially be used for silicon metal production, depending on technical feasibility, source material quality, and economic viability.
2. **Magnesium salt**: Produced through solution mining of bischofite-carnallite deposits as a potential raw material for magnesium-metal production.
3. **Metallurgical coal**: Based on information from the Dutch coal mining era, which ended in the 1970s, significant resources of metallurgical coal (cokes) for steel production are believed to be present in the subsurface of South Limburg.

Table 3.1-1. Recent production figures for the extraction of mineral resources in the Netherlands

| Mineral Resource | Quantity | Unit | Extraction period | Source |
|---|---|---|---|---|
| Natural gas | 10.2 | billion Nm3 | 2023 | 1 |
| Petroleum | 385.1 | 1000 Sm3 | 2023 | 1 |
| Gas condensate | 110.7 | 1000 Sm3 | 2023 | 1 |
| Rock salt | 4.69 | Mt | 2023 | 1 |
| Magnesium salt | 190 | Kt | 2023 | 1 |
| Gravel | 5.01 | Mt | 2021 | 2 |
| Clay | 1.86 | Mt | 2021 | 2 |
| Concreting and masonry sand | 15.57 | Mt | 2021 | 2 |
| Other industrial sand | 1.56 | Mt | 2021 | 2 |
| Filling sand | 77.38 | Mt | 2021 | 2 |

Source 1: Ministry of Climate Policy and Green Growth, Annual Report 2023
Source 2: CBS 2024

For surface mineral deposits, models are available through Delfstoffen Online, a minerals information system on DINOloket that provides insight into the occurrences of sand, gravel, and clay on a national scale. It is based on detailed subsurface models that cover the Netherlands to a depth of 50 metres below ground level. The Minerals Information System (DIS) is a policy and decision-support model that covers the designated sand-extraction zone of the North Sea and provides insight into the quantity and quality of the available sand resources up to 12 metres below the seabed. These models are used to constrain future resource calculations for surface minerals.

Several studies have been conducted on high-purity silica sand, indicating where it can be found and defining its quality and volumes, though these are rough estimates with a high degree of uncertainty. Similarly rough resource estimates have been made for coal deposits less than 1,500 metres below the surface. Nedmag, the only magnesium-salt producer in the country, estimated its total magnesium-salt volumes at their Veendam production concession at 3,500 million m³ (Nedmag production plan 2013).

Table 3.1-2. Estimates of raw material resources based on local geological models. The estimates do not take into account which volumes would realistically be recoverable. The North Sea is excluded in the estimates of stocks of sand and gravel.

| Mineral Resource | Quantity | Unit | Source |
|---|---|---|---|
| Gravel | 12 | $km^3$ | Van der Meulen et al 2005 |
| Concrete and masonry sand | 520 | $km^3$ | Van der Meulen et al 2005 |
| Silica Sand | 6 to 15 | $km^3$ | Van der Meulen et al 2009 |
| Coal | 12.99 | Mt | Van Bergen & Koster 2025 |
| Magnesium salt | 3.5 | $km^3$ | Nedmag 2013 |

# 3.2 Potential for future production

The Netherlands being a densely populated country, where mining operations of any kind face societal resistance. Historic peat excavations (as well as extensive land reclamations) have left an enormous impact on the surface environment, on the one hand exposing large tracts of arable land, on the other, the required dewatering has caused significant land subsidence that continues to date. More recently, coal production in Limburg left scars in the landscape and caused environmental pollution of water, soil, and air (SodM, 2021). Assuming that conventional, standalone ore deposits will not be identified in the near future, any economic CRM potential will either be restricted to co-production with other activities in the subsurface or be facilitated by innovative mining methods such as solution mining and in-situ recovery.

## 3.2.1 Co-production

Considering the scale of industrial production, handling, processing, storing, and trading of raw materials in the Netherlands, there are several opportunities to develop CRM production in tandem with existing activities. Some examples of potential CRM co-production with other industrial processes are listed in Table 3.2-1 and will be discussed in more detail in Chapter 5.

Table 3.2-1. Examples of potential co-production of CRM with existing subsurface activities

| Industrial process | Potential CRM co-production |
|---|---|
| Construction sand and gravel | Heavy minerals containing niobium, tantalum, titanium, tungsten, and rare earth elements |
| Coastal sand suppletion | Heavy minerals containing niobium, tantalum, titanium, tungsten, and rare earth elements |
| Oil, gas, and geothermal brines | Lithium, strontium, magnesium, boron |
| Bottom ash from waste incinerators | Copper, aluminium, nickel, other |
| Wastewater treatment | Phosphorus |
| Zinc production (Nyrstar Budel) | Germanium |

Since 2007, the Netherlands has seen a significant development from the identification of a small inventory of prospective areas with no active geothermal systems, to 27 realized geothermal systems at 1-1-2022. Nineteen of the 27 systems were in operation by 2021 (Mijnlieff et al., 2025). With increasing development of geothermal heating sourced from deep aquifers, the possibility arises to extract metal ions from solution, for which lithium would be a prime candidate, followed by magnesium, strontium, boron, and others. Currently, a joint project to delineate geothermal heat potential in the Netherlands (SCAN) is underway to accelerate the development of geothermal energy projects.

In Germany, the company Vulcan Energy Resources has started producing lithium by direct lithium extraction (DLE) from deep geothermal brines in the Upper Rhine Valley. They are in the process of developing geothermal energy as a co-product of lithium production, for both the lithium-extraction process itself as well as district heating. A similar case could be made for producing lithium and other CRM in combination with geothermal heat from brines in the Netherlands, albeit that data coverage of lithium concentrations in brines is currently insufficient to examine its potential for economic extraction (Sanjuan et al., 2022), which will be discussed in more detail below.

Another opportunity for co-production exists with mineral sands, which in places comprise a substantial fraction of the sand and gravel deposits that are extracted at industrial scales, as discussed above. A conservative “back of the envelope” calculation based on total annual sand production of about 90 million tonnes, containing 1% heavy minerals with compositions equivalent to those listed in Table 3.2-2, could hypothetically yield the following: 14,000 tonnes of Ti from rutile (60% Ti) and ilmenite (32% Ti) – more than double current annual imports (5.75 kt), according to World Bank data – 1.600 tonnes of Hf from zircon (4.7% Hf), 450 tonnes of total rare-earth oxides from monazite (50% TREO), and 55 tonnes of boron from tourmaline (3.1% B). While this example is speculative, without considering the technological challenges of recovery or mineral processing, it highlights the geological potential of mineral sands as a significant source of CRM, within existing volumes of sand production, which is currently not exploited.

Table 3.2-2. Composition of dark beach sands (adapted from Schuiling et al., 1985).

| Mineral | Weight % |
|---|---|
| Light fraction | 72.1 |
| Epidote | 1.7 |
| Garnet | 16.3 |
| Rutile | 0.9 |
| Zircon | 3.5 |
| Ilmenite | 3.3 |
| Monazite | 0.1 |
| Magnetite | 0.1 |
| Tourmaline | 0.2 |
| Other | 1.9 |

### 3.2.2 Technological innovation

The global surge in lithium exploration has spurred several parties to develop innovative ways of extracting lithium from brines through a range of processes collectively known as direct lithium extraction, including ion-exchange, selective adsorption, solvent extraction, and membrane technologies. In their race to commercial production, DLE developers have greatly improved the processing efficiency, being able to economically recover lithium down to about 30 mg/kg Li concentrations in brine (e.g., Volt, E3 Lithium). Provided that suitable brine compositions of adequate volume can be identified in the Netherlands, DLE would enable the commercial extraction of lithium from these brines, whether in combination with other CRM or geothermal heat, or standalone (Sanjuan et al., 2022).

Another noteworthy technological development is the progress of in-situ recovery (ISR), which has been applied to salt and uranium mining for several decades but is being expanded into copper-oxide and most recently also copper-sulphide extraction. Rather than physically extracting ore and waste from conventional open-pit or underground mines, some commodities are amenable to underground dissolution and extraction. A solvent or lixiviant is pumped into the orebody through injection wells, selectively dissolving ore minerals in situ, after which the pregnant solution is pumped to the surface through extraction wells for metal recovery. Residual water and dissolved salts are pumped back underground through the injection wells (Fig. 3.2-1).

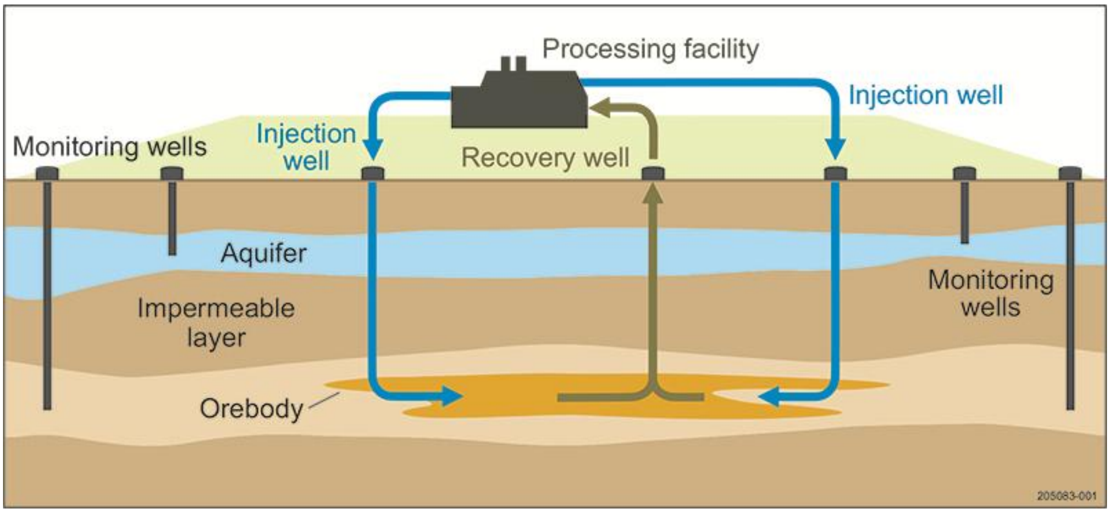


Figure 3.2-1. Schematic cross-section of in-situ recovery process. Source: Government of South Australia

In the Netherlands, the ISR process could circumvent three major challenges with respect to resource development: depth of mineralization, low metal grades, and the lack of surface real estate for conventional mining operations, while other competing subsurface activities might be recast as potential co-production opportunities. Solution mining of salts, which is a similar process that just uses water as the solvent, is already well established within the country for large-scale rock-salt operations as well as precisely targeted magnesium-salt layers. Advanced drilling technology required for precise targeting of deep horizons has also been proven over several decades of hydrocarbon exploration and production. The combined knowledge, expertise, and operational excellence in the exploration and production of deep-seated resources is well positioned to support the implementation of ISR in the future, provided that amenable mineral deposits can first be identified.

# 4 Economic, Legal, and Environmental constraints

## 4.1 Overview

The raw-materials sector is a mature commercial industry, driven by value creation along the entire supply chain. It is important to understand economic considerations all along this value chain, from intrinsic value of material in the ground, to capital requirements for business development, cost-efficient operations, and trade, constituting a value-generating market proposition. Similarly, value-destructive risks must be understood, including the probability of these risks to occur and their material impact. These risks can be of a technical geological, engineering, or economic nature, but are often also related to legal, environmental, and social concerns.

As an illustration, conventional mining in the Netherlands ended 50 years ago with the closure of the last coal mine in Limburg in 1974. The closure was mostly driven by economic considerations including excessive cost of underground mining of a relatively low-value material, in economic contrast to developing low-cost production sites abroad. Around the same time, the discovery and exploitation of the Groningen gas field shifted national energy interests northwards. Closure of the coal mines did leave 75.000 people without a job, one third of whom would not be adequately compensated, and contaminated sites were not fully reclaimed (Gales & Hölsgens, 2017). For any future development of CRM extraction to be successful, the lessons from such past events must be considered and addressed.

## 4.2 Economic considerations

This section will give a brief introduction regarding the basic economic concepts of mineral resource development, from intrinsic value of mineral exploration to capital requirements for project development, production costs, and revenues. It provides the reader with further understanding of the main development steps of the complete cycle of mineral extraction, the applied terminology, the way to materially classify resources, and how all the above relate to the geological CRM potential in the Netherlands.

### 4.2.1 Mineral resources and classifications

A natural resource is a material source of wealth that occurs in a natural state and holds intrinsic economic interest and potential value. A large group of natural resources is renewable (like timber, agricultural resources, renewable energy), whereas another group of natural resources is non-renewable, like oil or mineral resources, i.e. they cannot be replaced by natural processes within human time scales.

A generalized definition of a mineral resource is an elevated (anomalous) concentration of one or multiple minerals that contain chemical elements of interest, predominantly metals, or have particular physical properties, e.g. for use in construction. The minerals are potentially feasible to extract from the subsurface and processed towards a concentration or purification stage. Several activities are required to initially discover the location of the mineral resource, quantify the potential mineral value, and to subsequently assess the viability of extracting the resource. These activities are associated with exploration, occur at the front-end of the mining cycle, and are described in more detail below.

In order to materially classify (i.e. express value of) identified mineral resources, most exploration and mining companies are governed by mineral resource classification guidelines for financial reporting, based on statutes, regulations, and industry best practice norms, depending on the country where the company is registered or has a stock exchange listing. Examples are the Canadian Institute of Mining, Metallurgy, and Petroleum (CIM) classification under National Instrument 43-101 (NI 43-101: Standards of Disclosure), the Australasian Joint Ore Reserve Committee Code (JORC Code), and the Pan European Reserve and Resources Reporting Committee (PERC Standard), all of which set out minimum standards, guidelines and recommendations for public reporting of exploration results, mineral resources and mineral reserves. The strict classification schemes provide a structure to material disclosure, i.e. companies are guided on expressing value to external stakeholders, particularly shareholders, investors, and mining authorities.

A mineral resource estimate is based on the mineral content, grade, tonnage (shape, volume, and density) and physical properties. In the above examples of resource classification schemes there are different classified resource categories based on the level of geological knowledge. With increasing confidence level (i.e. increasing understanding of what is in the ground) the resource classification progresses from unclassified, to Inferred Resource, to Indicated Resource, to a Measured Resource (Figure 4.2-1).

Upon completion of a feasibility study, including a mining method, mine plan, production schedule, plant design, and costing, the extractable portion of a mineral resource will be defined as a Proven and/or Probable Mineral Reserve (Fig. 4.1-1).

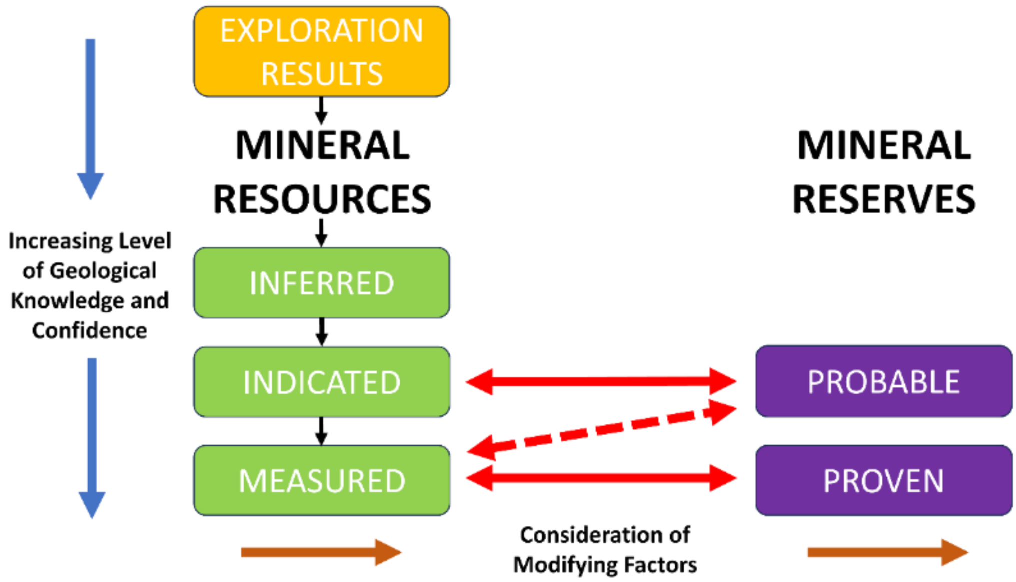


Figure 4.2-1. Schematic overview of the resource classification scheme.

### 4.2.2 Mineral project development from concept to mine closure

The main objective of mineral exploration is to identify a mineral resource that is potentially economic to extract. The main objective of mining is achieving a cost-effective extraction of an economically viable mineral resource. Although the two objectives present a different business rationale, they are obviously related, and they occur along a complex development process, that typically takes about two decades from the initial idea to production.

Along this pathway, several development decisions are required to push a project towards increasing feasibility and ultimately extract the identified resource, while considering all necessary societal, economic, environmental and geopolitical factors, while preparing the actual physical activities of exploration and engineering. The flow diagram below (Figure 4.2-2) indicates these major stages from a conceptual model all the way to mine closure and rehabilitation of the land.

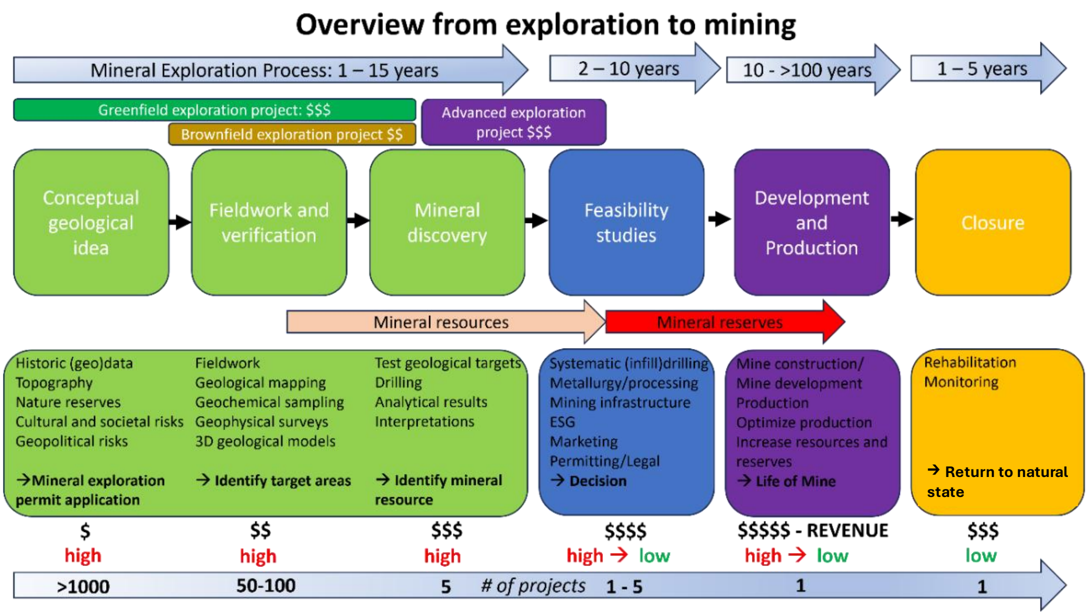


Figure 4.2-2. Overview of the various stages of development of a mine.

On the left side of the flow diagram, greenfield or grassroots exploration in areas without known mineral resources is targeting relatively large areas, testing concepts, and aiming to vector towards areas with an elevated probability of making a discovery. The targeted areas need extensive geological investigations, which take time, and therefore imply execution risks and require considerable capital investments. The probability of success in identifying a new mineral resource is small (<1%). Brownfield exploration or near-mine exploration occurs in areas where mineral resources are known from historic or existing production. In theory these areas have an advanced level of understanding, which could increase the discovery potential. Pre-existing infrastructure can positively contribute to the economic and technical viability of the project.

Once an initial mineral resource has been identified, a phase of “advanced exploration” is entered which focuses progressively on further defining the size, grade, and quality of the identified resource while understanding risk factors that potentially affect the project, in support of engineering considerations at increasing confidence level and to work towards investment decisions on subsequent steps ultimately until feasibility is confirmed. A positive outcome of the definitive feasibility study is often used as the base for a mining permit application.

The most capital and therefore risk-intensive phase is the actual development of the mine before production can commence. The ultimate duration of production, i.e. the "life-of-mine," depends on the established mineral reserves, potentially newly identified resources during production, the production capacity, and supporting ancillary infrastructure, regulatory constraints, and evolving market conditions. Most mining companies try to expand their resources with exploration activities in and around the mine to extend the life-of-mine, to benefit from additional production in the preexisting capital infrastructure. Production rates can be optimized or expanded by improving the mining infrastructure and processing capacity.

A mine closure scenario will become reality when future production is projected to occur at a loss or when reserves are exhausted. A detailed mine closure plan, including a reserved budget, is generally a requirement for the initial mining permit application.

## 4.3 Current legal and policy domain for CRM extraction in the Netherlands

This section provides an overview of the national legal and policy framework for CRM in the Netherlands. While not exhaustive, it serves as a foundation for further analysis in subsequent stages of the project. Despite the low likelihood of discovering viable CRM deposits in the Dutch subsurface, understanding national legislation is essential.

In the Netherlands, the legal framework for mining activities is established by the Mining Act (MBW) and its subsidiaries, the Mining Decree (MBB), the Mining Regulation (MBR), and the Environmental & Planning Act ("Omgevingswet", for surface mineral resources). The Mining Act applies to raw materials found at depths of 100 metres or deeper (MBW Art 2, 2). The Ministry of Climate Policy and Green Growth is the competent authority, while the State Supervision of Mines acts as the independent mining regulatory authority. For depths up to 100 metres, the province is the competent authority.

Article 3 of the Mining Act states that minerals are the property of the State. This property can be transferred to the holder of a production license, subject to further regulations and arrangements.

Article 1a of the Mining Act defines minerals as substances of organic origin present in the subsoil, in a concentration or deposit formed naturally, in solid, liquid, or gaseous form, excluding marsh gas, limestone, gravel, sand, clay, shells, and their mixtures.

Article 1 also outlines the common stages in the search for minerals:

- Reconnaissance survey: A survey that does not use a borehole to detect minerals or gather additional data about them.
- Exploration: A search for minerals or additional data using a borehole.
- Production: Extracting minerals from the subsoil using a borehole, tunnel, shaft, or other subsurface work, excluding samples or formation tests.

For the exploration and production phases, an exploration or production license must be obtained before commencing work. For reconnaissance surveys, a report must be submitted before starting the work. Health and safety for people and the environment are essential elements in the license and survey grants. Risks of induced ground motion and land subsidence must be described. Depending on the location and environmental impact of the mining operation, additional licenses may be required under the Environment and Planning Act. If negative effects on European protected Natura 2000 areas are anticipated, an Environmental Assessment is necessary.

Article 24 MBW defines a special license for exploration or production of minerals for pure scientific research or in line with central government policies. In some cases, CRM can be co-produced, such as the potential extraction of lithium from geothermal water. Articles 24x and 24am state that in geothermal energy production, co-produced minerals that cannot be economically produced as standalone mining activities can be harvested under the geothermal license. Further analysis may reveal similar arrangements for CRM co-produced with coal, gas, oil, and salt production.

For all surface installations in the exploration and production phases, the Environmental & Planning Act (Omgevingswet) applies. Any structure erected temporarily or semi-permanently for the project must be licensed and approved by local authorities. Due to significant subsidence and seismicity caused by gas production and coal mining, society and policy are sensitive to the potential aftereffects of mining activities. Thorough evaluation of these issues is a prerequisite for license applications, and CRM projects will be no different.

Under the Environmental & Planning Act, superficial mineral extraction is licenced by Ministry of Infrastructure and Water Management when undertaken in state waters, and by the provinces in all other cases. The licensing authorities will consider the environmental impact and weigh extraction against other land-use functions. Given the nature of the surface-excavation activities, safety of operations is less stringently regulated than deeper operations that are governed under the Mining Act.

# 4.4 Responsible mining

## 4.4.1 Mining and ESG

Over the past centuries, the international mining industry has earned itself a questionable track record when it comes to environmental, social, and governance (ESG) performance. Economically, the impact of mining has largely been positive on a global scale, providing metals and other raw materials for construction, urban development, and technological revolutions, contributing to higher standards of living for most. Its greatest challenge, however, is that the negative impacts are borne locally in the communities and environments around the mine site, while owners, traders, and consumers, often in faraway lands, enjoy the benefits.

While there is a growing movement throughout the industry towards more sustainable practices, there remains plenty of room for improvement. One of the organisations leading the way in this respect is the Initiative for Responsible Mining Assurance (IRMA), which captures the current state as follows: “Mining operations are complex and disruptive, and we have a collective responsibility for reducing their impacts. While many sectors rely on mining, from jewellery and cosmetics to travel and agriculture, the energy transition has heightened our reliance on mining, particularly related to the electrification of vehicles and the production of renewable energy. While responsible sourcing of all mined materials is essential, our efforts to address the climate crisis and create a more sustainable future have further magnified the importance that mining is done responsibly.”

The International Council on Mining and Metals (ICMM) definition on what responsible mining is supposed to be: “Responsible mining refers to practices that prioritise environmental stewardship, social responsibility, and ethical governance throughout the entire mining lifecycle. This includes avoiding, minimising, and mitigating environmental impacts, respecting human rights, ensuring worker safety, engaging with communities, and fostering long-term social and economic development.”

### 4.4.2 Mining impact in the Netherlands

While small-scale mineral extractions like sand pits and quarries usually meet with local resistance only, larger mining operations in the Netherlands have had significant environmental and social impacts. The after-effects of coal mining in Limburg, which ended in 1974, are still noticeable, including sink holes and surface rebound after flooding of old mine shafts. Production of gas from the Groningen Field had to be terminated because of the damage and social unrest caused by induced seismicity. Lessons learned are described in reports by OVV (2014) and PCEG (2023), which are worth consulting when considering CRM exploration activities and potential extraction while navigating their ESG implications.

### 4.4.3 Regulatory HSSE framework

The Dutch regulatory framework for Health, Safety, Sustainability, and Environment (HSSE), and Occupational Safety and Health (OSH) includes several laws and regulations that pertain to mining operations and minerals supply chains. These regulations are designed to protect workers and ensure safe and healthy working conditions not only in the Netherlands, but also in supplying countries. The Working Conditions Act (Arbeidsomstandighedenwet) mandates the preparation of an OSH risk assessment. The Working Hours Act (Arbeidstijdenwet) regulates working hours, while the Minimum Wage Act ensures fair compensation. Child labour laws, such as the Child Labor Due Diligence Act (Wet Zorgplicht Kinderarbeid), aim to prevent child labour and ensure due diligence in supply chains.

### 4.4.4 Sustainability standards

The energy transition is driven by the recognition for the need of climate action, a cause committed to by nations worldwide since the adoption of the Paris Agreement in 2016. The Dutch contribution to the Paris Agreement is legally embedded in the Climate Act (Klimaatwet, 2019), which mandates a 49% reduction in $CO_2$ emissions by 2030 (compared to 1990 levels) and the achievement of $CO_2$-free production of electricity by 2050. Additionally, the Dutch legislative proposal for the implementation of the EU’s Corporate Sustainability Reporting Directive (CSRD) and Corporate Sustainability Due Diligence Directive (CSDDD) has been submitted to Parliament in January 2025. These directives are part of the European Green Deal and require a broader set of large companies and listed SME to evaluate and report on sustainability (Heinen, 2025).

The Netherlands Commission for Environmental Assessment has extensive experience in applying environmental and social impact assessments (ESIA) to the extractive sector. Their work ensures that potential societal and environmental impacts are considered in major decision-making processes (Netherlands Commission for Environmental Assessment, 2019). Furthermore, addressing the negative impacts of extraction and processing is one of the five key strategies outlined in the National Raw Materials Strategy (EZK, BZ, and I&W, 2022). This strategy emphasizes the importance of sustainable practices in securing the availability of critical minerals and metals necessary for the energy transition, while minimizing environmental and social impacts.

# 5 Exploration Themes

The national exploration program is structured around six themes, categorized by mineral systems (Table 5.1-1). Each theme is subdivided into known or probable mineral occurrences and potentially economically interesting deposits. Based on current knowledge, certain materials from the latest EU CRM list can be excluded from further investigation for their known absence in the Dutch subsurface. For instance, there are no known occurrences of bauxite (aluminium ore), graphite, or feldspar (granite) in the Dutch subsurface, making these materials irrelevant for further study. Nickel and platinum group elements can also be excluded because they are found in mafic or ultramafic rock types, which have never been encountered at accessible depths in the Netherlands and are geologically very improbable to be found at all. For most others, the potential may be small but non-zero, warranting further investigation. Additionally, mineral-like waste products such as steel slags and incineration ashes will be investigated for their CRM potential as these are commonly used as aggregate or construction materials, even if they are formally not a part of the subsurface geology.

The six themes guiding the national exploration program have been defined as follows:

1. Mineral Sands
2. Iron, Manganese, and Phosphorus Concretions
3. Waters & Brines
4. Sulphides
5. Mined Deposits
6. Industrial & Municipal Waste products

## 5.1 Mineral Sands

Hf Nb Ta Ti W REE

### 5.1.1 Background

Much of the near-surface geology of the Netherlands, including the Dutch extents of the continental shelf below the North Sea, consists of unconsolidated sediments like gravel, sand, and clay. Some of these materials are accessible for excavation and dredging, and are used as construction materials, aggregates, or for coastal sand suppletion.

Through erosion by glacial, fluvial, and marine processes, rocks are broken down into mineral grains. Softer minerals like micas and feldspars break down more easily than quartz, resulting in varied grain sizes and compositions. These grains are subsequently transported while being sorted by density, grain size, and morphology, before they are deposited as gravel, sand, silt, or clay in sedimentary basins. In coarse-grained fluvial and marine deposits, the sand fraction may also contain concentrations of heavy minerals.
In this way, nature pre-processes and concentrates these materials, turning them into potential mineral resources that would otherwise require significant amounts of energy for blasting, excavation, hauling, comminution, and recovery in mining operations. Even so, the heavy mineral fraction receives little attention from sand and gravel producers.

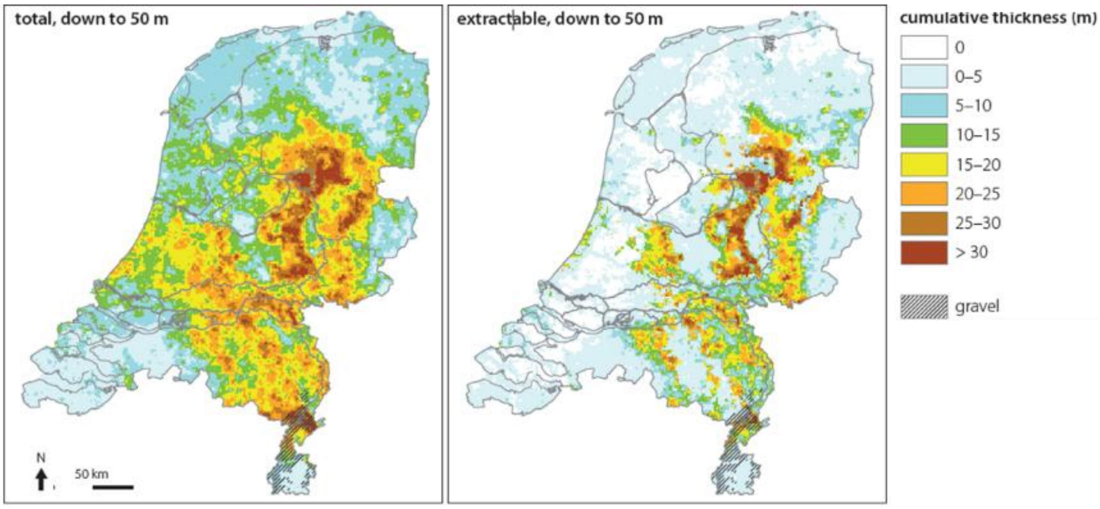


Figure 5.1-1. Resources of coarse sand and gravel down to 50 m below the surface, based on a nationwide 3D lithological model (Van der Meulen et al., 2005, 2007, 2025).

Heavy mineral enrichments have been identified along the North Sea shoreline from North Holland to the Wadden Islands (Schuiling et al., 1985, de Meijer et al., 1989). These mineral sands comprise garnet, amphibole, epidote, iron oxides, ilmenite, rutile, cassiterite, monazite, columbite-tantalite, barite, and zircon, which are of potential interest for economic extraction of their CRM contents (Table 5.1-1), warranting further investigation into their abundance and distribution.

Table 5.1-1. Common heavy minerals in sediments, by increasing specific gravity. Potential CRM sources in bold. Source: Mindat

| Mineral | Sp. Gravity | Hardness | Composition |
|---|---|---|---|
| Tourmaline | 3.1 | 7 | $NaMg_3Al_6B_3Si_6O_{27}(OH,F)_4$ |
| Topaz | 3.6 | 8 | $Al_2SiO_4(P,OH)_2$ |
| Garnet | 3.8 – 4.2 | 7 – 7.5 | $(Fe,Mn,Mg)_3Al_2(SiO_4)_3$ |
| Corundum | 4.0 | 9 | $Al_2O_3$ |
| **Rutile** | **4.2 – 4.3** | **6.5** | **$TiO_2$** |
| Chromite | 4.3 – 4.6 | 5.5 | $FeCr_2O_4$ |
| **Ilmenite** | **4.3 – 5.5** | **5.5** | **$FeTiO_3$** |
| **Xenotime** | **4.4 – 5.1** | **4.5** | **$YPO_4$** |
| **Zircon** | **4.4 – 4.8** | **7.5** | **$(Zr,Hf)SiO_4$** |
| Magnetite | 4.9 – 5.2 | 6 | $Fe_3O_4$ |
| **Monazite** | **4.9 – 5.3** | **5.5** | **$(REE,Th)PO_4$** |
| Pyrite | 5.0 | 6 - 6.5 | $FeS_2$ |
| **Columbite** | **5.4 – 6.4** | **6** | **$(Fe,Mn)(Nb,Ta)_2O_6$** |
| **Scheelite** | **5.9 – 6.2** | **5** | **$CaWO_4$** |
| Cassiterite | 6.8 – 7.0 | 6.5 | $SnO_2$ |
| **Wolframite** | **7.1 – 7.5** | **4.5** | **$(Fe,Mn)WO_4$** |
| Gold | 15.6 – 19.3 | 2.5 | Au |

Heavy minerals being more resistant to weathering than micas and feldspars become concentrated during transport and deposition in high-energy environments. While soft minerals transform into clay, heavy minerals are mainly found in the fine-sand fraction. Griffioen et al. (2016) highlighted the importance of heavy minerals as provenance indicators that survive long and destructive transport processes. Heavy minerals often contain significant amounts of uranium and thorium, which can be measured by radiometric sensors and helps to determine the heavy mineral contents in sediments. Field measurements of gamma-ray emissions can assist in identifying and quantifying the heavy mineral fraction.

In fluvial systems, heavy minerals are concentrated in the active stream bed, on point bars, and in channel deposits, rather than overbanks that tend to accumulate clay and silt fractions under lower-energy conditions (Fletcher et al., 1992). Heavy minerals have been identified in the river systems in the Netherlands, related to the present-day Rhine, Meuse, and Scheldt river systems to the south and east, as well as the Pleistocene Baltic River System that drained its hinterland of the Baltic Shield and Fennoscandia to the northeast (Huisman & Klaver, 2007).

In the Dutch marine environment, heavy-mineral sorting resulting from tidal and wave action primarily occurs in two zones along the shoreline, involving separate sedimentary processes (Koomans, 2004). One location for placer formation is at the depth of closure (below the wave base), where even with low concentrations of heavy minerals in the original sediment, selective sediment-transport processes can concentrate them. Heavy minerals can also accumulate quickly in the inner surf zone. Thus, the inner surf zone acts as a natural sorter concentrating valuable minerals (Figure 5.1-2). By removing the upper layer of heavy minerals from the inner surf zone, sediments are sorted again, and new placers form until the bulk sediments are depleted of heavy minerals (Koomans, 2000).

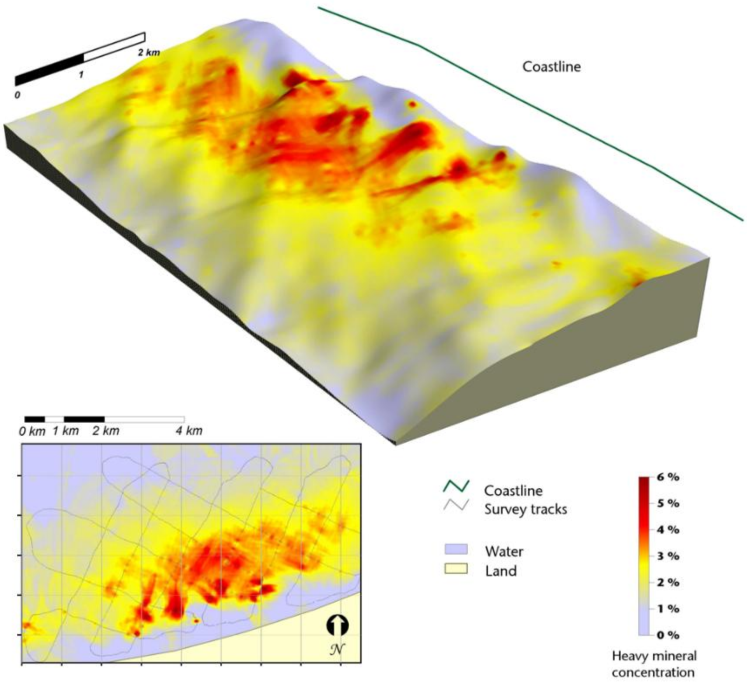


Figure 5.1-2 Example of mapping heavy mineral accumulation in beach sand using radiometric sensing, as presented by Medusa Radiometrics BV.

### 5.1.2 Resource potential

Heavy minerals often contain valuable elements, including several CRM such as titanium, tungsten, and rare earth elements (Table 5.1-1). In several countries, mining these sediments provides significant revenue. The economic value of heavy-mineral concentrations depends on the composition and accessibility of the layers where enrichment occurs. While the occurrence of significant heavy-mineral enrichment has been identified in areas along the coast of the Netherlands, systematic analyses of total metal content and extractable volume have not been conducted to date. Similarly, the total heavy-mineral contents and their bulk chemical compositions in fluvial sediments excavated commercially inland for aggregate materials remain to be investigated.

### 5.1.3 Suggested research activities

**Sampling fluvial sand and gravel at recent or active excavations**

- Collect samples from sand or gravel pits at various locations, ensuring a representative analysis.
- Use dense-media separation to extract and analyse the heavy mineral fraction from the bulk material.
- Conduct mineralogical and chemical analyses of the heavy mineral fraction to identify valuable minerals and assess their concentrations.

**Sampling beach sand in areas of elevated heavy mineral contents**

- Identify and target specific beach areas known for high concentrations of heavy minerals.
- Collect samples from various locations within the active operations to ensure a representative analysis.
- Use dense-media separation to extract and analyse the heavy mineral fraction from the bulk material.
- Perform mineralogical and chemical analysis to determine the composition and potential economic value of the heavy mineral fraction.

**Investigate possibilities of separating the heavy mineral fraction during sand-suppletion activities in the North Sea**

- Explore methods for efficiently separating the heavy mineral fraction during dredging, transport, or suppletion processes.
- Collaborate with industry partners and researchers to develop innovative solutions for mineral separation.

**Drone-based radiometric survey of beaches along the Netherlands shoreline**

- Use drones equipped with radiometric sensors to conduct detailed surveys of beach areas.
- Collect data on the spatial distribution and concentration of radioactive and CRM-bearing minerals.
- Analyse the radiometric data to identify areas with heavy mineral potential.

**Radiometric survey below the wave base in selected areas along the shoreline**

- Use underwater sensor equipment to measure radiometric signals and map the distribution of heavy minerals.
- Integrate the survey results with mineralogical and geochemical data to assess the potential for CRM extraction.

# 5.2 Iron, Manganese, and Phosphorus Concretions

As | Mn | P | V

## 5.2.1 Background

Historically, shallow deposits of phosphorite, iron ore, and manganese soils were mined on a small scale in the Netherlands for phosphate, manganese, and iron production. During World War I and II, shallow phosphorite layers were locally mined in Twente for agricultural purposes. Since then, no targeted research has been conducted into potential reserves in the area or in similar formations elsewhere in the country. Relatively small iron ore deposits in stream valleys are no longer of interest for metal extraction today, but if these materials are found or excavated on a larger scale in connection with civil engineering works such as dike reinforcement or dredging, they could still be considered as potential sources of CRM. Whether this is economically feasible depends on the amount of material, metal values, and available processing technology.

## 5.2.2 Bog iron

Historically, iron was produced in the Netherlands from the Roman Period until the twentieth century (Joosten, 2004). Bog iron and rattle stones were the primary sources for iron production. Bog iron is strongly associated with stream valleys where it forms through the oxidation of anoxic, exfiltrating groundwater (Fig. 5.2-1). Major iron-producing areas included the River Vecht area in Overijssel, and the Veluwe and Montferland in Gelderland. The Veluwe produced an estimated 55,000 tons of raw iron during the early Middle Ages. Rattle stones were retrieved from ice-pushed ridges in Gelderland (Van der Burg, 1970).

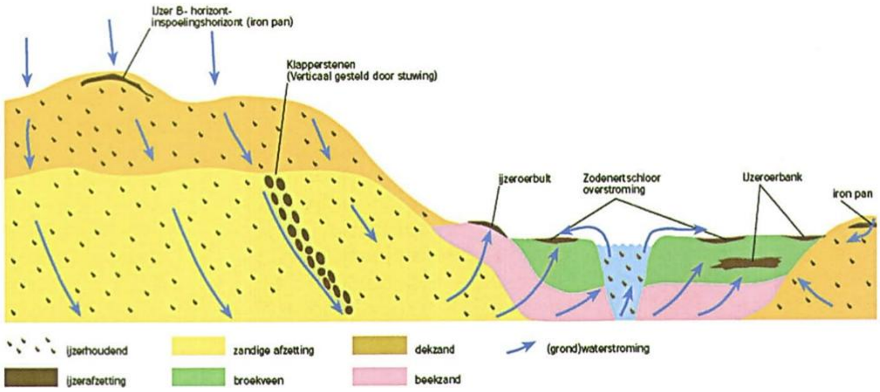


Figure 5.2-1 Geographical conditions where rattle stones and bog iron (in brown) have been found (adapted from Van Duijvenvoorde, 2006)

National interest in bog iron rose in the 19th century, leading to commercial production and processing in Germany. In the early 20th century, bog iron from Drenthe was used in the Netherlands, Germany, England, and elsewhere, for removing sulphur and cyanide impurities from coal gas, with annual production reaching approximately 100,000 tonnes before ceasing in the 1960s following the introduction of natural gas.

Goethite is the main constituent of bog iron ore in the Netherlands (Joosten, 2004; Pit et al., 2017), which may be rich in silicon (Van Bemmelen & Reinders, 1901; Ramanaidou & Wells, 2014), impacting the recrystallization of amorphous ferrihydrite to more crystalline iron oxides. Bog iron ore can also refer to siderite and vivianite concretions found in fens and bogs in Drenthe (Booij, 1986). These concretions have been studied for over a century (e.g. Van Bemmelen, 1896; Nauta et al., 2024), with three recognized origins: 1) cementation of sand with iron oxyhydroxides, 2) precipitation in inundated areas, and 3) precipitation of siderite or its amorphous equivalent within fens. The formation of siderite is still enigmatic, either by primary precipitation from groundwater, or by secondary anaerobic transformation of iron oxyhydroxides (Postma, 1981).

Bog iron has also been found in the western Netherlands during construction projects (Van Rossum, 2001; Stuurman, 2008), and on the “Sand Engine” (Zandmotor) in Zuid Holland, a coastal mega-nourishment with sand dredged from the North Sea (Pit et al., 2017). This suggests bog iron ore formation during the Pleistocene and/or Early Holocene, when the shoreline was further out. The distribution and recoverable amounts of bog iron under the North Sea are less well understood.

Seepage of iron-rich groundwater is an ongoing process, and the formation of iron precipitates during groundwater exfiltration continues. Changes in water management have impacted bog iron formation due to major anthropogenic changes in the drainage network, including alterations in groundwater exfiltration intensity in brook valleys.

Limited geochemical analyses of bog iron ores are available from publications (Joosten, 2004; Van Pruissen & Zuurdeeg, 1988) and the GDN DINO database. Samples from the Singraven Member of the Boxtel Formation (table 5.2-1) show that values above the intervention level are common for arsenic, with potential exceedances for cobalt and nickel. These findings illustrate that bog iron ore may be rich in trace metals. Further investigation is necessary to determine the controls on trace element contents and their variation.

Table 5.2-1. Statistics for three datasets on bog iron ore. Individual analyses were available for the Joosten (2004) and DINO datasets. Averages for four geographical groups were available from Van Pruissen & Zuurdeeg (1988) where the groups comprised 5 to 11 samples. The intervention value for soil remediation (ne = not existing) holds for a reference soil composed of 10% organic matter and 25% clay; most soils contain less organic matter and clay and thus have a lower intervention value.

| | Intervention value | Joosten | | DINO database | | Van Pruissen |
|---|---|---|---|---|---|---|
| | | avg (n = 15) | max | avg (n = 18) | max | Range in avg |
| $Fe_2O_3$ (%) | | 69.5 | 94.8 | 32.1 | 57.2 | 31.7 – 55.7 |
| MnO (%) | | 1.8 | 6.1 | 1.18 | 3.41 | 0.4 – 3.6 |
| $SiO_2$ (%) | | 22.5 | 41.2 | 37.4 | 49.0 | |
| $P_2O_5$ (%) | | 3.0 | 8.8 | 1.09 | 1.66 | 0.8 – 2.1 |
| As (ppm) | 76 | 95.4 | 315 | 303 | 1022 | 80 - 390 |
| Co (ppm) | 190 | 29.3 | 65 | | | 120 – 270 |
| Cu (ppm) | 190 | < 1 | 10 | 10.4 | 16.1 | 13 – 30 |
| Li (ppm) | ne | < 5 | 10 | | | < - 20 |
| Nb (ppm) | ne | | | 4.70 | 6.64 | |
| Ni (ppm) | 100 | 67.9 | 265 | 20.7 | 34.4 | |
| Sr (ppm) | ne | 123 | 550 | 55.0 | 138 | 30 – 70 |
| V (ppm) | ne | 77.5 | 190 | 40.1 | 82.3 | |

## 5.2.3 Rattle stones

Rattle stones are common objects in the fluvial Pleistocene sand and gravel deposits of the Netherlands (van der Burg, 1960; van Loef, 2000, Figure 5.2-2). These deposits are rich in iron oxide/hydroxides, containing 73 to 88 wt% $Fe_2O_3$ as determined by XRF after heating (Joosten, 2004). The present iron oxide/hydroxides consist of a mixture of goethite, hematite, and lepidocrocite (van der Horst et al., 1994; van Loef, 2000). Some reports also indicate the presence of siderite, a ferrous iron carbonate (van der Burg, 1969).

Rattle stones can be enriched in manganese (see following section) and other trace elements such as arsenic, nickel, and vanadium. Arsenic, nickel, and vanadium values range from 10 to 105 ppm, 100 to 315 ppm, and 50 to 165 ppm, respectively (Van Loef 2000; Joosten, 2004). The arsenic and vanadium contents are generally above the Dutch intervention values.

Rattle stones have mainly been investigated for major elements (van der Horst et al. 1994; van Loef, 2000), and measurements of trace metals are widely lacking. Thus, it is challenging to estimate the current arsenic or vanadium content in rattle stones. This information is needed to assess whether rattle stones could be an important source for the recovery of any of these elements.

Figure 5.2-2. Maps showing the distribution of rattle stones in the Dutch pre-Saalian Pleistocene (left) and presence of siderite concretions at a depth of more than 20m in boreholes in fluviatile pre-Saalian Pleistocene deposits (right). Dotted line: ice-frontline of the Saalian glaciers at their widest extension; stippled areas: outcrops of the fluviatile pre-Saalian Pleistocene (derived from Van der Burg, 1970).

## 5.2.4 Manganese

High quality manganese deposits are unknown in the Netherlands. However, gravel deposits with manganese-rich cements have been encountered along the Meuse River near Stein (Limburg), with cements containing up to 35.8 wt% $MnO_2$, or 22.6 wt% Mn (Koning et al., 1946). These deposits were not considered economic at that time because of difficulty separating the manganese oxides from iron oxides and fine quartz-rich sand grains. Lower-grade manganese enrichments (up to 7 wt% Mn) have been reported in bog iron, rattle stones, and siderite concretions, which are briefly discussed below.

Besides iron, bog iron may contain substantial amounts of manganese, often in the form of poorly crystalline hydrous manganese oxides, such as vernadite ($MnO_2 \cdot nH_2O$) (Rzepa et al., 2016). The manganese content of these deposits varies widely, even within a single deposit (Elburg, 1992; Joosten, 2004; Joosten et al., 1998).

Manganese also occurs in rattle stones of varying compositions. The more soluble layers around ferruginous cores in sandy to loamy sediments dissolve away, leaving a central part that becomes detached from the outer sediment layers, such as an iron oxide/hydroxide concretion filled with loose sand. Similar to bog iron, rattle stones can be enriched in manganese with varying, but low, content (0-7 wt%, van Loef, 2000; Joosten, 2004).

Siderite concretions, which may contain manganese carbonates, have been found in the Waalre Formation at sand excavations in the province of Limburg (Griffioen et al., 2016). Figure 5.2-2 shows other locations in the Netherlands where siderite concretions have been found. However, comprehensive chemical analyses of these siderite concretions are not available.

## 5.2.5 Phosphorite

Phosphorus does not occur as a free element in nature due to its high reactivity. However, it is widely distributed in many minerals, most commonly in phosphates, with the apatite mineral series determining the most abundant family with the chemical formula ($Ca_5(PO_4)_3(F,Cl,OH,Br)$). The geological concretions of phosphate minerals are called phosphate rock or phosphorite. Fluorapatite is the most insoluble and most common phosphate mineral (Desmidt et al., 2015). Typically, phosphate rock for mining contains 30-40% $P_2O_5$ (Schipper et al., 2001). Besides apatite, phosphate rock often contains trace element impurities such as cadmium, uranium, and zinc, which can reach relatively high concentrations.

Phosphorite nodules occur in the eastern part of the Netherlands and in the Rhine Delta in the southwest of the Netherlands. Phosphorite has also been reported in Upper Cretaceous rocks in southern Limburg. Historically, none of these occurrences were considered economically important. Most reports on this topic date back to 1960-1980 (Geologische Dienst Nederland, 1969, 1971; Harsveldt, 1973; van Enk et al., 2011), at which time the economic considerations were different from today.

During WW I, sedimentary phosphorite of the Palaeogene was discovered in Drenthe and Overijssel provinces. A discontinuous bed, 18-100 cm thick, containing 6.9 to 9.2% of $P_2O_5$, was found at the junction of Eocene and Oligocene sediments close to Hengelo (Phalen, 1920). The bed is present from the surface to a depth of 8 m. Overall, phosphorite nodules are abundant in the eastern part of the Netherlands at the base of the Middle Oligocene succession, occurring in glauconitic sand (Keizer & Letsch, 1963). Due to a phosphorus shortage during WW I, the deposits near Ootmarsum were mined, producing about 10,000 tons of phosphate rock. However, the irregularity of the bed made mining challenging and expensive.

In South Limburg, the Upper Cretaceous boundary between Campanian and Maastrichtian is marked by a glauconitic horizon containing phosphorite nodules. The nature and phosphorus content of these nodules are unknown.

The Delta Works conducted by Delta Dienst Rijkswaterstraat close to Haamstede found three layers of phosphorite nodules between 123 to 137.5 m below the surface (Harsveldt, 1973, Table 5.2-2). The layers are present in the Miocene Breda Formation. Further investigations found phosphate nodules also on Walcheren, Tholen, Zuid Beveland, Zeeuws Vlaanderen, and in the Western Scheldt estuary. The nodules consist of light green glauconite globules and subangular to rounded quartz grains, embedded in a brown matrix consisting of apatite. Phosphorus content of the nodules at these locations varies between 4.88% to 13.64% and thus represents lower grade phosphate rock. The nodules are also enriched in uranium (up to 300 ppm; Laban, 1988). Preliminary investigations showed that a leaching technique using diluted sulfuric acid could extract the phosphorus. However, the area is used as a groundwater protection zone, so any contamination must be prevented. In 1971, it was concluded that the technical extraction would be possible but at high financial costs, making phosphorus mining economically unfeasible (Geologische Dienst Nederland, 1969, 1971). Consequently, no further exploration activities have occurred since.

Because of low grades and sparse distribution, no estimates of the phosphate-rock resources in the Netherlands have been made to date, and current data is too scarce for extrapolation. While past assessments deemed the known occurrences economically unimportant, this evaluation may differ today and could be worth reconsidering. Besides deriving better estimates of the phosphorite contents in Southern Limburg and Zeeland, it is important to consider the technological and economic viability of potential recovery.

Table 5.2-2 Phosphorus content of phosphate rock nodules at different borehole locations in Zeeland. Data originally published by Harsveldt (1973).

| Borehole no. | Location | Content P in wt% | Content $P_2O_5$ wt% |
|---|---|---|---|
| 42B-20-3 | Schouwen | 4.88 | 11.17 |
| 42B-40 | Schouwen | 6.00 | 13.74 |
| 49A-22 | Tholen | 5.68 | 13.01 |
| 48A-6-8 | Walcheren | 11.00 | 25.19 |
| 48C-41 | Walcheren | 5.96 | 13.65 |
| 48D-56 | Walcheren | 6.37 | 14.59 |
| 48F-34 | Zuid Beveland | 13.64 | 31.23 |
| 69b-33 | Western Scheldt | 5.76 | 13.19 |
| 69b-31 | Western Scheldt | 8.82 | 20.20 |
| 69b-32 | Western Scheldt | 5.28 | 12.09 |
| 54B-46 | Zeeuws Vlaanderen | 11.85 | 27.13 |
| 55A-16 | Zeeuws Vlaanderen | 5.90 | 13.6 |
| 49B-190 | W. Brabant | 5.82 | 13.33 |

## 5.2.6 Resource potential

Despite historical production of bog iron and phosphorites in the Netherlands, current available data is lacking for an estimated resource potential. The phosphate deposits near Ootmarsum have historically produced about 10,000 t of phosphate rock. The total amount of iron produced at the Veluwe during the early Middle Ages is estimated at 55,000 t. During the 20th century, bog iron was mined in Drenthe, with an annual estimated production of 100,000 t.

## 5.2.7 Suggested research activities

**Increase data density on phosphorite occurrences using the national geology collection**

- Enhance the geological data related to phosphorite occurrences by leveraging the Naturalis database to systematically gather and integrate data from various sources, including field surveys, historical records, and existing research. This will involve systematic cataloguing of occurrences and mapping their spatial distribution.

**Sampling phosphorite from existing materials in core-storage and Naturalis collections**

- Use X-ray fluorescence (XRF), inductively coupled plasma mass spectrometry (ICP-MS), and electron microprobe analysis to measure the mineralogical and geochemical composition of representative phosphorite samples.

**Sampling and analysis of large-scale exposed bog-iron occurrences**

- Inquire with industry partners to generate an inventory of large-scale bog-iron occurrences in lakes (e.g., Veluwemeer) and in offshore sand-extraction areas and obtain representative samples for mineralogical and geochemical analysis.
- Select the most promising location based on preliminary data and acquire a representative sample set of bog-iron material for mineralogical and geochemical analysis.

# 5.3 Waters & Brines

As | Li | Ni | P | Sr

## 5.3.1 Brines

Porous sandstone layers in the deep subsurface contain formation water or hydrocarbons in their pore spaces, which can be produced for geothermal heat, oil, or gas. As underground formation water increases in salt content with time and depth, it turns into a brine. Some brines have elevated CRM concentrations of elements like strontium and lithium. The occurrence of CRM in brines has not yet been quantified systematically for the Netherlands. The NMO aims to investigate the potential for direct CRM extraction by analysing brine compositions collected over the years by the GDN and commercial operators. Determining the concentrations of CRM, total quantities, and extraction technologies is essential for assessing the potential of economic recovery. When brines are produced for geothermal energy, the combined value of geothermal heat and mineral extraction could be decisive in economic analyses. Since direct lithium extraction from geothermal brines has already been successfully applied in Europe, lithium is the first focus of the brines exploration program.

### 5.3.1.1 Lithium context

Lithium consumption in the world is rising due to the increased production of lithium-based batteries for electric vehicles. With high demand and limited resources, Europe relies heavily on lithium imports. In response to the CRMA, and considering the fact that the Netherlands already produces brines, this report suggests to further investigate the potential for extractable lithium resources in these brines.

Currently, lithium is mainly mined from three deposit types: 1) near-surface brines in arid regions, 2) hard-rock sources like pegmatites, and 3) sedimentary deposits such as volcanic clays. The largest lithium reserves are in brines from salt lakes (salars) in Chile, Argentina, and Bolivia, with concentrations up to 6400 mg/l. Lithium is extracted through evaporation and precipitation processes. The second largest reserves are in pegmatite rocks, primarily in Australia, the USA, Canada, and the Democratic Republic of Congo. For Europe, 27 potential hard-rock deposits have been identified with estimated lithium resources of almost 9Mt of $Li_2O$ (Gourcerol et al., 2019). The third group is currently dictated by the occurrence of lithium clays (jadarite) in Jadar, Serbia.

An alternative yet still unconventional lithium source is deep subsurface brines. Significant concentrations have been found in oilfield brines in the USA and China, and geothermal brines in Russia (Figure 5.3-1), with concentrations up to 250 mg/l (Qaidam Basin in the Tibetan Plateau), 440 mg/l (Salton Sea, USA), 450 mg/l (Verkhnekostinskoe in the Krasnoyarsk region), and 692 mg/l (Texas/Wood oilfields, Smackover formation, USA), respectively.

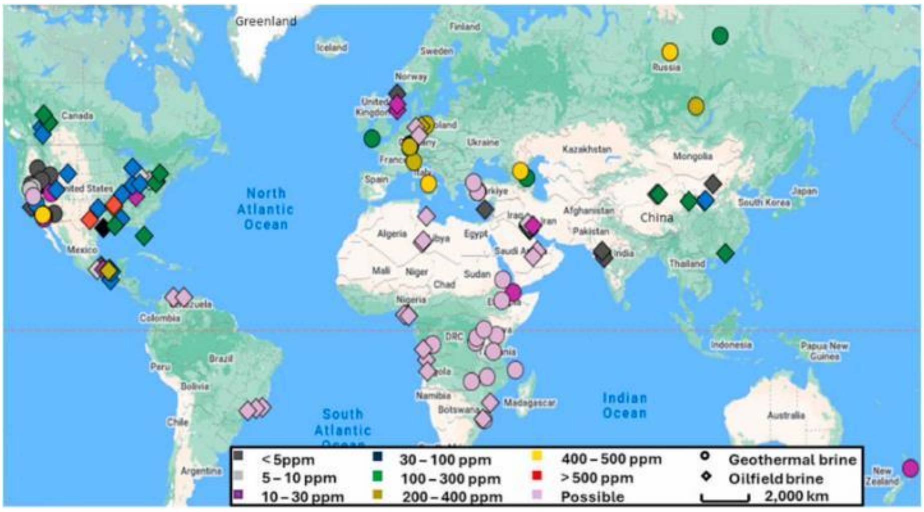


Figure 5.3-1. Global lithium concentrations in subsurface brine (from Disu et al., 2024)

Sanjuan et al. (2022) and Gourcerol et al. (2024) identified 182 occurrences of lithium-bearing geothermal fluids in Europe, with concentrations above 15 mg/l (Figure 5.3-2). Six geothermal areas have economically viable lithium concentrations between 125 and 480 mg/l. In Germany, three regions have lithium-rich brines: the North German Basin (~200 mg/l), the Molasse Basin (142-162 mg/l), and the Upper Rhine Graben (173-210 mg/l), which extends into France. Italy has the richest lithium-bearing brines, with concentrations up to 480 mg/l in Mofete in the Campi Flegrei. The UK has lithium-rich geothermal brines in Cornwall (>250 mg/l), currently produced by direct lithium extraction.

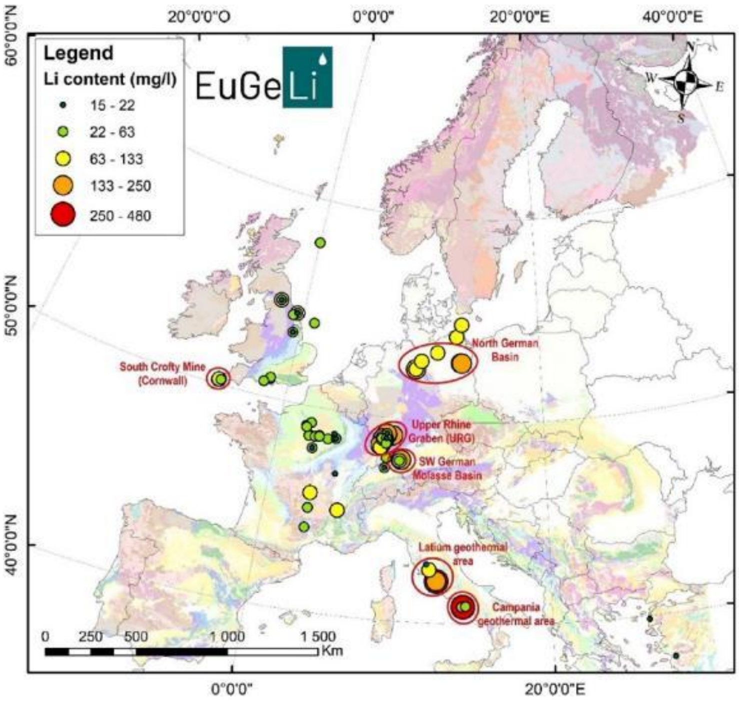


Figure 5.3-2. Map of Europe showing the six main geothermal areas with Li-rich fluids (red circles) and Li-concentration ranges in such fluids. (from Sanjuan et al., 2022).

## 5.3.1.2 Brine locations

Maps of CRM concentrations were created based on a dataset of brine compositions collected by the GDN (Fig. 5.3-3). This dataset includes over 75 years' of analyses of water produced for geothermal energy or co-produced with oil or gas, from depths between 1.5 and 5 km. More than 1100 water analyses from 275 wells have been collected, with data points concentrated in areas where geothermal water or hydrocarbons are extracted. However, there is almost no data for large parts of the South and East of the Netherlands. Additionally, many CRM are not included in the analyses, with fewer than 30 sites having data for lithium.

Within the available dataset, lithium concentrations range between 0 and 50 mg/l. Strontium concentrations of up to 3300 mg/l are the highest of all measured CRM. Other locally enriched CRM include borate (1600 mg/l), manganese (300 mg/l), and scandium (100 mg/l). Magnesium concentrations can be relatively high but may be due to contamination with drilling fluids. Minor trace amounts of rare earth elements are observed in some brines.

Within the 30 wells where lithium has been measured, concentrations remain below 50 mg/l, while present-day viability for direct lithium extraction requires concentrations exceeding 50 mg/l. However, data for lithium concentrations is scarce (Fig. 5.3-3), and large gaps remain. No data has been found for brine compositions just across the Dutch German border, limiting the ability to extrapolate from German information.

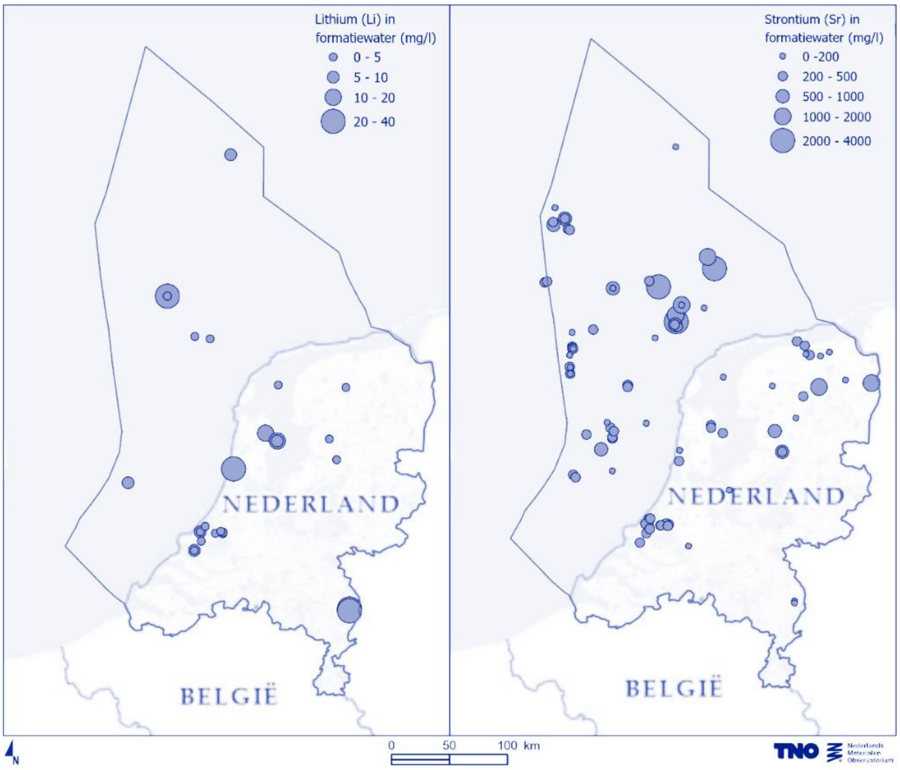


Figure 5.3-3. Maps of lithium concentration (left) and strontium (right) concentrations in the deep subsurface (1 to 3.5 km depth).

### 5.3.1.3 Brine resource potential

Lithium concentrations vary with depth and may be linked to specific formations. In Northern Germany, high lithium grades have been reported in Permian Rotliegend sandstones, Permian Zechstein carbonates, and Triassic Middle Bunter sandstones (Alms et al., 2025; Sanjuan et al., 2022; Figure 5.3-4). These formations have estimated resources per surface area of 9.84 t/km² in the Bunter Sandstone, 19.39 t/km² in the Zechstein carbonates, and 76.26 t/km² in the Rotliegend (Gourcerol et al., 2024). The current dataset indicates that the Rotliegend Slochteren sandstone is generally the most enriched in CRM, although lithium was not included in the analysis. One data point from Carboniferous carbonates shows a comparable lithium concentration. Lithium could also be present in the carbonate or salt layers of the Zechstein, which were formed by salt precipitation at the surface and may contain elevated lithium concentrations. Rock salt is exploited by dissolution salt mining in the Netherlands, but data on brine compositions are yet to be shared.

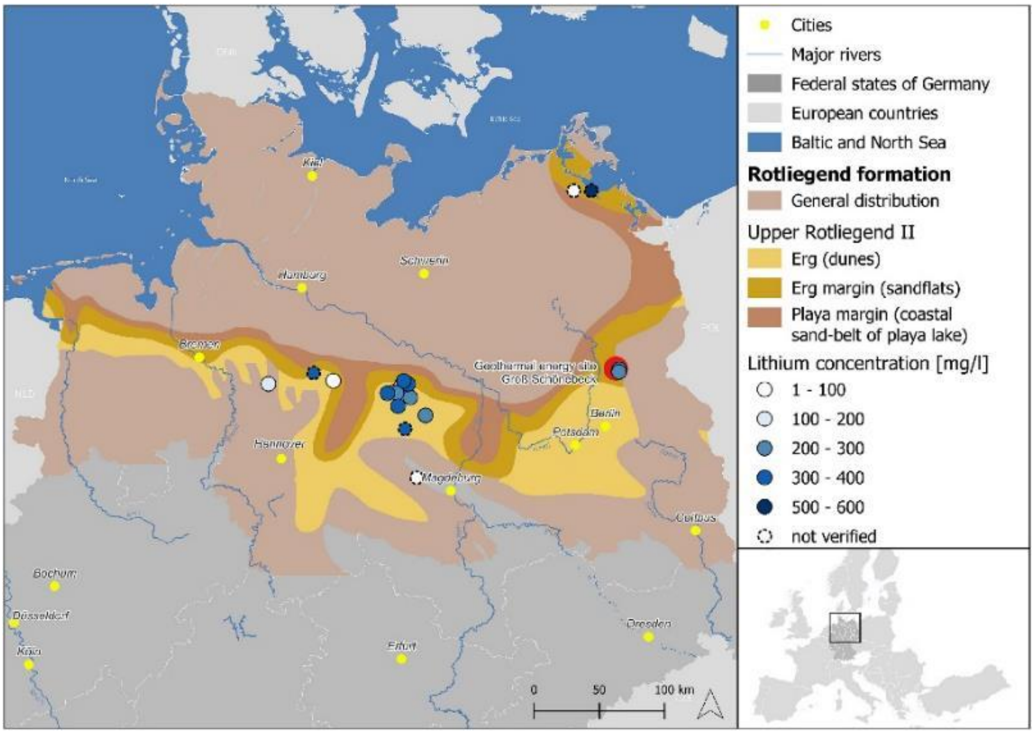


Figure 5.3-4. Distribution of Rotliegend strata in northern Germany (from Alms et al., 2025)

To assess lithium resource potential in different formations, it is essential to understand the processes of lithium enrichment. Sanjuan et al. (2022) concluded that fluids need to be very saline (Na >18 g/l, Cl >25 g/l) for lithium to dissolve, and brines in the Netherlands often exceed these values. Lithium enrichment also requires temperatures above 120°C, which in the Netherlands occur in the deep subsurface (>4 km), where low rock permeabilities may pose a challenge. Additionally, lithium enrichment involves contact with lithium-bearing rocks. Various geological processes contribute to lithium sources, such as lithium-rich mica from Permian acidic volcanics or biotite and chlorite layers of the Zechstein sediments (Alms et al., 2025, Jungmann et al., 2025 and Möller et al., 2017). Micas and biotite from the Triassic Bunter Sandstone and granite basement also contribute to lithium enrichment (Sanjuan et al., 2022).

Lithium is released into brine through hydrothermal alteration during fluid-rock interactions with evaporite layers and crystalline rocks, and possibly by fluid migration through deep faults. Gourcerol et al. (2024) found that most brines with high lithium concentrations (250–480 mg/l) also have high B, Rb, K, $SO_4$, Na, Cl, and F concentrations. Moderate lithium concentrations (133–249.9 mg/l) correlate with Ca, Ge, Sr, and $PO_4$, while low concentrations (15–63 mg/l) correlate with Mg, Mn, U, and $NH_4$. High concentrations of Mg, Mn, U, and $NH_4$ in may indicate lithium enrichment in brines.

Various extraction technologies have been developed for geothermal and oilfield brine exploitation, including precipitation, adsorbents, solvent extraction, and electrochemical and membrane technologies (Mends and Chu 2023 and Nikkhah et al., 2024). Adsorbents are the most viable due to their selectivity, considering the complex chemistry of brines. Innovative technologies or unconventional production strategies may eventually enable direct lithium extraction in the Netherlands, as discussed in Chapter 3.

Other CRM like strontium, borate, and scandium are present in brines, but tend to occur at low concentrations and are difficult to recover due to interference from higher concentrations of major elements like Na, K, Ca, and Mg (Pramanik et al., 2020). For example, extracting low concentration REE or platinum group elements is technically possible but not economically viable (Smith et al., 2017). Strontium occurs in higher concentrations in Dutch brines, but there limited documentation on selective extraction of Sr. Alshuiael et al. (2022) found over 80% lithium recovery with only 3-10% of strontium. Boron removal may be more feasible (Wang et al., 2015).

For a brine to be considered having resource potential, it must flow easily through its host-rock formation during production, requiring adequate porosity, permeability, and reservoir thickness. Proximity to heat demand such as greenhouses or district heating is also important for any CRM co-production with geothermal heat to be viable.

## 5.3.2 Ground-, surface-, and wastewater

Purifying groundwater and surface water for producing drinking water generates waste streams that may contain CRM. Wastewater from sewage, agriculture, and the food industry also requires cleaning before discharge. CRM extraction and reuse are essential for ecological and environmental reasons, though resource potentials are not yet fully assessed.

### 5.3.2.1 Groundwater and surface water

In some areas in the Netherlands, groundwater and surface water contain elevated concentrations of CRM, exceeding intervention values. Measures may apply when extracting groundwater with high concentrations, such as during excavation or for drinking water. High concentrations of elements like arsenic, barium, and strontium are common in coastal areas. Arsenic and nickel frequently exceed intervention values (Van der Grift and Van der Meulen, 2011). Arsenic concentrations can reach up to 124 µg/L, surpassing the intervention value of 60 µg/L, particularly in the Rhine delta, IJssel area, Boxtel Formation, Drenthe Formation, and glacial deposits. Elevated arsenic levels are also found in glacial deposits in the centre of the Netherlands and in Holocene layers along the coast (Figure 5.3-5). These concentrations are often associated with iron hydroxides around seepage zones or with deeper groundwater where iron-oxide reduction occurs. In shallower groundwater, arsenic can be released by pyrite oxidation. Nickel concentrations, exceeding the intervention value of 75 µg/L, are found in Noord Brabant, with levels up to 223 µg/L (Figure 5.3-5). Currently, these critical elements are generally not removed from extracted groundwater with elevated concentrations, except by drinking water companies as discussed below.

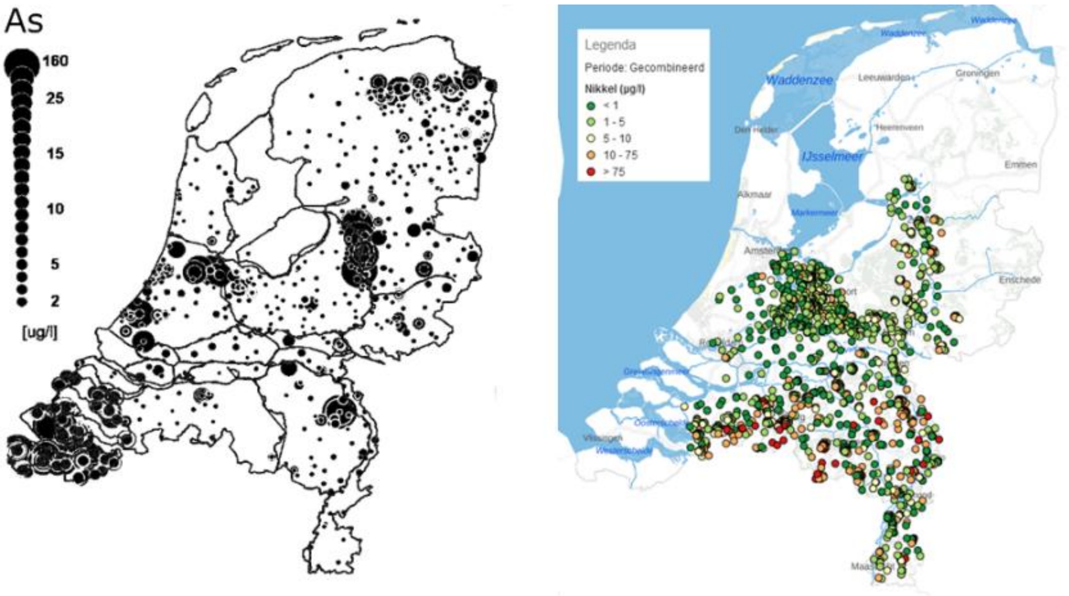


Figure 5.3-5. Left - Arsenic concentrations in Dutch groundwater (image adapted from Spijker, 2008). Right - Nickel concentrations in Dutch groundwater (image produced in grondwatertools.nl).

Groundwater in the Netherlands is typically anoxic, necessitating the removal of dissolved iron for drinking water production. This process produces iron sludge, known as "waterijzer" (water iron). Water iron can also be produced from surface water during drinking water production. If groundwater is rich in arsenic, water iron may contain high arsenic levels, depending on aeration conditions. In 2020, drinking water companies produced 88,248 tonnes of water iron, managed by AquaMinerals. About one-quarter was solid (30% solids), and three-quarters were slurry (10% solids) (Vewin, 2022; KWR, 2022).

Virtually all water iron (99.4%) was reused in various sectors, including agriculture and energy production, where it helps remove sulphur, producing Fe-sulphide. Recently, research explored transforming water iron into a flocculant for phosphate removal in sewage water (KWR, 2022). Water iron contains 80-100% $Fe_2O_3 \cdot 3H_2O$ and 1-10% inert sandy material, with Ca, P, and Mn contents up to 4-5%, and Mg and Al contents up to 0.3% (AquaMinerals, 2016).

Water iron can be reused in fertilizer production or sewage-water treatment if arsenic content is ≤150 mg/kgds, and for other recycling if arsenic content is ≤500 mg/kgds (Ministerie I&W, 2024a). Other legislation applies if additional contaminants are present. Mixing batches to meet standards is prohibited. Despite high reuse rates, innovative recycling methods may further enhance material extraction.

### 5.3.2.2 Wastewater

The Dutch water authorities ("waterschappen") manage over 300 sewage- or wastewater-treatment plants (WWTP) in the Netherlands, including municipal and commercial WWTP. To comply with the Water Act, wastewater is purified before being discharged into surface water. The water authorities extract various raw materials and energy from sewage water, with phosphate being the most abundant CRM. Other extracted materials include cellulose, bioplastics, Kaumera, and biomass (De Koning et al., 2023).

Recovered substances from wastewater are labelled 'waste' until they meet the end-of-waste criteria from the Waste Framework Directive (2008/98/EG). This can be achieved through self-assessment, legal judgment, or end-of-waste regulation. For the mineral struvite ($MgNH_4PO_4.6H_20$), a safety study by AquaMinerals and Waternet (De Jong and Vriend, 2021) led to a legal judgment granting struvite end-of-waste status, allowing it to be marketed as a fertiliser.

Sewage water contains high concentrations of phosphate, which must be removed at treatment plants to meet effluent standards. Phosphate can be bound in the mineral struvite, which forms in a basic environment. Struvite can naturally form during water purification, causing blocked pipes. In a struvite reactor, struvite is deliberately formed and separated from wastewater by adding magnesium salts to sludge or water under specific conditions. Struvite is also produced in private WWTP, particularly in the food industry, which also has high phosphate concentrations in its wastewater (Geertjes et al., 2016).

Struvite is a valuable nutrient due to its high magnesium and phosphate content, making it suitable for agricultural use. The AquaMinerals partnership ensures that recovered struvite is marketable. In 2023, 592 tonnes of struvite residue were produced from wastewater (Aquaminerals Annual report, 2023). Other forms of phosphate, such as vivianite ($Fe_2(PO_4)_2 \cdot 8H_2O$), are also recovered from wastewater, with recovery processes currently under development (Vivimag® technologie, TRL 5-6) (Nijholt, 2022).

Sewage treatment plants produce approximately 1.4 million tonnes of sewage sludge annually (Unie van Waterschappen, 2019), which contains around 30-40 grams of phosphate per kilo of dry matter. During mono-incineration, phosphate is concentrated in the ash at 200 grams per kg. Sludge processing company SNB recovers around 30 grams of phosphate per kg of ash (1% P) and predict they can produce 3,000 tonnes of phosphorus from recycling sewage sludge if a new phosphate recycling factory is realised (SNB, 2024).

Other solid phases containing substantial amounts of phosphorus include animal manure, food production by-products, animal by-products, crop residues, compost, and carbonation mud from the sugar beet industry (van Enk et al., 2011). Most phosphorus in these forms is already recycled, except for sewage sludge, which contains around 27,000 t/y $P_2O_5$ in the Netherlands, with only 200 t re-used (van Enk et al., 2011). Sewage sludge is mainly incinerated, and the ash is disposed of or used in the cement industry. Obstacles to reusing ash as fertilizer include heavy metals and organic contaminants. Phosphorus in ash is mainly bound to iron, making its recovery challenging. Research projects have targeted phosphorus recovery from incineration ashes, but further research is necessary (Sustainable Sludge Wageningen, 2020).

Phosphorus is primarily used as a fertilizer in the Netherlands and globally. Forty to 90 years of phosphate fertilization has led to the accumulation of phosphate in agricultural soils (van Enk et al., 2011). Further research is needed to examine potential phosphorus recovery.

In 2016, the Netherlands Statistics Bureau (CBS) analysed CRM in wastewater and waste sludge (Geertjes et al., 2016). The report summarises concentrations of 12 elements in wastewater and sludge (Table 5.3-1). Currently, 66% of sewage sludge is incinerated, without recovery of metals. The recovery potential and methodology of recycling trace metals from wastewater, sludge, and ash have been investigated by KWR (Muñoz Sierra et al., 2019; Roest et al., 2018; Buijzer et al., 2016), which concluded that copper, zinc, silver, titanium, palladium, iron, gold, and tungsten might be of interest for commercial recovery.

Table 5.3-1. Total content of critical elements in sewage sludge from WWTP in 2012 and total and relative content in ash from sludge incinerated by SNB and SVI Dordrecht over 2012-2014 (Geertjes et al., 2016).

| | Total in sludge WWTP | Total in ashed sludge | Content in sludge | Content in ashed sludge |
|---|---|---|---|---|
| | Tonnes per year | Tonnes per year | mg/kg ds | mg/kg ds |
| Copper | 130.8 | 61.3 | 404 | 1101 |
| Nickel | 10 | 4.9 | 31 | 84 |
| Aluminium | 2430 | 2170 | 10000 | 36000 |
| Antimony | 1.5 | 0.9 | - | 14 |
| Manganese | 78 | 51.6 | - | 2300 |
| Chromium | 13.8 | 7.6 | 41 | 130 |
| Molybdeen | 2.7 | 1.8 | - | 30 |
| Cobalt | 1.8 | 1 | - | 17 |

### 5.3.3 Suggested research activities

There is currently not enough data coverage to accurately assess the potential for CRM and especially lithium presence and extraction potential from brines. A number of research topics are suggested to better assess CRM potential in brines.

**Improving the data coverage and mapping**

- Acquire additional data from national oil and gas operators, as well as salt-mining operators and geothermal projects. Currently, data from departing operators is collected by the GDN, which may include more water compositions. Cross-border data can help to better assess lithium concentrations. These data may be obtained from the literature and by reaching out to institutes in Germany and Belgium.
- Generate CRM-target maps of prospective formations for detailed assessment of lithium, strontium, boron, and magnesium potential in brines.

**Geological sweet spots for lithium enrichment**

- Investigate the distribution of known formations, brine reservoirs, and conceptual mineral systems of interest for their lithium potential (Sanjuan et al., 2022; Gourcerol et al., 2024). For example, the possibility of rock-salt deposits as a potential source of lithium has not been investigated to date. Volcanic rocks or deep-seated faults may contribute to lithium enrichment. And isotopes of lithium may provide insights into possible lithium source rocks and enrichment in brines.
- Specific elements in brines can be used as proxies for lithium concentrations. Brine-composition datasets can be investigated for high Mg, B, Mn, U, and $NH_4$, which may indicate high lithium concentrations.
- In the USA, oil-field brines appear to be richer in lithium than geothermal fluids, possibly due to the presence of organic compounds in the brine. It is worth investigating whether this could also be the case in the Netherlands.

**Direct extraction of CRM**

- Evaluate DLE technologies most relevant to Dutch brine environments and industrial context. Consider DLE testwork if suitable brines can be identified.

- Investigate the technological possibilities for co-production of CRM and geothermal heat.
- Study possibilities of direct extraction of other elements than lithium (international practices, existing extraction technologies, economically viable concentrations).
- Assess the sustainability of lithium extraction from geothermal brines with reservoir flow models. Geothermal water is re-injected after lithium extraction and may over time dilute lithium concentrations in the reservoir.

**Investigate the co-production of phosphorus, nickel, and arsenic from groundwater at locations where intervention values are exceeded, requiring environmental measures:**

- Conduct targeted studies at sites where phosphorus, nickel, and arsenic concentrations exceed safe limits. This involves sampling groundwater, analysing the co-occurrence of these elements, and identifying their sources.

## 5.4 Sulphides

As Bi Co Cu Ga Ge Ni Sb

Many metal ores naturally occur as sulphide compounds, including copper, zinc, lead, nickel, and critical trace elements like cobalt, arsenic, antimony, gallium, germanium, and bismuth. In the Netherlands, zinc and lead sulphide occurrences are known mainly in South Limburg, extending from Belgium, and in East Gelderland around Winterswijk. These occurrences may also contain associated gallium, germanium, and bismuth, though their presence is not well-documented.

At great depth in the Dutch subsurface, the "Kupferschiefer" (copper shale) has been encountered during gas drilling. This thin shale layer, averaging one metre, crops out in Germany and Poland and is mined for copper production. The Kupferschiefer lies at the base of the Zechstein formation, which is the main cap rock of Dutch gas fields. It is present in most of the Netherlands, except for the southwest, but lies deep: from about 700 m in East Netherlands to >5000 m below the seafloor of the North Sea. Its copper content has not been systematically investigated since it has never been considered economically viable with conventional mining methods at the observed depths.

Deep igneous rocks are a third candidate, present both on- and offshore, the majority is linked to the Variscan foreland or the magmatic activity of the North Sea Central Graben. Drill cores exist but have not yet been investigated for potential mineralisation.

### 5.4.1 Lead, zinc and associated metals

#### 5.4.1.1 Context

Lead and zinc are classified as base metals and are not part of the EU's CRM list. However, low concentrations of germanium, gallium, indium, and barium are potentially associated with these metals and can be economically feasible by-products. Historically, these CRM were not analysed due to the lack of economic interest, but recent changes have highlighted their importance.

Significant historic lead-zinc deposits are found just across the border in the La Calamine-Moresnet region in Belgium and around Aachen in Germany. These deposits brought wealth to the region from Celtic times through the Middle Ages, the French Revolution, and into the early 20th century. The largest non-sulphide zinc deposit in Belgium, the historic "La Calamine Mine" is located here. Known by various names, this mine produced zinc silicates and carbonates, which were important for global zinc metal and brass production. The ore minerals form as oxidation products of nearby primary sulphide ores (Coppola, 2008). Bleiberg (Plombières), a historic mine north of La Calamine, is dominated by lead and zinc sulphide mineralization and is geologically related to La Calamine. The historic mining company "Vieille-Montagne," played a significant role in mining and processing zinc and lead ores, becoming a leader in the European zinc industry two centuries ago before it was incorporated in the present-day Umicore (Dejonghe, 2024).

Dejonghe (1998) reviews lead-zinc deposits in Eastern Belgium, explaining the complex geological context of the Verviers Synclinorium. Mississippi Valley Type (MVT) ore deposits are epigenetic, precipitated from dense seawater brines at low temperatures along tectonic structures. These deposits are typically found in platform carbonate sequences in foreland thrust belts and lack genetic affinities to igneous activity. Around 24% of global Pb and Zn resources are related to MVT-style deposits, consisting mainly of sphalerite (ZnS), galena (PbS), and lesser iron sulphides. Silver can be an important by-product, while copper content is generally low. CRM like indium, germanium, and gallium are typical by-products of Pb-Zn deposits. These deposits have varied relationships with host rocks and include stratabound, discordant, stratiform, and vein-type ores (Leach, 2010).

Most Zn-Pb ore deposits in Eastern Belgium are brecciated vein-type deposits and associated flats, hosted by Dinantian carbonates and Namurian shales along the Variscan foreland. Two dominant fault systems, longitudinal (NE-SW) and transverse (NNW-SSE), facilitated hydrothermal fluid precipitation. Belgian vein-type deposits were capped by gossans, making them easy to discover and exploit (Dejonghe, 1998, 2024). The referred Calamine deposit is a palaeokarst-type deposit with karstic cavities allowing hydrothermal fluid precipitation. The non-sulphuric zinciferous ore is completely oxidized and occurs as irregular bodies in mottled clays (Dejonghe, 1998, Bongaerts, 2002).

Mineralized faults associated with La Calamine, Bleiberg, and Sippenaken trend NNW-SSE and continue into southern Netherlands along the Geul Valley. Lead, zinc, and barite occurrences in Carboniferous rocks are reported around Bommerig, Cottessen, and Camerig. Evidence of historic excavation activities includes waste piles, iron slags, and collapsed mine shafts, though details are unclear (Felder and Engelen, 1989).

#### 5.4.1.2 Lead-zinc occurrences in South Limburg

The first documented mineral exploration activities in South Limburg date back to the mid-19th century. The "Maatschappij Bergwerk-Vereeniging voor Nederland," founded in 1856, aimed to map out the mineral potential in the Netherlands. A drilling campaign in 1856 intersected lead mineralization around Bommerig (east of Epen) at 56 metres depth. The detailed log described a 0.8-metre interval of quartz-bearing host rock with high-quality lead, drawing parallels with nearby Bleiberg (Plombières). However, a second hole drilled in 1857 did not intersect any mineralization, resulting in a negative recommendation for the exploitation permit 'Maria' (Kuiperi, 2012).

During the early 20th century, coal miners in South Limburg reported multiple lead-zinc occurrences in shafts and drifts (Felder and Engelen, 1989). Bongaerts (1993, 1999, 2002) described coarse-grained sulphide occurrences found by coal miners, dominated by sphalerite and galena, hosted in Westphalian shales and sandstones, and associated with brecciated quartz infills due to faulting.

Exploration activities ceased due to the extensive area with Pb-Zn occurrences and limited success in locating areas with elevated economic potential. In 1936 new exploration activities were initiated in the Geul Valley. An electromagnetic (EM) geophysical survey and eight drill holes targeted the Geul Valley fault system around Bommerig between 1936 and 1938, but only trace sulphide mineralization was found (Felder and Engelen, 1989).

An exploration shaft was initiated around Bommerig during World War II (Figure 5.4-1), again with limited success (Felder and Engelen, 1989). De Wijkerslooth (1948) published a scientific article summarizing lead-zinc occurrences in South Limburg, emphasizing the mineralization paragenesis and geological setting. He concluded that accessory minerals indicated high-temperature crystallization of ore minerals, suggesting South Limburg was closer to the centre of mineralization formation, making it appealing for exploration. He also summarized exploration activities around Bommerig, including maps and geological sections, concluding that the exploration drilling was too short and did not intersect the prospective horizon (De Wijkerslooth, 1948a).

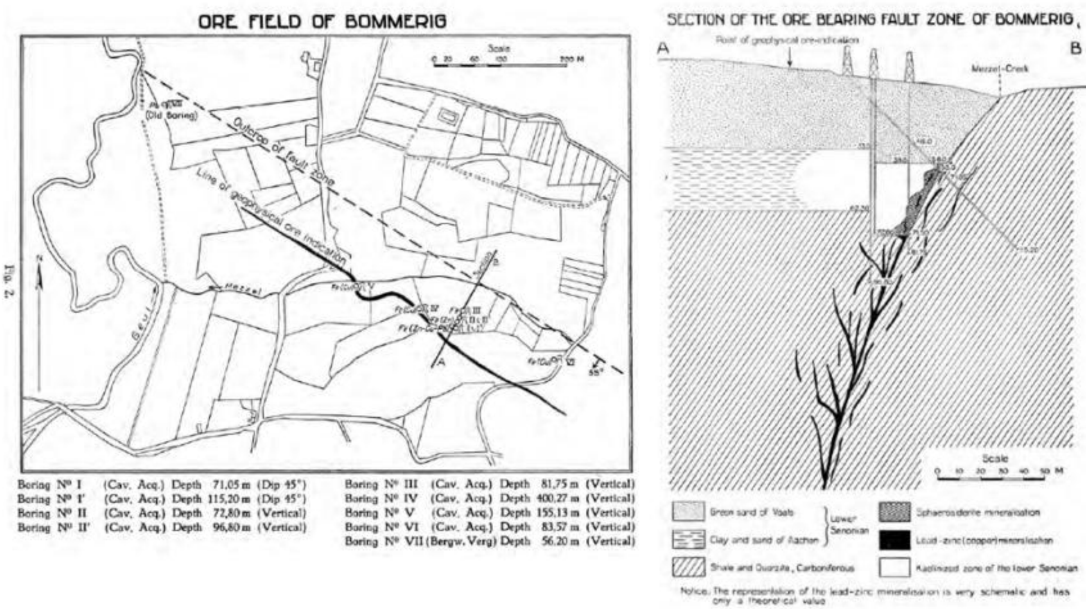


Figure 5.4-1. Left - Sketch map of the Bommerig area indicating the historic bore hole locations and geophysical signature (De Wijkerslooth, 1948a). Right - Profile line A-B as indicated on the left.

In 1951, the "Oost Borneo Maatschappij N.V." requested information on mineral occurrences in South Limburg. The Geological Agency provided a report summarizing exploration activities, findings, and analytical results of pyrite nodules (Thiadens, 1951). A mineral exploration permit was granted in 1953, but it is unclear if activities were conducted. Patijn (1954) suggested geophysical surveys to map fault systems in Bommerig, emphasizing first-order faults and cross-cutting secondary faults, but it is unclear if this was investigated.

While interest in mineral exploration ceased with the closure of coal mines in South Limburg, most recent lead-zinc occurrences were reported during the construction of the Thermae 2000 complex in Valkenburg. Pilot holes drilled for geothermal water intersected mineralization zones characterized by sulphide-bearing minerals hosted by altered Dinantian carbonate rocks. Detailed investigations suggested leaching and silicification occurred near the surface, with erosional processes and hydrothermal fluids causing mineral precipitation (Friedrich, 1987). Similar observations were made in other boreholes, warranting further investigation (Bless, 1981).

#### 5.4.1.3 Lead-zinc occurrences in the Eastern Netherlands

Lead and zinc occurrences are described around the limestone quarries of Winterswijk and Enschede in eastern Netherlands (De Boorder, 1985). These metals are hosted by a stromatolitic dolomitic lime-mudstone sequence in the Muschelkalk formation. Small quantities of pyrite, galena, sphalerite, celestite, and fluorspar are found in coarser-grained intercalated sequences with shell fractions, interpreted as storm-layer deposits in a tidal algal mat environment. Interaction between metal-bearing fluids and permeable stromatolitic sequences could concentrate metals in algal mats. Although the area is considered immature for metal concentration, systematic investigation could reveal significant base metal concentrations. De Boorder (1985) advocates for detailed mapping of the mineral potential.

### 5.4.2 Kupferschiefer – shale-hosted copper

#### 5.4.2.1 Background

The Kupferschiefer ("Copper shale"), is a thinly laminated, bituminous, calcareous, and clay-rich shale at the base of the Zechstein Group, dating back to the Permo-Triassic period (252 Ma). It is crosscut by hematitic alteration known as "Rote Fäule." The Kupferschiefer is approximately 1-2 metres thick and spans 600,000 km² across northern Europe, from Belarus to eastern England (Keith et al., 2018, Figure 5.4-2).

The Kupferschiefer is one of the largest sediment-hosted copper-ore accumulations globally, with an estimated endowment over 60 million tonnes of copper. Its mining history dates back to at least 1199 A.D. in Germany's Mansfeld district (Borg, 2012). Currently, Kupferschiefer ores are mined in Poland, with the Rudna Mine in the Lubin district being the largest copper mine in Europe (resources estimated at 513 Mt @ 1.78% Cu and 42 g/t Ag). The copper-rich mineralization in Kupferschiefer is dominated by copper-sulphides and copper-iron-sulphides. Orebody thickness ranges from 0.3 metres to over 50 metres, with mining targeting the thickest and richest mineralization. The ore zone can occur at different stratigraphic levels, from below the Kupferschiefer black shale interval to several metres above the Zechstein limestone.

The copper deposits exhibit a zonation pattern adjacent to a major redox front (Rote Fäule), including a hematite ($Fe^{3+}$) zone, a precious metal zone (Au, Pt, Pd), a copper zone (chalcocite, bornite, chalcopyrite), a lead and zinc zone, and a distal pyrite ($Fe^{2+}$) zone.

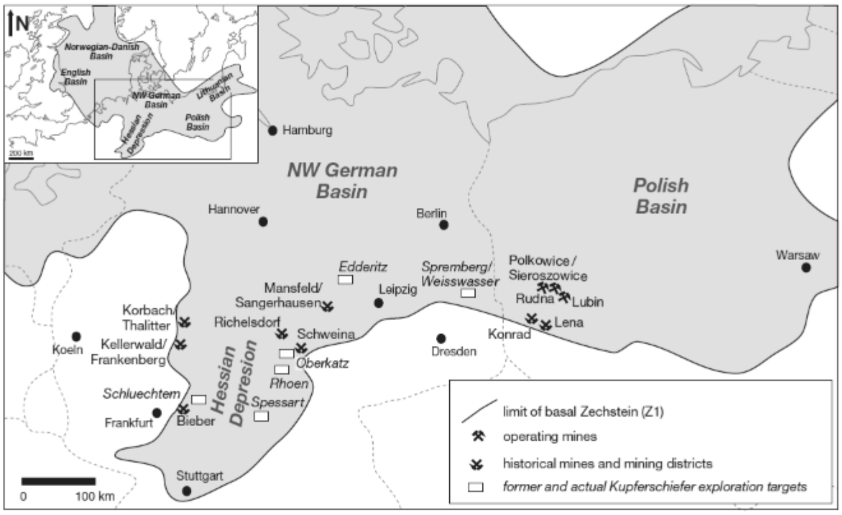


Figure 5.4-2. Simplified map of the Kupferschiefer basin in northern central Europe including the copper mining districts (Borg, 2012)

Kupferschiefer mining districts are located within an arcuate belt above magmatic arc basement rocks, typically at fault intersections. Metal distribution, orebody geometry, and grades are structurally controlled. Recent paleomagnetic dating suggests late epigenetic mineralization ages of 149 and/or 53 million years, supporting a metallogenic model involving two major pulses of metal introduction.

Understanding the Central European Basin's geological history, from the Late Carboniferous to the Palaeogene, is crucial for contextualizing Kupferschiefer mineralization within European plate tectonics. Major crustal rearrangements from the Late Jurassic to Mid-Cretaceous, including the breakup of Pangaea, likely remobilized metalliferous brines, forming Kupferschiefer and Upper Silesia's MVT Pb-Zn ores. A younger, Palaeogene, event also influenced base-metal provinces, linked to crustal movements and metalliferous fluid flow, accompanied by regional magmatic pulses. Late vein-type Co-Ni-rich mineralization, upgrading existing ores, evidences this hydrothermal activity in German districts like Spessart and Rhön-Richelsdorf (Borg, 2012).

In the Netherlands, the Kupferschiefer is part of the Zechstein Group, Z1 (Werra) Formation, covering the northern part of the country (Figure 5.4-4). It occurs as a ~1m thick, finely laminated marker horizon with a total organic carbon content up to 5%, at depths from 700 to >5000 metres (Geluk, 2007). The Kupferschiefer has been intersected by many oil and gas exploration and production wells, forming the cap rock for major Dutch gas fields hosted in the underlying Rotliegend sandstones. The economic significance of oil and gas resources in the Rotliegend overshadows the potential metal production from the Zechstein-Kupferschiefer. Despite its considerable depth, limited thickness, and lack of observed copper mineralization, the mineral potential of this unit has never been systematically tested. However, considerable material is available in the Geological Survey of the Netherlands' core repository for testing its mineralogical and chemical composition. One report mentions fine-grained chalcopyrite in the Kupferschiefer horizon, deemed economically insignificant at the time (Van Waterschoot van der Gracht & Tesch, 1918).

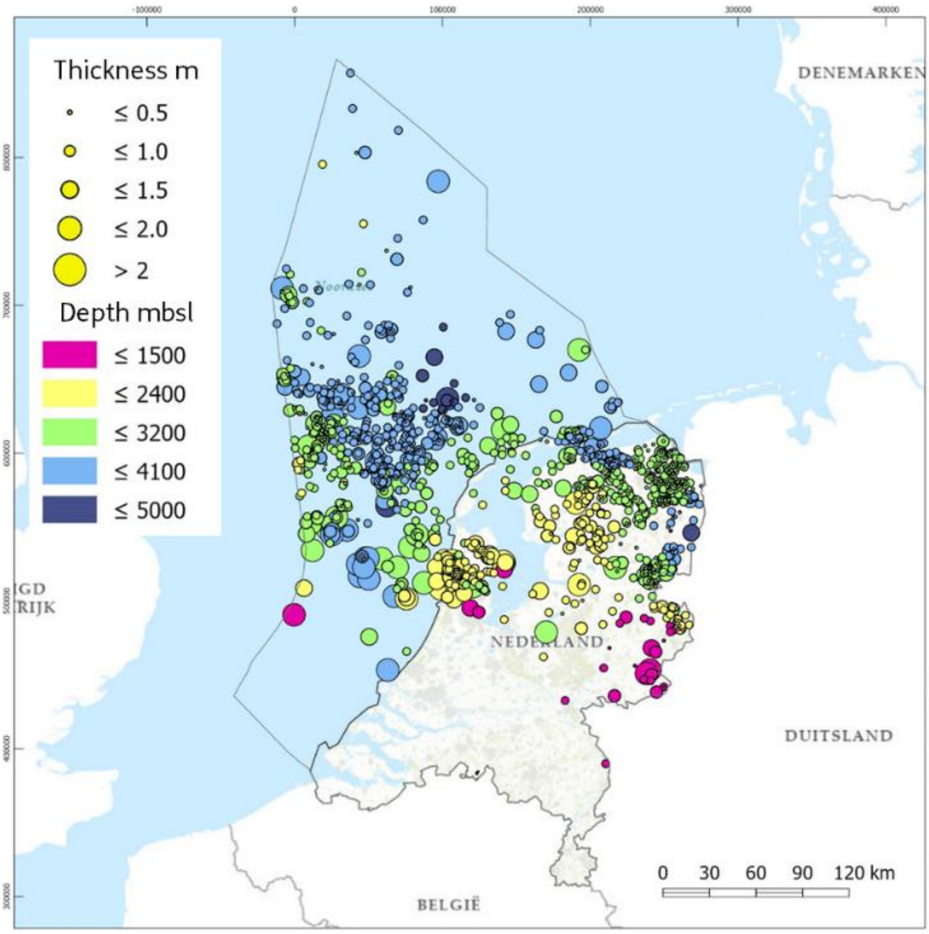


Figure 5.4-3. Intersections of Kupferschiefer in bore holes for oil and gas exploration indicating depth and thickness. Data source: NLOG.

## 5.4.3 Igneous rocks

The latest overview of where magmatic rocks have been encountered, published in Geology of the Netherlands (Van Bergen et al., 2025), compiles data from 101 boreholes containing various igneous rock successions. Radiometric ages were determined for 33 samples, and geochemical analyses were conducted on 80 samples from 15 boreholes. This data, combined with seismic, gravity, and magnetic information, forms the basis of current understanding of magmatic processes in the Dutch subsurface.

Since the first discovery in 1923, episodes of magmatic activity from the Palaeozoic and Mesozoic eras have been identified. Cenozoic igneous materials, mainly glacial erratics and volcanic ash from outside the Netherlands, are not discussed here. The magmatic episodes align with northwestern European events like the Variscan orogeny and Jurassic magmatism around the North Sea Central Graben (Figure 5.4-4). The oldest unit, a Caledonian granite, is found offshore at the Elbow Spit High. From the Carboniferous to lower Permian, multiple intrusive and extrusive rock successions are present, mainly in the east. These rocks formed during lithospheric stretching and rifting related to the Variscan foreland. Carboniferous sections are dominated by mafic intrusions, while the upper Carboniferous-lower Permian 'Rotliegend volcanics' show subalkaline to mildly alkaline rhyolitic and basaltic compositions. Late-Jurassic igneous rocks, including the Zuidwal and Mulciber volcanoes, are found both offshore and onshore, deposited in shallow marine environments with near-surface subvolcanic intrusions and lava flows. All sampled rocks exhibit a silica-undersaturated alkaline composition.

Two additional magmatic intrusions have been inferred from geophysical data and geothermal anomalies. The East Groningen Massif, inferred from a positive magnetic anomaly, structural contours of the Rotliegend top, and coalification in upper Carboniferous sediments, is located to the northeast. The Erkelenz intrusion, near the Peel Boundary Fault Zone of the Roer Valley Graben in the southeast, is modelled after a positive magnetic anomaly and a small gravity anomaly, with observed coalification of overlying sediments.

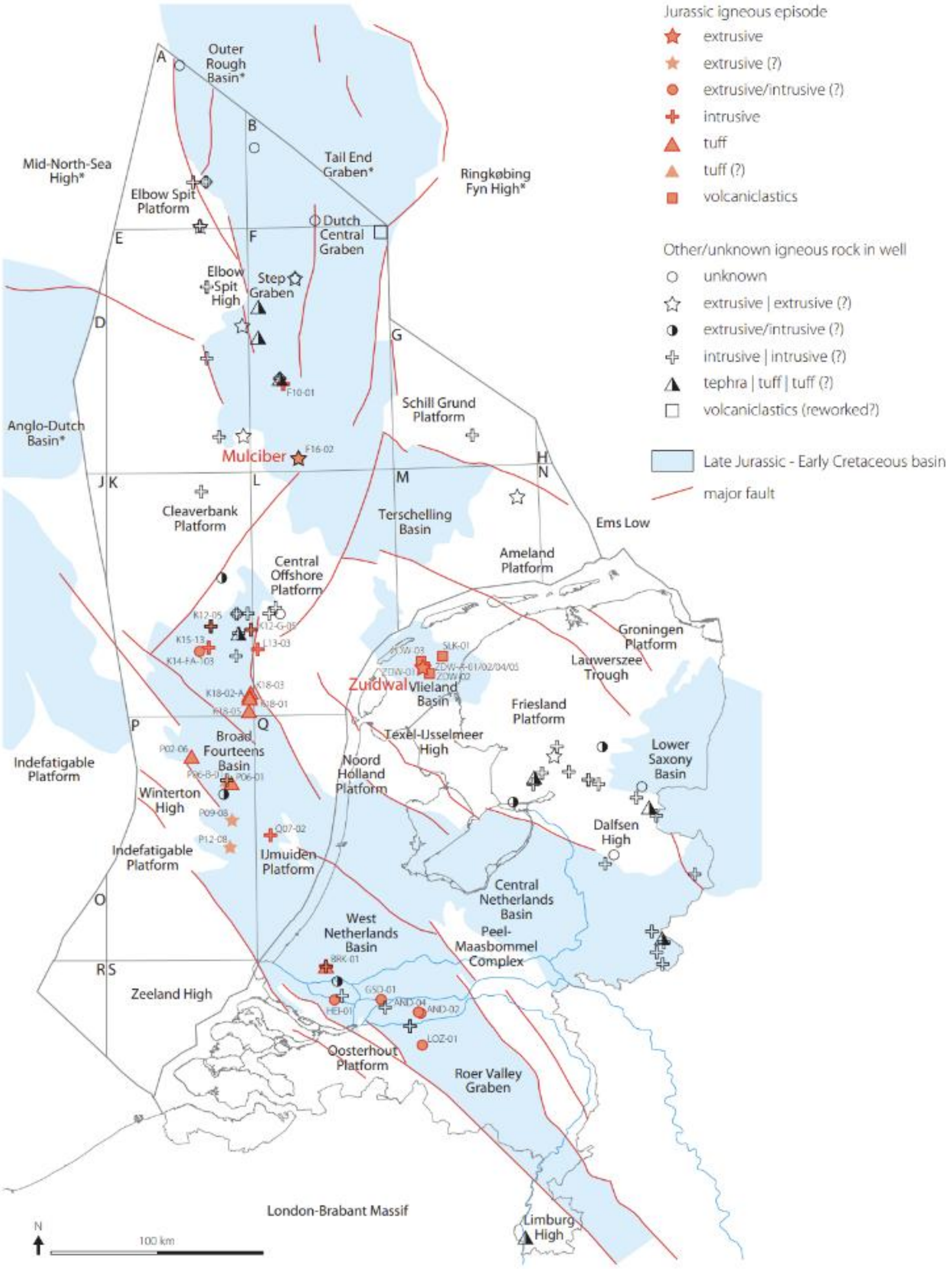


Figure 5.4-4. Wells located in the Netherlands in which igneous rocks have been found.

### 5.4.4 Resource potential

It is difficult to define and quantify the economic potential for lead-zinc sulphide mineralization and associated CRM based on the current knowledge of the Dutch subsurface. In general, it is perceived that the economic potential is rather low. Based on the present literature review, the vicinity of historic lead-zinc mining in East-Belgium makes the southern part of Limburg a logical next step for geological research projects.

The resource potential of the Kupferschiefer in the Netherlands is considered small and largely unknown. The regionally extensive shale horizon contributes to the potential. Hypothetically, a 2-cm thick layer of bornite (common copper-sulphide mineral in Kupferschiefer mineralization) over a 4 x 4 km area could host over 1 million tonnes of copper. However, this is likely an overestimation and prior to considering the technical challenge of accessing and recovering copper at such depths. Major mining companies like BHP, Rio Tinto, and Anglo American are exploring in-situ recovery techniques. Anglo American has acquired exploration licenses in Germany, where mineralization is more intense and at shallower depths.

All studied igneous rocks from various magmatic events show alteration features, though the exact processes and timing remain unknown. Hydrothermal activity related to the emplacement of igneous rocks may concentrate valuable minerals along fluid migration paths. Anomalous $CO_2$-rich gas compositions, linked to Upper-Jurassic volcanic events in areas like Zuidwal and P01-P2 offshore blocks, suggest hydrothermal activity. Fluid and gas migration may leach, mobilize, and precipitate minerals, including CRM.
However, the exploration potential of igneous rocks in the Netherlands is extremely limited due to their location at depth and partly offshore. This inaccessibility, combined with limited data, has discouraged exploration initiatives. Further study is needed to assess the potential of magmatically sourced CRM and validate exploration efforts.

### 5.4.5 Suggested research activities

To comprehensively assess the sulphide mineral resource potential the Netherlands and South Limburg and East Gelderland in particular, several steps are recommended:

**Geophysical data inventory**

- Compile existing geophysical surveys to identify uncovered areas and assess data quality. Digitize analogue data and paper maps. Evaluate the suitability of existing data for supporting CRM exploration.

**New geophysical surveys**

- Conduct ground and airborne geophysical surveys (using planes, helicopters, drones) to gather subsurface information, especially in areas covered by glacial soils. These non-invasive methods offer extensive depth penetration and systematic execution. Technological advancements have improved data quality and depth penetration. Evrard (2018) demonstrated the effectiveness of various geophysical techniques for lead-zinc exploration in East Belgium, which could be applied to southern Limburg. Start with a small area of interest, like Bommerig, using magnetic drone surveys and ground EM surveys to map structures and identify conductive areas.

**Historic boreholes inventory**

- Review historic boreholes and log descriptions stored in geological survey repositories. Utilize modern technologies like hyperspectral core scanning and portable XRF to detect previously unnoticed geological and geochemical signatures. Re-examine and sample historic drill cores, integrating new mineral systems analysis concepts and technological advancements.

**Zn-Pb-mineralization potential**

- Investigate the CRM potential for Zn-Pb mineralization associated with the Muschelkalk formation in eastern Netherlands. Compile an inventory of available boreholes and review log descriptions.

**Kupferschiefer potential**

- Conduct systematic chemical analysis of existing drill core and cuttings from GDN and oil/gas operators. Use portable XRF for initial screening, followed by detailed geochemical and mineralogical lab analysis. If significant mineralization is found, invite commercial and scientific partners for further research. Monitor technological advancements in drilling and in-situ recovery.

**CRM potential of igneous rocks**

- Select relevant borehole sections to assess the CRM potential of igneous rocks by whole-rock geochemical characterization, petrography, and hyperspectral scanning.

## 5.5 Mined Deposits

C | Mg | Si

Some minerals with CRM potential like magnesium salt and silica sand have been mined for several decades and continue to be extracted in the Netherlands. These minerals can be used to potentially produce critical materials such as magnesium metal (ultra-light alloys) and silicon metal (computer chips), respectively. The reserves and extraction potential will be assessed in collaboration with industrial parties. Other industrial minerals like feldspar and fluorite are not found in sufficient volumes or at mineable depths in the Dutch subsurface.

The EU CRM list also includes metallurgical or coking coal, which is found in known and historically mined coal deposits, making up about half of total coal resources in the Netherlands. This form of high-purity coal is suitable as a source of cokes production, which is used in steel manufacturing.

### 5.5.1 Silica sand

Silica sand, a quartz resource, is used in various industries (Van der Meulen et al., 2009, van der Meulen et al, 2025). Silica sand with minimum $SiO_2$ percentages from 97.0 to 99.8%, is used in various industries, including glass (~55%), chemical (15%), ceramic (~20%), and foundries (~10%). Lower-grade silica sands are used for masonry, sand joints in pavements, and sand-faced bricks.

Most natural silica sands do not meet high-purity requirements and need upgrading through washing, wet screening, attrition, acid leaching, froth flotation, and magnetic or gravity separation. In the Netherlands, silica sands usually require only washing or a combination of washing and attrition. Production of silica sand in the Netherlands increased from around

0.4 Mt/yr in the 1980s to around 0.8 Mt/yr in the early 2000s, driven by the use of lesser-grade silica sands. Significant exports go to Germany, and imports come from Belgium and Germany.

Ultra-high-purity silica sand could potentially be used to produce silicon metal, a critical raw material with high economic importance and supply risk due to dependency on imports from a few countries and lack of substitutes. However, Dutch silica sand is not currently used for silicon metal production due to impurity levels (>25 ppm) and technical challenges in arc furnaces due its fine grain size.

The Miocene Groote Heide Formation in South Limburg, near Heerlen, contains some of the purest silica sands in Europe (Van der Meulen et al., 2009, van der Meulen et al, 2025, Munsterman et al., 2025), resulting from a combination of quartz-rich source material, coastal depositional sorting, and paedogenic processes. These sands are often intercalated with lignite layers, which may have acted as carbon adsorption filters reducing the mineral content of percolating groundwater.

Other silica sand occurrences are found in eastern Gelderland, Overijssel, and southern and northeastern Noord-Brabant (Figure 5.5-1). These areas have been added to the silica sand inventory based on geological evolution, depositional environment, stratigraphical unit, and physical properties of the sand (e.g., Gruijters and Menkovic, 2002; van der Meulen et al., 2009). This includes silica sands within the Oosterhout, Peize, Stramproy, Kieseloolite, and Breda formations.

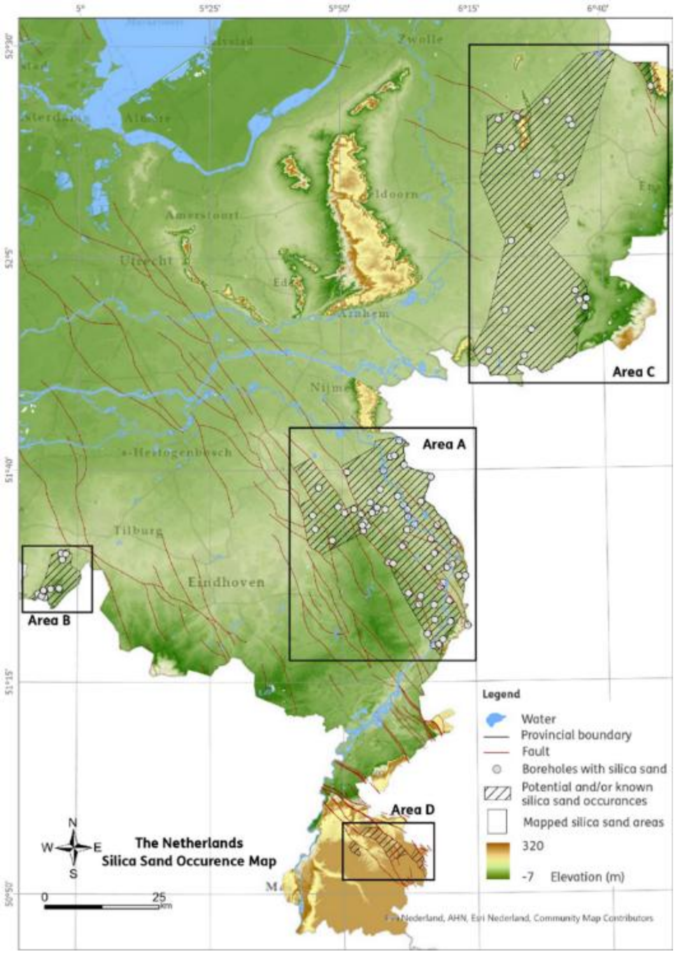


Figure 5.5-1: Mapped silica sand target areas, including available bore hole information

## 5.5.2 Magnesium salt

The upper Permian Zechstein salt is the most widespread and thickest salt formation in the Netherlands and Western Europe, stretching from the Scottish coasts to western Belarus and southern Latvia. It contains rock salt, potassium-magnesium salts, and thick sulphates (Bouroullec & Geel, 2025). Salt has been exploited in the Netherlands since 1919 through solution mining. Rock salt was first discovered in the eastern Netherlands during the 1880s in a drinking-water well (Wassmann & Brouwer, 1987). Later, during the drilling campaign by the National Agency for Exploration of Minerals between 1903 and 1923, more deposits of rock salt and potassium-magnesium salts were found in the east of the Netherlands (Van Waterschoot van der Gracht & Tesch, 1918). Additional salt domes and pillows were identified from seismic surveys conducted between the 1950s and 1980s, leading to new concessions, including potassium-magnesium salts) in the Veendam concession.

Magnesium salts within some of the salt pillows have been confirmed through gas well drilling from the 1960s onwards, with pure magnesium chloride salt, bischofite, found exclusively in the area between Veendam and Slochteren. Three evaporation cycles have been recognized in this salt, with potassium and magnesium salts separated by layers of halite (sodium salt). The first cycle contains most of the magnesium salts and all of the bischofite, while the second and third cycles contain only carnallite. The depth ranges from 1300 to 1800 metres. Halite layers occur in all wells with equal thickness and composition, but magnesium salts are interbedded with thin layers of halite, reflecting daily or seasonal variations in the depositional brine concentration.

The Veendam pillow contains approximately 1700 Mt of $MgCl_2$ in minerals carnallite and bischofite, excluding kieserite), of which a small portion is permitted for production. About 10 Mt have been produced since 1973, with an additional 2.1 Mt remaining as reserve. Magnesium-salt production is constrained by total permitted subsidence levels as well as technical-economic factors, such as the estimated recovery rate of 10-15%. The Veendam concessions also include the Sappemeer pillow, which is assumed to contain about half to equal amounts $MgCl_2$ compared to the Veendam pillow. This wide range in estimated contents is due to the limited availability of seismic data on which volume calculations are based.

Magnesium salt can be used to produce magnesium metal using electrochemical refining. However, magnesium-metal production from the Veendam salt is currently not considered economically feasible with known technologies due to the energy-intensive conversion process and high energy prices. Theoretical production from Veendam could be around 50 kt/y, representing 5% of current global annual magnesium metal production (USGS 2025).

Limited information is available regarding the position and thickness of Dutch magnesium salts outside the Veendam concession. A 2022 study (Pichat, 2022) produced isopach maps using open data, hinting at larger bischofite occurrences below the Dutch North Sea. Although there is no known viable offshore bischofite production, further research could enhance knowledge of magnesium salt occurrences in the Dutch subsurface.

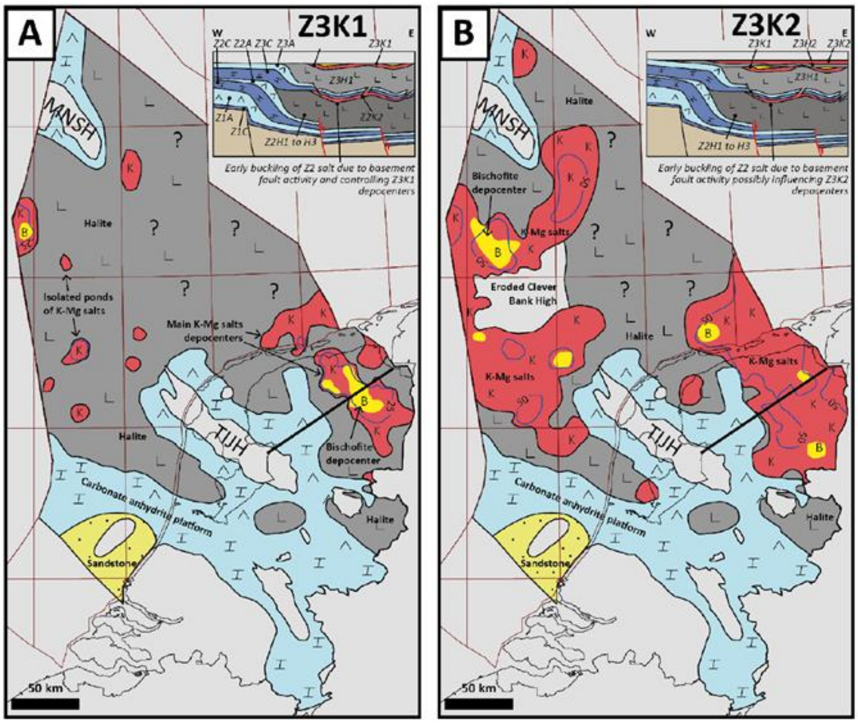


Figure 5.5-2. Examples of facies and isopach map of Zechstein 3 with indications of possible bischofite occurrences (Pichat, 2022)

### 5.5.3 Coking coal

Coal can be classified from both industrial and geological perspectives, both of which are essential for assessing coking coal resources. Industrially, coal is categorized into non-coking (thermal) coal and coking (metallurgical) coal. Non-coking coal does not soften and resolidify during carbonization, making it unsuitable for coke production. Coking coal, when heated in the absence of air, transforms into a plastic state, swells, and solidifies to form coke, which is used as a fuel and reducing agent in steel production. Coking coal is hard, contains about 90% carbon, and has low levels of impurities such as volatile components, sulphur, and phosphorus. It also has a low ash content of 1-10% (Meshram et al 2015).

Carboniferous coal-bearing sedimentary deposits of Westphalian age underlie most of the Netherlands. They accumulated for more than 60 million years and have a present-day maximum thickness of 5.5 km (Van Buggenum & Den Hartog Jager, 2007; Kombrink, 2008). These deposits contain numerous organic-rich layers classified as anthracite or bituminous coal, with anthracite typically buried deeper than bituminous coal.

Coal-bearing deposits are found at shallow depths in the southernmost Netherlands but deepen northward to more than 3 km, reaching up to 10 km offshore in the northern Central Graben. The main coal-bearing deposits belong to the Baarlo, Ruurlo, and Maurits formations of Langsettian to lower Bolsovian age (321-311Ma - Huis in 't Veld & Den Hartog Jager, 2025). During over half a century of production, an estimated 582 Mt of coal were produced from thirteen mines in South Limburg. Despite this historic production, large coal resources remain in Limburg and elsewhere.

Interest in coal was renewed in the 1980s due to the second oil crisis and new techniques like underground coal gasification. This led to an inventory of coal deposits down to a depth of 1500 m, revealing a coal resource of 591 Mt in the fault block between the Tegelen Fault and the Peel-Boundary Fault zone. Based on results from deep wells and shallow boreholes, reserves of about 2500 Mt of coal exist at depths less than 1500 m below mean sea level in seams of exploitable thickness.

In the Achterhoek area in the east of the Netherlands, bituminous coal reserves at depths between 900 and 1500 m were estimated at about 360 Mt. However, mining never took place due to prohibitive costs and risks, along with a lack of economic interest (Visser, 1987). Further investigations since the 1980s estimated total coal resources shallower than 1500 m in the greater Achterhoek area, including south Overijssel, to be about 9100 Mt (Van Bergen et al., 2000).

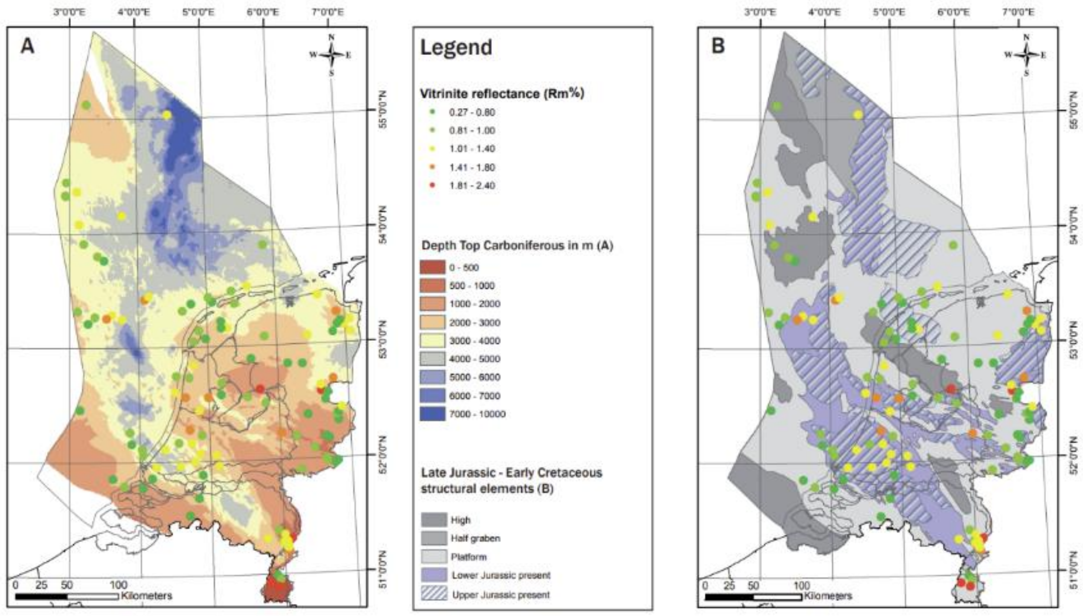


Figure 5.5-3. Maturity at the Top Carboniferous. Source: nlog.nl

## 5.5.4 Resource potential

The quality and volume of silica-sand deposits have been studied across the Netherlands (Van der Meulen et al., 2009, van der Meulen et al, 2025). Up until now the results encompass rough estimations with large error margins. Currently, the volume of silica sand is estimated at 6 – 15 km3 (van der Meulen et al., 2009).

According to Nedmag, there is 3500 $Mm^3$ of magnesium-salt resources available in the Veendam pillow, however the maximum production under permit equates to 3.7 million ton. For its kind, the Veendam pillow is a particularly large resource, but due to limitations to the permitted land subsidence full volume will not be produced. Currently there are no resource estimates for the areas outside of the Veendam pillow. As shown in Figure 5.5-2 there are multiple locations where bischofite is encountered in boreholes, but no volume estimations have been made.

In the absence of a well-established ratio of coking vs non-coking coal in the Netherlands, a ratio of 50% is used as applied by the German and Belgium geological surveys for the same northern European coal basin. Under this assumption the estimated potential resources of coking coal in the Dutch subsurface would be equivalent to around 6000 Mt combined for the Peel (2900 Mt total estimated coal resource) and greater Achterhoek (9100 Mt total estimated coal resource) area.

## 5.5.5 Suggested research activities

### Silica sand

- The resource potential of silica sand is fairly well understood, although resource quality should be further investigated. In cooperation with the two existing operators of silica sand quarries, an inventory of high-quality silica sand will be updated, further integrating borehole information, geochemical data, and land-use information.

### Magnesium salt

- For magnesium salt, carnallite and bischofite occurrences are recognizable using seismic data and gamma logs from oil and gas wells. Building on the research of Pichat (2022), magnesium salt occurrences in the Dutch subsurface can be mapped and thicknesses can be calculated. If desired and feasible, 3D models can be constructed and be cross correlated with information from Nedmag. Strategic development of the Nedmag product line and the economic and strategic considerations for producing magnesium metal could be taken into account.

### Coking coal

- The coal resources are sufficiently well understood. Additional studies could assess the estimation in further detail and could integrate the presence and depth of the richer Westphalian A and B deposits versus the less rich Westphalian C/D deposits through geological interpretation and modelling. An integral part of this work is the re-evaluation of available logs and samples from core-storage facilities to assess the coal quality and better quantify its coking-coal percentage.

## 5.6 Industrial & Municipal Waste

Al | Cu | Mg | Mn | Ni | Ti | V

The recovery of CRM from residual waste streams is rapidly evolving due to increasing material demand and evolving technologies capable of treating low-grade ores and secondary materials. The global mining sector is actively pursuing the reprocessing of tailings for secondary CRM extraction, as highlighted by the CRMA (2024). The Netherlands lacks such tailings, apart from ponds from coal washing with negligible CRM potential. Additionally, the Netherlands produces significant volumes of mineral-like industrial waste, such as steel slags and bottom ashes from municipal waste incineration. These materials are formally not a part of the subsurface geology, they are often used as aggregate. A recent study on CRM recycling in the Nordic countries highlights the potential of these materials for secondary CRM recovery (Bergfald et al., 2024 (Figure 5.6-1).

Despite widespread processing and application of these waste products, they are not yet optimized for metal recovery. The present exploration program will make an inventory of available quantities and assess the recoverability of critical and strategic materials from these waste products. Bottom ashes and steel slags, used as aggregate in the subsurface, offer a more suitable target for CRM recovery than household-waste landfills. Slags and ashes are both products of high-temperature processing, concentrating CRM in specific mineral phases, which makes them more amenable to extraction, if not immobilisation. Their controlled placement and geochemical stability ensure greater accessibility and predictability compared to household waste, which poses regulatory and environmental challenges. Studying steel slags and bottom ashes aligns with circular economy goals and could enhance secondary resource recovery without disrupting existing land use.

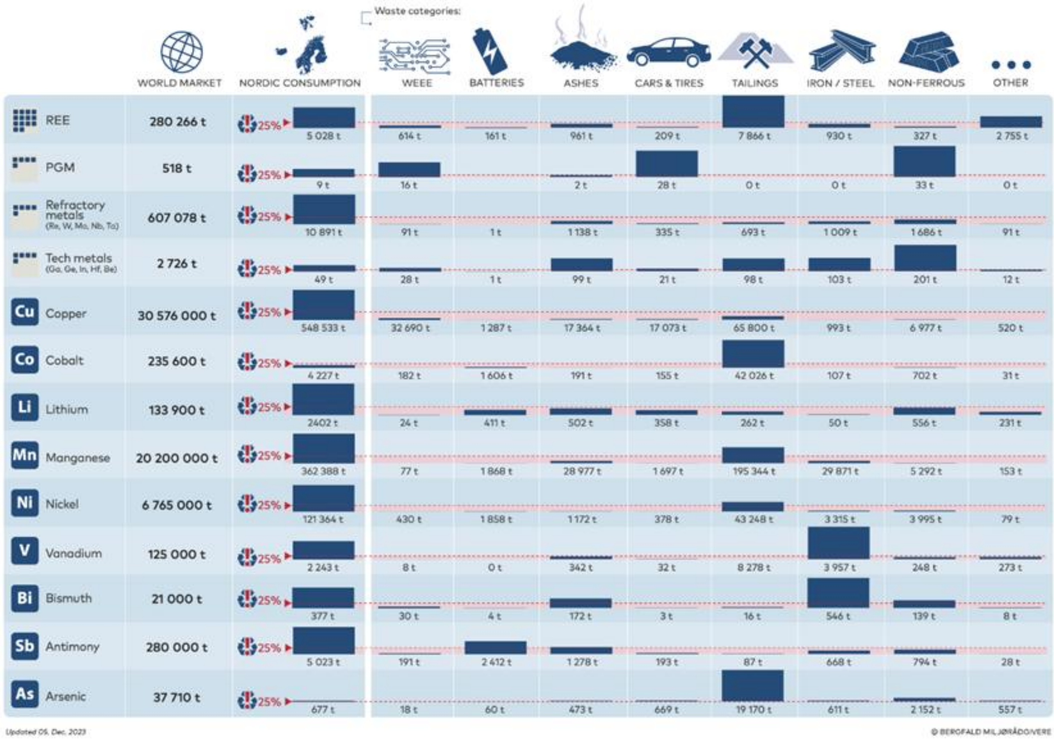


Figure 5.6-1. CRM fraction in tonnes of various waste categories produced in the Nordic countries. Source: Bergfald et al., 2024

## 5.6.1 Slags and ashes

The Netherlands annually produces approximately 700 kt of Linz-Donawitz (LD) steel slags, originating from Tata Steel operations in IJmuiden. Most of this slag is used as foundation material in infrastructural works, replacing primary aggregates. Coarse fractions (90-180 mm) are used in hydraulic engineering works, while finer fractions (<90 mm) are used in infrastructural works. Before application, slags must comply with legal contaminant-leaching limits (Soil Quality Decree/Environment and Planning Act). A recent study by the National Institute for Public Health and Environment recommended further research on leaching values of applied LD-steel slags (RIVM, 2023). Considering the volume of LD-steel slags and their metal contents, these mineral-like materials comprise a potential source of CRM that could be recoverable.

Municipal solid waste incineration (MSWI) bottom ashes and fly ashes are produced in 13 waste-to-energy plants in the Netherlands. Bottom ash is the solid residue after incineration, while fly ash is collected from air emission-control systems. The Netherlands produces about 1.7-2 Mt of MSWI bottom ash annually (Rijkswaterstaat, 2022), representing 10% of the EU's total (CEWEP, 2021, 2018). Advanced recovery techniques collect ferro- and non-ferro metals (~200 kt) from these ashes. The remaining 1500-1800 kt of bottom ash is primarily used in infrastructural works. Like LD-steel slags, bottom ashes must meet legal contaminant-leaching limits. Bottom ashes that do not meet these limits are used in landfills as supporting or cover layers. Over the past decade, MSWI bottom ash has been increasingly treated by washing and carbonation to improve environmental quality and expand its use in construction. After treatment, it can be used in concrete as a secondary aggregate (Informatiepunt Leefomgeving, 2025).

A significant fraction of MSWI ashes and LD-slag is used as secondary aggregates in construction. Since 1986, approximately 36 Mt of MSWI bottom ash has been produced in the Netherlands, with most of it used in infrastructure at around 550 locations (TAUW, 2020), primarily in road shoulders and beds.

MSWI fly ashes are produced at about 200 kt annually. Around 120 kt is stabilized in cementitious products to prevent contaminant leaching and is then landfilled. The remainder is used as filler material in asphalt.

Slags and ashes contain trace elements in relatively high concentrations compared to the average soil composition (Allegrini et al., 2014; Dijkstra et al., 2019). LD-steel slags are enriched in Cr and V, while MSWI bottom ashes are enriched in metals like Cu, Zn, and Pb, with fly ashes containing even higher concentrations. MSWI ashes also contain a wide range of trace elements, including rare earth elements and platinum group metals. The composition of MSWI bottom ash and LD-steel slag varies within narrow boundaries across the EU but may change over time due to evolving waste composition or operational differences.

Ferro and non-ferro metals are recovered from MSWI bottom ash soon after production using magnetic separation and other recovery methods. However, recovery is not complete, and MSWI bottom ash remains heterogeneous, containing metals in various forms. The mineralogy of Dutch LD-steel slag is complex but well-defined (Van Zomeren et al., 2011).

When used in construction, slags and MSWI ashes must be tested for leaching potential to ensure compliance with environmental limits. These tests use prescribed column test procedures (NEN, 2003) and demineralized water under local equilibrium conditions (TNO, 2024). Limit values apply to a curated set of elements, not covering the full spectrum of potential leachates. Certain elements, such as Li, are of interest due to their mobility and value as CRM. Treatments like artificial carbonation can enhance the leaching of elements like V, which are both CRM and contaminants.

Tailings and waste rock have garnered increasing attention for CRM recovery. There are no metal-mining tailings in the Netherlands, but historical coal production in Limburg generated waste in the form of mine water, waste rock, and sedimentation ponds from coal washing. These waste products may contain minor residual metals, possibly CRM, but their coal origin reduces their potential compared to metal ore. Today, Dutch spoil tips or 'terrils' are either integrated into the landscape or have been remediated, primarily containing limestone and sandstone, and are no longer available for any form of processing.

During coal production in Limburg, sedimentation ponds were used to dispose of various materials, including bottom ash and fly ash (Cattoir & Schouten, 1985). These incineration products are interesting from a CRM perspective (Thomas et al., 2024), though the exact share of ashes in sedimentation ponds is unknown. Dilution of ashes mixed with waste rock was in the order of 1:8 (Cattoir & Schouten, 1985), negating any recovery potential. Moreover, like the terrils, most sedimentation ponds have been remediated or integrated into the landscape.

## 5.6.2 Resource potential

Slags and ashes are potentially valuable resources for CRM recovery in the Netherlands due to their composition and continuous large-scale production, provided recovery is economically and technically feasible. MSWI ashes contain a wide range of elements in various impure chemical forms, including glassy phases that may be chemically inaccessible (Alam et al., 2019; Bayuseno and Schmahl, 2010; Dijkstra et al., 2006; Piantone et al., 2004; Zevenbergen et al., 1998). Elements enriched in steel slags, such as Cr and V, are also present in relatively inaccessible forms (Neuhold et al., 2019; Van Zomeren et al., 2011). Recovery can potentially be achieved through leaching for the more mobile elements, although not all elements of interest may leach significantly due to being strongly bound in the solid phase. Artificial carbonation may stimulate leaching in some cases. Table 5.6-1 indicates the potential annual availability of CRM in these materials, assuming full recovery based on concentrations presented.

Table 5.6-1. Estimation of CRM potential in Dutch MSWI bottom ash and LD steel slags, in kt/y (Dijkstra et al., 2006).

| | Annual NL production kt in MSWI Bottom ash | Annual NL production kt in LD steel slag | | Annual NL production kt in MSWI Bottom ash | Annual NL production kt in LD steel slag |
|---|---|---|---|---|---|
| Si | 367,2 | 44,1 | Cl | 6,8 | <0,7 |
| Ca | 147,9 | 214,9 | Ti | 10,2 | 4,9 |
| Fe | 156,4 | 128,1 | P | 5,1 | 4,2 |
| Al | 68 | 7 | Cu | 5,1 | <0,7 |
| Na | 35,7 | <0,7 | Pb | 5,1 | <0,7 |
| Mg | 22,1 | 31,5 | V | <1,7 | 4,2 |
| K | 15,3 | <0,7 | Cr | <1,7 | 0,7 |
| S | 13,6 | <0,7 | Mn | 1,7 | 24,5 |
| Zn | 6,8 | <0,7 | | | |

### 5.6.3 Suggested research activities

**Evaluation of existing compositional data from slag and ash materials**

- Extensive data on the leaching properties of various waste materials, including slags and ashes, have been generated over time. The existing data will be evaluated to assess the potential for CRM recovery from refined slags and ashes.

**CRM potential in secondary aggregates**

- Improve mapping and characterisation of mineral-like industrial waste products that are or have been used as secondary aggregate in the Netherlands. To the extent possible, map the spatial distribution and estimate volumes of reused LD-steel slags and MSWI bottom ashes.

# 6 Planning & Implementation

## 6.1 Implementation framework

The previous chapter describes the current understanding and level of knowledge of six exploration themes. Several research activities are suggested here to progress our understanding in the various themes and to arrive at an objective position on the potential of identifying mineral resources hosting CRMs in the Dutch subsurface. In the first half of the previous century, two major mineral-exploration campaigns were initiated and funded by the Dutch government directly. One comprehensive study ran from 1903-1916 (Van Waterschoot van der Gracht & Tesch, 1918) and another was conducted during World War II (Koning et al., 1946). The suggested activities in this program constitute a list of research trajectories, some of which have been initiated under the 2025 NMO activities. The majority of the research activities is yet to be budgeted and planned.

The NMO has the capacity and capabilities to initiate many of the suggested research activities. These activities align with GDN's mandate to acquire, assess, and manage subsurface information at a national scale to benefit research, policy advice, and economic activities, as well as raising public awareness. Analogous to the role of the GDN in hydrocarbon and geothermal exploration and production, enhanced understanding of the mineral-resource potential provides a basis for future activities following up with (public or private) exploration activities in those areas where potential may be high, or again contributing to informed land-use planning in areas where potential is low or negligible. Regulations that cover data and data management under the Mining Act could inspire similar arrangements with respect to CRM potential.

General aims of the research are: growing the knowledge base through the progressive compilation and assessment of geochemical and geophysical databases relevant to CRM-hosting mineral systems, acquiring additional analytical and surveying data to fill spatial data gaps and increase data density with a focus on CRM, and reviewing innovative extraction methods to assess the feasibility of responsible extraction practices.

In addition to the research activities under the six exploration themes, a few broader general activities are proposed to support the execution of the national exploration program and communicate its outcomes to relevant stakeholders.

- Firstly, existing databases with relevant geological, geochemical, and geophysical data will be assessed for their potential value in providing new insights through data analysis. Selected databases will then be interrogated using advanced analytics and, where appropriate, AI applications for deep learning, to identify any CRM-exploration potential. In this effort, expert groups at universities will be engaged to leverage their knowledge and data-processing capabilities.

- Secondly, any new geochemical and mineralogical data gathered during the suggested activities will be stored in a central database. This database can be harvested by the European Min4EU database and provides EU-wide insights into its mineral resources on the EU platform EGDI. The development of the central database is an essential step in the national exploration program and will serve as the source for a public portal through which the information about the mineral resource potential will be released.

- Thirdly, relevant research outcomes will, once released, be published in news releases, conference presentations, research papers, and other communications, and used for future stakeholder-engagement purposes, including outreach to local communities, regional authorities, industry organisations, and the scientific community.

Results generated throughout the execution of the national exploration program and their implications with respect to the CRM-hosting mineral resource potential in the subsurface will be aggregated annually for reporting to the Netherlands' Ministry of Economic Affairs, and every five years to the EU CRM Board, as stipulated in the CRMA (2024).

## 6.2 Suggested research activities

Possible research activities have been recommended throughout this review. The selection of relevant research topics for further investigation will be made in close collaboration with the Ministry of Economic Affairs. Once selected, detailed estimates of total effort and related budgets will require consideration and costing of the suggested research in comprehensive proposals. It is important to state that the suggested activities reflect an initial effort to understand CRM-hosting mineral-resource potential in the Netherlands, which may generate follow-up initiatives that are not included here, depending on the initial research outcomes.

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