DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2025/11**

Assessment of the Critical Raw Material potential of Denmark

Diogo Rosa, Kasper H. Blinkenberg, Anders Mathiesen, Niels Hemmingsen Schovsbo & Florian W.H. Smit

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

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Abstract

This report reviews the geological potential for critical raw materials (CRMs) in Denmark by assessing possible metallotects, defined as tectonic, geological, mineralogical or geochemical features which play a key role in controlling mineral deposit formation. The review is made despite the uncertainties arising from the existence of only limited data, which was essentially acquired within the scope of hydrocarbon and geothermal exploration, rather than mineral exploration targeting CRMs. Nevertheless, the potential for the Danish subsurface to host CRMs is generally considered to be low. Whereas metallotects favourable for the presence of CRM occurrences do exist, these are often found at significant depth, disrupted, and/or the documented CRM grades are relatively modest. Furthermore, in some instances at least, detrimental chemical associations or inadequate grain size constitute challenges to the economic recovery of CRMs.

The available information suggests a low potential for feldspar and possibly fluorspar (in the Precambrian crystalline basement), vanadium and nickel (in the Cambrian-Ordovician Alum shale), magnesium (in Zechstein potash salts), copper (in the Upper Permian Kupferschiefer mineral system), lithium, boron and magnesium (in formation brines), phosphorus/phosphate rock (in Cretaceous conglomerate and sandstone), silicon (in Miocene silica sands), and titanium (in Miocene-Quaternary heavy mineral placers). Only the potential for helium stands out as being considered to be low to moderate, since the key constituents for a helium kitchen have been documented and the presence of elevated concentrations, of potential commercial interest, of this gas have been confirmed in Denmark, albeit only in one well.

Introduction

Critical raw materials (CRMs) are defined by the European Commission (2023) as materials that exceed certain thresholds of supply risk and economic importance (Figure 1). The list includes antimony, arsenic, baryte, bauxite, beryllium, bismuth, boron, cobalt, coking coal, copper, feldspar, fluorspar, gallium, germanium, graphite, hafnium, helium, lithium, magnesium, manganese, niobium, nickel, phosphorus, phosphate rock, platinum group metals, rare earth elements, scandium, silicon, strontium, tantalum, titanium, tungsten and vanadium. These materials are vital for many industries, including renewable energy, electric vehicles, defence, and digital technologies. They form the backbone of a green and digital economy, playing an essential role in achieving the EU's climate neutrality and technological leadership goals.

As a result, the European Union's Critical Raw Materials Act (CRMA, 2024), which was published on 3 May 2024, and entered into force on 23 May 2024, highlights the necessity for member states to enhance their domestic sourcing of CRMs. This legislation seeks to reduce the European Union's dependency on foreign supplies of essential metals, minerals and gases, ensuring the strategic autonomy and industrial resilience of Europe in a rapidly changing global landscape. Within this framework, European Union member states are expected to draw up national exploration programs aimed at targeting CRMs.

Presently, no CRM extraction takes place in Denmark, and only limited amounts of feldspar and phosphorite were mined in Bornholm in the late 1800s and early 1900s, respectively. Therefore, Denmark holds a relatively low profile in global mining. However, an in-depth assessment of its CRM potential is warranted, triggered by the CRMA.

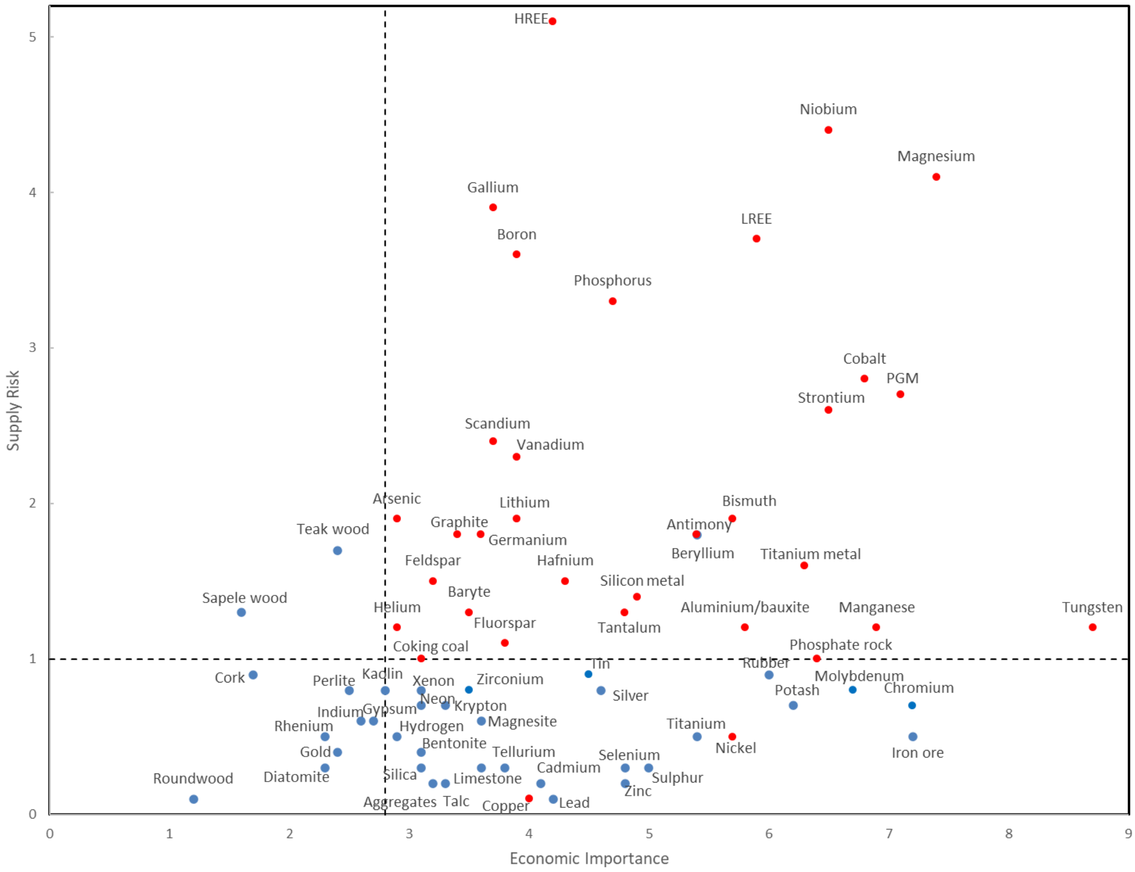


Figure 1. *EC (2023) plot of economic importance vs supply risk. CRMs are shown in red, whereas non-CRMs are shown in blue.*

Approach

This report carries out a review of Denmark's geological history, and identifies possible metallotects, defined as a specific tectonic, geological, mineralogical or geochemical feature which could have played a key role in controlling CRM deposit formation. Alternatively, in the case of the more mobile helium, occurrences are identified and discussed. Each of the identified metallotects is subsequently characterised in terms of their lithologies, depositional environments, geographical distribution and their possible CRM endowment is evaluated. However, it should be stressed that this evaluation is mostly based on data collected within the scope of hydrocarbon and geothermal exploration (mainly well reports and maps archived in the Danish Deep Subsurface Database accessible at: https://eng.geus.dk/products-services-facilities/data-and-maps/subsurface-data-denmark), rather than mineral exploration specifically targeting CRMs and hence not all relevant aspects related to the metallotects have been documented.

This endowment evaluation will focus primarily on host metals, which constitute main products during mining, instead of the so-called companion metals (Figure 2). The latter share chemical properties and, consequently, tend to occur together with the host metals. Companion metals recovery typically takes places during metallurgical processing, rather than during mineral processing. However, whereas companion metals can be important by-products, their concentrations are normally only determined at the reserve delineation stages or even during smelting and are therefore seldom reported. As a result, their potential is often not possible to anticipate during a more preliminary metallotect scoping study, as undertaken in this report. Therefore, the potential for many of the CRMs, which are considered companion metals, will remain unassessed.

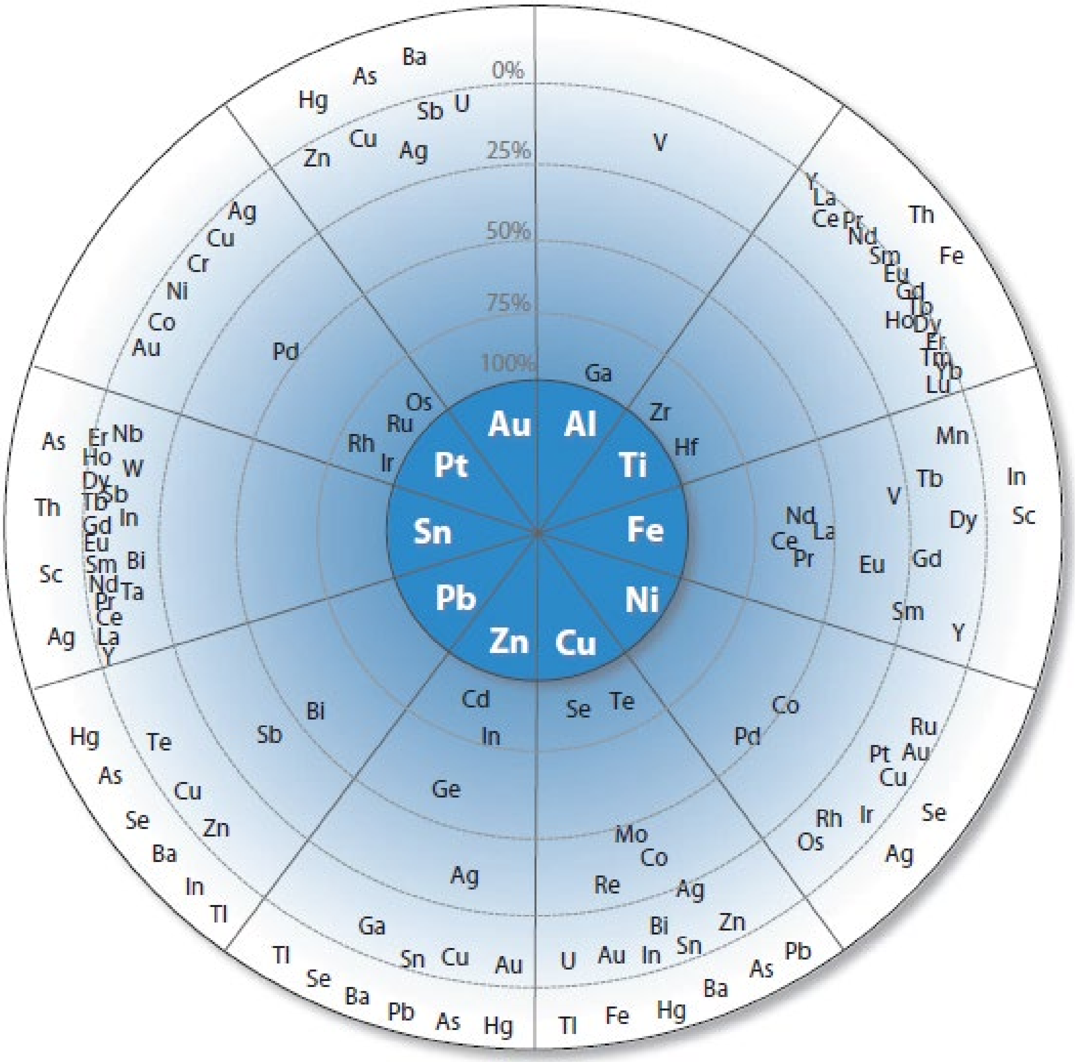
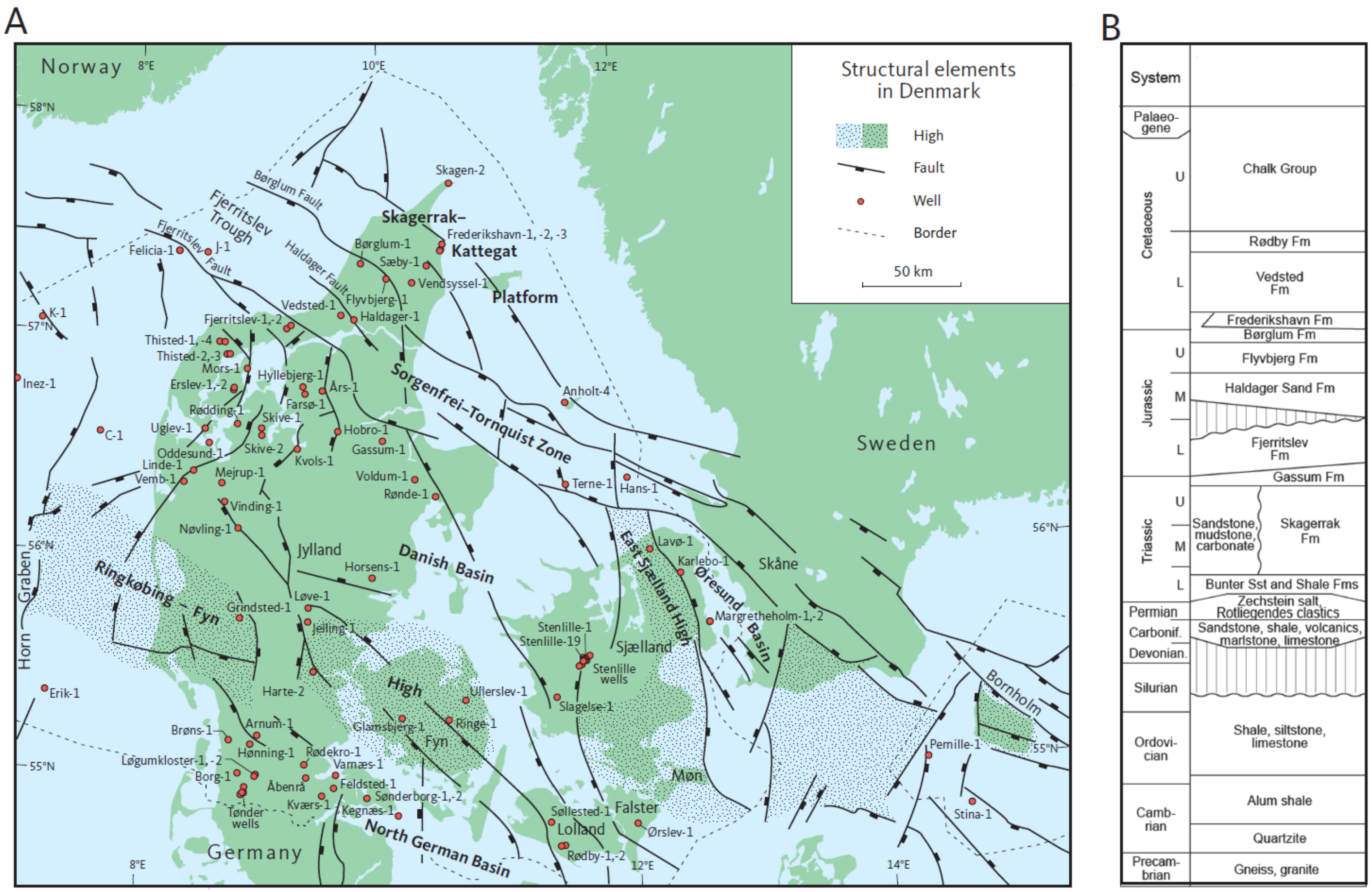


Figure 2. *The wheel of metal companionality from Nassar et al. (2015). Host metals (main or target product during mining) are shown in the inner circle and, distributed outwards along decreasing recovery from respective mineral deposits, their companion metals, typically produced as by-products.*

Geological Setting and Evolution

The Danish Basin (Figure 3A), a prominent intracratonic structure, extends WNW-ESE, bordered by the Ringkøbing–Fyn High to the south and the Sorgenfrei-Tornquist Zone and Skagerrak-Kattegat Platform to the north (Ziegler, 1990; Michelsen & Nielsen, 1991, 1993; Vejbæk, 1997; Abramovitz et al., 1998; 2000). The North German Basin is situated south of the Ringkøbing-Fyn High (Figure 3A). The Danish Basin constitutes the eastern sector of the more extensive Norwegian-Danish Basin, spanning from the Norwegian North Sea to Zealand. The region further to the east (Bornholm and southern Sweden) forms part of the Sorgenfrei-Tornquist Zone (Figure 3A), where complex strike-slip tectonism and pull-apart basins evolved (Erlström *et al.,* 1997; Vejbæk, 1997). The stratigraphic record spans Palaeozoic, Mesozoic and Cenozoic sedimentary sequences (Figure 3B).



From Gregersen *et al.* (2025)

From Erlström *et al.* (2018)

Figure 3. *A) Geotectonic setting and structural elements surrounding Denmark, with positions of deep wells. B) Composite schematic stratigraphic scheme showing the geological record of the Palaeozoic, Mesozoic and Cenozoic sedimentary sequences.*

The basin's development is closely tied to late Palaeozoic crustal extension, characterised by normal faulting and extensive magmatism (Ziegler, 1990; Abramovitz et al., 1998; 2000), leading to a highly heterogeneous stratigraphic framework controlled by tectonic, sedimentary, and climatic influences. This structural evolution plays a critical role in the location of economically significant mineral occurrences.

The foundational sedimentary sequences underlying the Danish Basin comprise Precambrian crystalline rocks [Metallotect, page 15] and Cambro-Silurian sequences, recorded in deep wells and exposed on Bornholm, Kattegat, and adjacent regions of southern Sweden and Norway (Nielsen & Japsen, 1991; Erlström et al., 1997; Erlström & Sivhed, 2012; Schovsbo et al., 2016; Nielsen & Klitten, 2023). The oldest sedimentary rocks comprise Cambrian sandstones and mudstones representing continental and near-shore deposition in a shallow epicontinental sea. Later, Cambrian and Ordovician deposition of organic-rich mudstones and carbonates resulted from continued transgression. Subsequently, a thick interval of organic-rich Silurian shale was deposited, within a deepening foreland basin (Nielsen & Schovsbo 2011, 2015; Schovsbo et al. 2016). The Danish Basin is located north of the E-W striking Caledonian Deformation Front straddling southern Denmark, along which the East Avalonia microcontinent collided with the Baltica plate (incl. Scandinavia) during the Ordovician to Early Devonian Caledonian orogeny (Ziegler 1990; Abramovitz et al. 1998). During the Caledonian orogeny, northwards movements of East Avalonia resulted in thrusting and deformation of the lower Palaeozoic succession in SE Denmark and the SW Baltic Sea (Lassen et al., 2001). These basement rocks can be locally mineralised and potentially constitute sources of critical raw materials [Metallotect, page 18].

During the Carboniferous-Permian, the interplay between lithospheric stretching and rifting facilitated the genesis of the Norwegian-Danish and North German basins, accompanied by extensive faulting and associated volcanic activity. Extensional faulting was associated with volcanism and led to formation of large, rotated fault blocks, extensive erosion, and widespread, mostly coarse siliciclastic deposition (Rotliegend Group and possible underlying Carboniferous deposits, known from a few wells in the North German Basin) (Vejbæk, 1997; Michelsen & Nielsen 1991, 1993; Stemmerik et al., 2000; Nielsen, 2003). Concurrently, the Ringkøbing-Fyn High emerged as a regional horst structure with relatively subdued extension in comparison to adjacent depocentres (Vejbæk, 1997).

The Upper Permian Zechstein Group marks a transition to late-rift thermal subsidence, characterised by the deposition of extensive evaporites and carbonates, in semi-restricted marine environments (Stemmerik & Frykman, 1989; Stemmerik et al., 2000; Peryt et al., 2010). Deposition during Zechstein time is characterized by a distinct carbonate–evaporite cyclicity, and traditionally the succession is divided into 5–7 carbonate-anhydrite-halite cycles (Z1–Z5/Z7) (e.g., Stemmerik and Frykman 1989; Peryt et al., 2010). Carbonate deposits are mainly restricted to the lower Zechstein cycles (Z1–Z3), with the system becoming progressively more siliciclastic and evaporitic over time. The Top pre-Zechstein surface (i.e. top of the Rotliegend Group) outlines the main structural elements described above and is unconformable and represents the deepest regionally mappable levels from the Danish seismic database (Vejbæk, 1997). The Zechstein evaporites are of economic interest due to their salt domes and associated mineral resources such as potash salts [Metallotect, page 23], their control on possible Kupferschiefer type copper mineralization [Metallotect, page 26], as well as acting as source for brines [Metallotect, page 30].

Subsequently, Triassic regional subsidence facilitated the accumulation of a thick siliciclastic succession, predominantly represented by the Bunter Shale and Bunter Sandstone formations, indicative of fluvio-lacustrine and arid terrestrial depositional settings (Bertelsen, 1978; 1980; Clemmensen, 1986; Bachmann et al., 2010). Deposition of the Bunter Shale and Bunter Sandstone formations occurred in fluvio-limnic and continental dominated environments with desert sand plains and sabkhas during deposition of the Bunter Sandstone Fm (Bertelsen, 1980; Clemmensen, 1986; Bachmann et al., 2010). This sandstone formation would become a significant reservoir for brines [Metallotect, page 30]. At the same time, the Skagerrak Fm developed further to the north reflecting the fluvially-alluvially dominated environment that bordered the Scandinavian Craton (Olsen, 1988). Later, during the Early Triassic, deposition occurred in large lakes, sabkhas, playas and maybe even ephemeral shallow seas especially in southern parts of Denmark (Bertelsen, 1980).

The connection to the Tethys Sea and the North European epicontinental sea in the south increased during the early Middle Triassic and mudstones and calcareous deposition took place (Bertelsen, 1980; Lindström et al., 2017). From the late Middle Triassic deposits became more sand-prone, influenced by fluvial processes and interbedded with finer grained sediments.

The Late Triassic was characterised by substantial tectonic restructuring, culminating in the Early Cimmerian Unconformity (ECU), which denotes a phase of regional uplift and erosion across the North Sea and onshore Danish region (Clausen & Pedersen, 1999; Ahlrichs et al., 2020). Contemporaneously, salt tectonics, extensional faulting, and rifting processes intensified, resulting in large variation in thickness throughout much of the Danish Basin governed by both salt motion, rifting and differential subsidence (Boldreel, 1985; Geil, 1991; Sørensen, 1998). During the uppermost Late Triassic, more humid conditions were established, and the Danish Basin became marine-influenced (Bertelsen 1980). Mud-dominated sediments with calcareous and sandy interbeds were deposited in shallow, brackish-marine environments in the deeper parts of the basin, while sand-dominated deposition was initiated at the margins (Bertelsen, 1980).

During the latest Triassic to earliest Jurassic, coastal to continental areas were repeatedly overstepped by the sea and fluvial, coastal and shallow marine sandstones interbedded with offshore mudstones (Gassum Fm) (Bertelsen, 1978; Nielsen, 2003). This sandstone formation would become another reservoir for brines [Metallotect, page 30]. Continued rise in relative sea-level, on a regional scale, during the Early Jurassic resulted in widespread deposition of thick clay-dominated successions with more silty and sandy interludes (Michelsen et al., 2003; Nielsen, 2003).

The Middle-Late Jurassic saw widespread regional uplift driven by the Mid-Cimmerian tectonic phase, resulting in pronounced erosional truncation (Nielsen, 2003). The Middle Jurassic to earliest Cretaceous tectonism and uplift contributed to sand-rich deposition mainly from the north across the Skagerrak-Kattegat Platform and Sorgenfrei-Tornquist Zone, and southwards into the Danish Basin (Figure 3A). Pauses in tectonism and renewed subsidence during the Late Jurassic to Early Cretaceous, caused increased clay and mud-rich deposition (Nielsen, 2003). Mud-dominated deposition continued during the Early Cretaceous and became more calcareous with marl and chalk units.

The Late Cretaceous was characterized by the deposition of deeper-shelf fine-grained chalks and deposition was punctuated by Late Cretaceous and early Palaeogene tectonic inversion related to the Alpine Orogeny with profound impact on the structural evolution of the Danish Basin and Sorgenfrei-Tornquist Zone (Ziegler, 1990; Vejbæk, 1997). In the Øresund Basin a 50–125 m thick Lower Cretaceous (Berriasian–Cenomanian) succession includes an up to 30 m thick sandstone overlying the base Middle Jurassic unconformity that truncates Lower Jurassic strata (Nielsen 2003; Lindström & Erlström 2011; Erlström et al., 2018). The sandstone interval is overlain by variegated claystone layers with interbeds of sandstone, followed by the Arnager Greensand (Aptian Cenomanian). The latter constitutes the top of the Lower Cretaceous mixed siliciclastic succession formed in a marginal-marine and shallow shelf setting (Norling 1981; Gravesen et al. 1982; Larsson et al. 2000). The basal part of the Arnager

Greensand, is phosphate-rich [Metallotect, page 38], and known from outcrops on Bornholm and from several wells in the Øresund Basin (e.g. The Swedish Falsterbo peninsula wells, FFC-1, Svedala-1 wells and the Danish Margretheholm-1, Lavø-1, Karlebo-1/1A wells), where the thickness is up to 60 m, possibly thinning to the north (Erlström et al., 2018).

The Cenozoic phase of basin evolution was dominated by post-rift thermal subsidence and the progressive opening of the North Atlantic. Hemipelagic sedimentation prevailed, comprising clay, marl, and diatomaceous deposits, followed by late Oligocene–early Miocene tectonic uplift (Ziegler 1990; Heilmann-Clausen, 1995; Japsen & Bidstrup, 1999; Japsen et al., 2007; Schiøler et al., 2007; Rasmussen et al., 2008; Rasmussen et al., 2010). The Miocene further witnessed the development of large-scale, sand-rich fluvio-deltaic systems in Jutland [Metallotect, page 41], reflecting significant sediment redistribution from uplifted source areas and hydrodynamic reorganisation associated with ongoing tectonic reactivation (Japsen & Bidstrup, 1999; Japsen et al., 2007; Rasmussen et al., 2008, 2010). These systems are known to host heavy mineral placers with accumulations of ilmenite [Metallotect, page 42]. During the Miocene, salt structures were active especially in the Central Graben region and more locally in the Norwegian-Danish Basin (Rasmussen, 2009; Rasmussen et al., 2010).

Quaternary deposits were predominantly governed by glacial-interglacial cyclicity, which drove extensive sedimentary reworking and geomorphological transformation (Houmark-Nielsen, 1987; 2004; Rasmussen et al., 2005, 2010). In the eastern part of the Danish area, Quaternary deposits overlay Upper Cretaceous chalk and Danian limestone, and towards the southwest they overlay Late Miocene sediments (Sorgenfrei & Bertelsen, 1954; Rasmussen et al., 2010). Glacial advances profoundly modified the contemporary topography, while post-glacial isostatic rebound and fluctuations in relative sea level influenced sediment distribution and basin morphology. These processes have resulted in the reworking and concentration of placer mineral deposits (e.g. Knudsen, 1998; Stendal et al., 2001; Lomholt et al., 2002).

Main metallotects with CRM potential

Denmark's geological history, reviewed in the previous section, is not widely recognised for its mineral wealth. Mining has traditionally focused on non-metallic minerals, particularly sand and gravel for the construction industry (Kallesøe et al., 2016).

However, the carried-out review has led to the identification of several metallotects with the potential to host CRMs. These metallotects are of varying geological ages and are associated with different phases in Denmark's geological history. The key metallotects are outlined below, highlighting their significance in the context of Denmark's geological evolution and potential to host CRM deposits.

Crystalline basement

Small-scale feldspar mining took place in Vestermarie Plantage, in Bornholm, between 1873-78. It appears that this occurrence is related to pegmatites of the Almindingen Granite, part of the islands' Mesoproterozoic crystalline basement (Waight et al., 2012). Also in Bornholm, fluorspar was observed in pegmatites in the Dalegård quarry (Bojesen-Koefoed, pers. comm.). However, these old mines and occurrences should not be considered more than geological curiosities, holding only a low potential to sustain a modern mining venture.

Significant deposits of CRMs related to Mesoproterozoic magmatism do occur in the Fennoscandian Shield, namely the REE-Hf Norra Kärr deposit in Sweden and Ti-(V) deposits in Norway and Sweden (Jonsson et al., 2023). However, these significant deposits are related to peralkaline and mafic magmatism, respectively, rather than felsic magmatism as registered in Bornholm.

Finally, the island of Bornholm is the only place in Denmark where crystalline basement is exposed. Elsewhere in the Danish subsurface, Mesoproterozoic crystalline basement has been intersected in two drillholes (Grindsted-1 and Glamsbjerg-1) at depths of ca. 900-1600 m. These wells were drilled along the Ringkøbing-Fyn High, and crystalline basement is expected to be at significantly larger depths elsewhere (Olivarius et al., 2015). As such depths (Figure 4), the potential for the crystalline basement to constitute a source of CRMs related to peralkaline, mafic or felsic magmatism can be considered negligible.

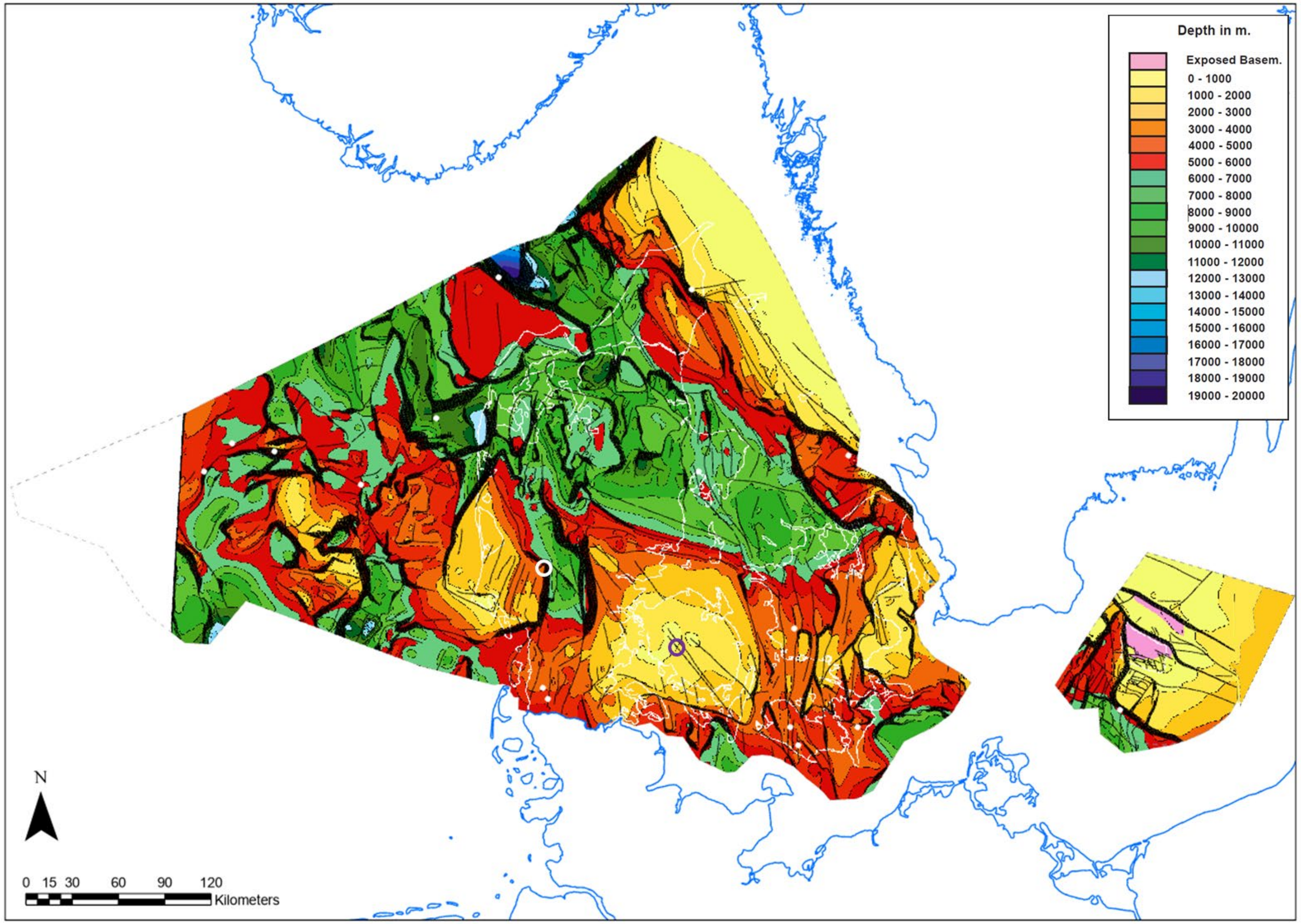


Figure 4. *Distribution at depth, drill intersections (white dots), of Precambrian rocks in Denmark. Notice the two circles around the Grindsted-1 (white circle) and Glamsberg-1 (purple circle) deep wells. Modified from Lassen & Thybo (2012).*

In summary (Table 1), whereas the crystalline basement can be a prolific metallotect elsewhere in the Fennoscandian shield, it is found at significant depths and appears to be lacking the fertile types of Mesoproterozoic magmatism (peralkaline or mafic) in Denmark. This metallotect is therefore considered to hold a low CRM potential.

Table 1. *SWOT analysis of the crystalline basement of Denmark as a potential source of CRMs (REE, Hf, Ti, V, feldspar, fluorspar, etc).*

	Helpful	Harmful
Internal	STRENGTHS Prolific REE-Hf and Ti-V metallotect elsewhere in the Fennoscandian shield	WEAKNESSES Outcrops only in Bornholm, present at significant depths elsewhere in Denmark Unknown or insignificant peralkaline and mafic magmatism, controlling the presence of REE-Hf and Ti-V mineralisation in Sweden and Norway
External	OPPORTUNITIES Expanded EU strategic autonomy requirement could attract interest	THREATS Increase in the complexity of the regulatory framework

Cambrian-Ordovician Alum Shale

The lower Palaeozoic Alum Shale Formation (mid Cambrian/Furongian–Early Ordovician) in Scandinavia (Figure 5) is widely recognised for its high concentrations of critical metals (Bergström & Shaikh, 1980; Andersson et al., 1985; Armands, 1972; Schovsbo, 2001, 2002; Nielsen & Schovsbo, 2007; Gill et al., 2011; Yang et al., 2020; Bian et al., 2021). In particular, the Ordovician "Dictyonema shale" contains elevated levels of the critical metals vanadium and nickel, used in batteries. Although this mineralisation is of considerable economic interest, the underlying enrichment processes, sedimentary mobility, and final residence sites of vanadium remain poorly understood.

The Alum Shale Formation reaches thicknesses of up to 180 m in Denmark and thins to less than 0.5 m in eastern Estonia and the St. Petersburg District of Russia. It has notably high total organic carbon (TOC) content—often exceeding 2 wt%, and in some intervals reaching up to 25 wt%—dominated by hydrogen-rich type I/II kerogen. Overall, the formation is lithologically uniform, composed predominantly of laminated pyritic shale. However, the Cambrian succession exhibits significant variation linked to differences in the abundance of carbonate concretions and beds. Within the Cambrian section, clay mineral and quartz contents tend to be higher, whereas K-feldspar levels are roughly half of those measured in equivalent Ordovician intervals. A large proportion of the K-feldspar, along with over 30% of quartz and illite in the Lower Ordovician shale, is interpreted to be of authigenic origin, suggesting that diagenetic processes were influential in shaping the formation's mineralogical characteristics.

Deposition of the Alum Shale Formation occurred in an extensive epicontinental sea along the western margin of the Baltica continent during the Miaolingian, Furongian, and Early Ordovician (Tremadocian) periods. The basin spanned an area of about 1,000,000 km², encompassing parts of what are now Denmark, Estonia, Finland, Norway, Poland, Russia, and Sweden. The depositional environment was oxygen restricted leading to enrichment in a range of trace elements notably redox sensitive elements such as V, Mo and U and chalcophile elements such as Ni, Zn and As (Buchardt et al., 1997).

Subsequent tectonic and thermal events heavily influenced the shale's current distribution and maturity. During the late Silurian–Early Devonian Caledonian Orogeny, Alum Shale in Denmark, Norway, Poland, and southern Sweden was deeply buried and reached oil window or even anchi-metamorphic conditions. Later, the intrusion of sills and dykes in the Late Permian locally raised temperatures in portions of Norway and Sweden. Ongoing tectonic activity from the late Palaeozoic through the Mesozoic and Cenozoic, combined with erosion and glaciation, caused considerable removal of Alum Shale in many regions. As a result, the formation is now preserved largely as isolated outliers in large parts of Norway and Sweden.

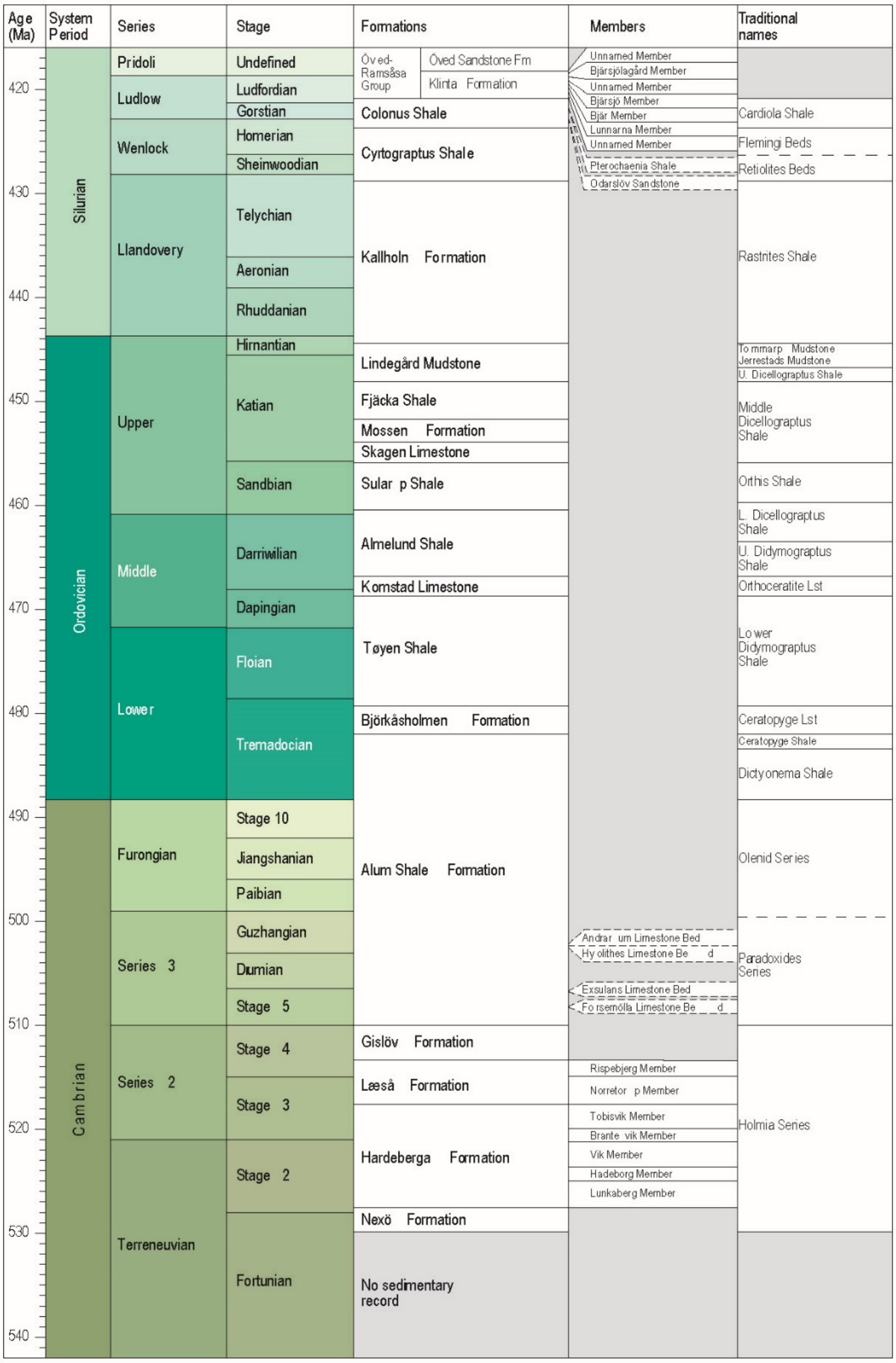


Figure 5. *Lithostratigraphic section of the Cambrian to Silurian succession of southern Scandinavia, modified from Calner et al. (2013), with numerical ages from Cohen et al. (2013).*

In southern Sweden, the Alum Shale has been studied and mined on a small scale since the mid-20th century. Historical test mining for vanadium took place in the 1940s at Flagabro, Skåne, and early resource assessments on southern Öland indicated more than five million tonnes of vanadium-bearing material. Numerous outcrops and old quarries across Sweden have provided valuable stratigraphical information, while core drilling campaigns—carried out both historically by geological surveys and more recently by private exploration companies—have further refined our understanding of the Alum Shale's mineralisation and lateral extent.

Beyond Sweden, the Alum Shale extends into large parts of Norway, Denmark, and the Baltic region, although subsequent tectonic, erosional, and igneous events have fragmented and sometimes thermally altered these shales. Despite these complexities, renewed interest in critical raw materials has sparked fresh exploration initiatives, particularly in southern Sweden and Estonia. The combination of substantial organic carbon content, favourable depositional conditions, and a demonstrated presence of critical metals makes the Alum Shale Formation an important target for future vanadium resource evaluation, as well as a broader contributor to European mineral security.

In Denmark, the Alum Shale Formation can reach significant thicknesses—up to around 180 m in certain offshore locations (well Terne-1) but is generally around 30 m thick —highlighting its importance as part of the broader Baltoscandian Basin. No depth structure map is available for the formation, but the depth is evaluated from the near top Precambrian basement depth structure map as the formation is assumed to be located around 100 m above this depth (Figure 4). For more details on the distribution see Nielsen & Schovsbo (2007). According to this interpretation the formation is typically buried to more than 1.5 km across Denmark. Onshore, the shale is found in more limited exposures, including a few outcrops and quarry sections, as well as in drill cores obtained through shallow exploration on the island of Bornholm (see Nielsen et al. 2018). These cores confirm the presence of elevated levels of critical raw materials (CRMs), notably vanadium (V) and nickel (Ni), which are closely linked to the formation's high organic content and anoxic depositional conditions.

Regional mapping of vanadium accumulation in Denmark, Estonia, Sweden and Norway (Figure 6) has been presented by Bian et al. (2021). Vanadium concentrations above 5000 ppm—the highest recorded in Scandinavia—have been documented in Skåne, southern Sweden (Bian et al. 2021). In addition to vanadium, the Alum Shale was mined for uranium in central Sweden during the 1970s (Andersson et al., 1985), and active exploration for vanadium continues in both southern Sweden and northern Estonia (Hade & Soesoo, 2014).

No mapping of nickel concentrations has been made, it is here assumed that the V/Ni (ppm/ppm) to be about 100. Typical concentrations of vanadium can approach or exceed the "hyper-enriched" threshold (c.f. Bian et al. 2021)—around 1000 ppm—in certain horizons, while nickel commonly ranges from tens to a few hundred ppm. Such variations largely reflect local sedimentary processes, thermal maturity, and the extent of post-depositional alterations. Where the shale remains relatively less thermally overprinted, preservation of organic matter tends to correlate with higher metal contents. Although much of the Alum Shale in Denmark has been affected by geological events over time, these local accumulations of CRMs remain of interest for both research and potential resource development.

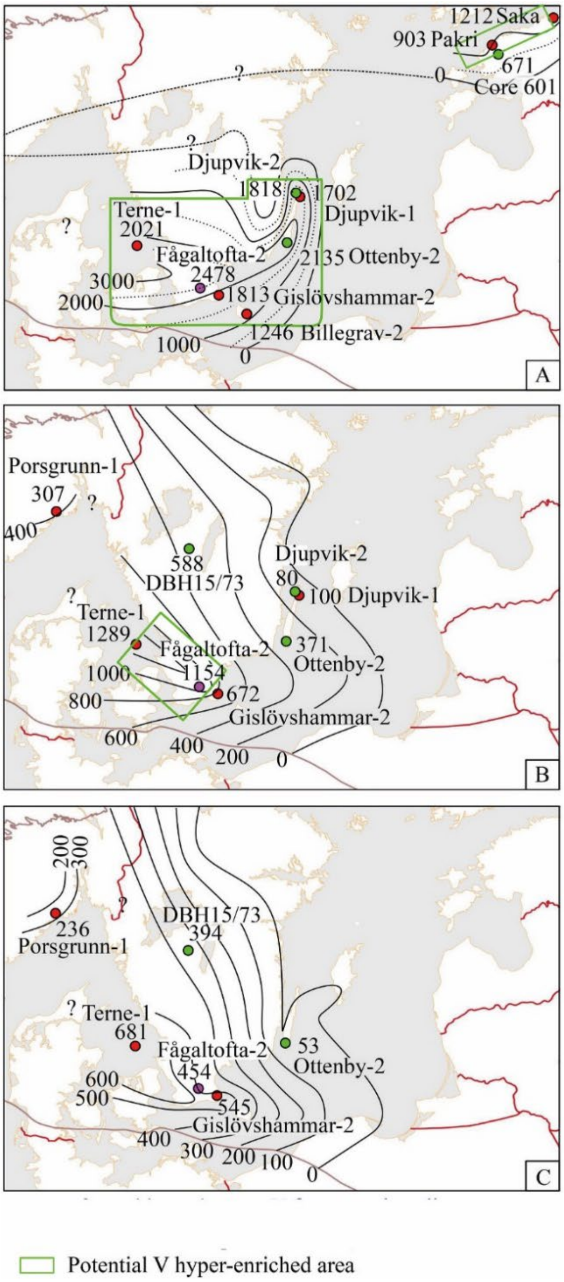


Figure 6. *Vanadium enrichment (in ppm) in Denmark, Estonia and southern Norway and Sweden. A) Upper Ordovician, B) Furongian, C) middle Cambrian (Miaolingian). Modified from Bian et al. (2021).*

Overall, Denmark's potential vanadium and nickel resources present a mix of opportunities and serious challenges (Table 2). Whereas the Alum Shale Formation is known to host significant concentrations of V, a critical raw material with an expected growing demand, and which could potential be extracted with Ni and U as by-products (U: typical range 50-300 ppm, Schovsbo 2002), this formation is typically thin and present at significant depths. Furthermore, the elevated organic carbon contents and potential greenhouse gas emissions as well as the presence of uranium and ensuing radiological issues could be constraints in possible mining developments. A strategy focusing on environmental stewardship and technological innovation will be key to determining whether these resources can be successfully and responsibly developed, but this metallotect is considered to hold a low potential for CRMs in Denmark.

Table 2. *SWOT analysis of the Alum Shale Formation in Denmark, as a potential source of V and Ni.*

	Helpful	Harmful
	Helpful	Harmful
Internal	STRENGTHS Significant V concentrations Potential recovery of Ni, U as by-products	WEAKNESSES Significant depth and thin beds in most of Denmark Different metals of interest accumulated in distinct horizons, implying mining of wider interval if they are all to be recovered
External	OPPORTUNITIES Vanadium demand expected to grow, for energy storage (e.g., redox flow batteries) and high-strength steel alloys Expanded EU strategic autonomy requirement could attract interest	THREATS Increase in the complexity of the regulatory framework High organic carbon content could be an issue in terms of greenhouse gas emissions Radiological risks

Zechstein potash-salt deposits

Potash salts form in response to prolonged evaporation of seawater and constitute the final precipitation-stage of the evaporation cycle (Friedman & Sanders 1978). The term encompasses a broad range of K and Mg-bearing chlorides and sulphate minerals (e.g. Warren, 2010), of which Mg is considered critical.

Halite and associated potash-salts were deposited within a deeper-shelf basin, developed in response to periods of prolonged evaporation of Zechstein seawater during the latest Permian in an area covering large parts of the Southern and Northern Permian Basins across Europe (Figure 7). In Denmark, Zechstein salt deposits are widespread across the onshore Danish Basin, North German Basin and the North Sea area and are observed as domes, ridges and diapirs in the subsurface and form volumetrically the most important potash-salt deposits in northwestern Europe (Figure 8).

Salt exploration activities started during the early 1930's and Dansk Salt began production in Mariager, northern Jutland during the late 1960's (Jacobsen et al., 1984). Today, commercial halite production by Nobian is mainly developed for industrial purposes and road salt production. Several attempts to delineate potash deposits have taken place over the years, however, today, no exploitation has taken place in Denmark. Early efforts to delineate potentially commercial K-Mg-salts were carried out in several shallow-lying diapirs but proved difficult to develop due to extensive tectonic disturbance and folding (Jacobsen et al., 1984). The deeper-lying salt structures proved commercially unviable, despite the presence of potash beds due to more demanding production costs caused by deep drilling (Jacobsen et al. 1984).

Potash beds are easily recognised utilizing modern well-log data. The Potash-salts are best developed in the Z2 and Z3 Zechstein cycles providing a predictive stratigraphic framework for exploration.

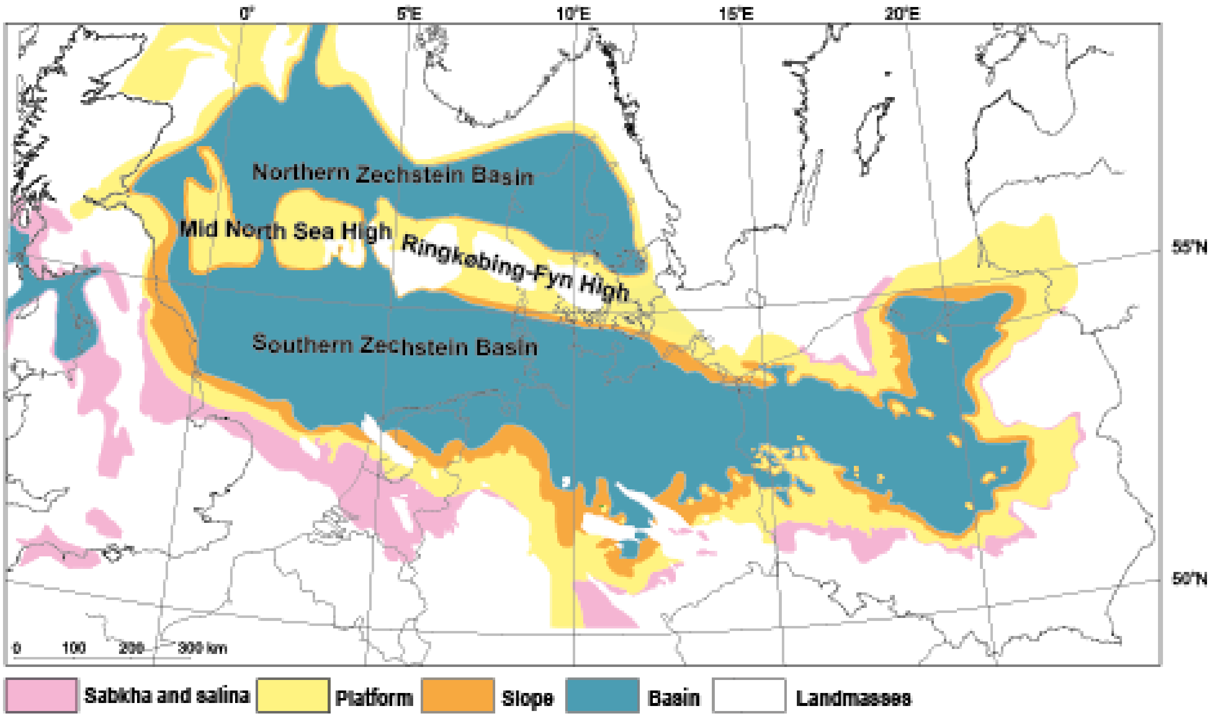


Figure 7. *Palaeogeographic reconstruction and distribution of the Zechstein during Z2 times. Halite accumulations are restricted to the deeper basinal settings (dark blue colour) where they occur with potash-salt accumulations. Modified from Słowakiewicz et al. (2018).*

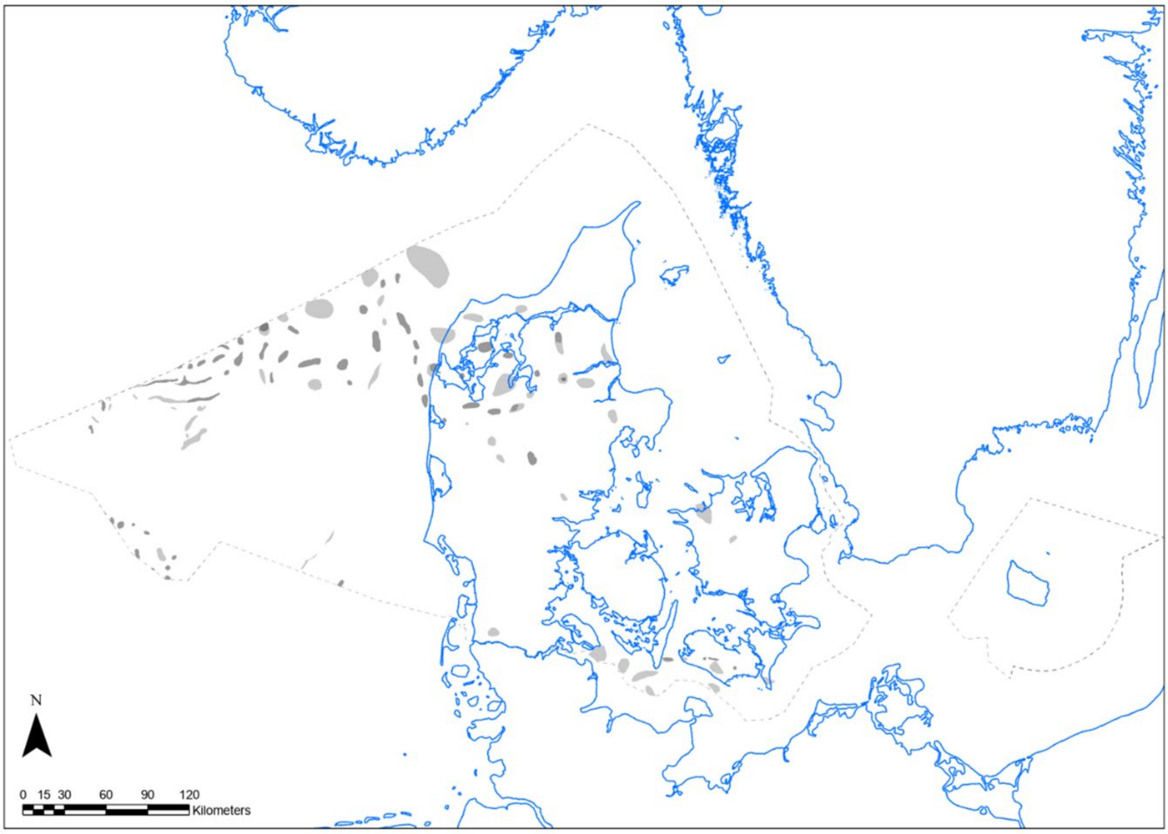


Figure 8. *Map showing the distribution of salt domes (dark grey) and salt pillows (light grey), in Denmark. Sourced from the Danish Deep Subsurface Database.*

In summary (Table 3), Denmark holds some potential for the production of Mg salts, as a co- or by-product of halite mining already taking place. This is provided the challenges of deep mining or of the mining of tectonically disrupted beds can be overcome. However, the CRM in the EC (2023) list is magnesium metal, rather than Mg salts, since the criticality is mostly linked to the large energy inputs needed for its production, rather than geological constraints. The high energy inputs for the production of magnesium metal have promoted the migration of its production to countries with lower energy costs or with lower greenhouse gas emission constraints. As such, the potential for Denmark to produce magnesium metal is considered low, even though source raw materials (Mg salts) can potentially be produced.

Table 3. *SWOT analysis of the Zechstein potash-salt deposits in Denmark, as a potential source of CRMs (Mg).*

	Helpful	Harmful
Internal	STRENGTHS Known Mg salt presence Potential for halite co-production Potential for caverns in salt diapirs to be used for energy storage, providing further economic synergies.	WEAKNESSES Mostly deep diapirs Shallower diapirs have the lateral continuity of Mg-rich horizons affected by folding and tectonism
External	OPPORTUNITIES Magnesium (metal rather than salts) demand expected to grow Expanded EU strategic autonomy requirement could attract interest	THREATS Increase in the complexity of the regulatory framework

Upper Permian Kupferschiefer mineral system

The Kupferschiefer mineral system is among the most important metal sources in Europe and one of the largest sediment-hosted Cu-systems worldwide (e.g. Hitzman, 2010; Borg et al., 2012). Exploitation takes place in Poland and Germany, where pyrite in Rotliegend-aged continental siliciclastics, and lowermost Zechstein-aged organic-rich shales (T1), marginal-marine carbonates and anhydrite (Z1), has been replaced by bornite, chalcocite and chalcopyrite and a suite of other economically important minerals (Borg et al., 2012). These sediments are widely distributed across Europe (Figure 9) and were deposited within an extensive intracratonic basin that developed during the Late Permian (e.g. Peryt et al., 2010).

The mineralisation, restricted to an approximately E-W trending belt along the southern margin of the Southern Permian Basin (Figure 9), crosscuts stratigraphy and is therefore epigenetic. Mineralisation took place from 255 to 245 Ma, according to the palaeomagnetic dating of hydrothermal hematite (Nawrocki, 2000) or at 240+/-3.8 Ma (Pasava et al., 2007) or 204+/-0.5 Ma (Pätzold et al., 2002), based on Re-Os dating of sulphides, whereas K-Ar dating of authigenic illite yielded results varying from 216 to 190 Ma (Bechtel et al., 1999) and palaeomagnetic dating of pyrrhotite and magnetite provided late epigenetic ages of 149 or 53 Ma (Symons et al., 2011). This variety of ages suggests that the mineralisation took place in several stages, from soon after Kupferschiefer deposition in the Late Permian and for at least 100 Ma after, possibly until the Jurassic, and is linked to the episodic release of hydrothermal fluids from the subsiding adjacent Southern Permian sedimentary basin.

In Denmark, Rotliegend- and Zechstein-aged sediments have been penetrated by numerous deep wells during several phases of oil and gas exploration activities in the 1950's, 1980's (Stemmerik & Frykman, 1989; Nielsen & Japsen, 1991), and a short-lived exploration phase during the late 2000's (Figure 10). It is unclear whether any core was analysed for base metals, but trace base metal sulphides have been reported from the Zechstein (Blinkenberg et al., 2024) and the Jurassic (Weibel et al., 2019, 2022)) in Norwegian and Danish offshore hydrocarbon wells. Furthermore, Rote Fäule, an alteration feature which confirms the circulation of metal-bearing oxidising hydrothermal fluids, occurs in northeastern Germany (Rentzch et al., 1997). This is interpreted as a favourable indicator for mineralisation along the southwestern flank of the Ringkøbing-Fyn High by Zientek et al. (2015). Notwithstanding these encouraging signs, and despite a similar stratigraphic and depositional development on and along the Ringkøbing-Fyn High to that described in the German and Polish part of the basin, no substantial copper mineralisation has so far been recognised in the Danish subsurface. This is likely a result of a different diagenetic and tectonic evolution of the area in comparison with the time-equivalent German and Polish part of the succession.

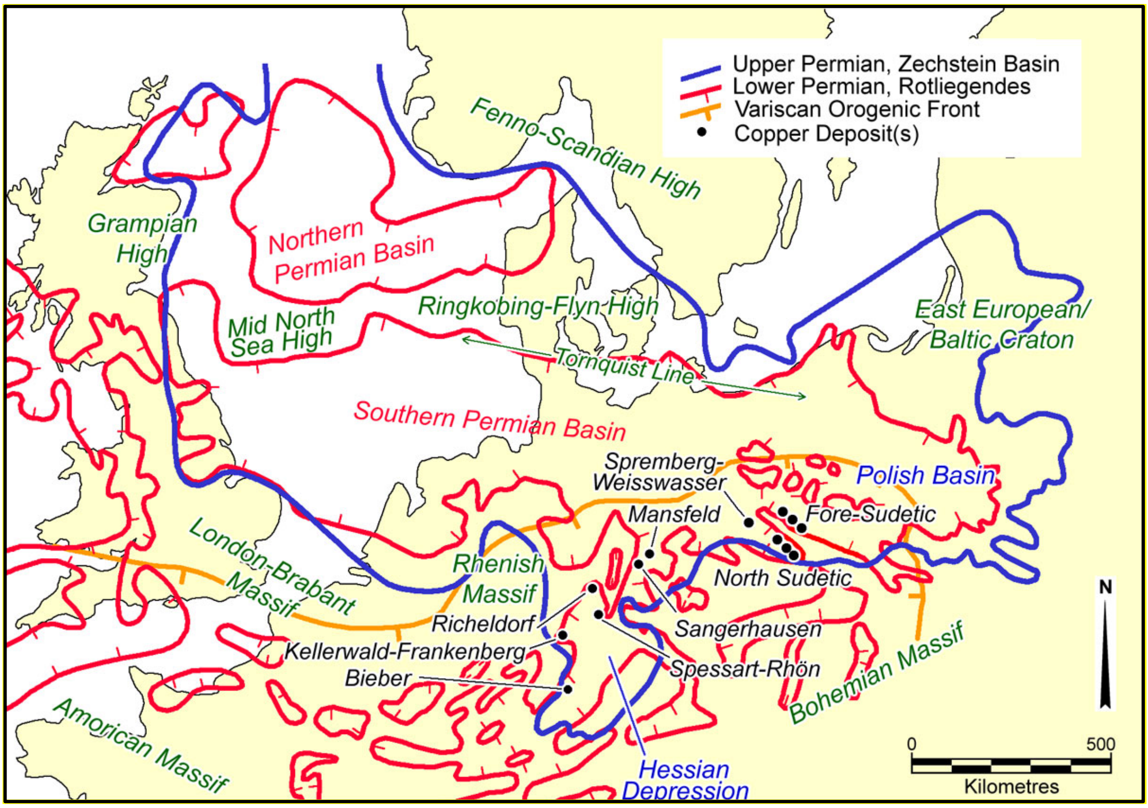


Figure 9. *European Zechstein basin and kupferschiefer sedimentary copper deposits in Poland and Germany (after Oszczeplaski)*.

In summary (Table 4), even though there is evidence for an active hydrothermal system affecting the sedimentary succession and the presence of traces of base metal sulphides in offshore oil wells has been reported, significant metal accumulations have not been documented in Denmark. This likely reflects a different diagenetic and tectonic evolution in Denmark than in southern Poland and Germany, so that volume of fluids and/or the effectiveness of the channelling of fluids could have been limited. Furthermore, the depth at which the key stratigraphic interval is located is considerable (Figure 10). For these reasons, the potential for the Kupferschiefer mineral system in Denmark for Cu and associated companion metals is considered low.

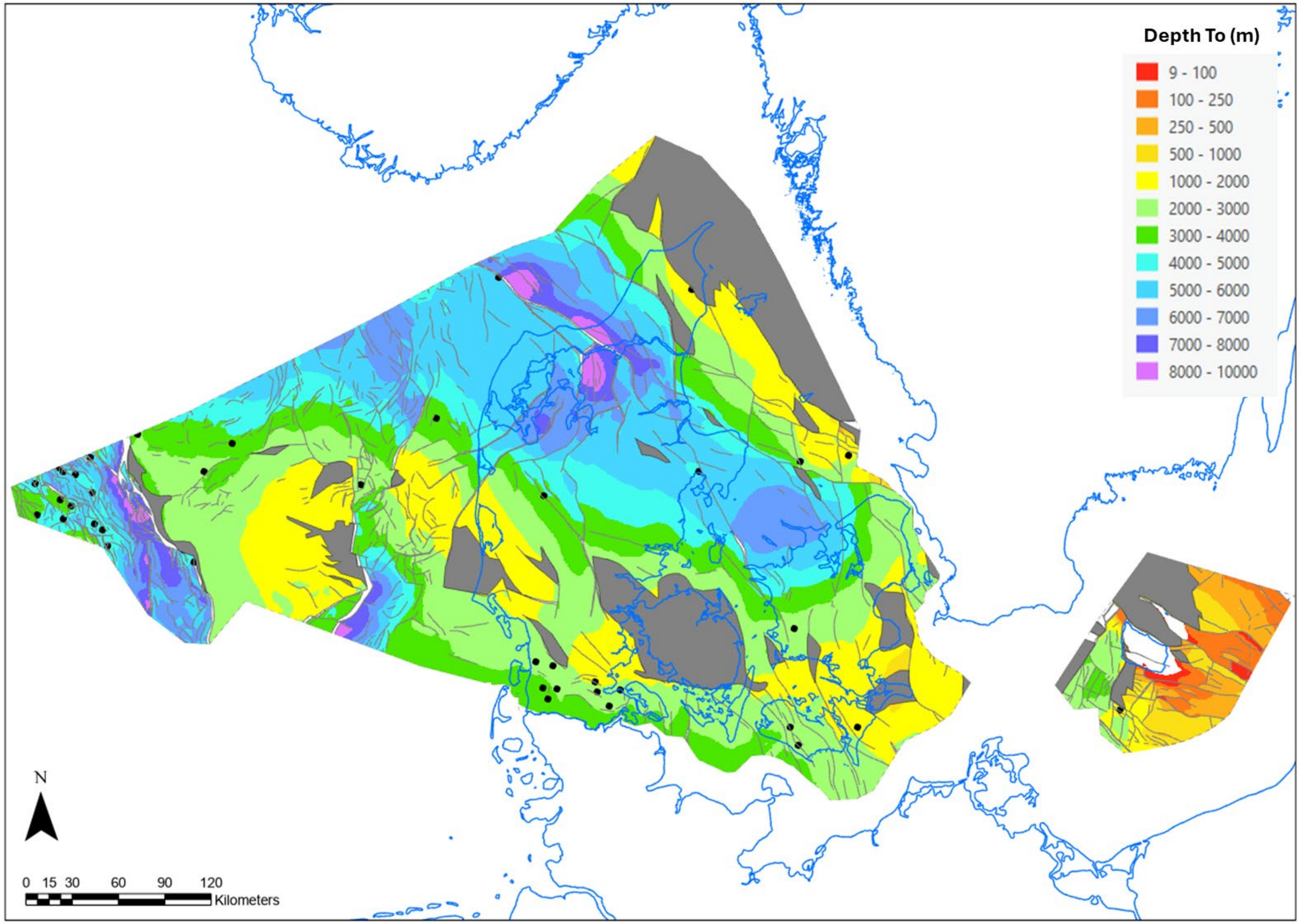


Figure 10. *Map showing the depth to the Top Pre Zechstein surface and distribution of wells (black dots) penetrating the surface. Notice the grey area where the Top Pre Zechstein surface is lying on top of Pre Permian units and Precambrian Basement. Sourced from the Danish Deep Subsurface Database*

Table 4. *SWOT analysis of the Upper Permian Kupferschiefer mineral system in Denmark, as a potential source of CRMs (Cu).*

	Helpful	Harmful
Internal	STRENGTHS Prolific mineral system elsewhere (Poland and Germany) Trace base metal sulphides reported in the Zechstein and in Jurassic from oil wells in the North Sea Evidence for hydrothermal activity (Röte Faule) in northeastern Germany.	WEAKNESSES Different diagenetic and tectonic evolution, in comparison with the time-equivalent German and Polish part of the succession Significant depth of the Rotliegend and Zechstein sedimentary rocks Significant metal accumulations have not been confirmed in the wells that penetrate the sequence
External	OPPORTUNITIES Copper demand expected to grow, key metal for the energy transition Expanded EU strategic autonomy requirement could attract interest	THREATS Increase in the complexity of the regulatory framework

Formation brines

Formation brines can have significant CRM concentrations, whereby Li is of particular interest, and can be extracted during oil and gas or geothermal energy production. Higher Li concentrations are generally found in deep saline fluids, in which evaporation of palaeo-seawater and precipitation of halite and potash salts took place, without subsequent flushing by meteoric recharge. Lithium enrichment can also result from fluid-rock interactions with diagenetically-altered shales and organic matter (Marza et al., 2024).

The following review on Danish Triassic to Cretaceous brine compositions is based on compilations by Laier (2008), Holmslykke (2019) and Schovsbo et al. (2025), based on the main geothermal and CO_2 and gas storage reservoirs of onshore Denmark, namely the Bunter/Skagerrak and Gassum formations, as well as the overview by Schovsbo et al (2016) on oil and gas brines of offshore chalk reservoirs. The spatial coverage of this brine compositional data is relatively low (c.f. Schovsbo et al., 2025), and is limited to data from three geothermal powerplants, one subsurface gas storage facility, and four oil fields reported in Table 5. More data may become available in the coming years due to the establishment of new geothermal power plants in the Aarhus region, as well as possible geothermal exploration efforts in the Copenhagen area. Furthermore, carbon capture storage licenses are currently being matured and may include pilot wells, to obtain information on the aquifers, and therefore may add further brine compositional data to the database.

As a caveat, it should be noted that a full assessment of a brine potential as a CRM source requires complete chemical analyses and the hydrochemical modelling of the potential interactions between different metals in solution, during changing temperature, pressure and operational conditions. This modelling is needed to provide insights into the possible roles of corrosion and precipitation/scaling, leading to the overestimation and underestimation of metal concentrations, respectively, but is well beyond the scope of this report.

Bunter Sandstone/Skagerrak formations (Lower Triassic):

The Bunter Sandstone/Skagerrak formations are present throughout the Danish area (Figure 11). Sandstones of the Bunter Sandstone Formation are dominant in the southern, western and central part of the Danish area and are gradually replaced by the Skagerrak Formation towards the northeastern basin margin. The Skagerrak Formation (termed Bunter in older studies) is the reservoir in the Margretheholm geothermal site (Table 5).

This sandstone-dominated succession forms a widespread unit with thickness around 300 m although it may reach 900 m in the central part of the Danish Basin. The succession is thin and locally absent across the Ringkøbing-Fyn High. It is anticipated that no strong primary hydraulic barriers exist within the sheet sandstone (Sørensen et al., 1998).

Reservoir properties are poorly known and often based on estimates from petrophysical logs (Michelsen et al., 1981). The porosity estimates typically range between 0–24% (maximum 38%), whereas the permeability is variable (10–100 mD) due to the relatively deep burial depth causing diagenetic changes and cementation. Unexpected, good reservoir properties have been found in the time-equivalent Ljunghusen Formation in the Copenhagen area.

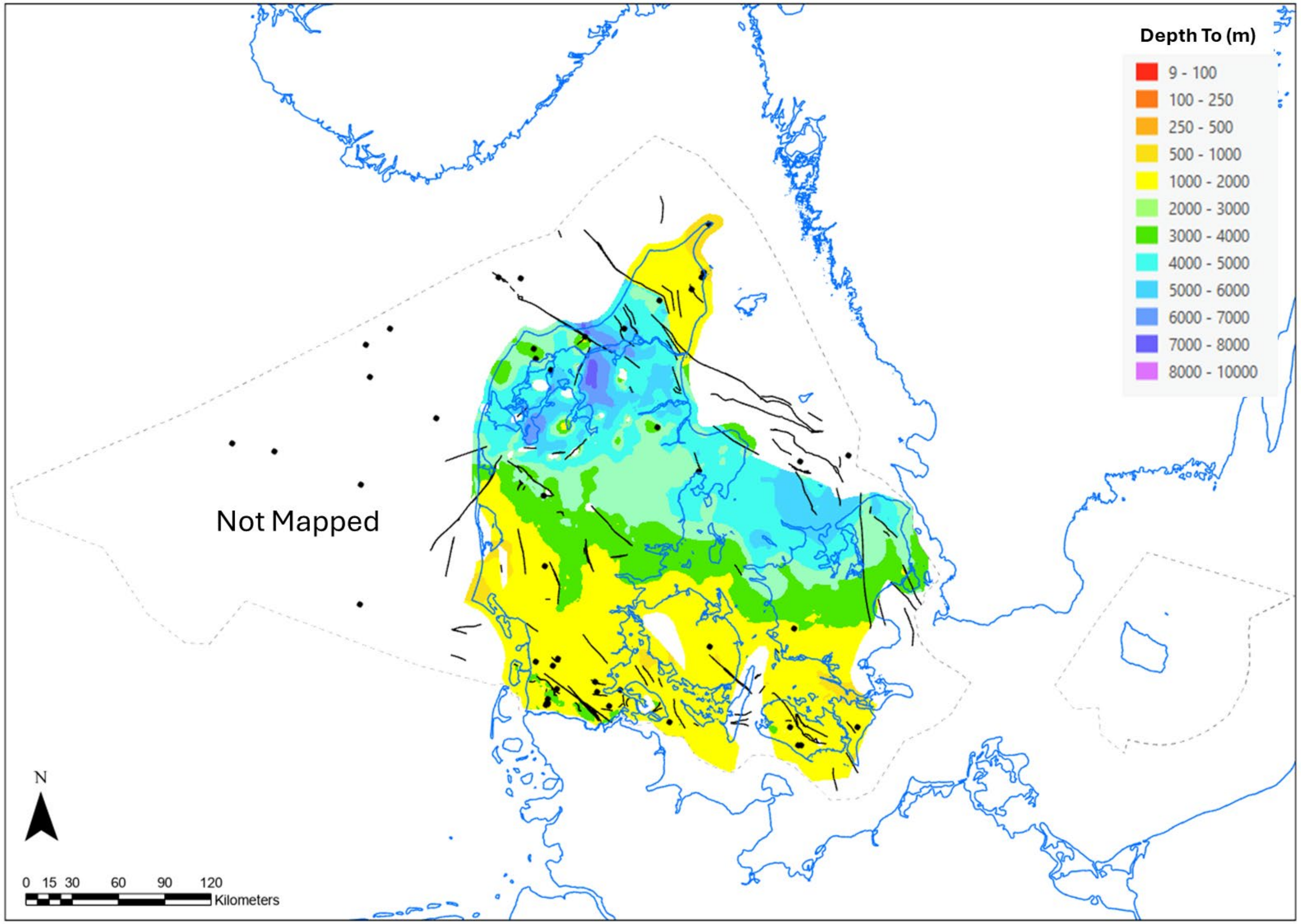


Figure 11. *Map showing the distribution of the onshore Top Bunter-Skagerrak formations and distribution of wells (black dots) penetrating the surface. Notice faults off-setting the Top Bunter-Skagerrak surface. Sourced from the Danish Deep Subsurface Database.*

Gassum Formation (Upper Triassic-Lower Jurassic):

This formation is present in the Norwegian-Danish Basin (Figure 12). It shows a remarkable continuity with thickness between 100 and 150 m throughout most of Denmark, reaching a maximum thickness of 300 m in the Sorgenfrei-Tornquist Zone. The Gassum is the reservoir unit in the Sønderborg, Thisted and Århus geothermal sites and is the main reservoir in the natural gas storage facility at Stenlille (Table 5).

The Gassum Formation consists of fine- to medium-grained, locally coarse-grained sandstones interbedded with heterolithic units, claystones and locally thin coal beds (Michelsen et al., 2003; Nielsen, 2003). In general, the reservoir properties are excellent with typical porosity range of 18–27% (maximum 36%) and permeability up to 2,000 mD.

The Gassum Formation forms the reservoir in the Stenlille natural gas storage site and has been studied in great detail (Nielsen et al., 1989; Hamberg & Nielsen, 2000; Nielsen, 2003, Weibel et al. 2017; Olivarius et al., 2022). The studies illustrate the facies complexity and the lateral variability present within the reservoir units. Each of these units may act as discrete reservoir units and is characterised by a set of variable porosity/permeability parameters. Based on palaeogeographic reconstructions it is anticipated that the sand content decreases towards the northwest.

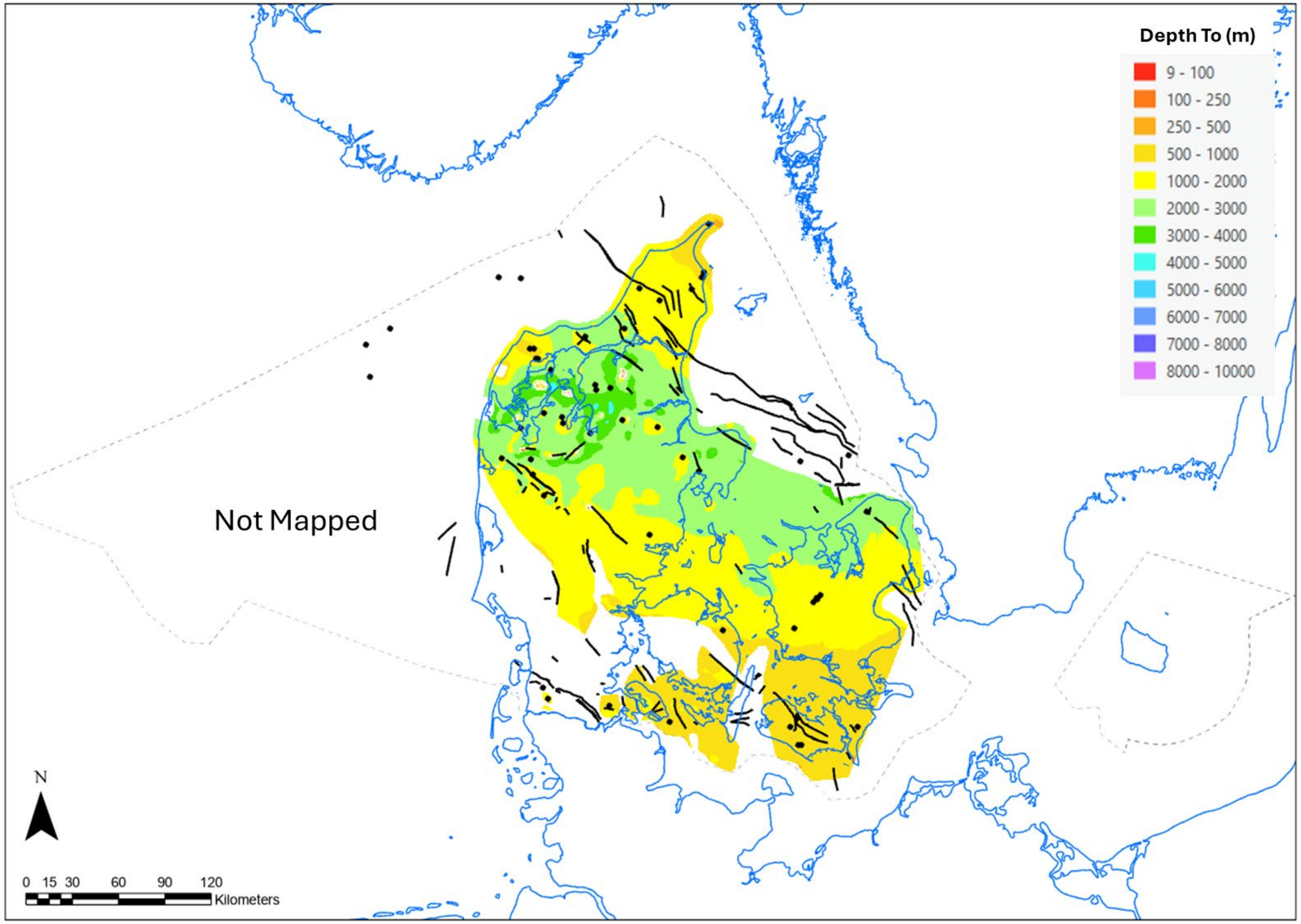


Figure 12. *Map showing the distribution of the onshore Top Gassum Fm and distribution of wells (black dots) penetrating the surface. Notice faults off-setting the Top Gassum surface. Sourced from the Danish Deep Subsurface Database.*

Chalk (Maastrichtian):

The Late Cretaceous to earliest Paleocene Chalk Group (Figure 13) comprises mud-grade biogenic carbonates, with very low permeability and fairly high porosities (Surlyk et al., 2003) and hosts the most important hydrocarbon reservoirs in the Danish part of the North Sea (Megson, 1992; Vejbæk et al., 2005). It is a fairly homogenous sedimentary rock, composed mainly of remnants of eukaryotic phytoplankton (coccolithophorids). In more marginal settings like eastern Denmark, shallower water depths in the late Maastrichtian to early Danian, and bottom currents created bryozoan mounds (Surlyk et al., 2003). Furthermore, coral facies of Danian age can be found in the Faxe area SW of Copenhagen (Hvid et al., 2021).

A general overview of brine major element chemistry in the North Sea chalk reservoirs is presented in Schovsbo et al. (2016). Brine trace element chemistry (Table 5) is available for four chalk fields in the Danish part of the Central Graben (Bonciani et al., 2024). The reservoirs are unnamed by the authors, but it is assumed to be Upper Cretaceous chalk lying between 1.5-2 km depth.

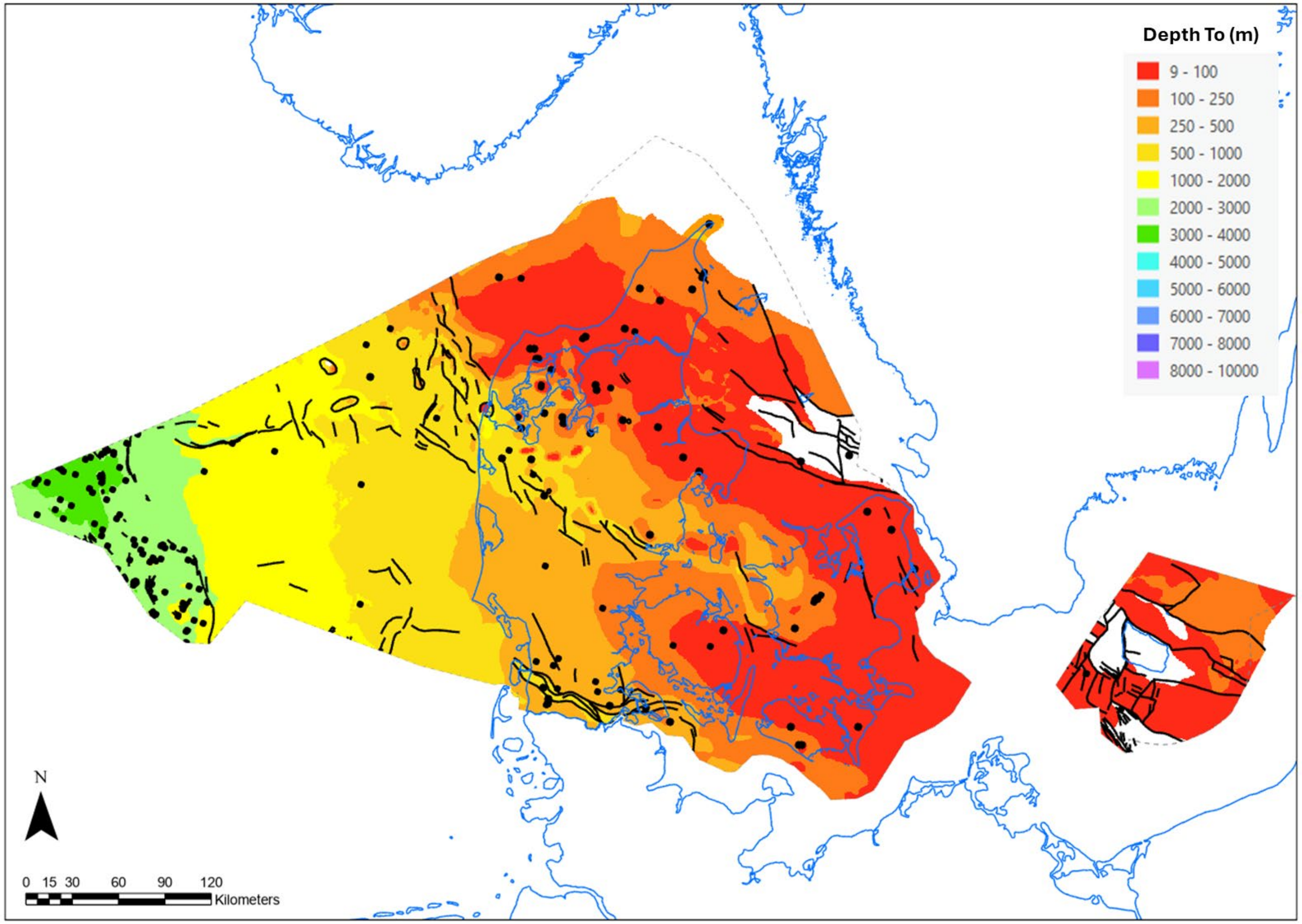


Figure 13. *Map showing the distribution of the Top Chalk Group and distribution of wells (black dots) penetrating the surface. Notice faults off-setting the Top Chalk surface. Sourced from the Danish Deep Subsurface Database.*

Table 5. Selected CRM concentrations (mg/L) in brines from Danish geothermal, gas storage sites and oil fields:

	Danish Basin	N German Basin	Danish Basin	Danish Basin	Central Graben
	Margretheholm	Sønderborg	Thisted	Stenlille	Chalk oil and gas fields
	(Bunter/Skagerrak Fm, 2.6 km, 73°C)	(Gassum Fm, 1.2 km, 48°C)	(Gassum Fm, 1.2 km, 45°C)	(Gassum and Bunter fms, 1.5 km, 60°C)	(Maastrichtian, 1.5-2.0 km, 70-80°C)
Li	14		13	3-22	3.5-6.8
Mg	2820	1174	1700	1140-4000	355-984
Cu	0.06				trace
B					59-95
Ba	8.95	0.68	12	8-39	
Sr	822	218	360	660-1010	
Ref:	Holmslykke et al., (2019)	Holmslykke et al., (2019)	Holmslykke et al., (2019)	Laier (2008)	Bonciani et al., (2024)

If we focus our assessment on Li, the CRM gathering most interest in terms of possible recovery from formation brines, the Danish Triassic to Cretaceous formation brines analysed (Table 5) have concentrations that are approximately one order of magnitude lower than the brines from Clayton Valley (Nevada), home to the only Li producing site in the US, or the oilfield brines from the Smackover Formation (Arkansas), where production is planned (Knierim et al., 2024). In turn, the Danish formation brines have Li concentrations that are approximately two orders magnitude lower than those found in Andean salar brines (Torres et al., 2024).

Higher CRM concentrations can be expected in hotter and deeper brines, as for example the brines within the Permian, expected to be found in southern Jutland, Lolland and Falster (~200 m thick at ~2000 m depth, Doornebal & Stevenson, 2010). Analyses of bittern brines collected within Zechstein salts at a depth of ca. 2200 m from the well Tønder-1 have been reported by Dinensen (1961). The lithium concentration was not established, but magnesium and boron concentrations are reported to be in excess of 70000 and 1300 mg/L, respectively. These concentrations are at least one order of magnitude higher than those found in Triassic to Cretaceous reservoirs included in Table 5. At such concentrations, these elements and possibly lithium (if comparable enrichment as that seen for Mg is confirmed) could potentially be produced as by-product of potash recovery. However, one should have in mind that hotter and deeper reservoirs will tend to be tighter so that smaller volume of brine will be able to be extracted, and therefore fracking or other reservoir enhancement might be needed. Furthermore, deeper brines can result in barite and galena or laurionite scaling (Regenspurg et al., 2010; Heberling et al., 2017), minerals which will tend to incorporate Ra and radioactive ^{210}Pb, respectively, so that these scales could potentially be a radiological concern.

In conclusion (Table 6), the assessed formation brines generally reveal relatively low CRM concentrations. Higher CRM concentrations have only been identified in deeper and tighter Permian reservoirs. Recovery of CRMs, namely Li, is therefore probably not feasible. Naturally, coupling CRM recovery from Danish brines with heat and/or power production will improve the feasibility. Furthermore, emerging direct lithium extraction using membrane crystallisers and supported liquid membranes will lower costs. These technologies offer multiple advantages, including reduced energy consumption, smaller process footprints, improved product quality, and the production of valuable by-products like freshwater, but can also result in unmanaged brine waste. In any case, the lowering of costs induced by this new technology will also benefit potential producers extracting brines with higher metal concentrations, who will therefore likely hold on to their advantage. So, Danish brines are thought to hold a low potential for Li, Mg and B, recovery, although volume availability and Li and other CRMs concentrations in bittern brines in Permian reservoirs should merit attention.

Table 6. *SWOT analysis of Danish formation brines as a potential source of CRMs (Li, Mg, B).*

	Helpful	Harmful
Internal	STRENGTHS Large volumes of brines available Combined heat-power-metals extraction can improve feasibility	WEAKNESSES Brines generally hold low concentrations of CRMs
External	OPPORTUNITIES Direct extraction technology (double edged sword, as it will also improve economics elsewhere)	THREATS Increase in the complexity of the regulatory framework Radiological risks in deeper, tighter, but potentially more CRM rich, brines

Late Cretaceous Arnager Greensand Formation

A small amount (1800 t) of raw phosphate rock was briefly mined in Madsegrav, Bornholm, ca. 1918–1920, but mining ultimately stopped due to flooding of the underground mine works (Jensen, 1991). This raw phosphate rock was sourced from phosphatic conglomerate corresponding to the ca. 40 cm-thick basal part of the Arnager Greensand Formation, developed in response to sea-level changes (Friis, 1985; Surlyk, 2006).

The Arnager Greensand Formation, found along the southern coast of Bornholm, Denmark, dates back to the lower to middle Cenomanian age of the Late Cretaceous (Figure 14; Hart et al. 2012). It overlies the Jydegård Formation from the Early Cretaceous and is characterised by a significant hiatus before the overlying Arnager Limestone (Surlyk, 2006). The formation is primarily composed of loose, poorly sorted fine-grained glauconitic quartz sand, often mixed with silt or clay, and includes layers of cemented coarse-grained sand (Friis, 1985, Solymar and Fabricius, 1999).

The main body of the formation is about 85 m thick, consisting of grey-green quartz sand heavily bioturbated by bottom-dwelling organisms, and contains fossils of ammonites, belemnites, bivalves, gastropods, brachiopods, and foraminifera. Most of the formation is studied in outcrop along the southern margin of Bornholm, between Arnager Pynt and Korsodde, and can be observed in the cliffs at Arnager Bay.

The distribution of the formation in the subsurface is not well known, but it has been encountered in boreholes towards Skåne and eastern Zealand at depths between 1200–1900 m (for example Falsterborev-1, Kungstorp-1, Haslov-1, FFC-1, Margretheholm-1, Karlebo-1, Lavø-1, as shown in Figure 15). Formation depths increase towards the Sorgenfrei-Tornqvist zone in a NW-SE trend. Encountered thicknesses in boreholes vary between a few meters to tens of meters, and up to 85 m. The Formation has not been mapped individually (e.g. top and base), but the top must occur close to the Base Chalk Group seismic marker within this region. Jones (2019) used seismic and borehole data to characterise the Arnager Greensand Formation within the context of compressed air storage in the Skåne region, which provides additional data for its location between Zealand and Bornholm. It is unknown how far west the formation can be traced beyond Karlebo-1 and Lavø-1.

The limited resource extent, confined to a single thin bed in faulted blocks in outcrops in Bornholm, presumably at significant depths elsewhere, suggests this constitutes an insignificant phosphorus or phosphatic rock resource.

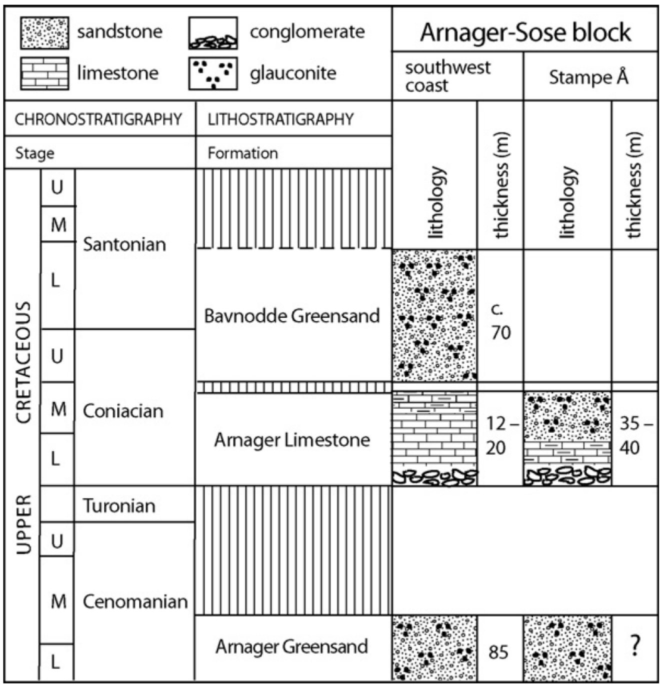


Figure 14. *Stratigraphy of the early Upper Cretaceous on Bornholm, showing the Arnager Greensand Formation with hiatus to the overlying Arnager Limestone Formation. From Hart et al. (2012).*

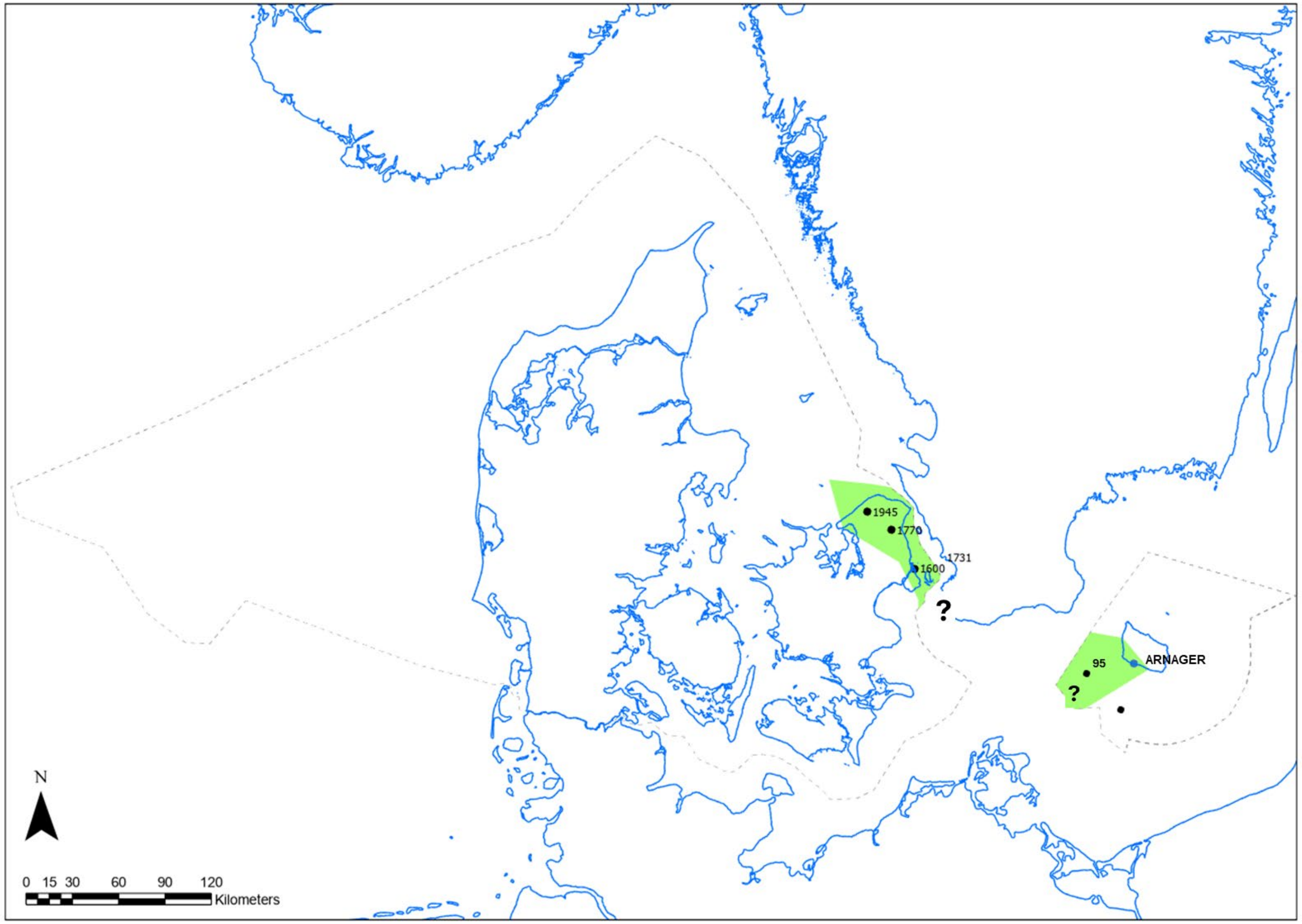


Figure 15. *Outcrop localities on Bornholm and boreholes intersecting Arnager Greenland. Depths are indicated next to the wells. Tentative occurrence in the Danish area is indicated by green polygons. Sourced from the Danish Deep Subsurface Database.*

Miocene silica sands

Silica sand is a type of sand dominated by quartz grains, and therefore with high SiO_2 concentrations and low impurity levels. This sand constitutes and indispensable raw material in industry, and can be used for water filtration, in the production of glass or ceramics, or used as construction material (concrete, mortar), as molds in metal casting, or as proppant in fracking for the oil and gas industry, etc.

In Denmark, such pure silica sands are the result of the leaching of well-sorted, fine-grained Miocene sands of the Odderup Formation, by humic acids originating from peat horizons. Silica sand deposits are primarily found in the area between Silkeborg and Vejle in Jutland, namely near Addit, where they are presently mined, with Dansand A/S producing ca. 500 000 t/year, contributing to ranking Denmark as the 11th in global silica sand sales.

Whereas silica sand is not considered a CRM, its potential as a source for silicon metal, which is a CRM, was evaluated. However, silicon is typically produced from vein quartz or quartzite, not from silica sand. This is essentially because of the relatively coarse nature of the feedstock needed (Elkem, 2025), which should be ca. 3-10 cm in diameter (Australian Silicon Action Plan, 2022). As a result of this analysis, it can be concluded that Denmark has a significant silica sand potential, but that this sand cannot be presently used for the production of silicon due to the technical reasons. Even if these technical hurdles could be overcome, silicon production would be very energy intensive so that, for the same reasons discussed for magnesium (from potash salts) or discussed below for titanium (from heavy mineral placers), it is unlikely that it would take place in Denmark considering the country's relatively high energy costs. Therefore, and since it would be out of the scope of this report, no further assessment of the Danish silica sand distribution and quality has been carried out.

Miocene–Quaternary heavy mineral placers

Sand accumulations have the potential to include horizons enriched in heavy minerals, resulting from the mechanical concentration of these resistant minerals during the sedimentary cycle. Heavy minerals can be economically recovered through gravity from so-called placer deposits. Placer deposits can be the source for CRMs such as titanium (in ilmenite or rutile), rare earths (in monazite or xenotime), niobium and tantalum (coltan) or platinum group elements (in native alloys).

In Denmark, the exploration and evaluation of ilmenite placers in Miocene sands has been reported by Knudsen (1998) and Stendal et al (2001) and the exploration of ilmenite in Quaternary sands, both onshore and offshore, has been documented by Lomholt et al (2002). The approximate depth distribution of the Miocene and Quaternary can be estimated from the depth to the base of the Quaternary shown in Figure 16.

In the Miocene, two alluvial ilmenite occurrences are described in Jutland; Vorslunde (barrier island play) and Skjern (marine play). The former was estimated to hold a volume of 12 million m^3 with more than 1 wt% TiO_2, whereas the latter has 150 million m^3 with more than 2 wt% TiO_2, which are both below the grade and tonnage objectives set by Stendal et al. (2001).

In the Quaternary, onshore and offshore (North Sea and Baltic) occurrences were found to only have low concentrations of ilmenite. Such low ilmenite concentrations were deemed not to justify further exploration work and ilmenite recovery during sand beneficiation was not considered feasible (Lomholt et al., 2002).

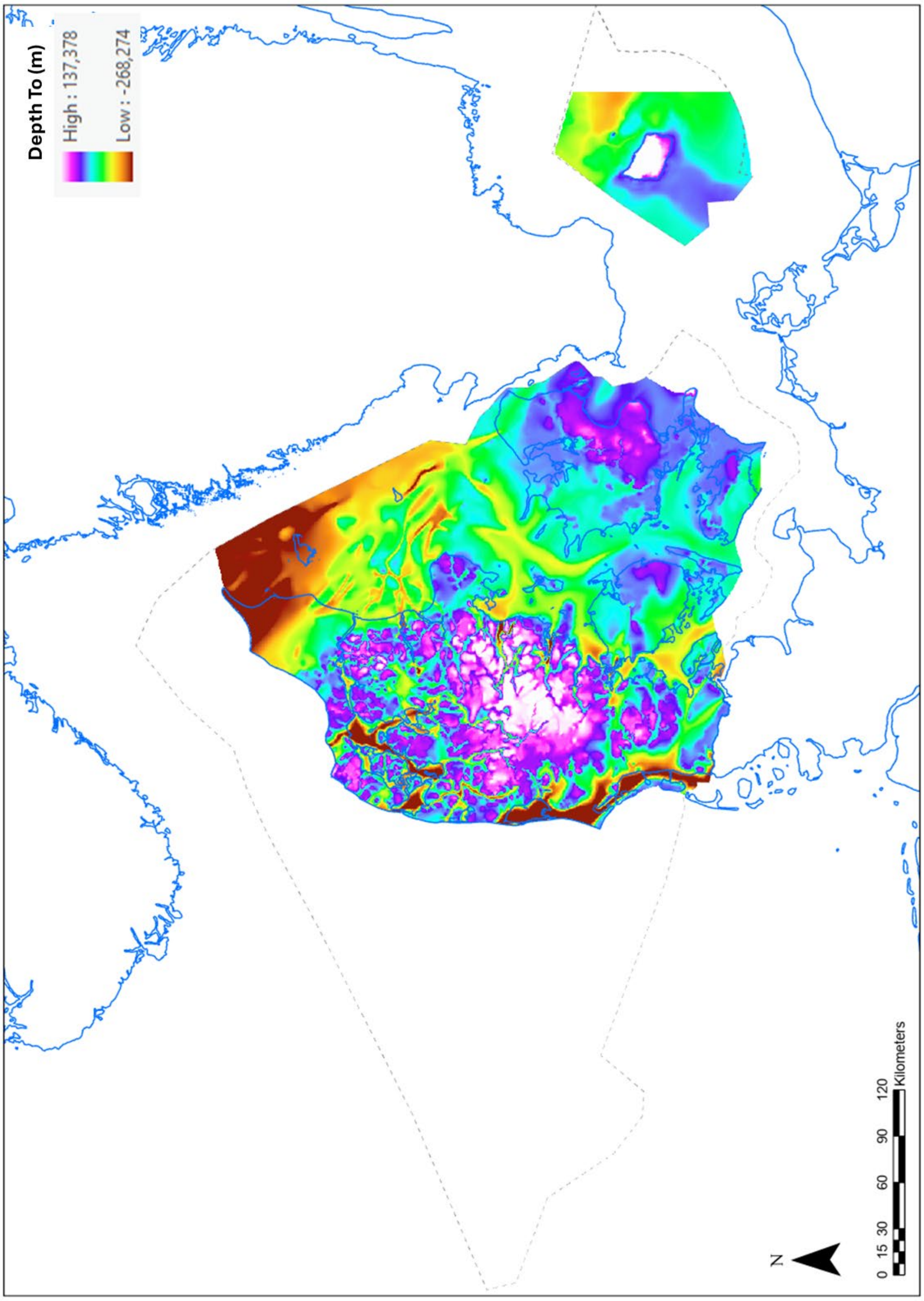


Figure 16. *Depth to the base of the Quaternary in Denmark. Sourced from the Danish Deep Subsurface Database.*

In short (Table 7), Denmark holds a limited potential for the production of ilmenite sands, which could be recovered as a by-product of sand aggregate beneficiation. However, identified grades are low and ilmenite fine grained, which makes its recovery difficult. Furthermore, analogously to what was described above regarding magnesium in potash salts or silicon in silica sands, the CRM in the EC (2023) list is titanium metal, rather than ilmenite. This is because criticality is mostly linked to the large energy inputs needed for titanium metal production, rather than geological constraints. The high energy inputs for the production of titanium metal have induced that industry to move to and concentrate in countries with lower energy costs or with lower greenhouse emission constraints. As such, the potential for Denmark to produce titanium metal is considered very low, even though source raw materials (ilmenite) could potentially be locally produced.

Table 7. *SWOT analysis of Danish heavy mineral placers as a potential source of CRMs (Ti).*

	Helpful	Harmful
Internal	STRENGTHS Ilmenite can be produced as a by-product during sand beneficiation Shallow occurrences require relatively low investments Disaggregated and simple mineralogy favours simple gravity separation	WEAKNESSES Low TiO_2 concentrations Fine grained ilmenite Extensive areal environmental impact
External	OPPORTUNITIES Titanium (metal rather than heavy minerals) demand expected to grow Expanded EU strategic autonomy requirement could attract interest	THREATS Increase in the complexity of the regulatory framework

Helium occurrences and distribution, onshore Denmark

Helium is generated from the long-lived alpha decay of uranium- and thorium-rich rocks, either radioactive carbonaceous shales or granitic and gneissic basement, and migrates, together with a carrier gas, into a structural or stratigraphic trap with suitable reservoir properties and an overlying impermeable seal (e.g. Tao et al., 2024). Historically, the main helium production in Europe has been restricted to the Eger Rift in Central Europe and large gas fields in the Polish Basin (e.g. Danabalan et al., 2022; Tao et al., 2024). Currently, exploration projects are ongoing in France, Spain and Finland but the European potential remains underexplored.

Testing for helium during oil and gas-related exploration activities has never been standard procedure in Denmark and uncertainties associated with the generation, migration, accumulation, and preservation of helium in the subsurface make it impossible to precisely determine potential resource volumes and extent at this time. Known helium occurrences are restricted to sporadic measurements from final well reports from the late 1940's and early 1950's and analyses carried out in relation to recent geothermal appraisal and oil and gas activities. Analogue reports may contain gas data, including potential helium concentrations, but have not been evaluated at this stage. Occurrences in three regions have documented helium in Denmark: southern Jutland, northern Jutland and Eastern Zealand, based on open access reports:

Southern Jutland
The Felsted-1 well (Figure 17) was drilled in 2011, as part of a new hydrocarbon exploration initiative targeting a three-way closure, located in the toe-of-slope of carbonate-sulphate platform within Zechstein carbonates in southern Jutland (PGNiG, 2012). A full suite of gas data is reported in the completion report and gas analysis was performed on 4 samples delivered in Schlumberger MDT samplers and in one sample collected on surface (released from the head). Samples were acquired from two intervals at 2257.5 m and 2259.5 m from porous Z2 Zechstein carbonates with up to 25% porosity. Helium concentrations are in the range of 0.051 to 0.085% while the main gas phase reported from the reservoir was nitrogen, ranging from 88.71 to 91.67%.

The Tønder-1 well is situated on the Tønder Salt Dome in southern Jutland, south of the Ringkøbing-Fyn High in the North German Basin (Figure 17). The well was drilled in 1952 as a wildcat in relation to early oil and gas-related exploration activities. Gas sampling was carried out in tight Zechstein evaporites and mudstones (possibly the Z5 depositional cycle) at 2186-2193 m and yielded helium concentrations in the range of 0.11 to 0.13%. The main gas phase recognised was nitrogen, ranging from 72.05 to 74.82%, with accessory methane (8.67–9.11%), argon (0.2–0.6%), and natural hydrogen (15.12–17.8%) (DAPCO, 1952).

Northern Jutland
The Suldrup-8 well (Figure 17) was drilled in 1948 as part of a salt exploration programme in northern Jutland targeting a shallow-lying salt diapir (DAPCO, 1951). Gas analysis was performed on a single brine sample taken at 1485' (453 m) and yielded a helium concentration of 0.02%. The bulk gas consisted of 67.82 methane with accessory nitrogen (28.1%) and natural hydrogen (3.7%).

Eastern Zealand

Well Magretheholm-1 is situated in Eastern Zealand, NE of the Ringkøbing-Fyn High and was drilled in the early 2000's, in relation to geothermal appraisal activities, targeting the siliciclastic sediments of the Lower Triassic Bunter Sandstone Formation (Figure 17). The well was not drilled within any stratigraphic or structural closure. Two gas analyses were carried out in well Magretheholm-1 at 2480 m yielding helium content of 1.3–1.7% with nitrogen content in the range of 84 to 88%. Accessory gas content includes CO_2 (7%), methane (3 to 7%), and hydrogen (<0.1%) (Magretheholm-1, 2003). Additional gas testing from the formation water from well Magretheholm-1 was carried out to constrain causes for reduced injectivity due to partial clogging of lead (see Olivarius et al., 2018). The gas sample yielded helium content of 2.26% with the main gas component being nitrogen (91.53%), with accessory hydrogen (0.06%), oxygen/argon (0.66%), CO_2 (0.24%) and methane (5.2%).

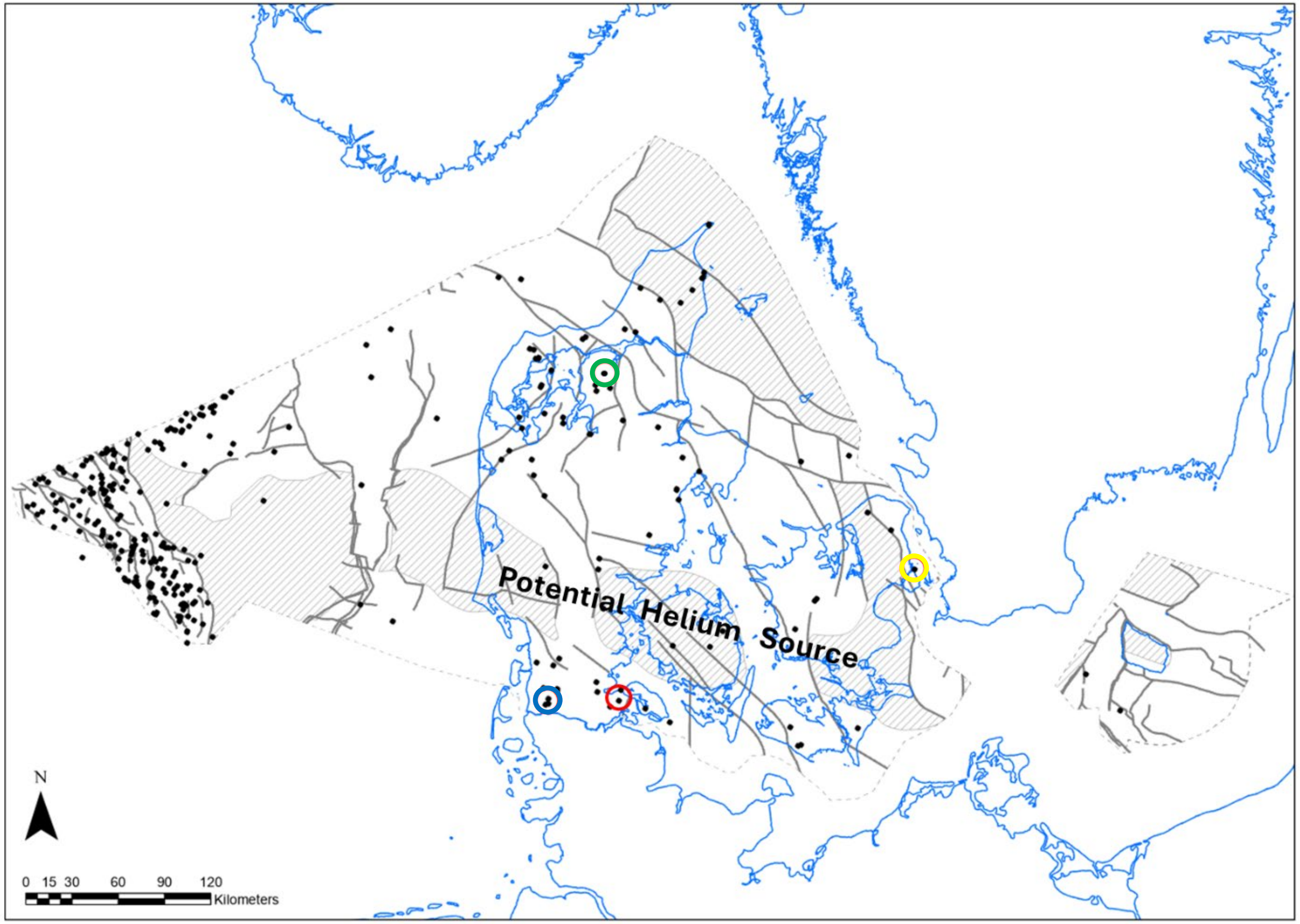


Figure 17. Map *showing a series of subsurface structural highs with the Tønder-1 (blue), Felsted-1 (red), Suldrup-8 (green) and Margretholm-1(yellow) wells highlighted with circles. Sourced from the Danish Deep Subsurface Database.*

In short (Table 8), helium presence has been documented in four locations, one of which with elevated concentrations. Helium could be recovered with hydrogen and/or geothermal energy production as by-products. However, the volume and concentrations available remain to be adequately assessed, and potential radiological risks linked to radon emissions, as well as the possible effects of the presence of methane, a greenhouse gas, need to be evaluated. As such, the potential for the Danish subsurface to be a helium producer is considered to be low–moderate.

Table 8. *SWOT analysis of Denmark's' potential for helium.*

	Helpful	Harmful
Internal	STRENGTHS An active helium kitchen confirmed by legacy well data Potential hydrogen recovery as a by-product	WEAKNESSES Variable helium concentrations Volume uncertainties
External	OPPORTUNITIES Combined heat-power-gas extraction could improve feasibility Expanded EU strategic autonomy requirement could attract interest	THREATS Increase in the complexity of the regulatory framework Radiological risks (radon?) Presence of methane, a greenhouse gas

Conclusion

Denmark's CRM potential is generally low, with no CRM deposits currently known and very limited exploration. However, Denmark hosts some metallotects with CRM potential which have been assessed.

The assessed metallotects hold a potential for feldspar and possibly fluorspar (crystalline basement), vanadium and nickel (Cambrian-Ordovician Alum shale), magnesium (Zechstein potash salts), copper (Kupferschiefer mineral system), lithium, magnesium and boron (formation brines), phosphorus/phosphate rock (Cretaceous Arnager phosphatic conglomerate of Bornholm), silicon (Miocene silica sands), titanium (Miocene-Quaternary heavy mineral placers), and helium occurrences.

However, whereas the available information is rather limited, the potential for these CRMs can generally be considered low (Table 9, Figure 18). This is essentially because of the limited and disrupted exposures (crystalline basement, Alum Shale and Cretaceous metallotects are only exposed in Bornholm) or the depth (many metallotects elsewhere in Denmark) at which many of the studied metallotects are present. Compounding this are the modest grades documented, lateral continuity problems due to tectonic disturbance, detrimental chemical associations (possible radioactive isotopes in Alum Shale and in brines; methane presence in helium reservoirs), and/or inadequate granulometry (silica sands as a silicon source) which can impose significant challenges to economic recovery. The only CRM which is considered to hold a low to moderate potential is helium (Table 9, Figure 18), although knowledge of its volumes and concentrations remain poorly studied.

Potential for other CRMs remains unassessed or unknown. In the case of the companion metals, their potential is tied to that of the host metal to which they are typically related and should therefore be also considered, at best, low.

Table 9. Potential (low, moderate, high) for CRMs in assessed metallotects in Denmark.

Critical Raw Material:	Metallotect:	Potential in Denmark:
Boron	Formation brines	Low
Copper	Kupferschiefer Mineral System	Low
Feldspar	Crystalline Basement	Low
Fluorspar	Crystalline Basement	Low
Helium	Helium kitchen	Low to moderate
Lithium	Formation brines	Low
Magnesium	Potash salts, formation brines	Low
Nickel	Alum Shale	Low
Phosphorus/phosphate rock	Arnager Greensand	Low
Silicon	Silica sands	Low
Titanium	Heavy mineral placers	Low
Vanadium	Alum Shale	Low

CRMs in *italic* are considered to be critical due to the high energy inputs needed for their production, which has led to industry migrating and concentrating in countries with lower energy costs or greenhouse gas emission constraints, rather than due to geological constraints.

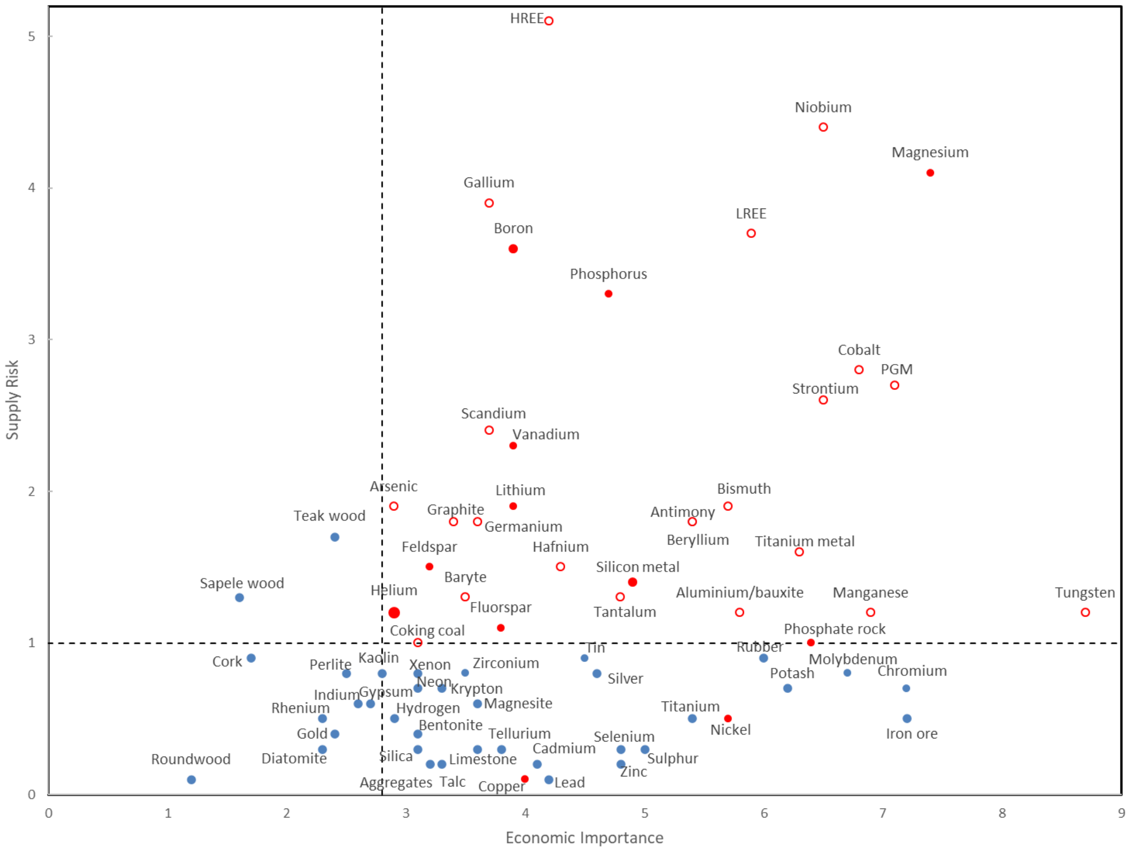


Figure 18. *EC (2023) plot of economic importance vs supply risk. Non-CRMs are shown in blue, whereas CRMs are shown in red. CRMs symbols are empty if potential is unknown or unassessed, or filled if their potential was estimated in the present report. In the latter case, symbols are sized according to estimated potential; smaller symbols for CRMs with low potential in Denmark, larger symbol for CRM with low-moderate potential in Denmark (helium). There are no CRMs whose potential is considered high in Denmark.*

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