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SMS resources on the Norwegian Mid-Atlantic Ridge (N-MAR), predicted by using Cyprus-type VMS as analogue

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Summary

The overall aim of this project has been to generate an objective resource estimate for Seafloor Massive Sulphide (SMS) ores in the Norwegian part of the Mid-Atlantic Ridge (N-MAR).

The presence and mineability of SMS ores are poorly constrained on a worldwide basis, and this project has applied well-constrained Cyprus-type volcanic massive sulphides (VMS) as analogues on land for a resource estimate. Several reports have recently been published with estimates of SMS resources on N-MAR. These resource estimates are mainly based on a limited number of grab samples, limited geophysics and limited mapping, a basis which makes the estimates very uncertain. Cyprus is the type-example of an ophiolite complex and is host to the type-example of the equivalent land-locked VMS deposits. Existing databases on VMS deposits has been upgraded and only ophiolite-hosted deposits were included using literature and internet resources, producing a database of 109 deposits with new grade and tonnage data. Fieldwork was carried out to obtain geochemical data on metals which could be of economic interest in addition to the base metals.

Monte Carlo simulation was used on data from the main ophiolite districts around the world to obtain estimates on deposit size and grade, deposit density and tonnage copper. This simulation resulted in a 50th percentile with a deposit size of 1.47 Mt with 1.47% Cu, and a density of 9.2 deposits/1000 km^2, and a tonnage of 0.18 Mt Cu/1000 km^2. The copper tonnage is considerably less than recent estimates for SMS resources on N-MAR, while the deposit density is similar. Most of the discrepancy is caused by using high average grades in previous estimates, based primarily on biased surface sampling.

The geochemistry of the Norwegian ophiolite-hosted deposits shows no systematic enrichment in precious and trace metals, except for elevated values of cobalt. From this, only copper and zinc, and in some cases cobalt, may be expected to have economic value in SMS deposits. If ultramafic rocks are involved in the hydrothermal processes, the contents of gold, cobalt, and perhaps copper and nickel, may be higher.

Keywords		
Mid-Atlantic Ridge	Cyprus	Ophiolite
VMS	SMS	Copper
Base metals	Database	

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1. INTRODUCTION

The overall aim of this project has been to generate an objective resource estimate for Seafloor Massive Sulphide (SMS) ores in the Norwegian Exclusive Economic Zone (NEEZ), along the Mohns and Knipovich Ridges, which make up the main part of the Norwegian Mid-Atlantic Ridge (N-MAR).

Given that SMS ores are extremely poorly constrained on a worldwide basis, and also for the NEEZ/N-MAR, the project has applied well-constrained Cyprus-type volcanic massive sulphides (VMS) analogues on land for this resource estimate. In contrast to SMS ores offshore, the applied VMS data are based on mined and/or thoroughly drilled ore bodies.

2. BACKGROUND AND MOTIVATION

Several reports have recently been published giving estimates of SMS resources on N-MAR (Juliani & Ellefmo 2018 a,b, Ellefmo & Søreide 2019, NPD 2023). These resource estimates are mainly based on a limited number of grab samples, limited geophysics and limited mapping, a basis which makes the estimates very uncertain (see below). In order to obtain a better understanding of metal potential, including size, metal content and frequency (density), on-shore VMS equivalents to offshore SMS deposits are used in this project.

Cyprus-type VMS deposits are related to ophiolites, which represent oceanic crust that has been obducted (thrusted) on land during orogenic processes. The advantages of using on-shore VMS deposits in SMS resource estimations are obvious: 1) Numerous deposits are accessible for studies, 2) there are very good data on size, metal content and metal distribution for many deposits, 3) the deposits may be studied in 3 dimensions, in contrast to SMS deposits, which in most cases are uncharted in the third dimension. Furthermore, the connection between SMS and VMS deposits provides essential and necessary insights into hydrothermal processes responsible for the accumulations of sulphides.

The studies of VMS deposits provide information on metal contents, number of deposits per area (density), and size distribution of deposits in a given area or district. Geochemical analyses are used to find out more about content of the base metals (copper, zinc and lead), as well as associated metals, such as cobalt, selenium, antimony, tellurium, tin, indium, germanium, silver and gold. These associated metals (some of which are on the EU list of critical metals), may be important by-products, and may in addition provide information about the sources of the metals and tectonic environment.

3. SMS AND VMS DEPOSITS, CURRENT KNOWLEDGE

3.1 Formation of SMS deposits

Seafloor Massive Sulphide (SMS) deposits are accumulations of sulphides forming at the present seafloor. They are regarded as the modern equivalents to Volcanogenic Massive Sulphide (VMS) deposits on land (Franklin et al. 2005, Hannington et al. 2005). The term SMS was introduced to distinguish the modern from the ancient.

Already in the 1960s and 1970s, ore geologists studying VMS deposits forecasted the presence of sulphide deposits on the modern seafloor, and the presence of metalliferous sediments were known in the Red Sea (Bischoff, 1969). The first warm-water vents and animals thriving in the hydrothermal environment were found outside Galapagos in 1977 (Corliss et al., 1979). Only two years later, the first active SMS (black smoker) occurrences were found at the East Pacific Rise (EPR 21°N) (Francheteau et al. 1979, Hekinian et al. 1980). Since then, SMS occurrences have been found in the entire spectrum of volcanic and tectonic settings, including Mid-Ocean ridges, Back-arc basins, Oceanic islands, Intra-oceanic arcs to Continental rifts and Rifted margins.

VMS and SMS deposits are syngenetic, formed by hydrothermal activity related to contemporaneous magmatism and volcanic activity. The general model for the formation is based on studies on both SMS and VMS deposits (e.g. Lydon 1984, 1988, Galley 1993, Franklin 1995, Franklin et al. 2005). The main elements of the model are shown in Figure 1, and include: 1) a heat source to drive the hydrothermal convection, which may also contribute some of the metals; 2) a high temperature reaction zone, from which most metals are leached from volcanic and/or sedimentary rocks by circulating and reactive seawater; 3) transport medium for the metals, which is a brine evolved from seawater during reaction with the rocks; 4) fractures and faults that permit focused charge and discharge of the hydrothermal fluids to and from the reaction zone; 5) wallrock alteration produced by interaction between the ascending metalliferous fluids and the surrounding rocks; 6) the massive sulphide deposit, formed at or below the seafloor; 7) distal products formed from the black and white smokers in the water column, as well as mass wasting during tectonic activity.

The massive sulphide deposit is generally zoned with a copper-rich core and stringer zone, grading into a zinc ± lead-rich outer zone (Figure 2). The reason for this zonation is the different solubility of the different metal complexes, when the metalliferous hot fluids are exposed to lower temperature and higher pH close to the seafloor (e.g., Franklin et al., 2005, Figure 3). Drop in pressure may also be important, especially if the fluids approach boiling conditions.

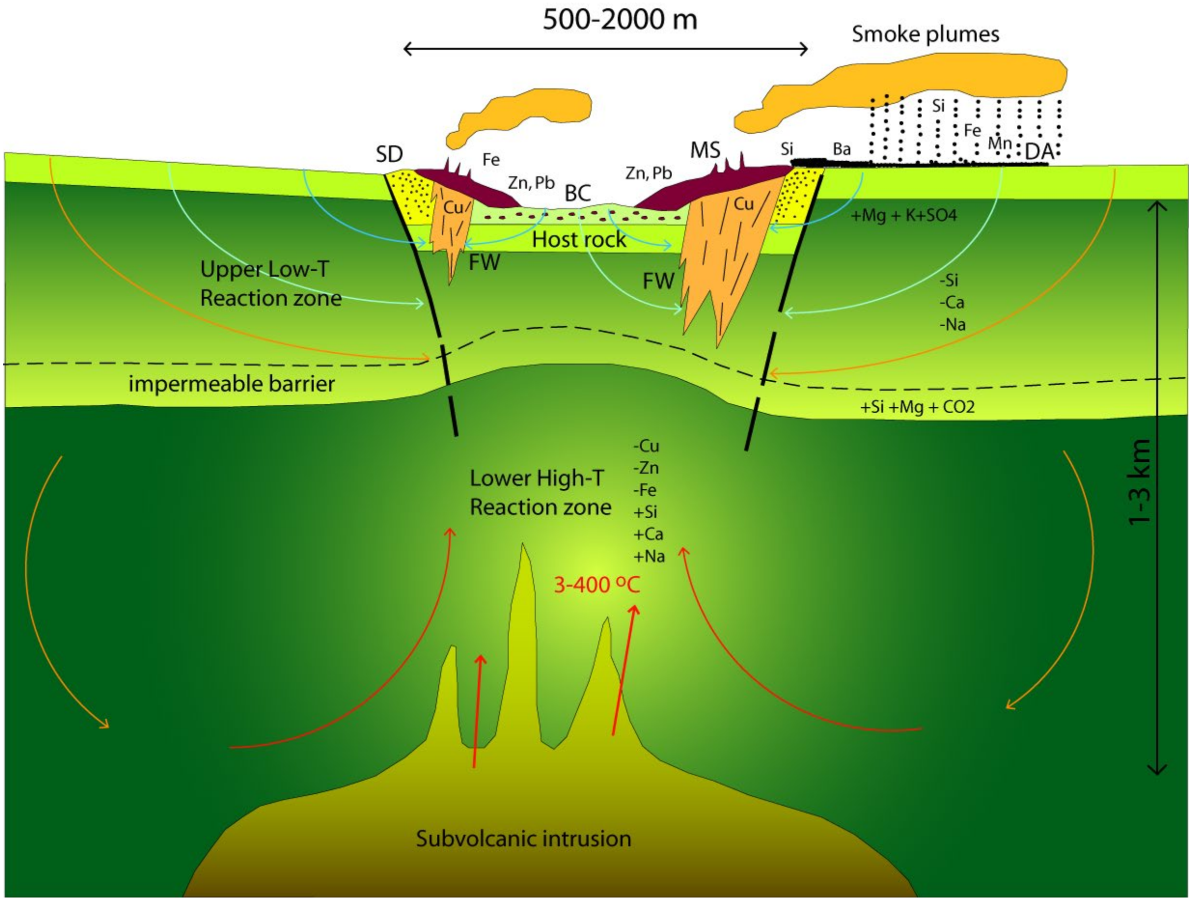


Figure 1: General model for the formation of a VMS deposit, showing the basic components in a high-temperature hydrothermal system (modified from Franklin et al. 2005). See text for explanation.

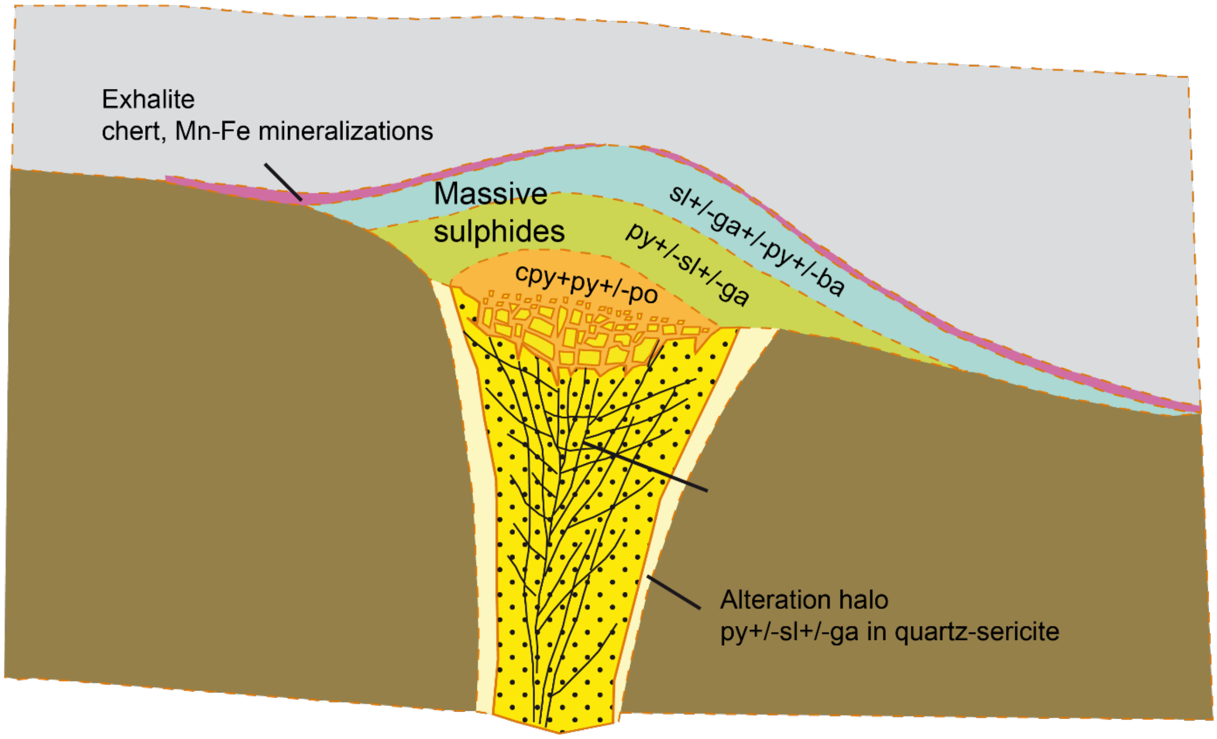


Figure 2: General architecture of a VMS deposit. py = pyrite, po = pyrrhotite, cpy = chalcopyrite, sl = sphalerite, ga = galena, ba = barite.

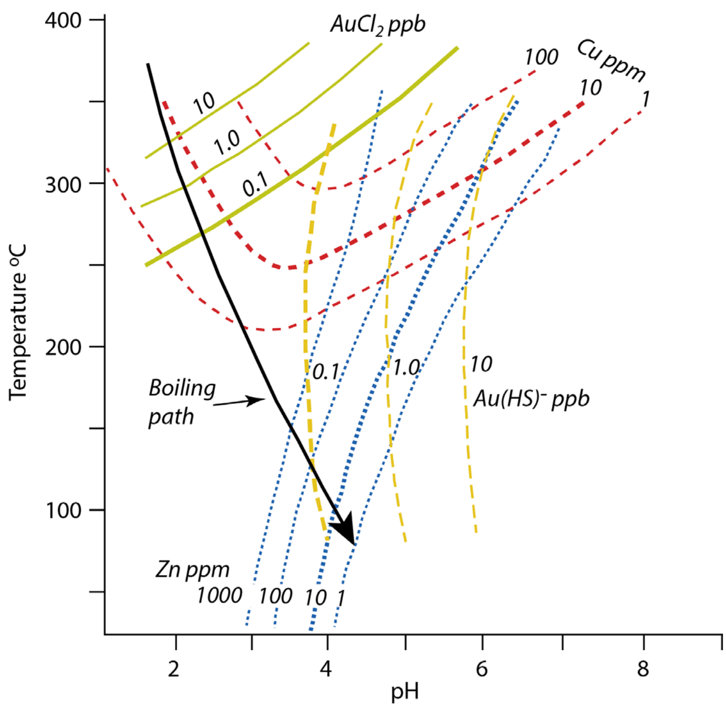


Figure 3: Solubilities of Cu, Zn and Au chloride/bisulphide as a function of temperature and pH. Note that Cu solubility as a chloride-complex is mostly temperature-dependent and Zn (and Pb) is mostly pH-dependent. Gold as a chloride-complex is mostly temperature-dependent, whereas Au-bisulphide is mostly pH-dependent. From Franklin et al. (2005).

3.2 SMS/VMS deposits and different tectonic settings

Massive sulphide deposits form in various tectonic settings, including mid-ocean ridges, back-arc basins, oceanic islands, intra-oceanic arcs to continental arcs and rifted margins. Each of these environments are characterized by their lithological assemblages and rock compositions which also to a large degree control the metal content of the sulphide deposits (Franklin et al. 1981, Barrie and Hannington 1999).

VMS deposits are marine massive sulphide deposits that have been transported on land due to various tectonic processes. Based on the different host rocks and geotectonic setting, the VMS deposits have been divided into five different lithotectonic types (Barrie and Hannington 1999, Franklin et al. 2005): 1) Mafic, 2) Bimodal-Mafic, 3) Siliciclastic (pelitic)-Mafic, 4) Bimodal-Felsic, 5) Siliciclastic-Felsic.

The mafic type is formed at mid-ocean ridges and mature intra-oceanic back-arc settings and is represented on land by ophiolitic sequences. It is dominated by basaltic flows of MORB composition, while boninites may be present in arc settings. Ultramafic and felsic rocks may be minor components. Examples: *VMS: Troodos (Cyprus), Løkken, Oman, Newfoundland ophiolites, SMS: Mid-Atlantic Ridge, East Pacific Rise.*

The bimodal-mafic type is formed in rifted intra-oceanic arcs and is basalt-dominated but may contain up to 25% felsic volcanic rocks. Examples: *VMS: Grong, Støren, SMS: the Kermadec and the Izu-Bonin arcs.*

The siliciclastic-mafic type is mainly formed in juvenile and accreted arc assemblages (oceanic mature back-arc settings) but also in sediment-filled ridges with subequal amounts of basalt and sediments, as well as marginal basins. Felsic rocks are generally absent. The sediments are mainly pelitic, often carbonaceous, while siltstone, sandstone and wackes are subordinate. Examples: *VMS: Besshi, Windy Craggy, Røros, Sulitjelma, Vaddas, SMS: Middle Valley, Guaymas basin, Grimsey, Jan Mayen.*

The bimodal-felsic type is formed in continental margin arcs and marginal back-arc rifts. Felsic volcanic rocks constitute up to 70% of the strata, basalt 20-50% and terrigenous sediments up to 10%. Examples: *VMS: Meråker, Stekenjokk, Skellefte, Hokuroku (Kuroko), SMS: Manus Basin, Tyrrhenian and Aegean Sea.*

The siliciclastic-felsic type is formed in epicontinental back-arc rifts and continental rifts and is characterized by sediments (up to 80%) with minor felsic volcanic and volcaniclastic rocks. Mafic volcanic rocks are very minor. Examples: *VMS: Iberian Pyrite belt, Rudny Altai, SMS: Red Sea, Okinawa Trough.*

Table 1: Metal contents ($Mean_{geom}$) of the various VMS types (From Franklin et al. 2005)

	Bimodal-mafic	Mafic	Pelitic-mafic	Bimodal-felsic	Siliciclastic-felsic
Cu (%)	1.24	1.82	1.23	1.04	0.62
Zn (%)	2.32	0.84	1.58	4.36	2.70
Pb (%)	0.30	0.02	0.68	1.14	1.09
Au (g/t)	0.81	1.40	0.75	1.06	0.59
Ag (g/t)	21	11	19	56	39
Tonnage (Mt)	3.421	2.699	4.721	3.321	7.139
Total metal (Mt)	0.129	0.063	0.133	0.198	0.325
N deposits	291	76	90	241	106

There are clear differences between the various VMS types with respect to grades and tonnages (Table 1). The contents of copper and gold are fairly similar, except for the siliciclastic-felsic type. The mafic and pelitic-mafic types have a much higher Cu/Zn-ratio, and lower zinc concentrations. Lead and silver are clearly higher in the two felsic types and lead is extremely low in the mafic type. With respect to size, the mafic type is significantly smaller than the other types and the mean tonnage of metal is only half of the tonnage of the two other mafic types. The siliciclastic-felsic type is larger than the others, and contain twice as much metals.

The Solwara deposit in the Manus Basin, a back-arc basin close to Papua New Guinea, was discovered in 1996 (Binns et al. 1997). Already in 1997 Nautilus Minerals Inc. was granted exploration licenses covering large parts of the Manus Basin, and a mining licence for Solwara 1 was granted by the PNG government in 2011. Based on geophysics and drilling, indicated resources of 1.0 Mt @ 7.2% Cu, 0.4% Zn, 23 g/t Ag and 5.0 g/t Au was presented by the company in 2012 as a basis for exploitation. However, the company went bankrupt in 2019 before any feasibility/pre-feasibility studies had been done. The mining rights and assets (including mining equipment) are now owned by Deep Sea Mining Finance Limited, planning to develop the Solwara 1 into production (https://dsmf.im/).

The Solwara deposit and other similar deposits in the Manus basin have been used as analogues to the MOR SMS, but this is very misleading. First of all, the Manus Basin is a back-arc basin where the igneous rocks are dominated by felsic volcanics and intrusions. Furthermore, it is more of a hybrid hydrothermal system, where much of the copper and gold are derived directly from the magmas. The present interpretation is that these deposits largely classify as high-sulfidation epithermal deposits and not SMS deposits (Yeats et al. 2014).

3.3 Cyprus-type VMS deposits as SMS analogues?

Ophiolites represent oceanic crust and underlying mantle that have been tectonically obducted onto continental margins. Notably, only a very minute amount of all formerly generated oceanic crust has ended up on land as ophiolites (e.g., Dilek, 2003); most of the oceanic crust has been subducted.

Although ophiolites have been studied for a century it was only after the plate tectonic paradigm shift that a modern understanding evolved, linking ophiolites to the seafloor spreading process. A GSA Penrose Conference on ophiolites held in Cyprus 1972 (Anonymous, 1972), represents a landmark in the understanding of ophiolites. This meeting led to the three-layer model for ophiolites: gabbros, sheeted dikes, and pillow basalts (Figure 4). An outcome of the conference was that ophiolites were interpreted to represent former mid-ocean spreading centres. Subsequent work has revealed a more complex picture, where geochemical signatures suggest influence from subduction zones, and it has since been accepted that e.g. the Troodos and Semail (Oman) ophiolites formed in supra-subduction settings, i.e. local spreading above a subduction zone (e.g. Adamides, 2010, MacLeod et al, 2013). A subsequent GSA Penrose Conference on ophiolites (Dilek et al., 2000) recognized several ophiolite types: a) Ligurian-type, b) Mediterranean-type, c) Sierran-type, d) Chilean-type, e) Macquaire-type, f) Caribbean-type and g) Fransiscan-type (Dilek, 2003).

Moores et al. (2000) suggested “that Earth’s mantle is isotopically heterogeneous at all scales and chemically modified by previous subduction events so that lavas erupted at oceanic spreading centres may not necessarily reflect the characteristic chemical fingerprint of their current tectonics settings” (in Dilek, 2003).

Tectonic exhumation of the Troodos ophiolite was initiated in the Pleistocene and resulted in a doubly plunging anticline that was eroded in the exhumation process. The erosional truncation provides excellent exposures of the entire Penrose three-layer succession (Figure 5).

The pillow lavas at Troodos contain a number of VMS deposits. Mining of these deposits started already in pre-Christian times although the main ore extraction occurred in the mid-late 1900's. Both tonnages and grades of the deposits are well-constrained.

The Troodos ophiolite formed in a slow-spreading setting (e.g. Abelson et al, 2001; Granot et al, 2011). The massive sulphide deposits reside within basalt-dominated host rocks and have been coined Cyprus-type VMS. The extensively drilled and studied TAG SMS (e.g., Humphris et al, 1996; Hannington et al, 1998) is considered to be a Cyprus-type deposit (Hannington et al, 1998) and serves as an important calibration against the onshore Cyprus-type VMS analogues. TAG is the only reasonably densely drilled mid-Atlantic type SMS deposit. In this study Cyprus-type VMS deposits are considered the best analogues for slow-spreading mid-oceanic SMS ores.

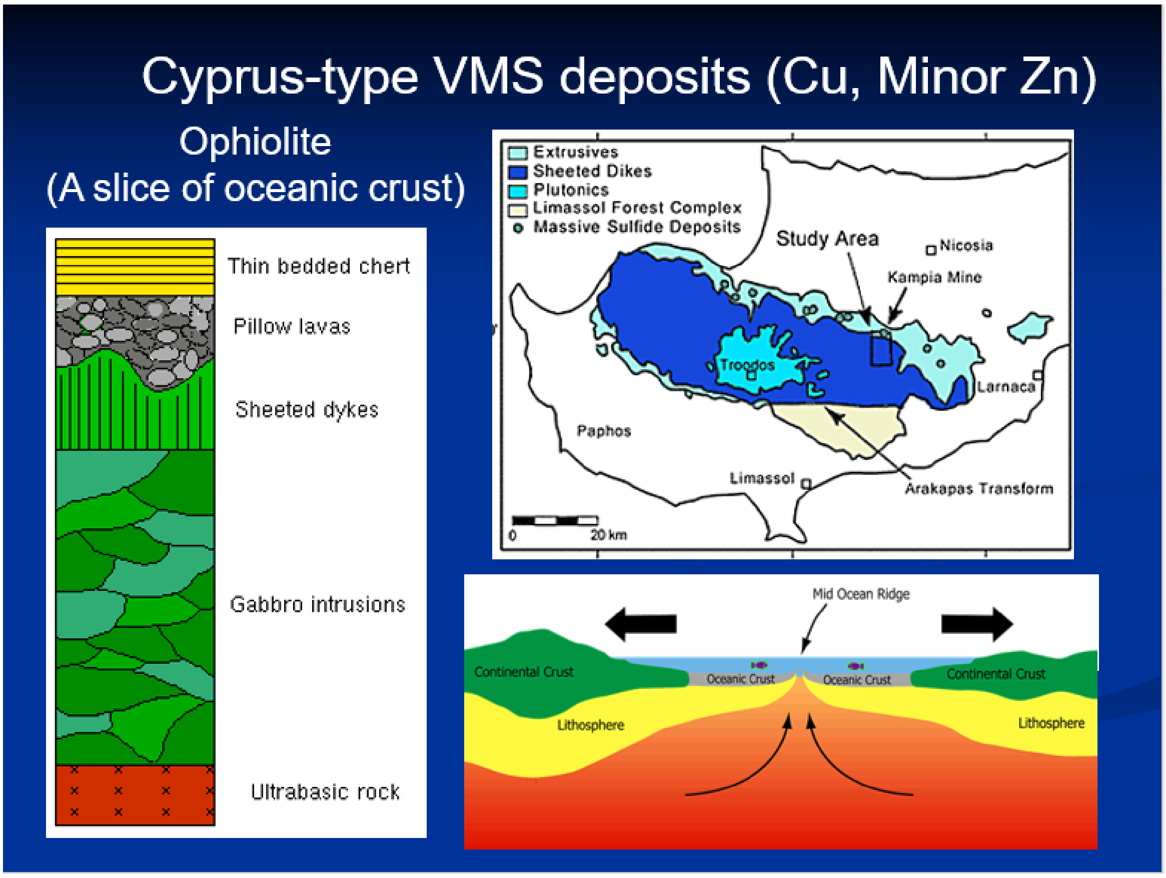


Figure 4: Simplified diagram illustrating the Penrose crust layering (left), the Troodos ophiolite and mined VMS ore bodies (top right) and the generalized plate tectonic setting for the formation of the oceanic crust (Penrose crust) at a spreading ridge (lower right). From A. Wilson (https://slideplayer.com/slide/4691115/)

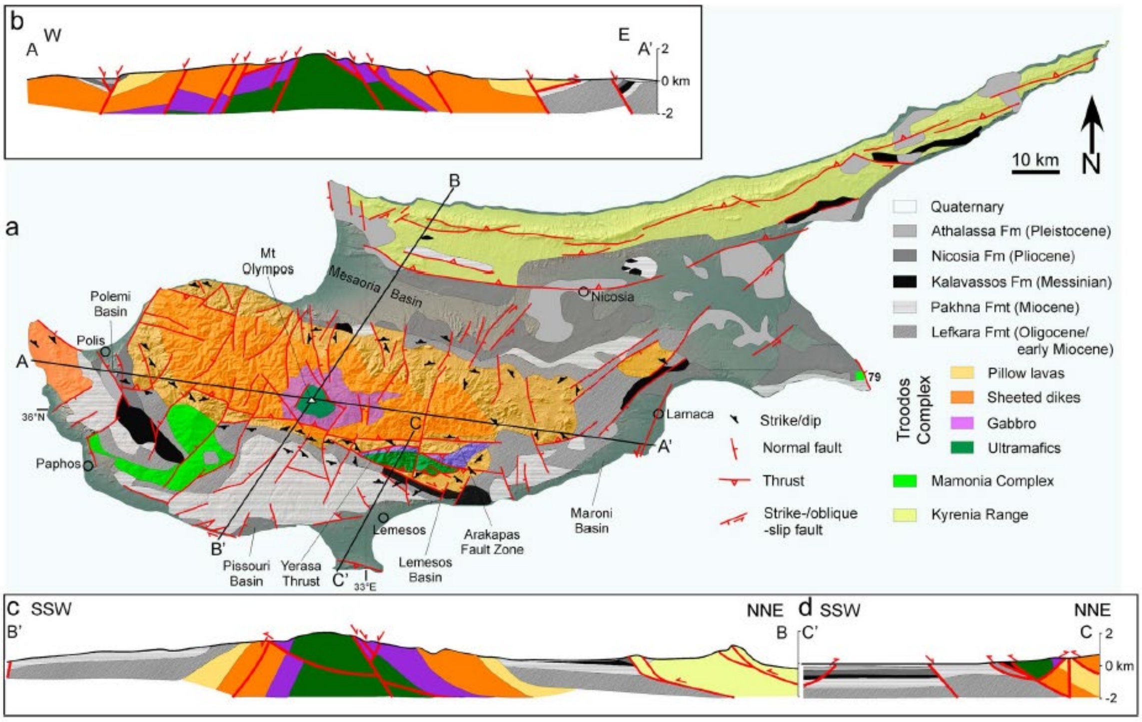


Figure 5: Geologic configuration of Troodos, illustrating both the Penrose layering and the structure of Troodos. From Ring and Pantazides, 2019.

4. PREVIOUS SMS RESOURCE ESTIMATES

The assessment of the resource potential in SMS at the modern seafloor is challenging due to the lack of reliable data on grades, tonnages, as well as density of deposits. A few attempts have been made on the global scale, notably by Hannington et al. (2010, 2011) and Singer (2014).

Hannington (2011) estimated the global abundance of SMS deposits in the neovolcanic zones, including 64 000 km along the mid-ocean ridges and 25 000 km of arcs and back-arc basins. This was done by examining deposit densities in 32 control areas of 5x5 degrees (lat./long.) which contained 106 deposits (vent complexes/sulphide mounds) with 2D dimensions of > 100 m^2 and spatially separated from any nearby deposits by more than 10 km. Based on heat fluxes and plume data (Baker 2007, Baker & German 2004), deposits are generally farther apart on slow-spreading ridges (174 km) than on fast-spreading ridges (54 km). The combined average spacing for the control areas were found to be 107 km and if this number is applied to the strike length of the oceanic spreading ridges, it yields an estimate of 8-900 deposits along the neovolcanic zone, with at least 500 at the 90th percentile, and not more than 5000 at the 10th percentile. Using a number of 1000 deposits, a median grade of 5 % Cu+Zn (close to grades of VMS deposits), and size distribution based on the knowledge about SMS in 2010 (from Hannington et al. 2010), the total amount of metal (Cu+Zn) along the global neovolcanic zones (89 000 km) was estimated to 30 Mt. With a width of the neovolcanic zone of 1 km, the content is 0.34 Mt Cu+Zn/1000 km^2, of which 0.21 Mt Cu/1000 km^2, using the Cu/Zn-ratio of the mafic data in Hannington et al. (2010).

Singer (2014) used the same oceanic plate boundaries as Hannington et al. (2011) but assumed permissive zones of 2 km on each side of the spreading centres, thus a permissive area of 256 000 km^2 (64 000 km x 4 km) along the oceanic ridges and 100 000 km^2 (25 000 x 4 km) in the back-arc basins. 175 deposits of the mafic-type VMS deposits of Mosier et al. (2009) were used for the frequency distributions of contained metals in the SMS deposits. The density of SMS deposits was based on 38 well-explored VMS tracts, and these were applied in the following formula (from Mosier et al. 2007), appropriate for simulation:

$$N_t = 10^{(-0.5846+0.3846\log10(\text{area})+e)}$$

where area is the permissive area in km^2, e is the error with a mean of 0 and a standard deviation of 0.338, and N_t is the estimated number of deposits in tract t. With the equation in log form, this is equivalent to assuming a lognormal distribution of number of deposits. In the ocean spreading tracts this results in a mean of 34 deposits, a median of 26, 69 deposits at the 10th percentile, and 9 deposits at the 90th percentile. These estimates are far below the estimates by Hannington et al. (2011). According to Singer (2014), this is due to the reliance by Hannington et al. (2011) on prospects and occurrences without any certain data on size or tonnage, compared to the reliable dataset used by Singer (2014). Combining the data on number of deposits with contained metals taken from mafic VMS deposits in Monte Carlo simulation yielded a probable median of 4.6 Mt copper (mean is 7.2 Mt) contained in the total area of 356 000 km^2 (oceanic ridges and back-arc tracts), i.e. 13 000 t Cu/1000 km^2 (mean 20 000 t Cu/1000 km^2). This is about a tenth of the result by Hannington et al. (2011) shown above, if we use 4 km width of the neovolcanic zones and 50 % of the resource is copper.

Resource assessment of the Norwegian part of the Atlantic Ridge (N-MAR) was first carried out for the Mohns ridge by Juliani & Ellefmo (2018 a, b). Based on geological criteria, including proximity to the axial volcanic ridge, distance from the neo-volcanic ridge axis, distance from fault zones and faults intersections, Juliani & Ellefmo (2018 a), estimated the number of undiscovered SMS deposits along the 2922 km^2 permissive tracts along the Mohns Ridge. The 90th percentile was calculated to be at least 3 deposits, the 50th percentile at least 8 deposits and the 10th percentile at least 23 deposits. The expected number of deposits was calculated to be 11. The total metal endowment along the ridge was calculated to 447 000 t using Monte Carlo simulation, combining the number of deposits with VMS grade and tonnage models (Juliani & Ellefmo 2018 b). The mean tonnage of copper was calculated to be 325 000, which is equivalent to ~0.111 Mt Cu/1000 km^2.

A new resource assessment, including both the Mohns and Knipovich Ridge, was carried out in 2019 (Ellefmo & Søreide 2019). The Troodos ophiolite was chosen as an analogue for the slow-spreading N-MAR ridges, which according to Singer (1986) contains 20 deposits/1000 km^2 hosted by the pillow lavas. Ellefmo & Søreide (2019) argued that several deposits could be buried or eroded away and therefore the deposit density of 20 deposits/1000km^2 corresponding to the 20th percentile in a lognormal distribution could be used for the SMS density. The entire area comprising 17 permissive subtracts (subplays) along the Mohns-Knipovich ridge was estimated to 11 389 km^2 based on some of the same criteria as in Juliani & Ellefmo (2018 a), but in addition also a geodynamical analysis. From this modelling and arguments, the area could contain 155 accumulations larger than 1700 t (corresponding to 50 t Cu and a surface expression of at least 0.04 km^2). The grades and tonnages were based on global SMS data (Hannington et al. 2010, 2011, 2013). From this Ellefmo & Søreide (2019) calculated a mean of 6.9 Mt Cu (median 4.6 Mt Cu) using Monte Carlo simulation, corresponding to a mean of 0.60 Mt Cu/1000 km^2 (median 0.41 Mt Cu/1000 km^2). This is 5x times higher than the value by Juliani & Ellefmo 2018 b, mainly because the Cu grades in the latter was much lower (2% compared to 5.8%). The median number of Cu accumulations was calculated to 126, corresponding to 11.1/1000 km^2.

In 2023, NPD presented their assessment on seabed minerals in the areas of Norwegian jurisdiction, including SMS resources (NPD 2023). Their area for assessment included the Mohns and Knipovich ridges and surrounding areas, but also areas around Jan Mayen (Figure 6). The extent of the areas was based on bathymetry and especially cover by sediments. The entire area was estimated to 106 000 km^2, where some parts were reduced in extent because of sedimentation making eventual sulphide deposits inaccessible.

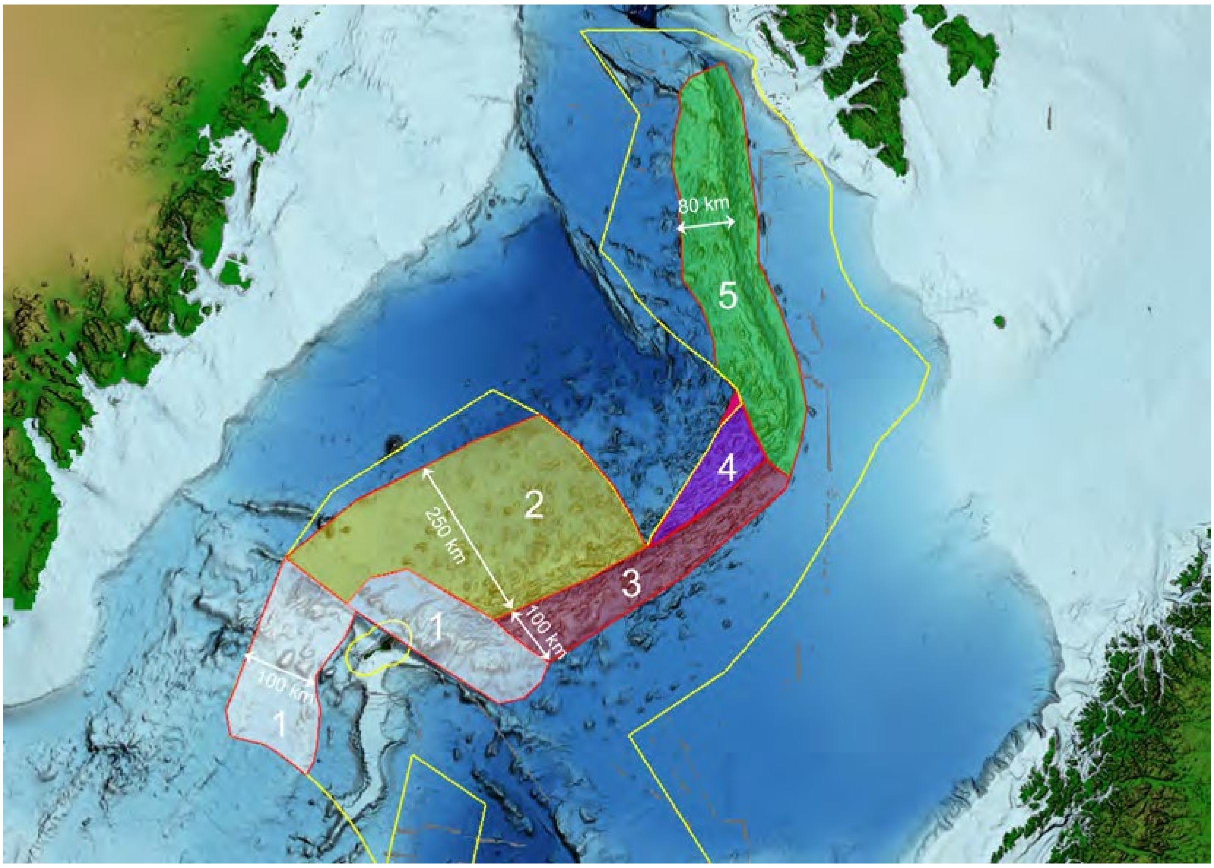


Figure 6: Prospective areas for modelling of sulphide deposits at N-MAR by NPD (NPD 2023).

The expected density of deposits was based partly on Hannington et al. 2010 and Cherkasov et al. 2010, and partly based on observations of occurrences along the ridges and was set to 9.5 deposits/1000 km^2 (minimum 4, maximum 12 deposits). From this, the number of deposits in the entire area is expected to be 1007 (minimum 424, maximum 1272 deposits). The number of deposits was divided into four different models, based on their tectonic position, which also influenced on their metal contents: the shallow water model around Jan Mayen (estimated 303 deposits @ 0.5 % Cu), the axial model along the ridges (176 deposits @ 1.2 % Cu), and a cobalt-rich (185 deposits @ 3 % Cu) and a Cu-Zn rich flank model (343 deposits @ 4 % Cu). Weighted average of these models is calculated to 2.27 % Cu (1007 deposits). The metal content in the different settings was estimated based mainly on data from known SMS occurrences along the Atlantic Ridge (e.g. Cherkasov et al. 2010, Hannington et al. 2010, Sahlström et al. 2022 and unpublished data from NPD and UiB). The size of the individual deposits was partly based on the size of the TAG deposit, the only SMS deposit along the Atlantic Ridge which has been drilled, but also based on other SMS occurrences listed in Hannington et al. (2010). The resource assessment by NPD based on Monte Carlo simulation yielded 38.1 Mt Cu, corresponding to 0.36 Mt Cu/1000 km^2.

The above-mentioned SMS resource estimates are summarized in Table 5 in Chapter 7, and discussed together with the results of this work.

5. THE DATASETS

5.1 Database on VMS deposits

Several databases have been compiled on VMS deposits in the world (e.g. Mosier et al. 1983, Barrie and Hannington 1999, Jenkins and Lydon 2002, Franklin et al. 2005, Mosier et al. 2009), as well as more regional and national compilations.

The most recent compilation of VMS deposits by Mosier et al. (2009) has been used as a basis for this work. In the database the authors discriminated between felsic, bimodal-mafic and mafic types of deposits, based on their host rocks. For our study this is too simplistic, as the tectonic setting has not been considered. Deposits in mid-ocean ridge setting are hosted by mafic rocks (i.e., basalts/tholeiites), but also deposits in arc to back-arc setting may be mafic-hosted, even though most of the arc-related deposits are classified as the bimodal-mafic type. In older classifications (e.g., Cox and Singer 1986), the mafic type is known as Cyprus-type and the bimodal-mafic type is assigned to the Kuroko-type deposits. In a mature back-arc to marginal basin with large sedimentary input sediment-hosted VMS deposits occur, which are also known as Besshi-type or pelitic-mafic type (Fox 1984, Franklin et al. 2005).

On this basis the database by Mosier et al. (2009) had to be edited and upgraded. Only mafic-type deposits which have been described to be in an ophiolite setting are included in the dataset. Literature and internet resources have been searched to get as up-to-date numbers of grade and tonnage as possible of the relevant deposits.

The entire dataset is presented in the appendix. It contains grade and tonnage data from 109 deposits from major ophiolite districts around the world, including Cyprus, Newfoundland, Oman, Turkey and Norway. A brief review of these main districts is presented below.

Table 2: Statistics of the database of ophiolite-hosted VMS deposits (see appendix)

	Mt	Cu (%)	Zn (%)	Pb (%)	Au (g/t)	Ag (g/t)
Median	1.51	1.43	1.00	0.04	0.48	10.30
P10	11.00	3.30	2.50		5.64	51.00
P50	1.51	1.43	1.00	0.04	0.48	10.30
P90	0.09	0.50	0.20		0.08	1.19
$Mean_{Geom}$	1.22	1.34	0.81	0.06	0.53	7.38
n	*109*	*109*	*41*	*6*	*35*	*25*

N = number of deposits

Statistics of the database of the 109 ophiolite-hosted VMS deposits around the world are presented in Table 2 (see appendix for the dataset). The median (P50) for an ophiolite-hosted deposit is 1.5 Mt with 1.4 % Cu and 1.0 % Zn. The geometric mean is 1.2 Mt with 1.3 % Cu and 0.8 % Zn which is considerably lower than for the mafic deposits shown in Table 1 above from Franklin et al. (2005). The P10 is 11 Mt with 3.3 % Cu and 2.5 % Zn, and the P90 is 90 000 t with 0.5 % Cu and 0.2 % Zn.

Figure 7 shows the distribution of the deposits in the database in a copper grade versus tonnage diagram. The median copper content in an ophiolite-hosted deposit is 21 600 t Cu.

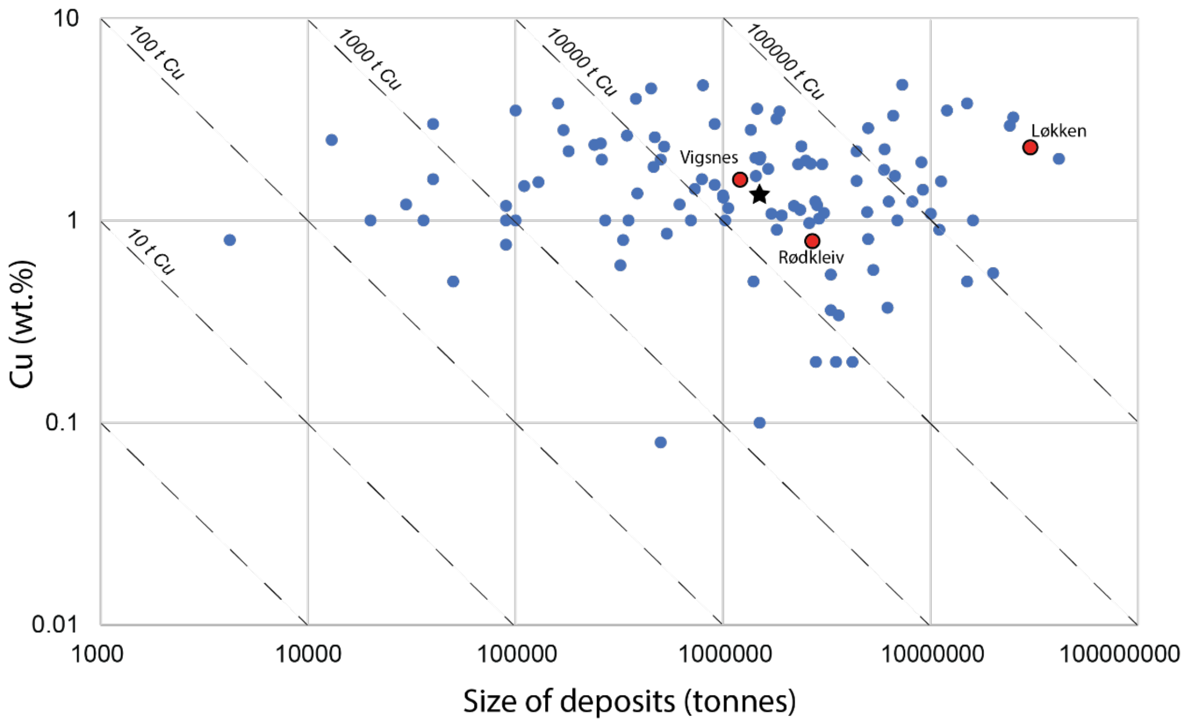


Figure 7: Copper grade vs. Tonnage of the ophiolite-hosted VMS deposits. The stippled lines show the contained tonnage of copper. The three major Norwegian deposits, Løkken, Vigsnes and Rødkleiv are shown by red dots. The star shows the median grade and tonnage of the 109 deposits in the dataset.

5.2 Description of major ophiolite districts

5.2.1 Troodos (Cyprus)

The Troodos ophiolite is one of the best preserved, essentially undeformed ophiolite complexes in the world. The ophiolite formed during the closure of the paleo-Tethys Ocean. It is not part of the Paleo-Tethyan seafloor but formed during local seafloor spreading in a supra-subduction zone while the Tethyan seafloor was being subducted. The age of the Troodos ophiolite is Turonian (92-90 Ma). The dome-shaped ophiolite was exhumed in the Pleistocene and resulted in superb exposures of the entire three-layer ophiolite succession, including the underlying mantle rocks. Troodos resembles a sliced onion with the deepest mantle rocks in the centre and the stratigraphically higher layers (gabbros, sheeted dikes, and pillow lavas) exposed radially away from the mantle core (Figure 8). Detailed structural mapping has revealed three time-successive axial grabens on the north side of the ophiolite, and that the axial grabens terminate against the Arakapas transform in the southern part of the ophiolite (Varga and Morres, 1985, Martin et al., 2019, Figure 9).

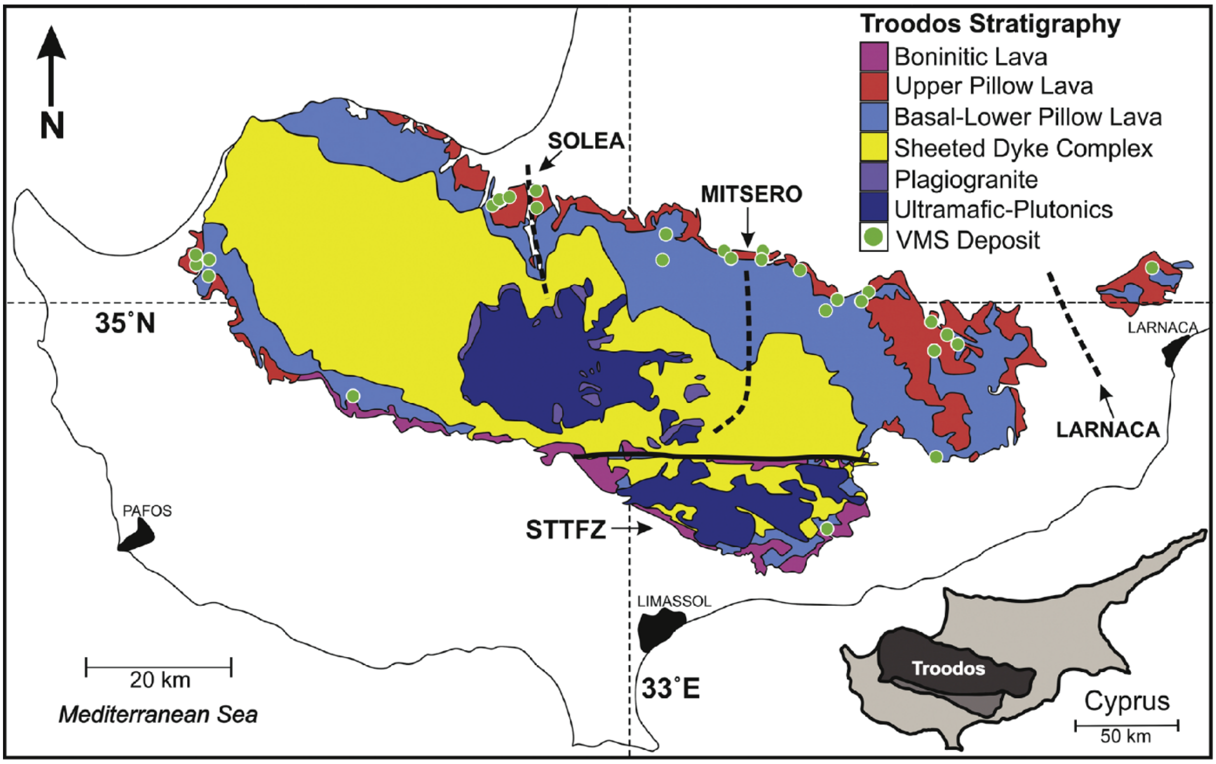


Figure 8: Troodos ophiolite with marked VMS deposits (green dots). The area of pillow lavas and sheeted dykes is ca 2015 km^2 (pillow lavas 1518 km^2, dyke complex 497 km^2). (Map from Martin et al., 2020)

Troodos contains 28 well-defined VMS deposits, located in the pillow lavas (Figure 8). The ores are enriched in copper with subordinate zinc in the distal portions of the ore bodies. A copper/zinc ratio around 100 is common (e.g., Adamides, 2010). The ore bodies are lens-shaped mounds overlying stockwork feeder stringer zones. The mounds typically contain brecciated massive pyrite ores in ophiolite-related basalt sequences whereas the underlying stringer zones are characterized by anastomosing quartz-sulphide minerals veins in brecciated and chloritized basalt (e.g., Hannington et al, 1998). The sulphides and host rocks display mineralogical and textural characteristics alike those of SMS deposits forming at currently active mid-oceanic spreading centres (e.g., Adamides, 2010; Hannington et al., 1998). The absence of carbonate-rich sediments in both the Periphedi and Kannaviou bentonite formations capping the ophiolite indicate that the sediments accumulated in deep water, below the carbonate compensation depth at ca 3500 m depth, in accordance with a spreading axis setting (e.g., Martin et al., 2019), and microfossils in the sulphides confirm an exhalative origin of the deposits (Little et al., 1999). Cyprus-type VMS ore bodies at Troodos are here considered to be valid SMS analogues.

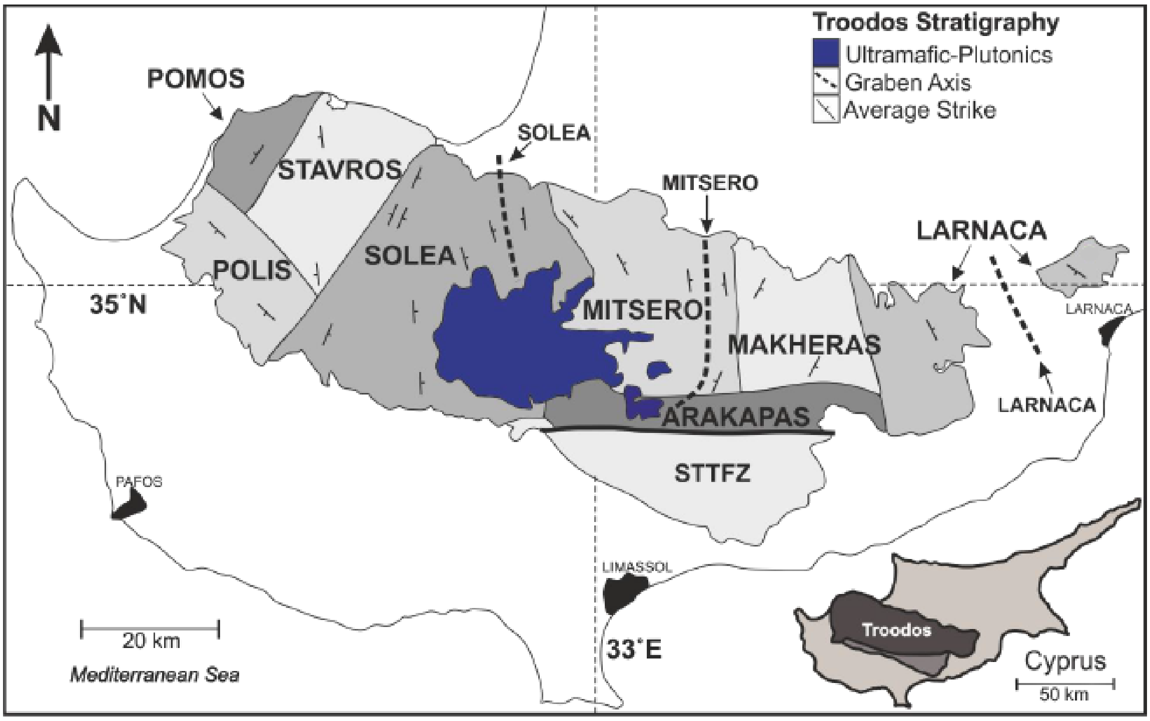


Figure 9: Simplified structural map of Troodos illustrating the three axial grabens Solea, Mitsero, and Larnaca. The axial graben is interpreted to have shifted from the Solea to Mitsero, to Larnaca and all terminate against the Arakapas Transform. From Martin et al. (2019).

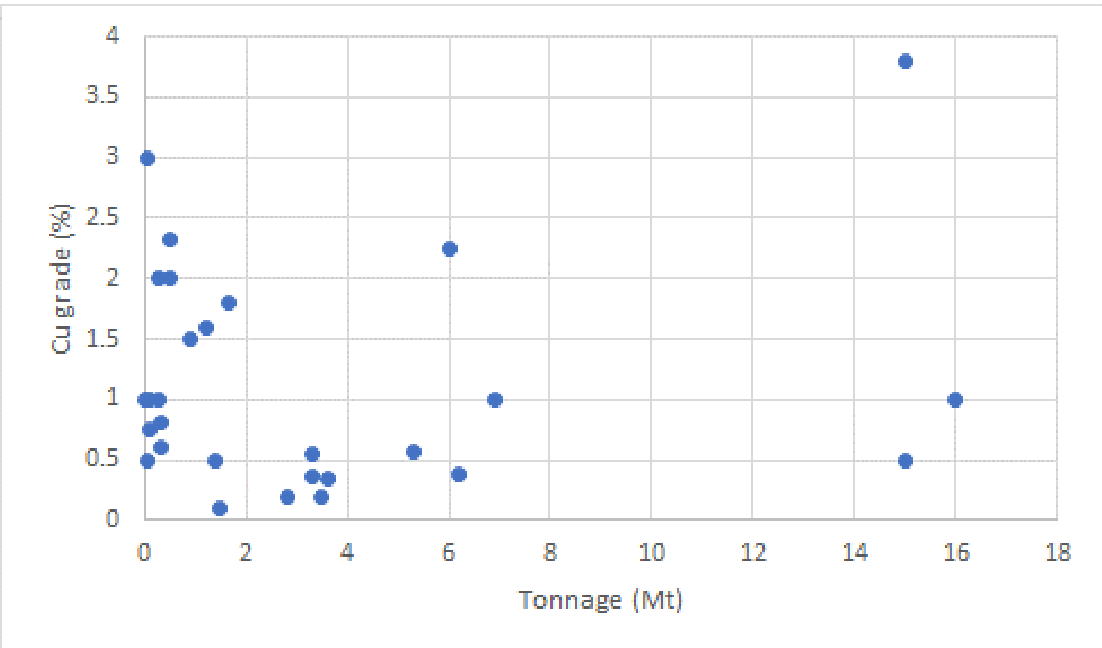


Figure 10: Cu grade versus tonnage for Troodos VMS ore deposits.

The average grade and tonnage for the 28 deposits in Cyprus is 3.4 Mt and 1.12% Cu. Copper grade vs. tonnage for these ore deposits is shown in Figure 10. Some general messages can be drawn from this plot, such as that most ore bodies are less than 6 Mt, and most ore grades are less than 2.5% Cu. Mavrovouni is an exception with a tonnage of 15 Mt and grade of 3.7% Cu. Notably, the 15 Mt Mavrovouni and 6 Mt Limni ore bodies are interpreted to have formed sub-seafloor (Adamides, 2010). Such ore bodies would likely be challenging to discover in an offshore setting and certainly difficult to mine in a setting like the Mohns Ridge.

While grades and tonnages of the ore bodies in Troodos can be read from the enclosed spreadsheet and from Figure 10, the number of ore deposits per area (density) requires calculation based on maps. The known VMS deposits at Troodos are restricted to the pillow lavas, but mineralisations are also present in the underlying sheeted dyke complex. Including both the lava and dyke units, the area measures ca. 2015 km^2 (Figure 8), which implies a density of 13.9 deposits per 1000 km^2.

5.2.2 Samail (Oman)

The Samail Ophiolite (also known as Semail) is located on the eastern corner of the Arabian Peninsula and lies in the Hajar Mountains in Oman and the United Arab Emirates and covers approximately 100.000 km^2. The ophiolite hosts copper-dominant, Cyprus-type VMS deposits. It was formed in Late Cretaceous times and consists of a lower and upper crustal part comprising a basal metamorphic sole, peridotite, gabbro, a sheeted dike complex and extrusives (Figure 11).

The extrusives consist of up to 1-3 km basaltic-andesitic lavas (Belgrano et al, 2019, Lippard,1986) and the volcanostratigraphy is shown in Figure 11. Four of the volcanic units host VMS deposits: Geotimes, Lasail, Tholeiitic Alley, and Boninitic Alley.

The Geotimes unit was formed during initial axial spreading between 96,5 and 95,5 Ma and consists of basal basalts and basaltic andesites. The petrogenic affinity is disputed and the lavas could be mid-ocean ridge basalts (MORB), back-arc basin basalts (BABB), or forearc basalts.

The Lasail unit is found as discontinued off-axis Low-Ti primitive basaltic occurrences. It is interfingering with, but mostly overlies, the Geotimes unit. The Tholeiitic Alley tholeiitic series spans a fractionation from basalts through high-magnesium andesites to rhyolites. The Boninitic Allay unit comprises high-Ca boninitic lavas overlying, but is also intercalated with, the Tholeiitic Alley unit (Belgrano et al. 2019).

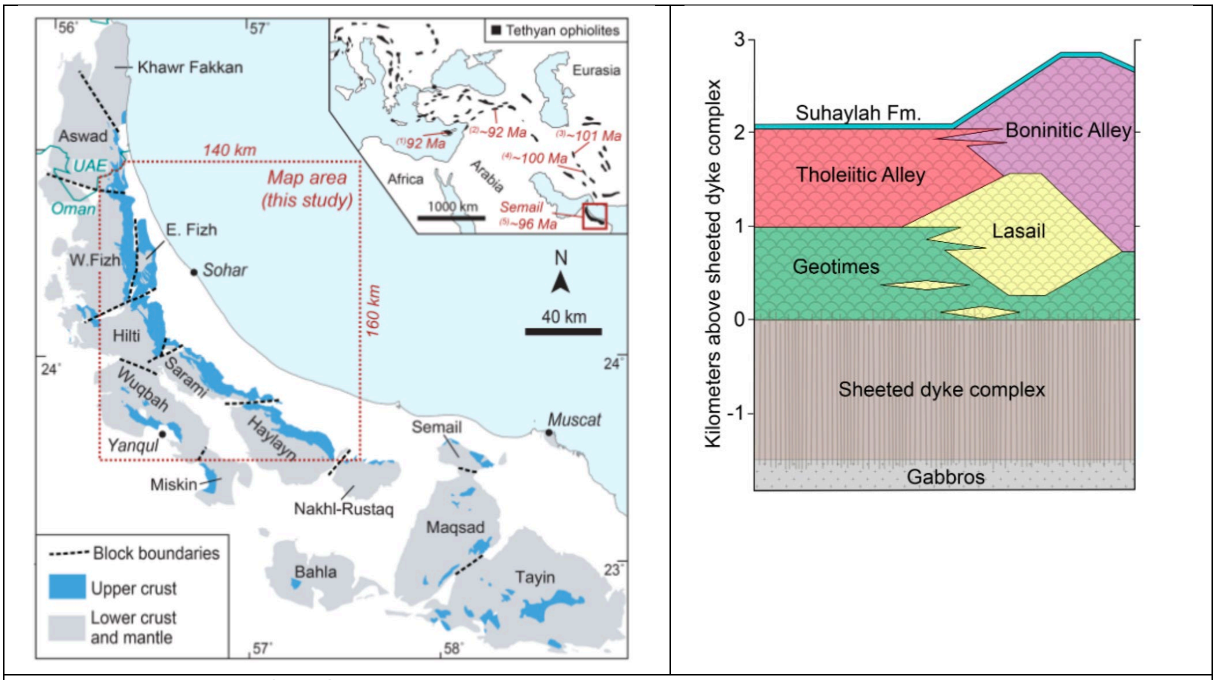


Figure 11: The extent of the Samail ophiolite (blue and grey). The volcanostratigraphy is shown to the right (from Belgrano et al. 2019).

The Geotimes and Lasail Units are interpreted as ocean-spreading ridge and off-axis volcanic environments respectively (MORB type), whereas the Tholeiitic and Boninitic Alley Units are interpreted as supra-subduction zone settings. Among the investigated deposits, the five with the highest copper grades are found in the Geotimes lavas and thus correlate with the MORB setting, whereas elevated gold grades are associated with younger units representing subduction-related volcanism (Gilgen et al. 2014).

The VMS deposits occur irregularly within the extrusive sequence. Most of these deposits are capped by gossans mostly consisting of strongly silicified iron-oxide caps with variable copper, and locally gold, concentrations. The Samail deposits have a classical Cyprus-type anatomy. They consist of an upper proximal lens of pyrite + chalcopyrite +/- sphalerite +/- magnetite with thicknesses varying between 5 m and 210 m. The deposits are typically underlain by stockwork and pyrite-chalcopyrite siliceous breccias emplaced below the paleo-seafloor. The deposits are usually found in half-graben settings and are controlled by extensional faulting. Some deposits are characterized by brecciated massive sulphides interpreted as collapse of sulphide structures and mass wasting in an active graben environment.

Umbers are found throughout the extrusive sequence and are Fe- and Mn-rich sedimentary rocks, which are distal indicators of hydrothermal activity on paleo-seafloor horizons. They are common at the boundaries between volcanostratigraphic units but can also be found within the units. Umbers are most frequent in the Tholeiitic and Boninitic Alley Units. Four different types of umbers are described: silica-rich, epidote-bearing facies affected by high-temperature alteration, Fe-rich siliceous umbers, Mn-rich hematite-quartz umbers, and siliceous umbers with varying Mn content. Umbers are indicators of local hiatuses in volcanic activity (Gilgen et al. 2014).

The VMS hosting part of the Samail ophiolite has an area of 2826 km^2 and contains 16 VMS deposits with defined tonnage and Cu grade averaging 3 Mt and 2.05 % Cu, respectively. This gives a density of 5.7 deposits per 1000 km^2. The grade and tonnage distribution of the deposits is shown in Figure 12.

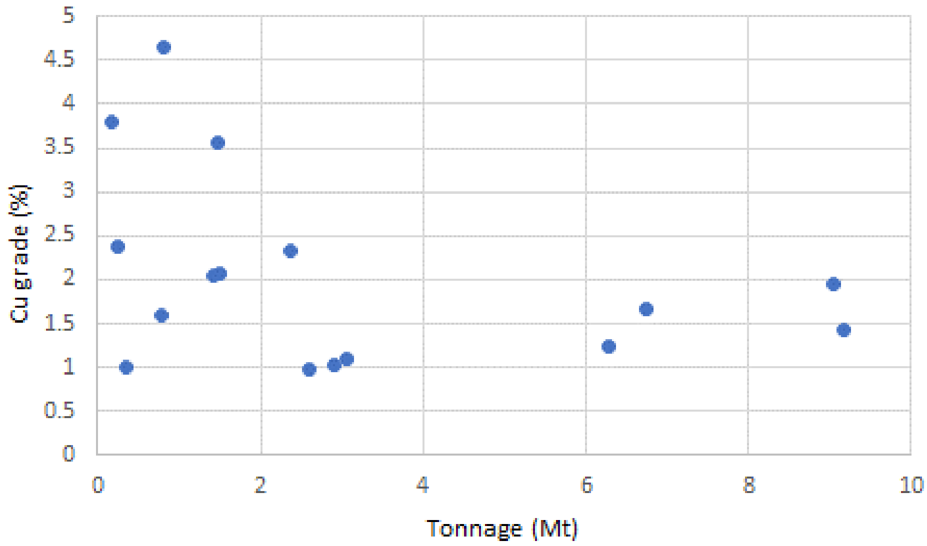


Figure 12: Copper grade vs tonnage for the VMS deposits in the Samail ophiolite.

5.2.3 Ophiolites on Newfoundland (Canada)

Newfoundland is host to one of the best known and preserved ophiolite districts in the world. However, the ophiolite sequences are strongly dismembered and are distributed in several districts on the island, including the Bay of Islands ophiolite complex, the Paquet Harbour Group, Point Rousse & Advocate Complex, the Lush's Bight Group and the Betts Cove Complex (Swinden & Kean 1988).

The Bay of Islands ophiolite complex

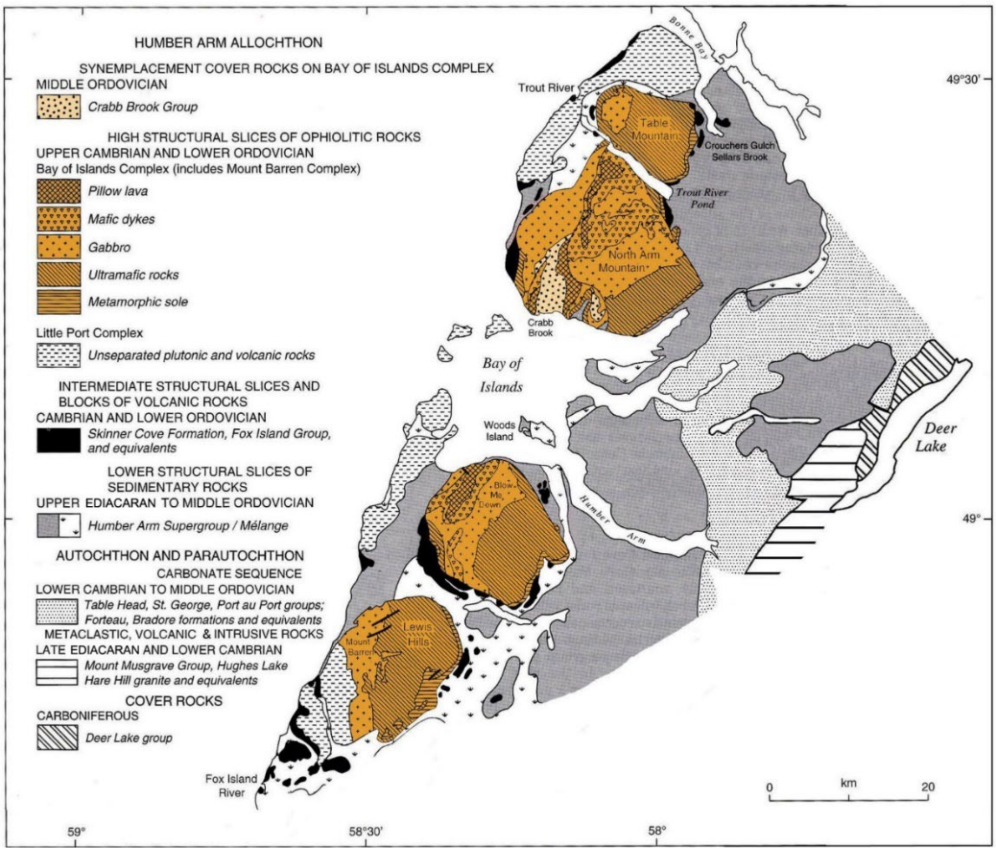


Figure 13: The Bay of Islands ophiolite complex (shown in brown), (Swinden & Kean 1988)

The Bay of Islands ophiolite complex is the westernmost of the ophiolite fragments on Newfoundland. There are three larger bodies, of which two include the entire ophiolite pseudo-stratigraphy, from the mantle to pillow lavas at the top (Figure 13). The three bodies have a total extent of 2800 km^2. The upper parts of the complex, excluding the gabbros have an extent of 423 km^2.

The complex hosts only one major VMS deposit, the York Harbour deposit, at 0.3443 Mt with 2.63 % Cu and 7.1 % Zn. The deposit was worked intermittently between 1897 and 1913, and about 90 000 t of ore was produced between 1900 and 1913 (Newfoundland-Labrador ore database). In addition are two minor deposits without certain tonnage and grades.

<u>The Baie Verte peninsula (Betts Cove)</u>

The Baie Verte peninsula at Newfoundland comprises several dismembered ophiolite fragments, including the Betts Cove ophiolite, the Advocate Complex, Point Rousse Complex, Pacquet Harbour Group, and the Lush's Bight Group (Swinden & Kean, 1988, Figure 14).

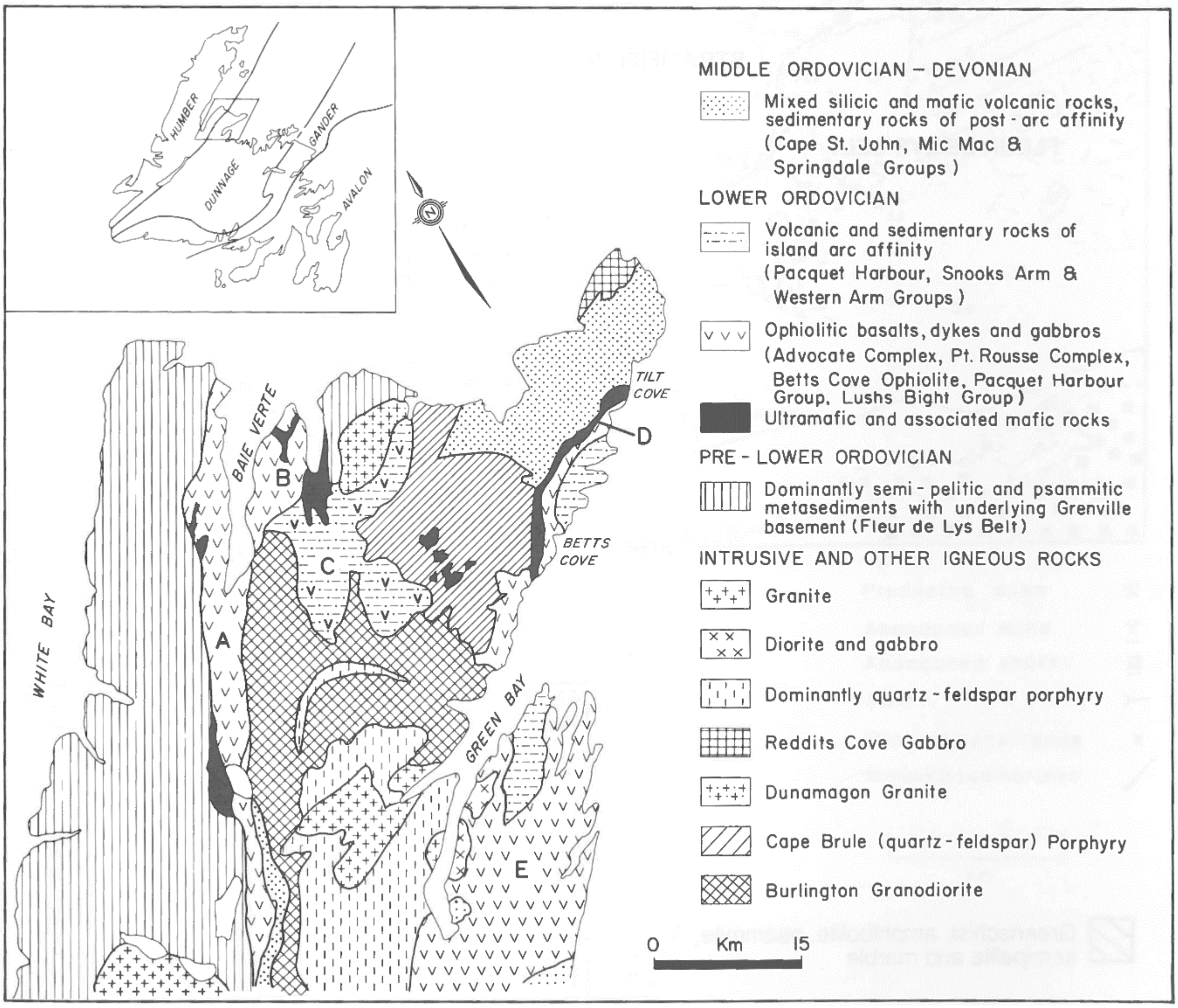


Figure 14: Geology of the Baie Verte Peninsula (from Strong, 1984). Ophiolite fragments: A – Advocate Complex, B – Point Rousse Complex, C – Pacquet Harbour Group, D – Betts Cove Ophiolite, E – Lush's Bight Group.

The Advocate Complex is highly dismembered, and appears to be incomplete, lacking a definite pillow lava member. The Point Rousse Complex is also dismembered but comprises a complete ophiolite suite. The Betts Cove ophiolite is intact, including ultramafic, gabbroic, sheeted dyke and pillow lava units. The Paquet Harbour Group consists of variably deformed and metamorphosed mafic volcanic rocks, as well as felsic and mafic volcaniclastics and mafic dykes.

Parts of this group may be non-ophiolitic. The Lush's Bight group is an ophiolite sequence divided into several fault-bounded blocks. The lowest exposed stratigraphic unit comprises sheeted dykes, and is overlain by various mafic volcanics, often pillow lavas, and minor tuff units.

Altogether, the ophiolite fragments at the Baie Verte Peninsula cover an area of 1773 km^2. The fragments contain 18 VMS deposits, which have been mined to smaller and larger extent. 14 of the deposits have reliable grade and tonnage data. The grades of these deposits vary from 1.0 % to 2.5 % Cu (average of 1.4 % Cu) and the tonnages from 0.013 to 8.2 Mt (average of 1.9 Mt), see Figure 15.

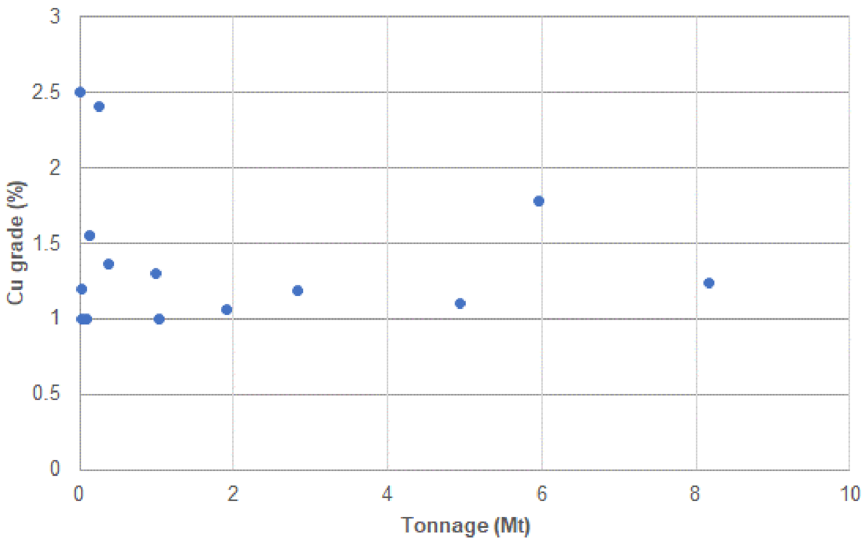


Figure 15: Grade and tonnage data for the VMS deposits hosted by the ophiolites at the Baie Verte Peninsula.

5.2.4 Ophiolites in Norway

There are several ophiolite complexes in Norway that were obducted during the Caledonian Orogeny in the Silurian and Devonian (Corfu et al. 2014, Grenne et al. 1999). These complexes host many VMS deposits and occurrences, which can be used to get a better understanding of the distribution, size and metal content of the SMS equivalents.

The major ophiolite complexes which contain known VMS deposits in Norway are 1) the Løkken-Vassfjellet-Bymarka ophiolite, 2) the Karmøy ophiolite, 3) The Lykling (Bømlo) ophiolite, 4) the Solund-Stavfjord ophiolite complex and 5) the Vågåmo ophiolite (Figure 16). These are described below.

There are also other units which have been recognized as ophiolites, but these do not contain any sulphide deposits, beyond small mineralisations of uncertain origin. The most important of these are the Leka Ophiolite Complex, the Gullfjellet Ophiolite Complex and the Lyngen Ophiolite. There are other units in Norway which have been interpreted as ophiolites, such as the Sulitjelma ophiolite in Nordland, the Vaddas district in Troms and the Støren Group in Trøndelag. All these units are briefly discussed below and are shown in Figure 16.

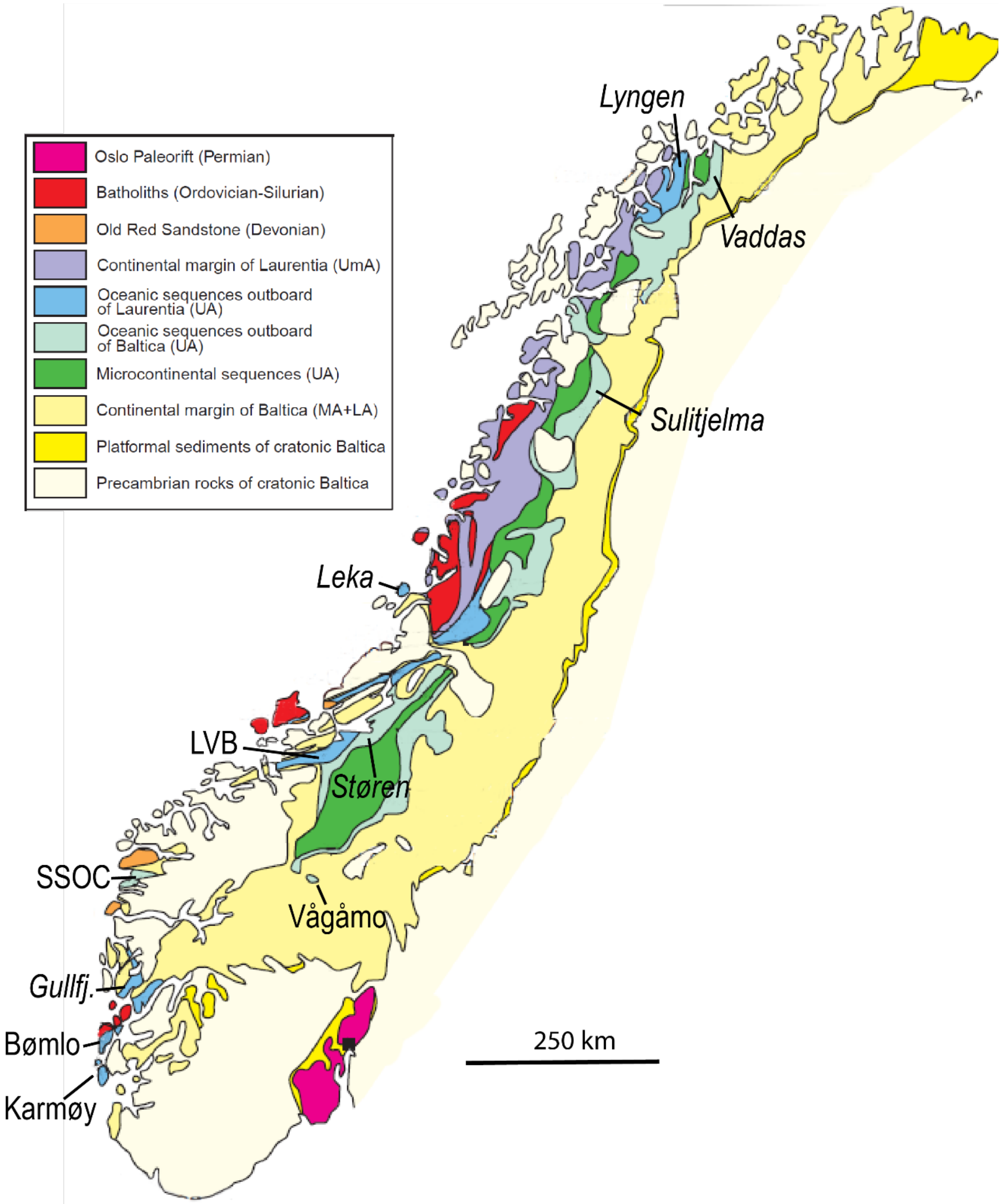


Figure 16: Ophiolite complexes in Norway. The major complexes are shown in regular font, whereas minor and disputed ophiolites are shown in italics. LVB – Løkken-Bymarka-Vassfjellet ophiolite, SSOC – Solund-Stavfjord ophiolite complex. Background map is modified from Grenne et al. 1999.

Løkken-Vassfjellet-Bymarka ophiolite

The Løkken-Vassfjellet-Bymarka (LVB) ophiolite complex in SW Trøndelag consists of a 1-2 km thick succession of pillow lava underlain by sheeted dikes and gabbros with comagmatic plagiogranite intrusions (Grenne 1989, Grenne et al. 1999). Geochemically, the LVB shows supra-subduction zone signatures and is interpreted to have formed in an oceanic back-arc marginal basin between 487 and 480 Ma, with subsequent obduction between 480 Ma and 475 Ma (Grenne et al. 1999; Roberts et al. 2002; Slagstad et al. 2014). The volcanic sequence in the

Løkken area shows a tripartite subdivision: Upper Volcanic Member (UVM) comprising pillow basalts and thrust-related bimodal basalt-rhyolite assemblage (MORB/IAT), Middle Volcanic Member (MVM) comprising predominantly sheet and minor pillow basalts (MORB) and Lower Volcanic Member (LVM) with pillow basalts (N-Type MORB) passing downwards into the sheeted dike complex (Grenne 1989). The primary ophiolite pseudostratigraphy is only locally preserved in Bymarka due to strong deformation (Slagstad 2003, Slagstad et al. 2014). Gabbro occurs in the lowermost part in the west, followed by poorly preserved sheeted dyke complex, overlain by basalt in the east (op cit.). A similar ophiolitic pseudostratigraphy, with basaltic pillow lava with ocean-floor tholeiitic composition on top, is also found at Vassfjellet (Grenne et al. 1980).

The metallogenically most important part of the LVB ophiolite complex is in the inverted and generally little deformed volcanic sequence in the Løkken area. By far the largest VMS deposit in the area is the Løkken deposit. It is located in the MVM and contained a pre-mining tonnage of 30 Mt grading 2.3 % Cu, 1.8 % Zn, 0.02 % Pb, 16 g/t Ag and 0.2 g/t Au (Grenne et al. 1999). About 24 Mt was mined over a period of 333 years between 1654 and 1987. The main elongate sulphide body had a total length of about 4 km, an average width of 150-200 m and a thickness of 50 m. The morphology can be ascribed to parallel features such as subparallel faults at the seafloor, and an extensive, fissure-related, hydrothermal vent system (Grenne & Vokes 1990). The massive sulphide ore predominantly consists of pyrite with subordinate chalcopyrite and sphalerite, whereas galena, magnetite, hematite and bornite are minor components locally, and fahlore is the most important accessory phase (Grenne 1989). Quartz is the main non-sulphide, constituting 12–14 % of the ore. Jaspers, consisting of silica and with up to 20 % microcrystalline hematite are associated with the Cu-Zn bearing pyritic ores, and may represent more distal facies of the hydrothermal system, and can be traced for several km along strike. Both oxide- and sulphide-facies iron formations are common at the top of MVM. The other Cu-Zn deposits of similar type in the Løkken district are much smaller and include the Høydal (1.16 Mt) and Åmot (0.04 Mt) deposits in MVM, and the Dragset deposit (0.1 Mt) within LVM. Minor occurrences are also found within the sheeted dyke complex.

Two minor Cu-Zn deposits have been exploited in the Vassfjellet part of the LVB ophiolite complex. They are in the lower part of the pillow lava sequence on top of the sheeted dike complex. 4.000 t of Zn-rich pyritic ore was mined at the Ulriksdal (Sjøla) deposit in the northern part of the area at the turn of the last century, and minor copper mining was carried out by the end of the 17th century. Test mining of Cu-Zn pyritic ore has been carried in four minor pits in the Flå mines in the southern part of Vassfjellet.

The LVB ophiolite complex covers a total area of 1028 km^2 and comprises 6 deposits with reliable production and/or resource estimates. However, only one of these, the Løkken deposit, had a total tonnage well above 1 Mt.

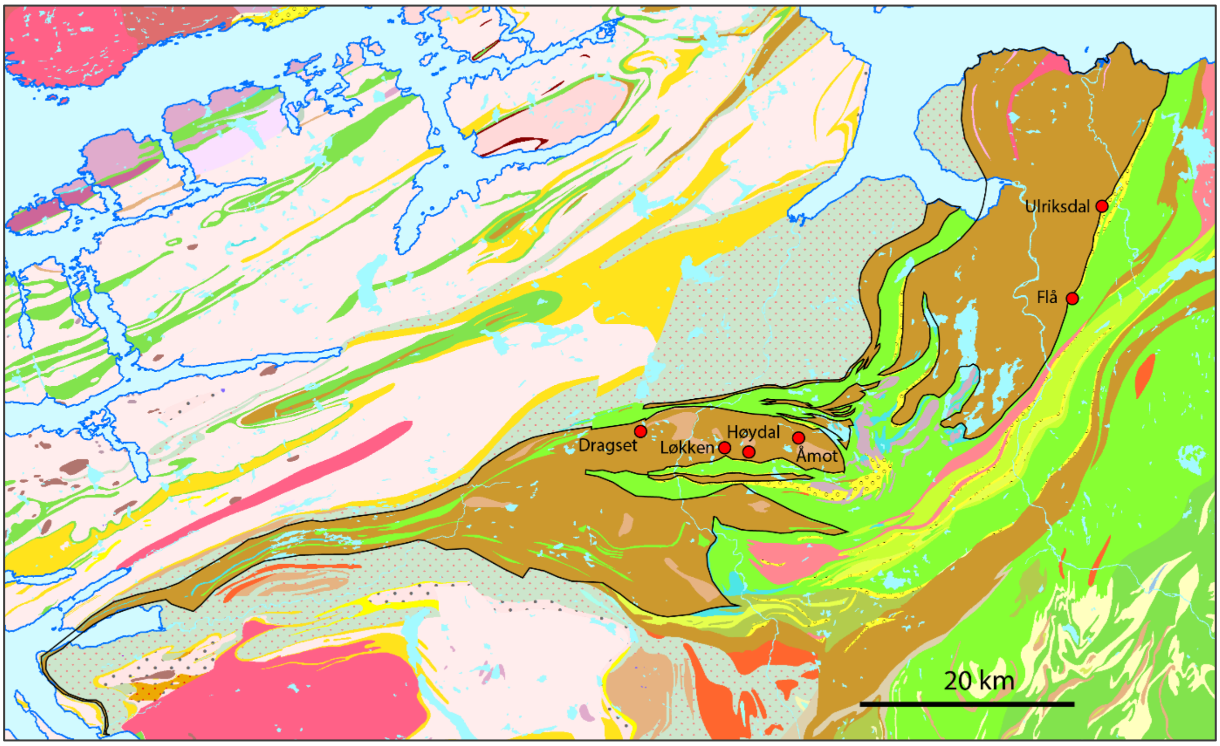


Figure 17: The Løkken-Vassfjellet-Bymarka ophiolite complex (in brown colour with black line) with the most important VMS deposits marked with red dots. The other brown units in the east belong to the Støren Group, which most likely represents arc-back arc setting. Bedrock geology modified from the bedrock database at NGU (https://geo.ngu.no/kart/berggrunn_mobil/).

Lykling (Bømlo) ophiolite complex

The Lykling (Bømlo) Ophiolite Complex is the stratigraphically lowermost unit on Bømlo island, SW in Vestland county. It comprises an almost complete sequence of oceanic lithologies, including serpentinites, layered and massive gabbros, sheeted dikes and pillow lavas (Figure 18). The Bømlo Ophiolite Complex is believed to have formed during the Late Cambrian – Early Ordovician based on similarities with other similar ophiolites.

The ophiolite has a tholeiitic geochemical signature and a subduction-related trace element composition and is therefore proposed to have formed in a supra-subduction zone (Pedersen and Dunning, 1997). Overlying the Lykling ophiolite is the Geitung unit, a unit which is composed of immature island-arc lithologies.

In the Lykling ophiolite, the largest VMS mineralisations are Alvsvågen and Lindøya, but no reliable tonnages for these exist. The Alvsvågen deposit was mined intermittently between 1865 and 1907. The four mineralized lenses are hosted by gabbroic rocks that belong to the Lykling ophiolite. Mineralisation is composed of chalcopyrite and pyrrhotite with grades up to 3.8 %.

The Lindøy massive sulphide mineralisation is composed mainly of pyrrhotite with minor pyrite. It is exposed over a length of 250 m and is up to 8 m wide (Wulff 1996). It is hosted by a relatively small basalt lens, that was later intruded by tonalite.

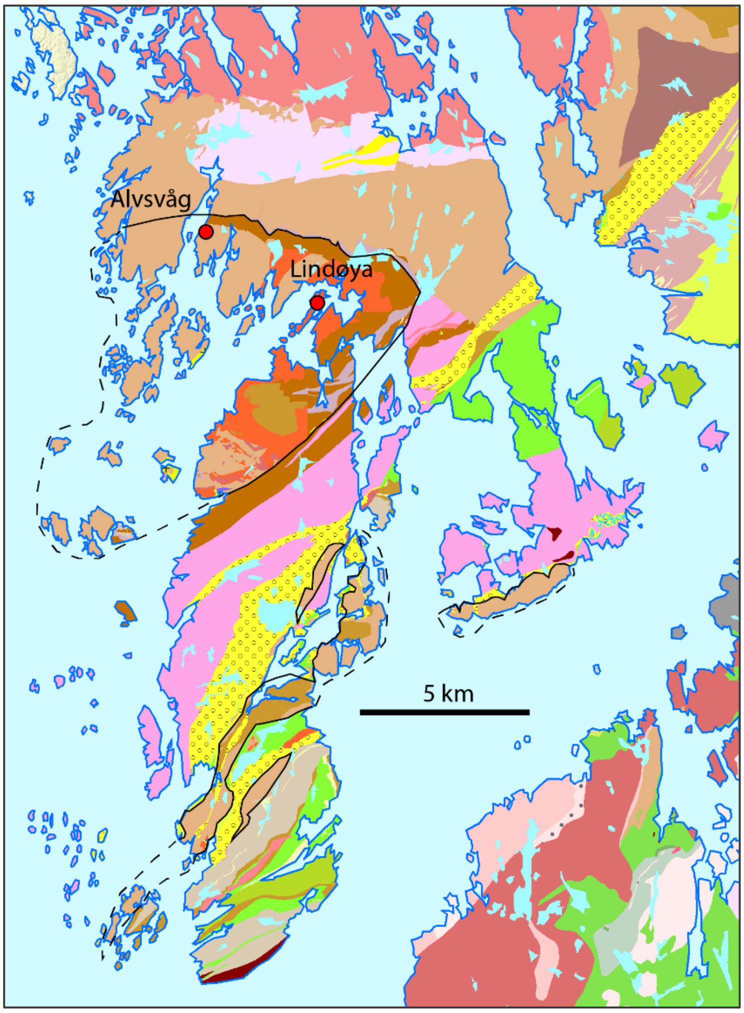
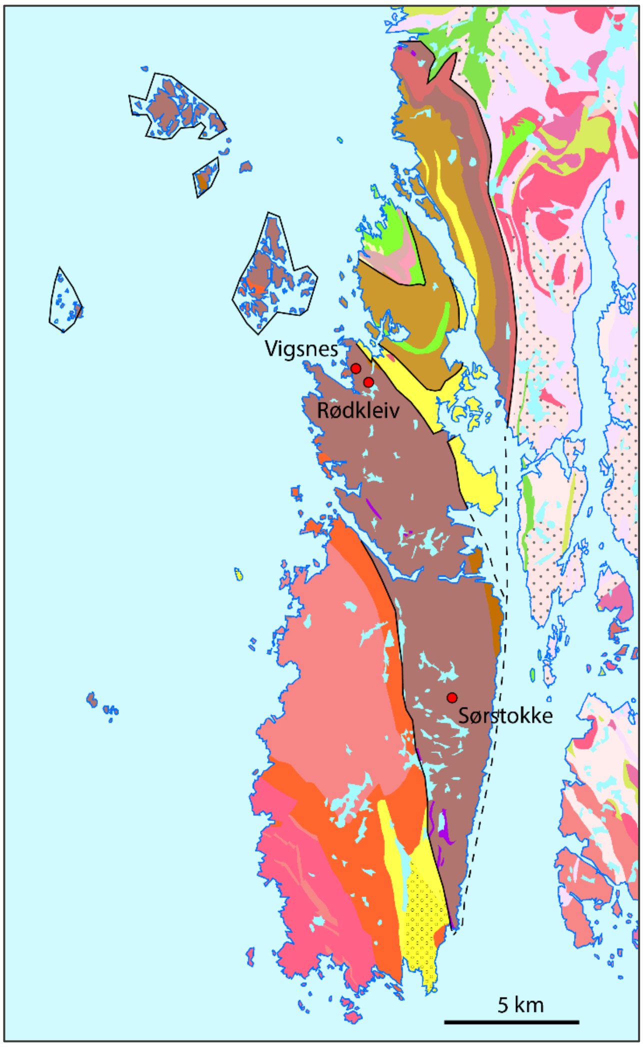


Figure 18: geology of the Bømlo area with the Lykling ophiolite complex (delimited by black solid and stippled lines). The two main deposits are shown (red circles). (https://geo.ngu.no/kart/berggrunn_mobil/).

Karmøy ophiolite

The Karmøy ophiolite complex in NW Rogaland County (Figure 19) comprises a more than 6 km thick sequence of oceanic crust formed at a spreading axis in a marginal basin positioned above a subduction zone. It is the result of back-arc spreading or arc rifting and is a supra-subduction zone ophiolite of Laurentian affinity (Pedersen & Furnes 1991, Grenne et al. 1999). The well exposed sequence ranges upwards from ultramafic and mafic intrusives to sheeted dykes, pillow lava, pyroclastic rock, volcanoclastic rock, and pillow lava and sedimentary units. The dyke density increases upwards until a true sheeted-dyke complex (1.5 km thick) is encountered. The dykes fed a thick (>1 km) sequence of non-vesicular and variolitic pillow lavas and pillow breccias (Sturt et al. 1980). These tholeiitic basalts, both dykes and extrusives, comprise the Visnes Group. The oldest axial part of the ophiolite is dated to 493 +7/-3 Ma from a plagiogranite, whereas arc-related trondhjemite crosscutting the ophiolite crystallized at 485 ± 2 Ma (Pedersen & Dunning 1997).



Cu-Zn VMS deposits are mainly confined to the lower pillow lavas and the sheeted-dyke complex of the Visnes Group. The most significant of these are Vigsnes and Rødkleiv, which are located only 650 m apart on the western side of the island of Karmøy. The Vigsnes deposit was discovered in 1865 and production commenced in the following year. In 1880 it was the largest mining company in Norway, but mining ceased in 1894 due to the declining Cu content of the ore. The total production was 1.44 Mt of ore grading 1.66 % Cu and 1.4 % Zn, (Geis 1957). Small-scale test mining was carried out on the Rødkleiv deposit before regular production started in 1910. The total production in Rødkleiv was 2.646 Mt with 0.78 % Cu and 1.71 % Zn until the mine closed in 1971 (Gvein 1977).

Figure 19: Karmøy ophiolite complex delimited by black lines) with the major VMS deposits marked with red circles. (https://geo.ngu.no/kart/berggrunn_mobil/).

The ore bodies at both Vigsnes and Rødkleiv are in a 50–60 m wide zone dominated by chlorite-rich greenschists that represent sheared dykes and lava of the Visnes Group. The shearing is assumed to post-date the formation of the massive sulphide bodies (Scott 1992). The strike of the sequence is NW–SE with a steep dip towards the NE and across the island. The stratigraphy of the hosting sequence from footwall to hanging wall is: greenstone, chlorite schist, ore, chlorite schist, greenstone with minor intercalations of felsic metavolcanic rocks and magnetite, and chert (Geis 1957).

The massive sulphide ores in the deposits are banded and pyrite-rich. In the Vigsnes deposit, chalcopyrite and sphalerite are enriched in the upper parts of the sulphide bodies, and chalcopyrite is also enriched in the thinner part of these. Minor stringers or veinlets and dissemination of chalcopyrite also occur in the hanging wall. The Rødkleiv ore is dominated by pyrite with thin bands of sphalerite with more irregular enrichments of chalcopyrite, especially on the hanging-wall side. Several small, massive sulphide occurrences is located along strike south-east from Vigsnes and Rødkleiv.

The Sørstokke deposit is located on the SE side of Karmøy (total production of 7,300 t with 0.5–0.6 % Cu) (Geis 1957). Both massive and disseminated pyrite-chalcopyrite occurrences are in doleritic greenstone in the lower part of the ophiolite complex. Stratigraphically above the Visnes Group, there are several minor occurrences consisting of thin layers of sulphide and oxide iron formations. The area of the Karmøy ophiolite complex exposed on land is 150 km^2 and thus includes the three VMS deposits Rødkleiv, Vigsnes and Sørstokke.

Solund-Stavfjord ophiolite complex

The Solund-Stavfjord ophiolite complex (SSOC) is of Late Ordovician age (443 Ma) and represents one of the youngest phases of oceanic crust in the Caledonides. The crust comprises pillow lavas, massive sheet flows and hyaloclastites, underlain by sheeted dikes and high-level isotropic gabbros (Furnes et al. 2012). The lavas and dikes are composed of N-MORB Fe-Ti basalts and have a weak subduction component according to trace element patterns. The extrusive sequence of the SSOC contains phyllitic interlayers and is conformably overlain by quartz-rich sandstone intercalated with N-MORB lavas and intrusions (Furnes et al. 2012). The SSOC was probably formed in a short-lived (<20 Ma) back-arc basin, close to Laurentia during the closure of the Iapetus Ocean. Similar modern tectonic setting is represented by the Andaman Sea in the Eastern Indian Ocean (Furnes et al. 2012).

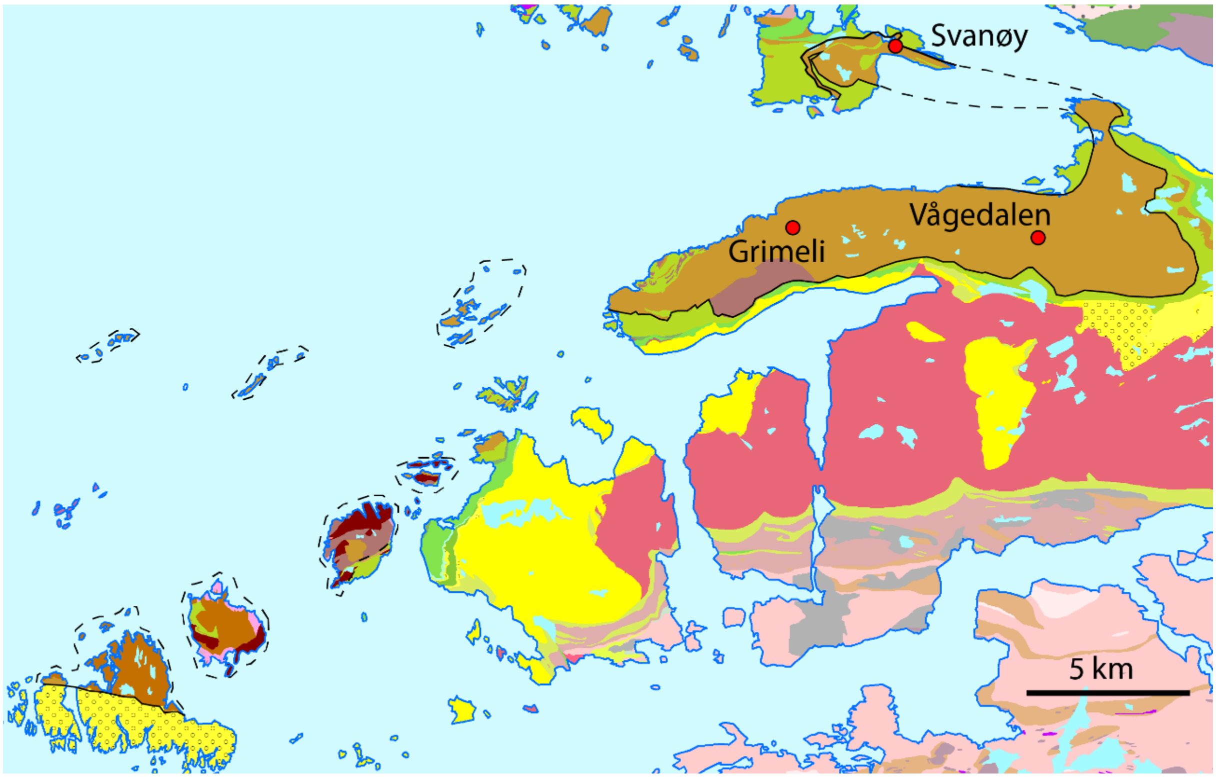


Figure 20: Geology and VMS deposits in the Solund-Stavfjord ophiolite complex (SSOC). The ophiolite is delimited by black solid and stippled lines. (https://geo.ngu.no/kart/berggrunn_mobil/).

The Staveneset part (northern part) of the ophiolite has an areal extent of 119 km^2 (excluding the water covered areas).

There are three VMS deposits in the SSOC; one on Svanøy (also two minor occurrences) and two on the Stavenes peninsula; Vågedalen and Grimeli (Figure 20). The deposits on Svanøy and Grimeli have been mined, whereas the Vågedalen deposit has only been test mined. Grimeli contains 1.5 Mt with 2 % Cu, 1 % Zn, Vågedalen 0.7 Mt with 1% Cu, 2.1 % Zn, whereas the production on Svanøy were 38 600 t and reserves of 63 000 t of copper-pyrite ore.

Vågåmo ophiolite

The Vågåmo ophiolite is located in the valleys of Gudbrandsdalen, Ottadalen and Vågå. The ophiolite was documented by bedrock mapping in the late 1980s and described by Sturt et al. (1991).

Sturt et al. (1991) states that "*the elements of a nearly complete ophiolite pseudostratigraphy is recognized in the area, however it is quite fragmented and occur in several smaller areas (Figure 21). The ultramafics consist of serpentinised harzburgites and dunites, locally turned into soapstones and talc-rich rocks, which were extensively quarried until recently. Gabbroic rocks are widely distributed, comprising both layered and isotropic types. Dyke swarms with up to 100 % dykes are found at several places*". Pillow lavas and/or pillow breccias are extensively developed in especially Ottadalen, close to the Åsoren sulphide deposit.

Geochemical analyses of samples from the sheeted dyke complex demonstrate an N-MORB composition, indicating that the ophiolite represent either mid-ocean ridge or a marginal basin (Sturt et al. 1991).

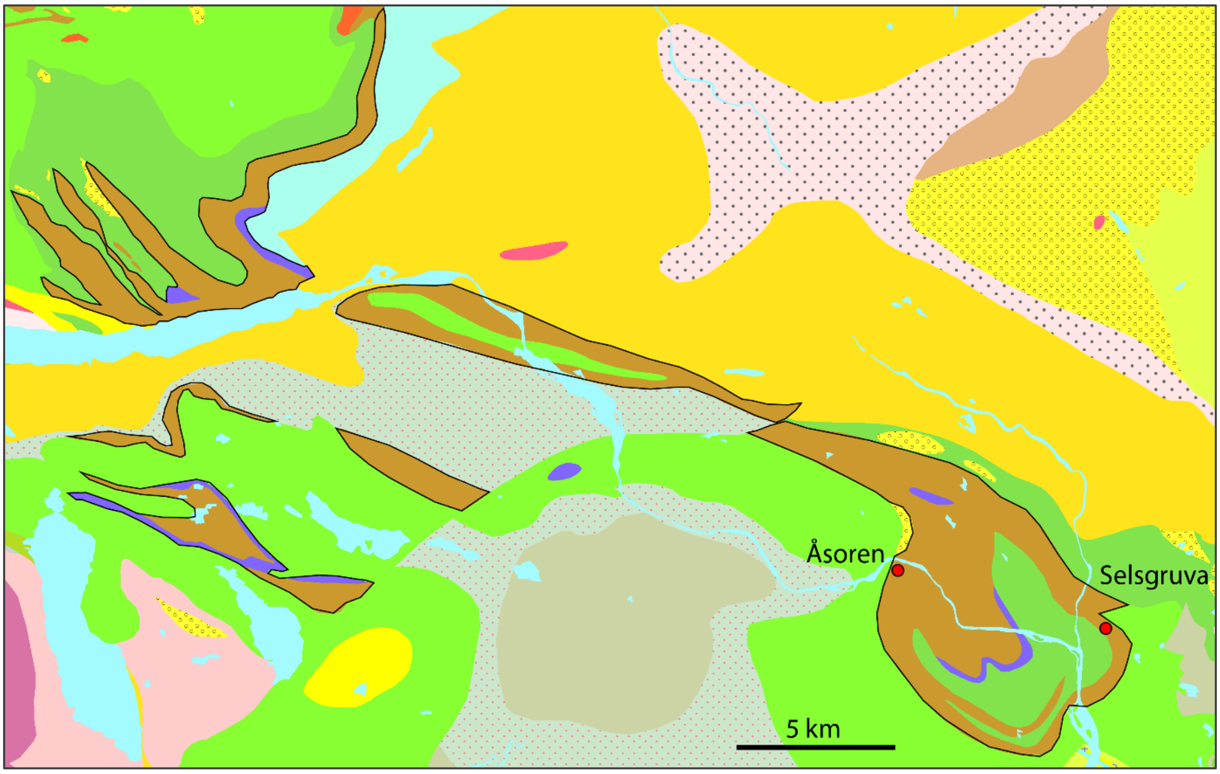


Figure 21: Geology and deposits in the Vågåmo ophiolite. Lithologies of the ophiolite is delimited by black lines. (https://geo.ngu.no/kart/berggrunn_mobil/).

There are two VMS deposits in the Vågåmo ophiolite; Selsgruvene (Rustgruvene) and Åsoren. Selsgruvene were mined for copper, possibly between 1624 and 1789, but the tonnage of mined ore is not known. Samples of ore in the NGU ore database contains between 1.4 % and 3.9 % Cu and between 0.01 % and 0.1 % Zn. There is no information about any resources in the deposit. Åsoren was probably mined at the same time as Selsgruvene, and likewise the ore production is not known, but was probably very low. Test mining was carried out between 1908 and 1912. Geophysics followed by drilling in the 1970s indicated a resource of 733 000 t with 1.43 % Cu (Rosenkvist 1975) or 170 000 t with 2.7 % Cu (Rui 1992). Sampling by NGU shows that the ore is partly rich in Zn and Co; the average of 13 samples shows 2.2 % Cu, 2.1 % Zn and 414 ppm Co.

Other ophiolites and possible ophiolites in Norway

The Leka Ophiolite Complex (LOC) in northwest Trøndelag contains all the components of a typical ophiolite, including ultramafics (harzburgites and dunites), metagabbros, felsic intrusions, mafic dyke complex, overlain by pillow lavas and volcaniclastics (Furnes et al. 1988, 1992). The volcanics have a very limited extent, and no obvious VMS deposits occur in the lava sequence. Some vein-type copper mineralisations do occur in the gabbros but are partly related to shear- and fracture zones. The age of LOC has been determined to 497 ± 2 Ma (Dunning and Pedersen 1988).

The Gullfjellet Ophiolite Complex belongs to the Major Bergen Arc and comprises plutonic rocks with layered to isotropic gabbros, underlying a dyke complex with pillow lavas on top (Heskestad et al. 1994). Geochemistry shows MORB signature with a weak arc signature. The ophiolite has been dated to 489 ± 3 Ma (Dunning and Pedersen 1988). Except for a few occurrences with chalcopyrite-pyrrhotite impregnation of unknown type, no hydrothermal or VMS deposits have been found in this ophiolite.

The Lyngen Ophiolite, situated to the east of Tromsø was discovered in the 1980s (Minsaas & Sturt 1985, Lindstrøm & Andresen 1995). It is dominated by the Lyngen gabbro, which is overlain by strongly deformed amphibolites and greenschists, representing the extrusive part of the ophiolite. Only few minor sulphide occurrences are known from this unit.

The Sulitjelma district in Nordland includes more than 20 VMS deposits hosted by amphibolites. These extrusives (the Otervann Volcanic Formation or Sulitjelma Amphibolites) have been assigned to the Sulitjelma ophiolite complex (Boyle 1989) and are underlain by sheeted dykes (the Mietjerpakte Intrusive Complex) and below that, the Sulitjelma Gabbro Complex. However, the gabbroic rocks (cogenetic with the amphibolites) have been dated to 437 ± 2 Ma (Pedersen et al. 1991) and contain inclusions of Precambrian gneiss, observations that suggest formation in an ensialic marginal basin (Cook et al. 1990) and implies that it is not an ophiolite complex *sensu stricto* (e.g., Grenne et al. 1999).

The Vaddas district in Northern Troms includes several VMS deposits hosted by greenstones (the Loftani Greenstone in the Vaddas Nappe, Lindahl et al., 2005). The greenstones represent partly pillowed basalts. Limited geochemistry shows a MORB signature for the basalts (ocean-floor tholeiites, Lindahl et al., 2005). Dykes and gabbros in the area have similar compositions and could represent feeders and source of the volcanics, respectively. More work is needed to confirm if these rocks represent an ophiolite.

The Støren Group within the Støren nappe in Trøndelag has earlier been interpreted to be equivalent to and correlated to the Løkken-Vassfjellet-Bymarka (LVB) Ophiolite. However, new data on geochemistry as well as dating shows that the two cannot been correlated (Gasser et al., 2021). Geochemistry shows more of an OIB/IAT signature and at least the central part of the Støren Group is younger (463-475 Ma) than the LVB ophiolite (481 Ma).

6. RESULTS

6.1 Results from fieldwork

Fieldwork was carried out to obtain new data on the most important deposits in the Karmøy, Bømlo and Solund-Stavfjord ophiolite complexes. Sufficient data already existed in the NGU Ore Database from the deposits in the LVB and Vågåmo ophiolites. The data collected, including field relations, host rocks, structures and geochemistry have been uploaded into the NGU Ore Database (https://geo.ngu.no/kart/mineralressurser_mobil/), and also included in the descriptions of the ophiolite complexes (see above, section 5.2.4).

One important aspect of the field work was to collect samples for sulphide analyses in order to assess if there are other metals, such as Au, Ag, Co, Se, Te and In, which could be of potential economic interest in addition to the base metals. Historically mainly copper, zinc and sulphur (sometimes Ag and Au) were analysed when the deposits were mined or explored by the industry.

Metal data including trace elements certainly exist from several ophiolite-hosted VMS deposits around the world, and is also partly available in the literature, but sample types and analytical methods may be different, making direct comparisons difficult. Data from the Norwegian ophiolite-hosted deposits are consistent and thus regarded as representative.

Table 3: Statistics of the chemistry of VMS deposits and occurrences in Norwegian ophiolite complexes

	Bømlo			Karmøy			Løkken			SSOC			Vågåmo		
no. deposits	**6**			**10**			**14**			**6**			**2**		
no. analyses	**29**			**46**			**65**			**19**			**19**		
	Avg	*Median*	**Stdev**	**Avg**	*Median*	**Stdev**	**Avg**	*Median*	**Stdev**	**Avg**	*Median*	**Stdev**	**Avg**	*Median*	**Stdev**
Cu	1.20	*0.82*	1.02	2.16	*1.49*	2.23	2.14	*1.58*	1.86	2.21	*1.85*	1.70	2.33	*2.49*	2.18
Pb	0.04	*0.003*	0.14	0.01	*0.00*	0.03	0.01	*0.004*	0.02	0.03	*0.01*	0.05	0.002	*0.0002*	0.01
Zn	0.95	*0.78*	0.87	1.14	*0.02*	2.43	1.20	*0.18*	2.88	2.05	*0.76*	2.86	1.48	*0.10*	3.60
totbas	2.19	*1.86*	1.30	3.3	*2.13*	3.2	3.35	*2.80*	3.15	4.29	*3.75*	2.89	3.49	*2.77*	3.19
Ag	15.6	*8.5*	23.4	7.2	*4.1*	7.3	11.0	*5.6*	12.3	9.1	*6.4*	7.0	3.7	*1.4*	5.4
Au	50	*22*	60	107	*65*	149	81	*50*	90	63	*46*	54	31	*10*	45
Ni	10	*3*	21	42	*25*	43	27	*18*	25	24	*23*	16	84	*70*	68
Co	144	*98*	107	145	*110*	121	327	*213*	337	668	*453*	548	307	*250*	276
Mn	613	*505*	511	602	*374*	580	523	*354*	476	455	*340*	366	366	*292*	304
Fe	12.7	*10.6*	6.4	18.0	*14.2*	9.2	29.0	*32.0*	10.1	33.9	*36.1*	9.2	25.5	*28.6*	12.4
As	53	*15*	75	37	*19*	45	155	*78*	181	76	*47*	106	11	*1*	21
Mo	15	*17*	12	8	*3*	12	25	*18*	25	20	*13*	16	9	*7*	8
Cd	50	*33*	47	33	*1*	72	35	*7*	90	69	*40*	121	55	*6*	128
Sb	2.9	*1.0*	4.1	12	*1.0*	70.5	2.5	*1.7*	2.5	0.5	*0.3*	0.4	1.8	*1.5*	0.7
Bi	39	*6*	139	6	*1*	18	4	*2*	5	10	*4*	13	7	*2*	11
V	73	*39*	142	54	*38*	55	89	*63*	86	46	*23*	67	41	*41*	37
Cr	42	*6*	118	59	*22*	80	24	*10*	38	18	*11*	24	37	*19*	34
Ba	6	*5*	2	10	*5*	13	24	*10*	35	9	*10*	5	2	*2*	0
W	42	*0.3*	101	0.005	*0.05*	0.10	0.49	*0.10*	2.28	0.13	*0.05*	0.15	1.95	*1.00*	1.76
Se	39	*20*	35	76	*48*	72	83	*59*	80	53	*38*	32	97	*94*	30
Te	3.1	*2.5*	2.5	4.7	*1.7*	9.2	3.6	*1.4*	5.4	1.3	*0.9*	1.1	7.5	*4.3*	6.6
Ga	11.5	*9.9*	5.6	10.8	*9.3*	6.9	7.1	*5.2*	6.0	10.3	*9.8*	5.4	7.2	*1.5*	9.7
Ge	0.18	*0.12*	0.11	0.38	*0.33*	0.20	0.38	*0.29*	0.24	0.43	*0.39*	0.23	0.50	*0.50*	0.19
Sn	0.96	*1.10*	0.43	1.83	*1.70*	1.34	3.27	*0.95*	7.94	3.94	*2.30*	3.82	4.66	*0.70*	7.00
In	1.02	*1.14*	0.64	4.77	*5.37*	3.80	1.75	*1.00*	1.92	1.97	*1.39*	2.63	7.44	*5.19*	9.39

Data for Cu, Zn, Pb and Fe in %, Au in ppb, otherwise ppm. Totbas is total base metals (Cu+Zn+Pb).

Table 3 shows the average and median content of various elements in the Norwegian ophiolite complexes (average data displayed in Figure 22). The data are based on samples collected from dumps and bedrock. In total there are 172 analyses from 38 different sulphide deposits and occurrences. Only analyses with total base metal content (Cu+Zn+Pb) above 0.5 % have been used in the calculation. This to avoid samples from country rock, alteration zones, and deposits with only pyrite (typical distal facies of VMS).

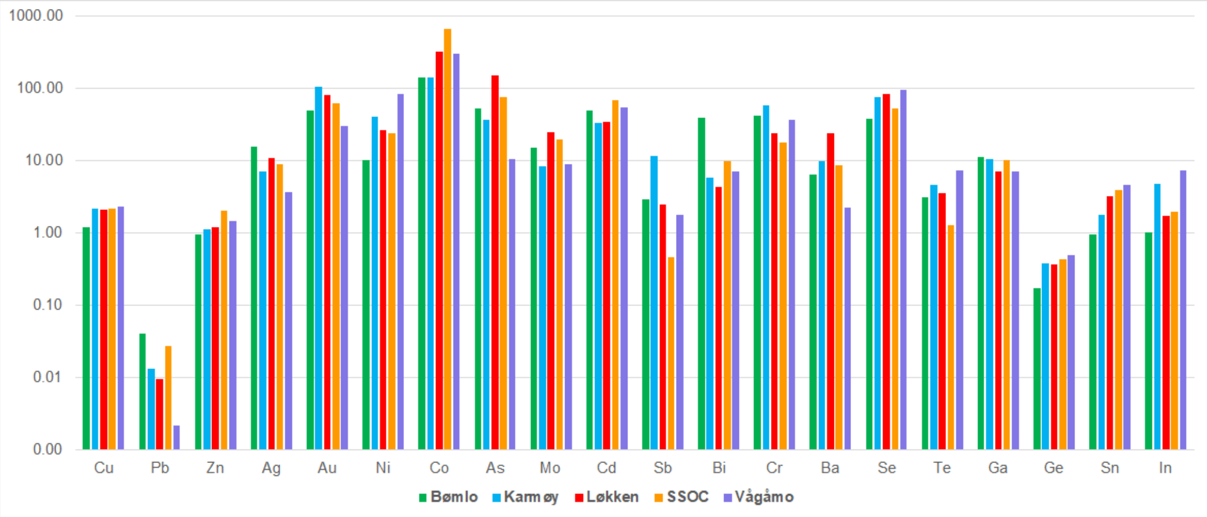


Figure 22: Average data from Table 3 shown in a diagram for better visualization. Cu, Zn and Pb in wt%, Au in ppb, all others in ppm.

Except for Bømlo, the data show very consistent Cu averages. All the complexes are copper-dominated and have lower content of zinc than copper, and very low content of lead. SSOC has the highest content of total base metals, while Bømlo is much lower. None of the complexes are enriched in silver or gold (Bømlo has 16 g/t Ag, and Karmøy 0.11 g/t Au as the highest average values). Except for elevated average values of cobalt (300-700 g/t) in LVB, SSOC and Vågåmo, there are no significant trace metals enrichment in any of the complexes.

6.2 Resource estimation

6.2.1 Resource estimate approach

This resource estimation is, as the assessment provided by Ellefmo & Søreide (2014, 2018), based on a probabilistic approach where individual frequency distributions for grade, tonnage, and density were convolved, equivalent to a Monte Carlo simulation. Histograms describe the data behind the three parameters, grade, tonnage, and deposit density, where each fit with individual best fit functions. Unlike the work by Ellefmo & Søreide (2014, 2018), this estimate is restricted to well-constrained Cyprus-type VMS ore bodies. Cyprus-type massive sulphides are here considered to represent the best-known analogues for SMS ores, as discussed in section 3.3. The database (see appendix) is refined after Mosier et al (2009), from which erroneously included data were removed or edited (other ore types etc.).

The primary reason for not using data from offshore SMS sampling is that samples have been collected almost exclusively from black smoker chimneys and exposed sulphide mounds and contain little to no subsurface data. Chimneys are known to have very high to high grades compared with subsurface ores. This is exemplified by the TAG site, where early surface sampling yielded copper grades from chimneys up to 32% (Humphris & Tivey, 2000) while later drilling (IODP leg 158) revealed an average copper grade of the total ore body of ca 2% (Hannington et al, 1998). Although the Mohn's Ridge is still very sparsely sampled, similar results are revealing a difference between surface and subsurface samples for the only drilled SMS site (Fåvne, NPD 2022). Tonnage is a poorly known parameter since most SMS deposits have not been areally delineated, and the third dimension, depth, is mostly not known at all. Reliable deposit density data for SMS's are non-existent.

It is convenient to divide mineral resource assessments into three independent factors: number of deposits per 1000 km^2 (deposit density), ***n***, the size (tonnage) of each ore deposit in megatonnes, ***s***, and the metal grade of the ore, ***g***. The variables n, s, and g are stochastic variables with associated statistical distributions.

The mass of metal per deposit is given by the product of ore size and grade,

$$m=sg,$$

and the amount of metal per 1000 km^2 can be written as

$$M=nm=nsg.$$

The variables m and M are also stochastic variables, given by products of stochastic variables.

If the density, size and grade have probability distributions p_n (n), p_s (s) and p_g (g), the probability distributions for metal mass per deposit and metal mass per 1000 km^2, can be computed by the convolution theorem for products of stochastic variables,

$$p_m(m) = \int_0^\infty p_s(s) p_g\left(\frac{m}{s}\right)\frac{1}{s}\,ds,$$

$$p_M(M) = \int_0^\infty p_m(m) p_n\left(\frac{M}{m}\right)\frac{1}{m}\,dm.$$

The corresponding cumulative distributions and survival functions, which are convenient for computation of percentiles, are given by:

$$P_x(x) = \int_0^x p_x(x')\,dx',$$

$$S_x(x) = 1 - P_x(x),$$

where $x=\{n,s,g,m,M\}$.

The integrals above where implemented in Python, using the scipy.stats module, and inheriting methods for computation of cumulative distributions, percentiles, mean, variance and skew from the rv continuous superclass in that module.

The scipy.stats module contains a large number of parametric statistical models. Given the data gathered in this study for grade, tonnage and deposit density, we chose the models that, when optimized, best represented the data, as shown in Figure 23.

For grade and tonnage, we chose Weibull and Pareto distributions, respectively. For deposit density, a uniform distribution appears to best fit the data. The data for deposit density contains a small number of samples. Therefore, this is the least robust distribution.

In this report we have focused on copper, as the data on other elements (e.g., zinc, lead, gold, silver) are insufficient and rather uncertain.

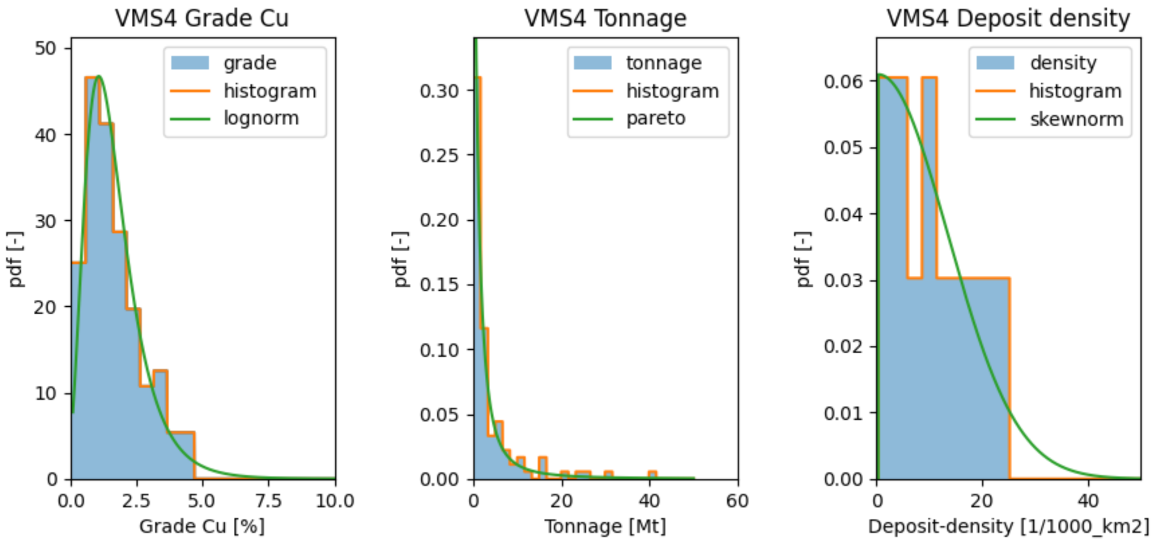


Figure 23: Best fit functions for grade, tonnage, and density (below).

6.2.2 The dataset

The data used for the probabilistic calculations are presented in Table 4. Ophiolite districts were chosen where there are the best data on number of deposits, tonnage and grade of the deposits, and areal extent of the ophiolite. The data allowed calculation of deposit densities and tonnes of copper per 1000 km^2 in each of the districts. The deposit densities and tonnage of copper show a large variation, from 0.4-25 deposits per 1000 km^2 and 8000 t to ~ 690 000 t Cu per 1000 km^2, respectively.

Table 4: Major ophiolite districts with areal extent, number of deposits and total contained copper.

Country	Ore District	# Deposits	Area (km^2)	Cu (t)	Ton Cu/1000 km^2	Deposits/1000 km^2
Philippines	Palawan Ophiolite Belt	1	2535	20250	7988	0.4
Philippines	Zambales Angat - 44-45	2	3632	45200	12445	0.6
Philippines	Antique Ophiolite Belt	3	185	7500	40541	16.2
Canada	York Harbour	3	423	13835	32707	7.1
Canada	Baie Verte (Betts Cove)	18	1773	354470	199927	10.2
Cyprus	Troodos	28	2015	1113174	552444	13.9
Oman	Samail	16	2826	816492	288921	5.7
Norway	Vågåmo	2	107	12000	112150	18.7
Norway	Solund-Stavfjord	3	119	38228	321244	25.2
Norway	Karmøy	3	150	41415	276100	20.0
Norway	LVB	6	1028	707429	688160	5.8
Norway	Bømlo	2	198	N.A	-	10.1
	Mean				***230239***	***11.2***

6.2.3 Results of the calculations

Convolution of the functions presented in section 6.2.1 led to the results shown in figures 24 and 25. Figure 25 shows the modelled average values for tonnage, grade and density, as well as the total "in place" mass of copper per 1000 km^2. The modelled P50 estimates indicate average tonnages of 1.47 Mt; average grades of 1.47 % copper and predict the existence of 9.2 deposits per 1000 km^2. The mass of copper is modelled to 0.18 Mt Cu/1000 km^2.

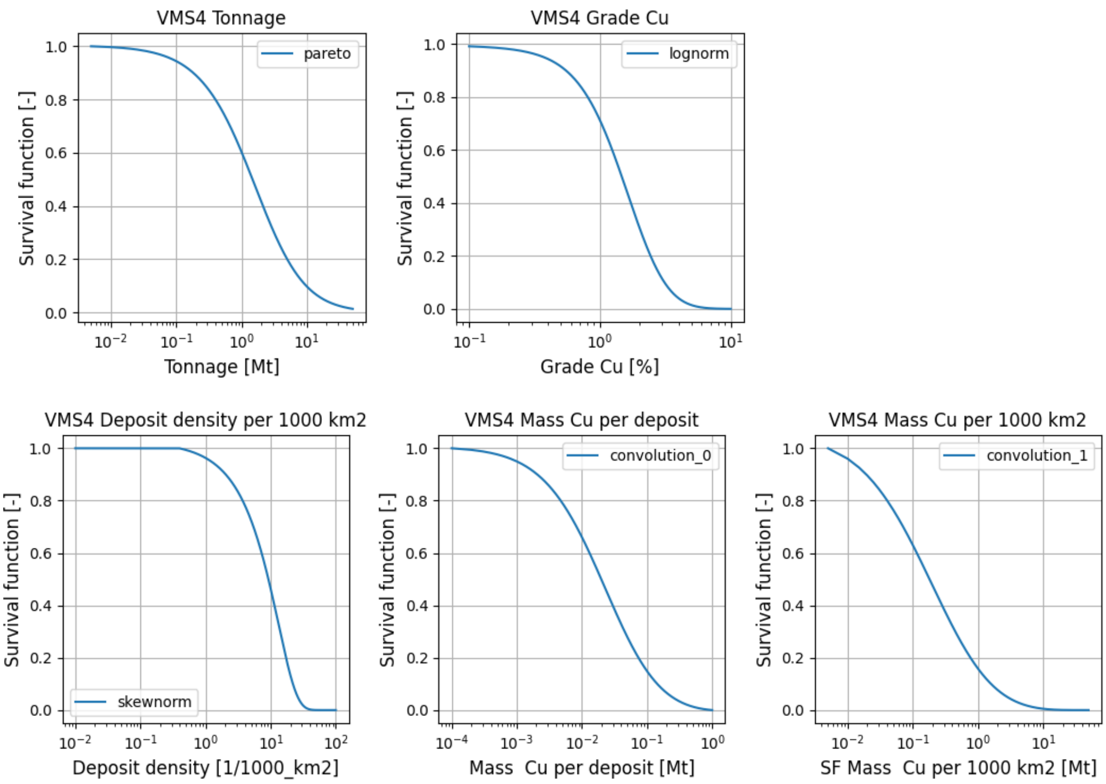


Figure 24: Cumulative probability functions (survival functions), computed by integration of the probability density. The P10, P50 and P90 estimates can be read off these curves.

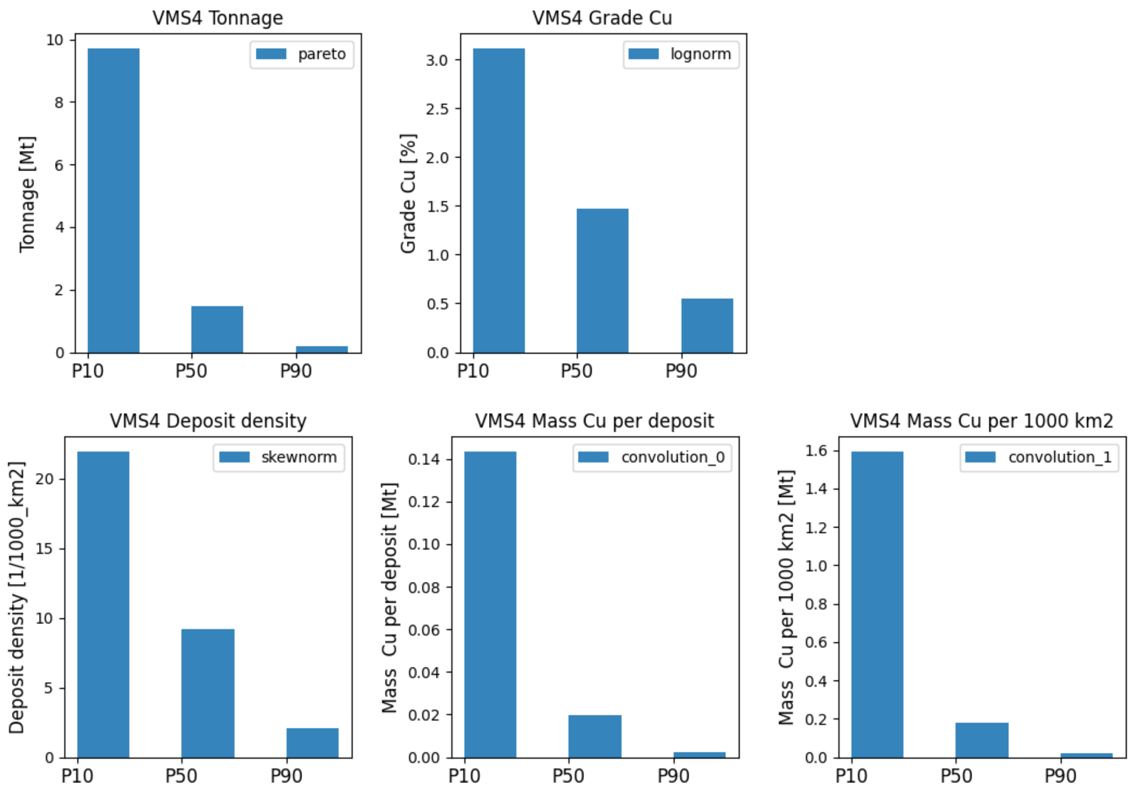


Figure 25: P10, P50 and P90 estimates for ore tonnage per deposit, Cu grade, deposit density per 1000 km^2, Cu mass per deposit, and Cu mass per 1000 km^2.

7. DISCUSSION AND CONCLUSION

The results from the calculations in section 6.2.3 (P50/median) are 0.18 Mt Cu per 1000 km^2, with a deposit size of 1.47 Mt and a copper grade of 1.47 %. The deposit density is calculated to 9.2 deposits per 1000 km^2. Because the data on zinc in the database is quite uncertain, the projected zinc grade has not been determined, but most likely between 1 and 2 %.

The results are based on a rather restricted dataset of 12 VMS districts as shown in Table 4. These districts contain 87 individual deposits with confirmed data on grade and tonnage, which represent 80% of the entire dataset of ophiolite-hosted deposits (109 deposits, see appendix). The median values calculated from the entire dataset (Table 2) yield a deposit tonnage of 1.51 Mt containing 1.43 % Cu, values which are very close to the current P50 calculation. This is a strong indication that the model is robust.

In Table 5 the results of our analyses are compared with most of the estimates presented in section 4. For the sake of comparison, all data have been normalized to an area of 1000 km^2. The copper grade used and calculated is very different, varying from 1.47 % in the present work to 5.78 % in Ellefmo & Søreide (2019). The present work is based on data from well characterised ophiolite-hosted VMS deposits, whereas Ellefmo & Søreide used available SMS data. Juliani & Ellefmo (2018b) included both VMS and SMS data in their analysis. NPD (2023) emphasized the TAG data in their approach.

The number of deposits per area is quite similar for all calculations, varying from 8 to 11.1 deposits per 1000 km^2, with the results of this work being in the lower range (9.2 deposits per 1000 km^2). However, our modelled value is close to the estimations by Juliani & Ellefmo (2018b) and NPD (2023), being 8 and 9.5 deposits/1000 km^2, respectively.

The most important results of the calculations are the tonnage of copper per unit area. The result of this work (0.18 Mt Cu/1000 km^2) is less than half the value given by Ellefmo & Søreide (2019), and also half the value in the model provided by NPD (2023). Most of this discrepancy is caused by basing the previous grade models on mainly surface sampling of SMS mineralisations. The copper tonnage per 1000 km^2 for the Mohn's Ridge calculated by Juliani and Ellefmo (2018b) is lower than the data provided in this work, mainly because of a lower deposit density. Compared to the more global approach by Hannington et al. (2010), the present tonnage is quite similar, however the copper grade used in our work is half the grade used by Hannington et al. (2011). The main reason for this being different size distributions; our based on VMS, Hannington using SMS deposits.

Table 5: SMS resource estimate of this study compared to estimates in the literature.

Publication	Cu/1000 km^2	Cu grade	#SMS/1000 km^2
Hannington et al. 2010/2011	0.21 Mt	3 %	10.1
Juliani & Ellefmo 2018b	0.11 Mt	2 %	8
Ellefmo & Søreide 2019	0.41 Mt	5.78 %	11.1
NPD 2023	0.36 Mt	2.27 %	9.5
This study	***0.18 Mt***	***1.47 %***	***9.2***

Median data, except Hannington et al (2010, 2011).

We conclude that using ophiolite-hosted VMS deposits to estimate average SMS grades, sizes and densities, yields a robust prediction of the resource and deposit potential of the N-MAR. The most likely deposits to be found should contain resources of 1.5 % Cu in 1.5 Mt deposits. The content of zinc is probably 1-2 %, according to the VMS data. On land such grades combined with the rather small tonnages probably are not economic, if they can be exploited offshore is another matter.

The geochemistry of the Norwegian ophiolite-hosted deposits (Table 3), show that none of the ophiolite complexes contain deposits that are enriched in precious metals (silver and gold), and except for elevated values of cobalt, there are no trace metals that are enriched beyond sub-economic concentrations in any of the complexes. Based on the Norwegian VMS data, probably only copper and zinc, and in some cases cobalt, may be extracted at profit from the SMS deposits.

Slow and ultra-slow spreading ridges such as the Mid-Atlantic Ridge (MAR) are prone to SMS deposits hosted by ultramafic rocks. Examples include Rainbow, Logatchev, Semenov and Ashadze along the central MAR, as well as discoveries in the Lena Through at the Arctic MAR (see Patten et al. 2022 and references therein). Surface samples from these deposits are often strongly enriched in gold (range 3.5-4.8 g/t), cobalt (range 0.04-0.29 %) and copper (range 12-26 %, e.g. see data in Patten et al. 2022). The high Cu-grades in ultramafic-hosted SMS are also evident in the plot shown in Figure 26 below (data from Juliani and Ellefmo 2018b). On-land equivalents may include Outokumpu-type deposits, Ural, Cyprus (Limassol), Quebec ophiolite belt and Philippines ophiolites (Patten et al., 2022). Average concentrations in the on-land ultramafic-hosted VMS deposits (35 deposits) presented by Patten et al. (2022) are 2.3% Cu, 0.7% Zn, 0.14% Co, 0.4% Ni, 1.3 g/t Au and 15 g/t Ag. Based on these data, it seems that if ultramafic rocks are part of the host rocks, we may expect higher contents of cobalt and gold, perhaps also copper and nickel. However, nickel is particularly enriched in the ultramafic-hosted SSZ setting, which is different from the N-MAR. At N-MAR ultramafic rocks may perhaps be part of the metal source, especially for deposits associated with major fault structures.

Another factor which may have profound influence on the composition of the deposits is the presence of sediments. Deposits with sediments in the sequence tend to have higher contents of especially zinc, lead and silver (Piercey et al. 2015). This is also demonstrated by the Zn-rich BHMS mineralisations in the sediment-filled Middle Valley graben along the Juan de Fuca Ridge (Zierenberg et al. 1998, Bjerkgård et al. 2000). At N-MAR sediments may come into play in the north, along the east and north-east flanks of the Mohns and Knipovich ridges.

A third factor which affects the composition of deposits is the water depth. Shallower waters mean lower temperature of the fluids. The reason is that boiling of the fluids is dependent on the water depth. Since the solubility of especially copper is very dependent on temperature, it means that deposits in shallower water generally will have a higher zinc/copper-ratio. At N-MAR this is the case in the areas just north of Jan Mayen, and further south along the Kolbeinsey Ridge.

7.1 SMS vs VMS deposits

There are distinct differences between grades and tonnages of VMS and SMS deposits, as shown in Figure 26.

The 50-percentile for tonnage of VMS deposits is 2 Mt and only 0.07 Mt for SMS deposits, according to the data from Hannington et al. (2010), shown in Figure 26. For comparison, our study yielded 1.47 Mt for the ophiolite-hosted deposits. There are several reasons for the large difference between SMS and VMS tonnages; one major reason is the scanty data of SMS deposits. Only a few SMS deposits have been drilled to reveal the third dimension, most are only known to a limited extent on the surface. Furthermore, the VMS data are biased: mainly deposits which are large and/or rich enough to be considered economic have tonnages determined. If uneconomic VMS deposits are included, the curve of VMS tonnages would shift towards the SMS curve in Figure 26.

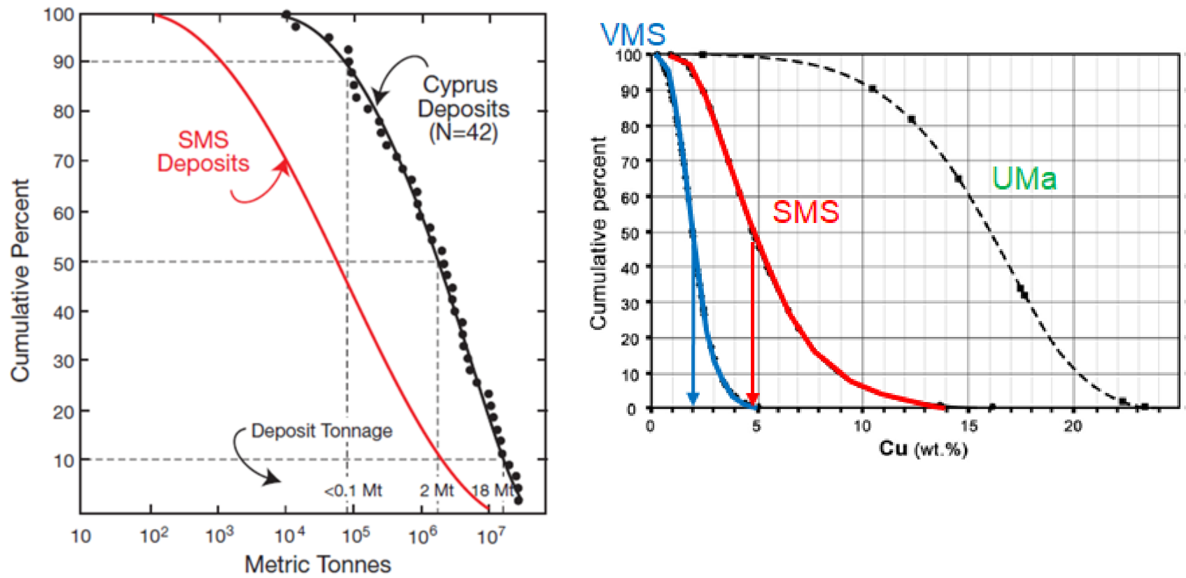


Figure 26: Cumulative frequency plots of tonnages and Cu-grades for mafic-hosted VMS and SMS deposits (from Hannington et al. 2010 and Juliani and Ellefmo 2018b, respectively). Cu-grades for ultramafic-hosted SMS deposits are also shown.

The median Cu-grade of ophiolite-hosted VMS deposits according to our study is 1.47% Cu (close to 2% Cu in Figure 26, data from Juliani and Ellefmo, 2018b), whereas the median SMS grade is 4.8 to 5.0% Cu. The main reason for this large difference is due to sampling bias; There are a few examples of sampling both from the surface and underground of SMS deposits, and they show that underground samples generally have significantly lower grades, e.g. from TAG (Hannington et al. 2010):

Surface	176 smpls	5.3% Cu	8.4% Zn	0.03% Pb	2.66 g/t Au	171 g/t Ag
Core	311 smpls	2.5% Cu	0.5% Zn	<0.01% Pb	0.35 g/t Au	5 g/t Ag

The interior of the TAG mound is dominated by pyrite and is quite similar to most ophiolite-hosted deposits (e.g. Cyprus, Petersen et al. 2000).

The metal-rich upper crust and chimneys will be subjects to weathering and oxidation at the seafloor and will dissolve due to interaction with the seawater if they are not covered (e.g. by sediments or volcanics). The other main process which changes the composition of a deposit is zone refining. This process involves hydrothermal fluids with changing physicochemical properties, including temperature, pH, salinity and saturation of the varying elements. Earlier deposited sulphides may for example be leached and remobilized because of new fluids infiltrating which have e.g. higher temperature or lower pH. This zone refining process is especially important in the later stages of the hydrothermal activity and probably also in the larger deposits. Thus, one should probably expect lower grades in deposits where the hydrothermal activity has been lowered, is dormant or shut down.

To summarize and conclude based on the discussions above, using Cyprus-type VMS deposits as analogue, provides a more realistic and probably better estimate of SMS resources on the Norwegian Mid-Atlantic Ridge (N-MAR). The present knowledge of tonnages and grades in SMS deposits is just too uncertain to be used in such calculations.

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Appendix

Grade and Tonnage data for ophiolite-hosted VMS deposits

NameDeposit	Country	Discovery	MiningStart	Tonnage	Cu(%)	Zn(%)	Pb(%)	Au (g/t)	Ag (g/t)	StringerZone?
Santa Elena	Argentina	1900	1941	0.5	0.08	3.3	2.1	4.2	87	n.d.
Little Deer	Canada	1952	1974	5.964	1.78			0.05	2.16	yes
Chu Chua	Canada	1978	none	2.6437	1.91	0.3		0.48	9.36	yes
Colchester	Canada	1878	1878	1.001	1.3					yes
Little Bay	Canada	1877	1878	2.835	1.19			0.07		yes
Miles Cove	Canada	1883	1898	0.1289	1.55			0.34	12	yes
Huntingdon	Canada	1864	1866	1.814	0.9			0.1	1.03	no
Rendell-Jackman	Canada	1900s	1900s	0.013	2.5			1		yes
Sterling Mine	Canada	1878	1880	1.024	1					
Sunro	Canada	1917	1962	2.783	1.24			0.15	1.7	yes
Terra Nova	Canada	1862	1862	0.257	2.41			1.68	9.94	no
Tilt Cove	Canada	1857	1886	8.165	1.24				0.18	yes
Whalesback	Canada	<1878	1965	4.942	1.1			0.01		yes
East Mine	Canada	1961	1966	1.918	1.06					yes
Big Rambler Pond	Canada	1961	1970	0.0297	1.2					yes
Rambler	Canada	1904	1963	0.386	1.36	2.07				yes
Mud Pond	Canada	1937	none	0.09	1					yes
Priest's Prospect	Canada	1962	none	0.036	1	2				no
York Harbour	Canada	<1897	1897	0.3443	2.63	7.1				yes
Brompton	Canada	1960		0.462	1.84					no
El Roble	Colombia	n.d.	1989	1.87	3.46			2.27		no
Buena Vista	Cuba	n.d	n.d	0.469	2.58					no
Jucaro	Cuba	n.d	n.d	2.5	1.98					no
Cacarajicara	Cuba	n.d	n.d	0.617	1.2					no
Carlota	Cuba	n.d	n.d	2.352	1.13					n.d.
Guachinango	Cuba	n.d	n.d	5.005	0.81					no
Victoria	Cuba	n.d	n.d	0.536	0.86					no
Oxec	Guatamala	1957	1975	0.91	3					yes
Threeman-Standard Copper	United States	1904	1904	1.71	1.08			0.72	10.5	no
Turner-Albright	United States	1890s	none	2.197	1.18	2.48	0.03	2.7	9	yes
Western World	United States	late 1800s	none	1.36	2.81	0.95		0.69	13.7	no
Barlo	Philippines	1961	1962	2.3	1.9	2.22		0.093	4	n.d.
Bongbongan	Philippines	1933	1943	0.09	1.18					no
Carawison	Philippines	1842	1935	0.17	2.8					no
Carmel	Philippines	1936	none	0.11	1.48					no
Lorraine	Philippines	1958	none	0.45	4.5					no
Malobog	Philippines	1943	none	0.18	2.2	2.5				no
Dragset	Norway	1867	1869	0.1	3.5	2.73				yes
Løkken	Norway	1654	1654	30	2.3	1.8	0.02	0.2	16	yes
Høydal	Norway	1659	1660	1.059	1.15	0.45				yes
Ulriksdal	Norway	1670	1901	0.0042	0.8	1.5				yes
Rødkleiv	Norway	1866	1910	2.646	0.78	1.71				no
Vigsnes	Norway	1865	1866	1.44	1.66	1.4				no
Grimeli	Norway		1759	1.5	2	1				
Vågedalen	Norway		1914	0.7	1	2.1				
Åsoren	Norway	1600	1624	0.73	1.43	1.32				yes

GEOLOGICAL
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- NGU -

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NameDeposit	Country	Discovery	MiningStart	Tonnage	Cu(%)	Zn(%)	Pb(%)	Au (g/t)	Ag (g/t)	StringerZone?
Agrokipia (A+B)	Cyprus	1951	1951	5.3	0.57	0.63				yes
Alestos	Cyprus			3.3	0.36					
Ambelikou	Cyprus	1954	1956	0.02	1					no
Apliki	Cyprus	1937	n.d	1.65	1.8					no
East Lefka	Cyprus			1.2	1.6					
Kapedhes	Cyprus	1955	1955	0.05	0.5					yes
Kokkinopezoula	Cyprus	1951	1953	3.5	0.2					yes
Kokkinoyia	Cyprus	1953	1954	0.91	1.5	0.2				yes
Kynousa	Cyprus	1950	1951	0.52	2.32	2.38				yes
Limni	Cyprus	-3000	1937	16	1	0.2				yes
Mangaleni	Cyprus			0.1	1					
Mathiatis	Cyprus	1937	n.d	2.8	0.2	1				yes
Mavri Sykia-Landaria	Cyprus	1952	1952	0.5	2					no
Mavrovouni	Cyprus	-3000	1922	15	3.8	0.5		0.3	39	yes
Memi	Cyprus			1.5	0.1					
Mousoulos-Kalavasos	Cyprus	1927	1937	6.92	1	0.5	0.01	1.7	6.1	yes
Peravasa	Cyprus	1954	1954	0.09	0.76					yes
Peristerka	Cyprus			0.33	0.8	0.3				
Petra	Cyprus	1953	1953	0.26	2					no
Pitharochoma	Cyprus			1.4	0.5	0.5				
Platies	Cyprus	>1930	1955	0.04	3					no
Sha	Cyprus	-3000	1936	0.32	0.6					yes
Skouriotissa	Cyprus	-2500	-2500	6	2.25	0.5		11	69	yes
Phoenix	Cyprus			15	0.5					
Three Hills	Cyprus			6.2	0.37					
Troulli	Cyprus	-3000	1956	0.27	1					yes
West Apliki	Cyprus			3.6	0.34					
Klirou East+West	Cyprus			3.3	0.54	0.6				
Karchiginskoe	Kazakhstan	ancient time	ancient time	5	2.86					n.d.
Bayda	Oman	1973	n.d.	0.79	1.6					yes
Lasail	Oman	1973	1976	9.18	1.42					yes
Aarja	Oman	1973	n.d.	2.6	0.97					yes
Aswad	Oman			2.38	2.33			0.2		
Daris East	Oman			0.24	2.37					
Ghuzayn	Oman			9.04	1.94			0.11		
Hatta	Oman			1.46	3.57			0.3		
Khaznah	Oman			0.35	1			0.1		
Mahab 4	Oman			1.51	2.06			0.2		
Maqail South	Oman			0.16	3.8			0.1		
Safwa	Oman			0.8	4.66					
Al-Bishara	Oman			3.06	1.09					
Rakah	Oman			2.9	1.02					
Mandoos	Oman			6.73	1.66					
Shinas	Oman			1.43	2.04					
Hayl As Safil	Oman			6.28	1.24					
Buribai	Russia			3	1.9	1.2	0.1			
Ivanovskoe	Russia	n.d.	n.d.	10	1.08	0.3		1.3	11.3	yes
Letnee	Russia	1965	n.d.	6.6	3.3	1.55	0.05	0.6	13.7	n.d.
Maukskoe	Russia	1955	n.d.	4.4	1.57	1.62		0.3	10.3	n.d.
Osennee	Russia	1967	n.d.	7.3	4.69	0.24		0.3	20.8	yes
Arinteiro	Spain	1969	1974	11	0.9					yes
Bama	Spain	1969	none	20	0.55					yes
Fornas	Spain	1969	n.d.	1	1.33					no
Ana Yatak-Ergani	Turkey	-2000	-2000	24.1	2.94			1.1	18.7	yes

NameDeposit	Country	Discovery	MiningStart	Tonnage	Cu(%)	Zn(%)	Pb(%)	Au (g/t)	Ag (g/t)	StringerZone?
Hacan	Turkey	n.d.	none	0.04	1.6					no
Kure (Bakibaba)	Turkey	1000	1951	4.4	2.2			1		no
Weiss	Turkey	1970	n.d.	1.81	3.18	0.48		2.6	18.4	no
Madenköy	Turkey			41.5	2.02	0.2				
Incekoz	Turkey			4.2	0.2	0.2				
Ortaklar	Turkey			12	3.5	1.15		6.3	1.3	
Magaradoruk	Turkey			25	3.24	0.2		5.2	1.5	
Asiköy	Turkey			11.23	1.56	0.2		10	2.48	
Toykondy	Turkey			0.38	4	0.2				