Ore Geology Reviews 95 (2018) 917–930

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

Probabilistic estimates of permissive areas for undiscovered seafloor massive sulfide deposits on an Arctic Mid-Ocean Ridge

Cyril Juliani*, Steinar Løve Ellefmo

Norwegian University of Science and Technology (NTNU), Department of Geoscience and Petroleum, Sem Sælandsvei 1, 7491 Trondheim, Norway

ARTICLE INFO

Keywords:
Mineral resource assessment
Mid-ocean ridge
Multivariate analysis
Seafloor massive sulfide
GIS
Exploration targeting

ABSTRACT

Norway explores its seabed mining potential including exploration studies on seafloor massive sulfides (SMS) at the outermost parts of its continental shelf, the Mohn's Ridge. Owing to the significant development potential and the general lack of knowledge of the SMS deposits, the evaluation of exploration targets and resource abundance are more than ever necessary. Given current exploration status, this study proposes to (1) develop a mineral prospectivity map (MPM) indicating favorable geologic environments for the occurrence of SMS deposits, and (2) estimate the number of yet-to-be found hydrothermal mineral deposits within volcanically active areas. The first part of this research focuses on the development of the MPM using a knowledge-driven approach. For this purpose, we apply the quantitative prediction framework characteristic analysis developed for terrestrial mining exploration. In this methodology, data must be captured and compiled into a relevant spatial data set that will be transformed, combined and weighted for prediction modeling. The data consist of morpho-structures and terrain attributes obtained from an interpreted bathymetric map. A multivariate analysis on the integrated data signature allow to calculate favorability values that will be projected on an exploratory grid. Each grid cell is given a likelihood of mineralization to indicate where SMS deposits might be located.

The second part of the paper estimates probabilistically how many SMS deposits remain to be found within neo-volcanic zones. These volcanic areas are geologically favorable to the occurrence of SMS deposits (permissive tracts) and provide the spatial basis for the probabilistic calculations. Estimates and associated confidence limits (10th and 90th percentiles) on the number of undiscovered deposits are calculated using regression equations. The resulting probability distribution function presents an expected amount of 11 SMS occurrences undiscovered.

1. Introduction

Interests have been growing over the last decades in exploitable deep seabed mineral resources. Recent exploration activities have been extended to global tectonic zones in oceans, including the mid-ocean ridges (MORs) (Hannington et al., 2010). While researches are not only limited to territorial waters, industrial countries seek to investigate new resource minerals in more remote locations. In particular, seafloor massive sulfides (SMS) draw great attention due to their abundant commodities (e.g. Cu, Zn, Au and Ag). Despite the limited knowledge about SMS occurrences, governmental concerns for deep-sea mining led to significant needs in further investigations of valuable resource potential in unexplored regions of the ocean floor. In this context, the Norwegian Research Council has funded a project to investigate exploitation technologies relevant to potential deposits off the country's coast along a large part of the Arctic Mid-Ocean Ridges (AMOR) located inside the Norwegian jurisdiction. Specifically, the Mohn's Ridge has become an important subject of investigation where a few identified SMS deposits occur in various localities (Pedersen et al., 2010). Past investigations of the ridge indicated major characteristics genetically essential for seafloor mineralization (e.g. Dauteuil and Brun, 1996; Bruvoll et al., 2009), and confirmed the inference that there exist significant unexplored prospective areas, and thus a mining potential to be evaluated.

Accurate positioning and deduction of the number of undiscovered seafloor sulfides is very challenging since general exploration guidance often relies on extremely poor amount of data about SMS. Nevertheless, recent studies attempted to delineate and assess quantitatively SMS deposits along MORs (e.g. Hannington et al. 2011; Singer, 2014), and notably along a broad portion of the AMOR (Ellefmo et al., 2017). These estimates are commonly considered for different components among which the location and the number of mineral deposits that are integral parts of a conceptual framework, the three-part form of mineral resource assessment (Singer, 1993; Singer and Menzie, 2010). This

* Corresponding author.
E-mail addresses: cyril.juliani@ntnu.no (C. Juliani), steinar.ellefmo@ntnu.no (S.L. Ellefmo).

https://doi.org/10.1016/j.oregeorev.2018.04.003
Received 15 February 2017; Received in revised form 24 March 2018; Accepted 2 April 2018
Available online 04 April 2018
0169-1368/

framework has been until now essentially applied for land-based studies (e.g. Singer and Menzie, 2010; Stensgaard et al., 2009; Eilu et al., 2015) and its application to unexplored offshore areas shall answer probabilistically the questions of "where" and "how many" mineral deposits are yet to be found in areas where limited geological and mineral occurrence data are available.

The outcome of estimating undiscovered occurrences is commonly expressed in terms of degrees of favorability within delineated prospective regions, i.e. the permissive tracts, in which geological criteria favor mineral deposits to occur (Singer, 1993). A technical way of achieving it is a proper management and compilation of targeted geological features extracted from data using a geographic information system (GIS). The power of combining data on a GIS-based environment offers efficient multivariate analysis for predictive mapping.

In an attempt to estimate where and how many SMS deposits may be found along the Mohn's Ridge, this paper will aim at developing and demonstrating how to produce a geologically-constrained predictive map of mineral potential, and ultimately evaluate probabilistically the number of undiscovered mineral deposits by regressive methods. For these purposes, identified geologic features are extracted from bathymetric data and then analyzed for subsequent evaluations of prospective areas and permissive tracts.

2. Study area and dataset

2.1. Study area

The Mohn's Ridge is an ultra-slow spreading center ($< 20\,\text{mm.a}^{-1}$) situated within the Norwegian-Greenland Sea that started opening approximately 55 Ma ago during the extension of the Mid-Atlantic Ridge (MAR) (Torsvik et al., 2001; Fig. 1). It extends WSW-ENE for about 550 km from its southernmost part, delimited by the Jan Mayen Fracture Zone (JMFZ), to its northern junction with the Knipovich Ridge. The ridge presently spreads at a rate of about 15 mm/yr (Vogt, 1986) with an oblique relative displacement between 30° and 45° (Fournier and Petit, 2007). Toward its center, the mean crustal thickness is of about 4.0 ± 0.5 km (Klingelhofer et al., 2000), a thickness considered lower than average for normal crust formed along the MAR, but typical at ultra-slow spreading ridges generally showing thinner and variable crustal thicknesses (Chen, 1992).

Apart from the anomalous segment adjacent to the Jan Mayen, water depths at the axial valley of the Mohn's Ridge range in average from 2.5 to 3.1 km and decrease progressively toward the southwest due to its proximity to the Jan Mayen hot-spot (Neumann and Schilling, 1984; Schilling et al., 1999). A characteristic aspect of the rift bathymetry is the strong asymmetrical configuration of the flanks delimiting globally higher summits on the north-western sides. Moreover, the axial valley and the bounding flanks are marked by series of en-échelon ridges interconnected by non-transform offsets (NTOs) that somewhat describe variations in the ridge obliquity. This segmentation pattern occurs with intermittent volcanism characterized by basement highs elongated at the scale of approximately 20–30 km and oriented perpendicularly to the spreading direction. Previous studies distinguished these ridge segments to be volcanic edifices (Géli et al., 1994) while some involved tectonic origins solely with trans-tensional bounding-faults (Dauteuil and Brun, 1993; Dauteuil and Brun, 1996).

Bathymetric data of the Mohn's Ridge have been collected by the Norwegian Petroleum Directorate (NPD) in collaboration with the Geological Institute of the Russian Academy of Sciences (GIN RAS). The data have been used to create a digital elevation map (DEM) that has been stored in a regular grid network (square grid) of 50 m-cells resolution, using GIS-based software. The data cover most of the rift valley from the JMFZ to the bend with the Knipovich ridge (ca. 73°N, 8°E). Investigation of the multi-beam data shows that the width of the axial rift valley, i.e. the distance between the rift walls, ranges from 7 to 16 km. The axial valley often deviates at NTOs where deep basins (≥3-km depth) trend at ~30° from the ridge axis within a spacing range of 18–25 km. These basins usually lack recognizable structures or volcanic edifices, but are commonly bounded by large dextral E-W transverse faults possibly accommodating the depth variation of the brittle/ductile boundary (Dauteuil and Brun, 1996). NTOs have limited lateral structural expression, but their off-axis traces remain visible from alternating sets of continuous ridge-parallel terrains and from structures that trend slightly oblique to the spreading direction. The volcanic activity at these transitions are quite restricted, and importance of such zones for hydrothermal venting remains to be shown.

In the south-western part of the ridge, segments and NTOs are difficult to identify because of irregular and complex bathymetric patterns associated to abnormally abundant volcanic activity and curved tectonic structures. In this region, the melting anomaly can be associated with more shallow and smoothed terrains because of the southward Jan Mayen hot-spot interaction, whereas the curved structures respond with strike-slip displacements along the ridge walls (Dauteuil and Brun, 1996). In contrast, the northernmost Mohn-Knipovich bend consists of a

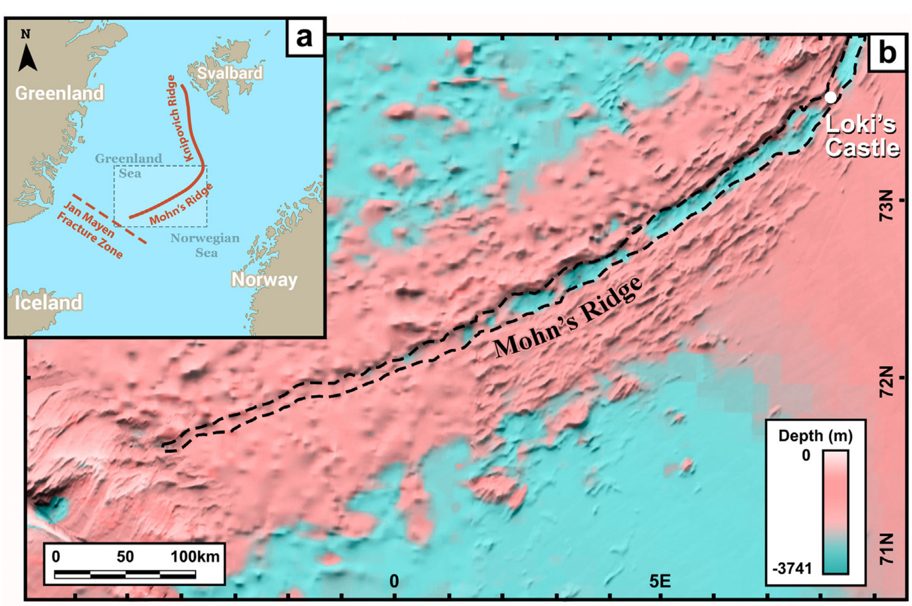

Fig. 1. (a) Map sketch and (b) bathymetry of the Mohn's Ridge. The black dashed lines delineate the ridge valley and the Loki's Castle vent field is shown at the northernmost part of the ridge. The basemap with shaded relief was taken and modified from the GEBCO database (available at http://www.gebco.net/data_and_products/gridded_bathymetry_data/).