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Acoustic seabed classification using QTC IMPACT on single-beam echo sounder data from the Norwegian Channel, northern North Sea

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ABSTRACT

Sediment mapping is important for understanding the physical processes, the impact of human activity, and the conditions for marine life on the seabed. For this purpose, the seabed classification tool QTC IMPACT analyses statistical variations in single-beam echo sounder data. QTC was applied in a large and physically diverse area of the Norwegian Channel, between 59°30′N and 61°N, to produce a new sediment map and to verify the QTC algorithm. The results were interpreted using ground truth (grain size analyses of 40 gravity cores and five grab samples), multi-beam echo sounder bathymetry (MBES), and seismo-acoustic profiles. Surficial sediments were divided into five classes: (1) mud and silt, (2) a variety of clay, silt and sand, (3) sandy mud with gravel, (4) sand with gravel, and (5) clay and sandy clay. Along the Norwegian coast, where MBES imagery shows evidence of glacial erosion, the surficial sediment distribution is variable. The echo shape analysis of QTC did not produce a natural partition of the data, and statistical assumptions did not always hold. Sediment classification was therefore sensitive to the choice of cluster algorithm. However, QTC produced the most physically plausible results on a large scale compared to other cluster algorithms. Class boundaries were consistent with supporting data. One exception is a transition from muddy to sandy sediments not visible in seismo-acoustic data. A possible explanation is that seabed fluid seepage and water current erosion cause sand particle transport into the western part of the channel. The study confirms the capability of QTC in a complex environment, but there are some possible improvements.

1. Introduction

Acoustic seabed classification (ASC) is a technology for mapping surficial seabed properties and sediment distribution with echo sounders (Anderson et al., 2008). The idea is that a change in sediment composition often implies a change in acoustic properties. This results in a systematic difference in the recorded echoes, provided the data have been corrected for extraneous influences, such as variable water depth or instrument settings. ASC may resolve fine variations in seabed properties with a high spatial resolution, which makes it a valuable complement to sediment sampling. Information about seabed composition is useful in a range of problems, including sonar performance prediction, the original purpose of this work, benthic habitat mapping and marine resource management (Brown and Blondel, 2009; Ellingsen et al., 2002; Freitas et al., 2003; Haris et al., 2012), environmental monitoring (Medialdea et al., 2008; Wienberg and Bartholomä, 2005), and geotechnical engineering (Bartholomä, 2006). A scientific understanding of the physical processes that form the seabed is also a goal in itself, and new acoustic techniques for seabed mapping are instrumental to achieve this.

Physics-based ASC methods estimate seabed acoustical parameters by fitting simulated data to observations (De and Chakraborty, 2011; Snellen et al., 2011; Sternlicht and De Moustier, 2003). Such methods are sensitive to instrument calibration errors and theory errors. Statistical methods search the data for systematic differences between distinct seabed types (Amiri-Simkooei et al., 2011; Haris et al., 2012; Madricardo et al., 2012; Van Walree et al., 2005). Such methods use pattern classification algorithms (Hastie et al., 2009; Theodoridis and Koutroumbas, 2009) and work best where observations divide naturally into a set of discrete classes, the nature of which may not be fully known in advance. Empirical relations have been used to estimate mean grain size from e.g. measured echo energy (Van Walree et al., 2006), but it is not straightforward to link acoustical response with

Abbreviations: ASC, acoustic seabed classification; BIC, Bayesian information criterion; CTD, conductivity, temperature and depth; FFI, Norwegian Defence Research Establishment; ML, maximum likelihood; MBES, multi-beam echo sounder; NC, Norwegian Channel; NGU, Geological Survey of Norway; PCA, principal component analysis; PDF, probability density function; QTC, Quester Tangent Corporation; SBES, single-beam echo sounder; UiB, University of Bergen; UiO, University of Oslo

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lithology. Sound scattering strength is sensitive to the seabed surface roughness (Jackson and Richardson, 2007), which may be influenced by coverage with benthic organisms and bioturbation, or sediment transport and attendant bedform development due to currents or ocean waves. As highlighted by e.g. Wienberg and Bartholomä (2005), an ASC system is best employed in conjunction with other data to avoid interpretational mistakes, particularly side scan sonar images (in their case) or multi-beam echo sounder (MBES) bathymetry.

The objectives of this paper are twofold. First, to present a new map of the surficial seabed composition in a large and physically diverse area of the Norwegian Channel (NC), northern North Sea, with water depths from 100 to 700 m. The primary tool has been the statistical ASC software QTC IMPACT (Preston et al., 2004), applied to single-beam echo sounder (SBES) data. QTC software is a widely used ASC tool which has proven successful in other studies (Bartholomä, 2006; Brown et al., 2011; Ellingsen et al., 2002; Freitas et al., 2011; Hamilton et al., 1999; Wienberg and Bartholomä, 2005). The second objective of the paper is to evaluate the QTC approach and result, including underlying assumptions, using an extensive supporting data set. Analysis of supporting data, especially ground truth (grain size analyses), is key to the interpretation and verification of the ASC results.

The paper first introduces the physical setting of the study area (Section 2). The established Quaternary stratigraphy, on which our interpretation of seismo-acoustic data is based, is briefly explained. Section 3.1 summarizes the data acquisition, in particular the pre-processing of the SBES data, and the preparation and analysis of the sediment samples. Section 3.2 examines the principles of the QTC method, which include a method for depth compensation of echoes, a data reduction step, and a clustering algorithm derived from Bayesian classification theory. Section 3.2.3 explains our approach to validate the QTC clustering algorithm. Section 4 presents the raw classification results, which required merging two datasets with different pulse lengths, and the results of the cluster validity analysis. The ASC method is an unsupervised one, so interpretation of the classes is subsequently done by comparison with the distribution of the sediment samples. The ASC classes are finally compared with parametric sonar profiles and geomorphology. Section 5 discusses the significance of the ASC results, the performance of QTC, and compares with previous work. The paper ends with the main conclusions from this work (Section 6).

2. Study area and seafloor geology

The NC is a depression in the continental shelf along the coast of southern Norway, with depths up to 700 m in the Skagerrak area (Fig. 1). It is a major topographic feature of the North Sea, which is a shallow continental sea bounded by the British Isles, Norway, and the northern European continent (Otto et al., 1990). The western slope of the NC is one of the major pathways for inflowing North Atlantic water. Mixed oceanic and fresh water flows out of the North Sea as the northbound Norwegian Coastal Current in the eastern and central NC (Winther and Johannessen, 2006). Thus the circulation pattern of the North Sea is influenced by the topography of the NC. Conversely, the NC is an important trap for water-borne sediments in the North Sea (De Haas et al., 1996).

The study area spans about 23 000 km^2 from the western Norwegian shoreline to the eastern margin of the North Sea plateau, between 59°30′N and 61°N latitude and to the east of 02°30′E (Fig. 1). The Quaternary sediments in this area consist of alternating layers of till and marine or glaciomarine sediments. The established Quaternary stratigraphy (Sejrup et al., 1995) is based in part on a drilled core sample (0–219 m below seafloor) from the Troll Field (Fig. 1). Of interest in this paper are the B1 unit and the A unit. Unit B1 is connected with seabed moraines in the eastern NC. Unit A is the top sediment layer in the central NC, truncated by the eastern moraines and, about 5–7 km from the shore, the crystalline basement (Fig. 2). Unit B1 is a till dating to the maximum of the Weichselian glaciation, corresponding to a homogenous diamicton in the Troll core with about 30% coarse material (grain size > 63 μm) and high shear strength (Andersen

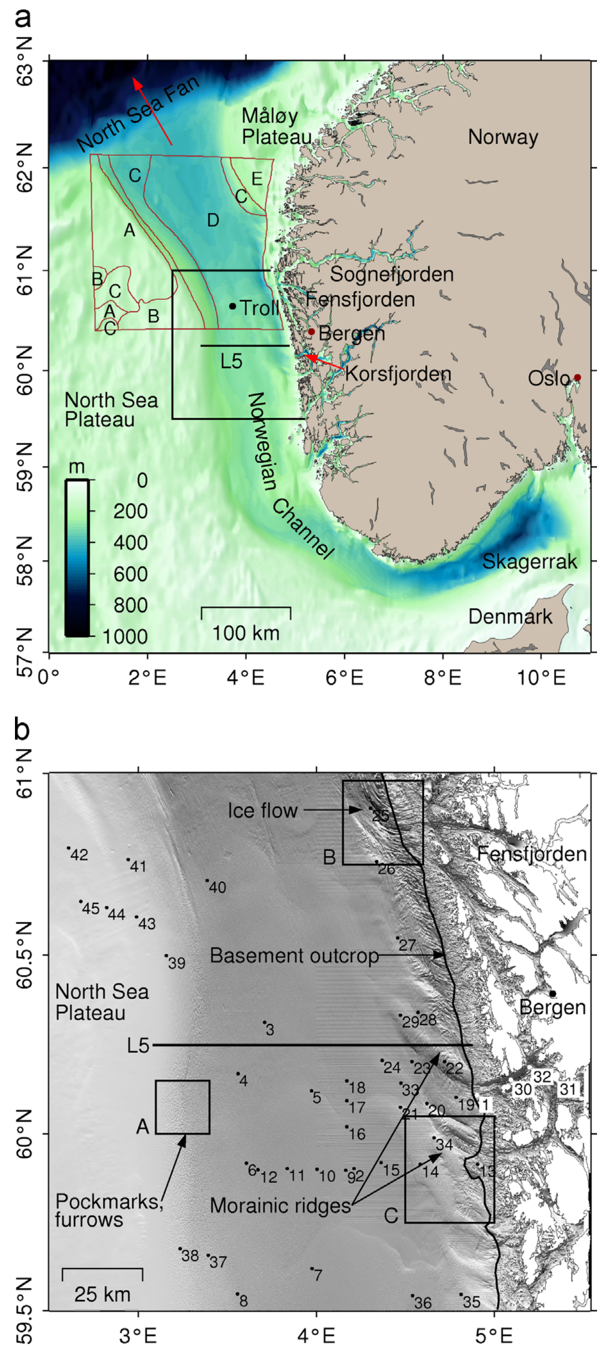

Fig. 1. (a) Overview and bathymetry of the Norwegian Channel. The study area to the west of Bergen is outlined. The Troll core is located at 60.64°N, 3.72°E. The brown polygons represent the sediment classes of Rise et al. (1984): sand with coarse material (A); very well-sorted sand (B); silty-clayey sand (C); silty, sandy clay (D); and variable (E). Map based on bathymetric data from (EMODnet, 2012), last accessed Dec. 2012). The line L5 is the transect of the seismic profile shown in Fig. 2. (b) Bathymetric relief of the study area based on MBES data, with principal morphological features indicated. The location of the 45 grain size analysed sediment samples (sample numbers given in Table 1) are also shown. The rectangular areas (A)–(C) are enlarged in Figs. 12 and 14. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)