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A BATHYMETRIC UNMANNED SURFACE VESSEL FOR EFFECTIVE MONITORING OF UNDERWATER AGGREGATE EXTRACTION FROM THE PERSPECTIVE OF ENGINEERING FACILITIES PROTECTION

ZDALNA BATYMETRIA JAKO EFEKTYWNA METODA MONITORINGU EKSPLOATACJI KRUSZYWA SPOD LUSTRA WODY W ASPEKCIE BEZPIECZEŃSTWA OBIEKTÓW INŻYNIERSKICH

The study aimed to apply the protection from damage to engineering facilities located near a planned underwater aggregate extraction. The analysis was conducted in compliance with mining regulations and expert opinions. The study also aimed to assess the precision and correctness of the extraction, due to economic aspects. To reach the goals, in-situ research of the mining area was conducted, with the help of an advanced bathymetric device, based on the USV methodology. The instrument – named by the author as Smart-Sonar-Boat – was especially designed for underwater surveys in open-pit aggregate mines. The study analyzed the "Dwory" open-pit mine, located in southern Poland in the city of Oświęcim. The bathymetric results obtained contributed to improving the observation of changes in the bottom during the extraction. The applied USV method allowed for conducting the reliable evaluation of the mining work.

Keywords: open-pit mine, economic mining, dredging machine, bottom composition, bathymetry, Smart-Sonar-Boat

Pierwszym celem artykułu była ochrona obiektów inżynierskich zlokalizowanych w bliskim sąsiedztwie planowanej eksploatacji kruszyw naturalnych spod lustra wody. Analiza przeprowadzona została w odniesieniu do obowiązujących regulacji prawnych oraz specjalistycznych ekspertyz geologiczno-inżynierskich. Drugim celem była ocena dokładności i poprawności eksploatacji w aspekcie racjonalnej gospodarki złożem. Do przeprowadzenia badań in-situ wyrobiska eksploatacyjnego zastosowano zdalnie sterowane urządzenie batymetryczne oparte na metodzie USV (unmanned surface vessel), co w wolnym tłumaczeniu oznacza bezzałogowy pojazd pływający. Instrument pomiarowy, autorsko nazwany „Smart-Sonar-Boat", został zaprojektowany do monitoringu podwodnej eksploatacji kruszyw. Obiektem badań była Kopalnia Kruszywa „Dwory" w Oświęcimiu. Uzyskane w ten sposób wyniki batymetryczne wraz z ich analizą statystyczną, w odniesieniu do wcześniej wykonanych ekspertyz badawczych, przy-

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czyniły się do poprawy bezpieczeństwa eksploatacji oraz umożliwiły ocenę dokładności wybierania złoża do spągu.

Słowa kluczowe: kopalnie odkrywkowe, dokładność eksploatacji, pogłębiarka, struktura dna wyrobiska eksploatacyjnego, batymetria, Smart-Sonar-Boat

1. Introduction

Over the past several years, remote sensing and Geographic Information System have rapidly developed, including the integration of geodesy with bathymetry (Owerko & Kwartnik-Pruc, 2011; Madusiok & Maciaszek, 2014; Ochałek et al., 2018). Nowadays, hydrological data collections, such as bottom characterization (Ivakin, 2006; Rzhanov et al., 2012; Haniotis et al., 2015; Awasthi, 2016), can be obtained by means of remote-controlled acoustic methods (Hitz et al., 2012; Romano & Duranti, 2012; Madusiok, 2016). To monitor open-pit exploitation of natural resources, mining surveying also uses bathymetric measurements (Patla & Rogosz, 2013; Madusiok, 2015).

The paper presents selected results from a doctoral dissertation (Madusiok, 2017) on bathymetric observations of underwater extraction of aggregates (sand and gravel) that was conducted from 2013 to 2017. Spatial data were obtained using an unmanned surface vessel (USV), constructed by the author and named as Smart-Sonar-Boat. The study dealt with the "Dwory" open-pit mine of aggregates, located in Oświęcim in southern Poland. The mine's owner decided to exploit the last parts of the deposit close to high voltage electricity lines and railway tracks.

The study had twofold objectives. First, it aimed to analyze the extraction in close vicinity to the engineering facilities, in compliance with the corresponding laws and regulations, such as the Polish Geological and Mining Law, mandatory norms, the geological documentation, the mining operating plan, and expert opinions. Second aimed to develop a plan for the management of the geological resources that would apply an advanced bathymetric USV methodology, using the aforementioned vessel, to assess – from an economic perspective – the precision and correctness of the aggregate extraction in the studied facility.

2. The facility

The Dwory open-pit mine of aggregates is located in southern Poland in the city of Oświęcim and exploits sand and gravel deposits. The mining area covers about 50 hectares, including a post-exploitation reservoir, engineering and processing facilities, and uncultivated lands with self-sown plants (Fig. 1).

Part of the aggregate material was formed below the water table, up to the depth of about 12 meters. Therefore, a special dredging machine, connected to the mainland by means of floating conveyors, was used for its extraction (Fig. 2). In a large part of the mining area, where the pit was flooded, the deposit was already extracted. The last parts of the deposit lay in close vicinity to high voltage electricity lines and railway tracks. Therefore, the mine owner, Kruszywo S.A., decided to exploit this area, providing protection to the engineering facilities and restrictive rules for avoiding the danger.

During the extraction time, the shore of the reservoir was constantly changing, increasing the risk of local landslides. As part of prevention of local shore instabilities, particularly in close vicinity to the engineering facilities, specialized expert analyses were conducted. Due to the ap-

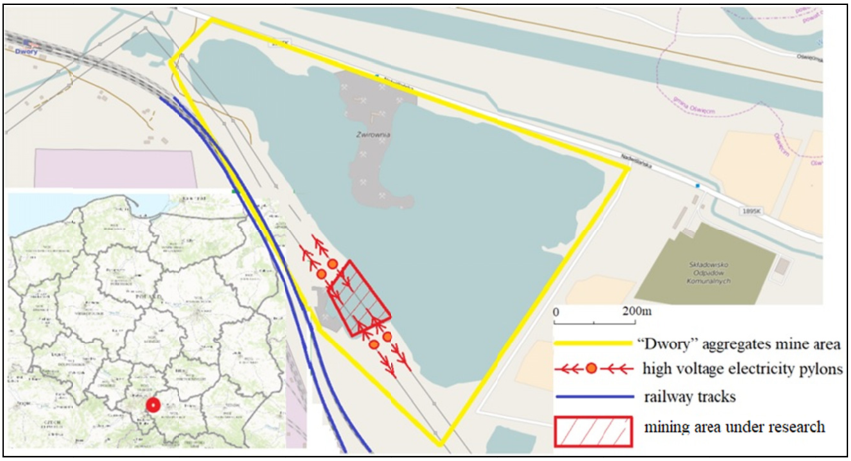

Fig. 1. A map of the “Dwory” open-pit aggregate mine

Fig. 2. The “Döpke” dredging machine near the high voltage electric lines

plicable Polish mining law (Statute, 2017), the local development plan (Act No X/138/11, 2011), and the Polish norm (Polish Norm, 1996), protective belts for the nearby high voltage lines and railway tracks were established. Intact areas (the protective belts) nearby the engineering facilities were marked out: ten meters from the railway track side and at least a width of a pylon height plus two meters from the electric pylons’ side (Fig. 3).

In addition, the maximum angle of a pit slope from a protective belt side was established at 30°. Two geotechnical analyses of the exploitation around a pillar confirmed that the protective belts parameters were correct and prevented larger landslides but did not prevent local shore landslips during extraction time (Glapa et al., 2008; Kurbiel & Nazimek, 2008).

To prepare the works planned in the study, mining exploitation analysis was conducted (Kurbiel & Nazimek, 2008). It confirmed the feasibility of the dredger operation under the electric lines, defined restricted areas, and indicated that the protective pillars absolutely had to be maintained. To ensure the safety of the mining works, a specialized working instruction was

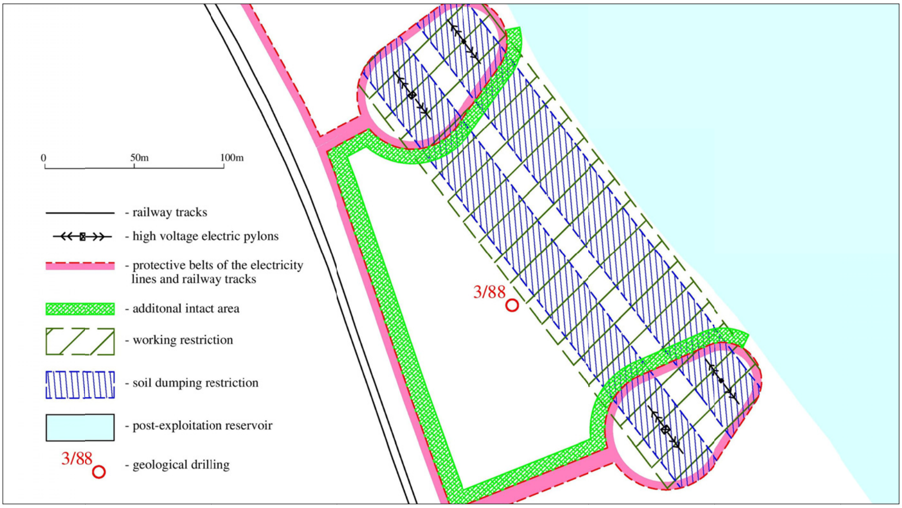

Fig. 3. Information about the research area

prepared (Kurbiel, 2008) that obliged the mining entrepreneur to adhere to the restrictions and requirements Based on an additional geological expertise (Kotas-Surówka, 2011), to keep the protective belt integral, the width of the intact area was enlarged by 8 meters and the maximum angle of the pit slope was reduced from 30° to 27°.

Ultimately, based on the above-mentioned analyses and the geological documentation of the deposit (Kapera 2008), the deposit development project and the mining operating plan – implementing the required technical assumptions – were prepared (Migda, 2012).

3. Methods

To study the underwater extraction, bathymetric measurements were conducted, based on acoustics. A perpendicular single signal was sent towards the bottom surface; then, after being reflected, it was received, and the travel time of the beam was measured (Fig. 4). The reservoir depth was determined based on the knowledge of the sound speed propagation in the aquatic environment, which is approximately 1500 m s^{-1}.

To record the trace of the survey, the acoustic measurements were integrated with the Global Positioning System. The initial stage of the research – based on classical bathymetry, with the integration of an acoustic sonar system with a GPS receiver – was performed on a boat (Madusiok, 2015) and required at least three surveyors. Such measurements were logistically difficult, and the results were not satisfactory enough to monitor the whole underwater mining area in the same way, therefore the author introduced improvements to the next stage of the research. The bathymetric measurements were conducted using a USV-based device (unmanned surface vessel) (Fig. 4). The constructed instrument, named by the author as Smart-Sonar-Boat, was designed for the research and inspection works in open-pit mines (Madusiok, 2016). The device enabled the surveyor to perform effective and efficient bathymetric measurements in hard-to-reach areas of the reservoir (Gawałkiewicz & Madusiok, 2018a, 2018b).

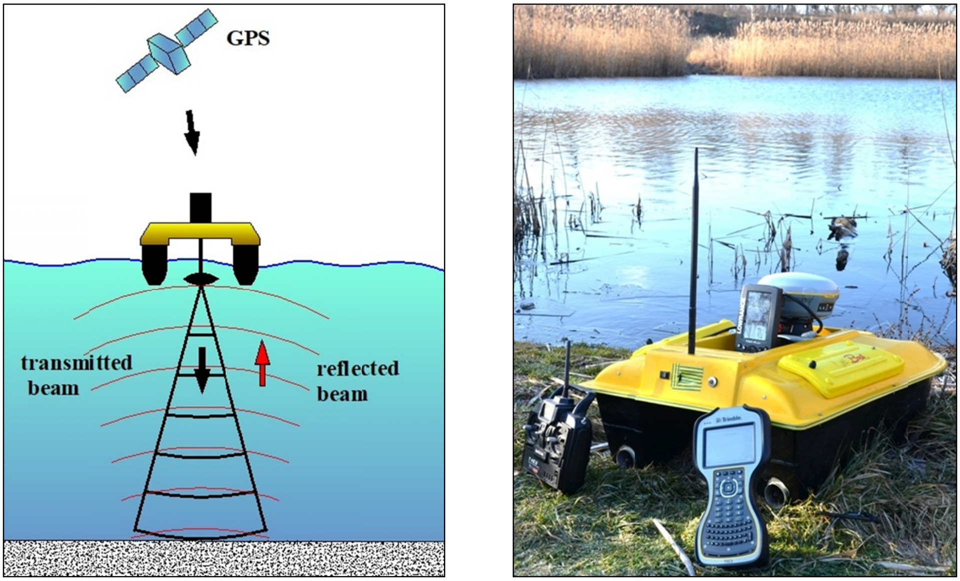

Fig. 4. Acoustics and positioning of bathymetry: basic rules (left), the applied unmanned surface vessel – Smart-Sonar-Boat (right)

To increase the precision of aggregate extraction in the researched area, acoustic reflection was analyzed. For this purpose, in addition to depth measurements, energy characteristics of the bottom-reflected acoustic beam were analyzed. The correlation of the echo strength and the relative hardness of the bottom was assessed, which confirmed the following relationship: The harder the obstacle such as rock, gravel or clay material, the higher the reflected energy of the signal; accordingly, the softer the bottom composition, such as silted structure, the lower the echo-energy (Orłowski, 1984; Bunchuk & Ivakin, 1989). This physical dependence was used to classify the bottom in the area analyzed, and, consequently, to identify the clay material laying below the aggregate deposit. The classification nomenclature was based on the soil texture triangle, illustrating the composition of sand, silt, and clay in the soil (Fig. 5).

The Lowrance Mark-4 echo sounder, used in the research, allowed for applying the bottom composition (hardness) algorithm, based on a relative and continuous scale of reflected sound energy in the range from 0 to 0.5 (Valley, 2014) (Tab. 1). Values within the softest section could indicate a loosely mixed structure, such as silted material or fine sand; those within both medium sections could indicate a loamy structure; and the hardest values could indicate compacted clay material or large stones.

4. Results

The results allowed for constructing spatial and structural models of the bottom, containing topographic maps (Fig. 6a-b), slope maps (Fig. 7a-b), and a composition structure map (Fig. 8). The models were used to analyze changes of the bottom during the mining extraction and after

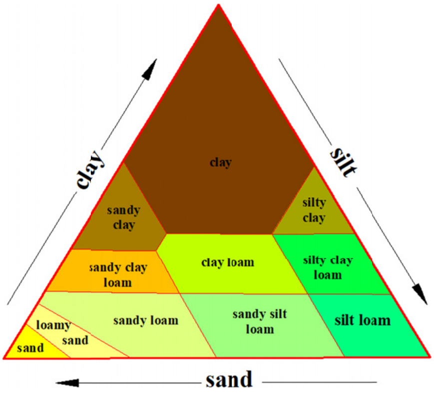

Fig. 5. Soil texture triangle

TABLE 1

Bottom composition factor

Composition Factor values	Structure Characteristics
0.0-0.2	softest
0.2-0.3	medium soft
0.3-0.4	medium hard
0.4-0.5	hardest

the reclamation of the mining area. The topographic models illustrated below highlighted steep-slopes of the bottom during the exploitation time and gentle-slope angles after the reclamation work. The last measurement indicated that the maximum angle of the pit slope remained preserved in accordance with the mining restrictions (i.e., 27°).

To assess the precision of the extraction, bathymetric measurements were conducted and compared with geological data. The structural drilling number 3/88 in the research area was executed before the mining works (Fig. 3) (Kapera, 2008). Based on the description of the core, the compacted clay material, which was the sub-layer of the deposit, lay below 214.0 m a.s.l. The post-extraction bathymetric map (Fig. 6a) also indicated that the deepest measured parts of the mining area oscillated around 214.0 m a.s.l. Information about the bed deposit level for one

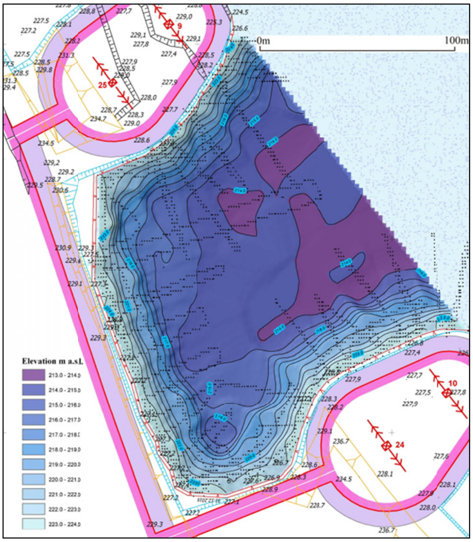

Fig. 6a. A topographic map during the exploitation

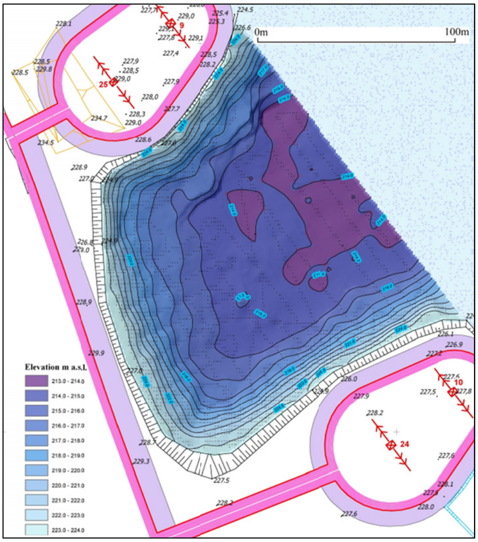

Fig. 6b. A topographic map after the reclamation

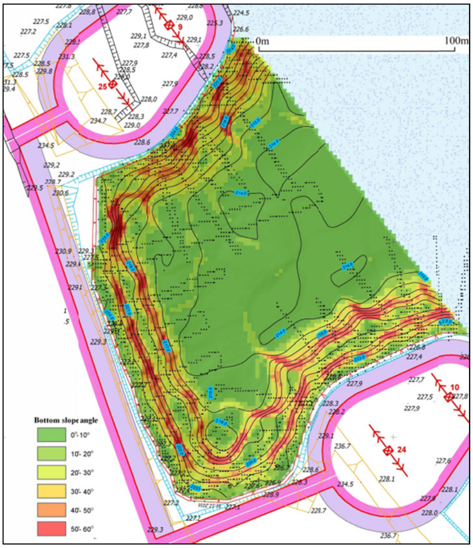

Fig. 7a. A slope map during the exploitation

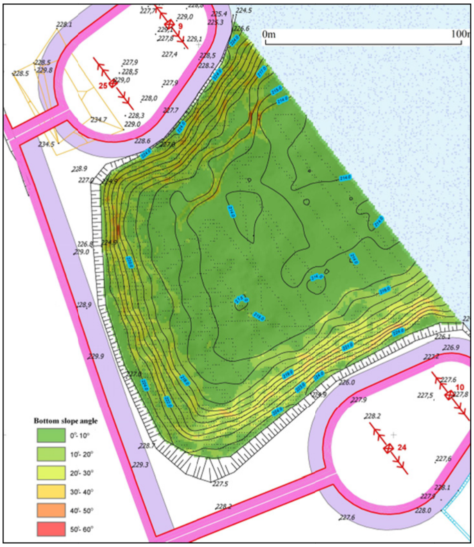

Fig. 7b. A slope map after the reclamation

structural drilling was not reliable enough for recognition. Therefore, bathymetric analysis of the bottom structure was conducted (Fig. 8).

The lithological information of the drilling was compared with the bathymetric composition factor. Statistical analysis, using the mean and the standard deviation, was used for the

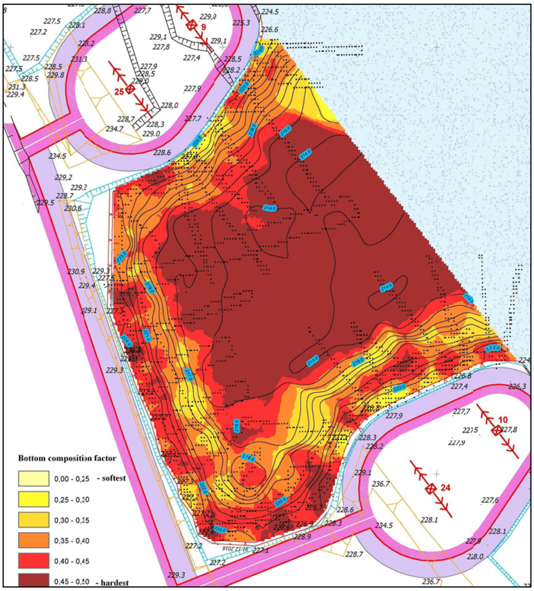

Fig. 8. A composition structure map (hardness) during the exploitation

assignment of the composition factor values to the specific lithological layers of the bottom of the reservoir (Fig. 9, Tab. 2).

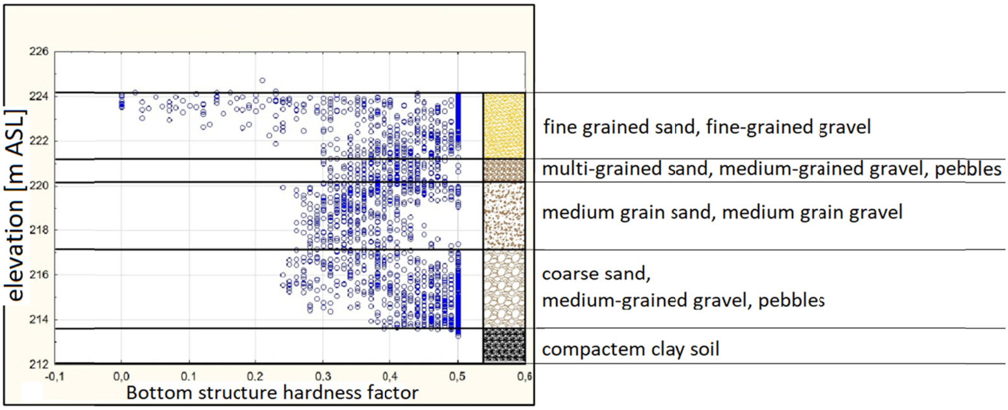

Fig. 9. Measurements of the bottom hardness factor

TABLE 2

Lithological layers and statistical summary of the bottom hardness factor

Soil fraction	Elevation	Bottom composition (hardness) factor	
	m a.s.l.	Mean	Stand. Dev.
fine grained sand, fine-grained gravel	222.0-224.9	0.38	0.12
multi-grained sand, medium-grained gravel, pebbles	220.0-222.0	0.37	0.06
medium grain sand, medium grain gravel	217.0-220.0	0.36	0.05
coarse sand medium-grained gravel, pebbles	214.0-217.0	0.40	0.07
compacted clay soil	< 214.0	0.46	0.04

Statistical analysis confirmed that, at the bottom of the reservoir, the most compacted material was the sub-layer of the deposit, the clay material. The acoustic signal was similarly reflected from this structure, with the values from 0.46 to 0.50 in the mentioned scale (the mean of 0.46), with the lowest standard deviation of 0.04. These results could mean that the loose mixture of sand and gravel was extracted in the area.

5. Conclusions

Specialized methods were implemented to provide protection to the engineering facilities during the exploitation located close to the high voltage electricity lines and railway tracks. First, before the mining works, advanced expert analysis of the research area was conducted, to establish the process of the protective belts', analyze geotechnical characteristics of the mining area, and prepare specialized working instructions and geological expertise. Considering all the restrictions and requirements above, the deposit development project and the mining operating plan were prepared.

Second, during the extraction time, to monitor the precision and the correctness of the mining works, automated bathymetric measurements were conducted, using the Smart-Sonar-Boat, a device applying an unmanned surface vessel (USV). The classical method (with a regular boat) was rejected because it was inefficient and prone to logistical difficulties, and above all, because a boat with surveyors could not reach certain places of the extraction area within an expected period. The USV method, on the other hand, can be used in a short period of time. Furthermore, it enables one to penetrate the entire extraction area, unlike the classical method, which is limited in this aspect.

Two bathymetric data – the depths and the information about the relative bottom type – were compared with the geological data. The measurements highlighted that the applied bathymetric method was effective and efficient in collecting spatial and structural data of the bottom of the reservoir in the research area.

The number of the points measured around the entire mining area allowed for constructing reliable models of the bottom, including topographic maps, slope maps, and structural maps. The above-mentioned models helped to assess the correctness and the safeness of the extraction, which was particularly important because the mining works were located near high voltage lines and railway tracks.

The study led to the following conclusions:

- The slope maps supported the assessment of the landslide potential and indicated the high-sloped areas of the bottom that should be re-formed.
- The composition map helped to assess how precise the extraction was. The high values of the composition factor marked the places where the aggregate had been completely extracted. This information would have been difficult to obtain using only the depth measure in the traditional method.

In summary, the simultaneous analysis of the bathymetric data and the comparison of the depth and the relative composition hardness of the bottom allowed for the improvement of the recognition where the deposit was extracted and where it was not.

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