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Research Article

Preliminary results and geological interpretations from an integrated marine geophysical survey for underwater archaeological prospection in the coastal waters of Kiten, Southern Bulgarian Black Sea Coast

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Abstract

The coastal waters around Cape Urdoviza near Kiten, Bulgaria, contain a concentration of submerged cultural heritage, including a prehistoric settlement and several documented shipwrecks, within a geologically complex setting of rocky reefs and sediment-filled bays. This study presents preliminary results from an integrated marine geophysical survey combining marine magnetometry and gradiometry, multibeam echosounding, side-scan sonar, and targeted sub-bottom profiling. The survey covered approximately 4 km^2 in two zones north and south of Cape Urdoviza, using reconnaissance line spacing of 50–100 m and denser grids of 10–20 m over selected anomalies.

More than 12 localised magnetic anomaly zones, generally 15–30 m in extent, were identified, together with more than 40 small and medium-sized side-scan sonar targets. Two magnetic anomaly zones were examined by divers: one contained a sediment mound without an exposed object, whereas the other yielded ship structural elements. Two additional, partially exposed wreck sites were identified from side-scan sonar imagery. The remaining targets are unverified and are therefore treated as potential rather than confirmed archaeological features.

The acoustic datasets also supported a generalised interpretation of three seabed substrate units: rock and reef, mud to sandy mud, and sand to silty sand. Because no contemporaneous sediment sampling was undertaken during the 2025 campaign, these units are considered acoustic interpretations and are compared with previously ground-truthed regional substrate mapping. The broad distribution is consistent with the mapped Kiten Reef and the transition from rocky coastal extensions to sedimentary bay fills reported in earlier studies.

The results demonstrate the complementary value of magnetic and acoustic methods for archaeological reconnaissance while also revealing important geological controls on the measured signals. They further show that magnetic or acoustic anomalies alone cannot be equated with archaeological objects without independent verification.

The study provides a reproducible preliminary framework for prioritizing future diver inspection, sub-bottom profiling, sediment sampling, and higher-density magnetic surveying in the coastal waters of Kiten.

Key words: Marine geomagnetic survey, underwater archaeology, archaeological prospection, shipwrecks, magnetic anomalies, coastal geology, Black Sea, Kiten Bay

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Introduction

High-resolution seabed mapping has become central to underwater archaeology, marine geology, habitat characterization, and coastal management. Acoustic systems provide spatially continuous information on seabed morphology and backscatter, whereas marine magnetometry can detect ferrous material and other magnetically contrasting sources, including objects buried beneath sediment. Nevertheless, the geological setting, survey geometry, sensor altitude, target orientation, spatial resolution, and availability of ground-truth observations all influence the resulting interpretation. Consequently, integrated surveys and independent verification are preferable to the interpretation of any single dataset in isolation (Brown et al. 2011; Quinn et al. 2005; Bates et al. 2011; Lecours et al. 2016; Misiuk and Brown 2024). Early integrated coastal surveys demonstrated the value of marine geophysical methods for locating and documenting submerged archaeological targets (Quinn et al. 2000).

Within this broader framework, the coastal waters around Cape Urdoviza near Kiten are particularly suitable for an integrated archaeological and geological investigation. The area contains a prehistoric, submerged settlement, several known shipwrecks, and numerous historical accounts of maritime disasters. At the same time, rocky coastal extensions, reef complexes, river-influenced sedimentary bays, and marked lithological contrasts create a heterogeneous geophysical background that must be considered when evaluating potential archaeological targets.

The earliest documented activities involving geophysical methods in the area date to 1986–1988, when one of the first underwater magnetometry surveys in Bulgaria was conducted in the waters of what is now Kiten Harbour in connection with the discovery of a prehistoric settlement (Georgiev et al. 1991). Subsequent underwater archaeological excavations were conducted over several years, during which part of the settlement was exposed and documented.

Between 2008 and 2010, airborne LiDAR scanning was conducted over the terrestrial area extending from the mouth of the Ropotamo River to Arapya Bay, with a spatial resolution of 1 × 1 m per pixel, while LiDAR bathymetry was acquired at a spatial resolution of 5 × 5 m (Popov et al. 2011). In 2013 and 2014, following the acquisition of new survey equipment, the Centre for Underwater Archaeology (CUA) focused its activities on the area and conducted two archaeological survey campaigns. These surveys employed a single-beam echosounder, multibeam echosounder, side-scan sonar, and sub-bottom profiler (Angelova et al. 2014; Angelova et al. 2015). An additional campaign was conducted in 2015 within the framework of the **Black Sea Maritime Archaeological Project (MAP Black Sea)** (Vagalinski et al. 2016). The main focus was the investigation of the seabed within the 12-nautical-mile zone offshore from Kiten and the adjacent bays, where more detailed surveys were conducted. The most recent high-resolution surveys in the area of Kiten Harbour and Atliman Bay were conducted in 2021 (Prahov et al. 2022; Prahov 2022). Predictive-modelling studies further emphasised the importance of combining archaeological records, palaeolandscape reconstruction, and remote sensing when assessing submerged-site potential along the southern Bulgarian coast (Prahov et al. 2011; Prahov 2013).

Based on the data obtained, regular archaeological excavations have been conducted since 2023 on a nineteenth-century shipwreck located immediately

adjacent to Kiten Harbour. This site represents one of three known shipwrecks in the immediate nearshore area.

The concentration of known archaeological remains raises two related research questions: (1) can integrated magnetic and acoustic observations identify and prioritize previously undocumented potential archaeological targets, including objects buried beneath sediment; and (2) to what extent are the observed magnetic patterns controlled by seabed substrate and regional geology rather than anthropogenic material? The actual number of wrecks may exceed the presently documented inventory because the shallow reef zones around Cape Urdoviza and the submerged Marmalyata formation have long represented navigational hazards.

Addressing these questions requires complementary methods. Side-scan sonar and multibeam bathymetry characterize exposed seabed morphology and targets, sub-bottom profiling provides information on shallow buried structures, and marine magnetometry responds to magnetically contrasting sources whether exposed or buried. Previous archaeological studies have shown, however, that only a subset of remote-sensing targets is ultimately confirmed as shipwreck material and that sonar backscatter can vary with material, orientation, range, and acquisition geometry (Quinn et al. 2002, 2005; Bates et al. 2011).

The regional geological and geomorphological framework has been investigated through integrated bathymetry, LiDAR, side-scan sonar, underwater video, and sediment sampling. Earlier mapping between Sozopol and Tsarevo distinguished rocky and unconsolidated substrate units using the Folk textural classification supported by grab samples and video observations (Dimitrov et al. 2019). Subsequent morpho-structural analysis identified the Kiten block and described the Kiten Reef as an approximately 8.5 km^2 rocky morphological feature extending from the coastal sector around Capes Konnik and Urdoviza to depths of about 38 m (Prodanov and Dimitrov 2020). These regional datasets provide an essential comparative framework for the present higher-resolution local survey. The regional data were also organised in an integrated geodatabase designed to support combined geological, hydrographic, and geomorphological analysis (Prodanov et al. 2018).

The present dataset was acquired primarily for archaeological reconnaissance using marine magnetometry, supported by multibeam echosounding, side-scan sonar, targeted sub-bottom profiling, and diver inspection. Its integrated character also permits a preliminary assessment of geological controls on magnetic variability and acoustic substrate patterns.

To the best of our knowledge, the present marine geomagnetic survey represents the first systematic investigation of this type in the Kiten area after an interval of more than a decade. A review of the available scientific literature did not identify published results from other geomagnetic surveys conducted in the area during this period.

Accordingly, this study aims to: (1) describe the survey design and processing workflow; (2) identify and classify magnetic and acoustic targets while distinguishing verified from unverified features; (3) present a generalised acoustic interpretation of the seabed substrate; and (4) compare the new observations with published regional geological and substrate maps. The results are explicitly presented as preliminary because only a limited number of targets were verified and no contemporaneous sediment ground-truth campaign was undertaken.

Study area and methods

Regional and local setting

The study area is situated off Kiten on the southern Bulgarian Black Sea coast and encompasses the two bays adjoining Cape Urdoviza, extending northward toward Cape Kyupriya and Primorsko and southward toward the Karaagach River mouth and Lozenets (Fig. 1). In the regional geomorphological subdivision of the Bulgarian coast, the sector belongs to the Medni Rid–Strandzha coastal region and, more specifically, to the coastal subregion that includes the waters off Primorsko, Kiten, and Lozenets. The shoreline is strongly indented and alternates between short rocky headlands, reef-fringed sectors, small embayments, beaches, and low-lying river-mouth areas. Rocky sectors are dominated by erosional and abrasion–structural landforms, whereas the bays contain gentler depositional slopes and unconsolidated sediment (Dimitrov et al. 2025).

The coastal morphology reflects the interaction of lithology, fault-controlled block structure, Quaternary sea-level fluctuations, wave abrasion, and sediment accumulation. Morphostructural analysis identifies Kiten as a distinct coastal block within the northern Strandzha sector. Upper Cretaceous volcanic complexes form resistant rocky headlands and submarine extensions, while Neogene sedimentary formations and Quaternary deposits occur in adjacent sectors. The lower reaches and mouths of the Dyavolska and Karaagach rivers form low-relief depositional corridors filled with alluvial, lagoonal, and recent marine sediments. This geological contrast between resistant rocky units and unconsolidated bay fill is fundamental to both the seabed morphology and the local magnetic background (Prodanov and Dimitrov 2020; Dimitrov et al. 2025).

The principal submarine landform is the Kiten Reef, which extends through the waters off Primorsko, Kiten, and southward toward Lozenets. Previous regional mapping describes it as an approximately 8.5 km^2 rocky morphological feature and the submarine continuation of Capes Konnik and Urdoviza. Its outer rock exposures reach water depths of approximately 38 m; locally, the reef rises 8-10 m above the surrounding seabed, with slopes reaching about 23° and, in places, near-vertical rock faces. Against the surrounding sandy seabed, this pronounced relief forms the most distinctive geomorphological element in the northern Strandzha coastal sector (Dimitrov et al. 2019; Prodanov and Dimitrov 2020; Dimitrov et al. 2025).

Earlier integrated seabed mapping between Sozopol and Tsarevo combined multibeam bathymetry, side-scan sonar, LiDAR, underwater video, and Van Veen grab samples. The resulting substrate map distinguished rocky outcrops and unconsolidated sediment using the Folk textural classification and direct geological verification. In the Kiten sector, rocky substrate is concentrated around the reef and the submarine extensions of the headlands. Sand dominates much of the shallow depositional seabed, locally enriched in shell debris and gravel near rocky reefs, whereas sediment generally becomes finer seaward and in sheltered or river-influenced depositional areas, grading toward silty sand, sandy mud, and mud (Dimitrov et al. 2019).

Cape Urdoviza separates the Northern and Southern survey zones and creates contrasting geomorphological and sedimentary settings. The Northern Zone includes Atliman Bay and extends toward Cape Kyupriya; the Southern Zone covers the waters from Kiten Harbour toward the Karaagach River

mouth, the Marmalyata submerged rock formation, and the northern part of the Lozenets coastal sector. River input and bay sheltering favour sediment accumulation in the southern bay, whereas exposed headlands and reef areas retain rocky or thinly sedimented seabed. These contrasts are directly relevant to archaeological preservation: sediment-filled areas can bury and preserve cultural material, while exposed reef surfaces are more strongly affected by wave abrasion and reworking.

The total surveyed area was approximately 4 km^2. Reconnaissance acquisition was conducted in two stages, with the main effort concentrated in the Southern Zone and a shorter targeted survey in the Northern Zone. For navigational safety, the shallowest reef areas and the nearshore zone landward of the 5 m isobath were not systematically covered. The present results therefore characterize the surveyed corridors and should not be interpreted as a complete inventory of the entire Kiten Reef or nearshore archaeological record.

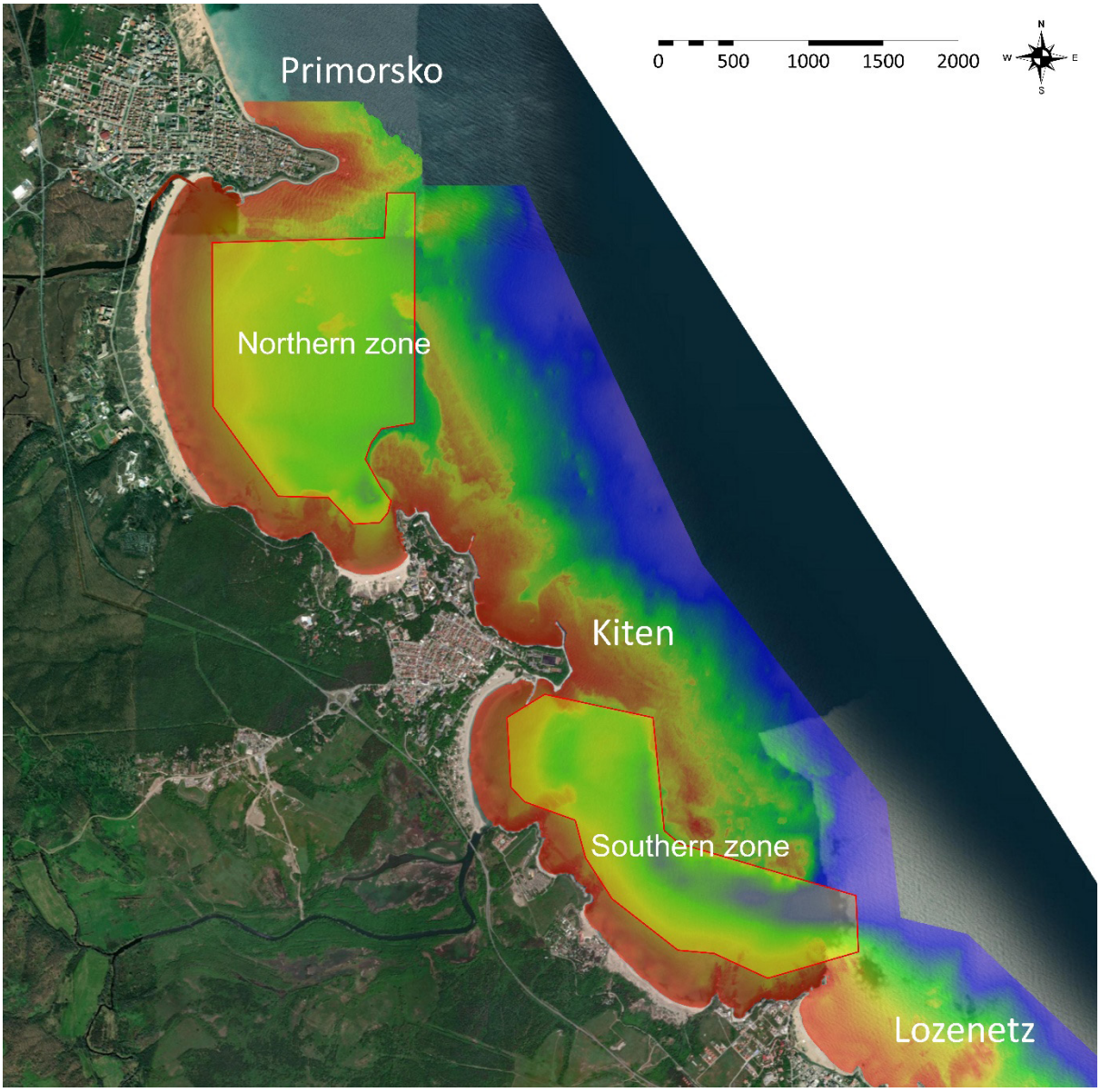

Figure 1. Location and extent of the Northern and Southern survey zones offshore Kiten and Primorsko. The colour scale represents water depth in metres.

Survey design and data acquisition

The vessel followed pre-planned survey lines with a standard spacing of 50 m. A reconnaissance spacing of 100 m was used in the more extensive Northern Zone. The preferred profile orientation was north–south/south–north. Denser grids with line spacing of 10, 15, or 20 m were acquired over selected anomalous zones, with orientation adapted to the geometry of the target. Figure 3 shows the actual vessel tracks derived from the onboard positioning and survey-coordination system. The unequal density along and across track is considered when interpreting the mapped gradients and interpolated products.

Vessel speed was maintained at **3–4 knots**. During data acquisition, the magnetometer was towed **50–70 m** behind the vessel, at an immersion depth of approximately **2–5 m** below the water surface. The magnetic data acquisition rate was set to **10 Hz**, which, at a vessel speed of 3–4 knots, provided a spatial sampling interval of approximately **10–30 cm** along the survey track. Data recording was continuous, including during transitions between individual survey lines. A similar data acquisition approach was applied to the other instruments used during the survey.

In reef areas, the vessel was navigated at a safe distance from underwater obstacles. In shallow sedimentary areas, operations were limited to depths of approximately **5 m** due to the risk of the towed instruments becoming snagged or buried in seabed sediments. Consequently, the area between the **5 m isobath and the shoreline** remained outside the coverage of the present survey.

During survey operations, data from all instruments were acquired and recorded simultaneously. When anomalous values were detected in the incoming data stream, they were marked in real time, allowing the preliminary localization and delineation of potential targets for subsequent detailed investigation and, where appropriate, verification by diver inspection.

Survey systems and positioning

Marine magnetometry and gradiometry constituted the principal method for detecting magnetically contrasting material, including potential wreck remains buried beneath sediment. Multibeam echosounding and side-scan sonar were acquired in parallel, and sub-bottom profiles were collected over selected areas. The complementary systems were used to characterize seabed morphology, acoustic texture, exposed targets, and shallow subsurface structure rather than to treat any single anomaly as diagnostic of archaeological material.

Following the first survey stage, divers inspected two selected magnetic anomaly zones. One inspection documented a sediment mound without an exposed object, whereas the second identified frames and planks interpreted as ship structural elements. These two cases are treated separately from the remaining unverified targets throughout the manuscript.

The survey provides data relevant to both archaeological reconnaissance and preliminary geological interpretation. However, the comparatively wide reconnaissance line spacing, incomplete shallow-water coverage, limited diver verification, and absence of contemporaneous sediment sampling constrain the degree of geological and archaeological certainty that can be assigned to the mapped features.

The survey platform used to carry the equipment was the research survey vessel (**RSV**) *Hristina* (Centre for Underwater Archaeology, Sozopol), which allows different types of survey activities to be conducted simultaneously.

A **Geometrics G-882TVG marine magnetometer–gradiometer** was used for the magnetic survey (Fig. 2). The instrument consists of two high-sensitivity caesium magnetometers mounted in tandem on a common support frame, with a separation of **1.5 m** between the sensors. The system is equipped with depth sensors and an altimeter and records the total magnetic field intensity at each sensor, as well as the magnetic gradient between them in a direction perpendicular to the central axis, i.e. perpendicular to the direction of travel.

The magnetometer–gradiometer was towed 20–50 m behind the survey vessel at an immersion depth of approximately 2–5 m below the water surface. The tow distance was selected to reduce vessel-induced magnetic interference while maintaining safe sensor altitude.

In parallel with the geomagnetic survey, the following remote-sensing instruments were also employed:

1. Multibeam echosounder
2. Side-scan sonar
3. Parametric sub-bottom profiler

Figure 2. GEOMETRIX G-882TVG marine magnetometer–gradiometer used in the survey – operational configuration.

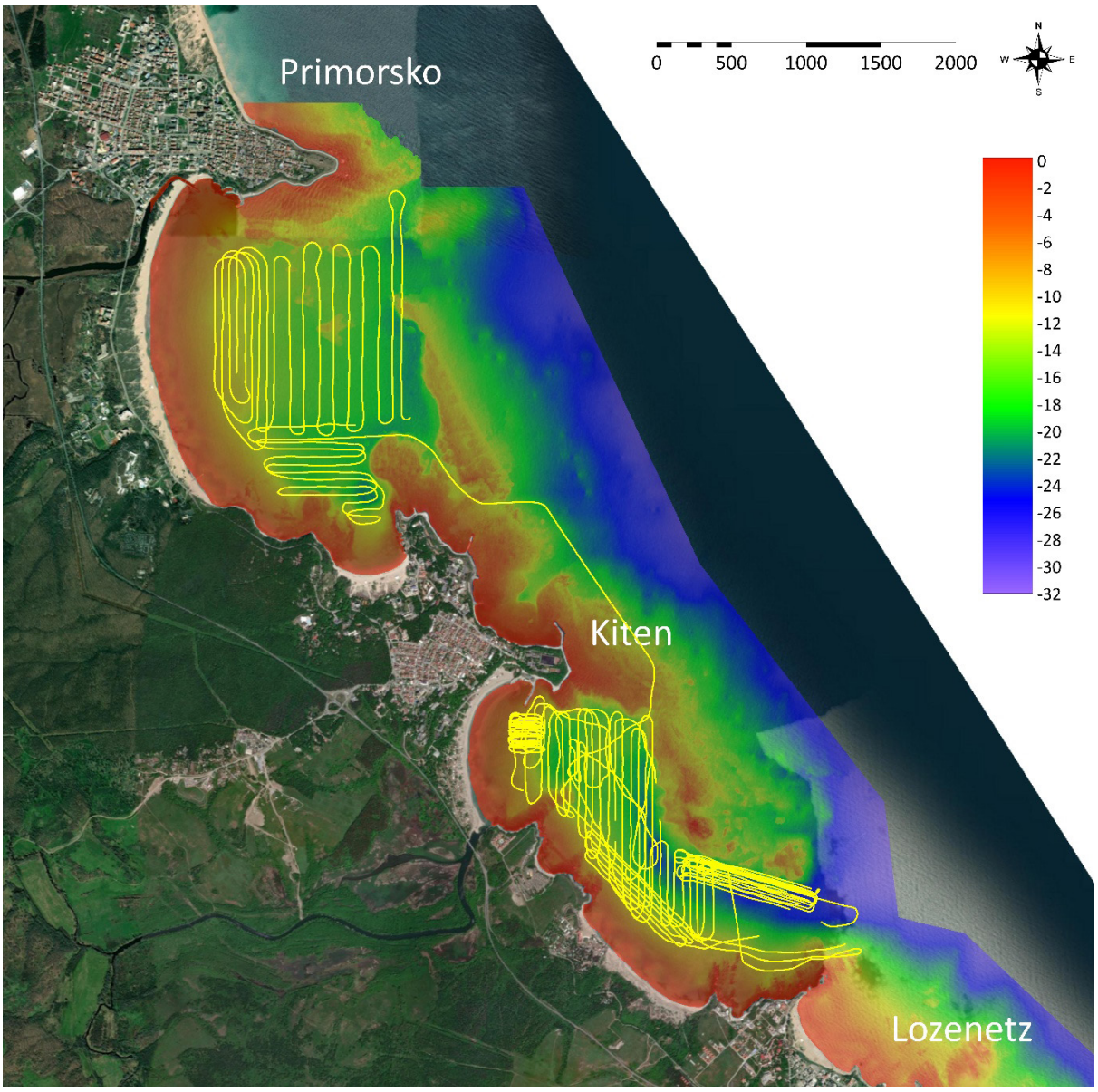

Figure 3. Actual survey tracks followed during the campaign based on the onboard positioning data.

The simultaneous use of multiple instruments was intended to provide complementary information with the maximum feasible spatial coverage and resolution while ensuring efficient use of the survey platform and enabling identified anomalous areas to be verified using more than one method. An additional advantage of this approach is the acquisition of information of different types, which increases both the interpretive potential and the scientific value of the resulting dataset.

The principal technical specifications, acquisition settings, processed products, and software are summarised in Table 1.

Positioning and navigation were provided by the following systems:

- Multibeam echosounder: Trimble GNSS integrated with an Applanix motion and attitude system and RTK corrections.
- Side-scan sonar, magnetometer–gradiometer, and sub-bottom profiler: Trimble DGPS with long-range differential corrections.

Table 1. Survey methods, instrumentation, and main acquisition parameters used in the marine geophysical and hydrographic surveys.

Survey method	Instrument	Operating frequency	Survey configuration	Spatial resolution / Sampling	Main output	Processing software
Marine magnetometry	GEOMETRIX G-882TVG	2 × Caesium magnetometer / gradient meter	Towfish, 20–70 m behind vessel	10 Hz (~10–30 cm along-track)	Total magnetic field; Horizontal magnetic gradient	MagLog / Excel
Multibeam echo-sounder	Teledyne RESON SeaBat T51-R	400 kHz	Hull mounted	0.25 × 0.25 m DTM; in very shallow water better	Bathymetry (DTM)	PDS-Teledyne
Side-scan sonar	Klein 4900	400/900 kHz	Towfish	Depending on range settings; 20 × 20 cm to 5 × 5 cm	Sonar mosaic; substrate interpretation	Sonar Pro / SeaView
Parametric sub-bottom profiler	SES-2000 Compact	4/8/12 kHz + 100 kHz	Hull mounted	Vertical resolution around 5 cm	Seismic profiles; sediment thickness	Innomar ISE Processing
GNSS with RTK	Trimble Applanix system with RTK correction	—	—	< 2 cm	NMEA 0183	—
GNSS DGPS	Trimble SPS461 DGPS	—	—	< 25 cm	NMEA 0183	—

Specialised software used for processing and analysis of geospatial, hydrographic, and geophysical data

Specialised software		
Application	**Developer / Provider**	**Software**
GIS	Blue Marble Geographics	Global Mapper
4D specialised software for complex data processing	QPS	Qimera; Fledermaus

Data processing

Magnetic data

Magnetic processing included diurnal correction, positional layback correction, resampling, calculation of transverse and along-track gradients, and preparation of visualization products. Archaeological interpretation was based on localised short-wavelength responses considered together with survey geometry, seabed setting, sonar observations, and available diver verification (Gearhart 2011).

Diurnal variations were corrected using reference data from the Panagyurishte geomagnetic observatory, approximately 280 km from the survey area.

Sensor coordinates were corrected for the along-track layback between the vessel positioning reference point and the towfish.

The observations were resampled from 10 Hz to 1 Hz to reduce redundancy and moderate the strong disparity between dense along-track sampling and wider across-track line spacing. Resampling does not compensate for the lower across-track resolution; this limitation is considered when interpreting interpolated magnetic surfaces.

The transverse gradient was calculated from the difference between the two sensors. An along-track difference was also calculated using observations separated by 10 s, corresponding to approximately 15–20 m at the reported vessel speed. This product was intended to emphasize anomalies at spatial scales comparable to medium-sized wooden vessels. It is treated as a survey-specific visualization metric rather than a conventional spatial derivative because the effective separation varies with vessel speed.

Multibeam echosounder

Teledyne PDS was used for acquisition and initial processing. Calibration was conducted before the survey, soundings identified as spikes were removed, and the cleaned point data were used to generate a 0.25 × 0.25 m bathymetric raster.

During the survey, **Sound Velocity Profiles (SVPs)** were periodically acquired according to the operating depth. The resulting SVP data were promptly used to correct the acoustic ray paths, with the corrections incorporated into the resulting depth data.

Side-scan sonar and acoustic substrate interpretation

During data acquisition, the manufacturer's proprietary **SonarPro v14** software was used. The data were recorded in the native **SDF format** of the Klein system and subsequently imported into **SeaView**, the standard processing software for side-scan sonar data.

The records were normalised, geometrically corrected using layback values, and processed to remove the water column before generation of a composite mosaic.

Discrete seabed targets were marked on individual records and the composite mosaic. Their interpretation considered target geometry, acoustic shadow, spatial context, and correspondence with magnetic anomalies; visual detection alone was not treated as proof of archaeological origin (Quinn et al. 2002, 2005).

The seabed was divided into three broad acoustic units based on relative backscatter intensity, texture, morphology, and spatial continuity: (i) rock and reef; (ii) mud to sandy mud; and (iii) sand to silty sand. The boundaries were manually interpreted and exported as vector polygons. No sediment samples or underwater video observations were collected specifically for ground truth during the 2025 survey. The units should therefore be understood as generalised acoustic substrate interpretations, not as laboratory-verified sediment classes. Regional comparison was undertaken using the ground-truthed substrate map of Dimitrov et al. (2019), which applied the Folk classification and sediment/video verification. Comparable mapping studies show that gradational substrate boundaries require cautious interpretation and validation (Brown and Collier 2008).

Sub-bottom profiler

All acquired profiles were processed as images using the standard methodology adopted at CUA using native ISE Processing software – Innomar GmBH. Within the resulting profiles, the main stratigraphic layers were identified, along with potential zones with unusual subsurface structures that were interpreted as possible targets. In the northern bay, two principal stratigraphic units were identified: sediments and bedrock. Based on this interpretation and subsequent vectorization, DTM surfaces were generated representing the boundary between sedimentary deposits and the underlying substrate. Individual profiles were prepared and exported in a specialised raster format known as "curtain wall", allowing their subsequent integration and visualisation within a Fledermaus 4D environment.

Results

Magnetic field and gradient patterns

The processed magnetic dataset comprises total-field measurements from both sensors, a transverse gradient derived from the sensor pair, and an along-track difference calculated over a 10 s interval (Figs 4, 5). The Northern Zone is characterised by a comparatively smooth, longer-wavelength decrease in total-field intensity, whereas the Southern Zone exhibits greater short-wavelength variability and a larger number of localised gradient responses. These statements describe the measured spatial patterns; their geological and archaeological implications are evaluated in Section 4.

For visualization, gradient values were clipped to ±30 nT. The along-track product is denoted dT/dX and the transverse sensor-pair gradient dT/dY. Because the effective along-track separation depends on vessel speed and because line spacing is much larger than along-track sampling, these products are used primarily to localize short-wavelength responses rather than for quantitative inversion.

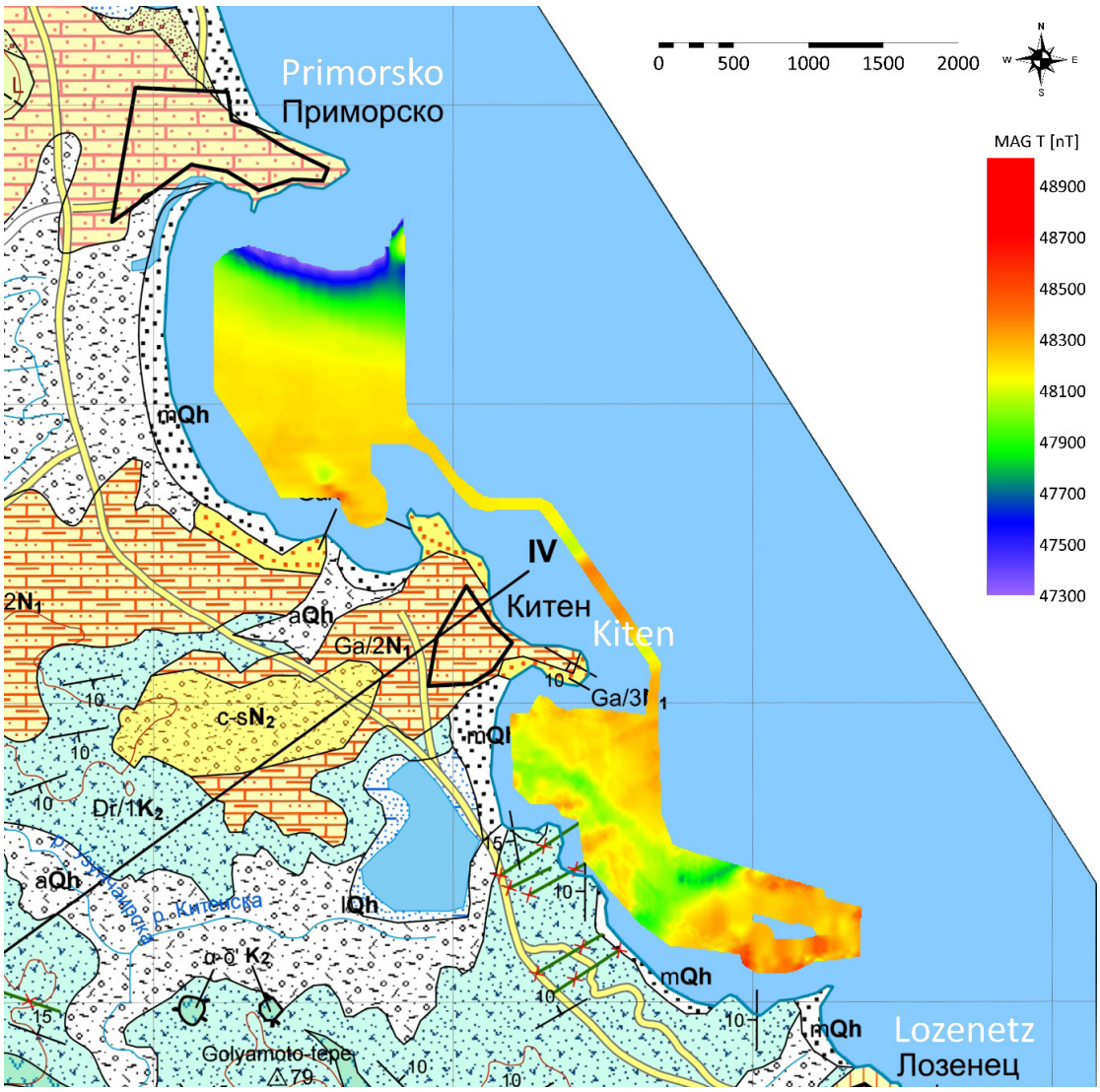

Figure 4. Total magnetic-field intensity in the survey area overlain on the geological map of the Kiten region (after Vassilev and Dabovski n.d.).

The complementary datasets include a 0.25 × 0.25 m bathymetric raster, a composite side-scan sonar mosaic (Fig. 6), a geospatial inventory of acoustic targets, and selected sub-bottom profiles. Two partially exposed wreck sites and more than 40 additional small to medium-sized objects of uncertain origin were identified in the side-scan sonar imagery. Sub-bottom interpretation in the Northern Zone distinguished recent sedimentary cover from the underlying acoustic basement and supported preparation of an indicative pre-sedimentation surface. These results remain preliminary because the profiler coverage was targeted rather than continuous.

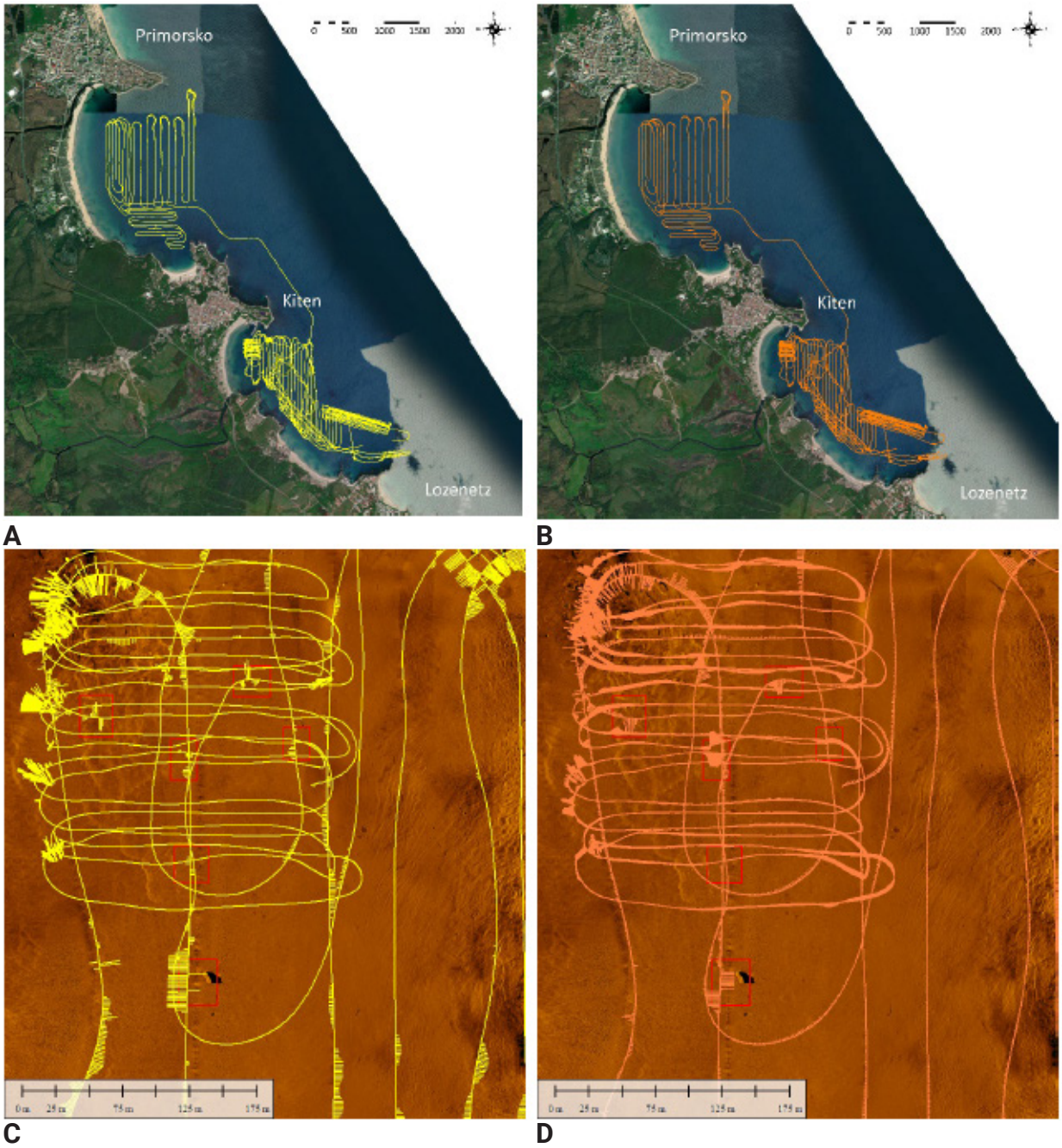

Figure 5. Magnetic-gradient visualization: (**A**) along-track difference (dT/dX); (**B**) transverse sensor-pair gradient (dT/dY); and (**C, D**) enlarged examples overlain on the side-scan sonar mosaic. Red symbols identify unverified magnetic targets potentially associated with buried objects.

All datasets were integrated in a Fledermaus 4D environment for joint visualization and spatial comparison.

Generalised acoustic substrate units

Three broad substrate units were mapped: rock and reef, mud to sandy mud, and sand to silty sand (Fig. 7). Rock and reef form spatially coherent, high-backscatter areas associated with coastal rock extensions and reef morphology. Lower-backscatter, comparatively homogeneous areas in the sheltered bays were interpreted as finer sediment, whereas intermediate and locally textured responses were interpreted as sand to silty sand. The map is intentionally generalised because acoustic response is influenced by incidence angle, roughness, sediment texture, shell or gravel content, and processing choices, and because no contemporaneous samples were available for direct validation (Brown et al. 2011; Lucieer et al. 2013; Misiuk and Brown 2024).

The overall pattern agrees with previous regional mapping between Sozopol and Tsarevo, which used multibeam and side-scan sonar data together with grab samples and video observations to delineate rocky substrate and Folk-classified unconsolidated sediments (Dimitrov et al. 2019). In particular, the mapped rocky unit corresponds broadly to the previously described Kiten Reef, an approximately 8.5 km^2 morphological feature extending offshore from the sector around Capes Konnik and Urdoviza, while the sedimentary units occupy bay and river-influenced depositional areas (Prodanov and Dimitrov 2020). This agreement provides regional contextual support but does not constitute station-by-station validation of the 2025 acoustic classes.

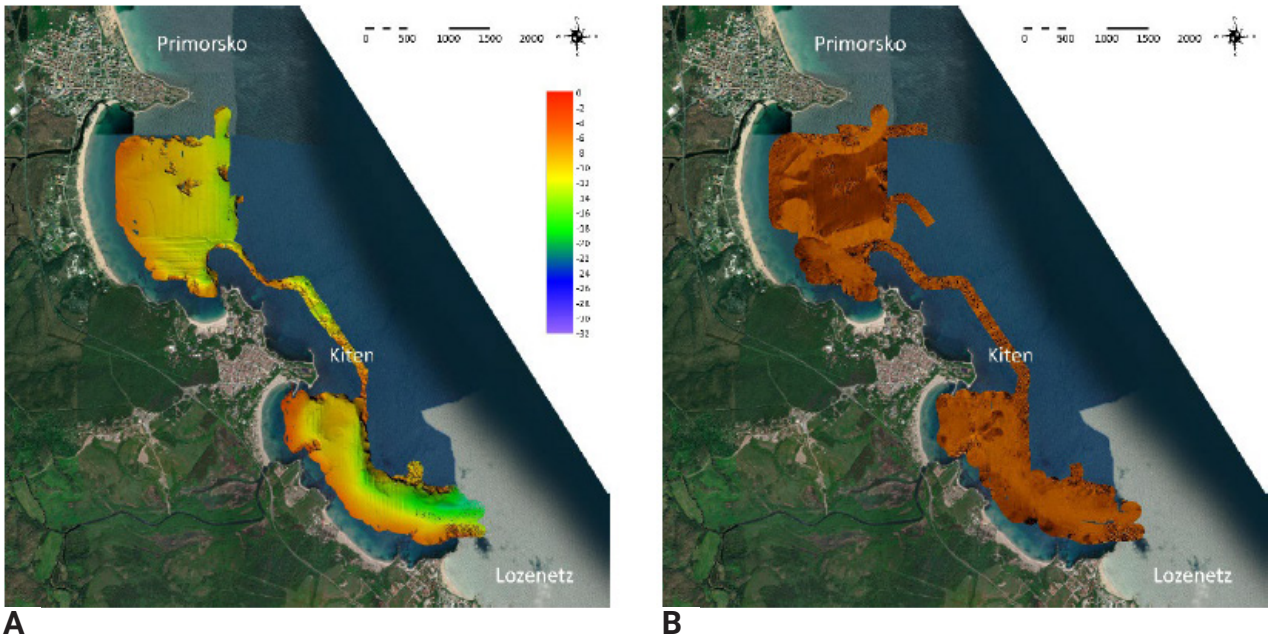

Figure 6. Complementary hydrographic and acoustic products: (**A**) high-resolution bathymetry derived from multibeam echosounder data; and (**B**) composite side-scan sonar mosaic.

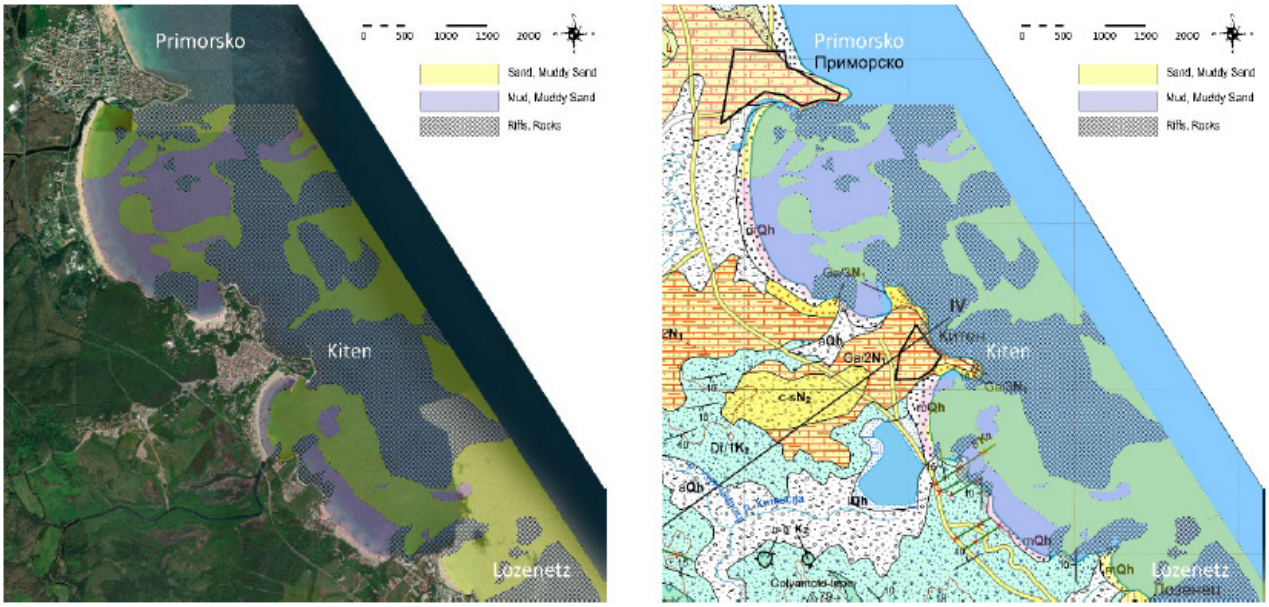

Figure 7. (**A**) Generalised acoustic substrate units interpreted from side-scan sonar backscatter and seabed morphology; and (**B**) comparison with the onshore geological map (after Vassilev and Dabovski n.d.).

Discussion

Archaeological interpretation

More than 12 localised magnetic anomaly zones, generally 15–30 m in extent, were identified, predominantly in the Southern Zone between Kiten Harbour and the Karaagach River mouth. Their size and short-wavelength character make them relevant for archaeological follow-up, but neither spatial scale nor magnetic amplitude alone establishes an anthropogenic origin. Geological contacts, reef structures, isolated ferrous debris, and survey geometry can generate responses that require careful discrimination (Gearhart 2011).

Only two magnetic anomaly zones were examined by divers during the present campaign.

- At the first inspected anomaly, no archaeological object was exposed; a sediment mound approximately 20 m long was documented. The possibility of a buried object remains unresolved and requires targeted sub-bottom profiling and, if justified, minimally invasive verification.
- At the second inspected anomaly, frames were identified and interpreted as part of ship structural elements, although the full hull extent was not established. This location is therefore treated as an archaeological target requiring further localization and characterization.

The remaining magnetic anomalies have not been verified and are classified as potential targets. This distinction is essential because comparable archaeological surveys have shown that only a subset of remote-sensing targets is ultimately confirmed through diver inspection or other ground truth (Quinn et al. 2002; Bates et al. 2011).

Two partially exposed wreck sites were identified in the side-scan sonar imagery. More than 40 other objects remain of uncertain origin. Some irregular targets near the Karaagach River mouth may be transported tree trunks or other natural debris, whereas regular geometric forms may indicate anthropogenic material. These interpretations are hypotheses for prioritizing future verification rather than definitive identifications.

At the local scale, approximately half of the cases in which magnetic and acoustic anomalies occur within the same target area show spatial coincidence. The remaining cases include acoustic targets without a detectable magnetic response and magnetic targets without a corresponding seabed expression. Such differences are expected because exposed non-ferrous objects may be acoustically visible but magnetically weak, whereas ferrous material or other magnetic sources buried beneath sediment may have no side-scan sonar expression. The complementary patterns support integrated interpretation but do not provide independent confirmation of target identity (Quinn et al. 2005; Bates et al. 2011).

Geological controls on the magnetic field

The magnetic background differs substantially between the Northern and Southern zones. The repeated decrease in total-field intensity toward Cape Kyupriya is a robust observation across seven passes, but its source cannot be uniquely resolved from the present survey. The hypothesis of a deeper volcanic unit is geologically plausible given the regional occurrence of Upper Cretaceous volcanic rocks, yet alternative explanations include changes in basement depth or magnetization, remanent magnetization, regional field geometry, and residual processing effects. Testing these alternatives would require denser line spacing, magnetic modelling, susceptibility information, and comparison with independent geological or geophysical data.

The Southern Zone exhibits greater short-wavelength magnetic variability near rocky coastal extensions and the Kiten Reef. Previous geomorphological mapping describes the reef as the submarine continuation of rocky coastal structures around Capes Konnik and Urdoviza (Dimitrov et al. 2019; Prodanov and Dimitrov 2020). The spatial association supports a geological contribution to the magnetic variability but does not demonstrate a direct one-to-one relationship between individual anomalies and mapped lithologies.

- Linear or clustered gradient responses near rocky substrate may reflect contacts, fractures, dykes, veins, or contrasts in magnetization within the bedrock. Because no magnetic modelling or rock-property measurements were undertaken, these features are interpreted as possible structural trends rather than confirmed fractures or veins.
- Sediment-dominated areas generally display smoother short-wavelength magnetic backgrounds than rocky areas. This relative quietness can improve the visibility of localised magnetic targets, but it does not eliminate geological or modern anthropogenic sources. Target significance must therefore be evaluated using morphology, multi-sensor correspondence, spatial context, and verification.

Substrate interpretation and regional comparison

The generalised 2025 substrate pattern is broadly consistent with the ground-truthed regional map of Dimitrov et al. (2019) and the morphostructural interpretation of Prodanov and Dimitrov (2020). The correspondence is strongest for the rocky Kiten Reef and for the contrast between exposed rocky extensions and sediment-filled bays. The present map adds locally detailed acoustic coverage but does not supersede the earlier sediment classification because the 2025 campaign did not include grab samples, cores, or systematic video ground truth.

Accordingly, terms such as mud, sandy mud, sand, and silty sand should be regarded as regional lithological interpretations supported by backscatter character, morphology, and published mapping, rather than laboratory determinations from the 2025 dataset. This limitation should be reflected in the map legend and metadata. Future sampling should target class interiors, acoustic transition zones, and locations where the 2025 interpretation differs from the earlier map.

Limitations and future work

The principal limitations are the wide reconnaissance line spacing relative to target size, unequal along- and across-track sampling, incomplete coverage landward of the 5 m isobath, targeted rather than continuous sub-bottom profiling, limited diver verification, and absence of contemporaneous sediment ground truth. In addition, the present analysis does not include formal positional, bathymetric, magnetic, or classification uncertainty estimates.

Future work should include tighter magnetic grids over prioritised targets, repeated crossing lines, explicit dynamic layback modelling, targeted sub-bottom profiles, systematic diver or remotely operated vehicle inspection, and sediment sampling across acoustic classes and class boundaries. Reporting confusion matrices or other validation metrics would allow future substrate maps to move from expert interpretation toward quantitatively assessed classification (Brown et al. 2011; Lucieer et al. 2013; Misiuk and Brown 2024).

The dataset should therefore be regarded as a strong reconnaissance and prioritisation resource rather than a complete archaeological inventory or definitive geological model.

Conclusions

The integrated survey identified a concentration of localised magnetic and acoustic targets in the Southern Zone, indicating that this sector has the highest priority for further archaeological investigation within the surveyed area. Two magnetic anomaly zones were inspected by divers: one yielded ship structural elements and is treated as verified, whereas the other contained an unresolved sediment mound. The remaining magnetic and acoustic targets require independent verification and cannot presently be classified as shipwrecks.

Magnetometry and side-scan sonar provided complementary rather than independently confirmatory evidence. Their combination improved target detection and prioritization because acoustic imagery records exposed morphology while magnetic measurements may respond to buried or visually inconspicuous material.

The Northern and Southern zones display contrasting magnetic backgrounds. The smoother northern decrease may reflect deeper geological controls, whereas the stronger short-wavelength variability in the south is spatially associated with rocky coastal extensions and reef morphology. These geological interpretations remain hypotheses pending denser surveying, magnetic modelling, and rock-property information.

Three generalised acoustic substrate units were mapped: rock and reef, mud to sandy mud, and sand to silty sand. Their broad distribution agrees with previously ground-truthed regional mapping and the documented extent of the Kiten Reef. Because the 2025 survey lacked contemporaneous sediment sampling, the new units should be presented as acoustic interpretations rather than fully validated sediment classes.

The study demonstrates the scientific value of integrating marine magnetic, bathymetric, acoustic, sub-bottom, and diver observations while explicitly separating measured patterns, geological hypotheses, potential archaeological targets, and verified archaeological remains.

The dataset provides a robust basis for a second-stage programme of focused geophysical survey, ground truth, and archaeological investigation in the coastal waters of Kiten.

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Additional information

Conflict of interest

The author has declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Artificial Intelligence (AI) use

The author accepts full responsibility for the content of the manuscript, including the disclosure of any use of AI.

Regarding the use of AI in the preparation of this manuscript, the author declares the following: GPT

Used for: Language, style and writing. For translation and style alignment.

Author contributions

K. Velkovsky designed and conducted the marine geomagnetic survey, processed and interpreted the geophysical data, and drafted the manuscript. D.Garbov and prof. K. Bachvarv coordinated the archaeological research, contributed to the interpretation of the archaeological results.

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Data availability

All of the data that support the findings of this study are available in the main text.

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