Exploring and Mapping Marine Placers in Vigo Estuary Shoreline Using GIS Cartographic Tools

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Abstract: Marine placer deposits are accumulations of heavy minerals in coastal areas, both on beaches and in shallow water, usually consisting of ilmenite, rutile and zircon, and less commonly rare earth minerals (REEs) such as monazite and xenotime. This study investigates marine placer deposits in the Vigo Estuary (NW Spain), focusing on integrating diverse on and offshore cartographic data (geology, mineral resources, drainage, bathymetry, tides, Earth observation and others) for exploration. Six hundred two information points of marine placers have been analysed, 379 of them from shallow water, where Thiessen polygons have been spatially calculated. Our results, integrating regional cartographies in a Geographic Information System (GIS), shown great potential of placer minerals on the Santa Marta and Vao beaches (with presence of garnet, ilmenite, zircon, monazite and, locally, xenotime). This work 1) highlights the importance of collecting and analysing different previous information for marine placer exploration in integrated digital cartographies, 2) allows to program new activities to investigate local areas, 3) remark the remote sensing applications (cheap, easy and non-invasive tool), better applied to inaccessible areas, and 4) contribute to allow a sustainable resource exploration and coastal management.

1 INTRODUCTION

Marine placer deposits are accumulations of heavy minerals found on beaches and shallow water near the coast (Rona, 2008; Van Gosen et al., 2014; Hou et al., 2017). Some minerals of economic interest include ilmenite and rutile (Ti), zircon (Zr), cassiterite (Sn), monazite and xenotime (Rare Earth Elements- REE), gold (Au), diamonds, and gems, which accumulate due to their higher density compared to other minerals. These deposits are distributed globally on most coasts (Rona, 2008). In particular, marine placer deposits with REE content are located on the coasts of South Carolina and Florida (USA), Australia, Brazil, India, Sri Lanka, China, Thailand and Malaysia (Segupta and Van Gosen, 2016).

Marine placers contain several critical raw materials (CRMs) that can contribute to the supply of the European Union (EU) (Grohol and Veeh, 2023) and other countries, thereby supporting the ecological transition. Indeed, the European platforms EMODnet Geology (https://emodnet.ec.europa.eu/en/geology), GeoERA-MINDeSEA and EGDI provide an overview of marine mineral resources in their reports

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and viewer, including marine placer deposits and occurrences (Zananiri et al., 2021; González et al., 2023; GSEU, 2024).

Multiple authors have described these deposits and proposed their exploration from different approaches, such as the commodity approach (e.g., focused on Ti according to Force (1991)), geological, geochemical and geophysical techniques (Van Gosen et al., 2014), and specialized mapping (GIS), aerial photography and topography, remote sensing techniques, geological methods, drilling, and 3D modelling (Hou et al., 2017). Recently, and along with advances in Earth observation (EO), remote sensing applications have been initiated for placer exploration (e.g., Rejith et al., 2020 and 2021; Cardoso-Fernandes et al., 2023; Ng-Cutipa et al., 2024). This work proposes a methodology for integrating land-sea information in a geographic information system (GIS), aimed at: 1) analysing existing information layers to select local pilot areas, and 2) applying field exploration and EO tools focused on the study of marine placers in NW Spain.

2 REGIONAL SETTING

The Vigo Estuary, one of the Rías Baixas estuaries, is located in NW Spain. The area's geology comprises intrusive and metamorphic rocks ranging in age from the Paleoproterozoic to the Jurassic (González and Vicente, 2004). The study area is situated within the MAGNA 50k map sheets of Cíes (0222) and Vigo (0223), where the estuary is located, with an approximate NE-SW orientation. In the outer part of the estuary, the Cíes Islands are located, which are oriented N-S and act as a natural geographic barrier that protects the inner area of the estuary (Figure 1). The main tributary river of the estuary is the Verdugo River; however, there are numerous smaller tributary drainages, with those located on each side of the central axis of the estuary being much shorter.

3 DATA AND GIS INTEGRATION

Previous studies have synthesized and grouped exploration techniques for marine placer deposits based on geological, geophysical, remote sensing conditions, etc. (e.g., Van Gosen et al., 2014; Hou et al., 2017). Within the S34i project, we have focused on geological information at regional and local scales, which can contribute to the successful search for marine placer occurrences in beach and shallow-water sands. In general, we have grouped the available data by their geographic environment with respect to their coverage: on-shore, off-shore and intertidal zones. To this, we have added a fourth group, "EO data" (Figure 2), that, depending on the characteristics of the image, can be used to obtain information from the three zones described above. We have also integrated a fifth group called "restrictive areas", which are areas of natural protection, economic activities or other specifications.

Figure 1. Location of Vigo estuary.

3.1 On-Shore Data

The analysed datasets correspond to:

-Topography from the National Geographic Institute (IGN) of Spain (https://www.ign.es/web/ign/portal/inicio), which constitutes the base layer with information on toponymy and hydrography. The sheets used are 0222 (Cíes) and 0223 (Vigo).

-Basins and drainages from MITECO (https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/agua.html) at a scale of 1:25,000 (© Ministerio para la Transición Ecológica y el Reto Demográfico), which are located within the map sheets 0222 and 0223.

-Continuous digital geological cartography at a scale of 1:50,000 (GEODE survey, https://info.igme.es/cartografiadigital/geologica/geode.aspx) from the IGME-CSIC (© CN Instituto Geológico y Minero de España (IGME), with geological and structural information of the Z1200 Galicia Tras-Os-Montes area. Around the estuary, a clear predominance of intrusive and metamorphic rocks with an approximate N-S orientation is observed. Quartz dikes can be secondary sources of heavy minerals of economic interest, such as tourmaline, cassiterite and gold; however, at a scale of 1:50,000, they are scarce around the estuary, according to GEODE.

-Mineral resources database (BDMIN, http://info.igme.es/catalogo/resource.aspx?portal=1&catalog=3&ctt=1&lang=spa&dlang=eng&llt=dropdown&master=infoigme&resource=23) from the IGME-CSIC (© CN Instituto Geológico y Minero de España (IGME)), is a database that integrates geological-mining information on evidence, deposits and exploitation of rocks and minerals in Spain.

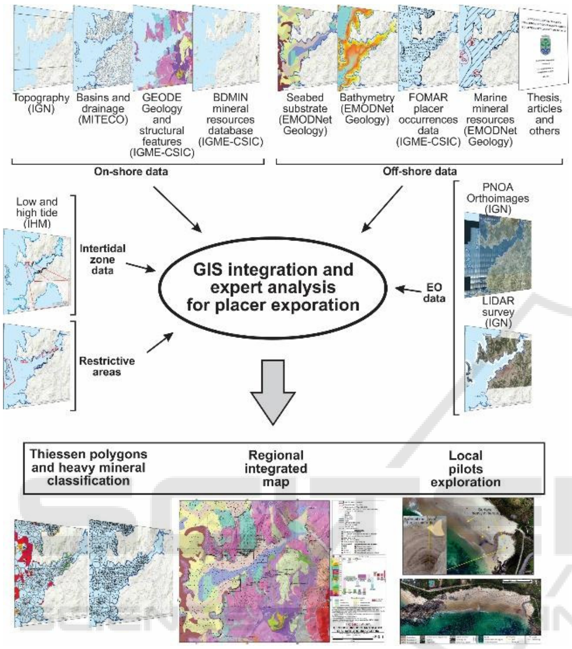

Figure 2. Integration methodology for marine placer deposit exploration in the NW Spain.

3.2 Off-Shore Data

Data related to:

-Bathymetry and seabed substrate data are from EMODNet Geology (https://emodnet.ec.europa.eu/en/geology), a European portal that provides harmonized data. These allow us to know the morphology and type of seabed. In the study area, the seabed substrate with Folk 7 classification is available.

-The mineral exploration studies of the continental shelf of the FOMAR project (IGME, 1976 and 1979) have samples of beach and shallow-water and semi-quantitative analyses of heavy mineral contents in Rias Baixas. The most abundant minerals are generally garnets, ilmenite, zircon and monazite.

-Thiessen polygons were calculated using ArcGIS from the samples collected on the shallow water in the FOMAR project, providing an approximate area of similar heavy mineral content. Ng-Cutipa et al. (2023) classified the heavy mineral content into five classes: <1 g, 1-5 g, 5-50 g, >50 g and absence.

-EMODNet-Geology marine resources (https://emodnet.ec.europa.eu/en/geology) provide us with marine mineral occurrences in point and polygon format.

-Other publications, such as these articles and conferences, include various data related to marine placer occurrences(Manso, 2001; Ng-Cutipa et al., 2024).

3.3 Intertidal Zone Data

Low and high tide data from the Hydrographic Institute (IHM) of Spain provide a regional overview of the intertidal area, which can influence the surface occurrence of placer deposits. As mentioned before, the NW area of Spain has a mesotidal regime, with variations of 2 to 4 m in height in the intertidal zone.

3.4 EO Data

National Aerial Orthophotography Plan (PNOA) and Light Detection and Ranging (LiDAR) surveys from IGN (https://pnoa.ign.es/web/portal/inicio), consist of orthorectified visible and near-infrared imagery, and digital elevation information at a very high local resolution. The PNOA images (PNOA 2020 CC-BY 4.0 ign.es) have a spatial resolution of 15 cm per pixel in the visible and 25 cm per pixel in the near-infrared. For geological mapping, the most current images in the area (year 2020) have been used; the near-infrared has been used to highlight faults and lineaments (Ng-Cutipa et al., 2024). The most recent LIDAR flight (PNOA LiDAR 2020 CC-BY 4.0 ign.es) is from 2015, with a minimum point density of 0.5 - 2 points/m².

Additionally, images were collected through a UAV survey using a DJI Mini Pro drone for specific beach research. In March 2024, drone flights were carried out at 80 and 50 m altitudes, obtaining a spatial resolution of < 3 cm in the visible range. The images were taken on the Limens, Santa Marta, Vao, Fontaiña and Fechiño beaches. EO data provide the map beach morphology and better identify rock outcrops, dykes, faults and lineaments, and delineation of modern placer boundaries.

3.5 Restrictive Areas

This level of information includes the on- and off-shore areas with access restrictions, areas of local interest, economic activities, environmental conservation, and those related to navigation and port activities of the Vigo Estuary (Figure 2).

4 RESULTS

4.1 Thiessen Polygons and Heavy Mineral Occurrences

In the Vigo Estuary, 602 information points from the FOMAR project (223 from the beach and 379 from the shallow water) have been identified, obtaining 379 Thiessen polygons on the shallow platform, maintaining the same semi-quantitative values of heavy mineral concentration (garnet, ilmenite, zircon, monazite and xenotime; Figure 3).

On the beach, occurrences of garnet of Class 4 (>50 g) are predominant compared to Class 3 (5-50 g, Figure 3). These are found in the middle-outer part of the estuary. Ilmenite (brown lines in Figure 3) are mainly associated with the same points where Class 4 (>50 g) garnets are located, except for the middle part of the estuary (E of Cangas), where there is an occurrence of ilmenite and zircon, both of Class 3 (5-50 g). In addition, zircon with concentrations of Class 4 (>50 g) is only related to Class 4 samples of garnets and ilmenite on the Santa Marta (W of Cangas) and Vao-Fuchiños (SW of Vigo) beaches.

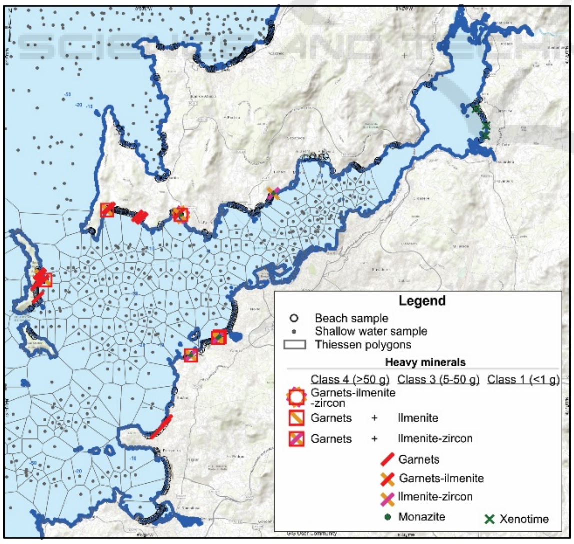

Figure 3. Thiessen polygons in shallow water and heavy mineral content classes 4 and 3.

To a lesser extent, there are also occurrences of REE minerals, such as monazite and xenotime. Monazite (green dots in Figure 3) is related to the Class 4 (>50 g) points described above, with abundant garnets, ilmenite and zircon (Santa Marta and Vao-Fuchiños). Monazite is also found to the E of Cangas, as well as ilmenite and zircon, all Class 3. Xenotime is only identified with Class 1 (<1 g) in 3 samples from the same Cesantes Beach, in the inner part of the estuary (green X in Figure 3). Also, on the beaches around the Cíes Islands, garnets and ilmenite predominate.

On the shallow platform, there are no concentrations of class 4 or 3 in the estuary, indicating that there are no areas of preferential concentration in these classes.

4.2 Regional Integrated Map

The geological environment of the Vigo Estuary is dominated by granites, where outcrops of orthogneisses, schists and amphibolites mainly alternate, and to a lesser extent, quartzites and para-gneisses. On the surrounding seabed, the rocky substrate and boulders continue from the middle to the outer part of the estuary, including the Cíes Islands. The interior of the estuary has a finer sediment (mud) that changes to mixed mainly. The other grain size transitions of the seabed appear more isolated towards the outside of the estuary. The faults and lineaments on land are generally NW-SE, NNW-SSE and NE-SW (Figure 4).

Mineral resources onshore are reported as indications of hematite (Fe, Mn, Ti) and feldspar (industrial mineral) in the inner part of the estuary around Redondela. There are several active and, to a lesser extent, abandoned exploitations of ornamental rocks (mainly granites). In addition, there are three zones with minerals hosted in rocks, pegmatites or dikes and one zone of marine placer occurrences. These last ones have identified garnets, ilmenite, zircon, monazite and xenotime, and other heavy minerals on the beach. As we have seen before in 4.1, these heavy minerals are less abundant on the shallow platform.

The areas of human activity and current restrictive areas have helped us to better plan our field trips and explore the occurrences of marine placers, previously identified in the 70s. Some areas of the estuary are no longer accessible due to the creation of new restricted areas.

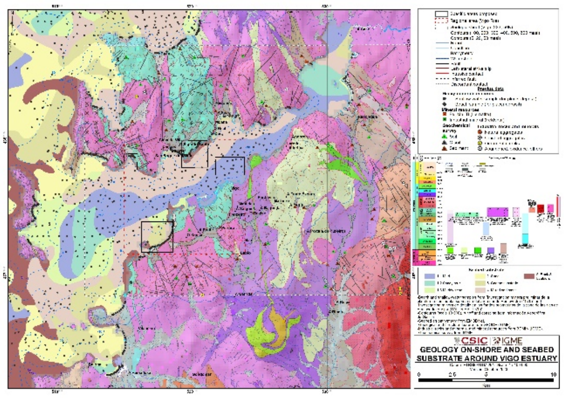

Figure 4. Integrated cartography for placer deposit exploration in Vigo Estuary, NW Spain.

4.3 Validation: Local Pilots' Exploration

With the information from 4.2 and the flowchart in Figure 2, we proceeded to schedule different local reconnaissance activities to validate the methodology, starting with an initial visit to confirm the presence of marine placers on beaches. Upon finding evidence of heavy minerals, we scheduled subsequent exploration activities to delve deeper into the study of marine placers, mainly on the Santa Marta and Vao beaches. For example, we carried out: detailed mapping using PNOA and UAV flights (for outcrops, beach extensions and areas with placers, Figure 5), identification of faults and dikes (in the field and with PNOA and UAV images), analysis of intertidal variation, pits to observe heavy minerals in depth, ground-penetrating radar exploration, among others.

Figure 5. Cartography from the UAV survey showing placer mineral (red polygons) in coastal areas of Santa Marta Beach (Ng-Cutipa et al., 2024).

The campaigns in different seasons have allowed to identify the variation of heavy mineral concentrations and the variation of small streams that contribute to the supply of these minerals from the onshore. The important role of tides in the redistribution and deposition of placers has also been observed. Likewise, in some areas, such as Vao, wind action plays an important role in accumulating heavy minerals at the base of the dune face where the wind has action (Figure 6).

Figure 6. Accumulation of reddish heavy minerals on the base of the coastal dune at Vao Beach, Vigo Estuary (November 2024).

Sand samples have also been taken from different beaches and shallow water, with and without placers, to conduct chemical and mineralogical analyses, and reflectance measurements for their correlation and use in multi- and hyperspectral images.

5 DISCUSSIONS AND CONCLUSIONS

Thiessen polygons offer a primary spatial distribution of occurrence of heavy mineral in shallow-water, that were perfomed using semiquantitative data. Placer occurrence on beach show greater accumulation than shallow-water areas using the same semi-quantitative data.

Regarding to regional integration map, the exploration of marine placer deposits, as evidenced by Van Gosen et al. (2014) and Hou et al. (2017), highlights the importance of collecting and analysing different previous information. These depend on the state of advancement of the region and on the knowledge desired to acquire about marine placer deposits. With this, it is possible to propose complementary studies at the regional level and others to deepen research at the local level of these placer occurrences. On the other hand, existing geological maps at a scale of 1:50,000 offer a great approximation to select areas of greater interest to explore these deposits. It is true that, in the case of

NW Spain, the occurrences of marine placers of FOMAR (IGME, 1976 and 1979) and the occurrences of heavy minerals previously identified in the MAGNA project carried out by IGME (https://info.igme.es/cartografiadigital/geologica/Magna50.aspx) have facilitated the visualization of the aforementioned areas of interest.

Due to the same difficulty of access and nature of each area, geological maps and information are more detailed and updated on-shore than off-shore.

In the local pilots, UAVs offer a high spatial resolution image where surface placers have been identified around the shoreline. This survey depends on the season and the stage of development of the ephemeral drainages. It is very likely that the large exposure of surface placers is mainly due to the large drainage combined with wave and tidal action.

This work highlights the importance of 1) integrating on- and off-shore information and the intertidal zone, and 2) knowing the characteristics of marine placer occurrences in NW Spain, providing very good results. They have also allowed for the increase of knowledge of the coastal "white band" (land-sea transition). Similarly, EO surveys offer a cheap, easy and non-invasive tool that can be better applied to inaccessible areas, allowing for sustainable resource exploration and coastal management. Finally, in these last 2 years, improvements have been developed in the knowledge of placers at the local level that include integrated and improved geological mapping, new geochemical and mineralogical data of marine placers, and EO applications and development of algorithms for images of different satellites (Sentinel 2, WorldView, EnMap, others).

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