ELSEVIER

Marine Geology 220 (2005) 153–179

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

# Quaternary evolution of the Ría de Vigo, Spain

Ana García-García [a,*,1], Soledad García-Gil [b], Federico Vilas [b]

[a] *Earth Sciences Department, University of California Santa Cruz, CA 95064, USA*
[b] *Department Geociencias Marinas, Universidad de Vigo. E-36200 Vigo, Spain*

Received 19 July 2004; received in revised form 19 April 2005; accepted 20 June 2005

**Abstract**

The seismic analysis of the sedimentary infill of the Ría de Vigo reveals that the infill comprises of a fifth order sequence (18 ky) bounded by a major discontinuity surface. Within the Holocene sequence, several seismic units have been identified; the oldest one originated after the Würm glaciation and the origin of its top discontinuity was eroded during the regression (sea level at −120 m) of this last glacial episode (isotopic stages 2 to 4), 18 ky B.P.

In some places below this ría infill, another sequence can be identified. This older sequence is associated with the pre-existing faults and troughs in the deepest parts of the ría, and it was deposited during the Würm glaciation (Miocene–Pleistocene). Eroded sediments were moved from the rías area to deeper zones, where they accumulated in the lowstand system tract. The next sea level rise occured in two steps, producing two transgressive units separated by an hiatus surface. This cycle was interrupted by the next sea level fall (to −55 m) marked on the seismic records by another recognizable boundary. The next sea level rise took place in several steps (back-stepping) with some stillstands, generating another transgressive system tract in the ría. From that time on, the relative sea level continued rising, depositing the most recent unit which represents the highstand system tract. Separating the highstand system tract and the transgresive unit below there is a consensed section.

The analysis of 29 cores provides groundtruthing for our hypothesis. The identified main lithologic units show a transgressive sequence: a granitic rock base, an overlying second unit-locally wedge shaped- and most recently, a marine muddy unit covering the present ría seafloor.
© 2005 Elsevier B.V. All rights reserved.

*Keywords:* high-resolution seismic analysis; marine transgression; Quaternary; Ría de Vigo; Galicia

## 1. Introduction

The term “ría” has historically been considered as a type of estuary, however, in many cases, only a minor part is influenced by estuarine processes (Evans and Prego, 2003; Vilas, 2000, 2002). The rías are efficient catch-basins for sediments. Sequences generated in the course of their sedimentary infilling contain evi-

* Corresponding author. Tel.: +1 8314623168; fax: +1 8316332684.
*E-mail addresses:* agarcia@es.ucsc.edu (A. García-García), sgil@uvigo.es (S. García-Gil), fvilas@uvigo.es (F. Vilas).
[1] Also at AOA Geophysics Inc., Marine Geoscience Division, 7532 Sandholdt Road, 2nd floor Moss Landing, CA 95039, USA.

0025-3227/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.margeo.2005.06.015

dence of the relative Holocene variations in sea level and of the climatic changes which occurred during the Pleistocene. Even though there are many published papers concerning the Galician rías, relatively few address their sedimentary infill (Acosta, 1984; Diz et al., 2002; García-García et al., 2004; García-Gil et al., 1999, 2000; Hernández-Molina et al., 1994; Margalef, 1956; Rey, 1993; Vilas, 2002).

In this paper we present a detailed study of the sedimentary infill of a ría for the first time. High-resolution seismic profiling systems have proved to be a perfect tool for that purpose. Direct cores in the area have provided the groundtruthing needed for our hypothesis. We will discuss the seismic stratigraphic record of this ría, and reconstruct the post-glacial (18,000 yr BP to the present day) story of its infilling.

## 2. Study area: Ría de Vigo

The Ría de Vigo (Fig. 1a) is located on the passive Atlantic margin of southwestern Galicia (NW Spain), the ría coast known as Rías Baixas. The Ría de Vigo's physiography presents a distinctive funnel shape, with an areal extent of 176.4 km$^2$. As shown on the geological map (Fig. 1b), it trends at nearly right angles to the region's Paleozoic basement structure which comprises Paleozoic metamorphic and granite rocks cut by NE–SW, NW–SE and N–S trending faults. The entire ría coast is possibly related to the post-Pyrenean extensional phase, which occurred during both the Oligocene and Miocene (García-Gil et al., 1999). Deformation during the Neogene along the southern side of the Iberian Plate propagated along its western margin and reactivated Paleozoic, Mesozoic and Paleogene structures as far north as the Galicia margin (Muñoz et al., 2003). Present-day seismic activity suggests that reactivation of the older structures is still taking place today.

The water depths within the ría range from 7 m in its inner part, to 53 m at the outer (southwest) entrance to the sea (Fig. 2a). Its north entrance is shallow, with a maximum depth of 30 m, although the southern one is somewhat deeper, 55 m. Transverse profiles show the differences in relief across the ría seafloor (at two entrances) (Fig. 2a).

The presence of a central channel is shown graphically in the Digital Terrain Model reconstruction

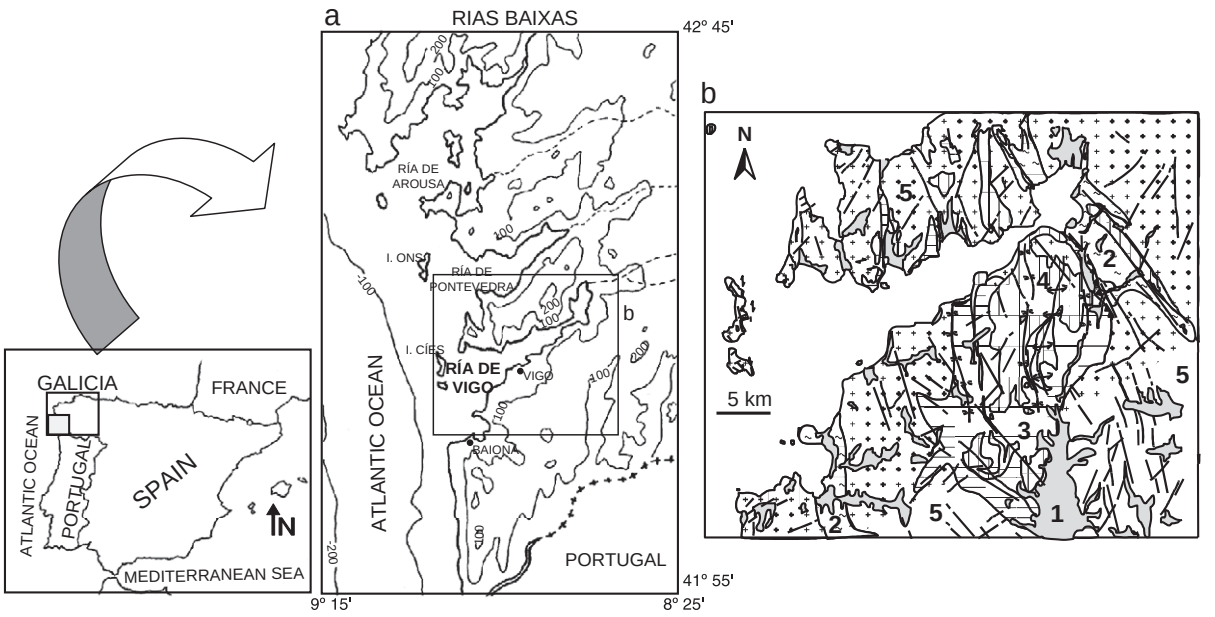



Fig. 1. (a) Geographical setting of the Rías Baixas and survey area in Ría de Vigo; (b) geological map of the ría: (1) Quaternary sediments, (2) metasediments, (3) paragneis, (4) orthogneis, and (5) granites. Continuous lines represent mechanical contacts, and dashed lines represent faults, anticlines and synclines. Modified from Rubio et al., 1981.

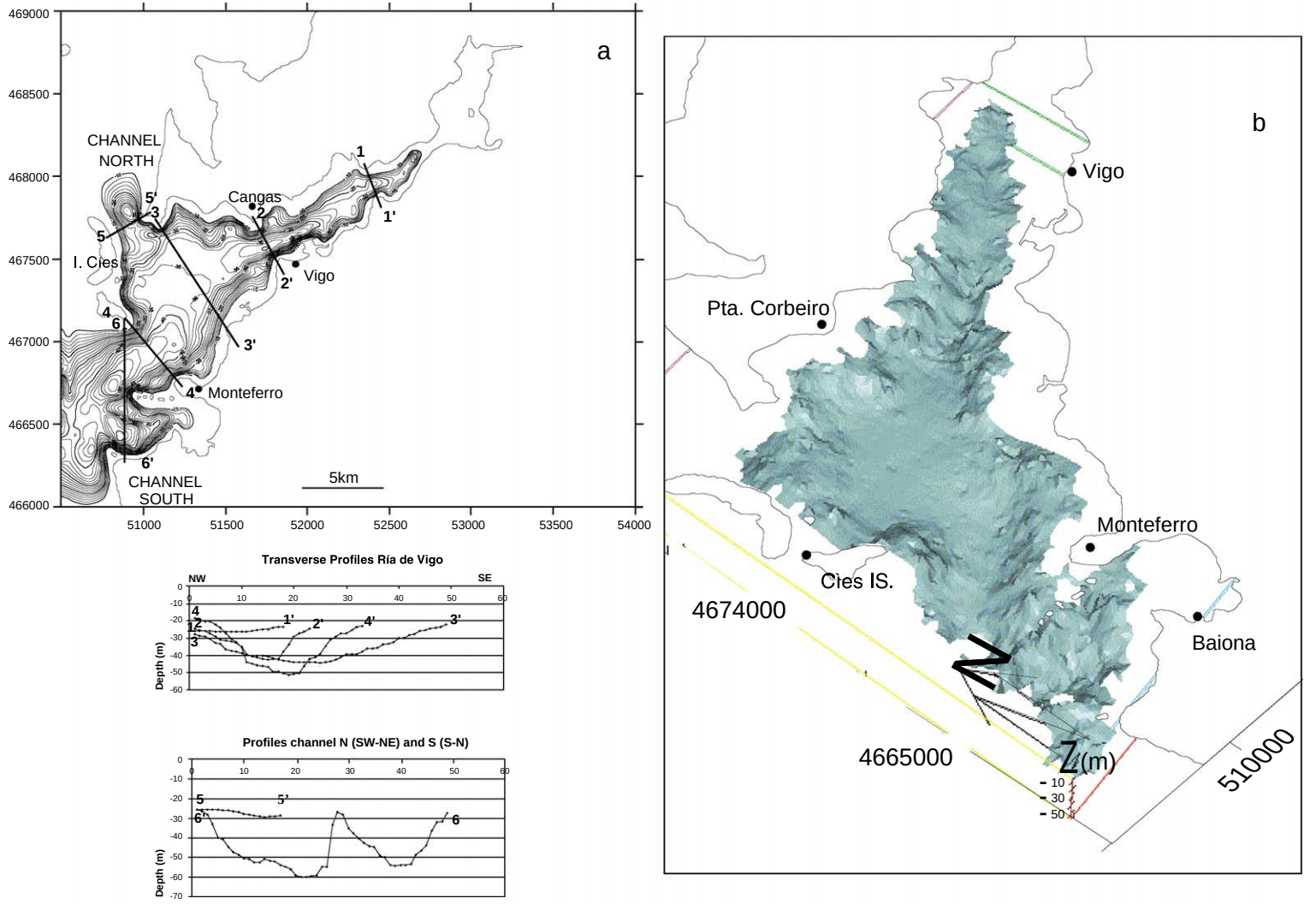



Fig. 2. (a) Map showing the bathymetry of the Ría de Vigo with contours at 2 m intervals. The inner part presents a central channel, where it attains its maximum depth. In the southern entrance, bathymetry is deepest. Notice the transversal profiles across the axis and in the entrances; (b) 3-D digital terrain model reconstruction for the present ría seafloor, with a grid of 200 × 200 m.

(Fig. 2b). From the main axis towards the coast, the depth decreases until the outcrops of basement appear near the coastline. The seafloor in the NE part has the most abrupt relief in the ría, whilst the central part is wider and flatter.

The grain-size distribution on the present seafloor consists of mixed siliciclastic and skeletal gravels in both the outer area and the edges of the ría, whereas the central and inner parts of the ría are dominated by clay and silt, which have an organic matter content as high as 10% (Vilas et al., 1995).

## 3. Methodology

A first seismic survey was performed during the summer of 1991. A total of 640 km of seismic lines were acquired aboard *R/V* "*El Investigador*" on a rectangular grid with lines spaced 66 (N–S) – 550 (E–W) m apart (Fig. 3a). A second survey was performed six years later, during the summer of 1997, aboard *R/V* "*Francisco de Paula Navarro*". A total of 67 km of seismic lines with a layout of lines NW–SE and NE–SW were acquired (Fig. 3a). Our seismic data were provided by a high-resolution single channel reflection profiler (EG and G Uniboom Catamaran 230 Model) operating at 300 Joules and a high-resolution seismic 1036 model ORE (3.5 kHz) sub-bottom profiler. For the conversion to meters, the following average internal velocities were applied to calculate depths within the study area: 1500 m/s for the sub-bottom profiler records, and 1550 m/s for the Uniboom records. Also, a side-scan sonar (Klein Model 595 operating at 100 kHz on 3 channels with a 150 m scan on each channel) and an Atlas Deso 20 echosounder (33–210 kHz) were employed. For navigation and position fixing, we used a Trimble 4000 RL Differential GPS station, combined with a transponder unit.

Besides the bathymetric mapping of the area, a digital model of the terrain has been created (Fig. 2b), using the Ibergis processing data (Muñoz et al., 1997). In that processing IRAP-Cfloor (Smedvig, Co.) was used to represent and map bathymetries.

Twenty nine continuous cores with an average length of 9 m were provided by the Spanish Autoridad Portuaria in the eastern coastal area (Fig. 3b). A detailed study of the sedimentologic information and the analysis of the correlated facies will give some new information about the infilling sediments in this area.

## 4. Results—seismic analysis of the Ría de Vigo

The seismic analysis comprises a detailed study of reflection terminations and reflection configurations which has been used for identification of seismic units and their boundaries (Mitchum et al., 1977; Vail et al., 1977; Posamentier et al., 1988; Vail et al., 1991).

As shown in Fig. 4, several seismic units can be distinguished on the Uniboom seismic records. After a detailed seismic analysis, we have named – from bottom to top – the identified discontinuities as: p, $L_2$, $h_2$, $L_3$ and $h_3$. Therefore we have considered seismic units U1 to U6 as the infill of this ría (Fig. 4).

### 4.1. Acoustic basement (U1) and discontinuity p

From a chronostratigraphic standpoint, the first detectable seismic discontinuity is "p" (see Fig. 4). This discontinuity is the top of the acoustic basement or unit U1, which in places can pinch out the record, but elsewhere cannot be distinguished clearly due to the limited seismic system penetration (less than 100 m in the Uniboom EG and G system).

Taking into account the seismic analysis of unit U1 (see Fig. 4), two different types of facies can be distinguished in the acoustic basement, both without internal continuity (U1, U2; Fig. 5). Type 1 facies shows abrupt topographies, and it has commonly convex, hyperbolic outcropping facies, with chaotic and discontinuous internal reflections (Fig. 5b). Type 2 facies has a smoother profile and a continuous and reflective top (Fig. 5c). Also, it has sub horizontal reflectors, locally continuous, with a smooth top, and it passes laterally into type 1 facies. This change in facies is always a faulted boundary.

A distribution map for the different types of basement has been done (Fig. 5a) and completed with the data from the nautical charts (Instituto Hidrográfico de la Marina, 1996a,b; charts 416B

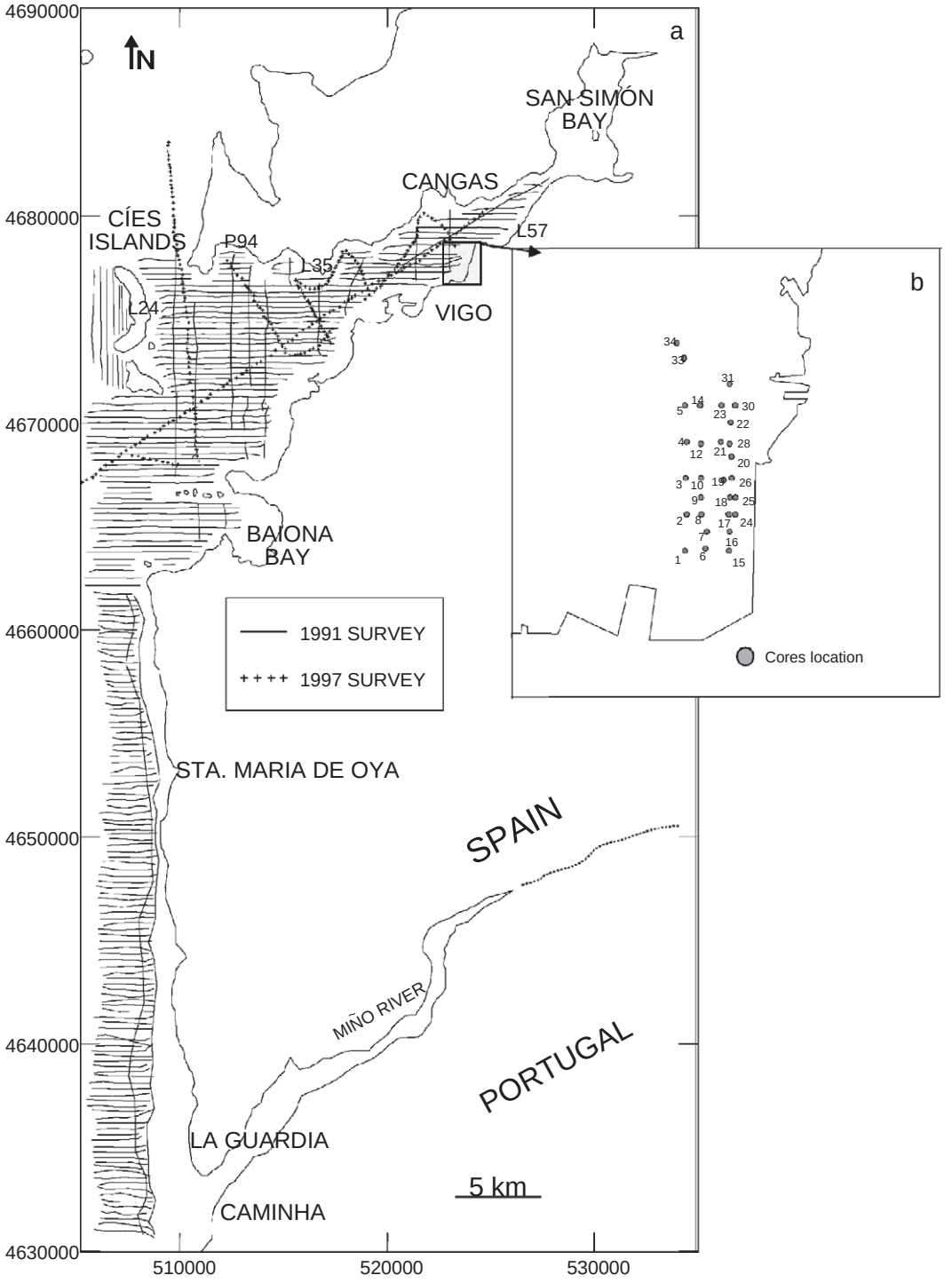



Fig. 3. a) Map of the 1991 and 1997 surveys tracklines in the area, with Fig. locations represented as dark lines in the seismic survey; b) core sites location.

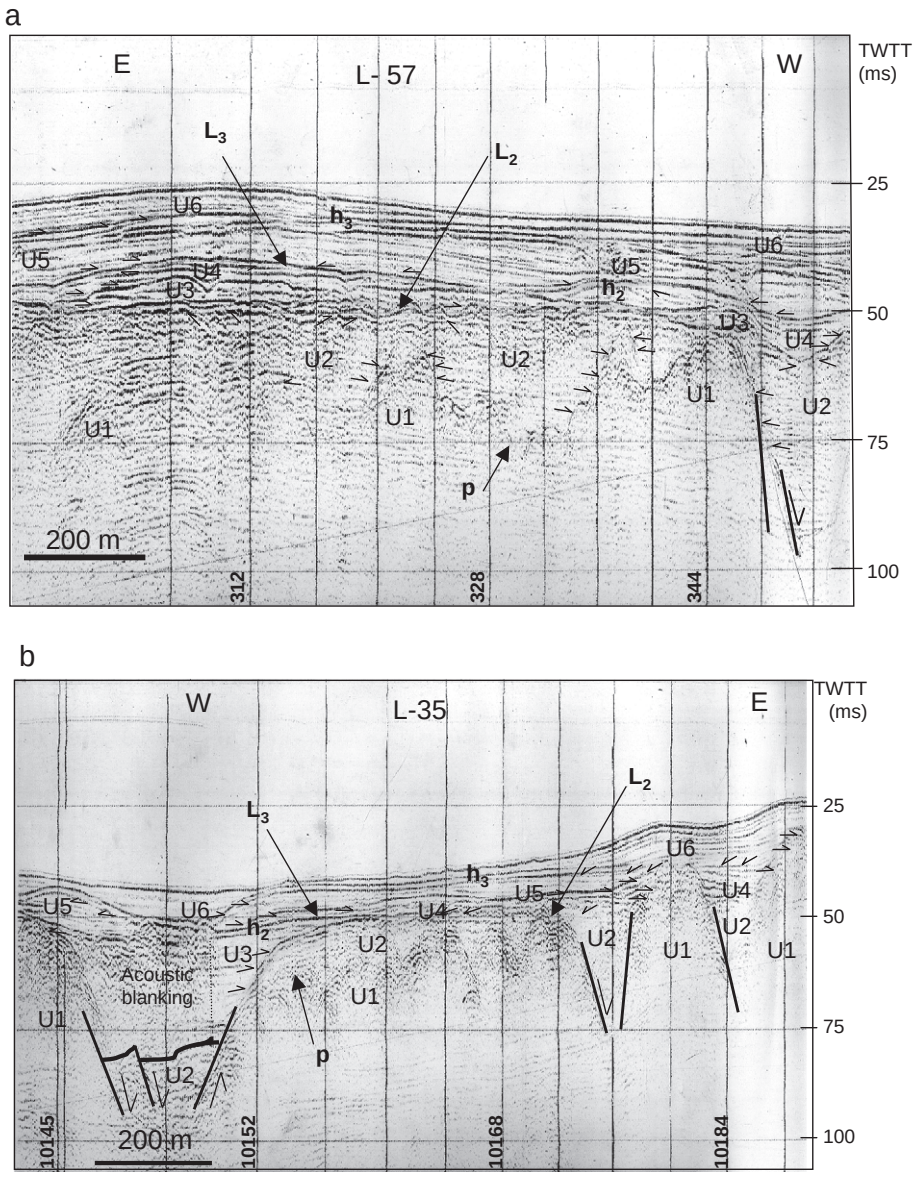



Fig. 4. a) Interpreted Uniboom seismic record (L 57); b) Interpreted Uniboom seismic record (L 35). See Fig. 3 for seismic lines location.

and 924 respectively). Considering the 176.4 km$^2$ entire surface area of the Ría de Vigo and excluding from this the 40 km$^2$ corresponding to the inner San Simón Bay (Fig. 3a) where seismic profiles are not available, acoustic basement type 1 in the 136.4 km$^2$ surveyed area represent 35.2% of the whole area (48 km$^2$) and type 2, which occupies 21 km$^2$, represents 15.4%. This means that a total of 50.6% of the surveyed ría (69 km$^2$) shows some kind of basement. The rest of the area has acoustic basement below the depth to which the utilized system can penetrate. In the southern neighbor coast, north of the river Miño mouth (see Fig. 3a), type 1 basement outcrops on all the seafloor.

This ría basement can crop out or be buried in the sedimentary record. Basement outcrops occur princi-

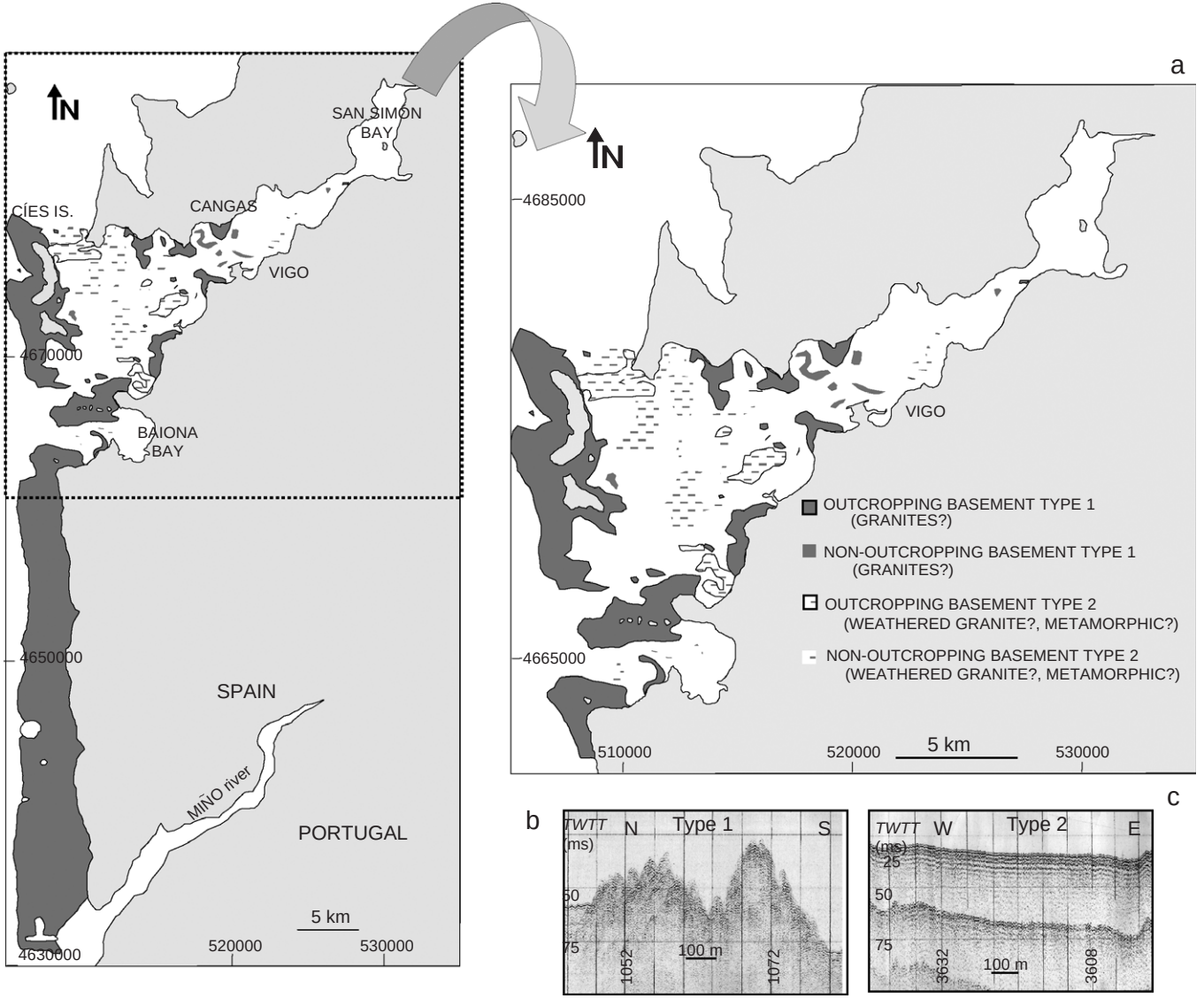



Fig. 5. a) Acoustic basement distribution in the surveyed area and mapping of the different acoustic basement facies types; b) Type 1 basement facies showing abrupt topography; c) Type 2 basement facies with a smooth profile.

pally in the shallower areas of the Ría de Vigo, continuing the outcrops onland, and in all the surveyed area between the ría mouth and the Portuguese coast to the south (Fig. 5). The buried basement appears below the sedimentary infill and mainly in the central parts of the ría (Fig. 5a).

The top of unit U1 is a very erosive and irregular limit (Fig. 4). The mapping of this surface-taking as a *datum* the present sea level-shows a sharp palaeorelief in the ría (Fig. 6a), sometimes limited by the penetration of the Uniboom source. Its deepest parts are located in the central axis, towards the south-western area. Also, in the inner part, some relative highs and lows can be distinguished.

### 4.2. Seismic unit U2 and discontinuity $L_2$

Above palaeorelief (p) several seismic units have been distinguished as forming the ría infill. The first unit is seismic unit U2, interpreted as the first sedimentary unit, although it could sometimes be a deposit of alteration of the basement (see Fig. 4). The next stratigraphic event is the top of U2 ($L_2$) which corresponds to a very erosive and irregular discontinuity.

Seismic unit 2 is apparently the first infill of the area with a lower contact that is very erosive and irregular (Fig. 4). Its internal reflectors onlap against this basal surface (p) and/or against the faults that are controlling the extent of that unit. It also shows erosive truncation on its top, against surface $L_2$. Internally, its reflectors sometimes show continuity and others are transparent.

In the northern Ría de Pontevedra (see Fig. 1a), García-Gil et al. (1999) defined an old sequence, S1, that could correlate to this first seismic deposit U2. These authors describe that sequence as folded continuous reflectors, with an erosive truncation on its top.

In Fig. 6b the isopach map of U2 is shown. This first sedimentary unit only occurs in the central axis, mainly filling the lowest areas of the ría. This unit appears with two depocenters, one near Cíes Islands, and another elongate one in the inner part of the Ría de Vigo. Both reach 30 ms (TWTT) deep. In between, some thresholds occur, with little or no sediment. This seismic unit appears also in front of Monteferro, in the south coast, reaching a thickness of 6 ms (TWTT). The sedimentary thickness of U2 diminishes significantly with distance from the depocenters.

Comparing the isopach and isochron maps (Fig. 6a and b), the two depocenters coincide with the deepest palaeorelief (p).

### 4.3. Seismic unit U3 and discontinuity $h_2$

Above seismic unit U2, or directly over the basement, lies seismic unit U3, locally conformable with the acoustic basement on the seismic records. Its very erosive bottom, $L_2$, corresponds to the top of U2. In Fig. 7a the palaeorelief $L_2$ is mapped. Its deepest part coincides with the present main channel of the ría.

Seismic unit U3 locally deposits over seismic unit U2 or directly over the basement (Fig. 4). Its internal reflectors are irregular, sometimes sub-parallel and sometimes chaotic, without any lateral continuity. Also, the reflectors onlap against basal surface $L_2$ and/or against the basement towards the limits of the sedimentary basin (see Fig. 4).

Generally, this unit is thin (see Fig. 7b) and it is located in the central parts of the ría, on its main axis, with a depocenter of 10 ms (TWTT) in front of Toralla Island. The biggest depocenters though, appear in the center-west of the ría and on the river Miño mouth, with 22 ms (TWTT) (Fig. 7b, inset). Inside the ría, the depocenter coincides with the lowest positions of the surface $L_2$ (see Fig. 7a and b).

Above seismic unit U3, seismic unit U4 occurs. Its bottom $h_2$ (top of the previous unit U3), and its top $L_3$, are quite both irregular (see Fig. 4). The isobath map of $h_2$ (Fig. 8a) shows it to be deeper than 60 m depths in the external zone, near Monteferro. The irregular and erosive top of seismic unit U4 appears enhanced on the records.

### 4.4. Seismic unit U4 and discontinuity $L_3$

Seismic unit U4 is more laterally continuous and thicker than the previous one. Its main characteristic is the presence of multiple palaeochannels, normally with an asymmetric infill, with onlapping reflectors against their erosive surface (Fig. 4). Internally subparallel and irregular reflectors onlap against the structural highs of the basement. There is downlap against the basal surface $L_2$ associated with these highs.

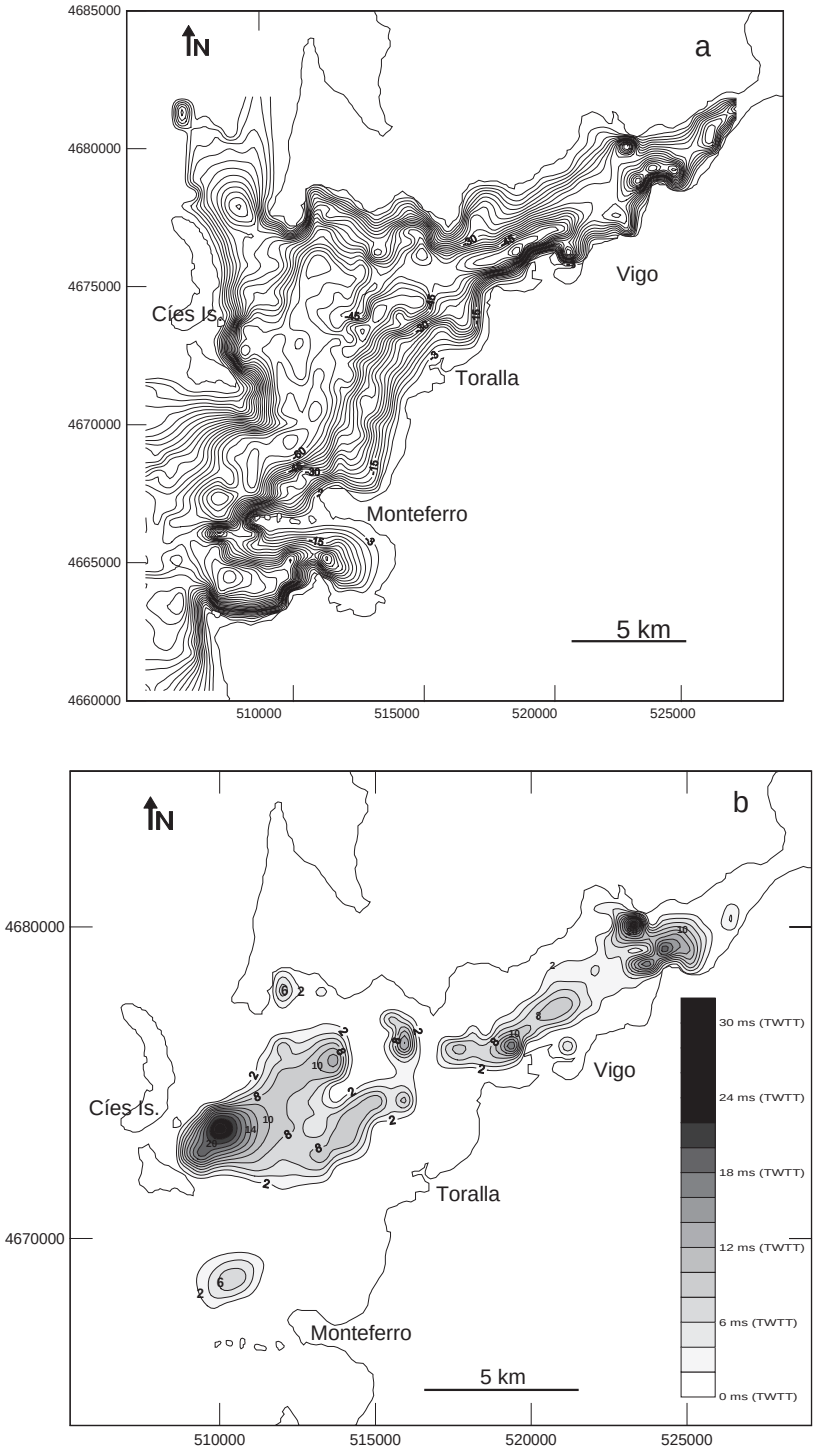



Fig. 6. a) Paleoisobaths of the erosive surface p, with isolines each 3 m and enhanced isobaths − 15, − 30, − 45 and − 60 m; b) contour mapping and location of seismic unit U2 (ms, TWTT). Isolines each 2 ms, and with solid line, 10 and 20 ms. Note the two depocenters (30 ms, TWTT).

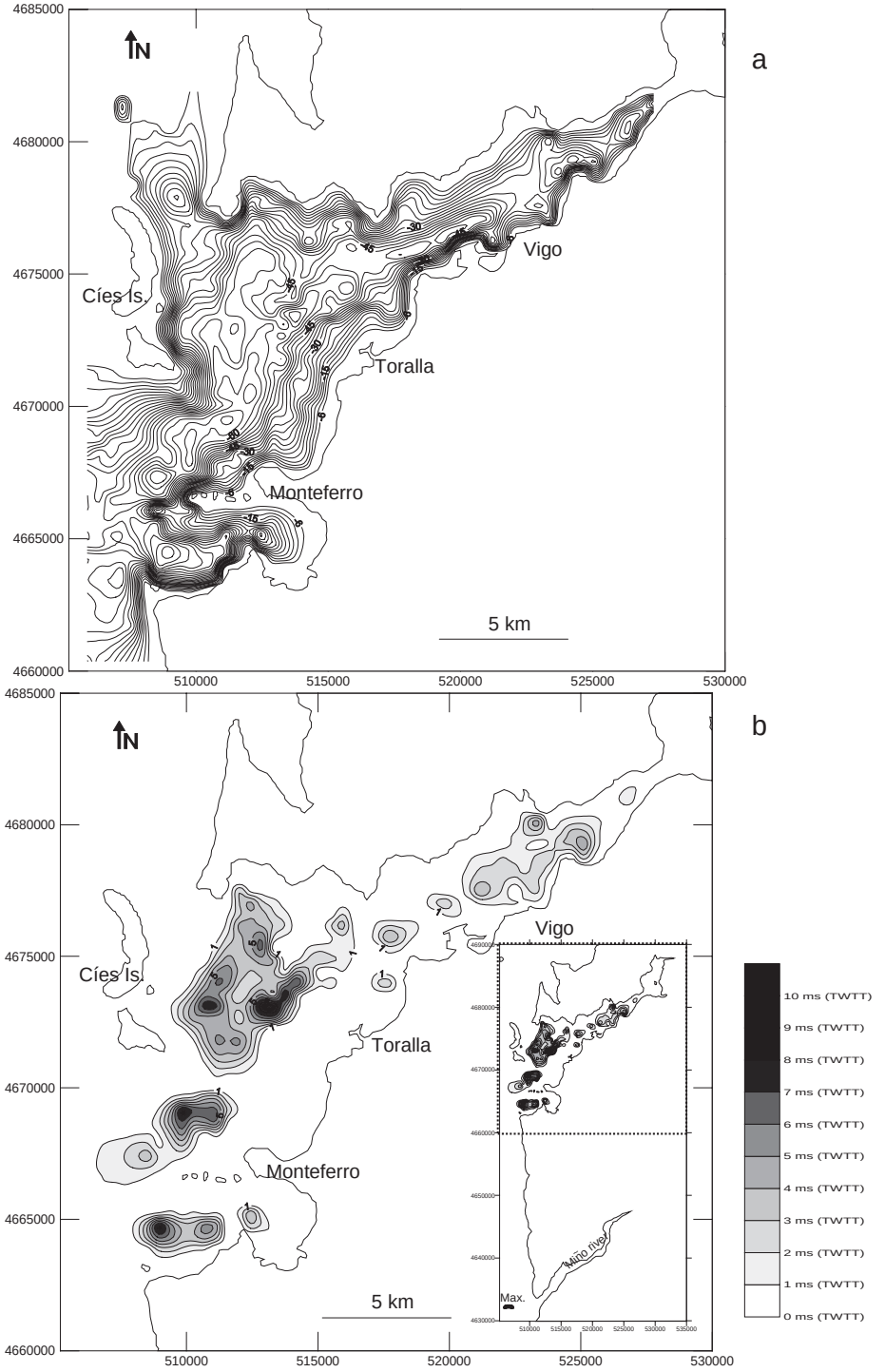



Fig. 7. a) Paleoisobaths of the erosive surface $L_2$, with isolines each m, y enhanced isobaths −15, −30, −45 and −60 m; b) contour mapping (ms, TWTT) and location of seismic unit U3. Isolines each 2 ms, and with solid line, 10 and 20 ms. Note the depocenter (10 ms, TWTT).

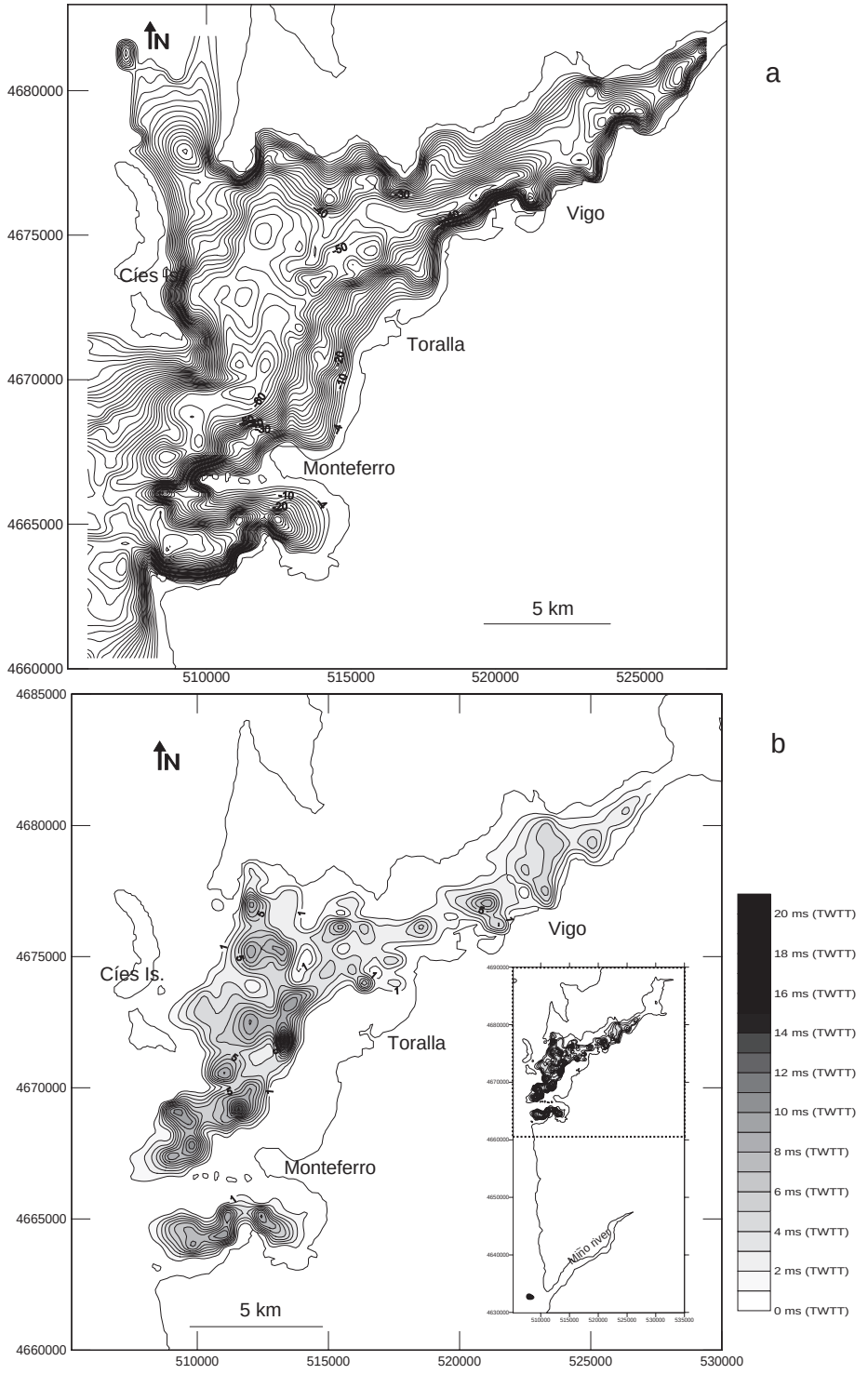



Fig. 8. a) Paleoisobaths of the erosive surface $h_2$, with isolines each m, and enhanced isobaths −15, −30, −45 and −60 m; b) contour mapping (ms, TWTT) and location of seismic unit U4. Isolines each 2 ms, and with solid line, 10 and 20 ms. Note the depocenter (20 ms, TWTT).

Unit U4 also shows ancient terrace levels and slumps near structural highs. Its isopach map (Fig. 8b) shows a depocenter in the west-central area, with 20 ms (TWTT). Towards the south, the unit U4 is only present in front of the river Miño mouth, with depths up to 4 ms (TWTT). This unit U4 is more regionally represented than the previous one, and appears practically over the whole ría area, but, in general, is very thin. Its depocenter coincides with the lowest locations of palaeorelief $h_2$ (Fig. 8a and b).

The top of this seismic unit U4 ($L_3$) constitutes the base for seismic unit U5 (Fig. 4). Surface $L_3$ is quite irregular, although its profile is smoother that of $L_2$. The isobath mapping (Fig. 9a) shows its maximum depths of −55 m in the central axis of the ría. The top ($h_3$) of unit U5 is sub-parallel (see Fig. 4), and it has a smooth stratigraphic discontinuity surface.

### 4.5. Seismic unit U5 and discontinuity $h_3$

The irregular base of U5 (see Fig. 4) shows onlap in the center of the basin and towards its limits. Its main characteristic is the occurrence of internal reflectors with large lateral continuity. Internally, the reflectors are parallel, sub-parallel, or even wavy.

U5 is a regionally extensive unit, and it only disappears towards the ría edges. This unit is affected by acoustic blankings and other types of inferred gas presence (García-García et al., 1999, 2003b; García-Gil et al., 2002). Also, it contains some terrace levels, slumpings and some progradational forms. These forms have internal reflectors which downlap against its base and onlap towards the edge.

The maximum depth of U5, up to 11 ms (TWTT), is located in the southeastern part of Cíes Islands (Fig. 9b). Along the southern coast, the depocenter is found in front of the river Miño mouth, with 4 ms (TWTT) as shown in Fig. 9b. This depocenter coincides spatially with a zone of maximum depth for palaeorelief $L_3$ (see Fig. 9a and b).

The limit between units U5 and U6 ($h_3$) is a sub-horizontal surface. This limit, the base of unit U6, shows its deepest depths in the external zone (Fig. 10a), with more than −55 m of depth.

### 4.6. Seismic unit U6

The base of seismic unit U6 onlaps towards the edges of the ría or relative highs (Fig. 4). Its top, which is practically sub horizontal, conforms to the present sea floor in the ría. Internally, the reflectors of U6 are parallel, horizontal to sub-horizontal.

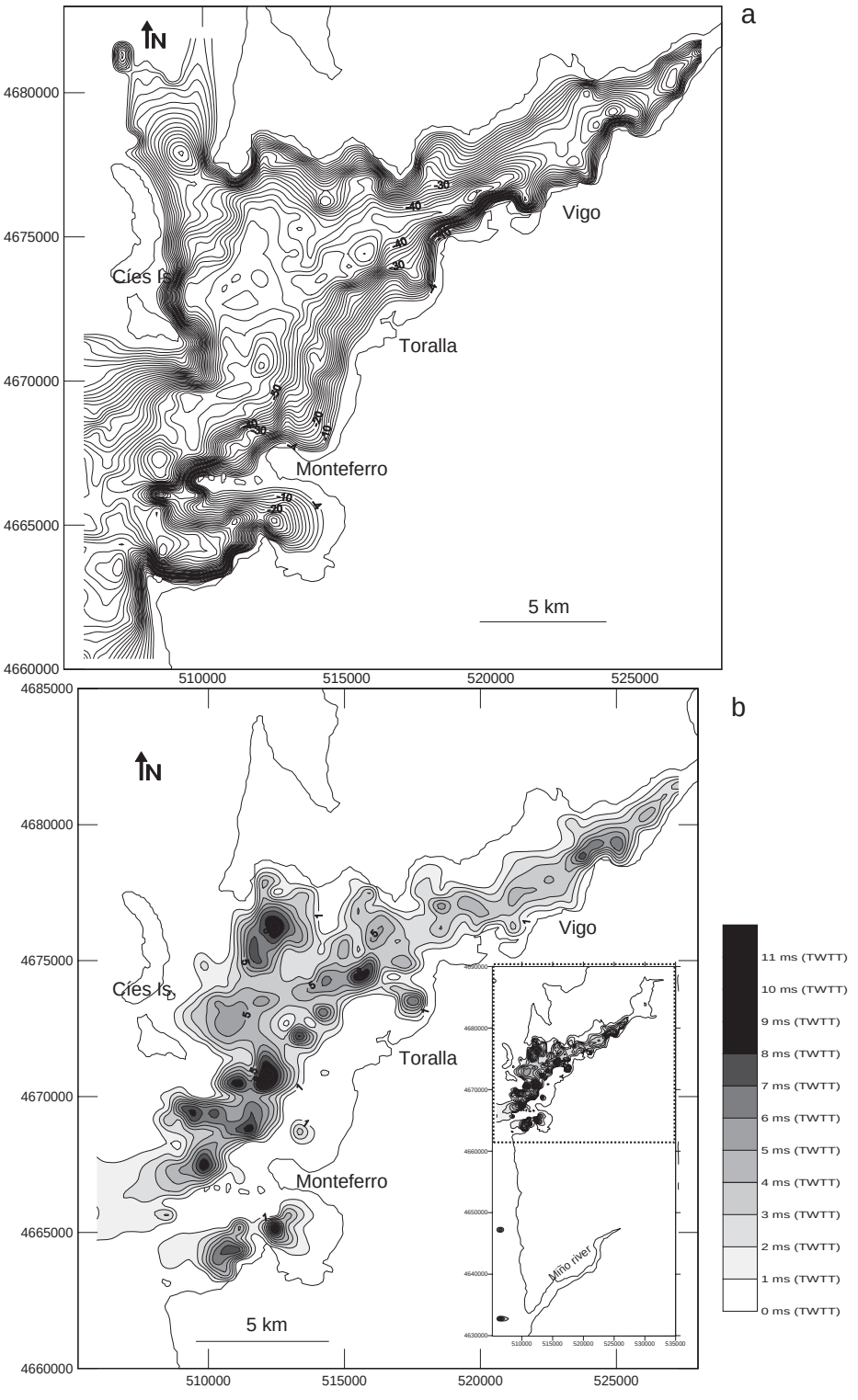
The depocenter for seismic unit U6 is about 23 ms (TWTT) in the southeastern part of Cíes Islands (see Fig. 10b), and in the southern coast, the depocenter is about 4 ms (TWTT).

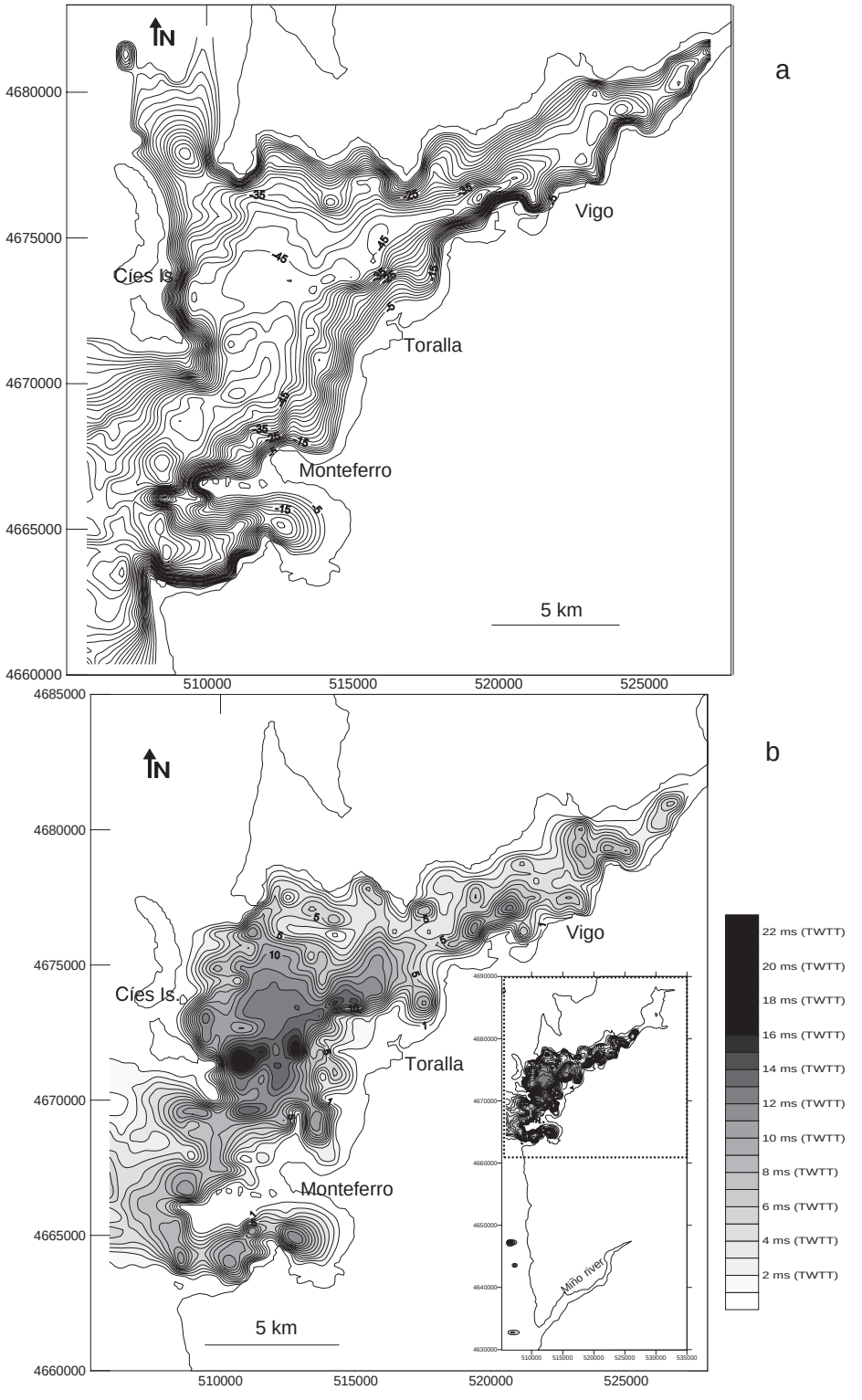
Being the most recent and expansive unit, it is also the more continuous one (Fig. 10b). It also creates the seal-unit for the acoustic blankings that occur in the ría (García-García et al., 1999, 2003b; García-Gil et al., 2002).

The most prominent prograding forms are localized within this unit (see Fig. 11). The mapping of those forms, as shown in Fig. 11a, illustrates that these forms mainly prograde towards the basin, within depths of 10–30 m, and downlap against the basal surface $h_3$ (Fig. 11b and c). Hernández-Molina et al. (2000) studied a progradational sedimentary body, the infralittoral prograding wedge (IPW), that developed from the mean fair-weather wave-base level to the storm wave-base level between the onshore (beach) and the offshore (inner continental shelf) depositional zones along the Spanish coast during the Late Holocene. The main sedimentary body is composed of large inclined master beds which prograde seawards parallel to the shoreline. The inclined beds downlap onto finer-grained offshore sediments and, in turn, are overlain by shoreface deposits. The prograding sedimentary forms shown in Fig. 11b and c resemble the IPW body. More specific work would be needed in order to prove that these forms are IPW bodies.

More information about the recent processes in this ría has been presented by García-García et al. (2004) where a detailed study of high-resolution (3.5 kHz) sub-bottom profiles reveals the presence of 17 different types of echo character (acoustic facies). By cor-

Fig. 9. a) Paleoisobaths of the erosive surface $L_3$, with isolines each m, and enhanced isobaths −15, −30, −45 and −60 m; b) contour mapping (ms, TWTT) and location of seismic unit U5. Isolines each 2 ms, and with solid line, 10 and 20 ms. Note the depocenter (11 ms, TWTT).


a
N
Vigo
Cíes Is.
Toralla
Monteferro
5 km
4680000
4675000
4670000
4665000
4660000
510000
515000
520000
525000
b
N
Vigo
Cíes Is.
Toralla
Monteferro
Miño river
5 km
4685000
4680000
4675000
4670000
4665000
4660000
510000
515000
520000
525000
11 ms (TWTT)
10 ms (TWTT)
9 ms (TWTT)
8 ms (TWTT)
7 ms (TWTT)
6 ms (TWTT)
5 ms (TWTT)
4 ms (TWTT)
3 ms (TWTT)
2 ms (TWTT)
1 ms (TWTT)
0 ms (TWTT)


a
N
Vigo
Cíes Is.
Toralla
Monteferro
5 km
4680000
4675000
4670000
4665000
4660000
510000
515000
520000
525000
b
N
Vigo
Cíes Is.
Toralla
Monteferro
5 km
Miño river
22 ms (TWTT)
20 ms (TWTT)
18 ms (TWTT)
16 ms (TWTT)
14 ms (TWTT)
12 ms (TWTT)
10 ms (TWTT)
8 ms (TWTT)
6 ms (TWTT)
4 ms (TWTT)
2 ms (TWTT)

relating the echo-character with surface sediments, the authors were able to infer the recent sediment dynamics in the ría seafloor, 60.5% being related to modern depositional processes. In the outer area, where wave activity is strong, erosive and high-energy depositional processes dominate, whereas in the protected area of the inner ría the majority of recent processes are low-energy depositional, progradational and/or a combination of both.

A compilation for the different seismic characteristics for the ría' seismic units is shown in Table 1.

## 5. Discussion

### 5.1. Sedimentological data

The study of the cores of the eastern coast (see Fig. 3b) and the seismic analysis allows us to correlate the sedimentological data to the seismic data (Fig. 12). The identified facies in the cores have been analyzed in detail and three main lithologic units have been distinguished. From bottom to top: Lithologic Unit 1, which is the granitic basement. It is the base of almost all cores in the Guixar area. The granite is frequently weathered.

Lithologic Unit 2 is mainly composed of siliciclastic facies (silty muds with sand, silty gravels, coarse sand). It has a variable thickness, with a maximum of 3 m in the area. It pinches out laterally in N–S direction and E–W. It only occurs locally in the central part of the survey area, with a clear wedged-shape.

Lithologic Unit 3 has mixed facies (carbonates and siliciclastics) composed by a lower bioclastic sand member and an upper member of muds with some bioclasts. It is an expansive unit above the previous one, with a thickness that varies between 3.2 m maximum and 0.8 m minimum.

After the detailed analysis of each core, multiple sedimentary correlations were done to ascertain the shape of those sedimentary layers (Fig. 12a). In particular, a specific analysis was done for the lithologic Unit 2. Its wedged-shape was confirmed in the area with 3 m of maximum depth (García-García et al., 2003a). The main source for those coarse sediments would come from inland just in front of that sedimentary body.

Our findings corroborate the study of a 10 m-core in that same area (core '3') and some others nearby (cores 'J3' and 'J2') done by Margalef (1956, 1959). In particular, the author finds a similar sequence in all the core sites. This information has been, in turn, correlated with our seismic profile data (Fig. 13).

After identifying the sedimentary data (cores) with the seismic information-Uniboom and sub-bottom profiler lines-(see Fig. 12b), three different lithoseismic facies can be distinguished. The first one, on the bottom, would be the basement (granite). The facies association analysis of unit 2 as well as its wedge-shaped geometry point out that this sedimentary body corresponds to siliciclastic sediments of an aluvial fan with its source somewhere on the eastern inland. The third one (mainly bioclasts and muds) would correspond to the marine sediments of the lithologic unit 3. This most recent unit has been identified in all the coring sites. It corresponds to the muddy sediments that cover the present ría seafloor, with an average thickness of 2 m in the area. Its facies association indicates a marine environment with two different types of facies (seismic units U6 and U5).

The analysis of the available cores gives new information about the type of sediments within the ría deep infilling and also, about the depositional environment. It also shows the correlation between the sedimentological and the seismic data. The identification of three lithologic units indicate: the base as granitic rock, an overlying second unit, locally wedged-shape, composed of siliciclastic facies and finally, a marine muddy unit covering the ría seafloor, showing a clear transgressive sequence.

### 5.2. Available datations and environmental framework

There are two main available sources of information about $^{14}C$ ages in the area. Margalef (1956) found fluvial sediments of at least 37000 yr BP (sea Fig. 13b). The vibrocore datation in the central part of the

Fig. 10. a) Paleoisobaths of the erosive surface $h_3$, with isolines each m, and enhanced isobaths −15, −30, −45 and −60 m. Contour mapping (ms, TWTT) and location of seismic unit U6 (b). Isolines each 2 ms, and with solid line, 10 and 20 ms. Note the depocenter (22 ms, TWTT).

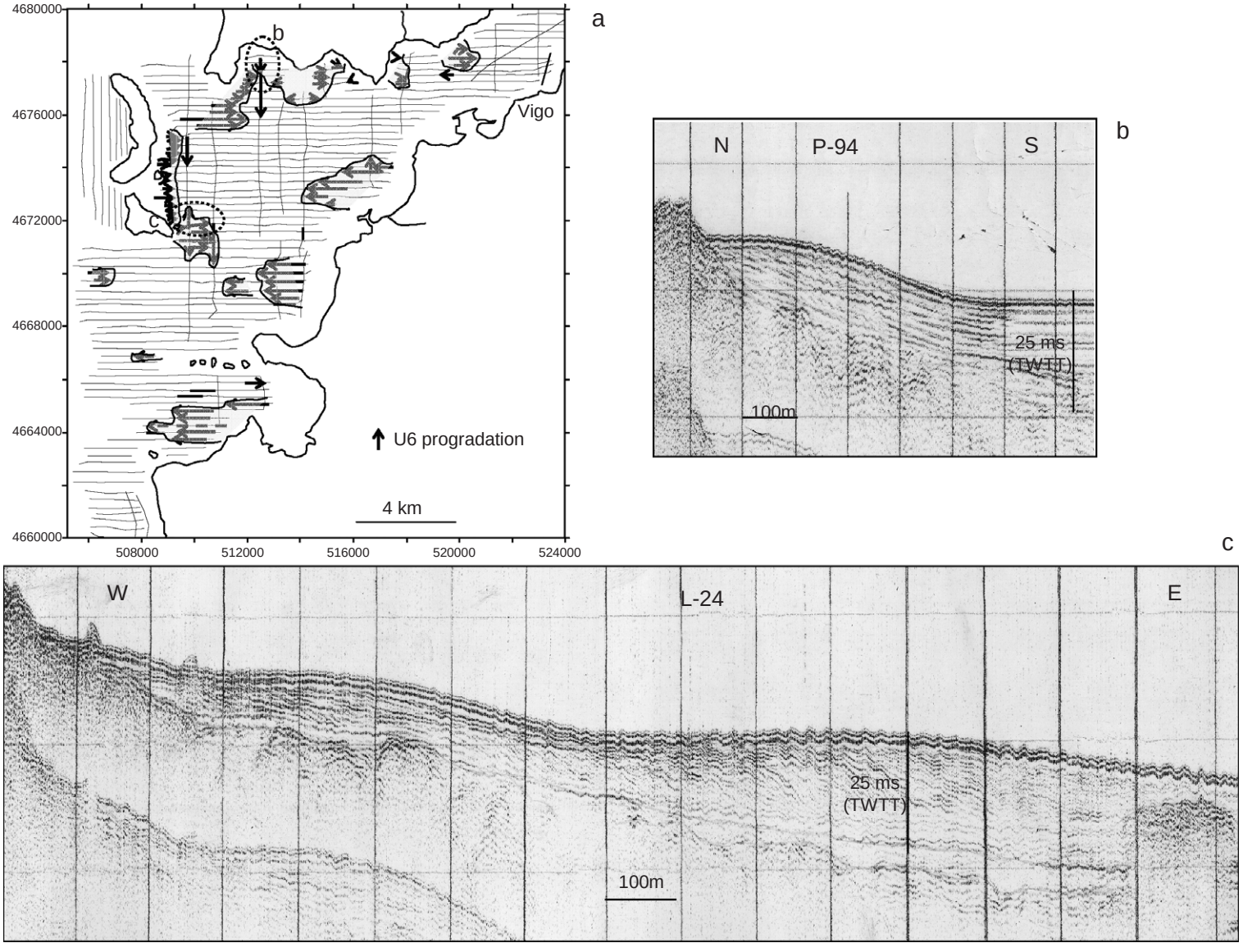



Fig. 11. a) Mapping of the progradational sedimentary bodies found in the most recent unit (U6) in the ría; b) and c) Uniboom examples of those bodies in the ría, P-94 (N-S) and L-24 (W–E) respectively. See Fig. 3 for seismic lines location.

Table 1
Seismic facies, seismic characteristics and description of seismic units in Ría de Vigo

| Seismic units | Seismic facies | Location | Thickness -Average/Max.- (ms, TWTT) | Areal extension ($m^2$) (*) | Estimated volume ($m^3$) (*) |
|---|---|---|---|---|---|
| Unit U6 | Sub-parallel reflectors. Agradding configuration | Central ría | 6.4/22 | $2.9x10^9$ | $3.1x10^9$ |
| | Acoustic blanking. chaotic | Most of ría (axis) | | | |
| | Downlap. Prograding configuration | Relative highs. Bottom of sedimentary forms | | | |
| | Onlap | Over outcropping basement. Basin borders | | | |
| Unit U5 | Erosive truncation | Top of unit | 3.6/15 | $2.3x10^8$ | $2.2x10^8$ |
| | Basal concordance | Central ría | | | |
| | Chaotic. Collapse structures and acoustic blanking | Shallow ría | | | |
| | Onlap | Over outcropping basement. Depression infills | | | |
| | Downlap. Prograding configuration. Back-stepping | Basin border | | | |
| Unit U4 | Erosive truncation Channels infilling/ incision | Top of seismic unit | 2.7/20 | $2.3x10^8$ | $1.7x10^8$ |
| | Onlap. Agradding configuration | Over outcropping basement. Channels infills | | | |
| | Downlap. Prograding configuration | Sedimentation basin border | | | |
| Unit U3 | Erosive truncation Channels infilling/ incision | Top of seismic unit | 1.3/10 | $2.3x10^8$ | $7.1x10^7$ |
| | Onlap. Aggrading configuration | Against faulted basement. Channels infills | | | |
| Unit U2 | Erosive truncation | Top of seismic unit | 2.1/30 | $2.3x10^8$ | $8.4x10^7$ |
| | Onlap | Over outcropping basement. Depressions infills | | | |

(*) Areal and volume estimations made with Surfer 6.0 software.

ría (Diz et al., 2001) gives two datations for the seismic unit U6 (Fig. 13c). The authors dated the bottom of 3 m long vibrocore VIR18 with a 2917 cal yr. BP.

The basement in the region of the Rías Baixas is composed of metamorphic Paleozoic rocks and granite rocks, affected by faults with northeast–southwest trends (IGME, 1981, 1987). The lineation and symmetry of the rías' boundaries with respect to these directions suggests that the rías were formed partly through erosion along those faults. García-Gil et al. (1999) propose that the present morphology of the rías

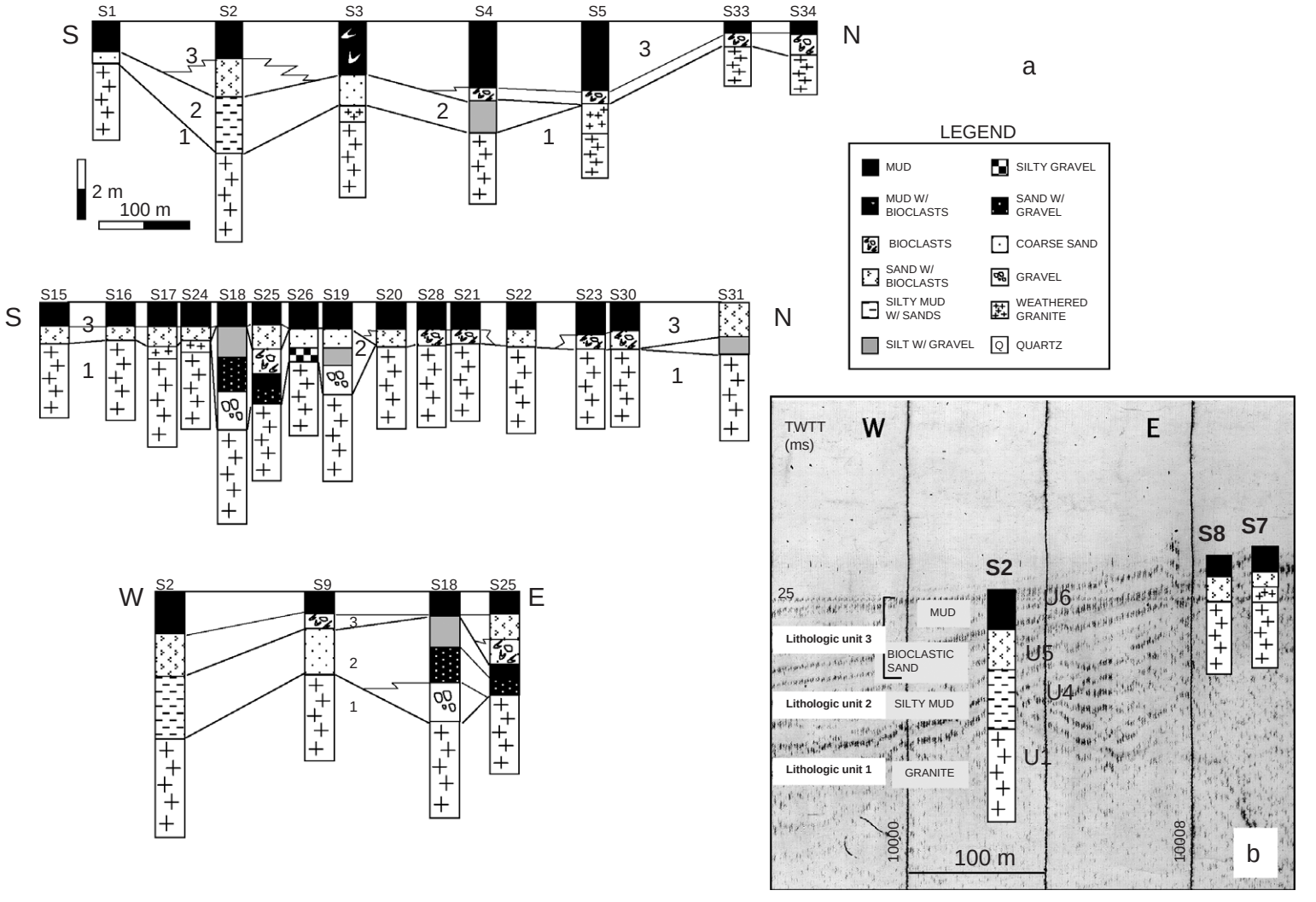
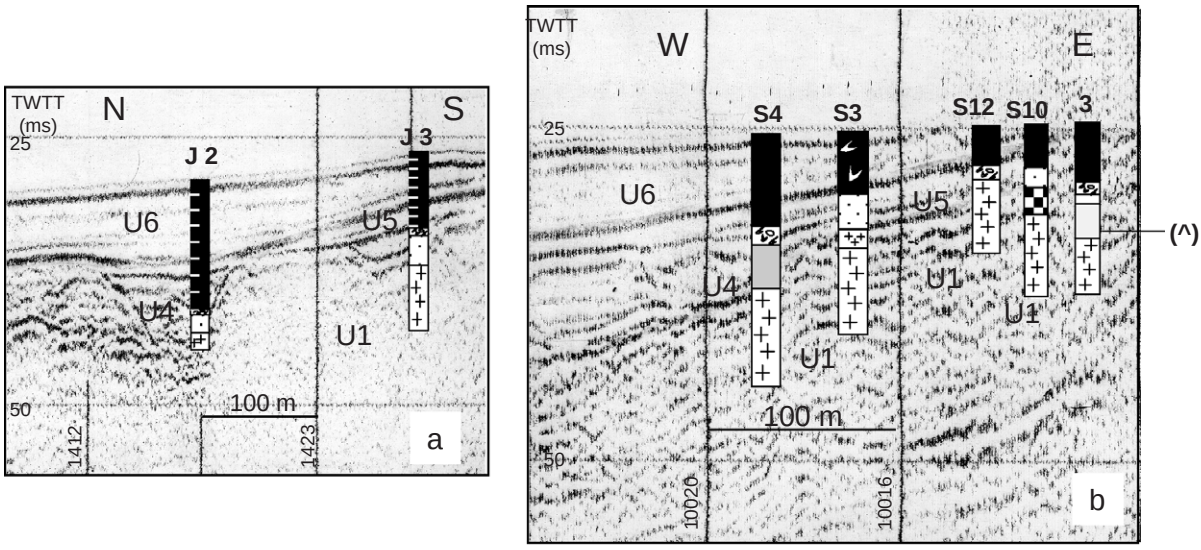



Fig. 12. a) Cores correlations (S–N and W–E). Numbers 1–3 indicate the lithologic unit; b) correlation of cores and seismic units (example of core 2). See Fig. 3b for cores location.



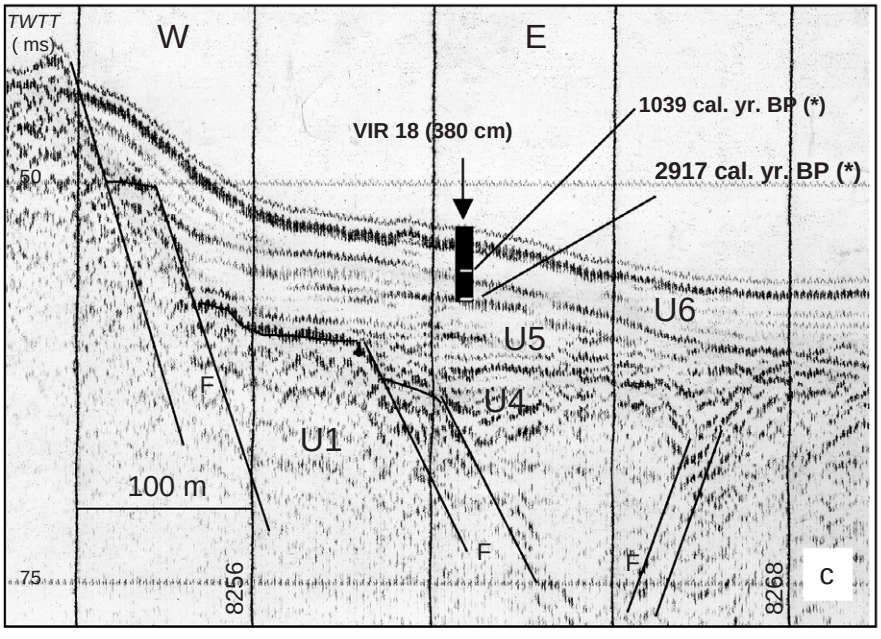




Fig. 13. a) Cores J2 and J3 (Margalef, 1956) correlated with seismic data. White horizontal marks in cores are calculated time for the ría every 1000 yrs cal BP (Margalef, 1956), with the deepest being 8000 yr cal BP; b) core 3 (Margalef, 1959) and some others correlated to seismic data; c) vibrocore VIR 18 (Diz et al., 2001) correlated to Uniboom seismic line. 'F' are interpreted faults.

is due to a combination of faults that slowly uplift/subside blocks towards the W-SW and N-NE (Pazos et al., 1994). This tectonic scheme is similar to the one proposed by Boillot and Malod (1988) for the Galician margin during its rifting stage in the Mesozoic. The available datations do not allow for establishment the rías' age of formation, but the inferred age of their sedimentary infill suggests that they are relatively young, probably from the Miocene or even younger.

Nevertheless, what it is more probable, is that the rías are the product of the tectonic activity associated with the Alpin orogene. This activity propagated along the eastern margin of the Iberian Peninsula, and it reactivated Palaeozoic faults and deformed the Mesozoic–Cenozoic sedimentary cover in Portugal and the Portuguese margin (Cabral and Ribeiro, 1993; Rodrígues et al., 1992, 1995). It was also responsible for the faulting, uplifting and generation of erosive surfaces in the Galicia margin (Lamboy and Dupeuble, 1975). Pannekoek (1970a,b) suggested the following scheme of a ría development: (1) during the Miocene the rías were eroded along preexistent faults; (2) new erosion of the ría during the tectonic period of the Pontiense, and (3) third erosive episode during the Inferior Pleistocene in which the rías got their actual morphology.

García-Gil et al. (1999) propose a fluvial origin for sequence $S_1$ in Ría de Pontevedra, north of Ría de Vigo (Fig. 1a) and also, they propose that sequence S1 could have been deposited during the Riss and/or Würm glaciations as a result of the fluvial erosion due to the drop in sea level. They also indicate that its top was built due to the erosion during the last glacial maximum, 18 ky BP. If that is true, and continuing that surface with the seismic records in this ría, that would imply that the sequence boundary $L_2$ corresponds to the last glacial maximum (Würm). This sequence S1 in Ría de Pontevedra corresponds to seismic unit U2 in the study area.

### 5.3. Reconstruction of the last 20 ky infilling

Considering the background data and taking into account the conceptual considerations of the stratigraphic models established by Vail et al. (1977), Mitchum et al. (1977), Posamentier et al. (1988), Vail et al. (1991) and Haq (1991) for siliciclastic systems, we provide a sequence analysis for the Ría de Vigo. We have also taken into account the environmental changes since 20 ky BP in the NE Atlantic (Ruddiman and McIntyre, 1981; Shackleton, 1987); that is, the polar front movements in the NE Atlantic in the last 20 ky (Ruddiman and McIntyre, 1981) and the oxygen isotope curve by Shackleton (1987). Thus we can also propose a correlation between the discontinuity boundaries and some of the climatic events.

The oldest sequence boundary identified on the records is the erosive and locally discordant surface $L_2$ (Fig. 4). It is a prominent palaeorelief developed over older sedimentary units and/or basement. This surface is characterized by the presence of channel incisions, which indicate an important relative drop of the sea level as well as a refreshment of the fluvial drainage and migration of facies and coast onlaps towards the basin. Therefore, surface $L_2$ is interpreted as a sequence boundary Type 1, which is developed over the top of the oldest sequence $S_1$, whose bottom is not visible. The seismic sequence $S_2$, developed over the boundary sequence $L_2$, is therefore a seismic sequence of Type 1. In the last glacial isotopic stage (2) 18 ky BP ago, a relative drop of $-120$ m in the global sea level is calculated (Berger et al., 1996). That relative drop of the sea level would be indicated in the ría by surface $L_2$. Fig. 14 shows a reconstruction of the ría area as it woud have been 18 ky ago, and also, a 3D reconstruction of the Würm surface is shown. As can be seen, by that time the ría was completely emerged, with a very erosive profile in the main channel, with the palaeocoastline was placed on the west.

Therefore, the Ría de Vigo infill is composed by a fifth order sequence (20 000 yrs). That denomination (Einsele, 1982) was also employed by other authors in a shallow environment (Lericolais et al., 2001). Below that surface $L_2$ there is another sequence S1, composed by seismic unit U2 in the ría. That sequence would be older than 20 ky and in the ría it is only visible locally and with a very erosive bottom, surface p.

Considering all the sedimentary infill in the ría, the map of total sedimentary thickness shows a depocenter of 57 ms (TWTT) located in the central part, as most of the individual seismic units (see Figs. 6–10) where the lowest basement is placed, and it is where the maximum infilling of the ría occurred.

This infilling sequence, composed of seismic units U3–U6, constitutes a transgressive sequence of three units (U3–U5) and one seismic unit U6 with typical

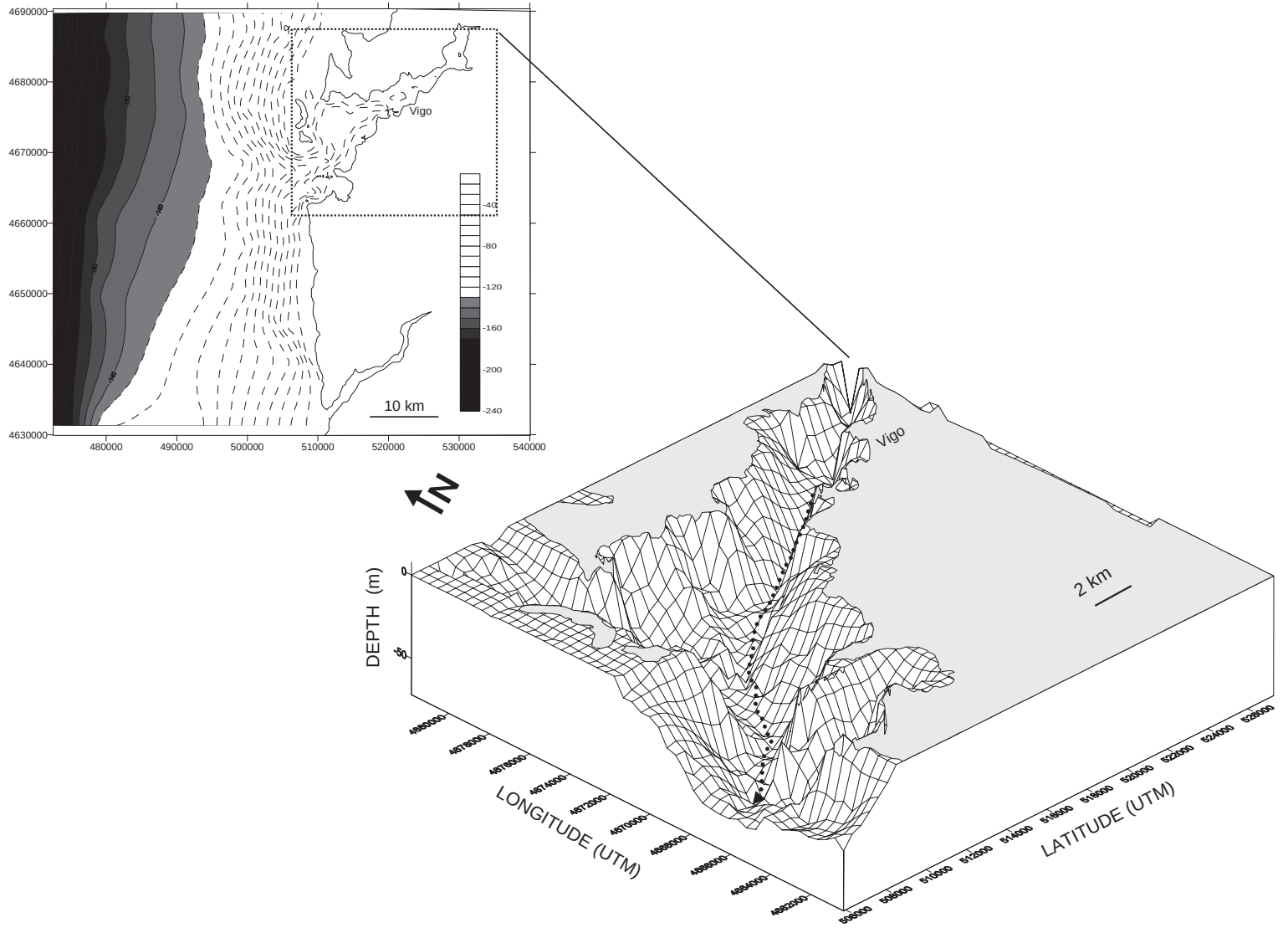



Fig. 14. a) Reconstruction of the emerged ría 18 ky ago with paleocoastline at − 120 m; b) 3D reconstruction of the 18 ky channel in the ría and main connection with open sea.

characteristics of sedimentation in conditions of a relative marine highstand (Fig. 15a). A chronostratigraphic model for the ría is proposed (Fig. 15b). We propose that surface $L_3$ is related to the Younger Dryas event in the ría, and therefore, that seismic units U5 and U6 would be Holocene, and U3 and U4 would be Late Pleistocene.

The surface that separate units U3 and U4 is a discontinuity of less importance ($h_2$) over which local downlaps and onlaps appear. This surface is interpreted to have originated in a period of stillstand during the relative sea level transgression, and it is a transgressive surface (see Fig. 15b). The presence of prograding reflectors, with onlap terminations towards

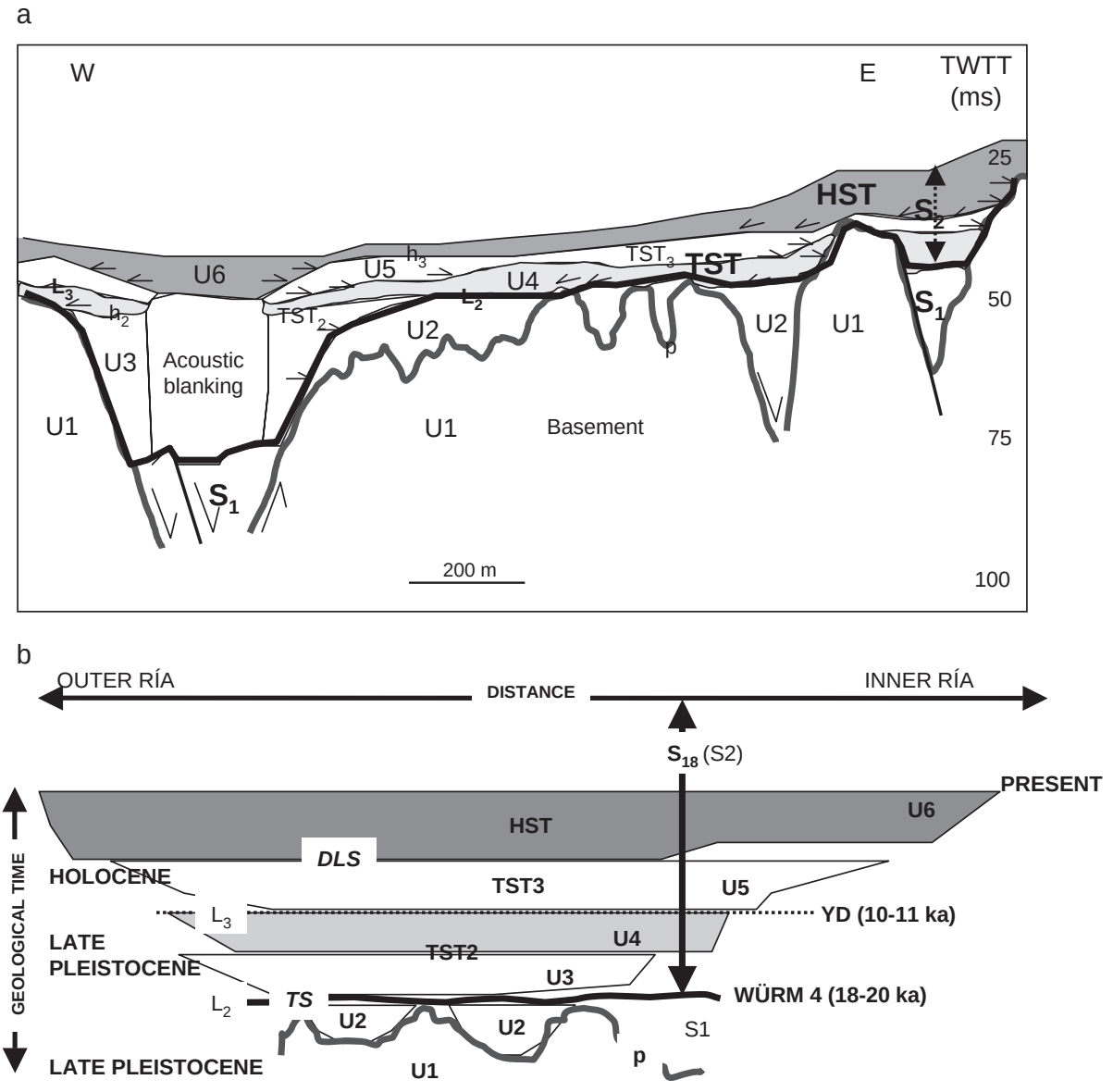



Fig. 15. a) Interpretation of the system tracks forming the fifth order sequence infill in the Ría de Vigo; b) schematic diagram with the sequence-stratigraphic sedimentation model proposed for the Ría de Vigo. 'DLS' is the downlap surface ad maximum flooding surface, 'TS' is the transgressive surface.

the basin border and downlap towards the inner part of it, indicate that unit U4 corresponds to sedimentation in a context of relative sea level rise, with a progressive lowering in that rise, that would cause the beginning of the progradation of sedimentary bodies in shallow waters.

The top of unit U4 is a surface with erosive truncation ($L_3$), with smooth palaeorelief and local channel incisions, restricted only in the basin border. Over this boundary $L_3$ there are basal terminations as onlap in unit U5, indicating a new relative sea level rise in the area. The presence of sub-horizontal reflectors, aggrading, with back-stepping indicate that this rise occurred in several steps, with small stillstands. Therefore, seismic unit U5 is interpreted as a TST, where the shallow marine facies belts move only as the transgression progresses. The marine flooding surface is located on the top of U5. This marine flooding surface is where the gas accumulations in the ría find an efficient seal suggesting that the origin of the gas is biogenic (mainly methane) from the bacterial degradation of the organic matter from the units of the TST and/or the HST.

The top of seismic unit U5 is marked by a new hiatus and non-erosive surface ($h_3$), a condensed section that coincides with the downlap surface, which the oblique-prograding reflectors of unit U6 finish against. Taking into account the seismic characteristics already pointed out, the unit U6 is interpreted as the $HST_3$.

In some cases the prograding sedimentary forms of this unit (see Fig. 11b and c) resemble the IPW body studied by Hernández-Molina et al. (2000) along the Spanish coast during the Late Holocene. The authors show the main sedimentary body as composed by large inclined master beds which prograde seawards parallel to the shoreline, formed by sediments swept offshore by waves from shallow-water littoral environments. The inclined beds downlap onto finer-grained offshore sediments and, in turn, are overlain by shoreface deposits. More specific work would be needed in order to prove that these forms are IPW bodies.

Numerous authors suggest that 10–11 ky BP registered as 'almost glacial' conditions, that is the Younger Dryas Event. In that period sea-level dropped and/or stabilized at approximately −55 and −60 m to the actual sea level (Pirazzoli, 1996; Rodrígues et al., 1991). The limit boundary $L_3$ could have been generated during the cold event with relative low of sea level, producing the partial erosion of former units U3 and U4. The analysis of the seismic records allowed us to estimate that sea level at $L_3$ was at ~ −45 m below present level. This suggests that the inner zones, at less than 45m, would have suffered subaerial exposure. Those erosion products would accumulate principally on land in the adjacent coast. A new relative rise of the sea level would occur in several steps, with the consequents stillstands, generating another TST. From that moment on, relative sea level keeps on rising until its present position, where the (HST) deposits accumulate. Margalef (1956) indicates a relative sea level of −24 m for the ría 8000 yrs ago. In Fig. 16a a reconstruction for that time is presented, using all the available datations close to our survey area and northern Iberian Peninsula (Dias, 1987; Diz, 1998; Magalhaes, 2000; Margalef, 1956; Pazos et al., 1994; Rodrigues et al., 2000). With all this information a relative sea level curve for the Ría de Vigo is proposed (Fig. 16b).

These new findings about the Holocene infill of a ría can be compared to other shallow environments worldwide. The ría basement (unit U1) with two different types of facies (type 1 with abrupt topographies and type 2 with a smoother profile; see Fig. 5) can also be found in Malaysia (Kudras and Schüler, 1994). These authors confirm the granitic nature of type 1 facies and metamorphic of type 2 facies, both also found also onland and separated by faults.

This ría infill is comparable with the incised valley on the shelf of the Bay of Biscay (Lericolais et al., 2001). The authors state that a single fifth-order cycle sequence is infilling the French valley coast. This sequence contains three system tracts (LST, TST, HST). In the Vigo ría case, the LST record is boundary $L_2$, and the transgressive period left three different units (U3, U4 and U5), below the only highstand unit U6.

Some similar Quaternary units have also been found in the Adriatic Sea (Ferretti et al., 1986) with asymmetric channel infills within the sediments similar to the ones found in this study. A study in the Norwegian fjords (Aarseth, 1997) states that five units form the 400–500 m of sedimentary infill, a much thicker pattern than the one found in the rías, where the maximum visible thickness is around 60 m. In the Korea Strait (Lee et al., 2005) the Holocene sediments

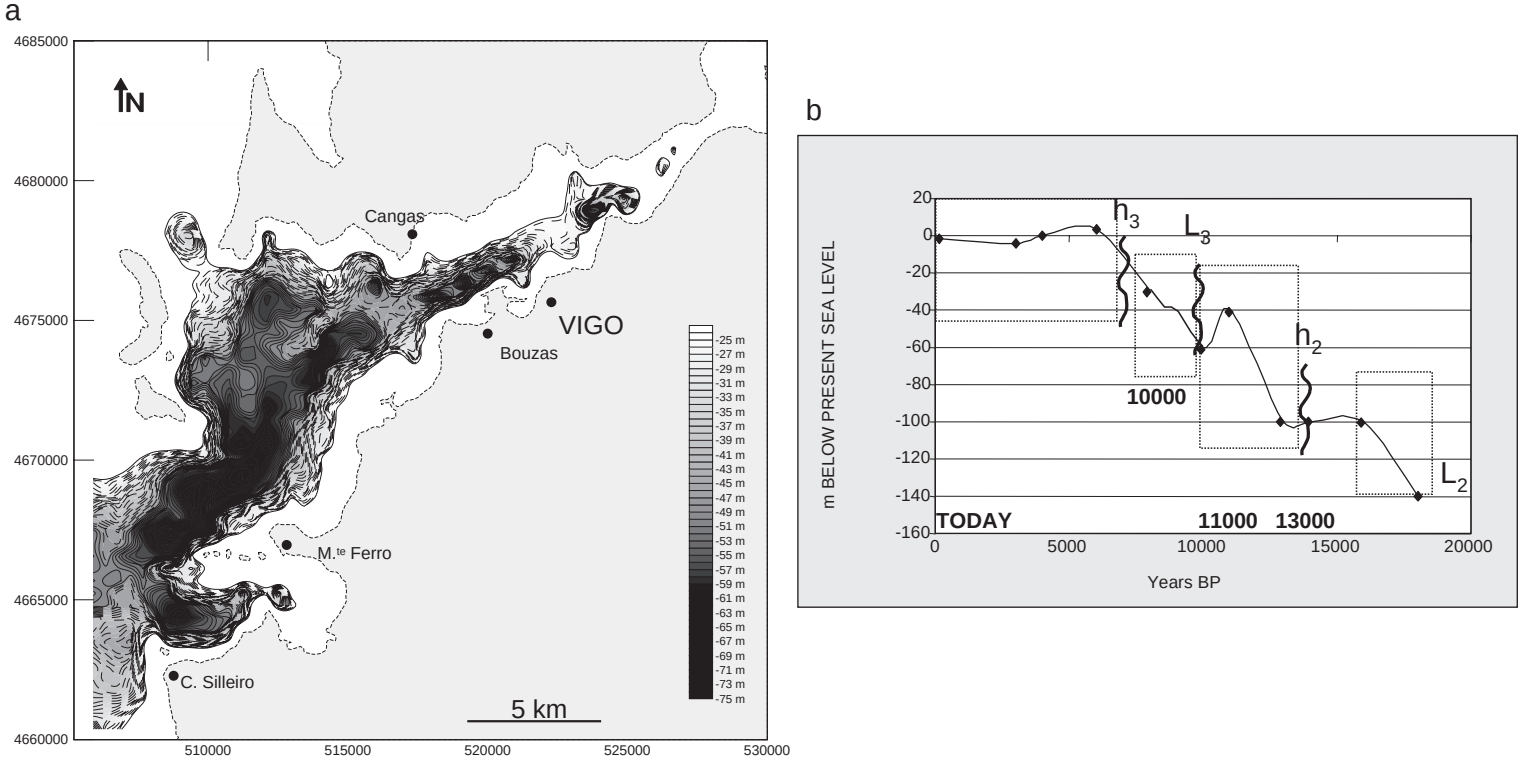



Fig. 16. a) Reconstruction of the ría 8000 yrs ago (8 ky palaeocoastline in the ría at − 24 m, Margalef, 1956); b) proposed relative sea level curve for Ría de Vigo. The dataset used for the plot was taken from Dias (1987); Diz (1998), Magalhaes (2000), Margalef (1956), Pazos et al. (1994) and Rodrigues et al. (2000).

are muds of up to 30 m thick that are deposited in a complex pattern.

## 6. Conclusions

In the Ría de Vigo seven seismic units have been identified: U1, corresponding to the basement, with the remainder, U2 to U6, constituting the sedimentary infill in the ría. These sedimentary units indicate a progressive enlargement of the sedimentary basin. The most recent unit U6 is the seal for the gas which is accumulating below. The identification of three erosive surfaces (p, $L_2$, $L_3$) give two main sedimentary sequences (S1, S2) for the infill of the ría. Sequence S2 represents the 18–20 ky infill. In addition, 2 hiatus surfaces have been identified ($h_2$, $h_3$). A tentative relative sea level curve for the last 18–20 ky in the Ría de Vigo is also presented.

The $L_2$ surface was eroded in the Last Glacial Maximum, 20 ky BP. The $L_3$ surface is correlated to the Younger Dryas cold event, 11–10 ky BP, indicating a drop in the relative sea level. Sequence S1 would correspond to the Late Pleistocene (aprox. 37 ky). Seismic units U3 and U4 represent 2 pulses in the transgressive trend, between 20–11 ky. Seismic units U5 and U6 would correspond to the TST and HST, respectively, in the Holocene. The sedimentary infill of this ria is also compared to other similar areas worldwide. Finally, a seismic-sequence stratigraphic model is proposed, in relation to the relative variations of the sea level during the last 18–20 ky for the Ría de Vigo.

## Acknowledgements

Ana García-García acknowledges post-doc research grant EX2002-0627 by the MECD. We are thankful to Spanish Autoridad Portuaria for sharing the core information. This work was partially funded by projects REN2003-02822 MAR, REN2003-03233MAR, VEM2003-20093-CO3-03, RTN ERBFRXCT98-0247 of the Spanish MEC and PGDIT03R-MA30101PR of the Galician Government (XUGA). Contribution No. 345 of XM2 group (GEOMA). We are thankful for the constructive comments of Dan Orange and Casey Moore. A thorough review of the manuscript was done by Isabelle Herbert. Contributions by Adam Hefernan and Norman Maher are also gratefully acknowledged. We appreciate the constructive suggestions from two anonymous referees and Editor De Lange which greatly improved the paper.

## References

Aarseth, I., 1997. Western Norwegian fjord sediment: age, volume, stratigraphy, and role as temporary depository during glacial cycles. Mar. Geol. 143, 39–53.

Acosta, J., 1984. Occurrence of acoustic masking in sediments in two areas of the continental shelf of Spain: Ría de Muros (NW) and Gulf of Cadiz (SW). Mar. Geol. 58, 427–434.

Berger, W.H.T., Bickert, M., Yasuda, K., Wefer, G., 1996. Reconstruction of atmospheric $CO_2$ from the deep-sea record on Omtong Java Plateau: the Milankovitch Chron. Geol. Rundsch. 85, 446–495.

Boillot, G., Malod, J., 1988. The north and north-west Spanish continental margin: a review. Rev. Soc. Geol. Esp. 1, 295–316.

Cabral, J., Ribeiro, A., 1993. Movimientos neotectónicos verticais em Portugal continental, tentativa de síntese. III Reuniao do Quaternario Ibérico, Coimbra, 27 Set.-1 Nov.

Dias, J.M.A., 1987. Dinámica sedimentar e evoluçao reçente da plataforma continental portuguesa setentrional. Tesis de Doctorado inédita, Universidade de Lisboa, Portugal, p. 500.

Diz, P., 1998. Evolución paleoecológica y paleoceanográfica de la Ría de Vigo durante el Holoceno. Tesis de Licenciatura Inédita, Universidad de Vigo, p. 200.

Diz, P., Francés, G., Alejo, I., Vilas, F., 2001. Asociaciones de foraminíferos bentónicos en el Holoceno de la Ría de Vigo: interpretación paleoecológica. Rev. Soc. Geol. Esp. 14 (1–2), 19–33.

Diz, P., Francés, G., Pelejero, C., Grimalt, J.O., Vilas, F., 2002. The last 3000 years in the Ría de Vigo (NW Iberian margin): climatic and hydrographic signals. The Holocene 12 (4), 445–458.

Einsele, G., 1982. General remarks about the nature, occurrence, and recognition of cyclic sequences (periodites). In: Einsele, G., Seilacher, A. (Eds.), Cyclic and Event Stratification. Springer-Verlag, Berlin, pp. 3–7.

Evans, G., Prego, R., 2003. Rias, estuaries and incised valleys: is a ria an estuary? Mar. Geol. 3299, 1–5.

Ferretti, M., Moretti, E., Savelli, D., Stefanon, A., Tramontana, M., Wezel, F.-C., 1986. Late Quaternary alluvial sequences in the North-Western Adriatic Sea from Uniboom profiles. Boll. Oceanol. Teor. Appl. IV (1), 63–72.

García-García, A., García-Gil, S., Vilas, F., 1999. A seeping seafloor in a Ría environment: Ría de Vigo (NW Spain). Environ. Geol. 38 (4), 296–300.

García-García, A., García-Gil, S., Vilas, F., 2003a. Seismic and stratigraphic correlation in Vigo harbour (Ria de Vigo, NW Spain). In: Vilas, F., Rubio, B., Diez, J.B., Frances, G., Bernabeu, A.M., Fernandez, E., Rey, D., Roson, G. (Eds.), Special Volume on the 4th Symp. Atlant. Iber. Contin. Margin, Vigo, Spain, 7–10 July, Thalassas, vol. 19 (2a), pp. 46–47.

García-García, A., García-Gil, S., Vilas, F., 2003b. Monitoring the Spanish gas fields in the Ria de Vigo (1991–2001). Geo Mar. Lett. 23 (3/4), 200–206.

García-García, A., García-Gil, S., Vilas, F., 2004. Echo characters and recent sedimentary processes inferred by 3.5 kHz high resolution sub-bottom analysis: the Ría de Vigo (NW Spain). Geo Mar. Lett. 24, 32–45.

García-Gil, S., Vilas, F., Muñoz, A., Acosta, J., Uchupi, E., 1999. Quaternary sedimentation in the Ría de Pontevedra (Galicia), Northwest Spain. J. Coast. Res. 15 (4), 1083–1090.

García-Gil, S., García-García, A., Durán, R., Vilas, F., 2000. Estudio sísmico de alta resolución en las rías baixas: pontevedra y vigo (no España). Cuad. Geol. Iber. 26, 65–79.

García-Gil, S., Vilas, F., García-García, A., 2002. Shallow gas features in incised-valley fills (Vigo ria, NW Spain). In: Judd, A., Curzi, P. (Eds.), Shallow Gas Studies, Cont. Shelf Res, vol. 22, pp. 2303–2315.

Haq, B.U., 1991. Sequence stratigraphy, sea-level, y significance for the deep sea. In: Macdonald, D.I.M. (Ed.), Sedimentation, Tectonics and Eustacy, Spec. Public. 12 of the Inter. Ass. Sediment. Blackwell Scientific Publications, London, pp. 3–41.

Hernández-Molina, F.J., Fernández-Salas, L.M., Lobo, F., Somoza, L., Díaz del Río, V., Alveirinho Dias, J.M., 2000. The infralittoral prograding wedge: a new large-scale progradational sedimentary body in shallow marine environments. Geo Mar. Lett. 20, 109–117.

Hernández-Molina, F.J., Somoza, L., Rey, J., Pomar, L., 1994. Late Pleistocene–Holocene sediments on the Spanish continental shelves: model for very high resolution sequence stratigraphy. Mar. Geol. 120, 129–174.

IGME, 1981. Mapa Geológico de España, e. 1:50.000 (hojas 222, 260, 261). Servicio de Publicaciones, Ministerio de Industria y Energía, Madrid.

IGME, 1987. Mapa Geológico de España, e. 1:50.000 (hojas 184, 185, 223). Servicio de Publicaciones, Ministerio de Industria y Energía, Madrid.

Instituto Hidrográfico de la Marina, 1996a. Carta Náutica 416B. Ría de Vigo, E. 1:25000, Cádiz, España.

Instituto Hidrográfico de la Marina, 1996b. Carta Náutica 924. Ría y Puerto de Vigo, E. 1:15000, Cádiz, España.

Kudras, H.R., Schüler, H.U., 1994. Development of cassiterite-bearing sediments and their relation to Late Pleistocene sea-level changes in the Straits of Malacca. Mar. Geol. 120, 175–202.

Lamboy, M., Dupeuble, P.A., 1975. Carte géologique continental nord-ouest espagnol entre le canyon Avilès et la frontière portugaise. Bull. Soc. Geol. Fr. 17, 442–461.

Lee, S.H., Lee, H.J., Jo, H.R., Bahk, J.J., Chu, Y.S., 2005. Complex sedimentation of the Holocene mud deposits in a ria-type coastal area, eastern Korea Strait. Mar. Geol. 214 (4), 389–409.

Lericolais, G., Berné, S., Féniès, H., 2001. Seaward pinching out ad internal stratigraphy of the Gironde incised valley on the shelf (Bay of Biscay). Mar. Geol. 175, 183–197.

Magalhaes, F., 2000. Sea level in Portugal in the last 18,000 years. Abstracts Volume of the 3rd Symposium on the Atlantic Iberian Continental Margin, 25–27 September, Faro, Portugal, pp. 205–206.

Margalef, R., 1956. Paleoecología postglacial de la Ría de Vigo. Inv. Pesq. V, 89–112.

Margalef, R., 1959. Nuevos datos para el estudio de la historia de la Ría de Vigo, desde la última glaciación. Mem. Real Acad. Ciencias y Artes de Barcelona XXXIII (2), 23–35 (666).

Mitchum Jr., R.M., Vail, P.R., Sangree, J.B., 1977. Seismic stratigraphy and global changes of sea level: Part 6. Stratigraphic interpretation of seismic reflection patterns in depositional sequences. Seismic Stratigraphy—Applications to Hydrocarbon Exploration, AAPG Mem., vol. 26, pp. 117–133.

Muñoz, A., Acosta, J., Uchupi, E., 2003. Cenozoic tectonics on the Galician margin, northwest Spain. Geo Mar. Lett. 23, 72–80.

Muñoz, A., Acosta, J., Palomo, C., Herranz, P., Sanz, J.L., Molinero, J., Gómez, R., Becares, M.A., Uchupi, E., 1997. Datos batimétricos y sísmicos en el ámbito de la investigación de la Zona Económica Exclusiva Española. I Asamblea Hispano-Portuguesa de Geodesia y Geofísica, Almería.

Pannekoek, A.J., 1970a. Pleistocene history of the Ría de Arosa. Leidse Geol. Meded. 37, 174–176.

Pannekoek, A.J., 1970b. Additional geomorphological data on the ría area of western Galicia (Spain). Leidse Geol. Meded. 37, 185–194.

Pazos, O., Vilas, F., García-Gil, E., García-Gil, S., Nombela, M.A., Alejo, I., Rubio, B., Rey, D., 1994. Holocene tectonic movements in the West Coast of Galicia (Spain). Littoral 94, 26–29.

Pirazzoli, P.A., 1996. Sea-level changes. The Last 20,000 Years. John Wiley and Sons, LTD, Chichester. 211 pp.

Posamentier, H.W., James, D.P., Allen, G.P., 1988. Eustatic controls on clastic deposition I-Conceptual framework. In: Wilgun, C.K., Hastings, B.S, Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C (Eds.), Sea-Level Changes: An Integrated Approach, Soc. Econ. Paleontol. Mineral., Spec. Public, vol. 42, pp. 109–124.

Rey, J., 1993. Relación morfosedimentaria entre la plataforma continental de Galicia y las Rías Bajas y su evolución durante el Cuaternario. Spec. Publ. Inst. Esp. Oceanogr. 17. 232 pp.

Rodrígues, A., Magalhaes, F., Alveirinho Dias, J., 1991. Evolution of the North Portuguese Coast in the last 18.000 years. Quat. Int. 9, 67–74.

Rodrígues, A., Alveirinho Dias, J., Ribeiro, A., 1992. First appraisal of active faults in the North Portuguese Continental Shelf. Gaia 4, 24–30.

Rodrigues, A., Ribeiro, A., Dias, J.A., 1995. Estructuras activas na plataforma continental setentrional: resultados do projecto SISMAR. Museu e Laboratorio Mineralogico e Geologico Memoria n, vol. 4, pp. 311–315.

Rodrigues, A., Dias, J.A., Ribeiro, A., 2000. The North Portuguese shelf during the last Glacial Maximum and Younger Dryas. Abstracts Volume of the 3rd Symposium on the Atlantic Iberian Continental Margin, 25–27 September, Faro, Portugal. , pp. 209–210.

Rubio, H., Abril Hurtado, J., García Salinas, F., Corretge, L.G., Floor, P., Zapartiel, J.M., 1981. Hoja geológica núm. 223 (Vigo). Mapa Geológico de España, E. 1:50.000. I.G.M.E., Madrid.

Ruddiman, W., McIntyre, A., 1981. The North Atlantic ocean during the last deglaciation. Paleogeogr., Paleoclimatol., Paleoecol. 35, 145–214.

Shackleton, N.J., 1987. Oxygen isotopes, ice volume and sea level. Quat. Sci. Rev. 6, 183–190.

Vail, P.R., Mitchum Jr., R.M., Todd, R.G., Widmier, J.M., Thompson III, S., Sangree, J.B., Bubb, J.N., Hatelid, W.G., 1977. Seismic stratigraphy y global changes of sea level. Seismic Stratigraphy—Applications to Hydrocarbon Exploration, AAPG Mem., vol. 26, pp. 49–213.

Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N., Pérez-Cruz, C., 1991. The Stratigraphic signatures of tectonics, eustacy y sedimentology. In: Einsele, G., Ricken, W., Seilacher, A. (Eds.), Cycles and Events in Stratigraphy. Springer-Verlag, Berlin, pp. 617–659.

Vilas, F., 2000. Geology of the Galician Rías (preface). J. Iber. Geol., 15–19.

Vilas, F., 2002. Rías and Tidal-Sea Estuaries. Knowledge for sustainable development, an insight into the enciclopedia of life suppot systems. UNESCO-EOLSS (Ed.) vol II, theme 11.6.3., pp. 799–829.

Vilas, F., Nombela, M.A., García-Gil, E., García-Gil, S., Alejo, I., Rubio, B., Pazos, O., 1995. Mapa de distribución de los sedimentos del fondo de la Ría de Vigo. Conselleria de Pesca, Marisqueo y Acuicultura, Xunta de Galicia, 41 pp.