Journal of Coastal Research	15	4	1083–1090	Royal Palm Beach, Florida	Fall 1999

Quaternary Sedimentation in the Ría de Pontevedra (Galicia), Northwest Spain

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ABSTRACT

GARCÍA-GIL, S.; VILAS-MARTIN, F.; MUÑOZ, A.; ACOSTA, J., and UCHUPI, E., 1999. Quarternary Sedimentation in the Ría de Pontevedra (Galicia), Northwest Spain. *Journal of Coastal Research,* 15(4), 1083–1090. Royal Palm Beach (Florida), ISSN 0749-0208.

It has been inferred that the rías of Galicia on the passive margin of northwest Spain which trend nearly at right angles to the Paleozoic structural grain appear to be the result of erosion along a weathered fault zone. New data from the Ría de Pontevedra appears to verify such an origin. The sediment fill in Pontevedra indicates that deposition along the eroded fault zone probably began during the emplacement of the late Pleistocene S1 sequence. Deposition of the Holocene S2 sequence, resting unconformably on S1, reflects not only the Younger Dryas regression, but also the transgressions prior and subsequent to the Younger Dryas regression. Both the Pleistocene and Holocene sequences are disrupted by mud diapirs at the mouth of the Ría de Pontevedra; the Holocene sequence at the mouth on its southeast side also is disrupted by faults which may be due to slope failure. Mobilization of the mud intruding the strata is probably due to sediment loading.

ADDITIONAL INDEX WORDS: *Pleistocene, Holocene, rías of Galicia, faults, sediment loading.*

INTRODUCTION

A Ría is defined in the *Glossary of Geology* of the American Geological Institute as a long narrow, sometimes wedge-shaped arm of the sea, whose depth and width diminishes landward, a feature which is inferred to have been created by drowning due to submergence of the lower part of a river. According to PANNEKOEK (1966), VON RICHTOFEN (1886, p. 208–310) used the drowned valleys in western Galicia, northwest Spain, as the prototypes for rías in a coast of submergence. In 1970, PANNEKOEK suggested that the rías, as proposed by COTTON (1965), were formed during the Miocene, Pliocene and Pleistocene by erosion along a pre-existing fault zone weakened by deep weathering.

In Ría Muros and Noya the Quaternary fill consists of: (1) a channeled Pleistocene fluvial sequence along the ría's axis; (2) a Holocene transgressive sequence consisting of a lower set of aggradding and prograding strata deposited during the initial flooding of the ría; (3) a middle progradation sequence correlative with the Younger Dryas event; and (4) an upper set of prograding units displaying a parallel, sigmoidal and oblique reflector geometry deposited during the closing phases of the Holocene transgression (HERNANDEZ-MOLINA *et al.*, 1994). According to SOMOZA and REY (1991) the prograding clinoforms of the upper unit in Ría de Muros and Noya can be related with delta type variability which depend on water depth (POSTMA, 1990). The parallel reflector unit is coeval with a shoal-water delta where bed-load transport is dominant, a sigmoidal reflector unit is a "Gilbert" type delta dominated by homopycnal conditions, and an oblique reflector unit is a delta-fed submarine fan system. According to ACOSTA (1984) the sediments on which these delta downlap contain abundant gas. In Ría de Arosa the fill consists of 7–12 m of Holocene marine muds at the top, 30 to more than 60 m of bedded fluvial deposits in the middle and colluvium and weathered granite at the base which appear as a terrace.

In the present investigation we describe new data, including high resolution seismic reflection data, from the Ría de Pontevedra which provide support for the tectonic origin of the rías. At the same time these new data provide additional information on its evolution, the tectonic-eustatic processes which controlled the deposition of the ría's sediment fill, and the occurrence and extent of neotectonism due to diapirism and slope failures in the environs of the Ría de Pontevedra.

98086 received 20 March 1998; accepted in revision 18 September 1998.

RÍA DE PONTEVEDRA

Survey

More than 340 km of seismic reflection, echosounding, seafloor acoustic classification and side scan sonar were recorded in the Ría de Pontevedra in July 1996 (Figure 1A). The seismic reflection data were obtained with a 300 joule EG&G Geopulse fired at one (1) second intervals. Signals were received via a 10 m long active EG&G streamer with 16 hydrophones, filtered at 200–1500 Hz and recorded on an EPC Recorder (model 4800) at scales of 250 and 200 milliseconds. Navigation was achieved by a D-GPS system.

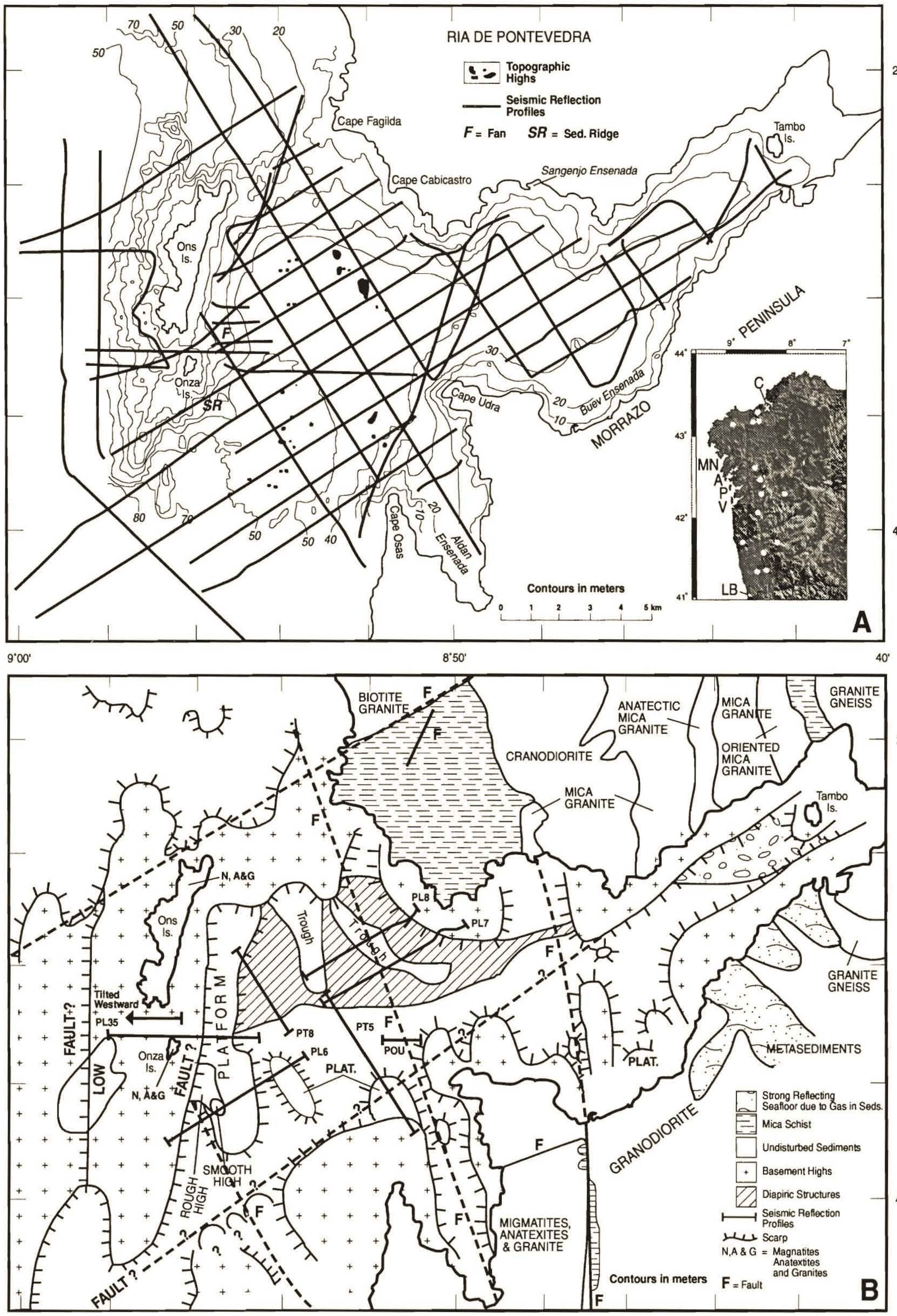

Figure 1. A. Bathymetric map of the Ría de Pontevedra showing locations on seismic reflection profiles. Insert map shows locations of rías in northwest Spain. Insert Map: MN = Ría de Muros and Noya; A = Ría de Arosa; C = La Coruña; P = Ría de Pontevedra; V = Ría de Vigo; dots = thermal springs. The springs are aligned along north-northwest-south-southeast to northeast-southwest trending faults. Distribution of springs from Waring (1965). B. Geotectonic map of the Ría de Pontevedra showing locations of seismic reflections in Figs. 2–3. Geology of area modified from FLOOR (1968) and IGME (1978).

Morphology

The country rock in the vicinity of the Ría de Pontevedra and the islands at its mouth consists mainly of post-Hercynian orogenic plutonics and Paleozoic metamorphics with a north structural trend; both units are cut in two by the northeastward aligned ría (Figure 1B). Topographically the Ría de Pontevedra is wedge-shaped in plan view, is 36 km long and has a maximum width of 53 km (Figure 1A). The entrance to the Ría de Pontevedra is partially blocked by a north trending ridge along whose crest are Onza Island at the southern end and the much larger Ons Island at the northern end.

Structural Setting

The four large rías in western Galicia (Muros and Noya, Arosa, Pontevedra and Vigo, insert, Figure 1A) trend northeastward nearly at right angles to the main north trending Paleozoic structural trends. The rías and their surroundings contain several major faults. To the east of the rías is a fault zone consisting of north-south trending 170 km long parallel highs and lows (insert, Figure 1A) filled with Miocene-Pliocene lignites and Quaternary sediments. This fault zone probably formed during the Hercynian was reactivated during the Miocene-Pliocene, and may have experienced activity into the Quaternary (PANNEKOEK, 1966; DE AGUIRRE and BUTZER, 1967; PAZOS *et al.,* 1995). Whereas the courses of the smaller tributaries were affected by the Pliocene rejuvenation of the faults, the main rivers associated with the rías do not display any deviation when they cross the fault zone (PANNEKOEK, 1966).

Geologic mapping on land and seismic reflection profiles offshore also show that at least one side, the northwest side, of the Ría de Pontevedra is rectilinear, indicating that it may be the creation of faulting. This fault extends extends southwestwards from Tambo Island to the ría's mouth south of the Ons/Onza Island ridge (Figure 1B). The ría's along-axis northeast-southwest trending fault appears to truncate north to slightly west of north trending faults. The valley debauching onto Sangenjo Ensenada on the north side of the ría appears to have been eroded along one of these faults located along the contact between mica granite/granodiorite and mica schist. The valley landward of Buev Ensenada also may have been eroded along a similar fault located along the contact between granodiorite and migmatites, anatexites and granite (Figures 1A and 1B). The linearity of Aldan Ensenada and also suggests that this features is fault controlled.

The seismic reflection profiles recorded offshore suggest that this faulting extends beyond the confines of the ría. It is the extent of this faulting which has led us to infer that the Ría de Pontevedra and associated ensenadas were created by differential erosion along faults. The offshore seismic data indicate that the high defined by the islands at the mouth of the ría is a horst tilted westward and that both sides of the horst are disrupted by secondary faults (Figure 1B). This high may be cut across at its northern end by a seaward extension of the northeast trending fault separating the biotite granite from the mica schist north of Cape Fagilda (Figures 1A and 1B). From these seismic reflection profiles we also infer that the platforms or benches on the east side of the Ons/Onza Islands ridge, off Cape Osas (PT5, PL35, Figure 2) and Buev Ensenada (Figure 1B) are erosional in origin and were carved by a combination of fluvial and marine processes out of the country rock along the fault traces. Northeast of the platform along profile PL6 (Figure 3) is a flat topped high which originally was part of the platform, but has been separated from it by erosion to form a narrow northwest trending high (Figure 1B). West of the platform along PL6 is a ridge whose smooth outline suggests that it is sedimentary in origin. Southwest of the ridge are three sediment sequences separated by unconformities with the oldest and youngest of onlapping the flank of the ridge and the middle one onlapping the lower one (profile PL6, Figure 3). At the northeast end of this ridge is a series of narrow basement highs having the appearance of fault slivers. They are oriented parallel to the master fault forming the north-south trending flank of the on the east side of Ons/Onza island ridge.

Sediment Fill

The sediment fill in the Ría de Pontevedra can be divided into two sedimentary sequences resting unconformably on one another (profiles PT5, PL8 and PL35). The lower sequence (S1) is found in the deeper parts of the Ría de Pontevedra and its distribution is controlled by the side slopes of the ría on which the sequence onlaps. The sequence is characterized by continuous reflectors and along some of the profiles we were able to distinguish at least three sedimentary units separated by hiatuses on which the units onlap. These units represent distinct sedimentary pulses into the ría, reflecting either tectonism or changes in sea level.

The top of the lower (S1) sequence is truncated by a prominent unconformity. Resting on this hiatus is sequence S2, which consists of at least three units (a, b, c, profiles PL8 and PL35, Figure 2) separated from one another by hiatuses. The units comprising sequence S2 become progressively more extensive with time. Unit S2a is of limited extent and fills lows on the unconformity on the top surface of the lower (S1) sequence, whereas unit S2b downlaps S2a, extends the width of the ría, and onlaps its basement side slopes. Unit S2c whose reflectors display greater continuity than S2a and S2b displays a fan geometry along the edges of the ría. The seaward edge of the topset surface of these structures, which may document former sea level stands, occur at depths of 14.25, 18.75, 26.5 and 33.75 m along the northwest side of the ría and at depths of 12.75, 13.50, 18.75, 19.50 m and 21.0 m along its southeast side. Off Cape Cabicastro the deltaic accumulation was mapped at a depth of 29.25 m.

Also included within unit S2c along the east side of Ons/Onza island ridge is a fan resting on the hiatus separating S2b and S2c (profile PL35, Figure 2). The surface of the fan is crenulated by mega-ripples oriented N65°E, having wave lengths of 10 m and covering an area of 200 × 50 m. Surface sediments on the fan range from gravelly sands at its apex to sandy gravel at the fan's slope to muddy sands with some gravel at its distal end. GARCÍA *et al.* (1998) have inferred that the fan was constructed by storm generated turbulence in the shallow protected environment of the Ría de Pontevedra. Similar structures also were noted on the surface sed-

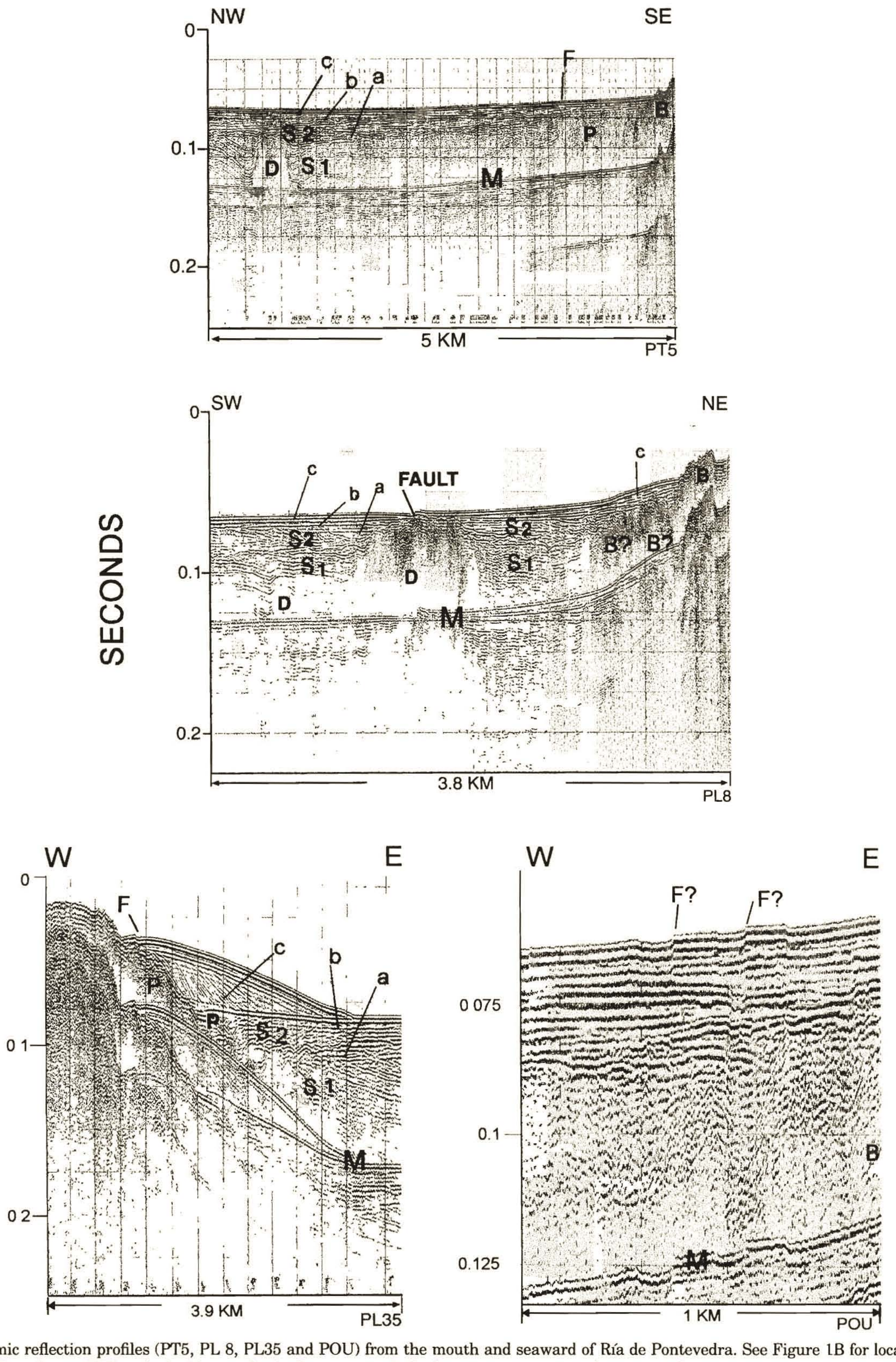

Figure 2. Seismic reflection profiles (PT5, PL 8, PL35 and POU) from the mouth and seaward of Ría de Pontevedra. See Figure 1B for locations of profiles. B = basement; D = diapir; F/F? = fault; M = multiple; P = erosional platform or terrace. Note that two such erosional terraces appear to be present along profile PL35. S1–S2 = sedimentary sequences; S2 sequence is made of three units a, b, c with unit c displaying a fan geometry along PL35. This fan was created by storm generated turbulence entering the Ría de Pontevedra between Ons and Onza islands. The box-shaped structures along profile POU may be due to slumping with the associated faults probably bottoming out on a shallow décollement as the lower horizons do not display any dislocation.

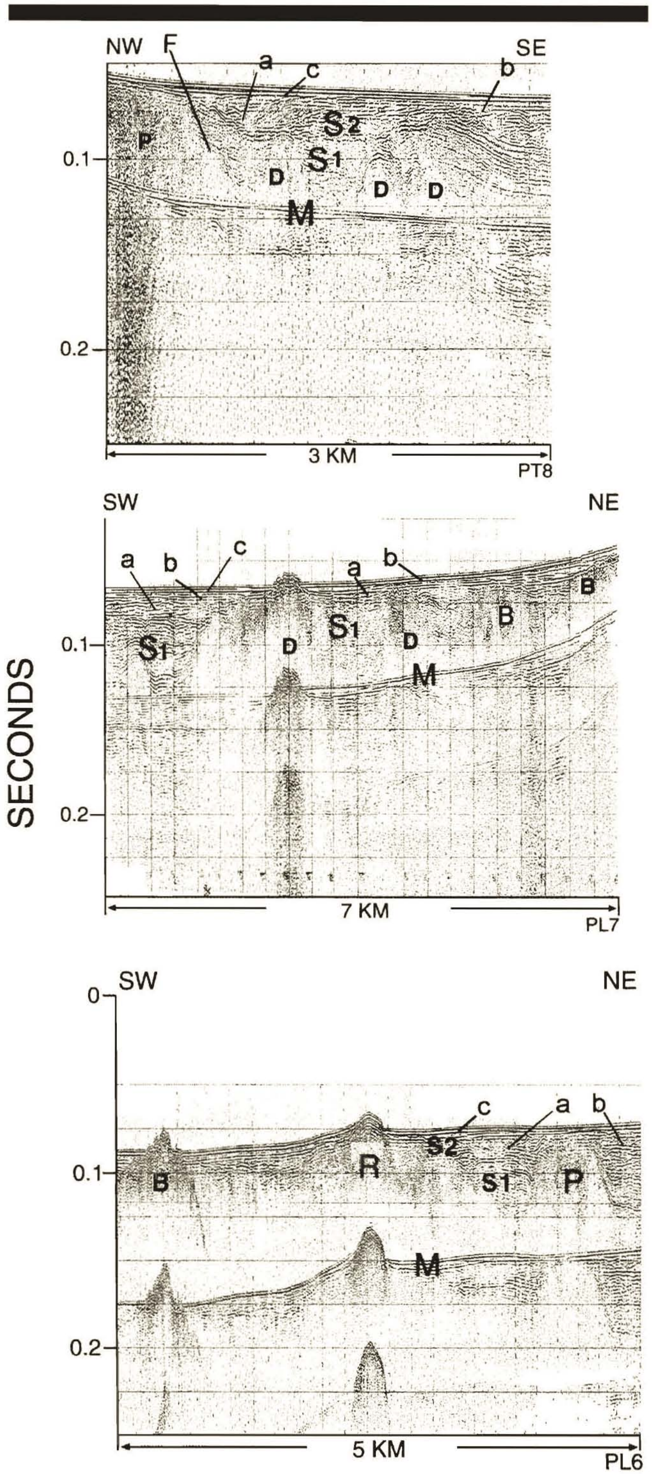

Figure 3. Seismic reflection profiles (PT8, PL7 and PL6) immediately seaward of the Ría de Pontevedra. See Figure 1B for locations of profiles. B = basement; D = diapir; F = fault; M = multiple; P = platform; R = sedimentary ridge. S1–S2 = sedimentary sequences; a, b and c = units of sequence S2. Note that one of the diapirs has surface expression on profiles PL7. Because of its isolation from the diapiric field and its linearity the high (R) having surface expression along PL6 we have inferred to be a sedimentary ridge. This ridge trends northwest and is located southeast of Onza Island (Fig. 1B) The flat top high (P) at the northeast end of PL6 is part of a northwest trending platform southeast of Onza Island (Fig. 1B).

iments northeast of the gap between the Ons/Onza island ridge and off Cape Osas. Off Cape Udra the seafloor is marred by box-shaped lows, features which may have been created by slope failure (profile POU, Figure 2). Faults (shear planes) associated with these gravitational structures probably bottomed out on a shallow décollement as the deeper reflectors do appear to be dislocated.

The most prominent features imaged by the seismic reflection profiles are the intrusions disrupting the sediments at the mouth and northern side of the Ría de pontevedra southeast of Cape Cabicastro (Figure 1B). No such structures have been reported from the other rías of northwest Spain. Along some of the profiles these diapirs are restricted to the lower unit, but in others they extend beyond the unconformity separating Sequences S1 and S2 and have seafloor expression (profile PL8, Figure 2; profile PL7, Figure 3). Along profiles PL7 and PL8 the diapiric intrusives form a massif consisting of at least three intrusives suggesting that diapirism may have been episodic. Possibly basement may be incorporated into some of the massifs, but similarity in the acoustic impedance between the structures and the surrounding sediments does not appear to support such a supposition. Similarly the highs next to the northeast side of the ría tentatively identified as basement (profile PL8, Figure 2) may be due to mud diapirism rather than representing basement peaks.

DISCUSSION AND CONCLUSION

Basement in the region of the rías in northwest Spain is composed of Paleozoic metamorphic and igneous rocks fractured by northeast-southwest and northwest-southeast faults. The general linearity and symmetry of the rías coast line and irregularities along their sides suggest that the rías were formed by erosion along these fractures. Differences in the erosives of the country rock also could have contributed to the morphology of the rías. Such a difference has been inferred by PANNEKOEK (1966) to have produced the irregular outline of the Ría de Arosa. We propose that the morphology of the rías is probably a combination of both with faulting being responsible for local and regional uplifts and subsidence either toward the west-northwest and north-northeast (PAZOS *et al.*, 1994). Such a tectonic scheme is similar to the model proposed by BOILLOT and MALOD (1988) for the Galicia margin during its rifting stage in the Mesozoic.

Lack of stratigraphic data prevent accurate dating of ría formation and the age of their sediment fill, but their youthful appearance and the inferred age of their fill suggest that they are quite young, probably Miocene or younger in age. Thus ría formation is not related to the Early Cretaceous opening of Bay of Biscay as suggested by GARCÍA-MONDEJAR (1966, see his Figure 3). However, the north coast of Spain did experience post-Pyrenean deformation extension, during both the Oligocene and Miocene. This extensional phase created rift structures on the shelf off northern Spain, rejuvenated source areas and filled inland basins (EMERY and UCHUPI, 1984, p. 623 and references therein). It is possible that the rías are related to this extensional phase. However, it is more probable that the rías are the product of tectonic activity associated with the Betic (Alpine) Orogeny along the southern side of the Iberian Peninsula. This activity which propogated along the western Iberian margin reactivated Paleozoic faults and deformed the Mesozoic-Cenozoic sediment cover in Portugal and the Portuguese margin (CABRAL and RIBEIRO, 1980; COPPIER and MOUGENOT, 1982; RIBEIRO *et al.,* 1988; RODRIGUES *et al.,* 1992, 1995; CABRAL, 1993), and is responsible for the faulting, uplift and the erosion of several hiatuses on the Galicia margin (LAMBOY and DUPEUBLE, 1975; GROUPE GALICE, 1979; MALDONADO, 1979; MURILLAS *et al.,* 1990). Based on NONN's (1969) chronology for the three erosional surfaces in Galicia, PANNEKOEK (1970a) suggested the following development scheme for the rías: (1) in the middle Miocene the rías were eroded along pre existing faults; (2) the rías were eroded again after a period of Pontian tectonism, and (3) they underwent erosion a third time during early Pleistocene when the rías were eroded to their present depth and the rías slopes were molded into glacis (according to the *Glossary of Geology* a gently inclined slope, less steep than a talus slope). Recent seismic activity as documented by the United States Geological Survey National Information Center and the World Data Center A for Seismology and the Council of the National Seismic System (CNSS), a Roman mile stone from Pontevedra showing that in 132 AD (1766 years ago) sea level was 1.5 m below its present level (PAZOS *et al.,* 1994) and tide gauge data which indicate that sea level in the Ría de Vigo is rising at a rate of 2.9 mm/year (EMERY and AUBREY, 1991, p. 89), in Cascais just north of Lisbon at 1.7 mm/year and in Lagos at the southern tip of western Portugal at 1.7 mm/year. These observations demonstrate that tectonic activity along the plate boundary separating the Eurasian and African plates on the south side of the Iberian peninsula continues to effect its west side as far north as Galicia.

The stratigraphy of the Ría de Pontevedra mapped during the present investigation consists of two depositional sequences (S1 and S2) separated by an unconformity. Included with the lower sequence are erosional terraces and with the upper one the marine muds being deposited ion the rías now. HINZ (1970) and PANNEKOEK (1970b) inferred that the colluvium and weathered granite in the form of a terrace at the base of the sedimentary fill in the Ría de Arosa were emplaced during Kansan (Mindel) or Nebraskan (Günz) glacial stages. HINZ and PANNEKOEK also proposed that the well bedded fluvial sediments resting on these coarse sediments were deposited by the tributaries and the trunk river (Ulla River) as fans in the Ría de Arosa during the Illinoian (Riss) and/or Wisconsin (Würm) glaciation as the result of major degradation upstream due to a drop in base level, *i.e.* drop in sea level. Sequence S1 and associated terraces at the mouth of the Ría de Pontevedra are possibly of fluvial origin and be may be coeval to the bedded fluvial sequence described by HINZ (1970) from Ría de Arosa. In the absence of stratigraphic control the possibility that S1, its component units, and their bounding hiatuses are pre-Wisconsin merits serious consideration. We have tentatively assigned a pre-Wisconsin age to it and inferred that the unconformity separating S1 and S2 was eroded during the glacially induced Wisconsin (Würm) regression. If this correlation is correct then the Ría de Pontevedra was a site of non-deposition during the Wisconsin regression and the detritus eroded upstream bypassed the ría and was deposited beyond its confines.

We infer that Sequence 2 resting unconformably on Sequence 1 is of Holocene age and was deposited during the last glacially induced transgression. It is equivalent to the transgressive and high stand deposits described by HERNANDEZ-MOLINA *et al.* (1994) from the Ría de Muros and Noya. The lower unit (S2a) of the sequence, filling lows on top of S1, was probably deposited during the initial marine flooding of the ría. Unit S2b, resting unconformably on S2a and filling most of the Ría de Pontevedra, is a marine unit whose erosional top has been correlated by GARCÍA-GIL *et al.* (In press) with the Younger Dryas regression which according to FAIRBANKS (1989) took place 11,000 to 10,500 years ago and to BARD *et al.* (1996) 12,900 to 12,700 years ago. The youngest unit of Sequence 2 (S2c) was emplaced during the post-Younger Dryas transgression and includes the modern marine muds being deposited in the rías today. The edges of the deltas associated with this unit range in depth from 12.75 to 33.75 m indicating that the post-Younger Dryas transgression was not as continuous as the curves of FAIRBANKS (1989) or BARD *et al.* (1996) suggest. According to NONN (1966; in CASTAING and GUILCHER, 1995), VILAS (1983), VILAS and NOMBELA (1985), NOMBELA *et al.* (1987) and REY (1993) modern sediments in the rías today display an increase in the silt-clay fraction toward the head and axial part of the rías with the deposits on their margins being affected by tidal currents during high tides. The lower reaches of the rías are sites of non-deposition of modern sediments and are covered by relict sand and gravel. Sedimentary features displayed by unit S2c include a massive storm fan east of the gap between Ons and Onza Island, current structures (sand waves and mega-ripples), and box-shaped channels which may be the result of slope failures.

The most significant features revealed by the seismic reflection recorded in the Ría de Pontevedra are the diapiric structures in the sediment fill at the entrance to the ría. No such structures were reported from the Ría de Arosa, or Muros and Noya. The orientation of two troughs in the diapiric field suggest that the structures may trend north-northwest to south-southeast, but more closely spaced profiles are needed to verify this. Lack of differences in the acoustic impedance between the structures and the surrounding sediments also suggest that most, if not all, of the diapirs are sedimentary rather than igneous in origin. Magnetic data will be collected in the next cruise to verify such an origin. If mud, the source appears to be within the S1 or pre S1 sediments. Mechanisms suggested for similar structures in British Columbia include subsidence associated with earthquake induced liquefaction and uplift driven by growth of localized gas hydrates in the near-surface sediments (BORNHOLD and PRIOR, 1989). Possibly the structures in the Ría de Pontevedra could have been created by rising hot springs which mobilized the mud leading to their intrusion of the overlying sediments. Such springs along the north-northwest-south-southeast to northeast-southwest faults are quite extensive in the region with water temperatures ranging from 25 to 60°C (Insert Figure 1A; WARING, 1965; ITGE 1985, 1990). However, such an origin is unlikely as rising springs, like rising thermogenic and biogenic gases, form pockmarks and even small mounds on the seafloor, not diapiric structures in the sediments they flow across on the way to the surface (UCHUPI *et al.*, 1996 and references therein). It is more probable that mobility of the mud was triggered by sediment loading

ACKNOWLEDGMENTS

This investigation was supported by the Spanish Comisión Interministerial de Cyanic y Technologia (CICYT) under the Project No. Mar 95-1953. We thank the Instituto Español de Oceanografia, Universidade de Vigo and Xunta de Galicia, for their help during this investigation. We are indebted to the Captain and crew of the B/O Valentin Paz-Andrade for their help during the cruise. We are indebted to Neal Driscoll and George Voulgaris for their comments of an earlier version of this manuscript. Drafting of illustrations was made possible by funds provided E. Uchupi by Woods Hole Oceanographic Institution. Contribution no. 9788 of Woods Hole Oceanographic Institution.

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