NATURE AND TECTONIC SETTING OF THE GUADALQUIVIR BANK (GULF OF CADIZ, SW IBERIAN PENINSULA)

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Abstract: During two oceanographic cruises on the Guadalquivir Bank (continental slope of the southwestern Atlantic margin of the Iberian Peninsula), Variscan basement rocks were dredged, as well as, lithified hardground-related carbonate sediments containing Late Tortonian-Early Messinian foraminifers. Basement samples contained graywackes, shales, quartzites, basic volcanics, and metabasites in amphibolite facies. All these sedimentary and volcanic rocks can be attributed to the Volcano-Sedimentary Complex of the Pyrite Belt (South Portuguese Zone of the Iberian Variscan belt). This correlation is based on petrological similarities and the occurrence of low-grade metamorphism in prehnite-pumpellyite facies, identical to those defined in the Pyrite Belt. The metabasites have been correlated with the Beja-Acebuches Ophiolite Complex. These results have led us to consider two problems: the relationship between the Guadalquivir Bank and the South Portuguese Zone and the situation of this bank in the context of the Mesozoic evolution of the continental margin.The outcrop of these rocks on the middle slope of the Portuguese margin implies Variscan fold-and-thrust tectonics of greater intensity for the South Portuguese Zone, and the erosion of the Culm Group in the Guadalquivir Bank area. This erosion is explained by the uplift of the continental side of the transform fault that gave rise to the Mesozoic margin of the Southern Iberian Peninsula.

Key words: Gulf of Cadiz, South Portuguese Zone, transform margin, Mesozoic

Resumen: En el curso de dos campañas oceanográficas realizadas en el Banco del Guadalquivir (talud continental del margen suroccidental atlántico ibérico), se han dragado rocas procedentes del basamento varisco y de un *hardground* carbonatado, que ha proporcionado foraminíferos de edad Tortoniense superior-Messiniense inferior. Las rocas del basamento corresponden a grauvacas, pizarras, cuarcitas, rocas volcánicas básicas y metabasitas en facies de anfibolita. El conjunto de estas rocas se puede atribuir al Complejo Volcano-Sedimentario que caracteriza la Faja Pirítica (Zona Surportuguesa). Esta correlación está basada en la similitud petrológica y en la ocurrencia de un metamorfismo de bajo grado en facies de prehnita-pumpellita, idéntico al definido en la Faja Pirítica. Por otra parte, las metabasitas se han correlacionado con el Complejo Ofiolítico de Beja-Acebuches. Estos resultados conducen a la consideración de dos problemas: la relación entre el Banco de Guadalquivir y la Zona Surportuguesa, y la situación del Banco en el contexto de la evolución mesozoica del margen continental. El afloramiento de estas rocas en el talud medio implica una tectónica tangencial varisca de mayor intensidad en la Zona Surportuguesa y la erosión del Grupo del Culm en el área del Banco del Guadalquivir. Esta erosión se explica por el levantamiento del borde continental de la falla transformante que determinó la evolución de la margen mesozoica del Sur de la Península Ibérica.

Palabras clave: Golfo de Cádiz, Zona Surportuguesa, margen transformante, Mesozoico

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The southwestern continental margin of the Iberian Peninsula was developed as a consequence of the relative movement between Africa and Eurasia (Iberia) (Maldonado *et al*., 1999, Vázquez and Vegas, 2000). In front of Faro, the E-W trending continental margin structure is characterized by a basement elevation along the middle continental slope, that constitutes the southern boundary of the Algarve Basin (Fig.1). Along this basement relief, clearly depicted on the bathymetric chart at 100 km from the shoreline, three basement highs can be differenciated: the Portimão and Albufeira highs, covered by sediments of variable thickness, and the Guadalquivir Bank, which is the sole outcrop of the Variscan basement on the southern Iberian continental margin.

Studies carried out by Baldy (1977) on the southern Portuguese margin describe some rocks dredged along the

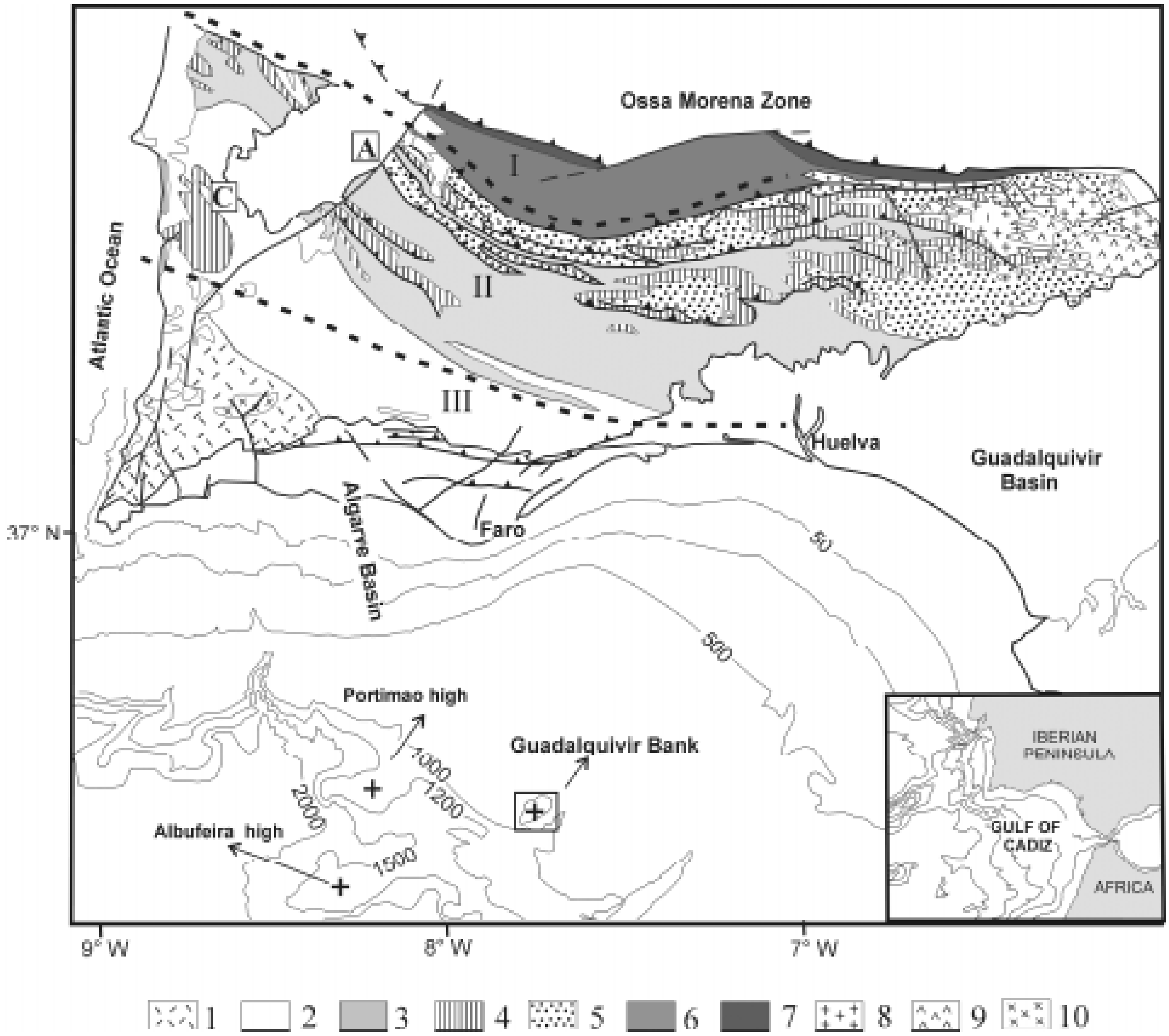

Figura 1.- Location of the Guadalquivir Bank on the continental margin of the southwest Iberian Peninsula (the square marks the studied outcrop of the Guadalquivir Bank) in relation to the South Portuguese Zone domains, after Oliveira (1990). 1: Brejeira Formation (Middle Namurian–Early Westphallian); 2: Mira Formation (Namurian); 3: Mértola Formation, Culm (Upper Visean); 4: Volcano-Sedimentary Complex (Upper Famennian-Middle Visean); 5: Phyllite and quartzite (Upper Famennian); 6: Pulo do Lobo Formations (Lower Devonian?-Famennian); 7: Beja-Acebuches amphibolites, (Lower Devonian?); 8: Granites and granodiorites (Upper Carboniferous); 9: Gabbros, diorites and tonalites (Upper Carboniferous); 10: Granitoids (Cretaceous). I: Northern Domain, II: Central Domain, III: Southern Domain; C: Cercal Anticline; A: Aljustrel Anticline.

southern scarp of the Guadalquivir Bank (L74-DR211, see Fig. 2a for location). Samples obtained include graywackes, which are characteristic of the South Portuguese Zone of the Iberian Massif; basalts or doleritic basalts; limestones with sponge spicules, tentatively attributed to a Toarcian age; and a marly sandstone with *Globorotalia hirsuta*, *Globorotalia puncticulata*, *Globorotalia gr.padana* and *Globorotalia truncatulinoides* resulting from present-day processes of contamination. This marly sandstone can be ascribed to Pliocene-Pleistocene sedimentation. Another dredge (H76-DR 37, see Fig. 2a for location) (Mougenot *et al.*, 1979) recovered a micrite cobble with radiolarians, small spicules and filaments, which were attributed to the Jurassic (Dogger).

These basement highs, that lies over a thinned continental crust of 22-23 km (González-Fernández *et al.*, 2001), are correlated to a NE-SW gravity anomaly of 140 mGal that extends to 8º 50' W (Dañobeitia *et al.*, 1999; Carbó *et al.*, 2000) and a magnetic anomaly of 300 nT (Dañobeitia *et al.*, 1999; Catalán *et al.*, 2000).

All of these data make the Guadalquivir Bank an important target. With this geological background in mind, we present the results of two seismic and sampling cruises (Anastasya00 and Anastasya01) carried out on the Guadalquivir Bank. This study of the outcropping materials on the Guadalquivir Bank has been undertaken to establish their meaning in the context of the Iberian Massif. Moreover, we discuss out their tectonic setting and the position of the Bank during the Mesozoic tectonic evolution of the south Iberian margin within the African-Iberian plate boundary.

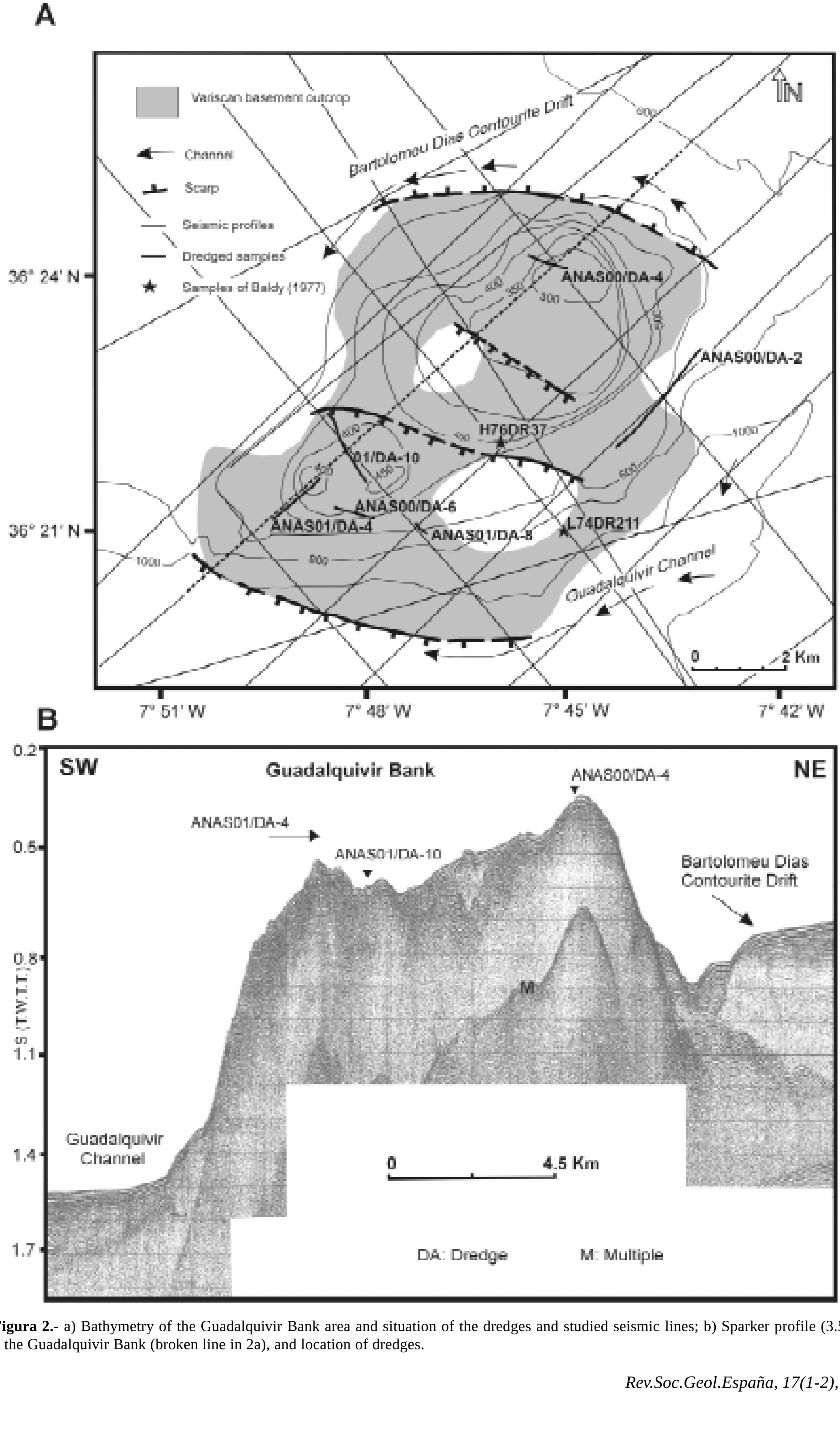

Figura 2.- a) Bathymetry of the Guadalquivir Bank area and situation of the dredges and studied seismic lines; b) Sparker profile (3.500 J) along the Guadalquivir Bank (broken line in 2a), and location of dredges.

Geological background

The South Portuguese Zone corresponds to the southernmost unit of the Western European Variscan Belt. As a whole, it represents the southern external zone of the Variscan Iberian orogen, characterised by thin-skinned tectonics related to a southwest verging, foreland fold-and-thrust belt (e.g. Ribeiro *et al*., 1983; Ábalos *et al*., 2002; García Alcalde *et al*., 2002). The type and age of rocks led to establish a classic division into three domains, following the general trend of the chain (Fig. 1).

The northern domain (I, Fig. 1) is associated with the Beja-Acebuches Ophiolite Complex and the Pulo de Lobo Formation (Oliveira, 1990). Ophiolites form a thin band, basically constituted of amphibolites as well as metabasalts and metagabbros. The Pulo de Lobo Formation is made up of phyllites, quartzites and metavolcanics of basic and acidic character. An Early Devonian (?)-Famennian age has been attributed to this formation.

The central domain (II, Fig. 1) is characterised by the outcropping of three formations of Late Famennian-Late Visean age, which, in ascending order, are: *Phyllytes and Quartzites Formation*, *Volcano-Sedimentary Complex* and the *Culm Group* (Schermerhorn, 1971). The Phyllytes and Quartzites Formation takes its name from its dominant rocks, comprising alternating layers of sandstones and shales; the sandstone lithologies include quartzite layers, quartzwackes, and some conglomerates. The Volcano-Sedimentary Complex contains massive sulphide deposits, and is formed by the interfingering of volcanic and sedimentary rocks. In the Volcano-Sedimentary Complex, a central area has been recognised, with three acidic volcanic episodes, and a northern area, with a single one. The volcanic horizons include pyroclastics, minor acidic lavas, reworked tuffs, and interbedded siliceous shales. Basic events are less abundant, and are associated with mafic lavas. The so-called Culm Group, also known as the Mértola Formation in Portugal (Oliveira, 1990), consists of sandstones and alternations of sandy shale and lutite sequences. In this central band, there is a significant occurrence of very low-to-low-grade metamorphism in prehnite-pumpellyite facies to greenschist facies (Munhá, 1990).

The southern band (III, Fig. 1) includes the Mira Formation and Brejeira Formation outcrops (Oliveira, 1990). Both formations correspond to the Baixo Alentejo Flysch Group, which also comprises the Mértola Formation. Taken as a whole, these formations are made up of an alternation of graywackes, sandstones and shales, which can be distinguished by some marker beds: continuous shaly beds at the bottom of the Mira Formation and thick-bedded and coarse-grained graywackes in the Lower Brejeira Formation. In this southern band it also crops out, although in a smaller area, in the core of two antiforms, two terrains of particular lithologies belonging to the Tercenas Formation of sandstone character, and the Carrapateira Group, which represents a condensed succession (Oliveira, 1990).

Four metamorphic zones have been defined in the South Portuguese Zone, according to the mineral assemblage of the mafic metavolcanics and data coming from illite crystallinity in some metasedimentary rocks. The northern zone corresponds to a medium-grade metamorphism in greenschist facies which affects the Pulo de Lobo Formation rocks. Towards the south, the grade of metamorphism decreases from greenschist facies in the transition zone to low-grade metamorphism in the northern boundary rocks, and in the more eastern area of the Pyrite Belt. Southwards, in the Pyrite Belt, a low-to-very low-grade metamorphism in prehnite-pumpellyite facies develops. In the Flysch of Baixo Alentejo, anchimetamorphism conditions are reached and zeolite facies appear (Munhá, 1990).

On the continental margin, the offshore prolongation of the Algarve Basin consists of Late Triassic to Quaternary deposits (Terrinha, 1998), which overlies the Variscan basement that crop out in southern Portugal (Mougenot, 1989). The basement is made up of Devonian and Carboniferous materials, that belong to the South Portuguese Zone.

Methodology

The present study includes rock samples obtained from the dredges ANAS00/DA-2, ANAS00/DA-4, ANAS00/DA-6, ANAS01/DA-4, ANAS01/DA-8, and ANAS01/DA-10, collected on the Guadalquivir Bank during the cruises Anastasya00 and Anastasya01 aboard B.I.O. *Cornide de Saavedra and Hesperides*. During these two research cruises, the Iberian continental margin was surveyed as part of the Tasyo Project. Rock samples were collected at 270-760 m depth with a rectangular, benthic-type dredge using a Global Positioning System. In all cases, dredging operations started in deep waters, ascending upslope towards the summits of the Bank. Duration of dredging averaged 15-20 minutes. The targets were identified from the interpretation of Sparker (3500-7000 J) and Topographic Parametric Sounder (TOPAS) profiles previously obtained during Anastasya99, Anastasya00 and Tasyo 2000 cruises, the last one aboard the B.I.O. *Hespérides*. Sample locations are shown in Fig. 2a and 2b.

The Guadalquivir Bank: Seismic and sample data

The Guadalquivir Bank is an elongated high, located on the middle continental slope of the Atlantic Southern Iberian margin, 100 km south of Faro (Portugal), and is the margin's only Variscan basement outcrop (Fig. 1). The Bank, with its main axis oriented at 080°, clearly shows a transversal morphological asymmetry: its northern slope emerges from a depth of 600 m and

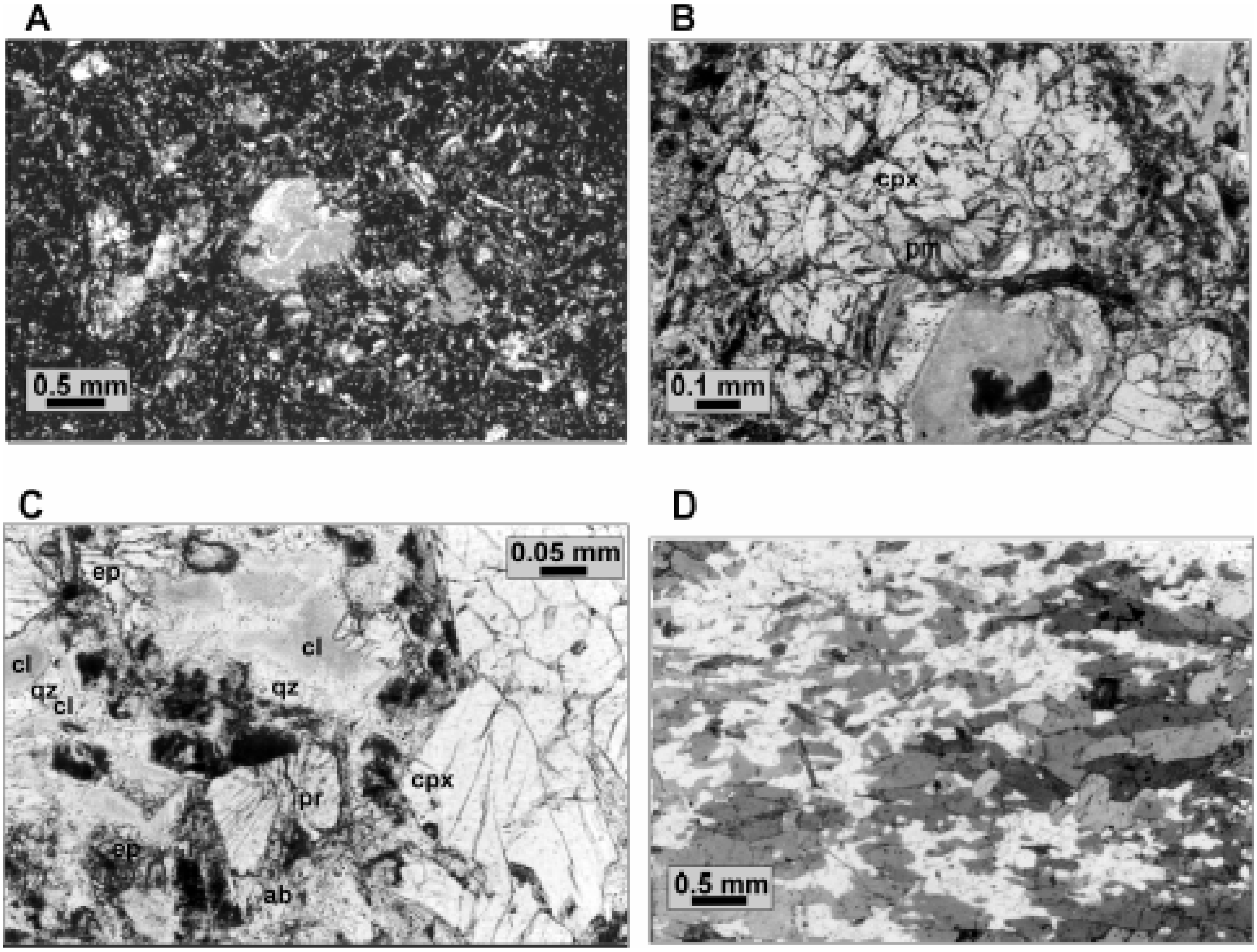

Figura 3.- a)Textural aspect of the basaltic volcanic rock corresponding to sample ANAS01/DA10-2. Note partial resorption in the augite phenocryst (crossed polars); b) Relationships between pumpellyte (pm) and glomerophyric aggregate of clinopyroxene (cpx). Quarzt (qz) and clorite (cl) are infilling an amigdule; c) Reinform prehnite (pr) aggregate occupying interstices in the matrix and being embraced by cloudy albitized plagioclase laths; ab: albite; ep: epidote; d) Textural aspect of amphibolite.

reaches 250-300 m at the summit, whilst the bottom of the southern slope, more abrupt, lies at 900-1,000 m. High-resolution seismic profiles and the bathymetric chart reveal two prominent summits on the Bank separated by an irregular slope, whose central part presents a sedimentary cover of about 150 ms T.W.T.T (Figs. 2a and 2b). The rounded northern relief is found at a depth of 250 m and the southern, of irregular shape, at 380 m. Southwards, seismic profiles show that the Guadalquivir Bank lies under the Allochthonous Unit of the Gulf of Cádiz (known as the "*olistostromic unit*", Maldonado *et al.*, 1999) and northwestwards, it is covered by Neogene-Quaternary sediments. The Guadalquivir Bank act as an obstacle for the advance of the allochthonous units to the north. These chaotic masses extend from the Iberian Peninsula to the Horseshoe and Seine Abyssal Plains, and were emplaced along the continental slope during the Tortonian (Maldonado *et al*. 1999; Maestro *et al.*, 2003).

Considering the sedimentary-erosional processes that have developed on the margin, the Bank constitutes a passive obstacle for the Mediterranean Outflow Water (MOW) that flows from the Strait of Gibraltar to the northwest along the continental slope of the Gulf of Cadiz. Consequently, the base of its northern and southern slopes corresponds to channels eroded by the MOW. The northern slope is cut by a tributary of the main MOW channel that flows close to the sandy contourite drift forming the marginal platform of Bartolomeu Dias, whilst the southern slope is bounded by the main channel of the Mediterranean undercurrent, called the Guadalquivir Channel (Fig. 2) (Díaz del Río *et al.*, 1999; Hernández-Molina *et al.*, 2003).

In relation to the materials dredged on the Guadalquivir Bank, the wide range of rock samples obtained can be ascribed to four different groups: a) sedimentary rocks; b) volcanic rocks; c) metabasites in amphibolite facies, which correspond to the Variscan basement of the southwestern Iberian Peninsula; and d) calcareous rocks related to a carbonated superficial crust.

Sedimentary rocks

This group comprises: graywackes (quartzwackes), shales and quartzites.

Sample ANAS00/DA 6-1 (the last number stands for the corresponding rock fragment) is the only one

	1	2	3	4	5	6	7	8	9
SiO_2	52.02	52.65	35.57	36.39	42.93	43.46	37.63	29.99	23.53
TiO_2	0.33	0.31	0.17	0.28	0.06	0.16	0.30	0.33	0.17
Al_2O_3	1.81	4.13	21.03	21.67	21.06	21.90	22.65	17.88	19.87
FeO_T	6.35	5.88	11.22	9.85	4.76	3.45	11.95	17.27	32.73
MnO	0.17	0.18	0.08	0.19	0.02	0.05	0.11	0.19	0.07
MgO	18.92	16.71	2.86	1.82	0.05	0.14	0.45	22.43	5.85
CaO	19.03	17.62	20.74	21.67	26.35	26.86	24.31	0.33	0.18
Na_2O	0.13	1.37	0.18	0.17	0.01	0.09	0.03	0.03	0.03
K_2O	0.11	0.17	0.05	n.d.	n.d.	n.d.	0.02	0.07	0.87
NiO	0.13	0.03	n.d.	n.d.	n.d.	n.d.	n.d.	0.05	0.01
Cr_2O_3	0.21	0.06	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.07
Total	99.21	99.11	92.07	93.38	95.24	96.11	97.45	88.27	83.38

Table I.- Micropobe analyses of minerals referred in the text. Numbers 1 to 8 correspond to sample ANAS01/DA10-2. Analyses 1 and 2: augi te (Wo_{38-39}, En_{52-51}, Fs_{10}); 3 and 4: pumpellyite; 5 and 6: prehnite (Fe^{+3}= 0.09-0.13; considering Fe as Fe_2O_3 total); 7: epidote (Ps_{25} calculated considering Fe as Fe_2O_3 total); 8: chlorite. Number 9 corresponds to chlorite from sample ANAS00/DA6-3; n.d.: not detected.

that could be considered a graywacke. In hand sample, it shows a greyish colour. In thin section, it consist of 15-20 % of matrix, and a fine-grained sand fraction within which quartz grains largely dominate over feldspar and lithic fragments. The latter are only represented for a few chert fragments and the former by very scarce plagioclase (albite-rich) grains. Therefore, this sample could be classified as quarztwacke. The matrix is an intergrowth of chlorite, white mica (illite?), and quartz grains, as well as by dusty hematite particles, which gives a reddish pigmentation to the matrix. Occasionally the mica flakes insinuate a preferred orientation, but not a very penetrative one.

Shales are represented by samples ANAS01/DA10-6, ANAS01/DA4-1, ANAS01/10-4 and ANAS01/DA8-4. The first two have a glossy golden colour and both show fissility in hand sample. They are thin-bedded quartzitic shales (or siltstones), in which beds rich in silt-quartz alternate with micaceous beds. In the former, quartz grains are cemented by quartz overgrowths, whilst in the latter, fine-grained aggregates of chlorite and white mica (illite?), as well as elongate quartz grains, seems to define a preferred orientation (slaty cleavage) parallel to bedding. The sample ANAS01/DA 8-4 is similar, but there were some noticeable differences. It shows a reddish colour and is also bedded, but the micaceous beds consist mainly of chlorite aggregates and abundant reddish-brown granules of iron oxide (hematite?) and minor quartz and white mica (illite?). In any case, micaceous components also roughly show a preferred orientation. The sample ANAS01/DA10-4 is a dark-grey shale which shows the highest quartz contents (siliceous shale) and abundant disseminate pyrite grains. In this rock, bedding is mainly built up by graded-size quartz grains, which are frequently cemented by overgrowths of quartz and microquartz. In the finest rock fraction, white mica (illite?) aggregates and small amounts of chlorite also appear; with both minerals pointing to an incipient preferred orientation. Pyrite occurs as trails, mainly concentrated in the finest grained beds of the sample. The presence of pyrite makes this type of siliceous shale similar to the "black shales" of the Volcano-Sedimentary Complex of the Iberian Pyrite Belt.

A different type of shale is represented by sample ANAS00/DA6-3. It shows a dark reddish colour and contains a smaller amount of quartz than the samples described previously. This shale is made up of stringers of quartz grains that are arranged in thin laminated beds or scattered in smaller amounts within the dark reddish matrix. The latter is formed by trails of abundant hematite grains and dark red amorphous aggregates of goethite-limolite, probably originating from alteration of the quartz grains. The interstices among iron components are filled by well-recrystallized chlorite aggregates. The chlorite is an iron rich variety (Table I, 9, FeO=31.92-30.17, MgO=5.85-5.58) of the chamosite group. In particular, it is very similar to the brunsvigite (Deer *et al.*, 1971), which is currently considered a transformation product of basic volcanic rocks. It is noteworthy here that the arrangement of chlorite aggregates seems to reproduce the shape of volcanic glass shards. Therefore, this sample could possibly represent a volcanogenic material or, more probably, a reworked equivalent. Moreover, it could be compared with those described as "hematite shales" in the Volcano Sedimentary Complex of the Iberian Pyrite Belt.

Sample ANAS01/DA8-3 is a medium-grained quartzite. It is almost wholly composed of monocrystalline quartz grains, which are cemented by quartz overgrowths and white mica, with chlorite as pore filling cement. In some irregular vein-like zones of the rock, quartz is recrystallized and forms a granoblastic aggregate that is accompanied by larger chlorite masses. There are also another veinlets made up of stretched fibbers of quartz aggregates. The sample ANAS01/DA8-3 represents a wider vein of the same type, but consisting of larger (1cm long) quartz aggregates.

We can conclude that all the rocks described here show a certain amount of recrystallization in their sedimentary components, in particular, in those represented by quartz, chlorite, white mica and some albite. The three former components frequently show a preferred orientation (slaty cleavage) superimposed and parallel to S_0, but not a very penetrative one. Therefore, we can assume that these rocks never reached the greenschist facies, but they probably reached temperatures corresponding to that of very low-grade metamorphism.

Volcanic samples

Volcanic rocks are represented by a sample of volcanic glass (ANAS00/DA6-4) and three fine-grained, massive volcanic rocks approaching a basaltic (ANAS01/DA10-2) or andesite (ANAS01/DA10-5 and ANAS01/DA10-1) composition.

Sample ANAS00/DA6-4 has the appearance of a silicic volcanic glass. It is characterised by curved concentric "perlitic" cracks (perlitic texture), which result from hydration and thus expansion of the glass, not from cooling processes. Thus, it can be considered as an obsidian. It contains some scattered grains of iron ore which were partially oxidized during hydration, giving rise to a golden-yellow coloured perlite. Incipient devitrification or recrystallization in a concentric arrangement also occurs.

The rock corresponding to sample ANAS01/DA10-2 is of basaltic affinity and shows a porphyritc-glomerophyric texture (Fig. 3a) with an intersertal to intergranular groundmass. The scarce phenocrysts and glomerophyric aggregates are made of colourless augite (Wo_{39-37}, En_{51-52}, Fs_{10-11}; Table I, 1 and 2), which appears often partially reabsorbed by the matrix. The latter was initially formed by plagioclase microlites enclosing interstitial glass and, probably, some clinopiroxene granules, but now the entire volcanic groundmass association is almost completely transformed. Thus, plagioclase microlites have become albitized and the yellow-orange interstitial glass transformed into Mg-Fe chlorite (Table I, 8) and abundant dusty granules of sphene. Additionally, pumpellyite, as well as prehnite, epidote-clinozoisite and quartz, also appear as the main alteration components of the matrix. Pumpellyite occurs in moderate amounts and sometimes shows border relationships with clinopiroxene (Fig. 3b), so that the former seems to growth at the expense of the latter. However, in the interface between both minerals, chlorite aggregates occur in several cases. This may result from a previous alteration of either clinopyroxene or old volcanic glass. The pumpellyite frequently shows its characteristic fibrous habit in needle-like clusters with radial (Fig. 3b) or stellate arrangements. The larger-sized aggregates are light-coloured and show a weakly pleochroism (colourless, pale green, pale yellowish brown). Only the tiny masses of variously oriented fibres, which appear scattered through the matrix, show pleochroism with bluish green tones (or shades) and anomalous interference colours. Nevertheless, in any case, as shown in Table I (3 and 4), microprobe analysis indicates the moderately iron-rich (FeO = 8.85-11.22, Fe as FeO_t) composition of this mineral.

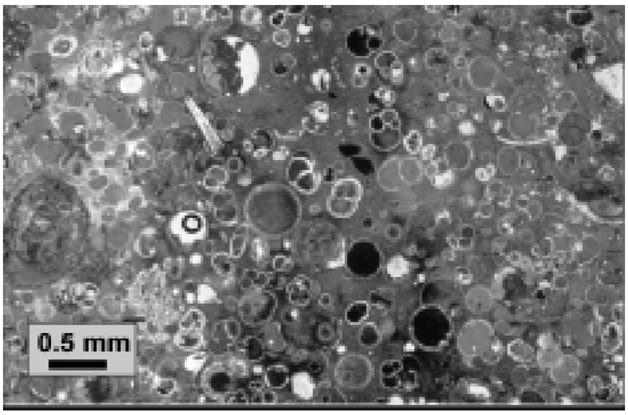

Figura 4.- Example of packed foraminifers in the lithified carbonate sediments that cap the Guadalquivir Bank.

Associate prehnite has also been found, although in very subordinate amount. The scarce crystal aggregates often appear occupying cavities enclosed by albitized plagioclase microlites (Fig. 3c). Prehnite seems to form at the expense of the plagioclase microlites, as well as from old chloritized glass. Its very pale greenish or colourless aspect, together with its lower refractive index and absence of pleochroism, make it clearly distinguishable from pumpellyite. In spite of its scarcity, some amount of prehnite occurs, forming reniform aggregates and displaying the characteristic columnar bow-tie appearance. As showed in Table I (5 and 6), it also corresponds to an iron bearing variety (Fe^{+3} = 0.09-0.13). Border relationships between prehnite and pumpellyite are not evident, but the abundance of quartz near the latter gives the impression that some of previous prehnite (+chlorite) was probably involved in the formation of pumpellyite.

Epidote is more abundant than both prehnite and pumpellyite and occurs as radial aggregates or individual crystals. Its composition is fairly consistent, corresponding to that of the pistacite molecule, ranging from Ps_{21} to Ps_{27} (Table I, 7). It grows frequently as pseudomorphs after pumpellyite. The character of the pumpellyte-epidote transformation, in the absence of actinolite, indicates that this process probably occurred through an oxidation reaction during the transition from prehnite-pumpellyte facies to the lower greenschist facies in an LP gradient type. Note the close analogy of the metamorphic association of this rock with those described in the basic volcanics of the Iberian Pyrite Belt (Munhá, 1976). In addition, both the textural appearance and composition of the augite relicts are identical to those described specifically for the so-called *lower mafic lavas* (Munhá, 1983)

The observed textures of the andesitic rocks (ANAS01/DA10-5) are predominantly intersertal to intergranular and more or less vesicular. No relict of igneous minerals has been found in these type of rocks, which are made up of plagioclase microlites completely transformed into aggregates of albite, calcite and sericite (illite?). The albitized plagioclase microlites enclose interstitial glass of yellow-orange colour, similar to that filling the amygdules. This glass denotes a previous alteration to fibropalagonite, which is in turn transformed into flake aggregates of Mg-Fe chlorites. Together with all these transformation products, trails of sphene granules and dusty particles of hematites are found. Additionally, abundant calcite filling veins and irregular amygdules also occur in the sample (ANAS01/DA10-2). The characteristics and metamorphic association of these rocks also display an overall similarity with those described as *upper mafic lavas* in the Iberian Pyrite Belt (Munhá, 1990).

Metabasites in amphibolite facies metamorphism

This group is represented by sample ANAS00/ DA6-102 which corresponds to a coarse-grained amphibolite (Fig. 3d) with pnematoblastic foliation defined by green hornblende. The hornblende contains elongate ilmenite inclusions, which mark an internal foliation parallel to the external one. The planar fabric is well marked by metamorphic banding which gives rise to amphibole-rich layers alternating with others made up by a granoblastic aggregate of plagioclase, quartz and subordinate amphibole. The lack of garnet, the presence of ilmenite in place of rutile and the An content in the plagioclase (An_{25-30}), indicate a low pressure regional metamorphism in amphibolite facies conditions. The characteristics of this rock bear a strong resemblance to the less deformed and coarse-grained types of amphibolites in the Beja-Aracena LP metamorphic belt, at the contact between the Ossa-Morena and South Portuguese zones of the Iberian Massif.

Deep water lithified carbonate sediments, associated with mineralised (phosphate and iron minerals) hardground surfaces

One of the dredged samples (ANAS00/DA4-1) corresponds to a fragment of about 3 cm thick limestone crust or hardground partially phosphatised (Mata *et al*., 2002). In thin section (Fig. 4), it was found to be a packed planktonic foraminifer micrite (wackestone to packestone). Additional skeletal grains, present in very small amounts, include benthic foraminifera, disarticulated and commonly fragmented ostracod carapaces, and echinoderm and molluscan skeletal debris. Non-skeletal carbonate particles are represented by scattered coarse, sand-grade lime mudstone and wackestone intraclasts, in part affected by dolomitization. Terrigenous components, mainly fine-grained detrital quartz, occur in trace amounts. Phosphates appear to have replaced micritic matrix preferentially, and the degree of phosphatization seems to increase, though irregularly, towards the inferred top of the hardground.

Among the planktonic foraminifers, *Orbulina universa* and *Orbitulina suturalis*, together with different species of *Globigerina* and *Globigerinoides*, prevail. Also occurring are *Neogloboquadrina*, with a chamber morphology pointing towards *N. acostaensis*, and keeled globorotalids, probably belonging to the group of *Globorotalia menardii* or *G. miotumida*. Thus, a Late Tortonian to Early Messinian approximate age is indicated for sample ANAS00/DA4-1.

Samples ANAS00/DA4-2 and ANAS00/DA4-3 are burrowed skeletal wackestones with sparite-cemented moulds of formerly siliceous sponge spicules and aragonite bivalve shell fragments, echinoderm fragments and occasional ostracods set in a micritic matrix. Similar to sample ANAS00/DA4-1, both of these samples contain rare detrital quartz grains (mono and polycrystalline) and some mica.

Tectonic framework of the Guadalquivir Bank

As far as the Guadalquivir Bank's tectonic framework is concerned, our data clearly indicate that the Bank belongs to the continental crust that characterises the South Portuguese Zone of the Hesperian Massif. Nevertheless, the dredged rocks used for our study present some correlation problems with regard to the internal division of the South Portuguese Zone. Moreover, the location of this Variscan basement high within the framework of the geodynamic evolution of the southwest Mesozoic margin of the Iberian Peninsula, must also be considered. These two points will be further discussed below, bearing in mind that the Bank has been definitely assigned to an uplift of the Variscan basement on the continental margin. We will also attempt to define the position of this basement within the South Portuguese Zone.

Location of the Guadalquivir Bank in the context of the South Portuguese Zone

Even though the banded shales and the graywackes that were dredged for the present study could represent a relatively banal facies, it is, at first, possible to establish a correlation between the outcropping rocks at the Guadalquivir Bank and the central domain of the South Portuguese Zone described previously. This assumption is based on the similarities between some metasedimentary and mafic volcanic rock samples and the typical rocks of the Pyrite Belt, and also on the same metamorphism grade that affects the mafic rocks, of very low-to-low grade in the prehnite-pumpellyite facies that characterised the central band of the South Portuguese Zone.

In this context, the metabasite in amphibolite facies recovered on the Guadalquivir Bank (ANAS00/DA6-102) should belong to the Beja-Acebuches Ophiolite Complex, and therefore should represent part of the northern zone, with medium-grade metamorphism in greenschist facies.

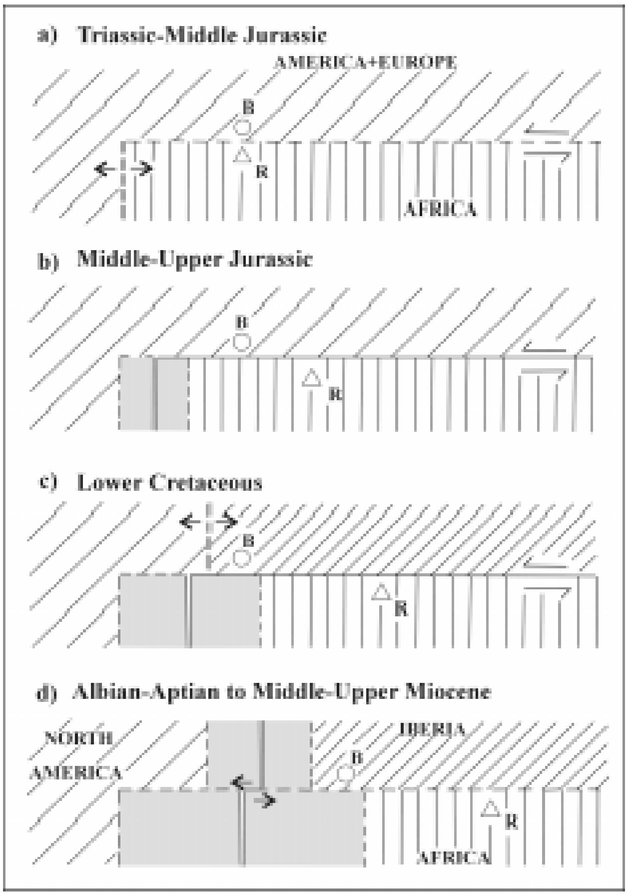

Figura 5.- Tectonic evolution of the southwest Iberian margin during the Mesozoic. Circle B represents a point of the Variscan basement that corresponds to the Guadalquivir Bank; triangle R is the conjugate point at the African margin, now located somewhere in the basement of the external zone of the Rif Belt. A) Intracontinental shear zone stage, Triassic-Middle Jurassic; B) Intracontinental transform fault stage, with the opening of the Central Atlantic, Middle-Upper Jurassic; C) Active transform margin stage, Lower Cretaceous; D) Inactive transform margin stage, from the opening of the Atlantic between Newfoundland and Iberian Peninsula until the re-initiation of the relative movement of Africa-Iberia in this region (Albian-Aptian to Middle-Upper Miocene). Noteworthy here is the different evolution of the conjugate American margin of Grand Banks. Based on the evolution sketch of transform margins by Reid (1989).

These data bring up the problem of how rocks of the central and northern bands can crop out into the Guadalquivir Bank. Following the direction of the sedimentary zones and main structures (Fig. 1), the outcropping rocks at the Guadalquivir Bank should correspond to the Brejeira Formation, to other equivalent materials, or to more recent materials of the Flysch of South Portugal, not affected by regional metamorphism.

The outcropping of rocks (with the same type of metamorphism) related to the metavolcanics of the Pyrite Belt could correspond to an anticline in the south verging set of folds and thrusts which characterise the South Portuguese Zone, as described in Silva *et al.* (1990) and, more recently, in Onézime *et al.* (2002). Nevertheless, the distance, perpendicular to the tectonic grain, between the southern alignment of the Volcano-Sedimentary Complex (defined by the Cercal anticline, Fig. 1) and the Bank, is more than 150 km. This implies a thrusting sheet of higher dimensions than that admitted in the tectonic models of the authors just cited. It could also indicate either a deeper main décollement zone or footwall thrust, or basement involvement in the thrust tectonics (limited thick-skinned tectonics). On the other hand, the thrust sheet with metavolcanics could not have reached the surface, and its outcropping at the Guadalquivir Bank is due to a post-Variscan intensive erosion. This erosive episode should be responsible of the lack of Culm rocks in such a southern zone.

The occurrence of metabasites in greenschist facies on the Guadalquivir Bank also introduces problems with regard to the geodynamic model of foreland fold-and-thrust belt. If the metabasites are part of the Ophiolite Complex that defines the suture from which the fold-and-thrust belt develops, it should be necessary to accept a more intensive thrust tectonics in this external zone of the Iberian Variscan orogen. This latter point (together with the outcropping of the typical metamorphic rocks of the Pyrite Belt) could be considered as an indicator of the occurrence of a basal thrust, which must be located at a higher depth than that proposed by Ribeiro *et al.* (1983) and Onézime *et al.* (2002). The occurrence of a deeper basal *décollement* is in agreement with data coming from the recently acquired Iberseis deep seismic reflection profile, which runs across the South Portuguese Zone and Ossa Morena (Carbonell *et al.*, 2001, Simancas *et al.*, 2003). Following this line of reasoning, it is possible to imagine a higher extension for the Variscan external zone off the South Portuguese Zone (Fig. 1).

Situation of the Guadalquivir Bank in the context of Mesozoic evolution of the southwest continental margin of the Iberian Peninsula

As it has been previously described, the Guadalquivir Bank is found in the middle slope of the SW continental margin of the Iberian Peninsula, which developed as a consequence of the relative movement between Africa and Eurasia. This movement began in the Triassic as a result of precursory rifting processes in the Central Atlantic opening, between North America and Africa. It continued during the Jurassic and Lower Cretaceous with the eastern drift of Africa from America-Eurasia, and ceased in the Lower Cretaceous (Aptian-Albian times) because of the North Atlantic opening, north of the Africa and America-Eurasia plate boundary. Since the Iberian Peninsula moved away from Newfoundland and an oceanic area developed between the Grand Banks and the Lusitanian margin, the Africa-Eurasia plate boundary jumped to the north of the Peninsula and the old, south Iberian boundary remained without substantial activity. Tectonic activity returned to this southern plate boundary in the Middle-Upper Miocene after the blocking of the movement in the Pyrenean-Cantabrian

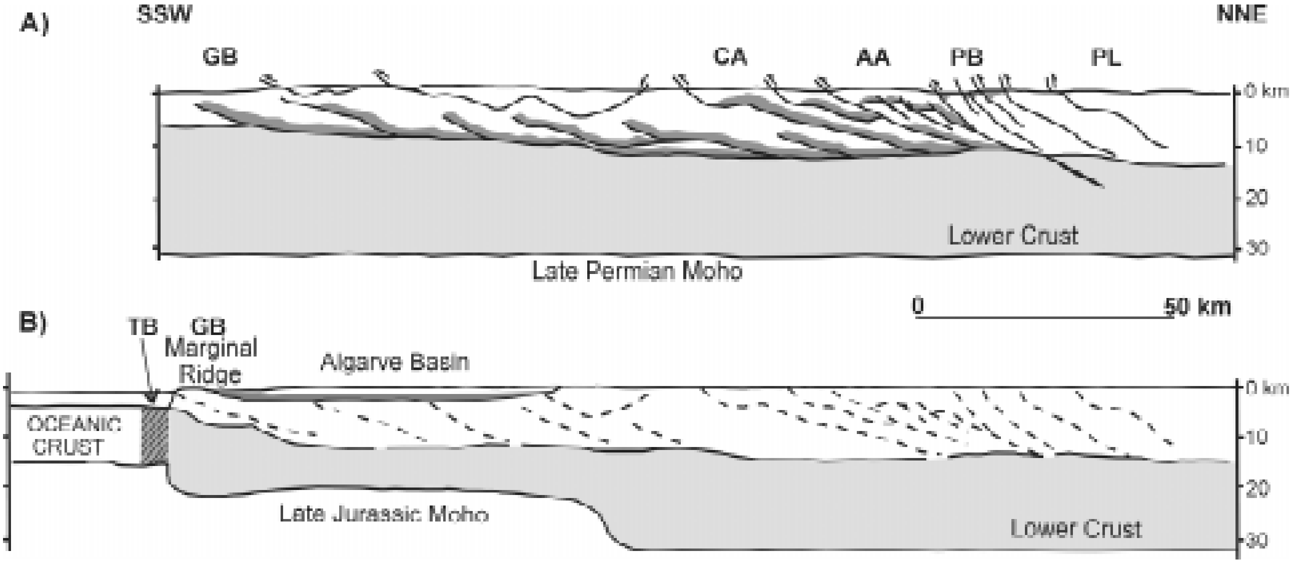

Figura 6.- Synthetic crustal cross-sections showing the tectonic models presented in this paper for the structure of the Variscan crust of the SW Iberian Margin. A) At the end of Triassic. Variscan structures largely modified from Ribeiro *et al.* (1983) and Onézime *et al*. (2002). B) At the end of Jurassic times. Moho depths based in González-Fernández *et al.* (2001) and Simancas *et al.* (2003). GB: Guadalquivir Bank; CA: Cercal Anticline; AA: Aljustrel Anticline; PB: Pyrite Belt; PL: Pulo do Lobo Formations; TB: Transform Boundary.

margin. Since then, a limited and distributed compression has been produced by the slow north-northwest convergence of Africa (Dewey *et al*., 1989; Srivastava *et al*., 1990; Vegas, 2001; Rosenbaum *et al*., 2002). During this stage (Tortonian-up to Present), a moderate inversion of the Mesozoic margin has been taking place.

In this tectonic evolution, the Variscan crust of the Guadalquivir Bank has been under different tectonic regimes, whose evolution has been depicted schematically in Fig. 5. In a first stage, a margin point situated in the position of the Guadalquivir Bank (point B in Fig. 5) successively passed from an initial stage linked to an intracrustal shear zone (Fig. 5a), through a continent-continent transform zone (Fig. 5b), and then to an ocean-continent transform zone, with the consequent inclusion in a transform margin (Fig. 5c). The change to the latter tectonic situation corresponds to the opening of the Central Atlantic, and to the development of marginal offsets which takes place in the intersection of transform faults and continental margins (Le Pichon and Fox, 1971). Since the separation between North America (Newfoundland, Grand Banks) and Iberia (Iberian Peninsula), the margin where the Guadalquivir Bank is located has become an inactive transform margin, as the transcurrent motion between Africa and Iberia ceases (Fig. 5d).

The plate tectonic model shown in Fig. 5 implies certain peculiarities for the Gulf of Cadiz margin. Opposite to its conjugate American plate margin (Grand Banks continental margin), in the evolution of the south Iberian margin, the change to an inactive transform margin has not taken place at the spreading axis pass but at the change of position of the Africa-Eurasia boundary (opening of the Atlantic, north of the transform fault). This means that the ridge has not passed by all the margin points and that the transcurrent movement has lasted a longer period of time, since the Upper Triassic to the Lower Cretaceous, along the entire margin. If this persistent relative shear movement is taken into account, it is then possible to explain the thinning of the crust on the continental side of the active transform margin, according to the viscous coupling model for transform margins of Reid (1989), as well as the uplift of the continental side at the point of contact between the continental and oceanic lithospheres, according to the thermo-mechanical coupling model proposed by Vågnes (1997). In this way, without resorting to rifting and marginal crustal extensional processes, it is possible to explain both the formation of the Algarve basin and the ascription of the Guadalquivir Bank to the edge of the continental crust, Variscan basement that bounded the Mesozoic Algarve basin. Under this tectonic scenario, the Guadalquivir Bank may be considered a marginal uplift of the Variscan basement situated on the continental side of the transform fault that separated the Eurasian-African plates from the Lower Jurassic to the Lower Cretaceous. Noteworthy in this context is the occurrence of a non-outcropping basement marginal high in an analogous situation, which marks out the base of the slope in the conjugate transform margin of South Newfoundland-Grand Banks (Auzende *et al*., 1970). The buried westward extension of the Guadalquivir Bank can be explained in a similar fashion.

Moreover, given that the local isostatic balance of the continental edge of the transform margins causes the erosion of an important part of the continental crust (c.f. Vågnes, 1997), the outcropping of rocks belonging to the Pyrite Belt on the Guadalquivir Bank could be explained as a consequence of this marginal edge erosion. Thus, the absence of Portuguese flysch on the Bank could be attributed to this erosion.

Conclusions

The nature of the rocks dredged on the Guadalquivir Bank indicates some considerations about the Variscan basement of the southwest Iberian margin and the Mesozoic evolution of this structural high. With regard to Variscan history, it has been possible to identify rocks whose composition and type of metamorphism is equivalent to the rocks that characterise the Volcano-Sedimentary Complex of the Pyrite Belt. Moreover, a single amphibolite recovered sample has been described as identical to the basic rocks of the Beja-Aracena Metamorphic Belt. The occurrence of these types of rocks 150 km south of the Pyrite Belt and 200 km south of the Beja-Acebuches Ophiolite Complex leads to the conclusion that the previously proposed tectonic model by Ribeiro *et al*. (1983) and Onézime *et al*. (2002) for the South Portuguese Zone should be modified to some extent.

In this way, it would be necessary to admit in the more external domain, the existence of a Volcano-Sedimentary Complex thrusting sheet under the external Portuguese flysch formations. The dimension of this sheet suggests the need to deepen the basal detachment proposed for the area, since until now only the Culm was considered to be involved in the fold and thrust set (Fig. 6a). It would be necessary to admit as well that part of the metabasites of the Variscan suture are in some way involved in the thrusts.

The outcropping of Pyrite Belt rocks on the Bank's surface also leads to some conclusions about the tectonic evolution of the southwest Iberian Peninsula Mesozoic margin. Firstly, this outcrop implies the erosion of the youngest formations of the Portuguese flysch (with approximately 1,000-2,000 m thickness, taking into account the lack of precise data). This erosion could be explained in terms of transform margin tectonic models, by the development of basement highs (high-standing marginal uplifts at the continental side of the transform fault) where important erosion takes place. In this context, the Guadalquivir Bank could be ascribed to part of the high-standing marginal uplift that formed the southern boundary of the Mesozoic margin of the Algarve (Fig. 6b). Consequently, it could be assumed that the Guadalquivir Bank does not form part of a rifted-type margin with a north-south extensional direction, perpendicular to the general trend of the margin.

Finally, the age assigned to the hardground-related, lithified carbonate sediments that cover part of the Bank seems to indicate the timing of the present uplift, and therefore the initiation of the moderate margin inversion. This Late Tortonian to Early Messinian age should correspond to the onset of the present-day Africa-Eurasia plate boundary, once again to the south of the Iberian Peninsula.

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