

Tertiary evolution of the São Vicente and Setúbal submarine canyons, Southwest Portugal: insights from seismic stratigraphy

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RESUMO

Palavras-chave: Margem Sudoeste Ibérica; Neogénico; canhões submarinos; turbiditos; leques submarinos.

Os canhões submarinos de Setúbal e de São Vicente localizam-se na margem Sudoeste Ibérica, ao largo de Portugal. Embora reconhecidos como estruturas de idade pliocénica a quaternária, o seu desenvolvimento durante o Cenozóico não foi, até à data, inteiramente compreendido. Foi usada uma malha de linhas sísmicas 2D para caracterizar os depósitos sedimentares dos flancos adjacentes aos canhões submarinos. Foi investigada a relação entre a estrutura geológica da margem e a localização actual dos canhões. A interpretação das principais unidades sísmicas permitiu o reconhecimento de três gerações de ravinamentos após o provável Oligocénico médio. Foram identificadas seis unidades agrupadas em duas sequências sísmicas e correlacionadas com dados estratigráficos da margem ocidental Ibérica. A Sequência Sísmica 2 (SS2), mais antiga, sobrepõe-se a unidades deformadas do Mesozóico e Eocénico superior. A Sequência Sísmica 1 (SS1) é composta por quatro diferentes unidades separadas de SS2 por uma superfície erosiva. A base dos corpos sedimentares estudados é marcada por uma extensa superfície erosiva, provavelmente resultante de uma descida relativa do nível eustático durante o Oligocénico inferior/médio. Após este evento, a deposição foi reiniciada no Oligocénico terminal sob a forma de depósitos transgressivos e de preenchimento de canais. Um novo hiato deposicional é registado durante o Burdigaliano na Bacia do Baixo Tejo, coincidente com a discontinuidade que separa SS1 e SS2. Esta pode ser correlacionada com a discordância da Arrábida e consequente fase paroxismal Burdigaliana do domínio Bético. Presentemente, os canhões submarinos de Setúbal e de São Vicente ravinam localmente SS1 e SS2, formando canais distintos dos evidenciados pelos dados sísmicos. Na parte superior da plataforma continental ambos dissecam zonas muito deformadas sujeitas a importantes processos erosivos.

ABSTRACT

Key words: Southwest Iberian margin; Neogene; submarine canyons; turbidites; submarine fans.

The Setúbal and São Vicente canyons are two major modern submarine canyons located in the southwest Iberian margin off Portugal. Although recognised as Pliocene to Quaternary features, their development during the Tertiary has not been fully understood up to date. A grid of 2D seismic data has been used to characterise the sedimentary deposits of the adjacent flanks to the submarine canyons. The relationship between the geological structure of the margin and the canyon's present location has been investigated. The interpretation of the main seismic units allowed the recognition of three generations of ravinements probably originated after middle Oligocene. Six units grouped in two distinctive seismic sequences have been identified and correlated with offshore stratigraphic data. Seismic Sequence 2 (SS2), the oldest, overlies Mesozoic and upper Eocene deformed units. Seismic Sequence 1 (SS1) is composed of four different seismic packages separated from SS2 by an erosional surface. The base of the studied sediment ridges is marked by an extensive erosional surface derived from a early/middle Oligocene relative sea-level fall. Deposition in the adjacent area to the actual canyons was reinitiated in late Oligocene in the form of transgressive and channel-fill deposits. A new depositional hiatus is recorded onshore during the Burdigalian, coincident with the unconformity separating SS1 and SS2. This can be correlated with the Arrábida unconformity and with the paroxysmal Burdigalian phase of the Betic domain. Presently, the Setúbal and São Vicente submarine canyons locally cut SS1 and SS2, forming distinctive channels from those recognised on the seismic data. On the upper shelf both dissect highly deformed areas subject to important erosion.

INTRODUCTION

The Setúbal and São Vicente submarine canyons are the two most prominent geomorphological features in the southwest Iberian margin (fig. 1). They form two independent channels deeply dissecting the latter in its northern and southern boundaries. The location of the submarine canyons has been related with major tectonic features (Boillot *et al.*, 1974). In fact, they both follow the trend of late-Hercynian faults recognised onshore. The upper sector of the Setúbal canyon is believed to constitute the continuation of the Grândola fault (fig. 1). The São Vicente canyon is aligned with the Odemira-Ávila fault, following its trend through the full length of the canyon's course (fig. 1). Previous studies have focused directly or indirectly the Portuguese submarine canyons, occasionally using seismic data with relatively shallow depth of penetration (Andrade, 1937; Boillot *et al.*, 1974; Vanney & Mougénot, 1981; Mougénot, 1988; Mauffret *et al.*, 1989). In these, the Tertiary evolution of the two canyon systems has not been fully understood. This paper aims to characterise the seismic facies of the Tertiary sediment ridges adjacent to the Setúbal and São Vicente canyons, proposing a lithostratigraphic framework for the interpreted sections (figs. 1 and 2). The studied ridges constitute independent depositional areas, separated from the upper shelf by NNW-SSE and NNE-SSW fault systems (fig. 6). Seismic facies analysis is used to recognise the depositional environments associated with the units. Finally, their evolution is discussed taking into account the onshore stratigraphy and the development of the southwest Iberian margin during the Tertiary. A revised interpretation of the canyons' evolution during the Tertiary is, therefore, proposed on this paper.

DATA AND INTERPRETATION METHODS

The data presented in this paper was collected in a non-exclusive survey carried out by GSI (Geophysical Service Incorporated) in November and December 1984, on-board of the M/V PE Haggerty. The GSI survey permitted the acquisition of data well beyond the acoustic basement of previous works. The seismic system used an airgun array operating at 2000 PSI as energy source. The data acquisition was guaranteed by a 3000-meter cable with 120 geophone groups and 27 geophones per group. The average estimated depth of the cable was 11 metres. The navigation was based on two independent systems: SYLEDIS (primary system) and GEONAV (secondary system). Seismic reflection lines of the SIN FAR 76 cruise, collected and supplied by IGM (Instituto Geológico e Mineiro), have also been interpreted (fig. 1).

The main seismic units have been established by delimiting the stratal terminations, onlap and downlap surfaces, and relevant unconformities between the internal reflectors of adjacent packages. These define erosional or non-deposition surfaces separating younger strata from older rocks and represents a significant hiatus (*sensu* Mitchum, 1977). Particular care was used in the identification of the seismic packages underlying the sedimen-

tary ridges. Recognition of their relative ages allowed the definition of the evolutionary framework proposed on this paper. Classification of the seismic facies is based on the nomenclature of Mitchum *et al.* (1977) and Posamentier *et al.* (1991). Interpretation of the unit's age is based on previous seismic data interpretations (Coopier & Mougénot, 1982), on dredge data supplied by the IGM previously compiled in Mougénot (1988), and on the onshore stratigraphic frameworks of Cunha (1992) and Pimentel (1998). The depositional models considered by Weimer (1991), Shanmugan & Moiola (1988), Mutti (1977) and Ricci-Lucchi (1975) have been applied on the depositional facies interpretations.

GEOLOGICAL SETTING

This study comprises the offshore region of southwest Iberia, between the co-ordinates 38°30'N - 37°00'N, and 9°30'W - 8°45'W, in what is currently denominated as Alentejo margin (fig. 1). The margin originated during the Mesozoic as a consequence of the multi-phased rifting responsible for the separation and expansion of the North Atlantic Ocean (Pinheiro *et al.*, 1996). The existence of Mesozoic units onshore in the Santiago do Cacém sub-basin (fig. 1), in parallel with dredge and seismic data collected offshore (Mougénot *et al.*, 1979), confirms the extension of the Mesozoic rifting deposits towards the south, in what is named as Alentejo basin.

The Alentejo margin is characterised by a narrow shelf and by a gentle continental slope extending from Arrábida to the Descobridores Seamounts (fig. 1). A shallow zone, the Sines Spur, stretching out from the Sines Cape to the Príncipes de Avis Seamounts, separates the northern and southern sectors of the margin. Setúbal Canyon dissects the northern sector approximately halfway its length, following an ENE to WSW trend in its upper part. In its intermediate zone becomes a very incised east-west oriented channel. After being intersected by the Lisboa Canyon and multiple submarine valleys, changes its course to a northeast-southwest orientation (fig. 1). The submarine canyon finally terminates its course on the Tagus Abyssal Plain, offshore Lisbon.

The southern sector of the Alentejo margin is characterised by a further enlargement of the slope. Here, the shelf is essentially composed of Paleozoic rocks constituting the basement of the Mesozoic Alentejo basin. São Vicente canyon, located roughly at 37°00'N, constitutes a major morphological feature separating Alentejo and Algarve margins (fig. 1). The canyon follows a simple NE-SW orientation forming a wide submarine channel terminating on the Horseshoe Abyssal Plain.

The studied zones referred on this paper are located on the flanks of the two submarine canyons, constituting Tertiary sediment ridges excavated by the present canyon-channels. Both ridges form thick (up to 1.0 seconds in two-way travel time) accumulations separated from the thin (averaging 300 milliseconds of two-way travel time thickness) Tertiary sediments deposited on the shelf. This boundary is marked by a fault system trending NNW-SSE to NNE-SSW in both studied zones (figs. 1 and 6).

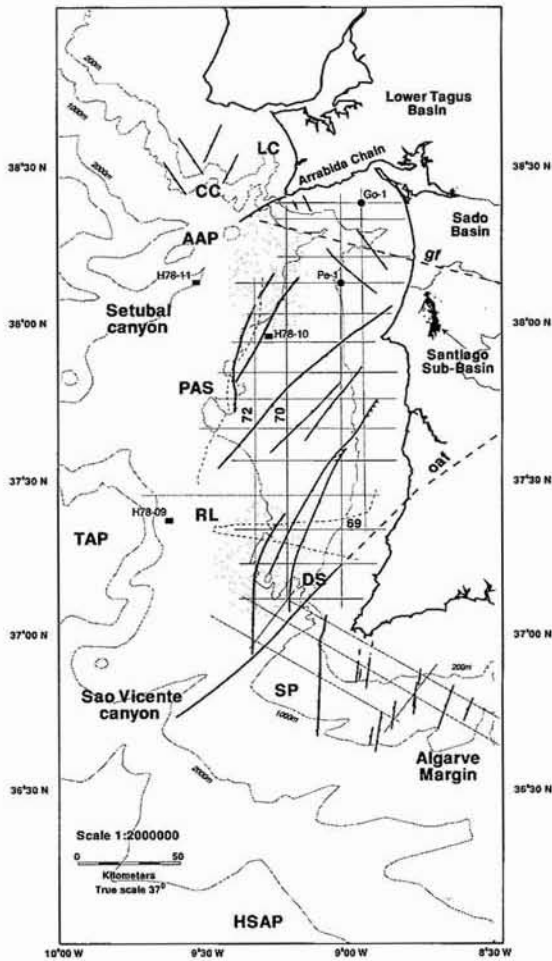


Fig. 1 - Location of the studied submarine canyons and referred seismic grid. SINFAR 76 data in dotted lines. The main offshore structures interpreted on seismic data are also shown. The bathymetry of the margin was obtained using GIS data supplied by the Instituto Geológico e Mineiro (IGM). Grey areas represent the location of the seismic data shown on this paper. Key: CC-Cascais Canyon; DS-Descobridores Seamounts; HSAP-Horseshoe Abyssal Plain; AAP-Afonso de Albuquerque Plateau; PAS-Príncipe de Avis Seamounts; TAP-Tagus Abyssal Plain; RL-Rincão do Lebre Plateau; SP-Sagres Plateau; gf-Grândola Fault; oaf-Odemira-Ávila Fault.

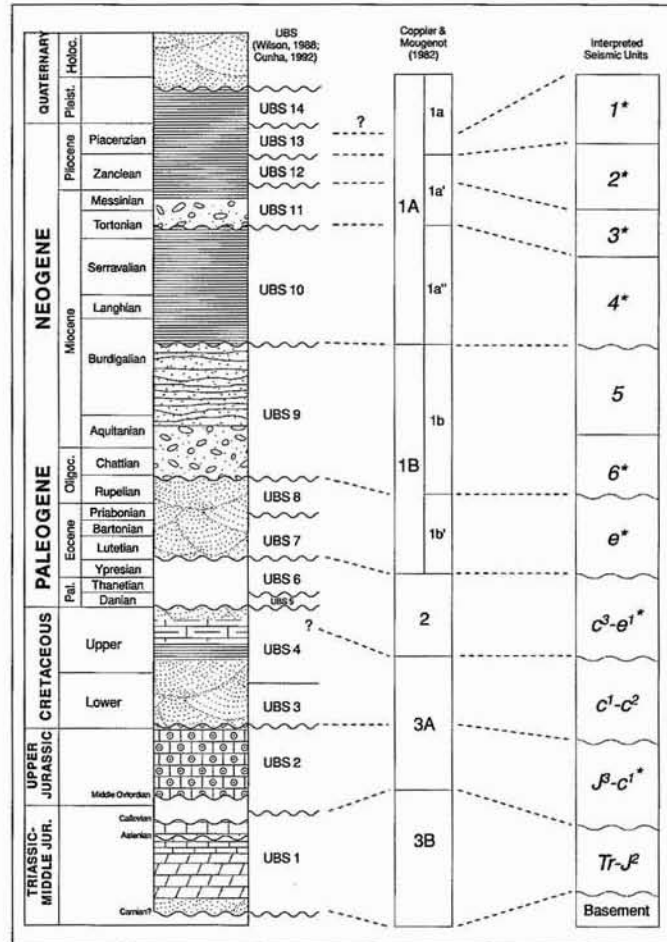


Fig. 2 - Sequence stratigraphy of western Iberia Tertiary (Cunha, 1992) and Mesozoic (Wilson, 1988) deposits correlatable with packages identified on the seismic data. The seismic stratigraphy of the units interpreted in this paper is represented in the right-hand side column. Signed units (*) have been dredged and dated (Mougenot, 1988).

STRUCTURAL SETTING

The Alentejo margin shows a different tectonic setting in comparison with the adjacent western and southern Portuguese margins. Well and onshore data reveal a relative absence of a ductile salt layer below the Jurassic to Tertiary units in the Alentejo basin.

The Alentejo margin can be divided into two distinctive structural zones based on their main structural trends. In the northern Alentejo margin the main fault-trend is NNW-SSE to NW-SE oriented, in similarity with the main faults dissecting the SSW-NNE Arrábida Chain (Ribeiro et al., 1990). A major inflexion of the structural trends occurs halfway in the margin. From the Sines Spur to the São Vicente Canyon, the NNE-SSW and NE-SW struc-

tural trends are dominant. On seismic data there are evidences that these faults have controlled the Mesozoic evolution of the Alentejo basin, forming fault-bounded horst and graben structures (figs. 3 and 4). Evidences of recent fault-reactivation are seen on the seismic data, although the relatively low seismic activity historically and instrumentally presently recorded on the margin (Cabral, 1995).

Alpine deformation in the Alentejo margin has a different character when compared with central-western and Algarve margins (fig 1). On the shelf, folding of Mesozoic to Eocene units and fault reactivation have been recognised on seismic data (figs. 3 and 4). On the deeper areas of the continental slope, subsidence has been recorded since late Oligocene, originating a thick Tertiary

basin over the southwest Iberian margin (Mougenot, 1988). Salt anticlines have not been identified on the seismic data. Folding of the Tertiary units is recorded by two broad E-W synclines ranging the southern and northern sectors of the Alentejo Basin. These are separated by the Sines Spur and covered by relatively thin Neogene to Quaternary units over the shelf and upper slope areas (figs. 3, 4 and 5). Deformation on the margin is, therefore, mainly confined to the Príncipes de Avis and Descobridores Seamounts region (fig. 1).

STRATIGRAPHY OF THE ALENTEJO MARGIN

Onshore data collected from the Santiago do Cacém sub-basin and offshore well data were interpreted using the same stratigraphic framework used for the Lusitanian and Algarve basins. Although with important basinal differences in relation to the structural and depositional evolutions, the three margins have been affected by the same rifting events during the Mesozoic.

Tertiary deposition was important in the Lower Tagus and Sado basins (figs. 1 and 2). The first was originated as a compressional foredeep basin with associated fault-bounded subsidence (Rasmussen *et al.*, 1998). Sado Basin was originated in the middle Eocene during the Pyrenean phase of the Alpine orogeny, and resumed its development during the late Neogene (Betic phases) and Quaternary (Pimentel, 1998). Elsewhere, the Tertiary deposition is only represented by Pliocene to Quaternary shallow marine and paralic deposits, aligned in a band parallel to the actual shoreline. Offshore, Holocene deltaic systems are developed on the mouth of the Sado and Tejo estuaries (Mougenot, 1988). On the Alentejo shelf, the Tertiary units show a distinctive distribution north and south from the Príncipes de Avis Seamounts (fig. 1). Cenozoic deposition was mainly located north from the seamounts, where deformed Eocene deposits underlay the Miocene to Quaternary units (Mougenot *et al.*, 1979; Mougenot, 1988). South of the same submarine features, on the outer shelf, thin Miocene to Quaternary sediments overlay deformed Mesozoic units. These abruptly change into thick sedimentary units on the continental slope.

SEISMIC STRATIGRAPHY AND SEISMIC FACIES CHARACTERISATION

The studied areas comprise the sedimentary ridges south and north of the actual Setúbal and São Vicente canyons, respectively (fig. 1). The ridges form part of the continental slope in depths ranging the 800 to 1200 meters and are marked by presenting a similar seismic stratigraphy. Six seismic units have been identified and divided into two distinctive seismic sequences (SS1 and SS2). These are separated by a major unconformity recognised in both canyons (figs. 4 and 5). The unconformity, resembling the character of an erosional surface on the seismic data, has been correlated with the

Arrábida tectonic event that marks the paroxysmal phase of the Betic domain, occurred during the Burdigalian (Antunes *et al.*, 1999). The seismic stratigraphy of the studied areas is represented in figure 2. From the top to the bottom, the interpreted sequences comprise the following units:

Seismic Sequence 1 (SS1)

The Seismic Sequence 1 includes Units 1 to 4. The uppermost Unit 1 shows a constant thickness ranging 150ms showing low amplitude to semi-transparent irregular internal reflectors. These are subparallel with onlap onto surface 2a (c.f. Mougenot *et al.*, 1979). The base of Unit 1 is marked by a high amplitude conformable surface occasionally showing onlap. The unit is interpreted as comprising turbidite or hemipelagic sediment sheets. Broad sectors with semi-transparent, flat reflectors are characteristic of these facies, a feature observed on the seismic data and confirmed the facies interpretation of Weimer (1991) and Shanmogan & Moiola (1988). Packages presenting parallel semi-transparent reflections have also been interpreted as distal turbidite and pelagic deposits of non-channelled environments in the Agadir Canyon, Morocco (Ercilla *et al.*, 1998). Dredge samples collected on the slope adjacent to the studied area (fig. 1) confirmed the pelagic character of the sediments composing Unit 1, allowing their dating as Piacenzian (Dredge H78-11; Mougenot, 1988). Thus, the unit can be correlated with UBS 13 of Cunha (1992). The location of Unit 1, out of the present mouth of the canyons, suggests that the unit does not comprise channel-derived material from Setúbal and São Vicente structures. Instead, the internal character of the package resemble fine pelagic to hemipelagic deposits directly derived from the adjacent continental shelf and locally deposited as sediment waves (figs 4 and 5).

The base of Unit 2 is marked by an onlap surface with high amplitude. Unit thickness ranges from 100ms to 200ms. Internally, it is composed of wavy sub-parallel reflectors with medium to low amplitude. These are interpreted as hemipelagic deposits, in similarity with Unit 1. The wavy character of the unit may be associated with contourite deposits, abundant on the Algarve Margin as a result of the Mediterranean water flow (Mougenot, 1988; Lebreiro *et al.*, 1997). High-resolution seismic reflection data of the SINFAR 76 cruise reveals the presence of broad sediment waves on Units 1 and 2. Extensive contourite sediment ridges have also been identified throughout the Algarve Margin in particular near the Gulf of Cadiz (Faugères *et al.*, 1999). However, localised synsedimentary deformation is also visible on the seismic data, along with faulting and tilting of some of the interpreted packages. Some of these deformation features seem to induce locally part of the wavy character of Unit 2 (fig. 5). Dredge sampling (Dredge H78-11; Mougenot, 1988) and seismic data previously collected on the shelf region (Coppier & Mougenot, 1982) suggest a Pliocene age for the unit, probably Zanclean (UBS 12 *cf.* Cunha, 1992).

The Seismic Unit 3 is bounded at its top by an onlapping surface. The thickness of the unit varies between 300ms

and 200ms. Internally, the package is dominated by wavy to even sub-parallel reflectors with low to medium amplitude. In the Setúbal Canyon the sub-horizontal parallel reflectors resemble the character of Units 1 and 2, interpreted as hemipelagic. In the southern part of the São Vicente Canyon a pronounced hummocky character is seen, in parallel with narrow channels and erosional features. In this area, the package is interpreted to comprise a complex pattern of overbank and sheet-like turbiditic deposits, lateral shifting into hummocky coarser channel-fill sediments. Towards the south, the unit cannot be followed accurately due to ravinement of the present canyon channel (fig. 5). Small-scale erosional features, less than 300 ms of time-depth, filled with Tortonian-Messinian deposits, have been identified on the shelf north of the Setúbal Canyon (Coppier & Mougenot, 1982). Onshore, the event is marked by widespread regression on the late Tortonian and absence of Messinian deposits (Cunha, 1992). Those features have been correlated with a Tortonian compressive stage, responsible for some important uplift and deformation on the Arrábida Chain. Also offshore, transgressive units form the bulk of the Tortonian due to subsidence of the margin (well Pescada-1) and Messinian channel-fill deposits have been identified in the several ravinement channels (Coppier & Mougenot, 1982). The similarity of these features to those of Unit 3 can possibly indicate a Tortonian-Messinian age for the unit (UBS 11 *cf.* Cunha, 1992).

The Seismic Unit 4 is bounded by an erosional surface at its base (Surface B) and by a downlap surface on its top. The unit fills wide eroded channels on both study areas, and shows values of thickness varying from 400ms in the channel troughs to 50 ms on the channel banks. The character of the unit is constant in both canyons with high amplitude internal reflectors show chaotic to complex-mounded geometries. Occasionally, these are cross-cutted by linear features resembling syn-sedimentary rotational slumps (fig. 6). The top of Unit 4 is composed of sub-parallel wavy reflectors with medium amplitude. These thin (less than 100 ms) deposits are interpreted as flat sediment sheets overlying a thick zone of submarine fan lobes with mounded geometries. Dredge data collected in the Rincão do Lebre Plateau, west from the study area (fig. 1), supplied Serravalian pelagic sediments over upper Eocene to Lower Miocene units (Dredge H78-09; Mougenot, 1988). This is in agreement with the seismic interpretation: Unit 4 overlays a major unconformity, identified over the southwest Portuguese margin, dated as intra-Burdigalian (Antunes *et al.*, 1999). Below the unconformity, two seismic units have been identified and correlated with the upper Eocene-lower Miocene deposits underlying the dredged Serravalian sediments, since both overlay an Oligocene erosional surface (*surface 2a*, Vanney & Mougenot, 1981). Therefore, Unit 4 is interpreted as comprising submarine fan and pelagic sediments of uppermost Burdigalian to Serravalian age, possibly also including lower Tortonian deposits (UBS 10 *cf.* Cunha, 1992).

Seismic Sequence 2 (SS2)

SS2 includes Units 5 and 6. The Seismic Unit 5 shows a distinct character in each one of the studied zones. Close to the Setúbal Canyon is in great part eroded and has a relatively poor expression. In the São Vicente Canyon it is well developed both vertically and laterally although showing similar ravinement features. The top of Unit 5 is marked by an erosional surface (Surface B, figs. 4 and 5). Unit 5 thickness ranges the 180ms in the Setúbal Canyon and varies from 200ms to 380ms in São Vicente. The base shows frequent downlap on both submarine canyons and the unit is composed of high amplitude parallel reflectors overlying the chaotic, sometimes semi-transparent, Unit 6. In the São Vicente Canyon, however, reflectors with low to medium amplitude and broad wavy geometry are seen. Distinctive interpretations can be suggested for Unit 5: the homogeneous parallel reflectors are interpreted as comprising shelf-derived sediments deposited at the base of the slope. Low-continuity reflectors with high amplitude, onlapping the underlying Unit 6 are believed to comprise hemipelagic deposits in a slope environment. At the São Vicente Canyon the existence of broad mounded reflectors resemble turbiditic/hemipelagic deposits, possibly affected by deep-sea currents as proved by the presence of wavy reflectors. The transgressive character of Unit 5, onlapping Unit 6 on line S84-69 (fig. 6) resembles Burdigalian deposits of the Setúbal area (Coppier & Mougenot, 1982). Moreover, the unit underlies Surface B, correlated with the intra-Burdigalian unconformity (figs. 4 and 5). These facts allow the dating of Unit 5 as lower-middle Burdigalian (upper UBS 9 *cf.* Cunha, 1992).

The Seismic Unit 6 is bounded as its base by an important erosional surface (*surface 2a*, *c.f.* Vanney & Mougenot, 1981), probably resulting from a relative sea-level fall recorded in the middle Oligocene (Mougenot *et al.*, 1979; Mougenot, 1988). The top of the unit is a concordant surface with occasional onlap. Its thickness varies from less than 50 ms to 300 ms, showing low to medium amplitude internal reflectors with a chaotic character (figs. 4 and 5). This characteristic is more pronounced in the Setúbal Canyon where tilted high amplitude non-continuous reflectors are visible in the interior of a low amplitude package (fig. 4). In the broader São Vicente Canyon the unit shows low to high amplitude internal reflectors showing onlap onto Surface 2a (fig. 5). The chaotic character is here replaced by more pronounced hummocky reflections. Dredging on the Alentejo Margin, offshore Sines, provided samples comprising shallow marine sediments and brecciated material rich in Miogypsinoids and Lepidocyclinoids from the top of the unit (Dredge H78-DR10), dated as Aquitanian (Coppier & Mougenot, 1982). Unit 6, therefore, is interpreted to comprise coarse transgressive sediments deposited over surface 2a. These may include large rock debris as suggested by the presence of isolated non-continuous reflections on the seismic data, and possibly Chattian transgressive deposits recognised on the Lisbon shelf (Coppier & Mougenot, 1982). Therefore, a Chattian-Aquitanian age for Unit 6 is here suggested (lower UBS 9 *cf.* Cunha, 1992).

DEPOSITIONAL EVOLUTION ON THE MARGIN

The data interpretation suggests that the evolutions of the Setúbal and São Vicente Canyons have been controlled by the geological events that affected the southwest Iberian margin in the Tertiary. Moreover, both ancient and modern channels are located on highly deformed areas of the margin, resulting from successive compressional phases of the Alpine Orogeny. Three main ravinement phases have been identified. Six main evolutionary stages can be considered by interpreting the referred data: 1) Widespread erosion of the margin with possible formation of paleo-canyons; 2) Partial filling of the paleo-canyons by SS1; 3) Second erosional period; 4) Partial filling of the recently-formed channels; 5) Deposition of turbidite/hemipelagic sediment sheets and contourites; 6) Incision and development of the actual canyons.

The first stage of the margin evolution, after the middle Oligocene erosional period, comprises the onset of deposition in late Chattian-Aquitainian due to extension (Mougenot, 1988). In the shelf area adjacent to Lisbon, units of this age cover the 2a surface itself dissected by multiple extensional faults (Coppier & Mougenot, 1982). The same erosional surface has been identified on the Alentejo margin (Vanney & Mougenot, 1981; Mauffret *et al.*, 1989). On the Moroccan margin southeast from the Madeira Islands, the incision of the Agadir Canyon has been also considered as a result of Oligocene erosion (Ercilla *et al.*, 1998). Similar features are seen on the analysed seismic data (figs. 4 and 5). Erosional processes acting on the Mesozoic substrate seem to have been dominant over the margin's faulting on the studied area adjacent to the São Vicente Canyon. Here, the Tertiary units are deposited inside an erosional valley cut into thick late Mesozoic units (fig. 5). Ravinement of these units appear to have been important during the Oligocene erosional period on both areas, with possible formation of channels and gullies over the margin. The existence of thick units on both sections (Unit 6), showing onlap onto narrow U-shaped valleys and small depressions (fig. 4), resemble the character of channel-fill sediments (c.f. Ercilla *et al.*, 1998; Shanmugam & Moiola, 1988; Weimer, 1991). Onshore, the Paleogene (Complexo de Benfica) and Aquitanian stratigraphic record, correlated with the Seismic Unit 6 and possibly the lowermost part of Unit 5, is composed of coarse red continental siliciclastic deposits in the first, and shallow tidal to fluvial facies in the latter (Antunes *et al.*, 2000). The occurrence of marine facies is restricted to coastal areas of the basin a character repeated throughout the Miocene in the Lower Tagus Basin (Antunes *et al.*, 2000). According to Cunha (1992), the onset of deposition in the Lower Tagus Basin can be related with tectonically-driven subsidence resulting from the Castillian tectonic phase. The same event can also be related with the folding and erosion of the pre-Unit 6 seismic packages (figs. 4 and 5).

Partial filling of the eroded channels followed the Oligocene uplift and erosion (fig. 7). The seismic character of Unit 5, in parallel with the dredge samples collected on the margin, suggest the deposition of deep-shelf and

pelagic sediments at the top of SS2. From late Chattian-Aquitainian until late Tortonian, two distinctive seismic sequences are distinguished on the Lisbon margin and onshore, separated by a Burdigalian compressive event (Mougenot, 1988; Antunes *et al.*, 1999). The same event may correspond to the surface separating SS1 and SS2, since a depositional break, materialised by an onlapping surface, is visible on the interpreted data (figs. 4 and 5). An identical seismic feature has also been recognised off-shore Lisbon and correlated with the Burdigalian compressional event (Coppier & Mougenot, 1982). Relative ages of Chattian to Aquitanian for Unit 6 and lower/middle Burdigalian for Unit 5 are, therefore, suggested. Onshore, the top part of UBS 9 (correlated with Seismic Unit 5) is composed by marine infralittoral sediments grading laterally into deltaic deposits towards the NE (Antunes *et al.*, 2000). This relatively deepening in relation to the Aquitanian deposits in the Lower Tagus Basin confirms the seismic facies interpretation for Unit 5.

An erosional period materialised by an irregular high amplitude surface on seismic data marks the third phase of the margin evolution (fig. 7). Major ravinement with the formation of distinctive channels is seen on the seismic lines on both study locations. Over the ravinement surface, Unit 4 internal character resembles deposition of fan lobes, typical from distal margin or fluvial settings. Gullies and minor channels filled by Messinian sediments have been recognised offshore, on the shelf, south of the Arrábida Chain (Coppier & Mougenot, 1982). The same author related the formation of these erosional features with a late Tortonian-Messinian sea-level fall, contemporaneous of the Mediterranean closure. A generalised erosional unconformity, which represents a sequence boundary, has also been recognised between the lower and upper Messinian depositional sequences in the Gulf of Cadiz (Maldonado *et al.*, 1999). On the Alentejo margin and on the Tagus Abyssal Plain, a main Neogene surface recognised on seismic data has been correlated with an intra-Burdigalian compressive phase (Mougenot, 1988). This surface, and related depositional hiatus, is materialised on the study area by an erosional surface (Surface B). Late Tortonian-Messinian ravinelements referred in Coppier & Mougenot (1982) are confined to the upper shelf. The lateral extension and geometry of the Burdigalian erosional channels suggests that paleo-canyons and submarine valleys have been originated during this stage, as underlined by the deposition of laterally restricted depositional fans within the erosional valleys (figs. 4 and 5). Onshore, Surface B is materialised by an angular unconformity in Arrábida and by a stratigraphic hiatus elsewhere in the Lower Tagus Basin (Antunes *et al.*, 1999) resulting from the Neo-castilian tectonic phase (Cunha, 1992). Deposition became completely absent in the Arrábida area until late Langhian, but was resumed during the latest Burdigalian in the Lisbon region (Antunes *et al.*, 2000). From this time until the Tortonian, the general facies distribution in the basin (with increasing marine influences towards the SW) became well established, only interrupted by depositional hiatus of regional importance related with

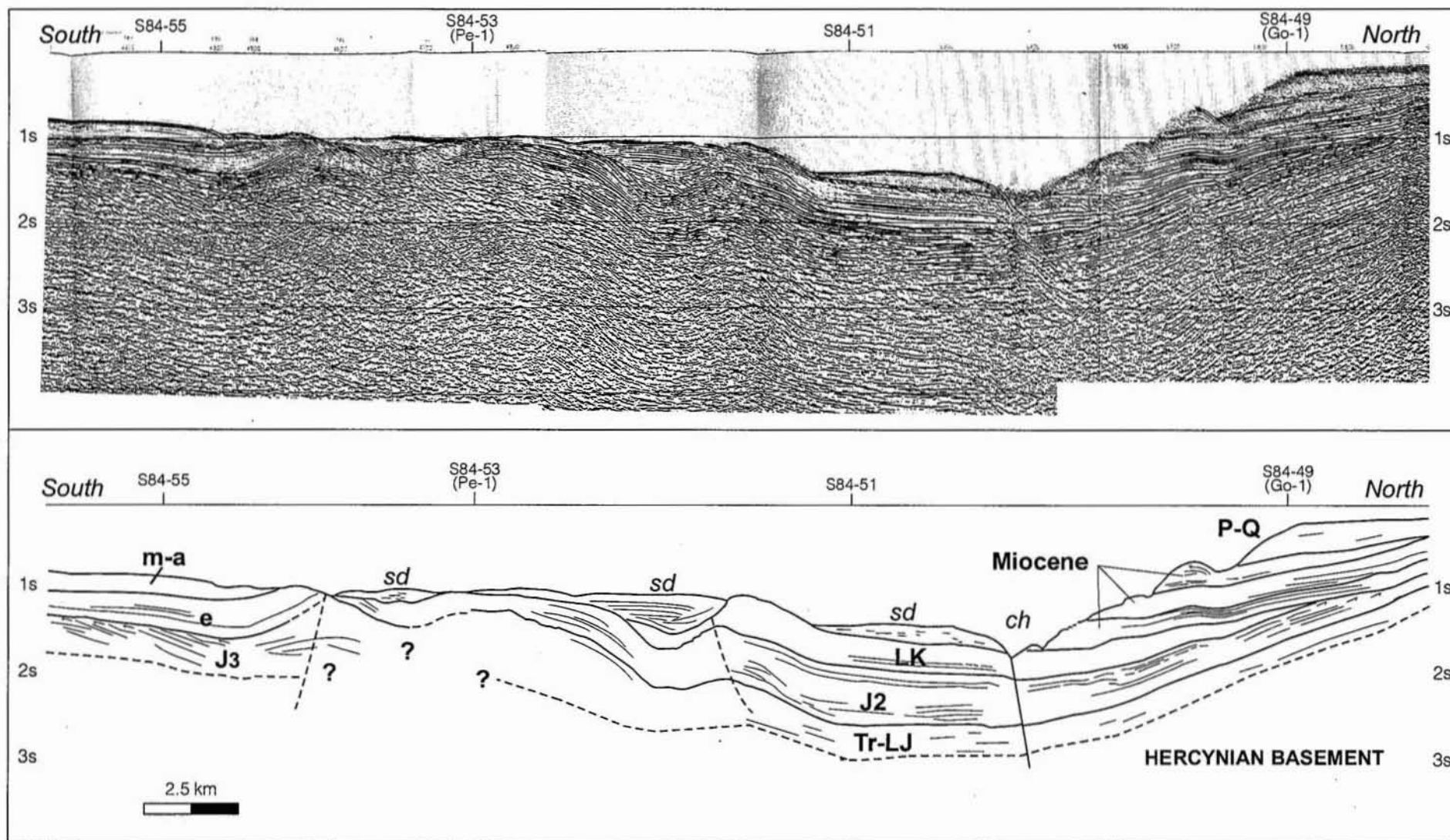


Fig. 3 - Resumed interpretation of the seismic line S84-70. Alpine deformation on the head of the Setúbal Canyon is shown on this line. The actual canyon channel (ch) is located in the northern sector of the line, forming an abrupt slope cutted onto Tertiary units. Towards the south, small sedimentary wedges (sd) mark the levees of the actual canyon. Faulting and folding of the underlying Tertiary and Mesozoic units are a result of Eocene and Miocene compressional phases. Pe-1 and Go-1, indicated between brackets, correspond to two wells used to date the seismic packages. They intersect lines S84-53 and S84-49, respectively.

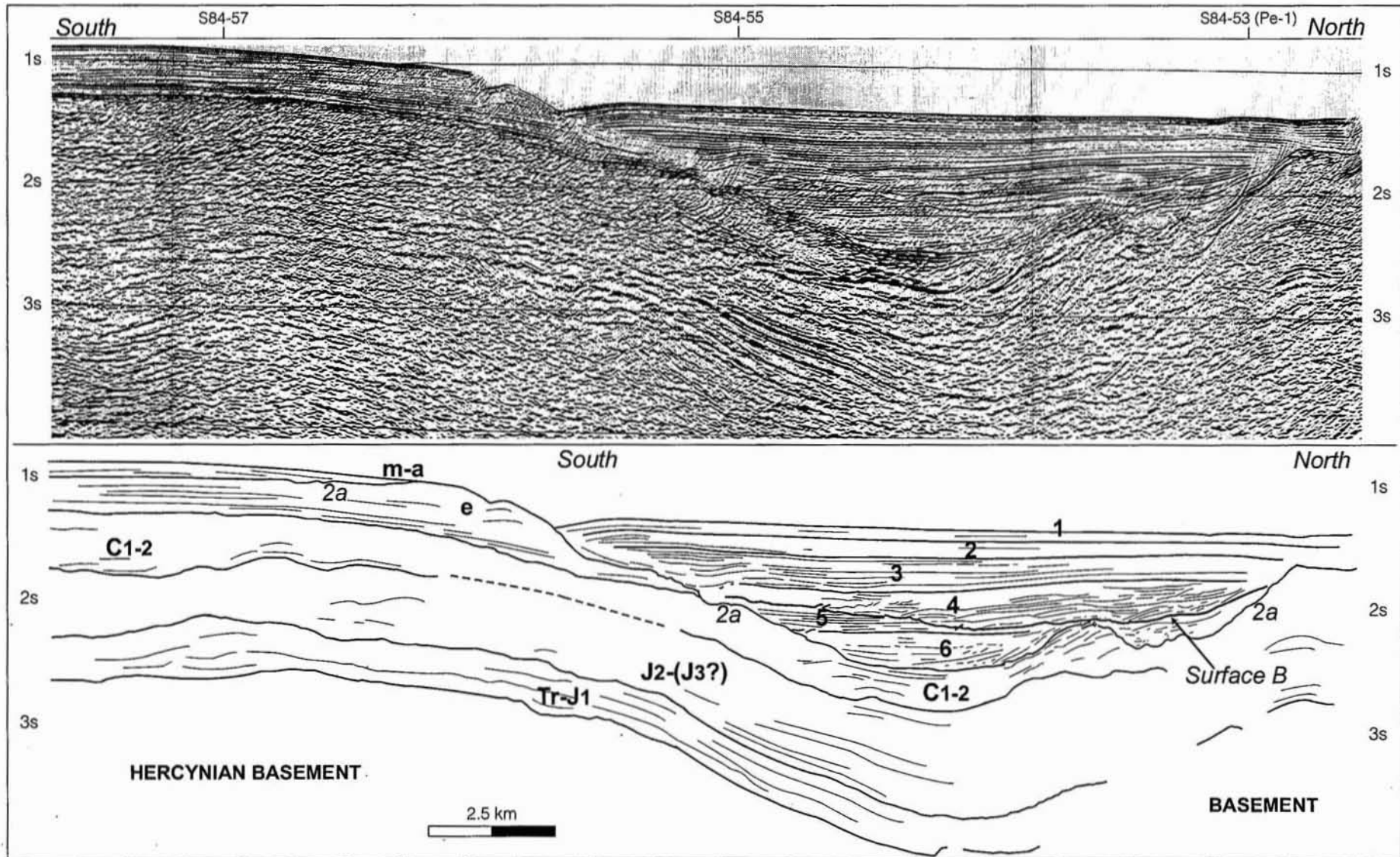


Fig. 4 - Interpretation of the seismic line S84-72. showing the sedimentary ridge adjacent to the Setúbal Canyon. Approximately 3000 meters (1100 miliseconds) of Mesozoic rocks constitute the base of the Tertiary ridge. This comprises more than 2000 meters of Chattian to Quaternary sediments (1200 miliseconds). Location of the line of figure 1.

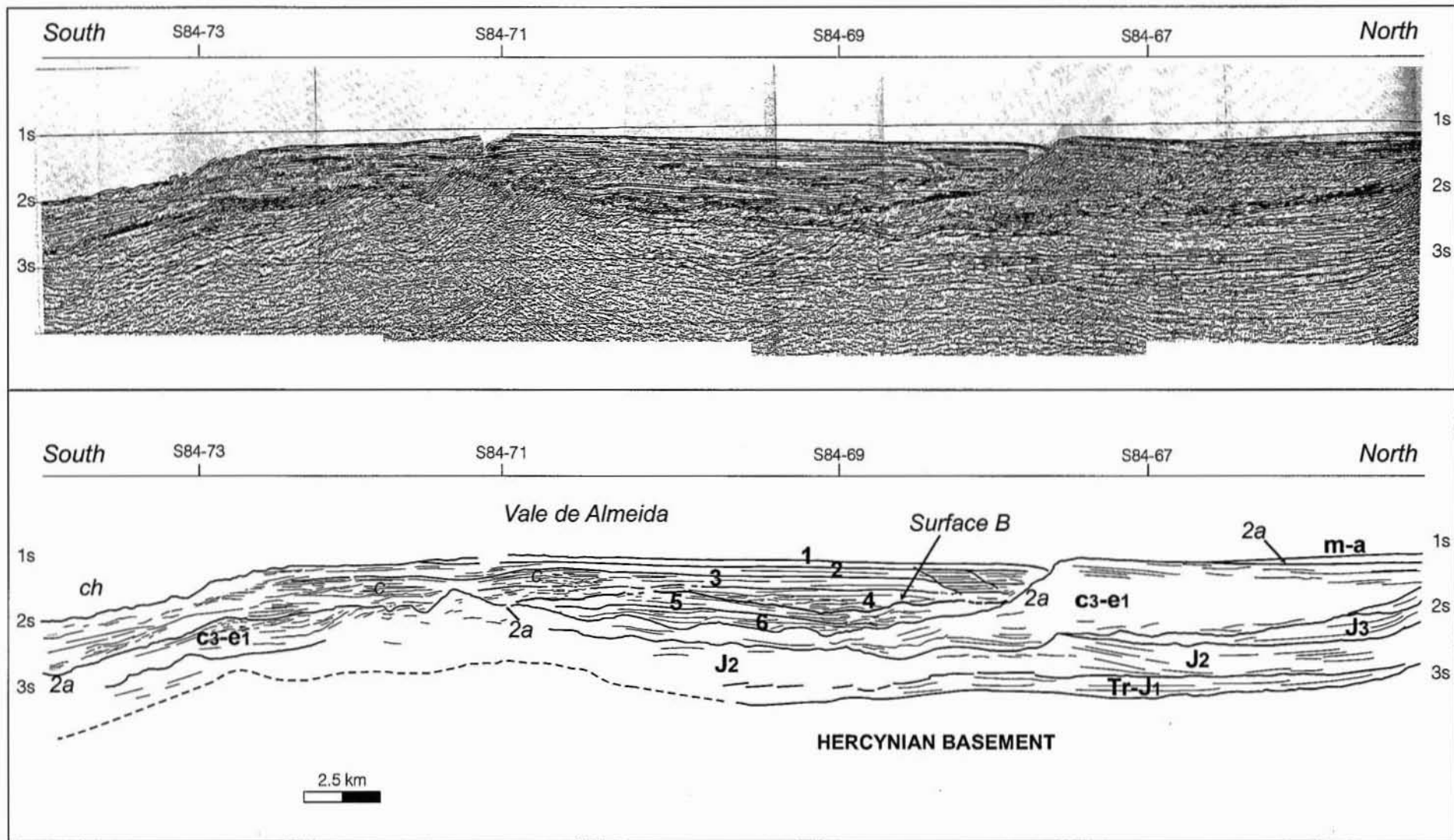


Fig. 5 - Interpretation of the seismic line S84-72, on the adjacent area to the São Vicente submarine canyon. Surface 2a constitutes the base of the Tertiary packages on the Alentejo Margin. Likewise in Setubal, three main ravinement periods can be identified here: a first coincident with surface 2a (early/middle Oligocene); a second stage materialised by the erosional surface separating units 4 and 5; a third stage coincident with the ravinement of the actual canyons (ch). A complex pattern of minor channels (c) is visible within Unit 3 on the southern part of the Vale de Almeida.

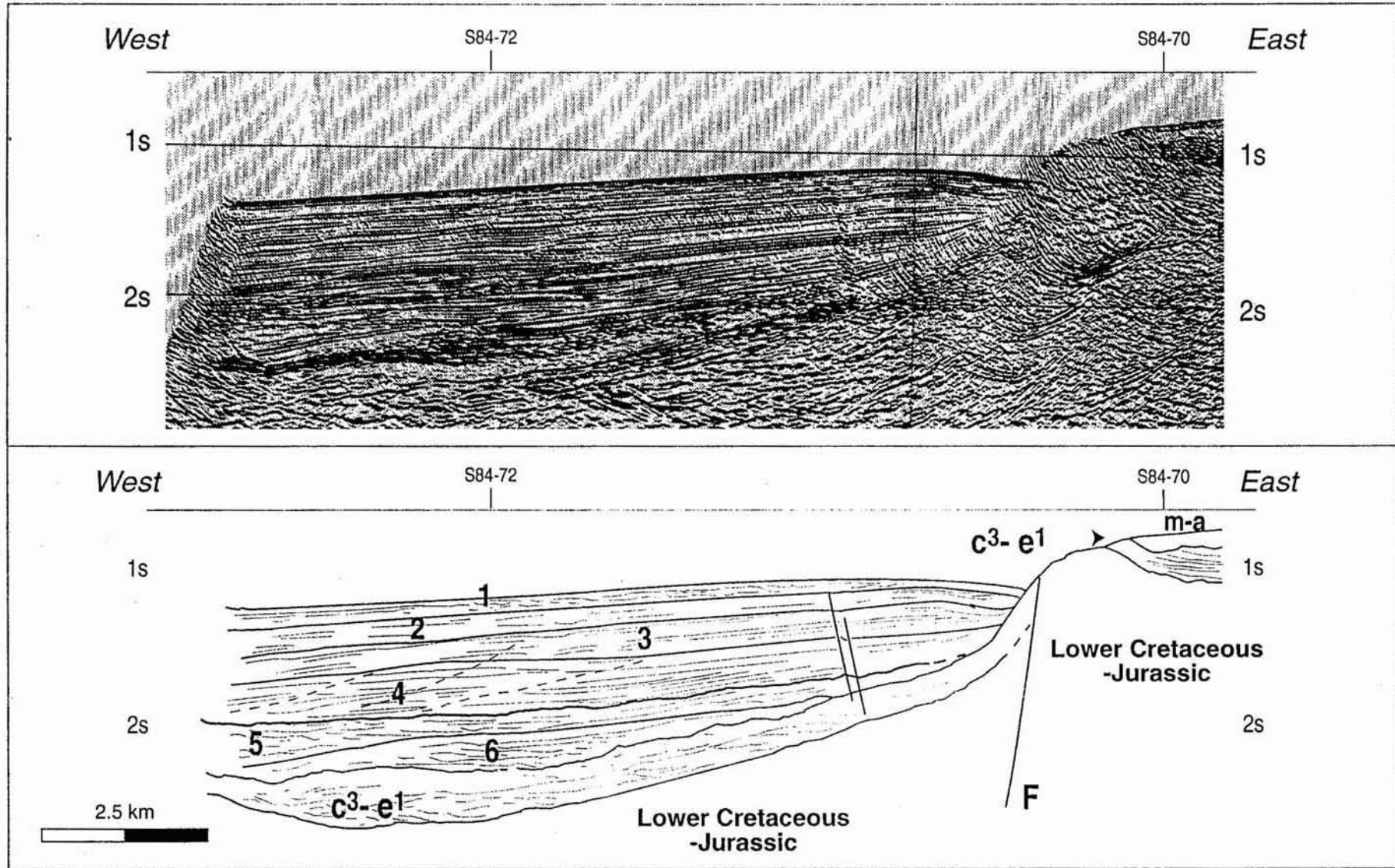


Fig. 6 - Interpreted section of the seismic line S84-69, showing curved linear features resembling rotational slumps and/or post-depositional deformation of the sedimentary packages. The deeper thick Tertiary package is separated from the shelf Miocene to Quaternary units by a fault system (F), trending NNW-SSE to NNE-SSW.

relatively minor tectonic/eustatic pulses (Antunes *et al.*, 2000). This time interval encompasses UBS 10 of Cunha (1992).

Stage five is materialised by Units 3 to 1, interpreted as including deep shelf/hemipelagic deposits (fig. 7). The late Tortonian-Messinian regression and subsequent Pliocene-Quaternary sea-level variations were responsible for the onset of the actual geomorphology of the margin. Pliocene deposits are mostly distributed over a narrow N-S band on the Alentejo margin, parallel to the actual coastline. Margin's subsidence resumed from Pliocene times to the Holocene, with subsequent canyons' headward erosion and incision (Coopier & Mougénot, 1982).

Overlying the fan-shaped units, sub-parallel horizontal packages resembling suspension-transported deposits have been deposited on the study areas. Contourite deposits may also comprise part of Units 3 and 2. However, linear features similar to rotational slumps, faulting and erosional scars can be particularly recognised on the east-west oriented seismic lines (fig. 6). Dating of the units is somehow problematic, in part due to their similar seismic character. Late Tortonian-Messinian ravinement was followed by the deposition of deep marine units on the continental slope. In parallel, onset of tectonic extension on the Alentejo margin created accommodation space for the post-Tortonian units (Mougénot, 1988). Therefore, units 3 to 1, overlying the late Burdigalian-Serravalian Unit 4, can be considered as upper Tortonian to Piacenzian in age. The actual morphology of the margin derives from the spatial distribution of these deep marine units, deposited in fault-bounded regions subsident since early Pliocene (Mougénot, 1988). Onshore, the post-Tortonian depositional record is scarce with the exception of continental deposits in the NE part of the Lower Tagus Basin and in the Mondego Basin (Cunha, 1992). The base of Unit 3 can be related with the Betic tectonic phase (Cunha, 1992) since this event has been recognised as the responsible for the development of the actual margin's morphology and with a increase of subsidence in the margin (Coopier & Mougénot, 1982). Although with reserves, the seismic boundaries identified on the seismic data can be also related with important stratigraphic boundaries resulting from tectonic events. Correlating Units 2 and 1 with the UBS 12 and UBS 13 respectively suggests that the base of Unit 2 can result from the Intra-Zanclean tectonic phase. Following the same line of thought, the base of Unit 1 possibly materialises the Ibero-manchegan I tectonic phase (*cf.* Cunha, 1992) (fig. 2).

The sixth evolutionary stage, synchronous with the onset of the present tectonic/geomorphologic conditions, materialises the ravinement of the actual canyon channels (fig. 7). Seismic data reveals a shift in the channels position from middle Miocene (Surface B) to the present (fig. 5). In the Vale de Almeida area, the actual channel of the São Vicente submarine canyon ravinates the seismic packages deposited over Unit 4.

The Setúbal canyon is also presently located on a distinct area from the studied region, and has been considered as a result of Pliocene-Pleistocene glacial-eustatic

events (Coopier & Mougénot, 1982). Messinian and Pliocene-Pleistocene ravinements in the Setúbal areas have been controlled, according with the same authors, by the reactivation of ancient Hercynian faults (Tagus lineament, Grândola fault). On the interpreted seismic lines, the São Vicente canyon seems to follow a tectonic depression located on the southern flank of the Descobridores seamounts. The seismic data underneath the canyon channel does not allow the recognition of complex structures below surface 2a (middle Oligocene erosional surface). However, the structural complexity on the adjacent Descobridores seamounts increases, since both the Tertiary and Mesozoic units are intersected by several faults reactivated during the alpine compression (Mougénot *et al.*, 1979). On the Setúbal area, the headward erosional part of the canyon is coincident with a highly deformed area of the shelf, northeast of the Príncipes de Avis Seamounts (Line S84-70, fig. 3). Strong erosion of the northern flank of the canyon is also observed on the seismic data, possibly resulting from the activity of sea-bottom currents. From the interpreted data is not possible to interpret the provenance and direction of the currents. Nevertheless, seasonal upwelling along the margin, broad Deep Geostrophic Currents, and important south-north contour currents have been recorded along the Alentejo Margin, the last related with the Mediterranean Deep Water Flow (MDWF) (Lebreiro *et al.*, 1997). Presently, both submarine canyons constitute bypass/erosional areas in most of their course, with relevant sediment deposition restricted to the deep areas of the margin close to the slope/abyssal plain transition (fig. 7).

CONCLUSIONS

Seismic reflection data obtained on the Alentejo margin has revealed the existence of a common evolutionary framework for the sedimentary ridges bounding the Setúbal and São Vicente canyons. Three ravinement periods have been recognised: a first ravinement probably early/middle Oligocene in age; a second tentatively dated as Burdigalian; a third Pliocene-Quaternary period responsible for the actual location of the canyon-channels. Six seismic units have been identified in both canyons, constituting two distinctive depositional sequences. The importance of the tectonic factors on the canyons' location and development is clear, since they both constitute the geomorphological expressions of major late-Hercynian faults limiting the Alentejo basin to the north and to the south. Both canyon areas are coincident with highly deformed regions of the margin. Their location is also coincident with two Mesozoic depocentres, as proved by the thickening of the Jurassic and Cretaceous units towards the zones adjacent to the canyons. However, no evidences of Mesozoic development of the submarine features have been recognised from the data. Onshore stratigraphy, seismic and well data collected on the continental shelf, allowed to relate the canyons' evolution with the main tectonic and eustatic events affecting the margin from Oligocene to the Present.

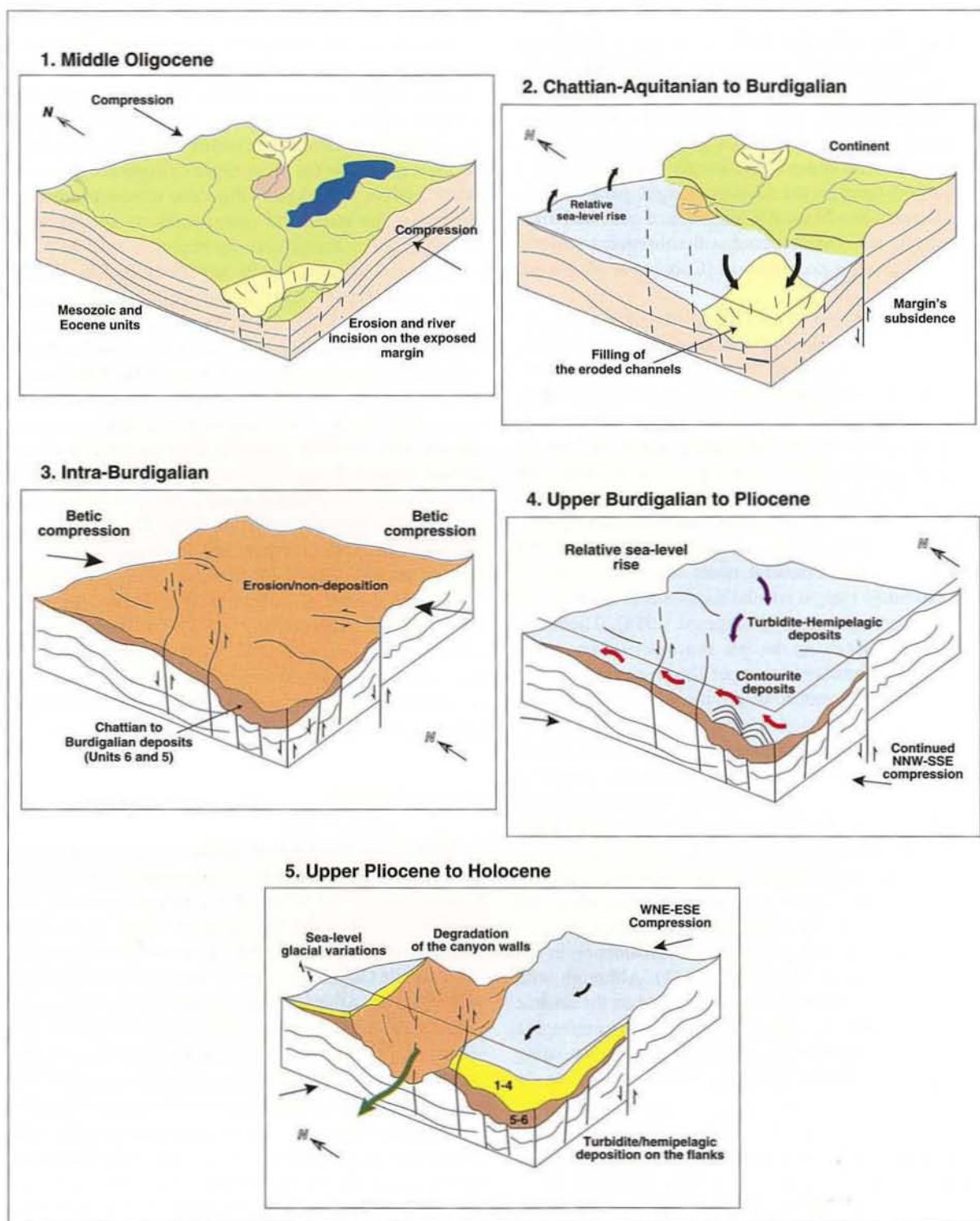


Fig. 7 - Geological evolution of the Setúbal and São Vicente Canyons according with the interpreted seismic and stratigraphic data. Ravinement of ancient canyon channels is suggested to have occurred during the Oligocene erosional period (1). A first generation of canyon-fill sediments was deposited between the late Chattian and the lower/middle Burdigalian (2). A second generation of ravinelements was originated in the Burdigalian during the paroxysmal period of the Neo-Castilian tectonic phase (3). Important subsidence of the margin was recorded then after, with a consequent relative sea-level rise (4). This allowed the filling of the second generation of paleo-canyons from the Burdigalian to Pliocene. Finally, the upper Pliocene (Piacenzian) to Holocene period is marked by the erosion of the actual canyon channels (5), ravinating the previously deposited units 1 to 6.

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