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Sedimentary Evolution of the Northwestern Alboran Sea during the Quaternary

G. Ercilla, B. Alonso, and J. Baraza

Instituto de Ciencias del Mar C.S.I.C., Paseo Nacional s/n, 08039 Barcelona, Spain

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Abstract. Five depositional bodies occur within the Quaternary deposits of the northwestern Alboran Sea: Guadalmedina–Guadalhorce prodelta, shelf-edge wedges, progradational packages, Guadiaro channel–levee complex, and debris flow deposits. The sedimentary structure reflects two styles of margin growth characterized: 1) by an essentially sediment-starved outer shelf and upper slope and by divergent slope seismic facies; 2) by a prograding sediment outer shelf, and parallel slope seismic facies. Eustatic oscillations, sediment supply, and tectonic tilting have controlled the type of growth pattern, and the occurrence of the depositional bodies. Debris flows were also controlled locally by diapirism.

Introduction

The Quaternary sedimentary evolution of the Alboran Sea has received little attention in spite of showing interesting complex depositional patterns (Huang and others 1972; Ammar 1987; Tesson and others 1987). Those studies point out that the interplay of tectonism, sea-level changes, climatic changes, and marine circulation system in the Alboran Sea allowed the development of different depositional patterns in a relatively small area.

Our investigation is centered on the northwestern Alboran Sea, from Malaga to the Guadiaro River mouth (Fig. 1). In this area, the main sources supplying detrital sediment seaward have been several small rivers: the Guadalmedina, Guadalhorce, Fuengirola, and Guadiaro (Fig. 1). The morphology, acoustic facies, depositional bodies, erosive features, and structural modifications will be described in order to define growth patterns and the factors responsible for the Quaternary sedimentary evolution of the northwestern Alboran Sea.

Methods

Analyzed data consist of 275 km of high resolution (15 in^3), single-channel, air-gun seismic profiles collected during a cruise (GC-90-1) onboard the B/O GARCIA DEL CID in 1990 (Fig. 1). Navigation was by MAXIRAM (accuracy of about 10 m), and by satellite (TRANSIT and GPS).

The lower and upper Quaternary seismic sequences in the northwestern Alboran Sea have been identified by correlation with the seismic sequence boundaries, P2 (top of the upper Pliocene sequence) and Q1 (top of lower Quaternary sequence), established by Campillo and others (1992).

Morphology

Based on the margin gradients, two types of physiographic profiles, smooth and steep, have been differentiated (Fig. 2). The smooth physiographic profile is characterized by shelf-break located at 95–105 m water depth, a wide (21 km average) slope with low gradients (0.55–0.60°), and a gently sloping base-of-slope area (0.28–0.31°). It has been identified in the eastern (from Malaga to the Fuengirola River mouth) and western (from Marbella to the Guadiaro River mouth) sectors (Figs. 1 and 2; profiles 101 and 105). The steep physiographic profile has its shelf-break at a water depth of 115 m, a narrow (10 km average) slope with steep gradients (2.65° average), and a relatively steep base-of-slope area (0.4°). It only occurs in the central sector (from the Fuengirola River mouth to Marbella) (Figs. 1 and 2; profile 104). These two types of physiographic profiles connect with a basin that has a very low average regional gradient (0.04–0.13°), showing a slightly concave-up to flat-lying profile (Figs. 1 and 2).

Acoustic Facies

Two types of acoustic facies have been recognized: chaotic and stratified (Fig. 3). The chaotic facies presents two subtypes: 1) characterized by wavy and disrupted reflections of medium amplitude that appear as mound or lens-shaped bodies, bounded by irregular erosional surfaces (Fig. 3A); 2) composed of strong, contorted reflections of high acoustic amplitude with hyperbolic and hummocky reflectors, sometimes showing traces of the original parallel bedding (Fig. 3B).

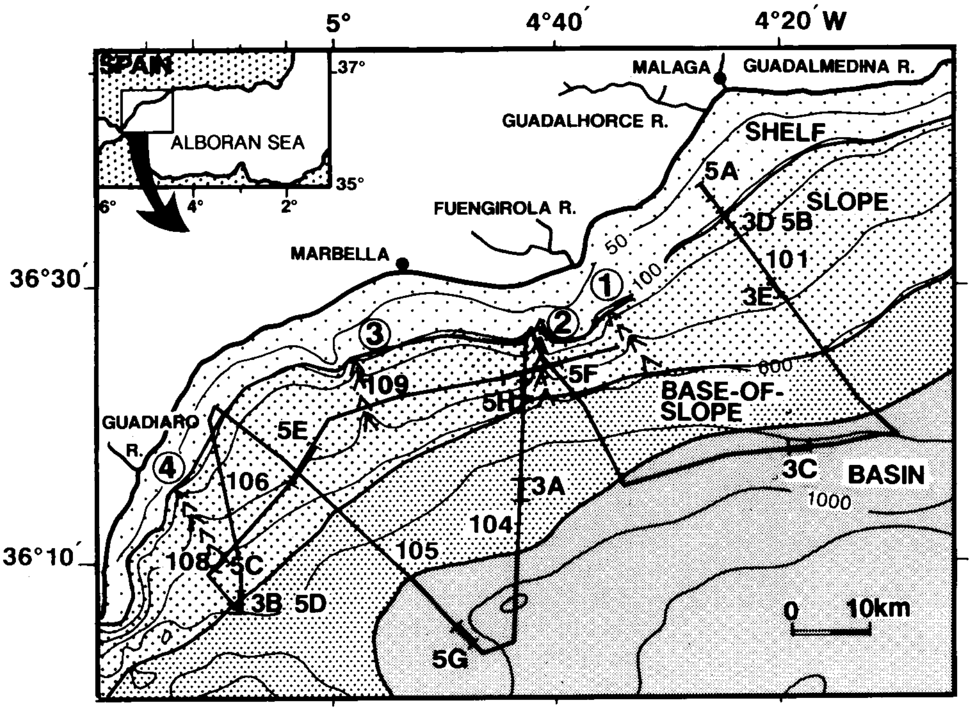

Figure 1. Location of study area showing bathymetry, physiographic provinces, canyon pathways, and location of seismic profiles; the numbers refer to profile interpretations illustrated in Figures 2 and 4; the numbers with letters refer to short, thick, seismic profiles shown in Figures 3 and 5; the circled numbers refer to the name of the Canyons: 1) Fuengirola; 2) Torre Nueva; 3) Baños; 4) Guadiaro. The reverse "V" symbols refer to canyon axis. Bathymetric contours in meters.

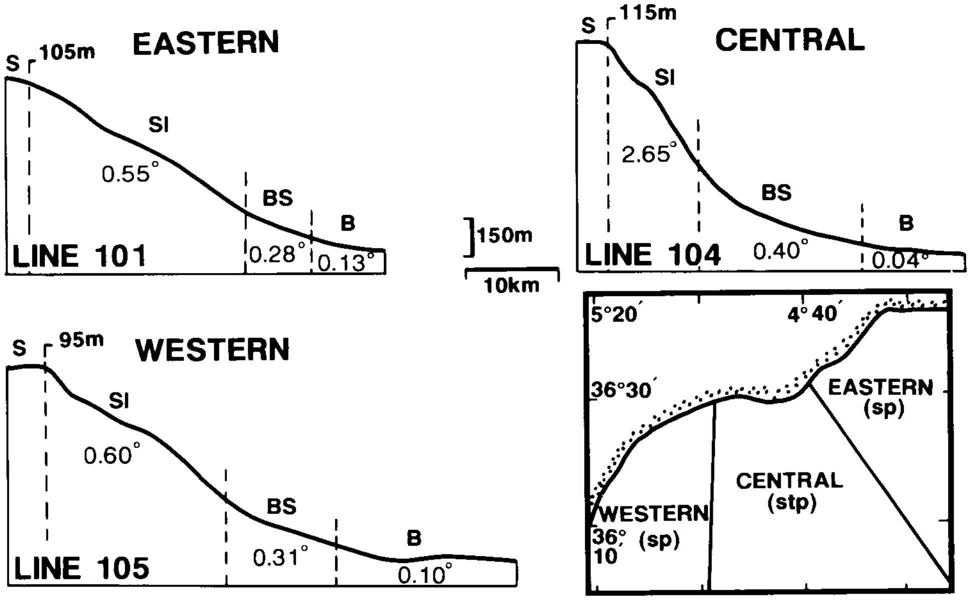

Figure 2. Shore-normal profile interpretations showing the gradients of the physiographic provinces in the eastern, central, and western sectors. Legend: S, shelf; SI, slope; BS, base-of-slope; B, basin; sp, smooth physiographic profile; stp, steep physiographic profile. Location of lines in Figure 1.

The stratified facies has been subdivided into 1) continuous, characterized by individual reflectors of high amplitude and high lateral continuity, and 2) discontinuous, characterized by individual broken reflections of low to moderate amplitude with high lateral continuity. Both types of stratified reflections follow three distinct geometries: parallel (Fig. 3C), oblique (Fig. 3D), and divergent (Fig. 3E).

Depositional bodies

Five different depositional bodies have been identified within the Quaternary seismic sequence, the Guadalmedina–Guadalhorce prodelta, shelf-edge wedges, progradational packages, the Guadiaro channel–levee complex, and debris-flow deposits. The Guadalmedina–Guadalhorce prodelta is a wedge composed internally of continuous stratified reflectors that prograde above the unconformity P2 (Figs. 4A and 5A). The shelf-edge wedges, with continuous and discontinuous stratified reflectors, are distinguished by having an oblique progradational pattern (Figs. 4 and 5B). The progradational packages are composed of oblique discontinuous and continuous stratified reflectors, that terminate downlapping onto the unconformity P2 (Fig. 4B). These packages are stacked vertically and result in an upbuilding and outbuilding (Fig. 4B). The Guadiaro channel–levee

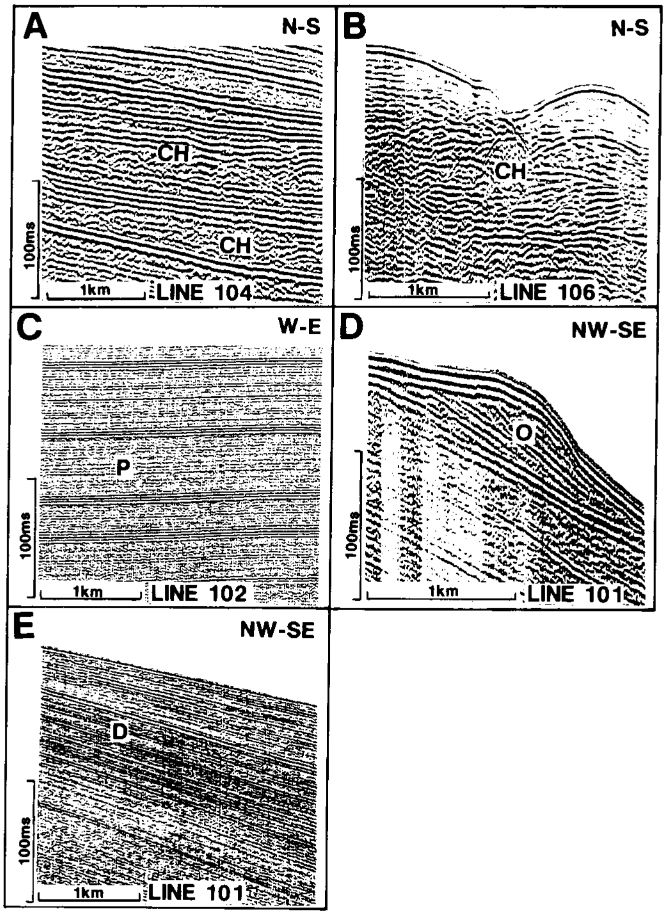

Figure 3. Main types of acoustic facies: (A) chaotic facies composed of wavy and disrupted reflections of medium amplitude that appear as mound or lens-shaped bodies; (B) chaotic facies characterized by strong, contorted reflections of high acoustic amplitude with hyperbolic and hummocky reflectors; (C) parallel stratified facies; (D) oblique stratified facies; (E) divergent stratified facies. Legend: Ch, chaotic facies; P, parallel stratified facies; O, oblique stratified facies; D, divergent stratified facies.

complex, which represents the seaward continuation of the Guadiaro Canyon, is an elongate lenticular body that contains chaotic facies in the channel-floor, and continuous stratified facies in the levees (Fig. 5C). This complex is 640 m wide and about 32 m deep, with steep gradients (0.96°) on the backside of the right-hand side of the levee (Fig. 5C). The debris-flow deposits occur as internally chaotic, lens-shaped masses up to 3–4 km in length and 30–40 ms thick (Figs. 4B and 5D).

Erosive Features and Structural Modifications

Erosive features and structural modifications affect the continuity of the Quaternary sediments and their seismic response. With respect to erosive features, five submarine canyons (Fuengirola, Torre Nueva, Baños, Estepona, and Guadiaro) and several gullies incise the Quaternary sediments (Figs. 5E, F and 6). The reliefs of the canyons are either steadily attenuated downslope or they evolve into a channel–levee complex, as occurs with the Guadiaro Canyon (Fig. 6). Only the Estepona and Torre Nueva Canyons show onlap fill (Figs. 5E, F). Similarly, several gullies, parallel and regularly spaced, ranging from 7 to 22 m in depth and averaging a width of 156 m, display divergent-onlap fill (Fig. 5F).

The structural modifications are found in three main forms, collapse structures, growth faults, and slumps. The collapse structures occur above the crest of diapirs (Figs. 4B and 5G) (Campillo and others 1992). The growth faults develop near to the collapse structures (Figs. 4B and 6A) and above the diapirs that affect the continuity of the Pliocene deposits (Campillo and others 1992). The slumps, which involve sediment up to 150 ms thick, occur in an area with a gradient of 2.65° (Figs. 4B and 5H).

Growth Patterns

Two styles of margin growth are identified during the Quaternary: 1) the margin of the eastern and western sectors, characterized by an essentially sediment-starved outer shelf and upper slope on which only prodelta and shelf-edge wedges, respectively, are well developed, and by slope seismic facies with a divergent geometry (Fig. 4A); 2) the margin of the central sector, formed by a sediment prograding outer shelf that continues seaward into the slope seismic facies with parallel geometry (Fig. 4B).

The eastern and western sectors show a lack of lower Quaternary deposits on the outer shelf and upper slope, whereas the Guadalmedina–Guadalhorce prodelta and the shelf-edge wedges identified on the outer shelf and shelf-break, respectively, were developed during the late Quaternary (Figs. 4A and 6). The slope seismic facies diverge seaward becoming parallel at the base-of-slope, and thin landward ending in a depositional pinchout in the upper slope (Fig. 4A). This sedimentary continuity, in the western sector, is locally interrupted by debris-flow deposits, the Guadiaro channel–levee complex, canyons, and growth faults (Fig. 6). The debris flow deposits gradually fade out toward the late Quaternary, although they occur locally in the present seafloor on the right margin of the Guadiaro channel–levee complex (Figs. 4B and 6B). The occurrence of this channel–levee complex has been identified back to at least the early Quaternary, and it may be identified in the present seafloor (Figs. 5C and 6). The Baños, Estepona, and Guadiaro Canyons are incised within the lower Quaternary deposits (Figs. 5E and 6A), and only the Baños and Guadiaro Canyons continue to cut through the upper Quaternary deposits (Fig. 6B). Finally, the scars of growth faults attenuate during the late Quaternary (Figs. 4B and 6).

The central sector is characterized by the development of progradational deposits in the early and late Quaternary (Fig. 4B). The sediment progradation observed on the outer shelf continues seaward into slope seismic facies with parallel geometry, which is conserved in the seismic facies of the base-of-slope (Fig. 4B). However, the slope and base-of-slope seismic facies have intercalated locally debris-flow deposits, where these facies are also eroded by canyons and gullies and deformed by collapse structures, growth faults and slumps (Figs. 4B and 6). The presence of debris-flow deposits decreases toward the late Quaternary (Fig. 4B). The Fuengirola and Torre Nueva Canyons have incised the Quaternary deposits (Figs. 5F and 6). The gullies, which are developed in both margins of the Torre Nueva Canyon,

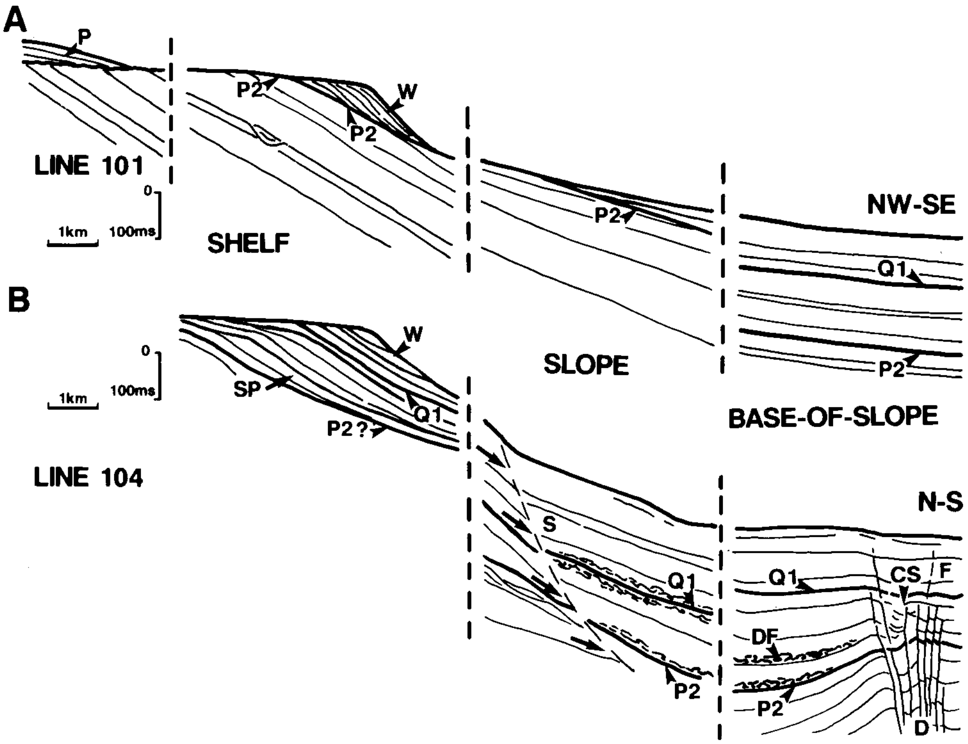

Figure 4. Representative line drawings of seismic profiles in the northwestern Alboran Sea showing the Quaternary margin growth patterns: A) in the eastern and western sectors; B) in the central sector. Legend: P2, top of the upper Pliocene sequence; Q1, top of the lower Quaternary sequence; P, Guadalmedina–Guadalhorce prodelta; W, shelf-edge wedge; SP, progradational packages; S, slump; DF, debris-flow deposits; CS, collapse structures; D, diapirs; F, growth fault. Location of seismic profiles are shown in Figure 1.

disappear toward the late Quaternary (Figs. 5F and 6B). The collapse structures are absent, and the scars of growth-faults and slumps attenuate in the late Quaternary, not reaching the present seafloor (Figs. 4B and 5G, H).

Geological Significance

Both styles of margin configuration observed on seismic profiles record the importance of eustatic oscillations, sediment supply, and tectonism during the Quaternary. The eustatic oscillations and sediment supply controlled the development of the progradational packages, shelf-edge wedges, the Guadalmedina–Guadalhorce prodelta, the Guadiaro channel–levee complex, some of the debris-flow deposits, canyons, and gullies. The development of the progradational packages in the central sector, and the shelf-edge wedges throughout the area, is related to the major progradational phases during the relative sea-level falls and lowstands (Figs. 4 and 6). During these periods, the seaward migration of the shoreline produces an increase of the sediment supply and basinward transport, generating the upward and/or seaward building of the margin (Posamentier and others 1988). The continuation of seaward building observed in the outer shelf could explain the parallel geometry of the slope seismic facies in the central sector (Fig. 4B). The edification of the Guadalmedina–Guadalhorce prodelta in the eastern sector took place during the last highstand, as a result of the landward migration of the coastline (Figs. 4A and 6B). This prodelta is attributed to the Holocene period by correlation with similar prodeltas that have been described in other shelves of the Spanish northwestern Mediterranean (Díaz and others 1990; Ercilla and Díaz 1990). The presence of the Guadiaro channel–levee complex in the western sector suggests a rapid terrigenous sedimentation from a proximal source (Guadiaro Canyon) (Figs. 5C and 6). Their acoustic facies are indicative of high energy deposition formed mainly by turbidity flows that occurred during the relative sea-level falls and lowstands (Bouma and others 1989). These flows are also responsible for the development of a series of elongate channel–levee complexes described by Alonso and Maldonado (1992) at the base-of-slope of the Motril and Almeria margins during the Quaternary. Other deposits related to high energy deposition are the debris-flow deposits located on the right margin of the Guadiaro channel–levee complex, which are developed due to the local high gradients (0.96°) observed on the back side of the right hand side of the levee (Fig. 5C).

With respect to the canyons and gullies, the limited number of seismic profiles is insufficient to determine the sedimentary or tectonic origin of the submarine canyons and gullies that incise the Quaternary deposits (Fig. 6). Nevertheless, we propose that the downcutting effect of these erosional features was most effective during the relative sea-level falls and lowstands. During these periods, the heavy sediment load induces high energy processes with greater erosive power to cut and deepen canyons (Shanmugam and Moiola 1982; Vail 1987). Submarine erosion has also been considered as the main factor responsible for the development of sea valleys in the northwestern Mediterranean during the Quaternary (Alonso and others 1991). The excavation of the canyons and gullies decreased during the relative sea-level rises and highstands, when the transport of sediment basinward decreased (Shanmugam and Moiola 1982; Vail 1987). The Estepona and Torre Nueva Canyons and gullies could have been infilled during these periods as a result of sediment supply changes that favored the onlap and divergent-onlap fill configurations (Fig. 5E, F).

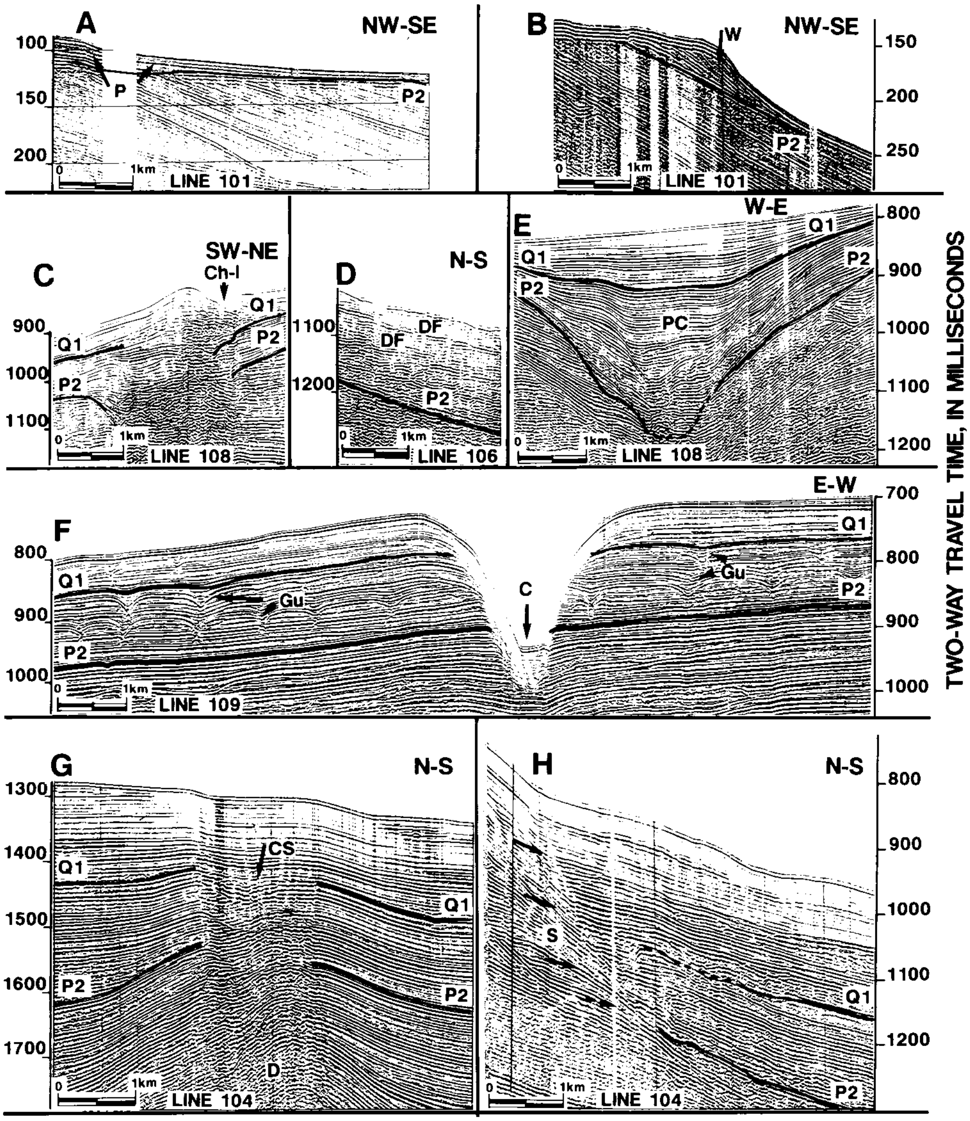

Figure 5. Depositional bodies and erosive and structural features recognized within the Quarternary sequences: A) Guadalmedina–Guadalhorce prodelta (P); B) shelf-edge wedge (W); C) Guadiaro channel–levee complex (Ch-l); D) debris flow deposits (DF); E) Estepona paleocanyon (PC); F) gullies (Gu) in the margins of the Torre Nueva Canyon (C); G) collapse structures (CS) and a diapir (D); H) slump (S). Locations are given in Figure 1. Key horizons as in Figure 4.

The main controlling factors of tectonic origin have been tilting and diapirism. The tectonic tilting, which probably took place during the structural compression since the early Quaternary (Armijo and others 1977), could help to explain two facts in the eastern and western sectors: 1) the essentially sediment-starved outer shelf and upper slope related to the simultaneous erosion of the uplifting Pliocene deposits (Maldonado and others 1992), which are truncated by the unconformity P2; 2) the divergent facies related to the deepening seaward of the offshelf areas (Fig. 4A).

Diapirism is only a minor controlling factor that affects the sedimentary continuity in the central and western sectors. This factor could help to explain the origin of the debris-flow deposits, collapse structures, growth faults, and slumps. The debris-flow deposits, except those located on the right margin of the Guadiaro channel–levee complex, may have been triggered by diapiric movements (Fig. 6).The upward movement associated with the diapiric intrusion probably leads to oversteepening of the affected areas, and consequently could produce instability. A similar triggering mechanism has been proposed to explain the origin of debris-flow deposits developed at the slope of the Gulf of Mexico (Bouma and others 1990). The diapiric movements could also be responsible for the development of collapse structures and growth faults, both related to the successive tensional and compressional forces caused by the changing of the diapiric intrusion rates. The slumps may also be related to the upward movements of diapirs (Bouma and others 1990). The steady decrease of debris-flow deposits and collapse structures and the attenuation of growth faults and slumps toward the late Quaternary could be attributed to a decrease of diapiric activity and consequent sedimentary instability.

We conclude that the relative importance of the different controlling factors changes through the area. The eustatic oscillations and sediment supply played a prominent role throughout the study area, but were especially responsible for the margin growth pattern developed in the central sector. Tectonic tilting has been clearly responsible for the type of margin growth developed in the eastern and western sectors. Finally, diapirism has played a minor role only affect-

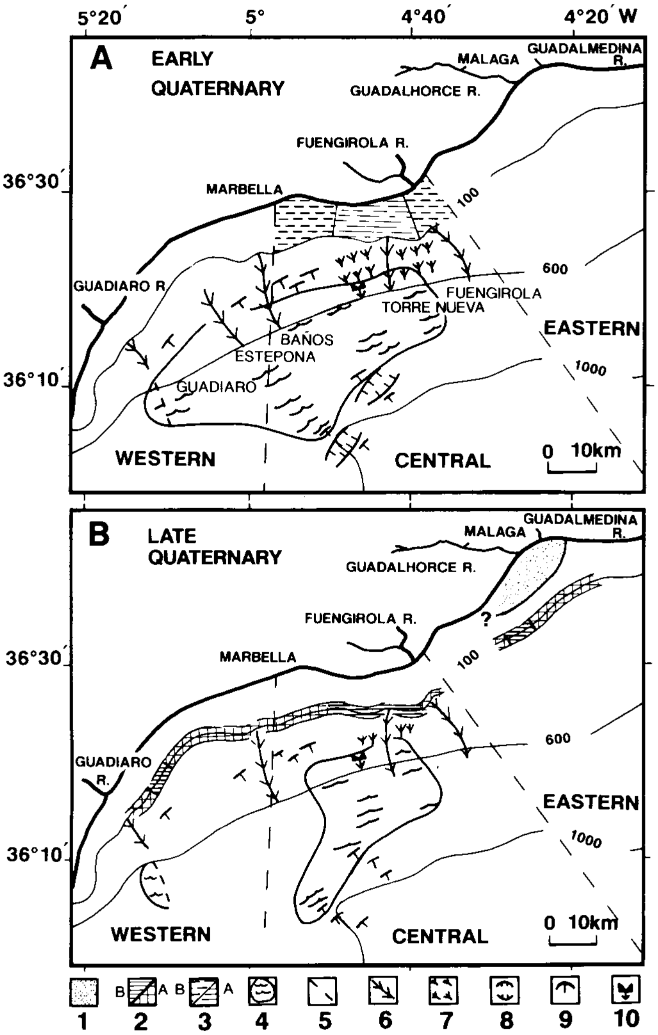

Figure 6. Distribution map of depositional bodies, erosive features, and deformational structures recognized in the early Quaternary (A) and late Quaternary (B) also showing the eastern, central, and western sectors. Legend: 1) Guadalmedina–Guadalhorce prodelta; 2a) shelf-edge wedge; 2b) presumed shelf-edge wedge; 3a) progradational packages; 3b) presumed progradational packages; 4) area of debris flow deposits; 5) channel–levee complex; 6) canyons; 7) gullies; 8) collapse structures; 9) growth faults; 10) slumps. Contours in meters.

ing the sedimentary continuity of the slope and base-of-slope deposits in the central and western sectors.

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