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Large-scale slope failure involving Triassic and Middle Miocene salt and shale in the Gulf of Cádiz (Atlantic Iberian Margin)

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ABSTRACT

Sheets of salt and ductile shale advancing beyond the thrust front of the Gibraltar Arc (Iberian–Moroccan Atlantic continental margin) triggered downslope movements of huge allochthonous masses. These allochthons represent the Cádiz Nappe, which detached from the Gibraltar Arc along low-angle normal faults and migrated downslope from the Iberian and Moroccan continental margins towards the Atlantic Ocean. Extensional tectonics initiated upslope salt withdrawal and downslope diapirism during large-scale westward mass wasting from the shelf and upper slope. Low-angle salt and shale detachments bound by lateral ramps link extensional structures in the shelf to folding, thrusting and sheets of salt and shale in the Gulf of Cádiz. From backstripping analyses carried out on the depocentres of the growth-fault-related basins on the shelf, we infer two episodes of rapid subsidence related to extensional collapses; these were from Late Tortonian to Late Messinian (200–400 m Myr^{-1}) and from Early Pliocene to Late Pliocene (100–150 m Myr^{-1}). The extensional events that induced salt movements also affected basement deformation and were, probably, associated with the westward advance of frontal thrusts of the Gibraltar Arc as a result of the convergence between Africa and Eurasia. The complexities of salt and/or shale tectonics in the Gulf of Cádiz result from a combination of the deformations seen at convergent and passive continental margins.

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Introduction

The migration of salt and shale can be attributed to various mechanisms. Several studies have shown that the buoyant rise of such low-density mobile sediments through denser overburden often fails to explain the initiation, shape and distribution of particular salt and shale structures (Bishop, 1978; Jackson and Talbot, 1986; Vendeville and Jackson, 1992). The movement of salt and/or shale can be initiated or accelerated by tectonic forces that stretch, wrench or compress the sequences containing them (Jackson and Talbot, 1986; Stephenson *et al*., 1992; Koyi *et al*., 1993; Jackson and Vendeville, 1994; Waltham, 1997). The influence of tectonic stress on the process of salt and ductile shale migration is very relevant to the interpretation of the tectonic structures in deformed continental margins. In this sense, several models have been proposed to explain the origin of the olistostromic deposits in the Gulf of Cádiz. Most authors attribute these deposits to large-scale gravity-driven mass wasting from the uplifted Betic-Rif (Lajat *et al*., 1975; Martínez del Olmo *et al*., 1984; Suarez-Alba *et al*., 1989; Flinch *et al*., 1996; Sierro *et al*., 1996) (Fig. 1C). By contrast, Berástegui *et al*. (1998) attribute their emplacement in the Guadalquivir basin to lateral diapirs emplaced by squeezing of Triassic materials from below the external zones pushing the Miocene sediments ahead of themselves. On the other hand, some authors (Hilde, 1983; Uyeda, 1983) consider that the olistostrome formations are specific slope facies related to subduction zones. In this respect, Gutscher *et al*. (2002) attributed the structure of the Gulf of Cádiz to an active subduction zone dipping eastward from the Atlantic oceanic to beneath the Alboran Sea.

The aim of this work is to describe salt- and shale-related structures along the continental shelf and upper slope in the Gulf of Cádiz and propose a new hypothesis for their emplacement as a huge mass-wasting structure, the so-called 'Cádiz Nappe'. We will also use detailed

Fig. 1 (A) Global view of the study area that shows the plate boundary between Eurasia and Africa (modified from Vázquez and Vegas, 2000): GO (Gorringe Bank); SV (San Vicente Promontory) and GU (Guadalquivir Bank). Convergence rate of the plates has been determinated by DeMets *et al*. (1990) and Westaway (1990). (B) Tectonic sketch map and structural subdivisions of the huge allochthonous masses ('mega-olistostromes') in the Gulf of Cádiz, integrating data from Roberts (1970), Lajat *et al*. (1975), Bonnin *et al*. (1975), Feinberg (1976), Malod (1982) and Torrelli *et al*. (1997). (C) Cross-section from the continental shelf to the Eastern Horseshoe abyssal plain based on the correlation between seismic lines AR01 (Torrelli *et al*., 1997) and line 80-366 (Fig. 4). Depth of Moho based on seismic refraction data from González *et al*. (1998).

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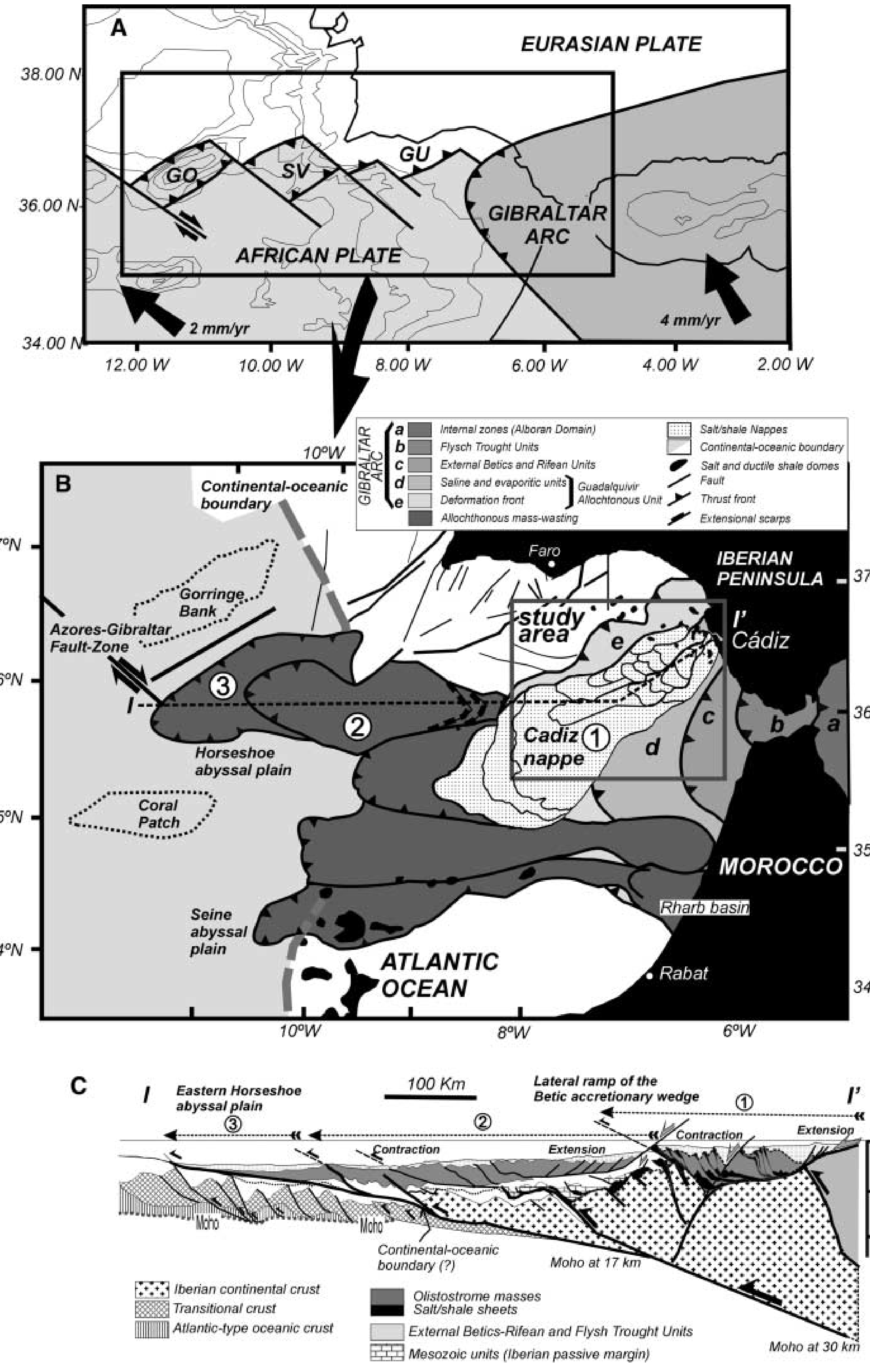
A
EURASIAN PLATE
38.00 N
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GO
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AFRICAN PLATE
2 mm/yr
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12.00 W
10.00 W
8.00 W
6.00 W
4.00 W
2.00 W
B
10ºW
GIBRALTAR ARC
a Internal zones (Alboran Domain)
b Flysch Trought Units
c External Betics and Rifean Units
d Saline and evaporitic units
e Deformation front
Guadalquivir Allochtonous Unit
Allochthonous mass-wasting
Salt/shale Nappes
Continental-oceanic boundary
Salt and ductile shale domes
Fault
Thrust front
Extensional scarps
Continental-oceanic boundary
37ºN
36ºN
35ºN
34ºN
Faro
IBERIAN PENINSULA
Gorringe Bank
Azores-Gibraltar Fault-Zone
study area
I'
Cádiz
e
③
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I
c
b
a
Cadiz nappe
d
Horseshoe abyssal plain
Coral Patch
MOROCCO
Rharb basin
Seine abyssal plain
ATLANTIC OCEAN
Rabat
10ºW
8ºW
6ºW
C
I
Eastern Horseshoe abyssal plain
100 Km
Lateral ramp of the Betic accretionary wedge
I'
③
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Contraction
Extension
Contraction
Extension
0
5
10
TWTT (sec)
Moho
Moho
Continental-oceanic boundary (?)
Moho at 17 km
Moho at 30 km
Iberian continental crust
Transitional crust
Atlantic-type oceanic crust
Olistostrome masses
Salt/shale sheets
External Betics-Rifean and Flysh Trought Units
Mesozoic units (Iberian passive margin)

analyses of subsidence rates in basins well known on the shelf to argue that post-Miocene convergence between Africa and Eurasia triggered gravitational gliding and spreading of the salt and shale deposits within the 'Cádiz Nappe'.

Geological background

The Gulf of Cádiz lies west of the Gibraltar Arc, the westernmost tectonic belt of the Alpine–Mediterranean system that formed in response to the African–Eurasian plate convergence (Fig. 1A). The contractional transport direction at the front of the Gibraltar Arc is radial: transport is NW-directed in the north-western part (Crespo-Blanc and Campos, 2001), WNW- to W-directed in the northernmost outcrops of Flysch Trough Units (Luján *et al.*, 1999) and near the Strait of Gibraltar (Balanyá *et al.*, 1995), and SW-directed in the Rif (Morley, 1987).

West of the Gibraltar Arc, along the Atlantic continental margin and parts of the Horseshoe and Seine abyssal plains, deep seismic profiles reveal highly reflective giant chaotic bodies with thickness exceeding 2 km (Vázquez *et al.*, 2001) (Fig. 1B). These masses have an overall length that may reach 400 km (Torrelli *et al.*, 1997). The overall structure of this giant body has been interpreted in terms of olistostromes and tectonic melanges and is attributed to tectono-sedimentary processes in the Africa–Iberia convergent plate setting.

Three main tectonic allochthonous provinces surround the internal zones of the Gibraltar Arc (Alboran Domain, unit a, Fig. 1B). These include (Fig. 1B): (unit b) the units of the Flysch Trough, (unit c) the External Betics and Rifean areas, a tectonically detached body of Lower Jurassic to Upper Cretaceous – Palaeocene formations, and (unit d) the Diapir Zone, composed mainly of Triassic salts, gypsum and shallow-marine carbonate deposits emplaced as diapiric extrusions during thrusting of thick Mesozoic nappes (Berástegui *et al.*, 1998), and Middle Miocene plastic clays and shales (Maldonado *et al.*, 1999). The most distal part of the Gibraltar Arc (units d and e in Fig. 1B) has traditionally been referred to as the 'Olistostrome Zone' (Perconig 1960–62) or 'Guadalquivir Allochthonous Unit' (Martínez del Olmo *et al.*, 1984). The allochthonous units in the Gulf of Cádiz were emplaced during the Tortonian (*c.* 7.1–11.2 Ma) (Maldonado *et al.*, 1999) as an accretionary wedge formed by the interaction of the Internal Zones of the Alboran Domain with the passive margins of Eurasia and Africa (Flinch *et al.*, 1996). The external part of the Gibraltar Arc (Fig. 1A) consists mainly of allochtonous Upper Triassic salts and Middle Miocene shales that are together known as the 'Olistostrome Unit' or

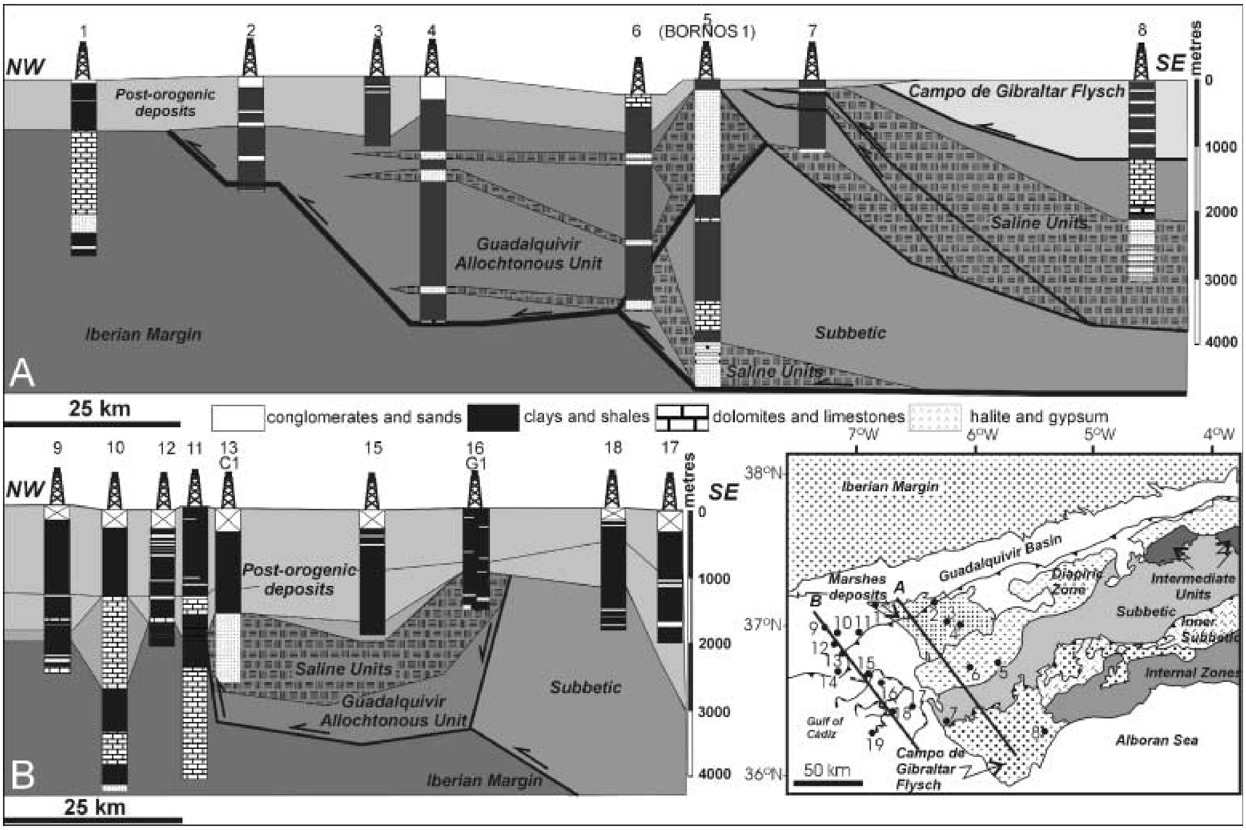


Fig. 2 Oil-well correlations for the onshore (A) and offshore (B) western Betics and Gulf of Cádiz and location map (modified from Berástegui *et al.*, 1998). Well number: 1, Moguer1; 2, Casanieves1; 3, Sapo1; 4, Bética14-1; 5, Bornos1; 6, Bética18-1; 7, Chiclana; 8, Cerro Gordo; 9, Atlántida2; 10, B1; 11, D1; 12, B3; 13, C1; 14, 6Y-1.bis; 15, E1; 16, G1; 17, Neptuno2; 18, Neptuno1; 19, MPC1 (IGME, 1987).

'Allochtonous Sedimentary Complex' (Azañón *et al*., 2002). The emplacement of this unit is related to the westward migration of the front of the Gibraltar Arc. Nevertheless, deformation structures observed on multichannel and high-resolution seismic lines along the shelf and slopes of the Gulf of Cádiz provide geometric evidence for structures involving salt and shale. Salt and shale dynamics are related to the ductile deformational history of this complex and strongly influenced the sedimentation and erosion processes at its surface (Llave *et al*., 2001; Hernández-Molina *et al*., 2003).

Data from oil wells located at the front of the wedge both onshore and offshore show large amounts of salt, shale and marly deposits, traditionally referred to as the 'Guadalquivir Allochthon' by the oil industry or the 'Olistostrome Mass' (IGME, 1987). Onshore, this mixture of Triassic evaporites and Miocene shales reaches a thickness of about 3000 m (Betica 14-1 well). In addition, more than 2500 m of Triassic anhydrites and salt have been drilled within this allochthonous unit (50 km eastward of the Cádiz coastline, e.g. the Bornos 1 well). Otherwise, the maximum thickness of Triassic evaporites drilled on the continental shelf varies from 500 m (G-1 well) to 1040 m (C1 oil well) following the arcuate front of the wedge offshore (Fig. 2C).

Data sources and methods

For the present study we used a complete dataset that consists of multichannel seismic reflection lines, swath bathymetry and well-log information from the Spanish continental margin (Fig. 3). We analysed ~30 seismic marine lines crossing the continental shelf that were shot and processed for several oil companies between 1974 and 1982. The data quality is generally good, and the available sections went through a standard marine processing scheme including post-stack time migration. Multichannel seismic lines collected during the TASYO cruise aboard de R/V *Hespérides* in 2000 have also been used. During this cruise, 1728 km of seismic profiles was obtained crossing the area in ENE–WSW, NE–SW and NW–SE directions. Seismic data were acquired by means of an airgun array of 22.45 and 34.8 L and a 96-channel streamer 2.5 km long recording for 10 s. A bathymetric multibeam mosaic (Simrad EM12S-120) and shallow high-resolution seismic profiles (Topographic Parametric Sound, TOPAS) were also acquired during this cruise. In addition, a dense network of single reflection seismic profiles was collected using a Sparker system during cruises Anastasya-99 and Anastasya-00

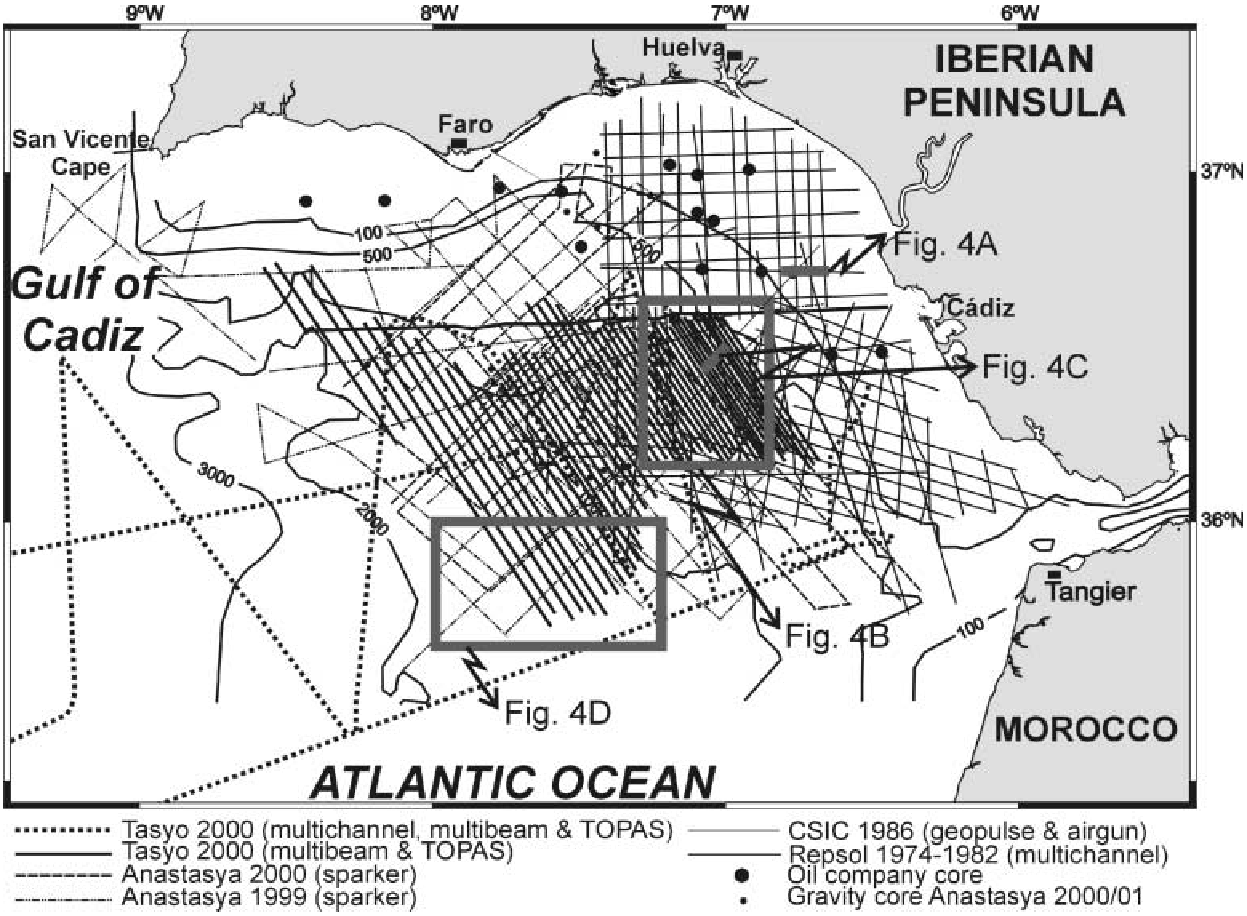


Fig. 3 Location of seismic profiles and multibeam dataset used to construct the morphosedimentary map. Contours are in metres.

aboard R/V *Cornide de Saavedra* in 1999 and 2000. These used an energy source that ranged between 3500 and 7000 J and a recording time of 2 s two-way travel time. Although these high-resolution seismic profiles are not shown here, we used some to complement mapping of allochthonous units. Further information can be found in Somoza *et al.* (2003). The sea-floor morphology of the study area was made from the bathymetric map, contoured at an interval of 10 m. The subsidence histories for depocentres in growth-fault-related basins located on the shelf were determined by means of backstripping analysis at basin depocentres selected using interpretations of seismic lines that cross-cut wells (IGME, 1987). These lines were interpreted following the regional seismo-stratigraphic units described by Maldonado *et al.* (1999) and, later, time to depth converted for each site using well velocity data. The backstripping was corrected for decompaction and sediment removal (Bond and Kominz, 1984) using the PC program 'SUBSIDE' (Hsui, 1993). This program plots the total subsidence curve of the decompacted sediments and their tectonic subsidence (see Fig. 7B).

Salt- and/or shale-related structures in the Gulf of Cádiz

The salt and ductile shale systems in the north-eastern Gulf of Cádiz form a complex network of interacting components that constitute the 'Cádiz Nappe'. In a preliminary study and after comparing the geometries of faults, welds, deformed strata and associated salt and shale bodies, it is possible to identify morphologies associated with basinward migration of salt and/or shale.

Down-to-basin listric growth faults and associated rollover anticlines occur in the shelf and upper slope. Many of these faults merge downward into the top salt at prominent cusps and many reach upward to the sea floor (Fig. 4A). Where salt has been evacuated from the hangingwalls, such faults define triangular salt rollers in their footwalls (Bally, 1981; Jackson and Talbot, 1991). In map view, growth faults strike approximately parallel to contours on the regional slope, although individual segments are arcuate (Fig. 4B). These growth faults accommodate downslope gliding of the overburden along the salt and/or shale detachments.

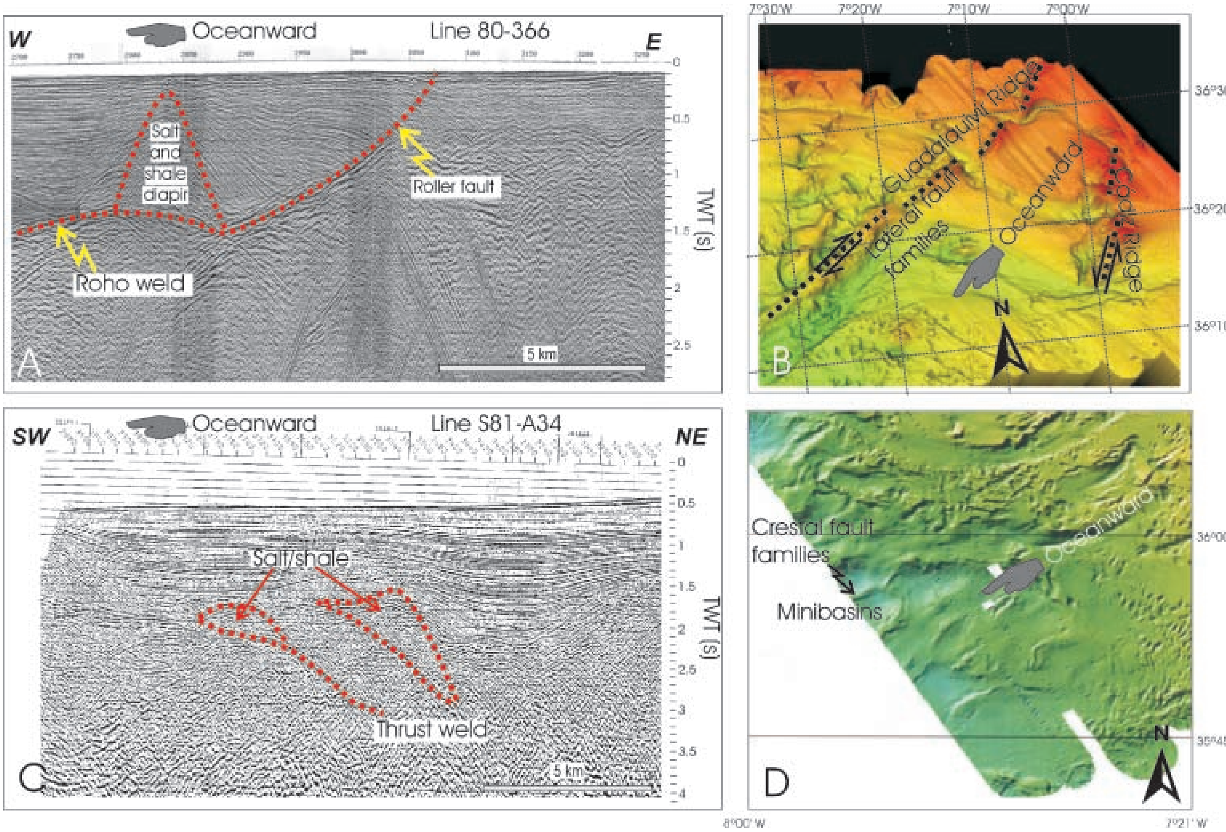


Fig. 4 Salt and ductile shale-related structures in the Gulf of Cádiz. (A) Seismic profile of roller fault soling into a salt layer. The diapir in the footwall was produced by regional extension after deposition. (B) Multibeam echosounder showing lateral fault families. *En echelon* right-lateral (Guadalquivir Ridge) and left-lateral (Cádiz Ridge) edge of the shallow salt/shale in the northern and southern Gulf of Cádiz, respectively. The dashed black lines show the lateral edges of shallow salt/shale. (C) Seismic profile showing a thrust weld. Contractional slip along the weld has raised the hangingwall relative to the footwall. (D) Multibeam echosounder of crestal fault families forming a polygonal pattern. The grabens border distinct minibasins subsiding into a salt/shale nappe. Location of these figures is shown in Fig. 3.

Thrust ramps develop along the fronts and sides of allochthonous salt and/or shale bodies where their base cuts up the stratigraphic section in their emplacement direction (Jackson and Talbot, 1991). In map view, lateral (or sidewall) faults show either linear or *en echelon* arrays striking downslope (Fig. 4B). Ridge structures (e.g. Guadalquivir and Cádiz ridges) develop above such lateral fault arrays (Fig. 4B). Individual lateral faults can have either normal or reverse offset, or even combinations of both that vary along strike. The position and geometry of lateral faults suggest that they originate as transfer faults linking the end of upslope normal faults to the

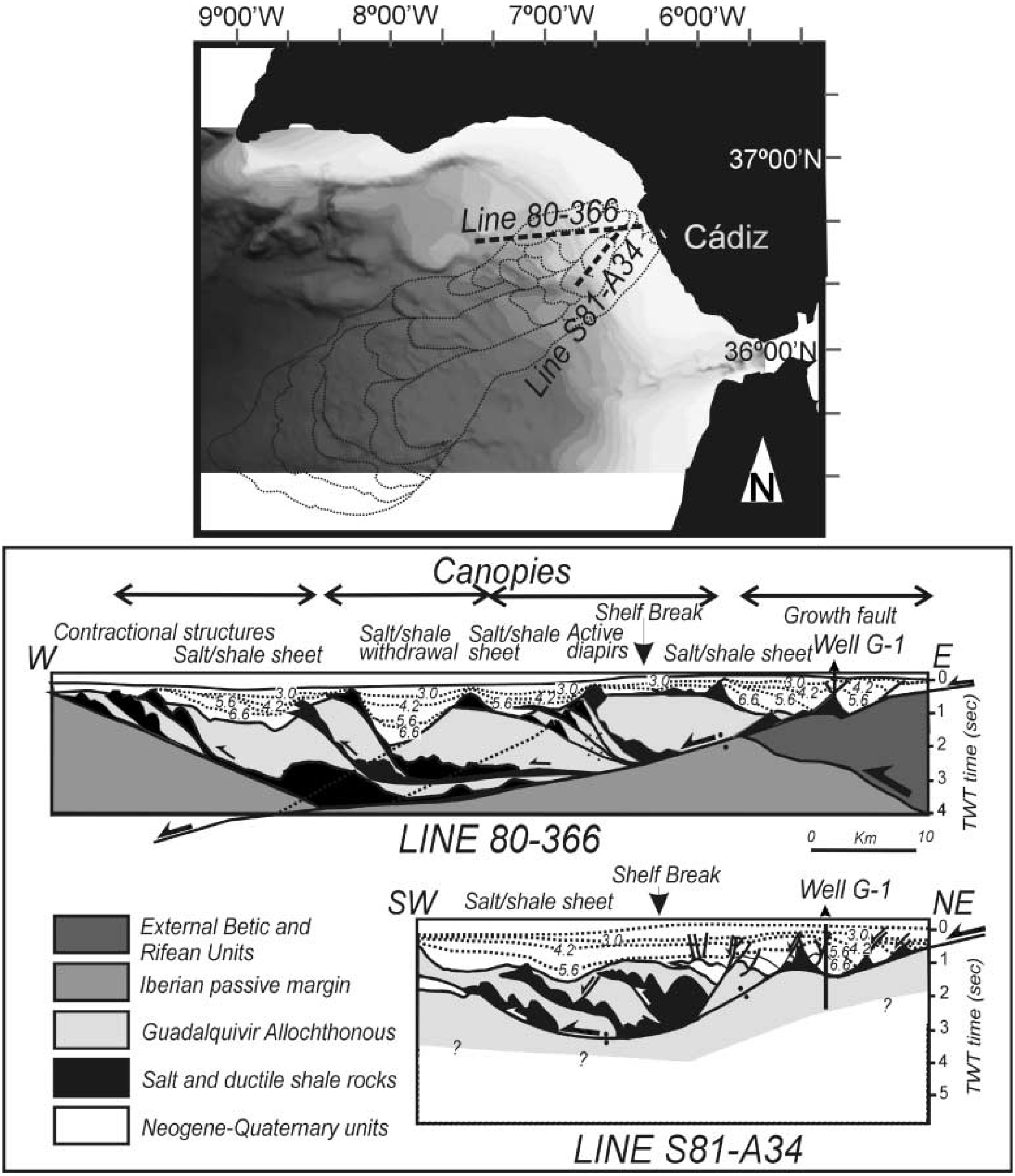


Fig. 5 Cross-section based on interpretation of seismic section 80-366 and S81-A34 through the Gulf of Cádiz shelf and slope.

end of downslope contractional structures (Harrinson and Patton, 1995) (Fig. 4B). In the Gulf of Cádiz, lateral faults occur in two main settings: (1) some separate extensional compartments with different downslope translations over allochthonous bodies; (2) others divide corridors in which overburden has translated downslope from adjacent areas with negligible downslope translation. Non-translated footwalls have sections expanded by differential subsidence. Differences in thickness between translated and static overburden sequences indicate that translating overburden was thinning by lateral extension as it gravity-spread beneath the upper slope. It could therefore move up its basal detachment as well as gliding downslope (Ramberg, 1981). Ridge structures (e.g. Guadalquivir and Cádiz ridges) develop above such lateral fault arrays (Fig. 4B).

Reverse faults dip upslope near the downdip toes of allochthonous bodies. Such toe thrusts are arcuate in map view and ramp-up basinward from basal salt and/or shale detachments. Most have reverse displacements that die out upward toward tip lines generally located in the hinges of associated contractional synclines (Fig. 4C). Toe thrusts form in response to downslope translation of the overburden above allochthonous bodies (Rowan *et al.*, 1999). Anticlines over downslope toe thrusts are linked to rollover anticlines in the hangingwalls of upslope normal faults by overburden that spread and glided along the intervening detachment (Fig. 4A). Diapirs were driven to higher levels in the front of the advancing allochthon. Some of these diapirs may have extruded and spread over the sea floor before being buried and reactivated by prograding sediments. Enough salt and ductile shale was allochthonous at shallow levels to form canopies in parts of the slope.

Other typical mobile-sediment-related structures on the slope in the Gulf of Cádiz are crestal faults. These root in the crests of diapirs with triangular profiles and form symmetric grabens that outline complex polygonal minibasins (Fig. 4D). The geometries of these minibasins are characteristic of those overlying reactive diapirs that rise along normal faults during radial or multidirectional lateral extension of the mobile layer and its overburden (Vendeville and Jackson, 1992; Jackson and Vendeville, 1995).

The venting of deep gas observed in the Gulf of Cádiz (Baraza and Ercilla, 1996; Somoza *et al.*, 2001a, 2002, 2003) relates to lateral movements of salt and/or shale in the olistostrome complex (Somoza *et al.*, 2001b). Basinward translation of the shelf sequence was accompanied by extrusion of sediments and fluids along contractional faults on the upper slope. Overpressures in compartments beneath salt wedges drove hydrocarbon gases, brines and fluidized sediments upward along contractional toe-thrusts to form regions of seepage on the sea floor (mud volcanoes, pock marks, and spreads of extruded salt and/or shale) (Lowrie *et al.*, 1999).

The Cádiz Nappe: a new hypothesis for the emplacement of a huge mass-wasting structure

The 'So called Olistostrome' (Berastegui *et al.*, 1998) is the most important unit in the Gulf of Cádiz and consists mainly of Triassic evaporitic sediments and Miocene shales. This study distinguishes in this area the 'Cádiz Nappe' consisting of bodies that migrated downslope toward the Atlantic by gravitational collapse. This mass-wasting was eased by the inherent weaknesses of the salts and shale involved. It was also eased by over-pressures developed in the formation waters and hydrocarbons in the 2.4-km-thick allochthonous complex and beneath its basal decollement. An extra factor in the 'Cádiz Nappe' is that weak sediments on the shelf may have collapsed downslope after having been oversteepened by the westward advance of the External Betic and Rifean Units (Fig. 5). The morphology and location of the salt and shale sheets downslope is also controlled by the oblique NW–NE convergence between Africa and Iberia during the Plio-Quaternary (Argus *et al.*, 1989).

Fig. 7 (A) Salt/shale–nappe system in the Gulf of Cádiz. (B) Tectonic subsidence curves using backstripping methods for representative points of the Cádiz Nappe System. The main tectonic events in its evolution are indicated.

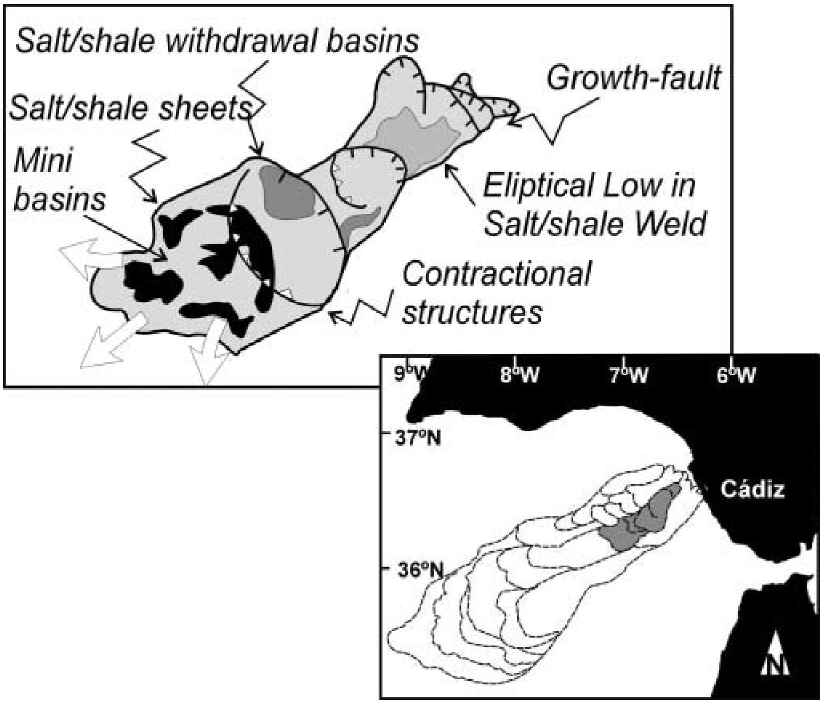
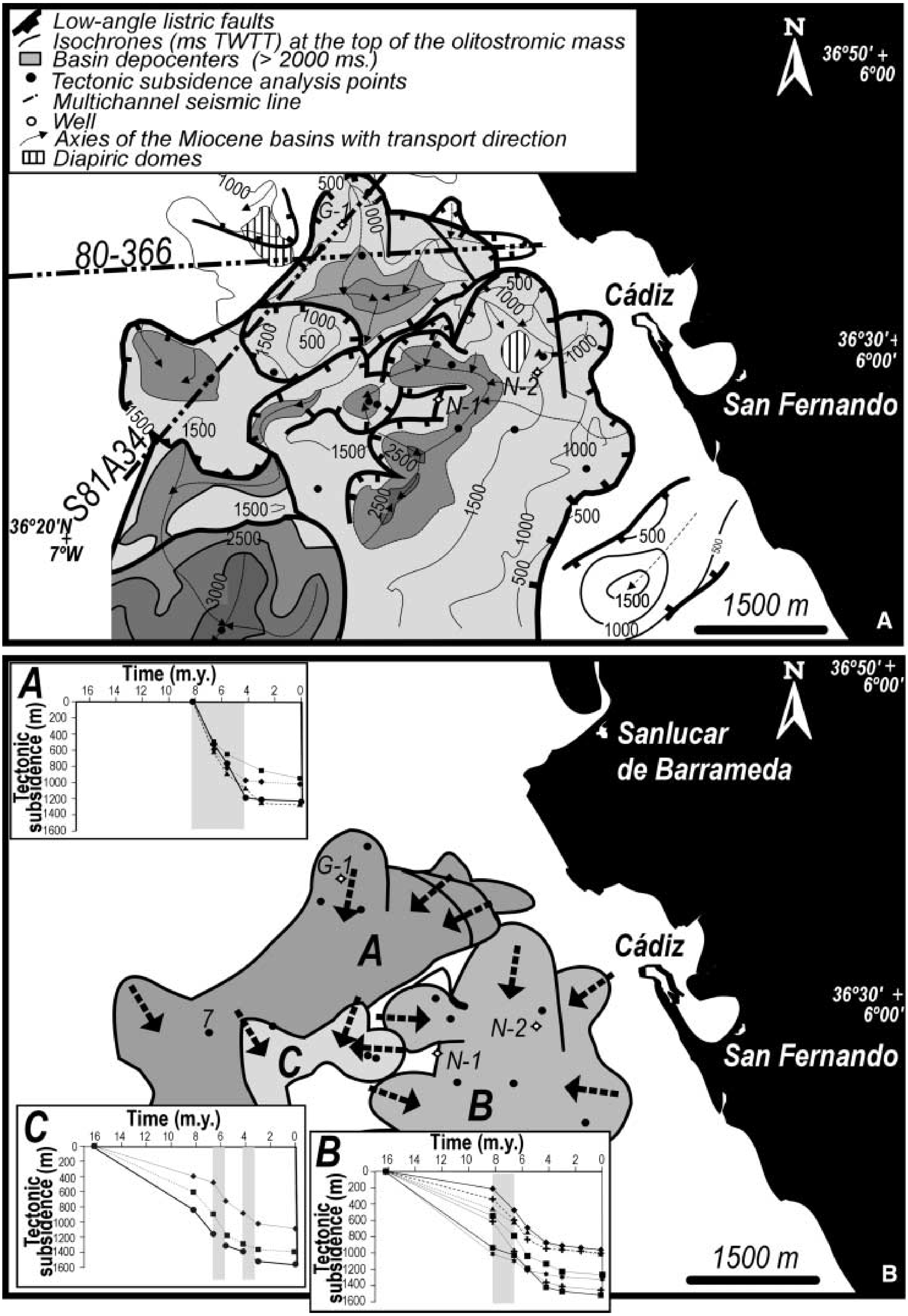


Fig. 6 Sketch of the main structures of the north-western part of the 'Cádiz Nappe' (grey shading on the location map). It is formed by a linked system of extension and contraction salt/shale canopies about 10–15 km across.


Low-angle listric faults
Isochrones (ms TWTT) at the top of the olitostromic mass
Basin depocenters (> 2000 ms.)
Tectonic subsidence analysis points
Multichannel seismic line
Well
Axies of the Miocene basins with transport direction
Diapiric domes
N
36°50' + 6°00
36°30' + 6°00'
36°20'N 7°W
80-366
S81A34
G-1
N-1
N-2
Cádiz
San Fernando
Sanlucar de Barrameda
500
1000
1500
2500
3000
1500 m
A
B
C
7
Time (m.y.)
Tectonic subsidence (m)
16 14 12 10 8 6 4 2 0
0 200 400 600 800 1000 1200 1400 1600

The term 'olistostrome' should be restricted to deposits genetically related to giant debris-flows driven downslope by gravity, and to tectonic or sedimentary melanges (Allaby and Allaby, 1990). We accept the olistostromes reported by Torrelli *et al.* (1997) on the Eastern Horseshoe and Seine plains (Fig. 1) but propose that most components of the 'Cádiz Nappe' were driven downslope in two events: (1) westward escape of the Gibraltar Arc that resulted in (2) gravity-driven collapse in which upslope extension and withdrawal of mobile sediments was linked to downslope folding and thrusting of sheets of allochthonous sediments (Fig. 6). We therefore suggest that the extensional faulting upslope in the wedge was contemporaneous with the advance of the thrust front toward the Eastern Horseshoe (Fig. 1B).

The collapse chronology

Extensional collapse of the 'Cádiz Nappe' resulted in rapid increases in tectonic subsidence in the Gulf of Cádiz during the late Miocene and Pliocene. Oceanward movement of the allochthon accelerated the formation of accommodation space of Upper Miocene to Quaternary sediments in basins deepening on the shelf and upper slope. Low-angle listric normal faults that cut successive thrust wedges are associated with the extensional collapse (see Fig. 7A). The plasticity of underlying Triassic evaporites and Neogene shales lubricated the oceanward movement of the 'Cádiz Nappe' and accelerated the rates of both the landward propagation of low-angle normal faults and the subsidence of basins on the shelf (Fig. 7B).

Subsidence rates (see Fig. 8) of between 50 and 80 m Myr^{-1} during the period 16.2–8.2 Ma (Langhian to Middle Tortonian) are related to upper crustal flexure induced by the advance of the Betic wedge. Tectonic subsidence increased to 400 m Myr^{-1} between 8.2 Ma and 6.5 Ma (Late Tortonian to Early Messinian) during the main extensional collapse of the Cádiz Nappe into the Gulf of Cádiz. Subsidence associated with extensional collapse slowed progressively to between 200 and 250 m Myr^{-1} (6.5–5.6 Ma) and decreased drastically to 100–125 m Myr^{-1} between 5.6 and 4.2 Ma (Early Pliocene). Renewal of collapse associated with the oceanward migration is indicated by a second increase in subsidence rate to 150 m Myr^{-1} from 4.2 to 3.8 Ma (Middle Pliocene to Late Pliocene). This last phase of lower subsidence is not evident over the whole area, implying that not all salt and shale in the 'Cádiz Nappe' migrated at the

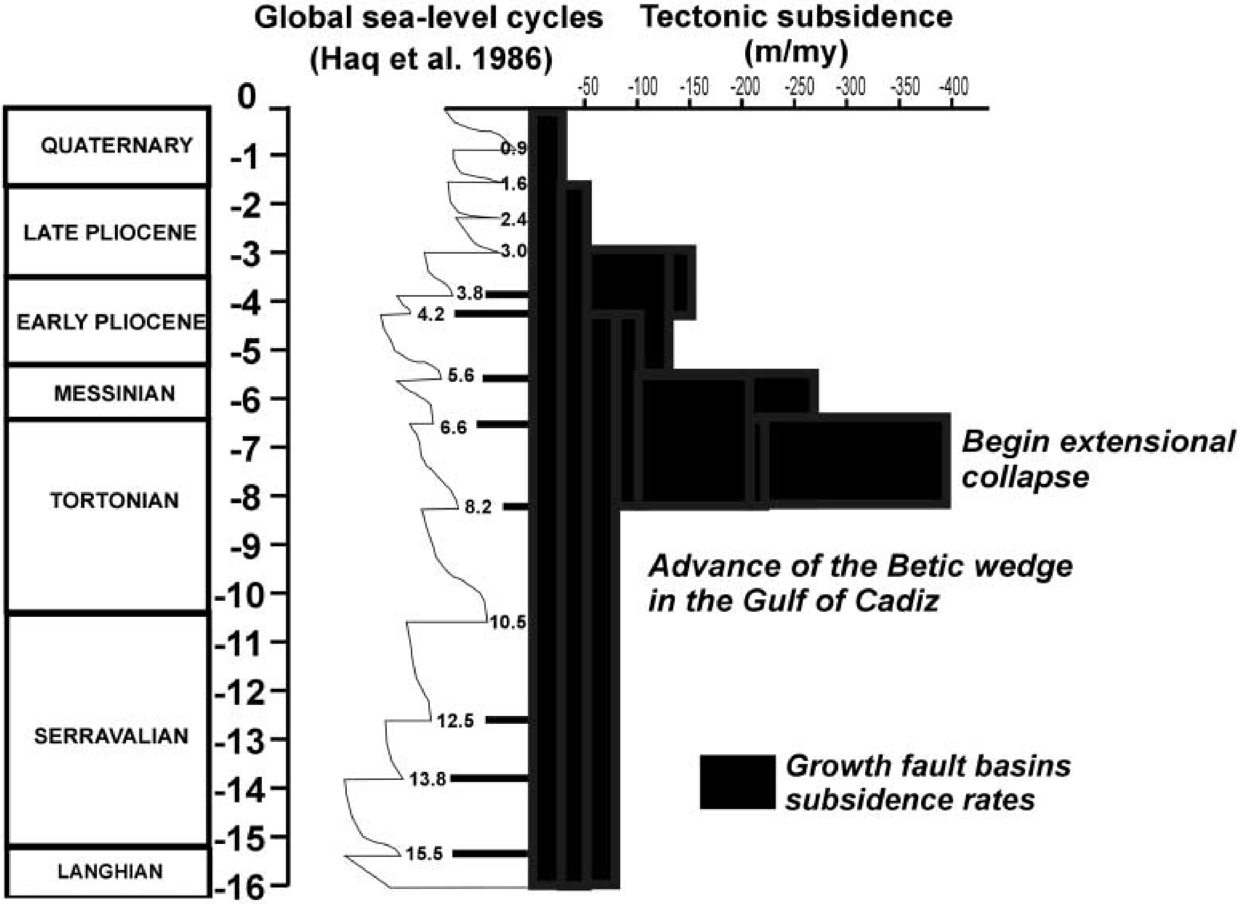


Fig. 8 Tectonic subsidence rates in the shelf from well G-1. The rapid increase in the subsidence rates suggests the onset of updip extension and listric growth faulting after the advance of the Gibraltar Arc during the Late Tortonian.

same time. The emplacement of giant allochthonous masses onto the Eastern Horseshoe and Seine plain took place during the Late Miocene and the Early Middle Pliocene (Torrelli *et al.*, 1997). This time coincides with the two stages of maximum extensional collapse in the 'Cádiz Nappe' in the Late Tortonian – Messinian and Middle Pliocene.

Discussion and conclusions

We propose that the 'Cádiz Nappe' was carried as the roofs of sheets and canopies of allochthonous salt and shale (10–15 km wide) detached from the Gibraltar Arc. We further propose that displacement of the salt and shale was triggered by recurring flexural uplift and extension (Flinch, 1993) that affected the Mesozoic and Palaeozoic basement and the thin Neogene–Quaternary cover along the outer margin of the foreland basin (Michard, 1976; Somoza *et al.*, 2002). Imbricated thrusting at the front of the 'Cádiz Nappe' triggered slope failures and consequent downslope movements of huge allochthons. These units detached from the thrust front along low-angle normal growth faults and resulted in sedimentary basins rapidly subsiding on the continental shelf of the Gulf of Cádiz.

The emplacement of the 'Cádiz Nappe' involved thrusting along frontal and lateral ramps that propagated basinward, incorporating and deforming giant mass-wasted allochthons already in foredeep basins. Thrust wedges that record the advance of both the slope and the deformation front (Gutscher *et al.*, 1996) were contemporaneous with extensional collapse basins on the actively accreting shelf and were linked to them by intervening detachments lubricated by salt and shale that closed to welds. The extensional events that induced movements of the salt also affected the basement deformation and were probably associated with the westward advance of frontal thrusts of the Gibraltar Arc in response to African–Eurasian convergence.

Tectonic subsidence curves calculated using decompaction and backstripping techniques reflect a two-fold increase in subsidence rates related to shelf collapse from Late Tortonian to Late Messinian and from Early Pliocene to Late Pliocene. These intervals match those proposed by Torrelli *et al.* (1997) for the development of olistostromes on the Eastern Horseshoe (Late Miocene) and the Seine (Early Late Pliocene) Abyssal Plains. The incorporation of rootless sheets of Triassic salt and overpressured Miocene shales into the allochthonous masses may have enhanced mass transport. Surficial megaturbidites may have been triggered by seismic activity during lower sea levels (Lowrie *et al.*, 1996; Rothwell *et al.*, 1998). This would explain the generation of the large volumes of turbidite deposits (e.g. Guadiana sands) filling the foredeep basin along the front of the fold-and-thrust belt during Late Messinian and Early Pliocene times.

We consider the salt and/or shale tectonics in the Gulf of Cádiz to be a combination of a thrust–fold belt driven over salt by tectonic convergence (as in the Western Mediterranean Ridge accretionary complex: e.g. Camerlenghi, 1998; Kukowski *et al.*, 2002) and structures formed by gravity gliding and spreading off 'passive' continental margins like those in the northern Gulf of Mexico and West Africa (e.g. Rowan *et al.*, 1999; Tari *et al.*, 2002). They therefore record the structural complexities that developed where the passive margins of Africa and Iberia converged at the free end of a major (Alpine–Himalaya) orogen.

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