[PS] Thin-Skinned Extension and Shale Tectonics in a Tilted Basin Margin: the Case of the Northern Alboran Sea (Western Mediterranean)*

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Abstract

We have studied the tectonic evolution of the northern margin of the West Alboran Basin (offshore Spain), a south-dipping margin containing important sedimentary accumulations of Miocene to recent, fine-grained, marine sediments and active mud volcanoes in the seafloor.

The analysis of this sedimentary basin has been conducted through seismic interpretation of a dense grid of 2D seismic lines. This interpretation has been tied with well data, which provide lithological and bio-stratigraphic information. Our analysis of the logging data in some of the commercial wells in this margin confirms the occurrence of overpressured sediments in the lowermost levels of the basin, formed by Early Miocene, shale-rich sediments. This sequence constitutes the source rock for the widespread shale diapirs that characterized the deeper West Alboran depocentre.

We have conducted a detailed reconstruction of the 3D geometry of the shale-cored diapirs and the relationships with the overburden, analyzing the geometries and timing of the syn-sedimentary deformations. It is inferred the occurrence of a punctuated history of deformations in basin margins through the Middle to Late Miocene, conducted by syn-sedimentary normal faults that root in the basement-to-cover surface, which represents a low-angle detachment surface. We reconstruct that thin-skinned extension in basin margin promoted down-slope migration of the overpressured shales forming diapir structures that evolve basinward from shale rollers, shale anticlines, walls and allochtonous shale sheets driven by thrusts in the thicker and deeper portions of the basin. Since the Messinian times, the most recent basin evolution is characterized by submarine canyons with a source area that switch during the Late Pliocene from a WE trend, with a source area in the Gibraltar Strait area, to the NW orientation, coming from the uplifting Betic Mountains.

We interpret that pulses of syn-sedimentary extension in basin margin and gravity-driven shale withdraw occurred during a continuous tilting of the basin floor, which was accompanied by massive sedimentation and burial of fine-grained sediments. The Alboran Basin is therefore a

useful area to analyze the structural pattern associated with shale tectonic processes and a key basin for comparing the geometries and evolution of shale with structures formed in salt basins.

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Thin-Skinned Extension and Shale Tectonics in a Tilted Basin Margin: the case of the Northern Alboran Sea (Western Mediterranean)

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2 Alboran Sea Topo

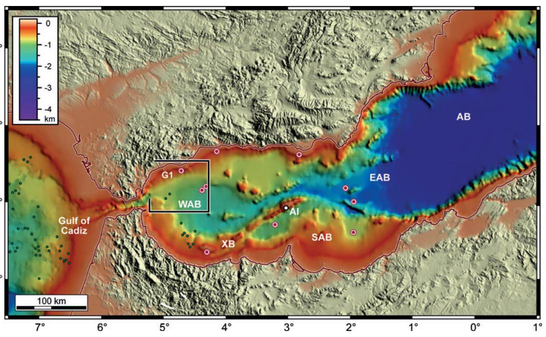


Figure 1. Topography of the westernmost Mediterranean (taken from Soto *et al.*, 2012). AB: Algerian Basin; AI: Alboran Island; EAB: East Alboran Basin; SAB: South Alboran Basin; WAB: West Alboran Basin; and XB: Xauen Bank. Mud volcanoes are shown as green dots (Sautkin *et al.*, 2003; Talukder, 2003; Talukder *et al.*, 2003, Blinova *et al.* 2009, Medialdea *et al.* 2009). Locations of ODP Leg 161 sites (976 to 979), DSDP Site 121, and offshore commercial boreholes are also included (G1: Andalucía G1).

3 Alboran Sea Geology

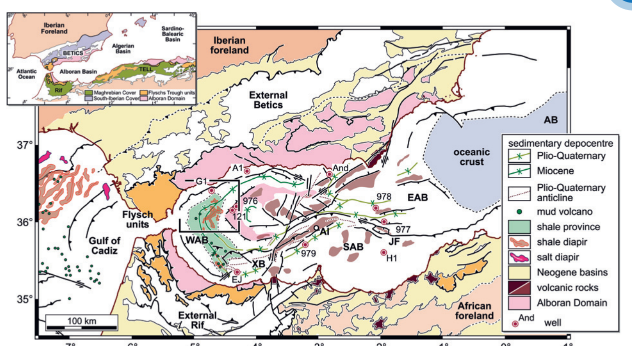


Figure 2. Geological map of the Alboran Sea and major tectonic features of the Gibraltar Arc formed by the Betic and Rif mountain chains (taken from Soto *et al.*, 2012; modified from Comas *et al.*, 1999, with data from Comas *et al.*, 2003; Sautkin *et al.*, 2003; Talukder *et al.*, 2003; Fernández-Ibáñez *et al.*, 2007; Blinova *et al.* 2009, Medialdea *et al.* 2009, and Martínez-García *et al.* 2011, 2013). Rectangle marks the position of the study area in the northern margin of the West Alboran Basin. Inset map shows location of the Alboran Sea between the Betic and Rif chains in the west Mediterranean with main crustal domains (taken from Comas *et al.*, 1999). Abbreviations like in Fig. 1 and YF: Yusuf fault. Locations of ODP Leg 161 sites (976 to 979), DSDP Site 121, and offshore commercial boreholes are also included (G1: Andalucía G1, Alb-A1: Alboran A1, And-A1: Andalucía A1, and EJ: El-Jebha).

4 Stratigraphy and Logging

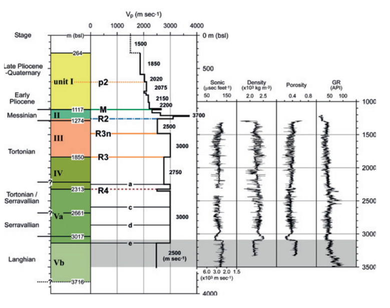
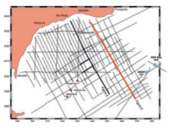


Figure 3. Sedimentary sequences sampled at commercial well Andalucia G1 (location in Figs. 1 and 2) including time stages, seismic units (Roman numerals), and the interpreted seismic discontinuities. Correlation with logging characteristics is also included. Light grey band marks the sedimentary section with overpressure characteristics. Seismic units and major reflectors according to Jurado and Comas (1992) and Comas *et al.* (1999). Depths are meters below sea level (bsl).

5 Regional Dip-Section I



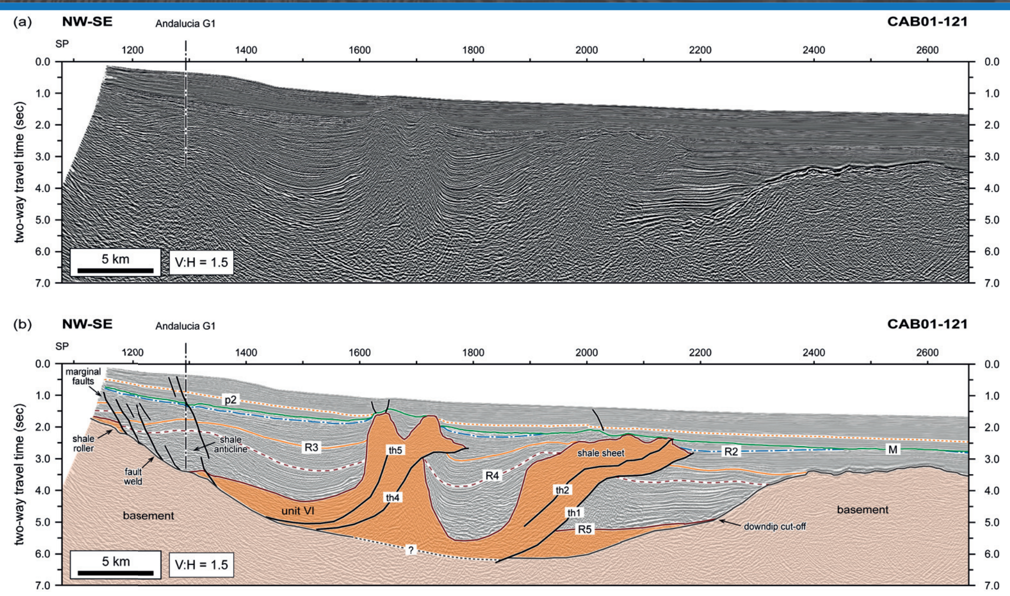
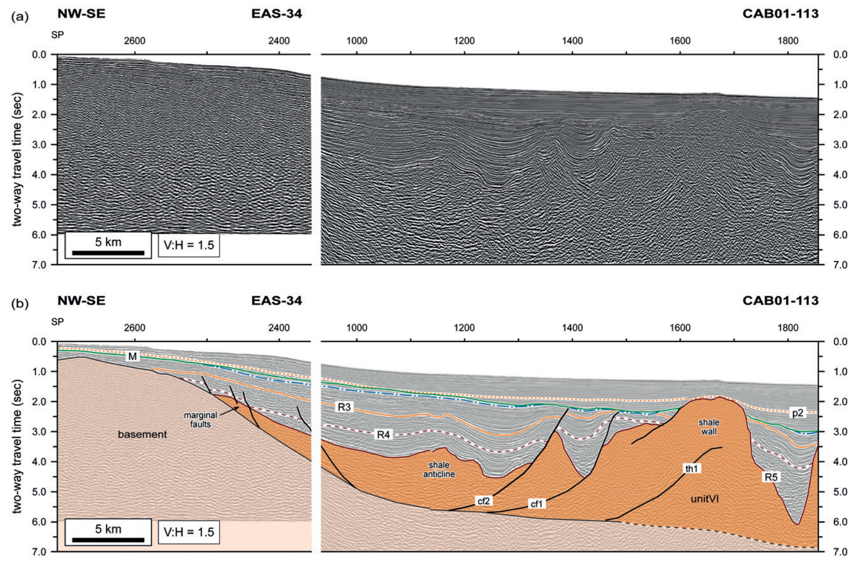


Figure 4. (a) Uninterpreted and (b) interpreted regional seismic section along the northern margin of the West Alboran Basin showing the structural evolution of shale from basin margin to basin depocenter. Marginal structures consist of growth faults, rollover anticlines, and shale rollers, passing downdip to an open shale-cored anticline.

6 Regional Dip-Section II



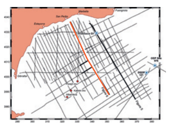


Figure 5. (a) Uninterpreted and (b) interpreted composite regional seismic section along the northern margin of the West Alboran Basin. Th-1 and cf1 to cf2 correspond respectively to major shale thrusts and normal faults associated with diapir collapse.

7 Diapir Map (Unit VI top)

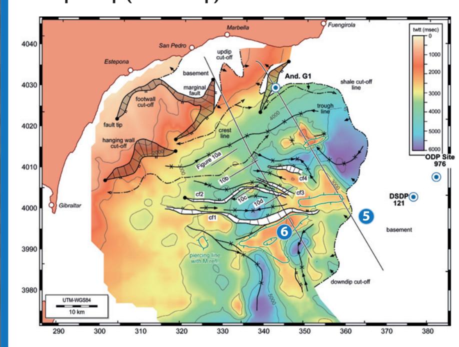
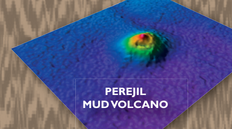


Figure 6. Structural contour map of the shale surface (R5 discontinuity) corresponding to the top surface of Unit VI. Contour interval is 1 sec (twtt). Cf1 to cf4 correspond to major normal faults associated with diapir collapse. Ticks along the piercing line with M reflector point toward diapir flanks with Miocene sequences.



8 Structures and Seismic Horizons

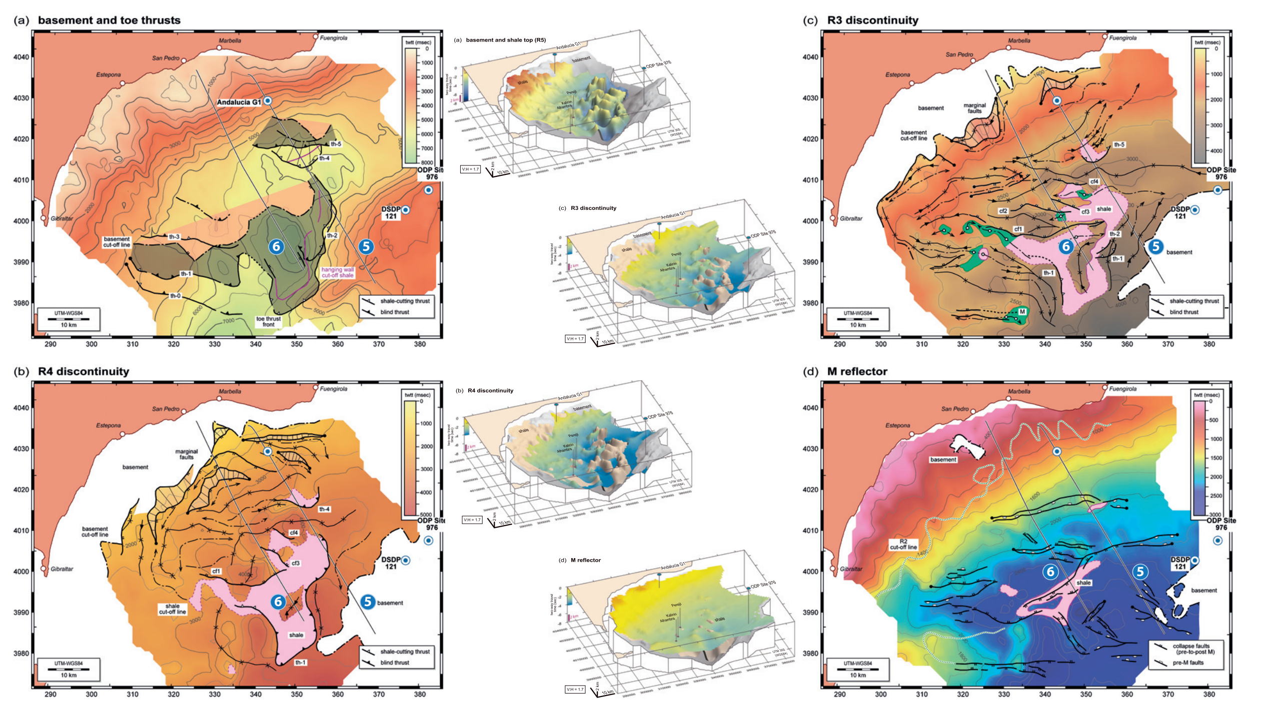


Figure 7. Structural contour maps of (a) the basement surface, (b) the R4 discontinuity, (c) the R3 discontinuity, and (d) the M reflector. Basement map includes structures of shale thrusts. Contour intervals in Figs. 7a to 7c are 500 msec (twtt) and in Fig. 7d is 200 msec (twtt). Th-0 to th-5 and cf1 to cf4 correspond to major shale thrusts and normal faults associated with diapir collapse, respectively. Areas in green (labeled with M in Fig. 7c) represent shale culminations where the R3 discontinuity is cut by the M reflector. Eroded fold culminations along anticline crest lines are indicated with open circles (Fig. 7c). The location of all seismic profiles is shown (Figs. 4 and 5). Other symbols as in Fig. 6.

9 Shale Migration

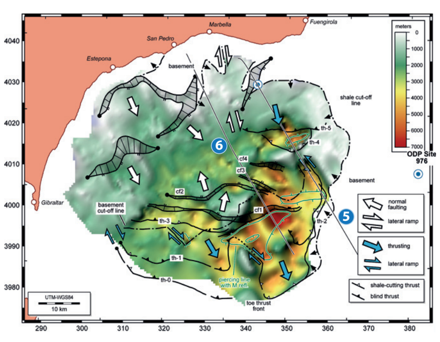


Figure 8. Thickness map of the shale, showing translation kinematics inferred for the normal faults and toe thrusts. Structures simplified from Figs. 6 and 7a. Depth conversion is made using a constant interval velocity of 2500 m sec-1 for overpressured shale of Unit VI. Model has a vertical exaggeration of 1.2 and is illuminated from the SE (135° azimuth and 65° of altitude or zenith distance).

10 Conclusions

1. We present the geometry of shale diapirs and associated structures in the northern margin of the West Alboran Basin, reconstructing their shape in three-dimensions by means of a dense grid of 2D seismic profiles. Our study characterizes shale tectonic processes, with particular emphasis on basin evolution during the Miocene.
2. The overall geometry of the basin consists of a sedimentary wedge thickening from basin margin to the basement horst at ODP Site 976. The source layer for the mobile substrate comprises overpressured (under-compacted) early Miocene shales thickening basinward. The resultant basin geometry, in conjunction with extensional deformational features and basement tilting, strongly influenced shale migration and diapirism.
3. Following the basement dip direction, four major structural domains are distinguished. (1) Marginal growth faults with rollover and shale rollers coalescing in the basement-cover detachment surface. (2) Open synclines and shale-cored anticlines with fold axes perpendicular to basement dip direction. (3) Shale walls showing two, sub-perpendicular orientations and developing long-lived piercing chimney-like structures at intersections. (4) Autochthonous shale sheets with associated toe thrusts and a maximum horizontal displacement of ~9 km occur coinciding with major sedimentary accumulations.
4. Shale tectonics during the middle-to-late Miocene consists of several faulting events accompanying simultaneous marginal extension and seaward shale thrusting. Shale sheet translation was driven by marginal faulting and ceased during the latest Tortonian. Shale emplacement was accompanied by asymmetric sheet collapse occurring up to the early Pliocene.
5. Inferred fault kinematics in marginal faults is parallel to shale advance along toe thrusts (southeastwards), coinciding with the main dip direction of the basement-cover detachment surface. Kinematics of counterregional collapse faults varies systematically from N to NE and show local variations above oblique structures in the basement surface, interpreted as lateral ramps.
6. Extension direction in listric growth faults in conjunction with the parallel and simultaneous advance of shale driven by toe thrusts are consistent with gravitational gliding of shale, driven by marginal extension and progressive basement tilting during the middle-to-late Miocene.

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