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Research paper

3D geometry of a shale-cored anticline in the western South Caspian Basin (offshore Azerbaijan)

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A B S T R A C T

The internal structure of one of the common fold structures in the western margin of the South Caspian Basin (SCB) has been characterized in 3D using a depth-migrated seismic cube in offshore Azerbaijan. The fold corresponds to a NNW-SSE anticline with a basinward vergence; i.e., eastwards, because in this direction of the margin the SCB is floored by a probable oceanic crust. The anticline has two culminations cut by mud-diapirs and is bounded by two parallel rim synclines with contrasting sedimentary thickness. This anticline deforms congruently the thick Productive Series (PS; Messinian to Late Pliocene), whereas the most recent sequences (<3.1 Ma; e.g., Akchagyl and Apsheron units) onlap or thin towards the fold crest.

We reconstruct the existence of two episodes of folding. During deposition of the uppermost PS sequences (ca. 3.5–3.4 to 3.1 Ma), fold uplift initiated with a significantly lower rate than sedimentation. During this epoch, folding was accompanied by basin tilting and by faulting in a basinward normal fault with a limited right lateral, strike-slip component. Motion along this fault zone promoted the downdip flow of a weak layer formed by fluid- and mud-rich sediments (Maykop Formation), which also migrated along strike to build-up the growing anticline. Henceforth, fold growth accelerated and sedimentary units like the Akchagyl (3.1–1.7 Ma) were deposited preferentially in the subsiding flanks. Seafloor upwarping due to folding conditioned the sediment transport, and large deltas adapted their prograding pattern to the growing anticline crest.

This structure resembles a detachment fold with a leading, East-vergent forelimb. Nevertheless, the occurrence of progressive tilting accompanying sedimentation and folding, or the mud inflation of the fold core by deep flow parallel to the anticline axis, make this example in the SCB a special example of this fold type.

1. Introduction

Most of shale-cored anticlines are located in compressive settings as folds-and-thrusts belts, and also in distal areas of passive margins, where a ductile and overpressured shale-rich unit occurs at shallow crustal levels (e.g., Morley and Guerin, 1996; Wu and Bally, 2000; Rowan et al., 2004; Morley et al., 2011). Shortening promotes mud diapirism and also the development of a bedding-parallel fault within the shale layer, called as décollement or detachment surface. Displacement is also transferred into folding in the decoupled overlying sediments according to a buckling mechanism (Dahlstrom, 1969; Hudleston, 1973) along the termination of the thrust plane, above the tip line or within the interior of the thrust sheet, where a sharp decrease in faulting rate occurs (e.g., Poblet and McClay, 1996; Shaw et al., 2005).

In many regions, detachment folds form hydrocarbon traps and developed diverse geometries, depending on the folding kinematics (e.g., Medwedeff, 1989; Poblet and McClay, 1996; Poblet et al., 2004). Detachment folds shape is asymmetric and independent of the fault shape, in contrast to other fault-related folds, like fault-bend folds (Rich, 1934) and fault-propagation folds (Dahlstrom, 1970; Mitra, 2002). When detachment folds interact and link, they have a final similar aspect to fault-propagation folds (e.g., Burberry et al., 2010).

Simple geometrical models of detachment folds assume that no thickness variations or shear within layers occur in the competent

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multilayer unit (e.g., Mitra and Namson, 1989; Poblet, 2004). Complexity increases if it is considered in three dimensions (e.g., Jamison, 1987; Mitra and Namson, 1989; Poblet and McClay, 1996). To unravel folding kinematics it is commonly used the geometry of the pre- and syn-growth strata, i.e., the sediments deposited before and during folding, respectively. Different geometrical methods are also used to calculate shortening rates and to estimate the depth of the detachment level using the pre-growth unit (e.g., Chamberlin, 1910; Epard and Groshong, 1993; Mitra, 2003; Wiltschko and Groshong, 2012).

The anticlinal structures in the South Caspian Basin (SCB; Fig. 1) are interpreted to be buckle folds overlying a regional ductile detachment zone that are commonly pierced by mud diapirs and volcanoes (e.g., Devlin et al., 1999; Allen et al., 2003; Brunet et al., 2003). These structures have been extensively studied due to their interest as stratigraphic traps for hydrocarbons. In the western SCB, folding is a response of the Caucasus shortening that occurred from the Pliocene to Present, simultaneously to a rapid basin subsidence and sedimentation (Nadirov, 1985; Chumakov et al., 1988; Sobornov, 1996; Devlin et al., 1999; Allen et al., 2003; Brunet et al., 2003).

We study the Kurdashi-Araz Deniz (KAD) anticline, a complex fold structure NNW-SSE-directed settled in the western margin of the SCB, to the South of the Kura River mouth, in offshore Azerbaijan (Figs. 1 and 2). We have accomplished a detailed interpretation of a 3D seismic dataset migrated in depth, provided by REPSOL Exploración S.A. This fold was generated during the Pliocene-to-Recent times and deforms both, the reservoir unit of the Productive Series (PS; Late Miocene to Late Pliocene) and the youngest sediments up to the seafloor surface, here referred as the Post-PS units. Recent folded structures of this type have been widely documented in the region, although a detailed reconstruction of their evolution, associated deformation rates or their kinematics are far from being well established. In addition, we believe that the studied case deviates from the classical detachment fold-type. One of the differences consists on the participation of overpressured mud that cut the sedimentary sequences shaping complex diapir-like structures.

The objectives of this contribution are: (1) to analyse the three-dimensional geometry of the KAD anticline; (2) to precise the timing of folding episodes through the characterization of the pre- and syn-growth geometries; (3) to examine the different fault structures to advance in the discussion on how they relate to folding processes; and (4) to reconstruct the shape of the mud diapirs and the relationship to the folded structure, to infer the role played by mud during deformation.

2. Geological setting of the SCB

The SCB is a presumable relict fragment of the Tethyan ocean generated in the Late Mesozoic during the N–S convergence between Arabia and Eurasia (Berberian, 1983; Nadirov, 1985; Zonenshain and Le Pichon, 1986; Lerche et al., 1996; Mangino and Priestley, 1998; Brunet et al., 2003; Yusifov, 2004). According to geophysical data, an oceanic-type crust probably floors the SCB.

Structures in the western SCB are affected by the orogenic processes that built up the Caucasus fold-and-thrust belt (Sobornov, 1996; Nadirov et al., 1997; Allen et al., 2003; Brunet et al., 2003). The deep, West Caspian Fault (Fig. 1) also promoted deformation partitioning into strike-slip and reverse slip (Khain et al., 1966; Nadirov, 1985; Alsop and Holdsworth, 2002; Jackson et al., 2002; Allen et al., 2003). Fold structures are commonly cored by mud intrusions, forming mud diapirs and mud volcanoes (Fig. 2; Yusifov and Rabinowitz, 2004; Davies and Stewart, 2005). These folds in the sedimentary cover seem to be decoupled from the basement surface. Axial traces that switch from NW–SE to NNW-SSE, along the western margin of the SCB (Fig. 1; e.g., Nadirov, 1985; Nadirov et al., 1997; Tagiyev et al., 1997; Lyberis and Manby, 1999; Jackson et al., 2002; Engdahl et al., 2006). Folding is Pliocene to Present in age and is represented by abundant detached and upright anticlines with domal culminations along the offshore Azerbaijan (Fig. 2).

Flexure and subsidence of the oceanic floor of the SCB have promoted exceptionally thick depocentres. The sedimentary section in the western SCB contains more than 20 km of Jurassic-to-Present sediments (Zonenshain and Le Pichon, 1986; Abrams and Narimanov, 1997; Nadirov et al., 1997; Mangino and Priestley, 1998; Brunet et al., 2003; Knapp et al., 2004). Thick, organic-rich shales constituting the Maykop Formation (~36–16.5 Ma) were deposited during the Oligocene to the Miocene in a euxinic shallow-water environment that was probably connected with the Black Sea (Inan et al., 1997; Hudson et al., 2008; Afandiyeva et al., 2009).

Up to 10 km of the sedimentary infill in the SCB correspond to the rapid deposition (~2 mm/y) of different shallow-marine-to-continental sediments during the last ~6 my (Nadirov et al., 1997; Brunet et al., 2003; Knapp et al., 2004). A significant part of this section (over 5–6 km) is the PS sequence, which consist of alternating sandstone and shale intervals deposited between 5.9 and ~3.4–3.1 Ma; i.e., Late Messinian to Late Pliocene (Berberian, 1983; Devlin et al., 1999; Brunet et al., 2003; Morton et al., 2003; Hinds et al., 2004). The PS sequence is commonly divided into Lower PS (5.9–5.2 Ma) and Upper PS (5.2 to ~3.4–3.1 Ma; Fig. 3). Lower PS is composed by the KAS, PK, KS, NKP and NKG formations, whereas the Upper PS is formed by the Pereryva (5.2–4.9 Ma), Balakhany (4.9–4.0 Ma), Sabunchi (4.0–3.7 Ma) and Surakhany units (3.7 to ~3.4–3.1 Ma). The top of the PS, referred in this work as the PS-top surface, corresponds to a regional unconformity, which shows significant evidence of erosion in the basin. Recent studies suggest that the PS-top is diachronous in the western margin of the SCB, becoming slightly younger from the offshore domain (3.2 Ma) to the Kura basin (up to 2.7 Ma; Van Baack et al., 2013; Forte et al., 2015).

The Post-PS sequence is divided here into three distinctive stratigraphic units, corresponding to the Akchagyl (~3.4–3.1 to ~1.7–1.6 Ma), Apsheron (~1.7–1.6 to ~0.8–0.7 Ma) and Gelasian sequences (~0.8–0.7 to Present) (e.g., Abdullayev, 2000). This group comprises sediments deposited between the Late Pliocene to Early Pleistocene (Fig. 3).

High sedimentation rates from the Pliocene to Quaternary resulted in excessive fluid pressure within the sediments throughout the basin. Overpressure conditions in the Maykop Formation originated subsurface mobilization, mud diapirism and mud volcanism in the SCB (Bredehoeft et al., 1988; Dadashev et al., 1995; Tagiyev et al., 1997). Rapid burial also created low temperatures gradients (14–16 °C/km; Devlin et al., 1999) suitable for hydrocarbon generation and preservation in the Maykop Unit, which is the main source rock for hydrocarbons in the SCB (e.g., Korchagina et al., 1988). The PS represents the major reservoir in the basin (e.g., Smith-Rouch, 2006). The SCB is part of the Great Caspian hydrocarbon province, which is a major producing region with a total proven oil and gas reserves ranging from 15 to 31 million bbl and 230 to 360 Tcf, respectively (Belopolsky and Talwani, 2007; EIA, 2013).

3. Dataset and methods

This study is carried out by the seismic interpretation of a pre-stacked seismic cube migrated in depth, which was provided by REPSOL Exploración S.A. In addition to the pre-stack depth