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Uplift-induced residual strain release and late-thrusting extension in the Anaran mountain front anticline, Zagros (Iran)

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ABSTRACT

In this work we present and discuss the pattern of extensional faults of the Anaran Anticline (Lurestan province of the Zagros, Iran), one of the most aesthetically appealing mountain front anticlines of the Zaros. This 100 km long structure is affected by extensional faults occurring in different along-strike sectors of the anticline, running parallel and oblique to the local trend of the fold hinge line, and having displacements of hundreds of metres. Relationships between fold growth and extensional deformation are investigated by quantitatively analysing the attributes (i.e. curvature, elevation and throw across faults) of a 3D surface representing the top of the Ilam formation. Results indicate that the main stage of extensional deformation occurred during folding. In particular, we deduce that extensional faulting was associated with the erosional uplift of the crestal sector of the anticline, where exhumation of previously shortened strata implied release of residual compressive strain, with consequent annihilation of the horizontal stress component paralleling the tectonic transport direction. This determined the onset of a large-scale extensional regime at the shallower structural levels of the growing anticline.

1. Introduction

The distribution of faults and fractures in fractured reservoirs has a primary importance in oil and gas research and development, due to their strong impact on fluid migration and accumulation (e.g. Aydin, 2000; Evans and Fischer, 2012; Graham Wall et al., 2006; Nelson, 1985). Typically, well data in reservoir anticlines located in foredeep–foreland systems have limited spatial distributions, so that fault and fracture data are not sufficient to determine robust interpolation criteria. Predictive models which allow the population of reservoirs with fracture attributes strongly benefit from studies in exposed analogue structures. Selecting a natural analogue structure, however, is not straightforward: it should expose the reservoir level and its deformation history should be very similar to that of the corresponding reservoir. Due to its geographic, paleogeographic and supposed structural proximity, the mountain front is frequently assumed to provide a suitable analogue for reservoirs buried in the foredeep–foreland system or, simply, it is the only available analogue. An example of this is the mountain front of the Zagros Simply Folded Belt, where abundant studies have been carried out to provide insights on the fracture patterns in the adjacent reservoirs (e.g. Ahmadhadi et al., 2008; Awdal et al., 2013; Casini et al., 2011; McQuillan, 1974; Stephenson et al., 2007; Tavani et al., 2011a; Wennberg et al., 2006).

The above discussion highlights the economic and scientific importance of having available well-constrained deformation pattern templates for interpreting mountain front anticlines. In this sense, the occurrence of syn-folding extensional faults running parallel to the trend of the host anticline has been classically interpreted in the framework of outer-arc extension (e.g. Fischer and Wilkerson, 2000; Lisle, 1994; Price, 1966; Ramsay, 1967; Turcotte and Schubert, 1982). However, it has been recently documented that syn-folding extensional deformation at the mountain front can be also associated with its abrupt uplift (Tavani et al., 2012), which would cause the annihilation of the horizontal stress components in the anticline's shallower structural levels, and the consequent onset of extensional conditions during late thrusting. This mountain front uplift-related extension template could help to interpret some intriguing data from the mountain front of the Zagros. In fact, as pointed out by Emami et al. (2010), major longitudinal extensional faults occur in some anticlines located at the mountain front of the Zagros, while – and regardless of the curvature – they are poorly reported in the neighbour anticlines not located at the mountain front. This alone would make questionable the use of outer arc extension template to interpret these longitudinal extensional faults. In addition, outer arc extension is not capable of explaining why some mountain front anticlines with a radius of curvature of many km are characterised by an intense array of extensional faults, like the Khaviz Anticline

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(Wennberg et al., 2007), while the neighbour and more curved mountain front anticline (i.e. the Bangestan Anticline) holds mostly outcrop-scale extensional faults, even in the hinge zone between the crest and the recumbent backlimb, where the radius of curvature is less that one thousand metres (Tavani et al., 2011a).

In this work we provide support for and an explanation of the mountain front late-thrusting extensional collapse template, by describing the extensional fault pattern of the Anaran Anticline at the mountain front of the Zagros Simply Folded Belt. The unavailability of field data covering the different structural positions and the different exposed units implied the use of a different strategy for the analysis of the deformation pattern of the Anaran Anticline. Evaluation of meso-structural data variability aimed at determining stress/strain evolution during folding is here replaced with the spatial analysis of major fault attributes, which were derived from a published high-resolution 3D layer model of the structure (Snidero et al., 2011). Such a model was built honouring thousands of bedding data, which were extracted from Aster and Spot images, and geological maps, draped onto a 30 m resolution digital elevation model (Snidero et al., 2011). Because of the observation scale, our procedure focuses only on the deformation process responsible for the development of major extensional faults, and included a qualitative and quantitative test of the different hypotheses which could be invoked to explain the occurrence of major extensional faults in the Anaran Anticline. Hypotheses not consistent with data have been progressively discarded, pointing out that the amount of syn-folding extensional deformation in the Anaran Anticline relates only with the amount of uplift during thrusting. At this point a mechanical explanation is provided, where extensional faulting is associated with the release of compressive horizontal tectonic strain (e.g. Mandl, 2005). We propose that strain was stored during pre- to early-folding layer-parallel shortening, and was rapidly released during uplift, this determining the syn-folding inversion between maximum and minimum stress components at the shallower levels of the growing anticline.

2. Geological outline

The Anaran Anticline is located along the mountain front of the Zagros Simply Folded Belt, in the Lurestan province (Fig. 1A). The NW–SE elongated Zagros fold-and-thrust belt is part of the Arabia–Eurasia collisional margin and formed in Late Cretaceous to Cenozoic times (e.g. Talbot and Alavi, 1996; Stampfli and Borel, 2002), with a first Late Cretaceous to Early Cenozoic stage (e.g. Alavi, 1994; Berberian and King, 1981), followed by a Late Oligocene/Early Miocene to Pleistocene pulse (Agard et al., 2005; Homke et al., 2004). The second stage is mainly responsible for the Simply Folded Belt development, which implied SW-directed thrusting and folding and the widespread oblique reactivation of N–S striking inherited basement faults (e.g. Al Laboun, 1986; Berberian, 1995; Falcon, 1969; Hessami et al., 2001;

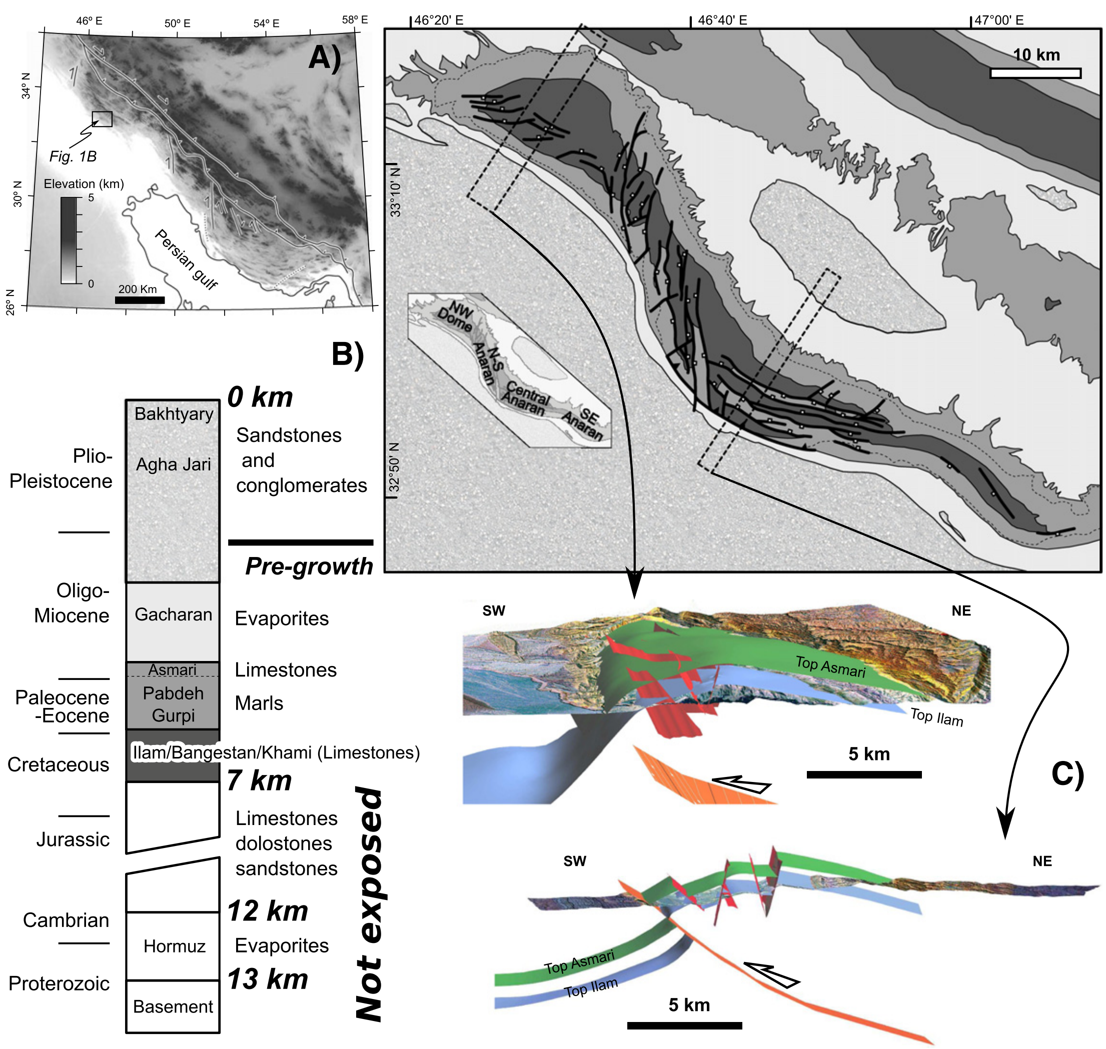

Fig. 1. (A) Elevation map of the Zagros mountain range with location of the study anticline. (B) Geological map of the Anaran Anticline (modified from Snidero et al., 2011), with synthetic stratigraphic sequence, structural scheme. (C) Slices of the 3D model used in this work, showing the cross-sectional geometry of the anticline in its central sector and across the NW Dome.