Tectonic evolution of the Zagros mountain belt: new approaches and their hydrocarbon implications

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ABSTRACT

Petroleum systems in the Zagros are dominated by compressional tectonics that have formed both the structure and the porosity of the principal reservoirs. At the regional scale, structural style is controlled by the interaction of the current kinematic (plate motion) framework with pre-collisional basement fabrics. Contractional structures are probably able to exploit these fabrics only if they have been
reactivated in the intervening rift phase, but rejuvenated strike-slip structures have been active in the basement throughout the Phanerozoic.

At the reservoir scale, folds are the key structural element for petroleum exploration, but little work has been done to discriminate between possible fold growth mechanisms. A modern, thin-skinned interpretation of the Zagros structure permits both cover detachments and basement-involved thrust structure at depth, with consequent variations in deep structure. In three dimensions, Zagros fold structures are seen to have different styles of lateral continuity and interaction with strike-slip zones. Field data reveal extensional structures related to longitudinal strain and stepovers in strike-slip domains (which may be more common than previously appreciated). As well as allowing better construction of sub-surface geometries, such observations will be crucial to predicting fracture distribution and fault compartmentalisation in reservoirs.

INTRODUCTION

The spectacular, petroleum-rich mountain belt of the Zagros has formed during the collision of the Eurasian and Arabian continents since the Miocene. Structural understanding of this collision therefore plays a crucial role in exploration and production in the region, primarily because both the anticlinal traps and the fracture porosity of the reservoirs were generated by compressional tectonics. However, there is more to the structural geology of the Zagros than a belt of buckle folds. The convergence of the two continents is accommodated by different mechanisms in different parts of the range, leading to different styles of deformation and so different subsurface geometries. Contractional structures also develop by variable mechanisms, with consequences for the internal deformation of reservoir units and the enhancement or destruction of fluid flow and storage systems. This paper examines the variability of deformation on a regional and oilfield scale, and assesses the petroleum system implications of the various tectonic models.

REGIONAL KINEMATIC FRAMEWORK

We identify three along-strike tectonic domains in the Zagros on the basis of the way the north-south plate convergence is accommodated by different kinematic regimes (Fig. 1). In the northwestern domain, the convergence is partitioned onto contractional structures with NE-SW shortening directions, and right-lateral strike-slip faulting on the NW-trending Main Recent Fault [1]. In the southeastern region of the Fars arc, active contraction has roughly north-south shortening vectors, so the plate convergence is taken up without the need for partitioning. A region of north-south, right-lateral strike slip faults accommodate the strain gradient between the two domains. Exploration strategies need to account for the variation in tectonic style that arises from different kinematic settings; the geometry of potential reservoirs, interactions between contractional and transverse structures, and the modelling of burial and uplift history all rely on this tectonic framework.

BASEMENT REACTIVATION
Strike-slip zones clearly reactivate transverse basement structures [2]. Reactivation may also be playing a role in strain partitioning of contractional structures. Inversion of normal faults is a well-known process, but the steepness of such faults makes it mechanically difficult to accommodate large degrees of shortening without low angle thrusts breaking through footwalls. However, the sedimentary architecture in extensional regions probably creates mechanical heterogeneities that localise later contractional structures, so basement fabrics still have a role in controlling the compressional architecture of the Zagros. In particular, the location of major basement uplifts, and subsequent scales of detachment and folding in the cover sequences, appears to vary depending upon the nature of the pre-collision passive margin sequences.

FOLD GROWTH MECHANISMS

Not all folds in the Zagros were created in the same way, and understanding two fundamental aspects of fold growth have important implications for exploration and development strategies (Fig. 2).

1) What controls the fold geometry? Is the fold detachment- or fault-related? (In other terminology, is it a free or a forced fold.) Accurate reconstruction of subsurface architecture requires an understanding of these fold types, but they are often difficult to distinguish because the final geometries can be very similar. Studies of the structural evolution through time, based on tectonic geomorphology, growth strata and other techniques, will constrain the growth mechanisms of different structural features. Explorationists can then make better predictions of deep structure based on the characteristics of exposed and imaged structures in areas of interest.

2) What mechanism accommodated the folding strain? Folding layers can be achieved by flexural slip or internal ductile strain, the precise nature of which will control density, location and orientation of fractures. In a region of reservoirs dominated by fracture porosity, it is clearly vital to have a good predictive model of fracture generation. Timing of fold formation may also be crucial for porosity/seal arguments. Field observation of strain markers can yield a good sequential model for fold growth, from which general fracture characteristics can be predicted.

EXTENSIONAL FEATURES

Locally extensional small-scale features are abundant in the Zagros. They give information on local kinematics, and may generate favourable faults and fractures for fluid flow. These may permit hydrocarbon migration, or they may become mineralised and hence compartmentalise otherwise porous reservoir units. Longitudinal (crestal) extension is seen on periclines, and is probably the most important extensional features because they compartmentalise reservoir units on an oilfield scale. Folds above oblique thrust relay zones, a hitherto unrecognised element in the Zagros, are also likely to
develop extensional features. Strike-slip zones have dilational stepovers, implicated in the upwelling of salt bodies. Field research programmes will be necessary to determine character of these zones.

CONCLUSIONS

Effective exploration strategies rely on a sound tectonic framework, which will predict the overall evolution of petroleum systems and thereby highlight play fairways according to structural style and thermal history. Regional tectonic understanding in the Zagros has been rapidly improved by applying modern concepts of strain localisation, and will benefit from future detailed studies aimed at quantifying deformation in space and time. Reservoir (oilfield) scale complexity is obscured by the first-order simplicity of the structural features. In detail, specific strain mechanisms need to be established for specific families of structures, and again the regional-scale deformation patterns have a profound influence on this local structural evolution.

REFERENCES


Figure 1. Kinematic model for the Zagros orogenic belt. Arabia-Eurasia convergence is accommodated by partitioned transpression in the northwest, where the shortening component is oblique to plate motion. Structures in the south-east reflect shortening orthogonal to the convergence. The zone between these two regimes accommodates the strain gradient by strike-slip faulting and structures with trends oblique to the orogen. Note that the plate motion vectors are different in the northern and southern belts, due to Arabia's rotation about a pole in west Africa.

Figure 2. Cross section from part of the frontal Zagros illustrating two different fold growth mechanisms and their implications for the development of fractures in reservoir units (shaded). (a) Folding is forced by fault geometry; fractures
are not only controlled by the accommodation of strain within the layers, so can cross layering. Contrast with tangential longitudinal strain in the simple detachment fold, where fracture orientation can be predicted within a competent layer. Note also that such a thrust interpretation has implications for modelling source horizons, which lie immediately below the lower reservoir unit.