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Salt-driven, thin-skinned tectonics and inherited deep seated fault-driven thick tectonics in the Dezful Embayment (Zagros, Iran), illustrated by regional 2D geomechanical restoration

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Abstract: Two-dimensional geomechanical reconstructions across the Front Flexure of the Zagros Mountains (Iran), based on 2D regional seismic interpretation, were carried out to investigate the salt kinematics and the influence of inherited structures at depth in the Dezful Embayment. This study identified a positive structural inversion related to detachment within the evaporites of the Miocene Gachsaran formation and diachronism in the deformation from NE to SW. Disharmonic tectonism was also observed, leading to a singular vertical succession with anticlines in deeper limestones (reservoirs) underneath shallow synclines. Finally, an earlier deformation controlled by previous deep-seated faults was proposed to explain the oil traps.

Keywords:thin-skinned, thick-skinned tectonics, salt, structural inversion, inherited structures, geomechanical restoration, Zagros.

The Zagros Mountains in Iran are located between the Caspian Sea in the north and the Persian Gulf in the south (Fig. 1).

From a larger perspective, the Iranian geological setting is mainly characterized by a succession of geological terrains trending NW to SE. In the NE lies the Urumieh Dokhtar arc (UD in Fig. 1) with intense Late Jurassic to recent volcanism (Berberian *et al.*, 1982). The next zone, toward the SW is the Sanandaj-Sirjan zone (SSZ in Fig. 1), where the deformation reflects the collision of Arabia and Eurasia with a south-eastward propagation of a fold-thrust belt (Alavi, 1994). The third zone, to the SE is defined by the Zagros Mountains which include the Main Zagros Thrust, proposed as a suture zone between Arabia and Eurasia (Dercourt *et al.*, 1986). Within the Main Zagros Thrust, the Mountain Front Flexure has been recognized. The Deformation Front marks the limit of deformation south-eastward (Fig. 1). The so-called Dezful Embayment, located between the Lurestan province in the NW and the Fars province in the SE, is formed by a sinuous "embayment" of the Mountain Front Flexure. It is an extremely rich hydrocarbon province. The area of study is in the embayment and indicated in figure 1.

Stratigraphy

The sedimentary column of the Zagros is about 12 km thick. The oldest sedimentary unit is thought to be the early Cambrian Hormuz Salt Formation (O'Brien, 1957). This formation is overlain by a dominantly clastic platform sequence (Cambrian up to Permian in age), followed by a thick carbonate-

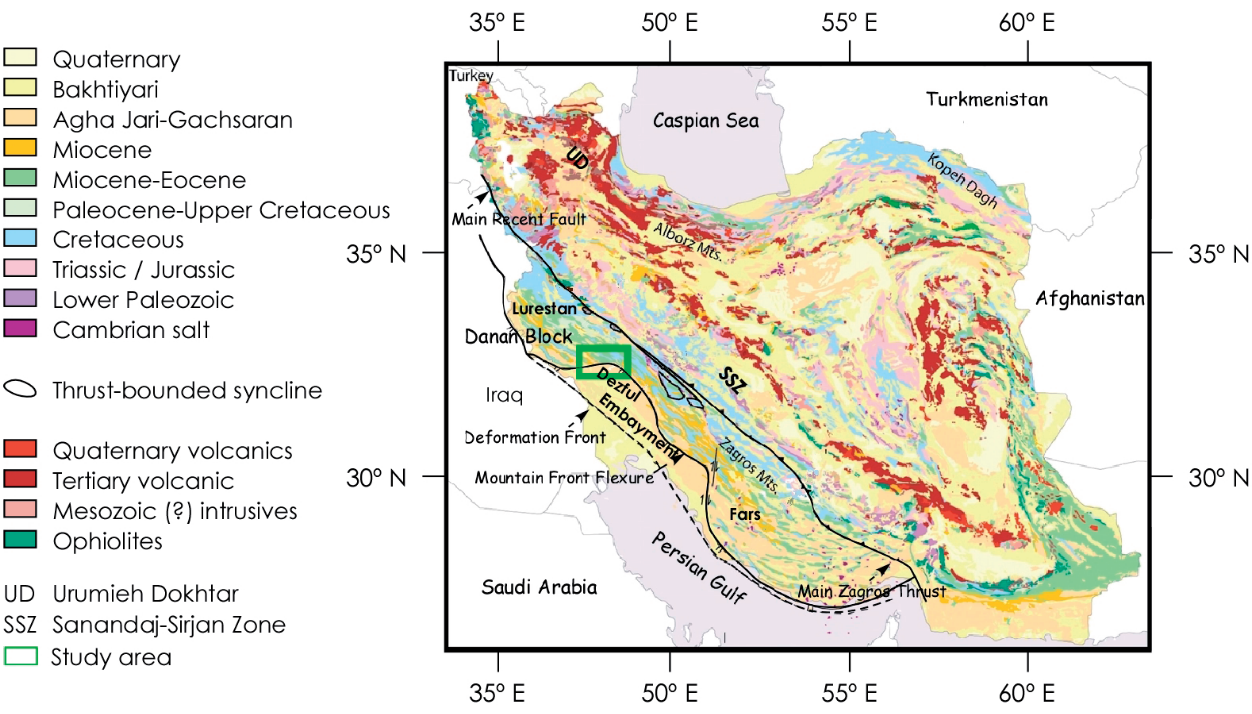

Figure 1. Geological setting of the study area.

dominated sequence (Upper Permian to Miocene in age). The upper part of this second sequence is formed by Upper Cretaceous carbonates of the Sarvak and Ilam formations, the Paleogene carbonates of the Pabdeh and Asmari formations and a thick Miocene salt unit included in the Gachsaran formation. The upper part of the stratigraphic column consists of a thick succession of Plio-Pleistocene clastics, mainly included in the Agha Jari and Bakhtyari formations. In the Dezful Embayment, only the Permian-Miocene carbonate succession and the Plio-Pleistocene clastic deposits have been imaged by seismic data. Together these are about 7 km thick. The thickness of the clastic unit varies significantly through the study area and this suggests a synorogenic deposition within the thrust-fold belt setting.

Cross section restoration and analysis

Two-dimensional geomechanical reconstructions were built in order to investigate the influence of the Miocene salt unit on the thin-skinned tectonics of the Zagros foreland and on the structuration of the deeper reservoir section. The geomechanically driven restoration, using the "Iterative Finite Element Method" (Maerten and Maerten, 2006), was applied to explain the thickening and thinning of the salt unit of the Miocene Gachsaran formation. This geomechanical method respects the physical laws which govern rock deformation as long as elasticity properties are also respected. This is in contrast to geometric restoration based on the conservation of the area (Dahlstrom, 1969; Suppe, 1983) which lacks a mechanical basis. Rock mechanical properties used in this approach are illustrated in table 1.

The reconstructions were based on two 2D seismic lines converted to depth (see figure 2 for location) and further supported by the regional seismic interpretation.

The fold thrust system, at present, shows two distinct structural steps: a gently folded area in the frontal part and, to the NE, an elevated and thrusted area with largest displacement in the southern part (Figs. $3a_1$ and $3b_1$). The depth to detachment of these folds varies according to the salt thickness, which increases to the SW (Line 75211) and decreases to the SW (Line 75213). This relative thickness variation suggests an overloading in the central thrust area by a squezing phenomenon in the salt formation. In general, the distance between two successive anticlines decreases from north to south according to the shortening ratio (Figs. 3a

Table 1. *Model parameters used for Dynel2D backward modelling*

	Poisson´s ratio	Young's modulus	Density	Friction angle
Sandstones	0.24	22 GPa	2480 kg m^{-3}	28 °
Limestones	0.25	48 GPa	2500 kg m^{-3}	42 °
Salt	0.18	28 GPa	2050 kg m^{-3}	5 °

Table 1. Rock mechanical properties used for geomechanical restoration.

and 3b). At deeper levels, the thrust faults are controlled by an older deep-seated fault system. A lateral shear component (out of section) along the main sub-vertical fault could explain the geometry and the evolution of the isolated micro-blocks involved in the kinematics of this structure in the reservoirs underneath the salt.

In the Agha Jari period, in the front of the structural system (SW), the total displacement due to thrusting was removed, whereas in the central thrust (NE), the displacement along the fault detachment was not fully restored. This diachronism in the compressive deformation could be the result of the visco-plastic behaviour of the salt with a thickness variation related to the overloading of the central thrust. The salt motions allowed the compressive and gravity structures to appear simultaneously. The geomechanical restoration allows discrepancies in the deformation to be managed at the same restoration stage (Maerten and Maerten, 2006). This leads us to interpret the frontal inverted structure as a fault-propagation fold reactivating a previous gravity fault.

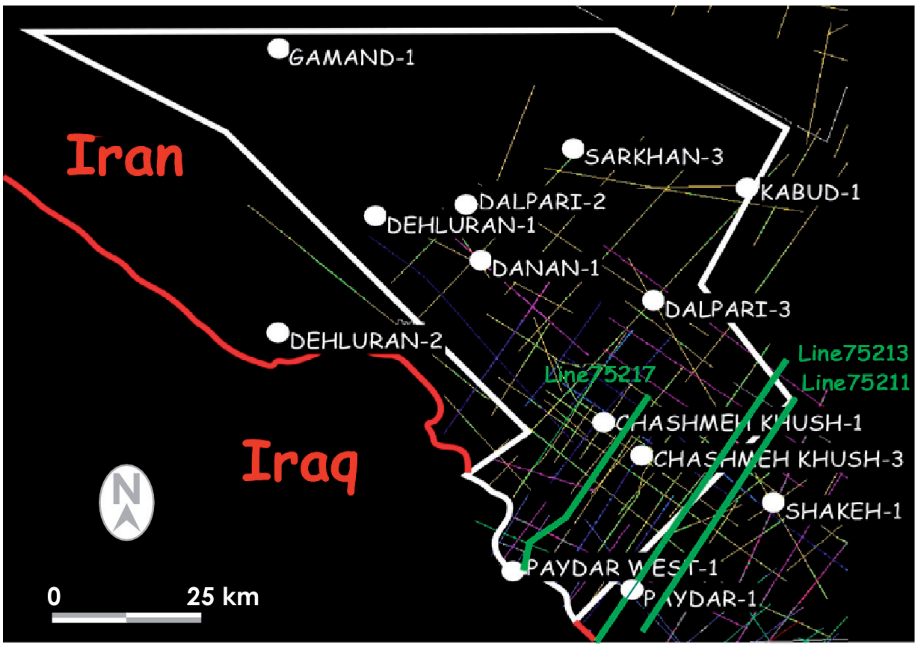

Figure 2. Location of 2D seismic lines. Lines 75213 and 75211 have been converted to depth.

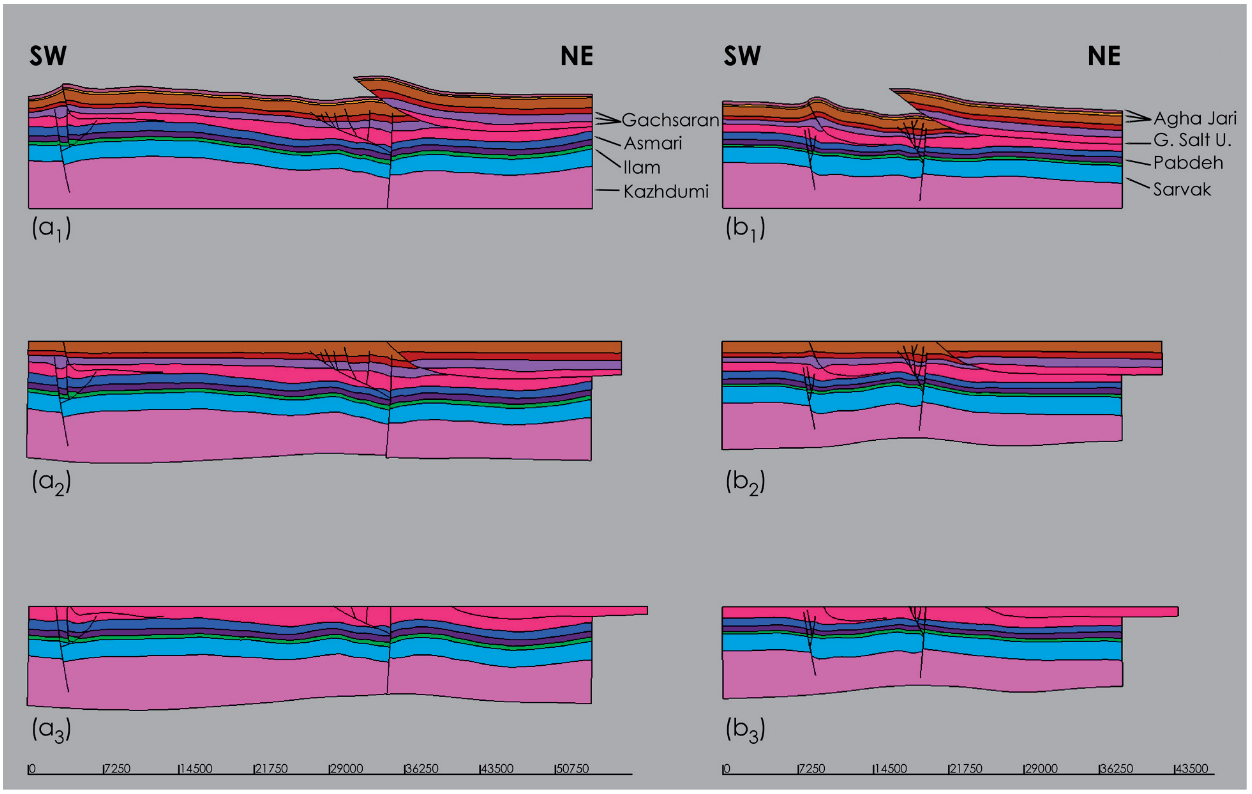

Figure 3. Geomechanical reconstructions through the study area in the Dezful Embayment based on 2D seismic lines converted to depth. The restoration has been carried out with a scale of 1:1. For display reasons, the scale here is 1:2. (a) Line 75213: (a_1) Present day, (a_2) Agha Jari time, (a_3) Gachsaran time; (b) line 75211: (b_1) Present day, (b_2) Agha Jari time, (b_3) Gachsaran time.

In Gachsaran time, the displacement along the detachment in the central structure is at a maximum. This structure is interpreted as a fault-bend-fold-like feature; nevertheless, the location of the shallow thrust system initiated right above the deep-seated fault can be used as an indicator of the deeper structure control. The shallow deformation above the salt is fully balanced and corresponds to a global shortening ranging between 9.8% and 14.2%. At depth, in the carbonate reservoirs, the folding is not totally balanced, suggesting the presence of a previous step in the compressive deformation (McQuarrie, 2004; Sherkati *et al.*, 2005). The deeper formations show a thickness increasing in the down-thrown block of the deep-seated fault system. This suggests an earlier deformation related to a shear horizontal component along the sub-vertical faults (Figs. 3 and 4).

Conclusions

The 2D geomechanical restorations show that salt mobility of the Gachsaran formation results not only from folding-related halokinesis. An early gravity-driven collapse has also been identified, in the frontal part, leading to thin-skinned tectonism (Fig. 4), whereas in the central part the thrust fault system is already activated and illustrates diachronism in the deformation.

The disharmonic tectonism between shallow and deeper structural features resulted in a singular geometry with anticlines in the limestone formations (reservoirs) underneath shallow synclines. Finally, the 2D geomechanical reconstructions allow a better understanding of the reservoir geometry that is clearly controlled by a deep-seated fault system. This system is part of an early deformation phase (Figs. 3 and 4) rather than a late basement control (Sherkati *et al.*, 2005).

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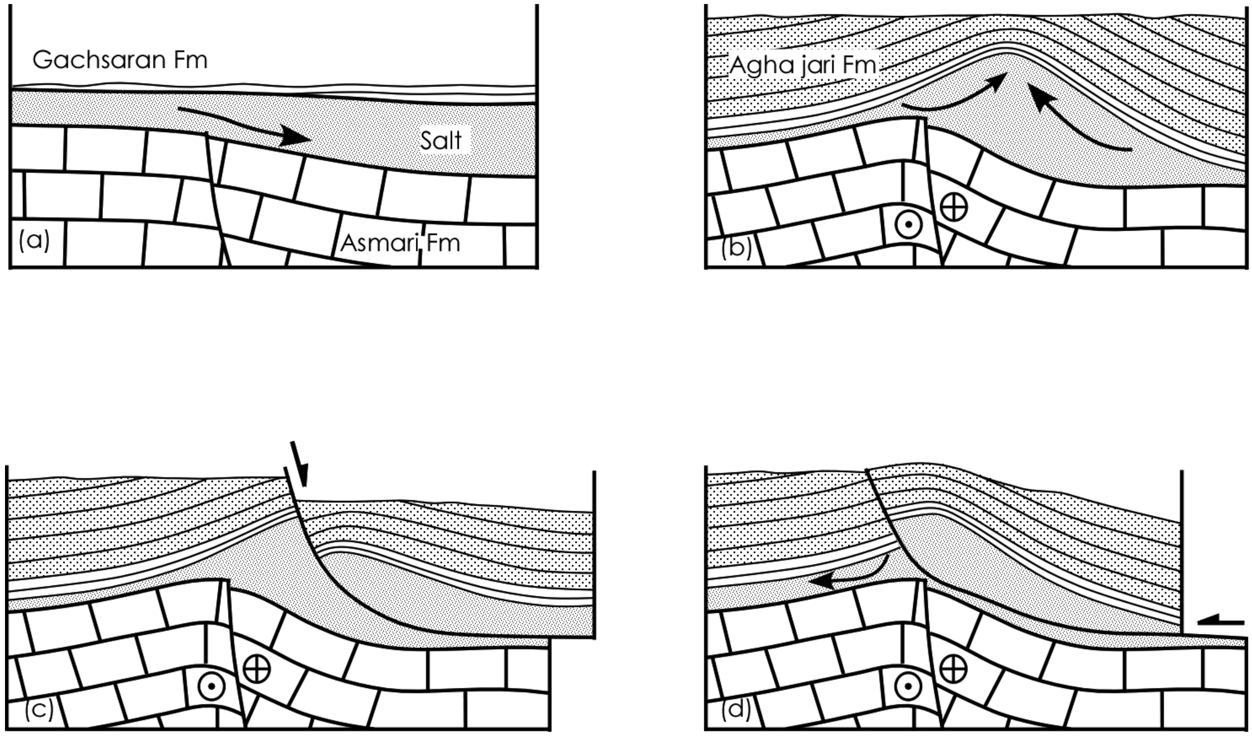

Figure 4. Reconstruction of kinematic evolution of salt driven fold propagation fault by structural inversion controlled by an inherited deep-seated fault system. Arrows in the Gachsaran Salt indicate salt flow. (a) Salt thickening with salt migration toward a depression due to an early deformation, (b) second step of the deformation with formation of a salt bulge and an associated antiform in the overlying sediment, (c) over-thickening in the salt led to a gravity-driven collapse along a growth fault, (d) positive structural inversion, the overloading by the fault-propagation fold resulted in salt flow in the foot wall.

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