Role of Multiple Décollement Horizons in the Structural Style of the Sefid-Zakhur Anticline in the Fars Province, Zagros Belt

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Abstract—The geometry of the Sefid-Zakhur anticline, a gas reservoir in the Fars province, and the main controlling factors of the structural style in this anticline are studied in this research. The integration of the 2D seismic profiles, well data, and the fieldwork was used to study the geometry variations of the Sefid-Zakhur anticline. The geometry of this anticline is different vertically and horizontally. It is a chevron fault in the western part and a box fold in the eastern part. Observed growth strata in the Mishan Formations show that the folding started in the Middle Miocene time in this area. The Sefid-Zakhur anticline indicates a significant over-thickening of the middle décollement horizon (Dashtak evaporites) in their crestal domain. In this region, the Triassic Dashtak evaporites and the Cambrian Hormuz salt are the main décollement horizons. The upper Cretaceous Gurpi shales are also minor décollement horizon. Decoupling across the décollement horizons is obviously visible in the Sefid-Zakhur anticline, especially across the thick Dashtak evaporites. The decoupling across the thick Dashtak evaporites causes the shift of the anticline crest in the underlying Permo-Triassic carbonates of the Dehram Group, which form the major gas reservoir. Therefore, the investigation of the décollement horizons is of utmost importance in the management of these reservoirs. The results of this research suggest that the presence of multiple décollement horizons is the main controlling factor of the structural style in this anticline.

Keywords: structural style, multiple décollement horizons, Sefid-Zakhur anticline, seismic profiles, growth strata, Hormuz salt, Dashtak evaporites, gas reservoir, Fars province

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INTRODUCTION

In the fold-and-thrust belts, the main controlling factors of the structural style are the mechanical stratigraphy [11, 29, 34, 38] and the presence of preexisting basement structures [16, 18]. Several previous studies demonstrated the effect of different decollement horizons on the structural style in the Zagros fold-and-thrust belt [6, 30, 37, 38, 44]. Also, recent regional studies have indicated that the mechanical stratigraphy has a significant role in governing the fold style in the Zagros [9, 17, 23, 34, 36−38].

In the Zagros fold-and-thrust belt, the presence of multiple décollement horizons caused the development of different geometry patterns and various kinematic evolution of anticlines [34, 38] that are the main oil and gas reservoirs. Geometry, thickness, and the depth of the décollement horizons play an important role in the deformation [29, 35, 42].

Numerous works have been performed to show the importance of intermediate décollement horizons in the folding style in the Zagros [3, 12, 24, 30, 34, 36−38, 44]. A structural style is different in both sides of the décollement horizons. The presence of incompetent layers (shale and evaporites) as décollement horizons in the sedimentary cover changes the deformation in layers situated above these levels [11, 29]. This state is observed throughout the Zagros belt, especially in the Fars province. In the Fars province, the basal and intermediate decollement horizons have an important role in the structural style of fold-and-thrust belts [38]. The decollement levels, or different mechanical stratigraphy within the sedimentary cover, are not uniform throughout the Zagros belt and indicate a strong spatial variation [15, 38].

In this research, the structural style of the Sefid-Zakhur anticline is studied. This anticline is a gas reservoir in the Fars province (Fig. 1). The study of the structural style of the Sefid-Zakhur anticline is very important in the management and development of the gas reservoir in this field. The main objectives of this study are to determine multiple décollement horizons in the Sefid-Zakhur anticline and investigate the effects of multiple décollement horizons on the fold geometry of this anticline.

The interpretation of 2D seismic profiles, well data, and the fieldworks was used to achieve the objec-
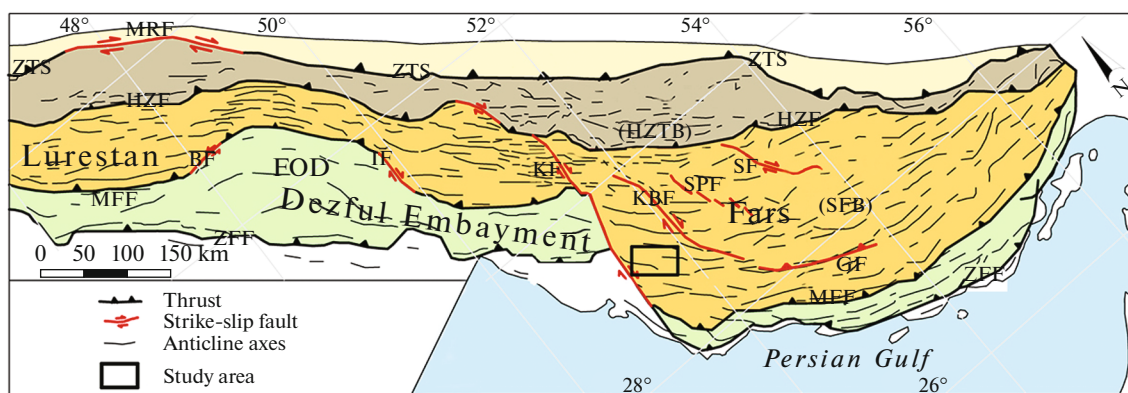
Fig. 1. Structural map and subdivision of the Zagros belt and the location of the study area [7, 36]. Abbreviations: ZTS − Zagros thrust system; MRF − main recent fault; HZF − high Zagros fault; MFF − mountain front fault; ZFF − Zagros foredeep fault; BF − Balarud fault; IF − Izeh fault; KF − Kazerun fault; KBF − Kar-e-Bass fault; SPF − Sabz-Pushan fault; SF − Sarvestan fault; GF − Ghir fault.

tives mentioned above. The results of this research will be utilized in the current and future hydrocarbon explorations of this reservoir and its management in this anticline.

GEOLOGICAL SETTING

The Zagros fold-and-thrust belt (ZFTB) is part of the Alpine-Himalayan belt. This belt is the result of the opening of the Neo-Tethyan Ocean at the Late Permian-Early Triassic [40] and the subsequent closing of this ocean [2, 8, 38]. The starting time of the collision between the Central Iranian and Arabian plates was in the Late Cretaceous, and Neo-Tethys closed completely in the Miocene time [2, 3, 8, 31].

The Zagros belt contains a 7−14-km-thick sedimentary cover (from the latest Precambrian to recent) [19, 25]. These sediments were deposited along the north-northeastern edge of the Arabian Plate. The sedimentary cover is decoupled from their underlying basement along the Lower Cambrian Hormuz Salt Formation [4, 30, 38].

According to the sedimentary characterizations, the Zagros belt is divided into the Lurestan basin, the Dezful embayment, and the Fars province (Fig. 1). Also, based on the stratigraphic characteristics, sedimentary and geological environment, the Fars province is divided into two parts: the Interior Fars and the Exterior Fars. The Exterior Fars is divided into two parts: Sub-coastal Fars and Coastal Fars subzones [43]. The Safid-Zakhor field is located in the coastal Fars sub-zones [5].

In the Fars Province, the stratigraphic sequence includes several competent units that are decoupled by the incompetent units (Fig. 2) [29, 30, 36, 38]. In all over the Zagros, Cambrian shale layers or Hormuz salt series are the main basal décollement horizons [4, 21, 28, 30, 36, 38]. The sedimentary cover of the Zagros belt is decoupled from its underlying basement along the Lower Cambrian Hormuz Salt Formation [4, 30, 38].

In the Fars Province, another well-known intermediate decollement horizon is the Triassic evaporites of the Dashtak Formation [36, 38] that plays a significant role in the deformation of the cover locally. The Dashtak Formation mostly consists of the evaporite deposits that are intercalated with dolomite and shale. The geological map of the studied area can be seen in Fig. 2.

METHOD

The methods used in this research include:

• Collection of various sources of data, such as 2D seismic network consisting of longitudinal seismic profiles in TWT oriented WNW−ESE (along the strike of the Sefid Zakhur anticline), transversal seismic profiles in TWT oriented NE−SW (perpendicular to the anticline strike), depth-converted seismic profiles, well data, and check-shots of Formations from NIOC (National Iranian Oil Company, Tehran, Iran);

• Interpretation of the seismic profiles in the Petrel software. The interpreted seismic data are used to construct the cross sections.

Several steps have been taken to interpret the seismic data in the Petrel software [45]:

—simple depth conversion of 2D seismic profiles applying the calculated seismic velocities from wells;

—line drawing on the deep seismic profiles;

—addition of tops of sedimentary formations and dipmeter data from wells.

STRATIGRAPHY OF SEFID-ZAKHUR ANTICLINE

The stratigraphic column of the Sefid-Zakhur anticline is determined by the drilled wells. The names, lithologies, and ages of the stratigraphic formations and groups are based on the classical stratigraphic chart for this region established by James and Wynd [19], and
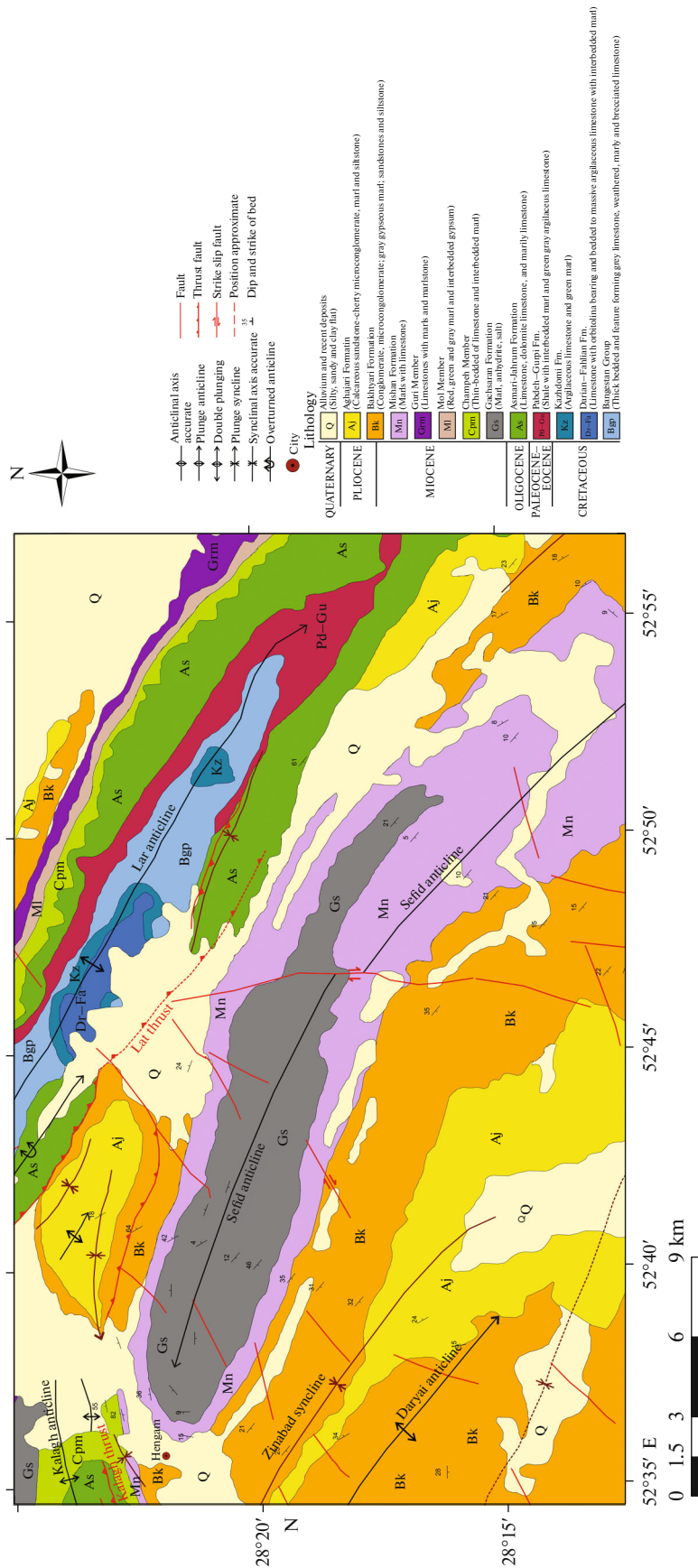
Fig. 2. Geological map of the studied area.

correspond to those applied by the NIOC in their regular exploration tasks.

The Paleozoic series contain the Faraghan (Early Permian) and Dalan (Late Permian) formations. These formations show the sandstone facies (Fig. 3).

The Mesozoic series contains rock units from Lower Triassic to Upper Cretaceous. The Kangan Formation (Early Triassic) indicates carbonates (limestone). The Dashtak Formation (Early-Middle Triassic) includes gypsum and anhydrite interbedded with dolomite. Early Jurassic Neyriz Formation consists of the thick-bedded to massive carbonates, and Late Jurassic Surmeh Formation includes shale and anhydrite interbedded with carbonates. The Lower Cretaceous is represented from older to younger rocks by shales and marly limestones, thick-bedded to massive carbonate sediments, marly-shaly limestones, thin-bedded limestones, and evaporites. The Upper Cretaceous consists of shales, marly-shaly limestones, and thin- and thick-bedded to massive carbonates.

The Cenozoic series ranges from Palaeogene to recent. The Palaeocene consists of the shales, marls, and marly limestones. The Eocene contains the thin-bedded limestones, and the Oligocene and Lower Miocene include thick-bedded to massive carbonate sediments. The Miocene is formed by gypsum, anhydrite, and salt interbedded with dolomite, marls, and marly limestones, and the Pliocene is made up of sandstones and siltstones.

STRUCTURAL STYLE
OF THE SEFID ZAKHUR ANTICLINE

In this section, geometry analysis of the Sefid-Zakhur anticline is explained based on five transverse cross sections and one longitudinal section, which are interpreted using seismic profiles as follows.

Cross Section AA'

Cross section AA' is a composite section in the Sefid-Zakhur and Helegan anticlines. This section has cut the western part of Sefid-Zakhur and Helegan anticlines (Fig. 4). In this section, the northern and southern limbs have been cut by the thrust faults. The dip of the thrust in the southern limb is less than the northern limb. The anticline is an asymmetric chevron fold in this section. The main structural complexity in this anticline arises from the effect of the Triassic Dashtak evaporites as an intermediate décollement horizon. The dip of the thrust fault in the northern limb of this anticline decreases in the Dashtak evaporites. The shift of the anticline crest across the Dashtak intermediate décollement horizon, with respect to the anticlinal crest in the underlying layers (in the Permo-Triassic Dehram Group), is observed in the interpreted seismic profiles in this section. In cross section AA', the anticline is decoupled above the Triassic Dashtak horizon, whereas
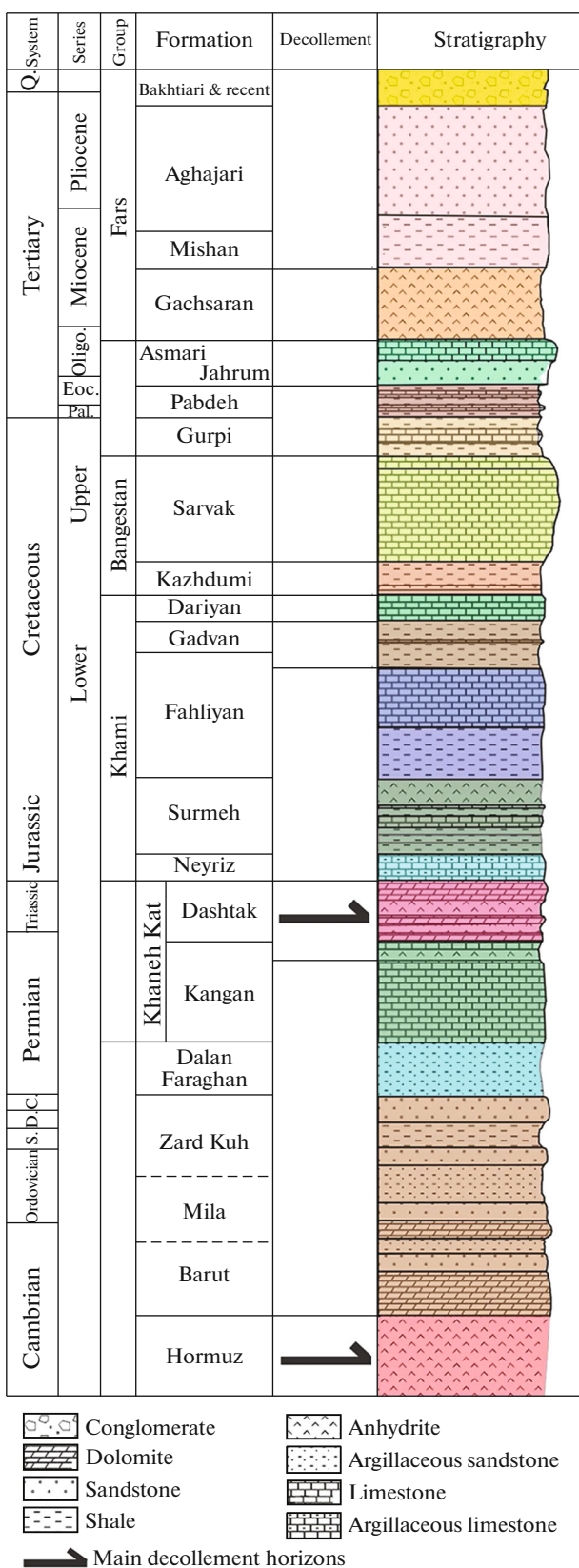
Fig. 3. Stratigraphic column of the Fars province (after [38], modified). Indicated (heavy black arrows) possible décollement horizons within the sedimentary succession. Abbreviations: Q — Quaternary; S — Silurian; D — Devonian; C — Carboniferous.
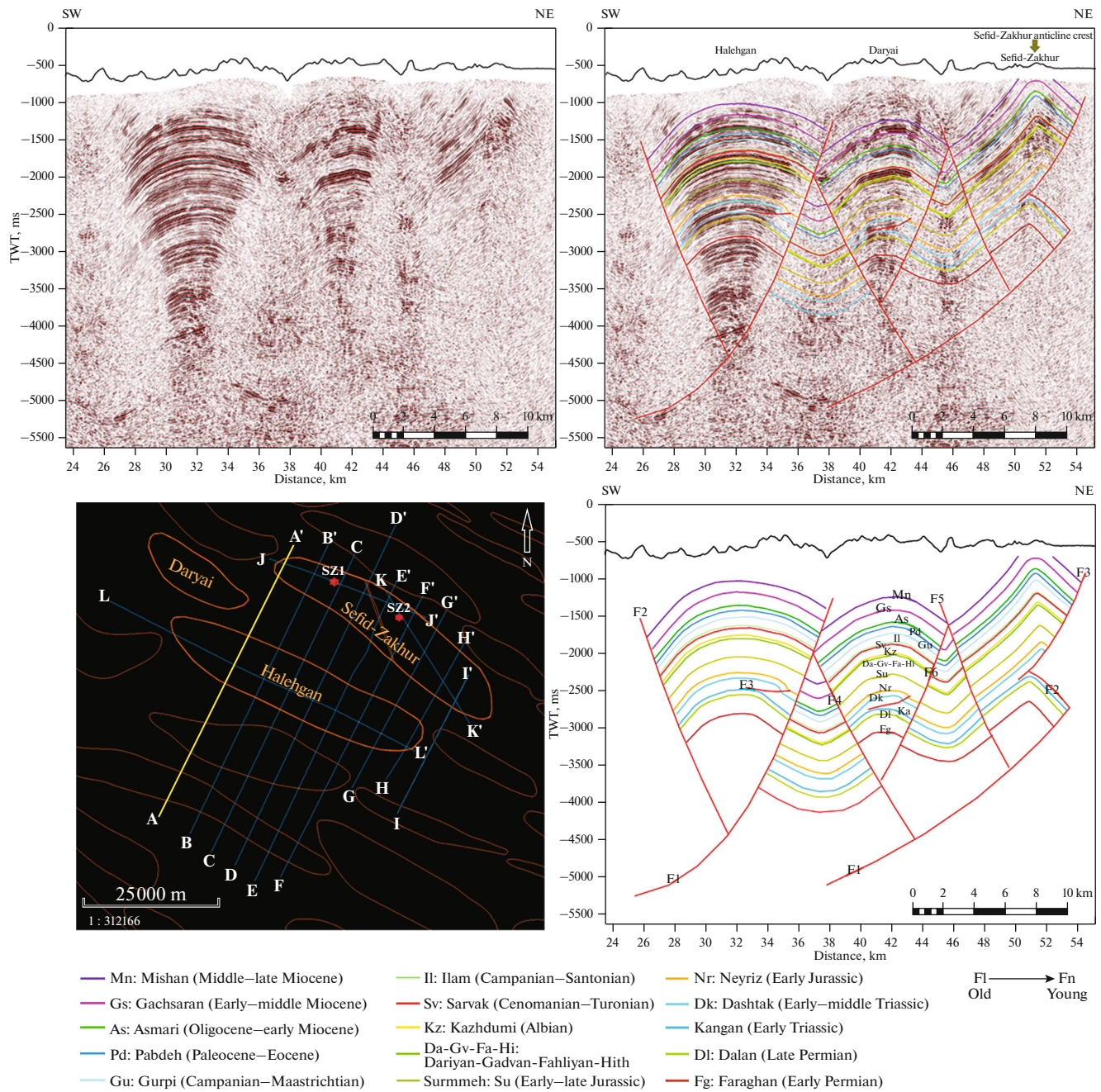
Fig. 4. Cross section AA′ across the Sefid-Zakhur and Helegan anticlines. Indicated (arrow) the shift of the Sefid-Zakhur anticline crest.

the underlying Permo-Triassic and older sedimentary successions define a gentler anticline.

The syncline situated between the Sefid-Zakhur and Helegan anticlines is observed by a change in geometry from the surface to the depth and from the western part to the eastern part (Fig. 4). In the cross section AA′, the upper part, which corresponds to a growth syncline, is observed as a tight and acute geometry. Besides, the lower part is characterized by open syncline geometry patterns in the seismic data. This is interpreted as the consequence of the occurrence of two opposed thrust faults on both limbs of the syncline in this syncline.

Cross Section CC′

Cross section CC′ is a composite section from the Sefid-Zakhur anticline and Helegan anticlines (Fig. 5). This section has cut the western part of Sefid-Zakhur anticline and the central part of Helegan anticline.
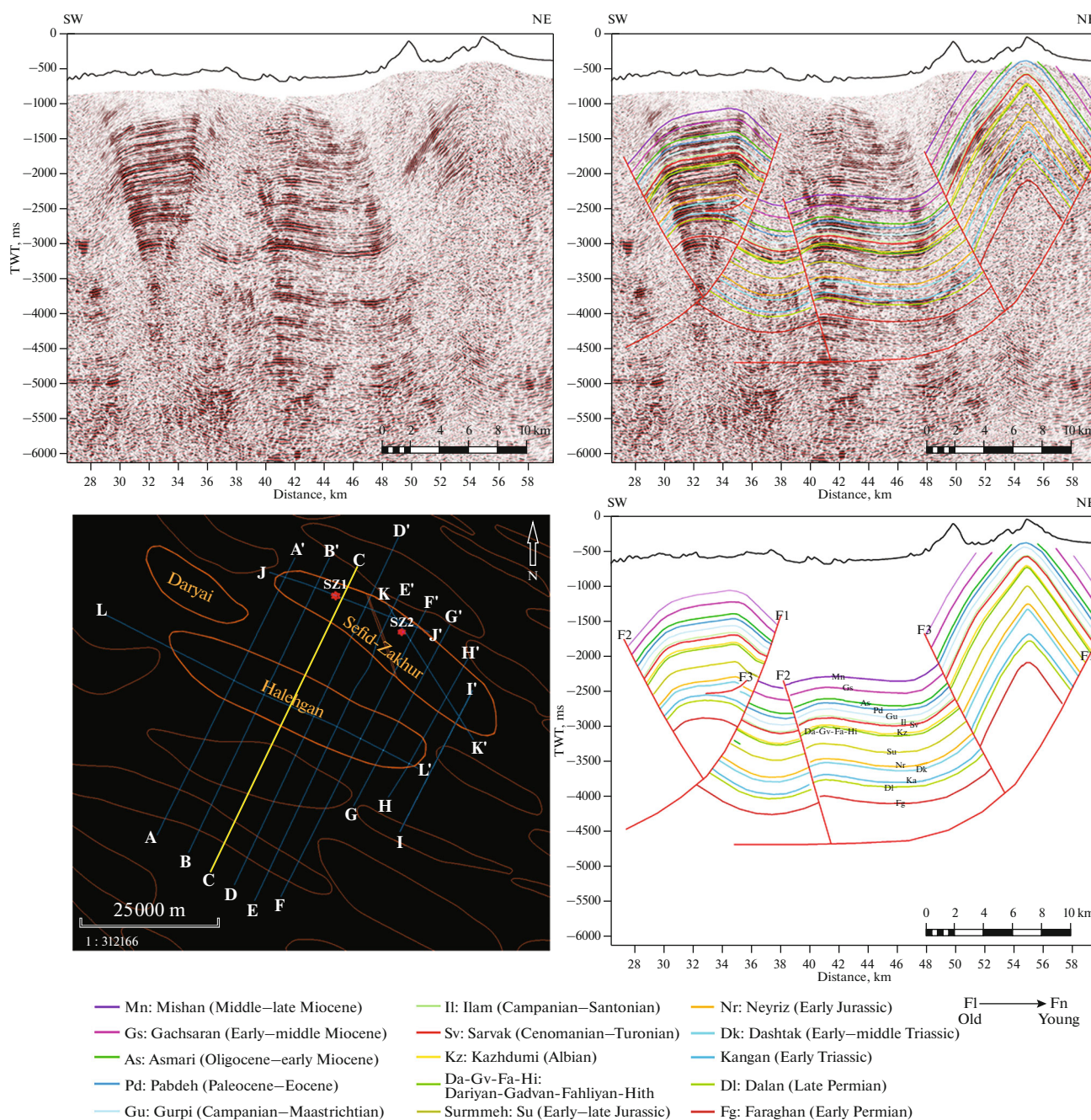
Fig. 5. Cross section CC' across the Sefid-Zakhur and Helegan anticlines.

The geometry of the Sefid-Zakhur anticline in this section is similar to the pop-up fold geometry that developed by the opposite verging high-angle limb thrusts. The northern and southern limbs have been cut by the thrust faults. The dip of thrust in the southern limb (75°) is similar to that in the northern limb. The anticline is a chevron fold in this section.

The decoupling across the Dashtak level is not observed in this section. A syncline between Sefid-Zakhur and Helegan anticlines is an open fold in the section CC'. The main visible feature in this section is

crestal thickening of the Dashtak Formation as middle décollement horizon (Fig. 6). The thickness of the Dashtak Formation is observed with its tectonic over-thickening in the crest. Also, over-thickening of the Dashtak Formation at the top of the Dashtak Formation and the top of the Dehram Group diverging toward the anticline core is observed in the Helegan anticline.

Cross Section EE'

Cross section EE' is a composite section from Sefid-Zakhur anticline and Helegan anticlines (Fig. 7). This
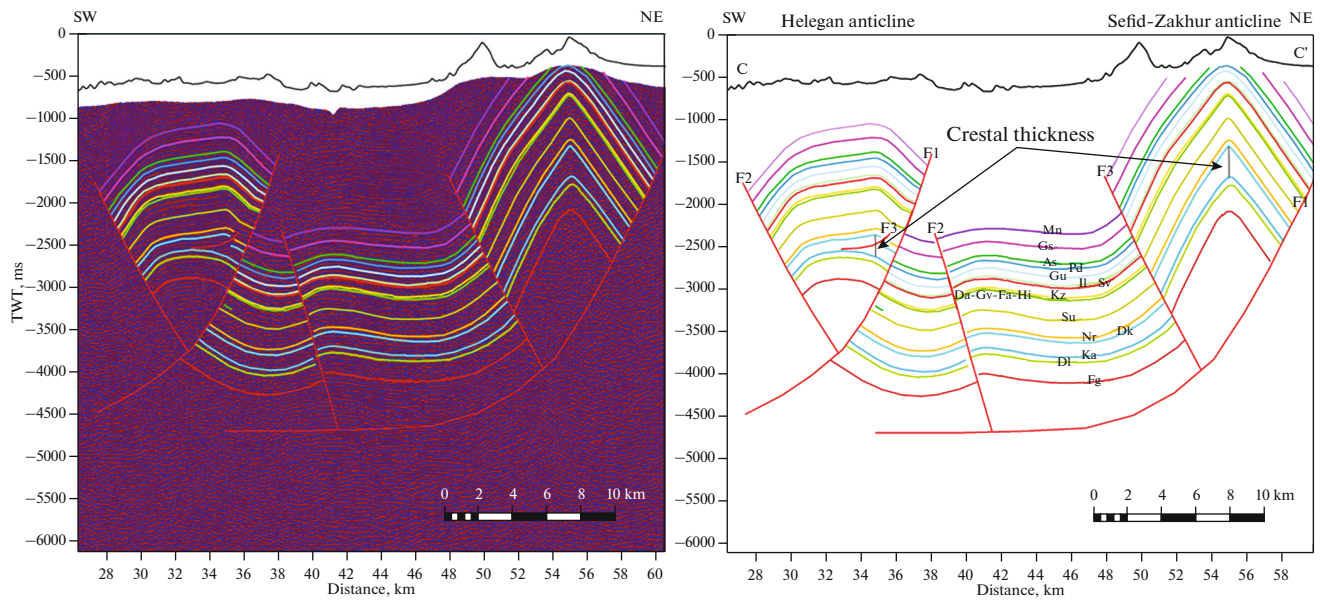
Fig. 6. Seismic reflectors indicating tectonic over-thickening of the Dashtak Formation at the crest of the Sefid-Zakhur anticline.

section has cut the central part of the Sefid-Zakhur anticline and the eastern part of Helegan anticline. The shift of the Sefid-Zakhur anticline crest (arrow) is well seen by comparing Figs. 4 and 7.

The northern and southern limbs of the Sefid-Zakhur anticline, which have been cut by the thrust faults, are listric faults. The dip of the two thrusts decreases in the Dashtak Formation as the middle décollement horizon. The anticline is an asymmetric chevron fold in this section. Decoupling in Dashtak Formation is observed in this section. The shift of the anticline crest across the Dashtak intermediate décollement horizon is observed with respect to the anticlinal crest in the underlying layers.

Cross Sections GG' and II'

Cross sections GG' and II' are composite sections from the Sefid-Zakhur anticline and Helegan anticlines (Figs. 8, 9). These sections have cut the eastern part of Sefid-Zakhur and Helegan anticlines. The two limbs have been cut by the listric thrust faults. The main structural complexity in this anticline arises from the effect of the Triassic Dashtak evaporites as an intermediate décollement horizon.

In these sections, the Sefid-Zakhur anticline is a symmetric and gentle box fold with a nearly rounded and broad crestal domain. The parallel pattern of the seismic reflectors indicates a parallel and harmonic folding geometry in different structural levels, from the surface to the depth.

Cross Sections KK'

The cross section KK' is a longitudinal section and oblique to the Sefid-Zakhur anticline axis (Fig. 10).

The performance of multiple décollement horizons is obviously visible in this section. The dip of the thrusts (Fig. 10; F1, F2, and F4), which have cut the forelimb of the Sefid-Zakhur anticline, decreases at the décollement horizons. Decoupling between geological layers has occurred in this anticline due to the presence of multiple décollement horizons. This section indicates the Gurpi shales, Dashtak evaporites, and Hormuz salt as décollement horizons in the Sefid-Zakhur anticline.

The Sefid-Zakhur fault is another visible feature in this section (Fig. 10, F3). This fault is detected in this section as a vertical fault and shows the strike-slip movement. In the seismic profiles, this fault has cut the Neyriz Formation in depth to recent sediments above.

SEFID-ZAKHUR FAULT

The Sefid-Zakhur anticline anticline has two peaks; the western peak is higher than the eastern one [13]. According to the satellite image, the overall length of the anticline is 37.5 km, with an average width of 6 km at the top of the Mishan Formation [41]. This anticline has been cut by a NNW−SSE-trending oblique fault (Fig. 11). The trend of the Sefid-Zakhur fault is an old lineament corresponds to the trend of the old lineament in the Fars province (e.g., the faults at the Surmeh salt domes and the Siah Kuh in Sarvestan) [29]. The Sefid-Zakhur fault has NNW−SSE trending. Also, some small-scale faults occur in the anticline crest and limbs. The Sefid-Zakhur fault has changed the trend of Sefid-Zakhur anticline. The trend of this anticline is WNW−ESE in the western part. In the eastern part, the trend of this anticline changes to NW−SE.

The Safid-Zakhur fault is obviously visible in the longitudinal seismic profiles (Fig. 10), on the satellite image Landsat 8 [46] (Fig. 11) and in the field (Fig. 12).
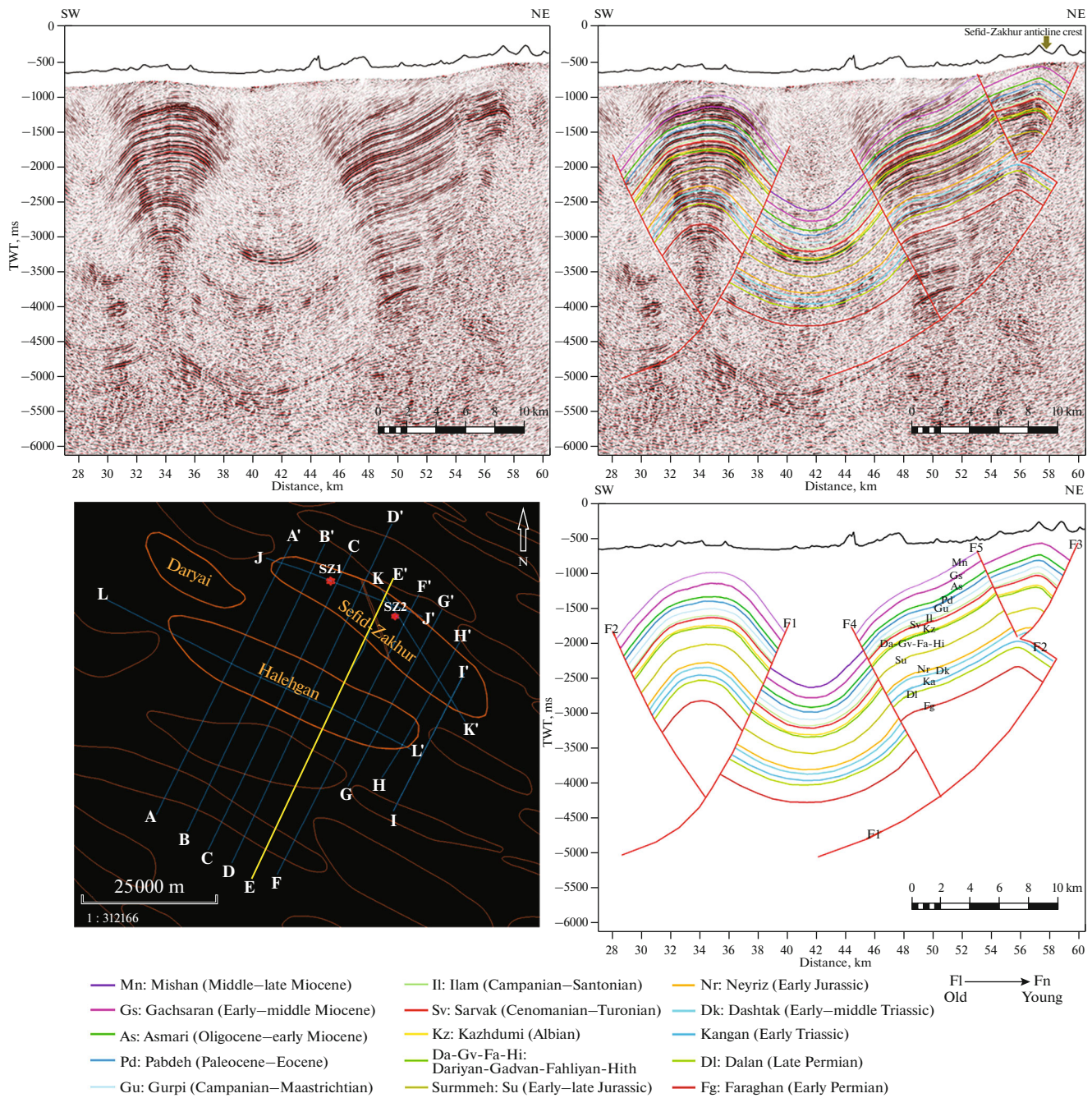
Fig. 7. Cross section EE' across the Sefid-Zakhur and Helegan anticlines.

SYN-COMPRESSIONAL SEDIMENTS IN THE STUDIED AREA

One of the main stratigraphic features in the studied area is the growth strata that is visible in the carbonate member of the Mishan Formation. The on-lap of the carbonate member of the Mishan Formation towards the crest of the Sefid-Zakhur anticline (Fig. 13) suggests that the starting time of the folding in the studied area is in the Middle Miocene time. The on-lap of Miocene layers shows that the

Sefid Zakhur anticline was active during the sedimentation of these stratigraphic units.

In the growth strata formed across the Sefid-Zakhur anticline anticline (Fig. 13), the greatest thickness has generally occurred in the basins adjacent to this anticline, so that the thickness of the beds is lower towards the crest of the anticline and very similar to the fan structures. Also, the dip decreases progressively up section (Fig. 13).
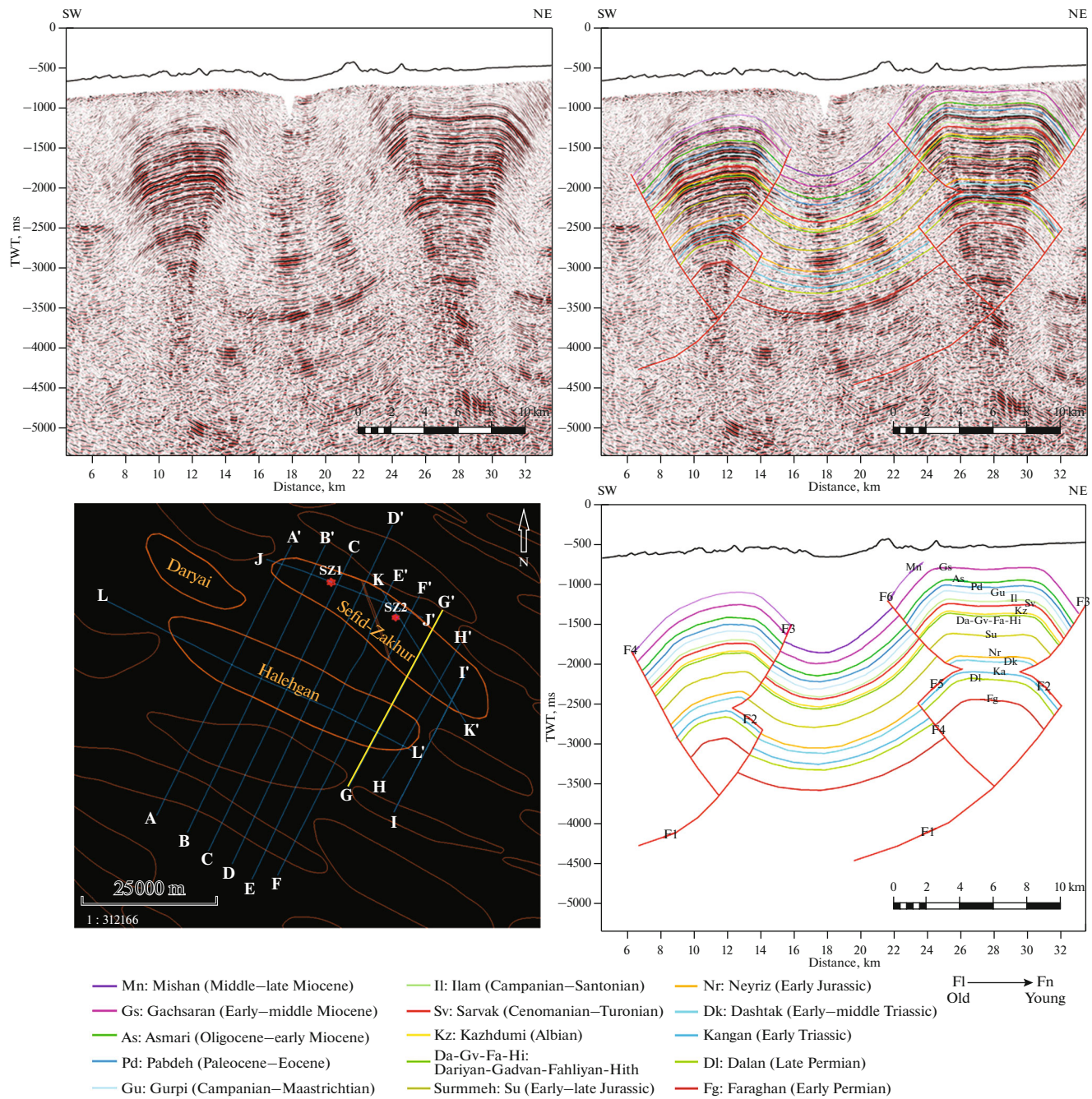
Fig. 8. Cross section GG′ across the Sefid-Zakhur and Helegan anticlines.

Legend:
- Mn: Mishan (Middle–late Miocene)
- Gs: Gachsaran (Early–middle Miocene)
- As: Asmari (Oligocene–early Miocene)
- Pd: Pabdeh (Paleocene–Eocene)
- Gu: Gurpi (Campanian–Maastrichtian)
- Il: Ilam (Campanian–Santonian)
- Sv: Sarvak (Cenomanian–Turonian)
- Kz: Kazhdumi (Albian)
- Da-Gv-Fa-Hi: Dariyan-Gadvan-Fahliyan-Hith
- Surmmeh: Su (Early–late Jurassic)
- Nr: Neyriz (Early Jurassic)
- Dk: Dashtak (Early–middle Triassic)
- Kangan (Early Triassic)
- Dl: Dalan (Late Permian)
- Fg: Faraghan (Early Permian)

Fl → Fn
Old → Young

RESULTS AND DISCUSSION

The Central Frontal Fars, with more than 1500 trillion cubic feet (TCF) of gas reserves, contains about 15% of the World's proven gas reserves [10, 24]. In the Central Frontal Fars, the Permo-Triassic Dehram carbonate Group is the main gas reservoir located below the Dashtak evaporites. The thick Dashtak Formation (Triassic) is an efficient décollement horizon in this region that has decoupled the post-Triassic succession from the Permo-Triassic reservoir rocks [24, 36, 38]. The structural decoupling along the Dashtak intermediate décollement horizon makes it complicated to drill the new wells in the Dehram group.

The Sefid-Zakhur anticline is located within the Dashtak Formation activity domain. The geometry of this anticline is different vertically and horizontally. The Sefid-Zakhur anticline indicates a vergence towards the north and close chevron geometry along its western termination (in the cross-sections AA') (Figs. 4, 5, and 7). This geometry is probably devel-
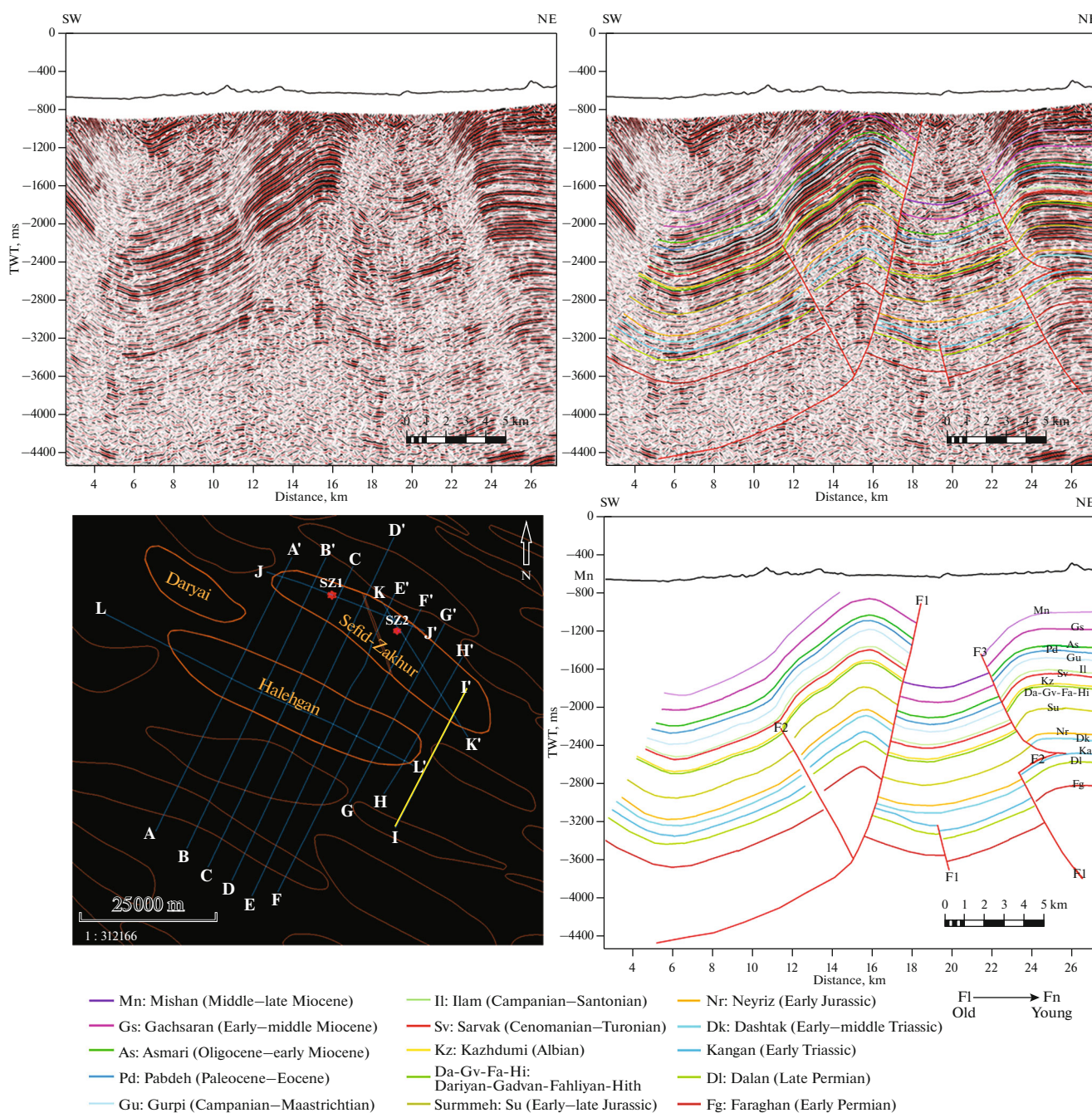
Fig. 9. Cross section II' across the Sefid-Zakhur and Helegan anticlines.

oped by a succession of competent and incompetent layers [29, 32]. Incompetent layers, Dashtak Formation, fill the spaces at the fold hinge by thickening and internal over-thrusting in the western part [29, 32]. In the western part, the anticline is a box fold.

In the previous studies, shortening is measured in different parts of this anticline [29]. The shortening is about 20% in the anticline in the western part, where the Sefid-Zakhur-1 well was drilled. The well 1 was drilled in the crest of the anticline (section CC'). In

this part, over-thickening of the Dashtak Formation is measured about 70%, assuming an initial thickness of about 800 m [29]. By contrast, the shortening in the eastern part is measured about 7%. The Dashtak Formation does not indicate over-thickening as evidenced by the 790 m thickness drilled in the Sefid-Zakhur-2 well, as well as 805 m thickness in the Sefid-Zakhur-3 well [29]. In other words, the anticline is parallel in the eastern part, and its style does not change from surface to depth. In the western part, the shift of the anticline
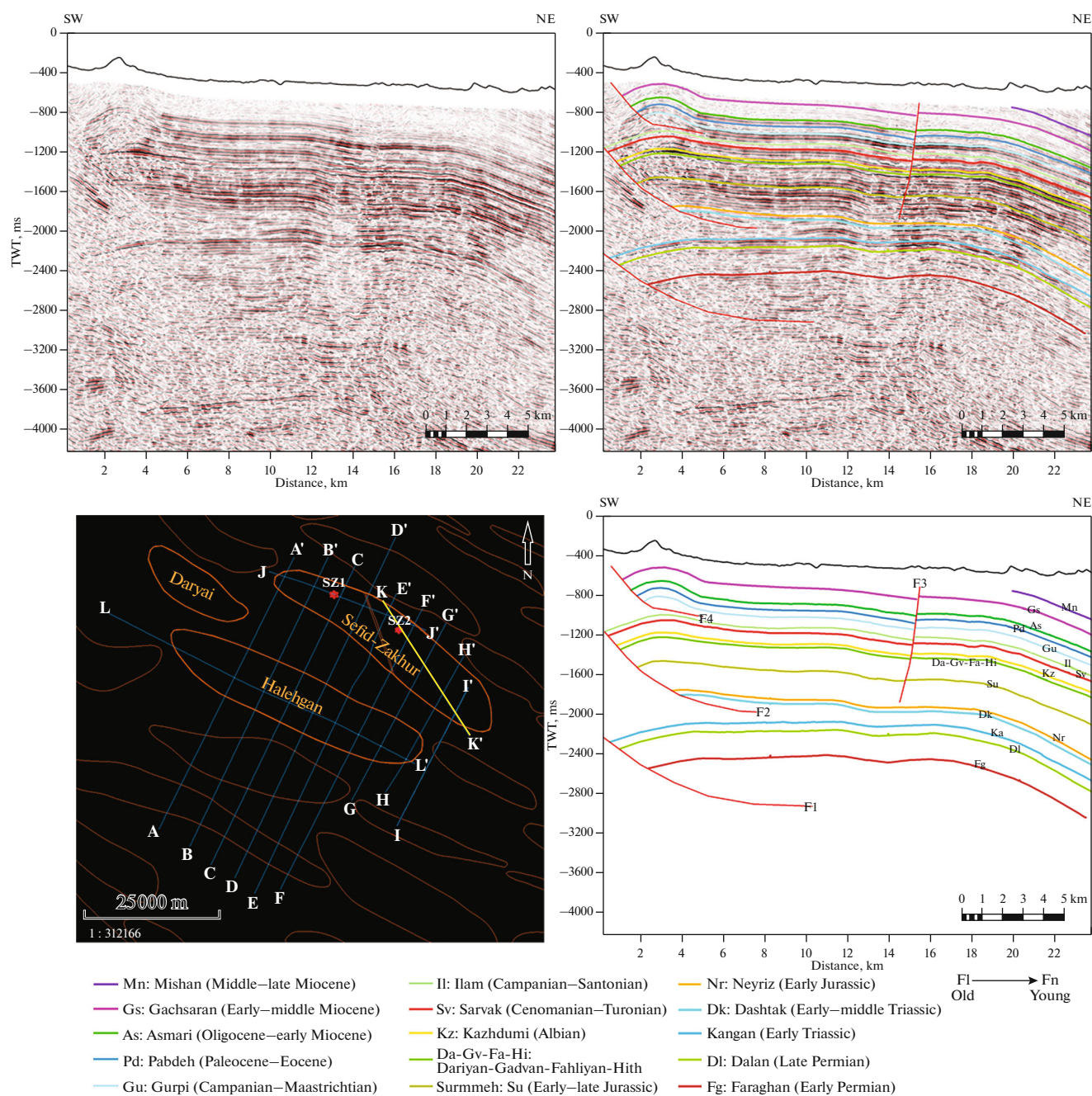
Fig. 10. Longitudinal cross section KK', oblique to the Sefid-Zakhur anticline axis.

crest happened in the underlying formation below the Dashtak Formation. The main controlling factors of the structural style in the Sefid-Zakhur anticline are the presence of middle décollement horizons (Dashtak Formation as the main middle décollement and Gurpi Formation as a minor middle décollement) and the amount of shortening. The box fold in the eastern part has been formed at the low shortening and then, in progressive deformation process, changed to a chevron fold in the western part [29, 34]. Also, shortening has accommodated the internal deformation within the Triassic ductile layer in the fold hinge as over-thickening of the middle décollement horizon (Dashtak evaporites) in the western part of the Sefid-Zakhur anticline.

The decoupling across the thick Dashtak evaporites causes the shift of the anticline crest in the underlying Permo-Triassic carbonates of the Dehram Group, which form the major gas reservoir. Thus, the investigation of décollement horizons is very important in the management of these reservoirs. Furthermore, the estimation of the crystal thickness of the
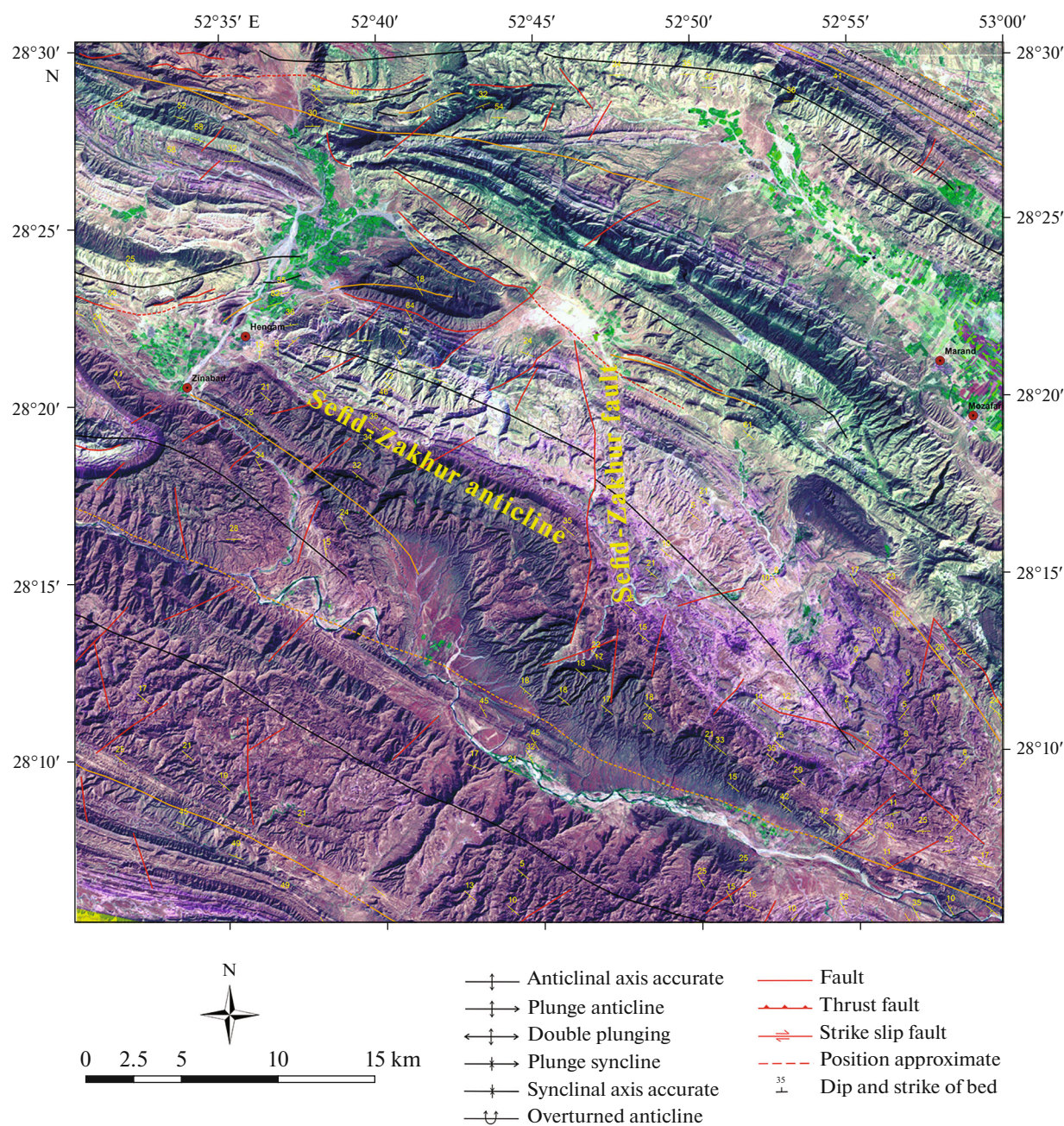
Fig. 11. Satellite image of Sefid-Zakhur anticline (after [46]). The Sefid-Zakhur fault cut the eponymous anticline.

Dashtak Formation and its decoupling behaviour in any anticline in the area, before drilling a new exploration well, is crucial in two ways: to avoid drilling out of trap, due to the potential crestal shifts, and to avoid engineering design of well when crossing thick evaporites.

Syntectonic sediments and growth structures have been reported from different stratigraphic horizons all over the Zagros belt [16, 27, 39]. The growth strata indicate the syn-compressional deposits and the timing of compressional deformation in the sequence stratigraphy [27]. Most of the previous studies consider the Gachsaran Formation as pre-growth strata [14, 17, 26], whereas Agha Jari and Bakhtiari formations from Middle Miocene to Pliocene are considered as the growth strata [1, 4, 14, 17, 18, 20, 22, 26, 27]. However, in the Sefid Zakhur anticline prospect, the growth strata occur in the upper members of the Mishan Formation in the Sefid-Zakhur anticline (Fig. 13). Therefore, the folding started in the Middle Miocene in this area.

Fig. 12. The Sefid-Zakhur fault cut the Sefid-Zakhur anticline. This fault is a thrust with a right-lateral component; dip direction is toward the west.
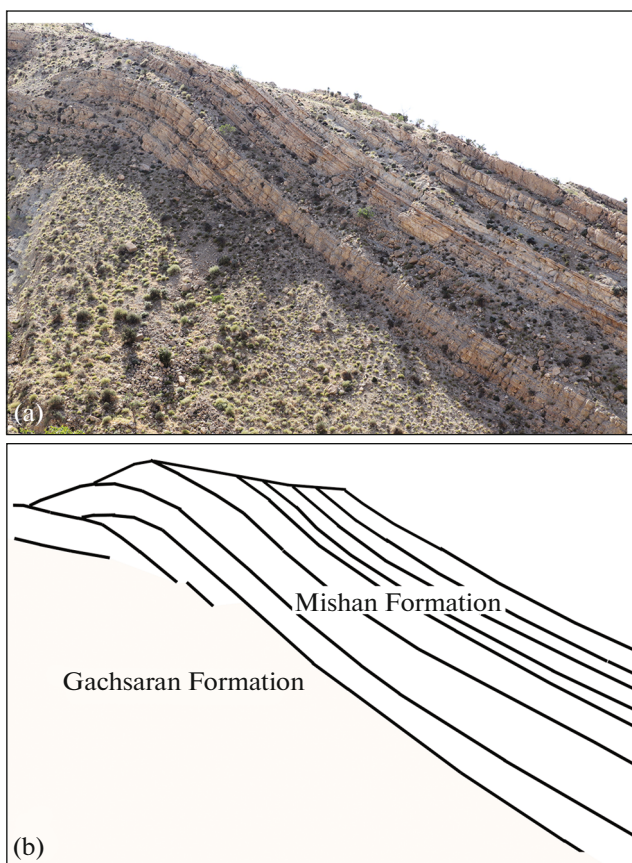

Fig. 13. On-lap of carbonate layers (Mishan Formation) towards the crest of Sefid-Zakhur anticline (growth strata) indicates the starting time of folding in the studied area.

CONCLUSIONS

The presence of multiple décollement horizons is the main controlling factor of the structural style in the Sefid-Zakhur anticline. The geometry of this anticline is different vertically and horizontally. This anticline is a chevron fault in the western part and a box fold in the eastern part. The Sefid-Zakhur anticline indicates a significant over-thickening of the evaporitic middle décollement horizon (Dashtak evaporites) in its crestal domain. The decoupling across the thick Dashtak evaporites causes the shift of the anticline crest in the underlying Permo-Triassic carbonates of the Dehram Group, which form the major gas reservoir. Thus, the investigation of décollement horizons is very important in the management of these reservoirs.

In this region, the Triassic Dashtak evaporites and Cambrian Hormuz salt are the main décollement horizons. The upper Cretaceous Gurpi shales are also minor décollement horizons in some parts. Decoupling across the décollement horizons is obviously visible in The Sefid-Zakhur anticline, especially across the thick Dashtak evaporites.

The observed growth strata in the carbonate member of the Mishan Formation suggest that the folding started in the Middle Miocene time in this area.

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