# Structural Style and Deformation of the Gachsaran Formation in the Dezful Embayment of the Zagros Fold Thrust Belt, Chamshir Area, Iran

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**Abstract** The Gachsaran evaporate Formation is the caprock of the Asmari oil reservoir in the Zagros oil province. This Formation is a main detachment horizon in the Zagros. As an intermediate detachment horizon, this Formation separates rocks of distinct structural features and folding styles in its overlaying and underlying units. Around 1600 m thick Gachsaran Formation has seven Members (Gs.1–7). The Formation consists of salts, anhydrites, coloured marls, limestones and a single layer of bituminous shale. In this work, we interpret the different Members of the Gachsaran Formation and study the structures in the Chamshir area, located in the lowland basin of the Zagros belt, using surface and subsurface data in 2D sections and 3D models. The presence of a thick layer of the Gachsaran Formation has affected the structural style in the Chamshir area. In the Chamshir area, Members Gs.5–7 crop out. The salt members of the Gachsaran Formation are deformed to several secondary folds and faults. Based on surface and subsurface data (up to 3000 m deep), the area has two types of faults. The faults seen in the exposed part of the studied area often continue to Gs.4, such as the Dezh Soleyman Fault, Chamshir Fault, F4 and F3 faults. The second category of faults developed within the Asmari Formation up to the approximate depth of the Triassic-Jurassic Formations. In other words, a thick layer of the evaporate member of the Gachsaran Formation (Gs.4), as the main detachment layer, has caused the structural style to be separated across it. As a result, the folds above and below the Gachsaran Formation in the Zagros belt

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significantly different geometries. As the Gachsaran Formation is the main caprock of the Asmari reservoir in Zagros, understanding the effect of this detachment level on the geometry of the anticlines as oilfields is crucial for future exploration in the region.

**Keywords** Gachsaran Formation · Structural style · Chamshir area · Zagros belt

## 1 Introduction

One of the factors controlling the deformation style in the fold-thrust belts is mechanical stratigraphy (e.g. Spratt et al., 2004; Tavakolian & Razavi Pash, 2022). The mechanical stratigraphy of sedimentary cover layers and the presence of incompetent horizons that can act as detachment horizons can be an important parameter controlling the folding style in fold-thrust belts (Cotton & Koyi, 2000; Davis & Engelder, 1985; Misra & Mukherjee, 2015; Razavi Pash et al., 2021a, 2021b; Spratt et al., 2004). The detachment horizons in the middle of the sedimentary cover caused structural separation and the change of the folding style of the upper units, so the geometry of the folds on the surface does not always represent the geometry of those at depth (e.g. O'Brien 1957; Tavakolian et al., 2022).

The Gachsaran evaporate Formation is a main detachment horizon in the foreland of Zagros. In the Dezful Embayment located in the foreland of the Zagros belt (Fig. 1), the Gachsaran Formation has seven Members and consists of salts, anhydrite, marls, limestones and a layer of bituminous shale (Fig. 2). This Formation is as the caprock of Asmari oil reservoirs in Zagros. Several studies have been made on the effect of the Gachsaran Formation on the geometry of petroleum anticlines in Zagros (Table 1).

The Zagros fold-and-thrust belt is one of the prolific petroliferous regions with ~12% of the world's oil reserves (Bordenave & Burwood, 1990). While fold-and-thrust belts have been doubted as suitable for hydrocarbon exploration, the Zagros orogenic belt has never been questioned in this regard (review in Razavi Pash et al., 2023).

Analysis of structural style and deformation in Zagros is crucial for the future exploration and production of hydrocarbons from the reservoirs. Gachsaran evaporate Formation as the main caprock of the Asmari reservoir in Zagros indicates a different geometry in its members in the Chamshir area. Analysis of the structural style of these members aid in hydrocarbon exploration.

Members 5–7 of the Gachsaran Formation are crop out in the Chamshir area. This area includes various types of folds in the different members of the Gachsaran Formation. The performance of the faults in this region has caused the anticlines to be closer to the surface towards the mountain front fault, and for this reason, Gachsaran Formation cropped out.

Member 4 of the Gachsaran Formation has a ductile behaviour in this area and has acted as a detachment layer. Also, evidence of a large salt wall structure can be seen in the Gach Haji anticline. This structure is the result of fault movement and

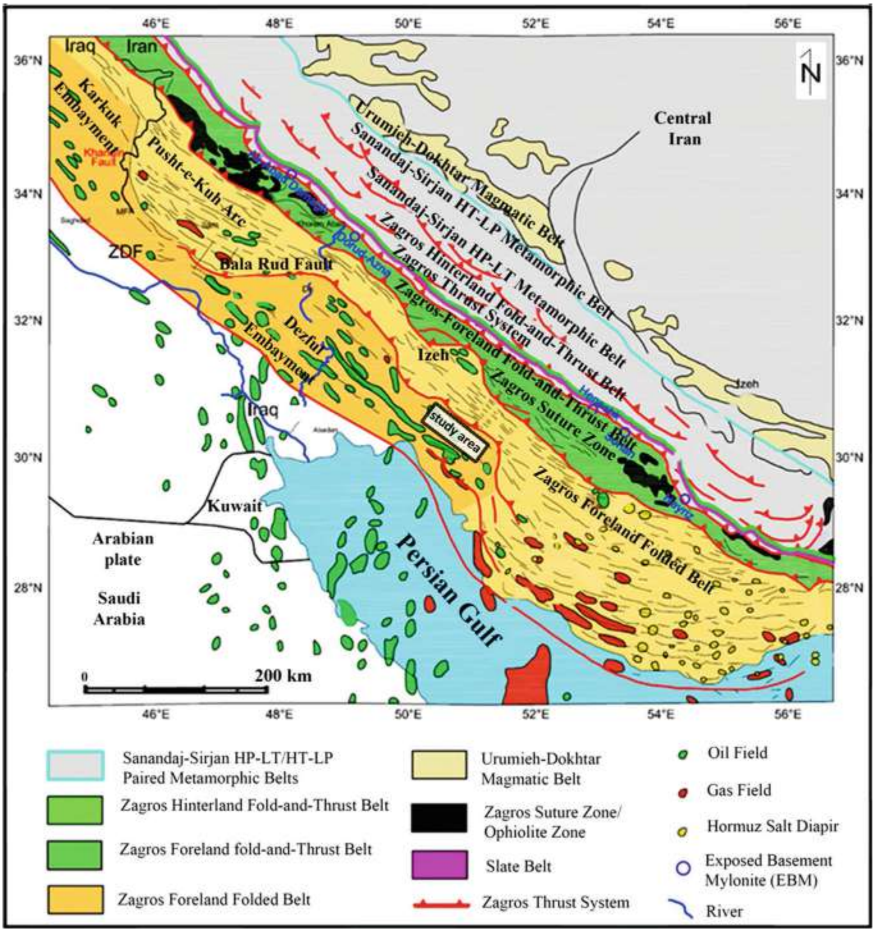


**Fig. 1** Location of the Chamshir area (white rectangle) in the foreland of the Zagros Mountain Front Fault (Sarkarinejad & Ghanbarian, 2014)

rising salt from the members of 5 and 6 of the Gachsaran Formation. As a result of the movement of salt, the member of 6 of the Gachsaran Formation has been exposed at the surface.

In this study, the structural style and deformation of the different Members of the Gachsaran Formation around Cheshmir located in the Dezful Embayment have been investigated by performing fieldwork. Seismic and remote sensing images have been used in the work for a better understanding of structures. Twelve seismic profiles within ~2500–3000 m depth have been studied and included in this study. In total, we study folding and faulting styles and deformation of the Gachsaran Formation from surface and subsurface. A 3D structural model of the Chamshir area is presented.

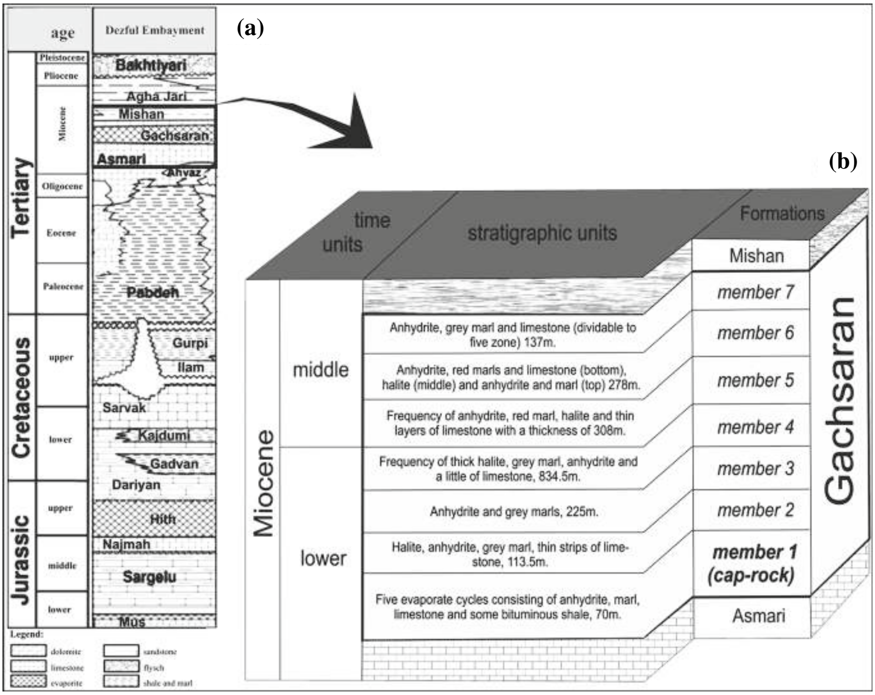


**Fig. 2** **a** Stratigraphic column of the Mesozoic and Cenozoic Formations of the Dezful Embayment in the foreland basin of Zagros fold-thrust belt (after Sepehr & Cosgrove, 2004). **b** Lithological units of the Gachsaran Formation (Soleimani & Bahadori, 2015)

## 2 Geology

The Zagros belt, as a part of the Alpine-Himalayan orogenic belt with a length of ~2000 km, which stretches from northern Iraq to the Strait of Hormuz, is the result of the oblique convergence between the Arabian and Central Iran Plates during the closing of the Neotethys Ocean (Alavi, 1994; Stocklin, 1968).

The Dezful Embayment is located in the southwestern part of the Zagros belt and was considered to be the foreland of Zagros. The Chamshir area is located in the southeastern part of the Dezful Embayment and near the border of the Izeh zone (Fig. 1). The central Zagros is subdivided from NE to SW into the part of High Zagros, Izeh zone and Dezful Embayment. The Dezful Embayment and Izeh zone are separated by the Zagros mountain front fault. The NW and SE boundaries of the embayment coincide with the Balarud and Kazerun faults, respectively. The Zagros mountain front fault is the NE boundary of the Dezful Embayment (Sherkati & Letouzey, 2004).

The Gachsaran Formation is the main detachment horizon in the foreland of Zagros (e.g. Sherkati et al., 2005; Tavakolian & Razavi Pash, 2022). The typical

**Table 1** Review on the effect of the Gachsaran Formation on the geometry of anticlines in Zagros

| References | Studied terrains | Outcomes |
|---|---|---|
| Bahroudi and Koyi (2004) | Zagros foreland basin | Differential propagation of the deformation front above the decollements (especially the Gachsaran Formation) with different mechanical properties (viscous vs. frictional) results in the along-strike irregularity of the Zagros deformation front |
| Sepehr et al. (2006) | Zagros fold-thrust belt | The folds above and below the incompetent units in the central part of the Zagros Folded Belt have significantly different geometries and wavelengths |
| Sherkati et al. (2005) | Central and Eastern Zagros fold-belt | Two main detachment levels in the Zagros are the Hormuz basal detachment and the Gachsaran upper detachment. Throughout the Zagros, detachment folds mainly developed during an initial thin-skinned phase of deformation. This was followed by the current thick-skinned stage |
| Sherkati et al. (2006) | Central Zagros fold-thrust belt | In the Zagros belt, the decollement levels are activated sequentially from deeper horizons to the shallower ones (as the Gachsaran decollement) |
| Tavakolian et al. (2022) | South Dezful Embayment | The lower–middle Miocene evaporites in the Gachsaran Formation decoupled the folded overlying succession from the underlying competent material, which includes the Asmari Formation reservoir |
| Tavakolian and Razavi Pash (2022) | Southern Dezful Embayment (Bibi-Hakimeh Anticline) | Asymmetric and disharmonic geometry of the Bibi-Hakimeh anticline is due to the forethrusting and backthrusting and the presence of the Gachsaran Formation as the detachment level |
| Razavi Pash et al. (2023) | North Dezful Embayment (Qaleh Nar, Lower and Upper Balarud Anticlines) | Changes in overburden pressure, rate of deformation and uplift in the different parts of the subsurface anticlines moved Gachsaran Formation towards both limbs of the anticlines |

section adopted from oil drillings in the Gachsaran area indicates that this Formation contains seven members (Fig. 2).

The folds in the Chamshir area are created in three parallel rows (Fig. 3). These three rows of anticlines from north to south are: (i) Se-Qanat–Sarab anticlines, (ii) Dara–Gachsaran anticlines and (iii) Chlingar–Garangan–Bidekarz anticlines.

Geologic Formations at the surface in the Chamshir area, from oldest to youngest are the different Members of the Gachsaran Formation (Early Miocene), Mishan Formation (Early-Middle Miocene), Aghajari Formation (Late Miocene–Pliocene) and alluvial sediments (Fig. 4).

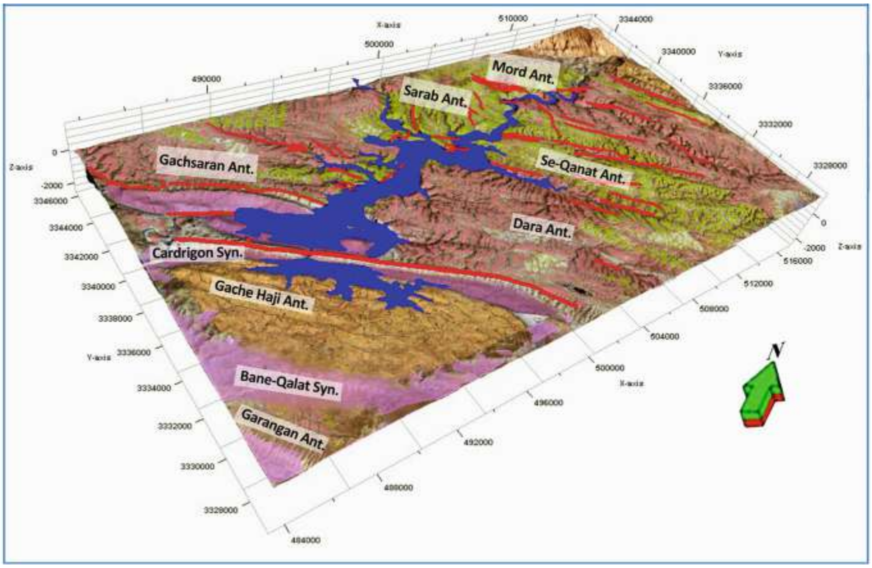


**Fig. 3** Location of the studied folds in the Chamshir area

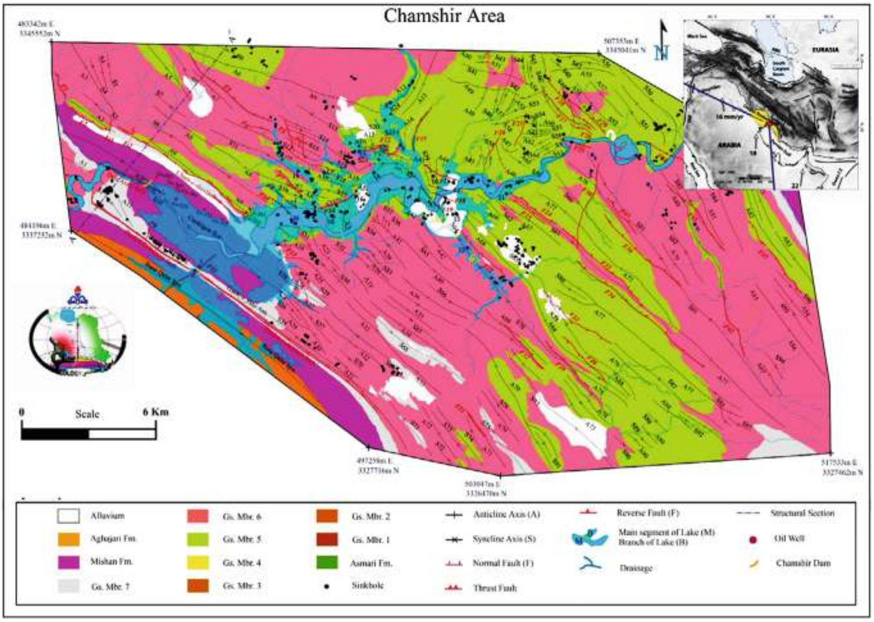


**Fig. 4** Geologic map of the Chamshir area. Line AA′ shows the location of cross-section AA′ prepared by the National Iranian South Oil Company (NISOC)

## 3 Structural Style in the Chamshir Area

To the interpretation of the geometry of the structure, a cross-section AA′ was prepared using surface and ~2500–3000 m deep subsurface data prepared by the National Iranian South Oil Company (NISOC). The AA′ section trends N38E and is ~15 km long (Fig. 4). The northern limb and the central core of the Bane Qalat syncline are located in the southern part of section AA′. The Aghajari and Mishan Formation in this syncline crop out (Fig. 5). On the northern side of the Bane Qalat syncline, the Gach Haji anticline has a low width with two steep and inclined limbs. In both limbs of this anticline, Member 7 of the Gachsaran Formation is exposed. In the hinge area of the anticline, Member 6 of the Gachsaran Formation crops out (Figs. 5 and 6). In this section, along the axial plane of the Gach Haji anticline, the Dezh Soleyman fault passes and uplifted Member 6 of the Gachsaran Formation. This steep fault (NE38/60) dies out in the detachment horizon of the Gachsaran Formation (Fig. 5). In the north of the Gach Haji anticline in section AA′, the Cardrigon syncline is asymmetric. The Mishan Formation crops out in the limbs and central part of this syncline. In the north of the Cardrigon syncline, in the northern part of the AA′ section, several large-scale anticlines and synclines (e.g. the A70 anticline and the S77 syncline) can be seen (Fig. 6c). Within these large-scale folds, called as the folded-faulted zone, disharmonic folds are formed on a smaller scale (Fig. 6d). Member 6 of the Gachsaran Formation has been removed from these anticlines, which shows the structural uplift of the folds in this section. Member 6 crops out as the limbs of the A70 anticline. Member 5 of the Gachsaran Formation is exposed in its central core at the surface. The steep reverse faults F3 and F4 have created the displacements in this folded zone (Fig. 5). The Chamshir fault is located between the Cardrigon syncline and the folded-faulted zone, which thrust Members 5 and 6 of the Gachsaran Formation on Member 7 of the Gachsaran Formation and the Mishan Formation on the northeastern side of the Cardrigon syncline (Fig. 6b).

## 4 Bane Qalat Syncline

This syncline extends ~17.5 km with a NW trend. Bane Qalat syncline is located between the Gach Haji anticline in the northeast and the Chlingar anticline in the southwest. The Bane Qalat syncline is a double plunging asymmetric fold. The dip of the northeastern limb ranges 30°–60° and the dip of the southwestern limb 15°–25°. Thus the dip of the northeastern limb is more than that of the southwestern limb. The surface outcrop of this syncline consists of the Mishan and Aghajari Formations. This syncline is also a mini basin.

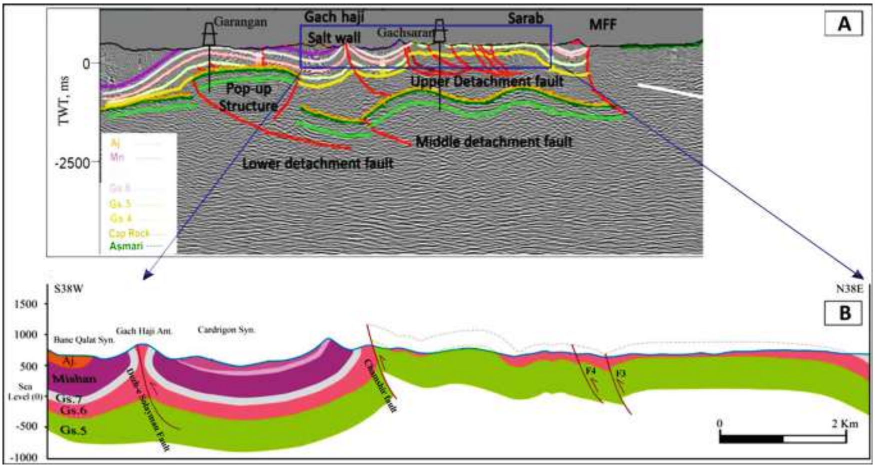


**Fig. 5** Regional cross-section AA′ in the Chamshir area. MFF: Zagros Mountain Front Fault

## 5 Gach Haji Anticline

The Gach Haji anticline is ~18 km long with a NW trend. It is located in the northeast of the Bane Qalat syncline. The Gach Haji anticline is one of the unique features in the Chamshir area. The structure of the Gach Haji anticline is a salt wall affected by the Dezh Soleyman thrust. The anticline is divided into three parts at northwest, middle and the southeast.

The middle part of the Gach Haji anticline can be considered as a salt wall. The southeastern part of the Gach Haji, like the northwestern part, is a salt-cored fold. The core is formed by the salts of the Member 6 of the Gachsaran Formation. In general, the shape of the Gach Haji anticline changes significantly from the surface to the depth, which can be recognized as changes in the structural style of the anticline. The core of the Gach Haji anticline is the salts of Member 6 of the Gachsaran Formation. The anticline is symmetric and fan-shaped. Its northeastern and southwestern limbs are very steep and overturned.

### *5.1 The Northwestern Part of the Gach Haji Anticline*

This part of the anticline is ~2.5 km long. It has a single-fold axis and it is a non-cylindrical fold. This part of the anticline actually consists of two anticlines and an intermediate syncline. This part of the anticline is an asymmetric fold. Its southwest limb has dip 40°–50° and its northeast limb has 25°–30° dip**.** The surface outcrop of this part of the anticline is Members 6 and 7 of the Gachsaran Formation. Member 6 covers the axial zone of this part (Fig. 7a, b). The difference in folding style in the

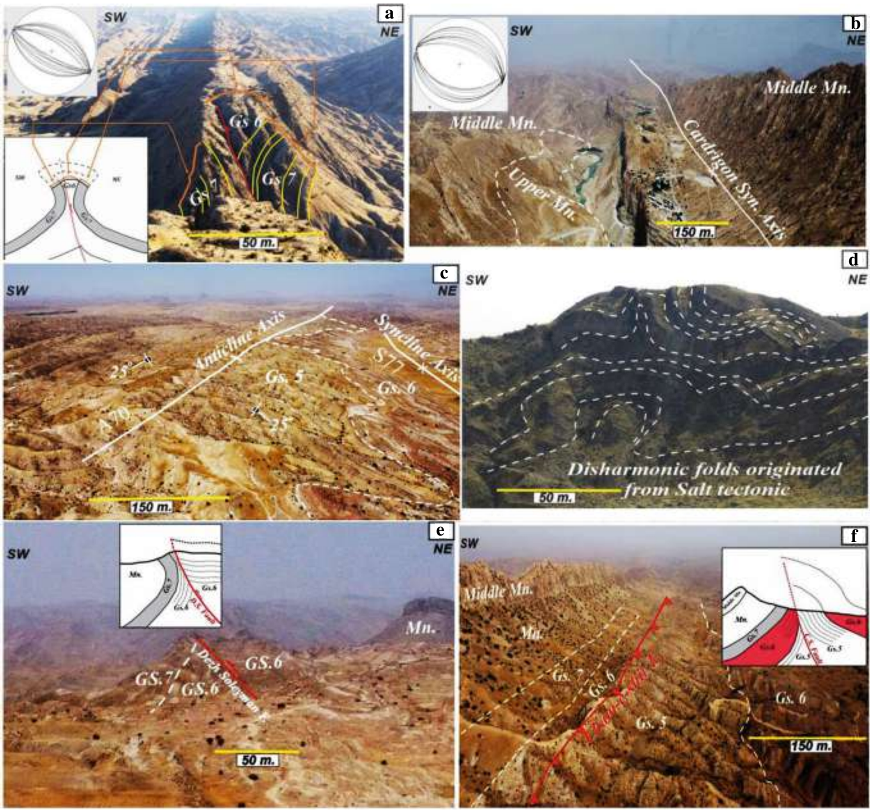


**Fig. 6** Satellite images and field photos of the Chamshir area. **a** Satellite image of the Gach Haji anticline, **b** satellite image of the Cardrigon syncline along with, **c** satellite image of the folded and faulted region in the northeastern part of the Chamshir area, **d** field photo of disharmonic folds within the large-scale folds in the folded and faulted region, **e** satellite image of the Dezh Soleyman fault, **f** satellite image of the Chamshir fault. Gs.5-7 are Members 5–7 of the Gachsaran Formation, respectively

core of the Gach Haji anticline (Member 6) and its outer cover (Member 7) is caused by the presence of salt and its rheological property (Fig. 7c, d).

## 5.2 *The Middle Part of the Gach Haji Anticline*

This part of the anticline is ~7 km long, has a very narrow axial zone, symmetric and has a fan shape. Its northeastern and southwestern limbs are very steep and overturned. The surface outcrop of this part is formed from Members 6 and 7.

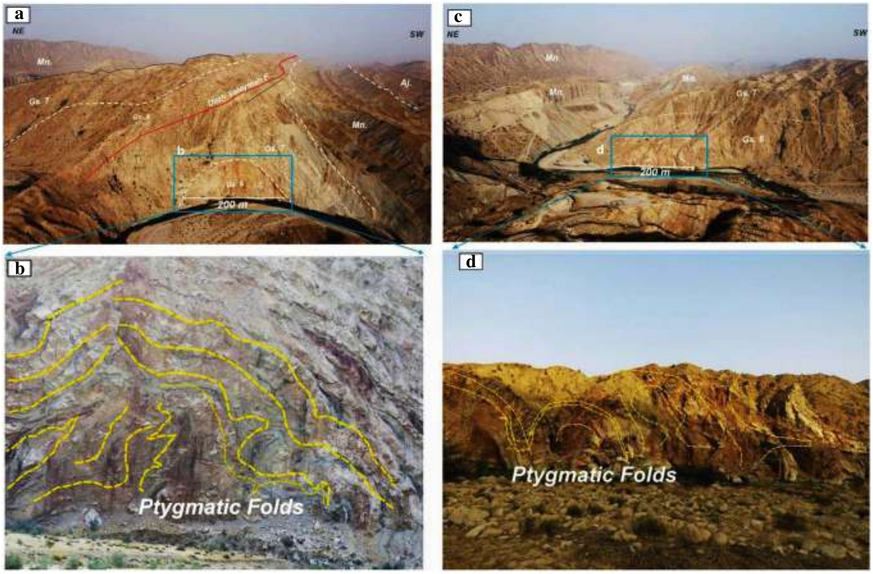


**Fig. 7** Gach Haji anticline (view towards the SE). **a** The southern part of the Gach Haji anticline. The core of the anticline is made of Member 6 of the Gachsaran Formation and the Dezh Soleyman fault, the overthrust of Member 6 of the Gachsaran Formation on Member 7 in the axial zone of the anticline happened. **b** The core of the southern part of the Gach Haji anticline and the disharmonic folds were created due to the presence of salt (the layers of Member 6 of the Gachsaran Formation). **c** The northern part of the Gach Haji anticline and Cardrigon syncline. **d** The core of the northern part of the Gach Haji anticline with Member 6 of the Gachsaran Formation and the disharmonic folds in its anhydrite-marl layers of the Gachsaran Formation

### *5.3 Southeastern Part of the Gach Haji Anticline*

In this part, the southwest limb is covered by Member 7 of the Gachsaran Formation, and the axial area is mostly covered by Member 6 of the Gachsaran Formation. Member 7 of the Gachsaran Formation in this part contains secondary folds. Member 6 of the Gachsaran Formation, which contains salt layers, is strongly folded.

## 6 Dezh Soleyman Fault

It is a reverse fault with 125° trend and ~16 km long along the Gach Haji anticline. The Dezh Soleyman fault passes through almost the hinge zone of the Gach Haji anticline. The dip of the fault plane is high (50°–70°) with a dip direction towards NE. With increasing depth, the dip of the fault gradually decreases. Most likely, it dies out in the salts (Members 2–4) of the Gachsaran Formation. The movement components of this fault are reverse and strike-slip. Its reverse component of this fault has caused

Member 6 of the Gachsaran Formation to be overridden on Member 7 in the axial zone of the Gach Haji anticline (along the entire length of this anticline).

## 7 Cardrigon Syncline

The syncline is ~11.5 km long and up to ~2.5 km wide. The fold axis trends 128° (NW–SE). The surface outcrop along the entire length of the Cardrigon syncline is the Mishan Formation. A normal fault is observed in the centre of this syncline (Fig. 8). At the southeast end of the Cardrigon syncline is the Mishan Formation exposed, Members 6 and 7 of the Gachsaran Formation (Fig. 9). In this place, Member 7 of the Gachsaran Formation consists of five zones (Z1-5, anhydrite, grey marl, anhydrite, grey marl and anhydrite, respectively).

## 8 Chamshir Fault

This fault with NW–SE trending can be traced on the northeastern limb of the Cardrigon syncline (Fig. 5). The Chamshir fault with ~65° dip and NE dip direction, like the Dezh Soleyman fault, can be considered as a reverse fault with a strike-slip component. The dip of the fault gradually decreases vertically down so that probably in the salty members of the Gachsaran Formation turns into a flat. On the surface, the effect of this fault is clearly evident, so that the fault has caused Member 5 of the Gachsaran Formation to be overthrusted on Member 6 of the Gachsaran Formation (at other places on Member 7).

To investigate the mentioned anticlines of the Chamshir area, four cross-sections with the northeast-southwest trend were prepared from different parts of the Chamshir area (Fig. 10). In the NE side of the Cardrigon syncline, there are Gachsaran, Sarab, Dara and Se-Qanat anticlines. In general, the thickness of the Gachsaran Formation in the northeast part of the Chamshir area (near the Zagros Mountain front fault) is more than in the southwest. Structural geometry is more complicated in the southwest of the Chamshir than at NE (Fig. 10).

## 9 Other Structures in Chamshir Area

There are several anticlines and synclines in the Chamshir area (Fig. 4). These folds are named as A1-90 for anticlines and S1-96 for synclines in the geologic map (National Iranian South Oil Company (NISOC) (Fig. 4).

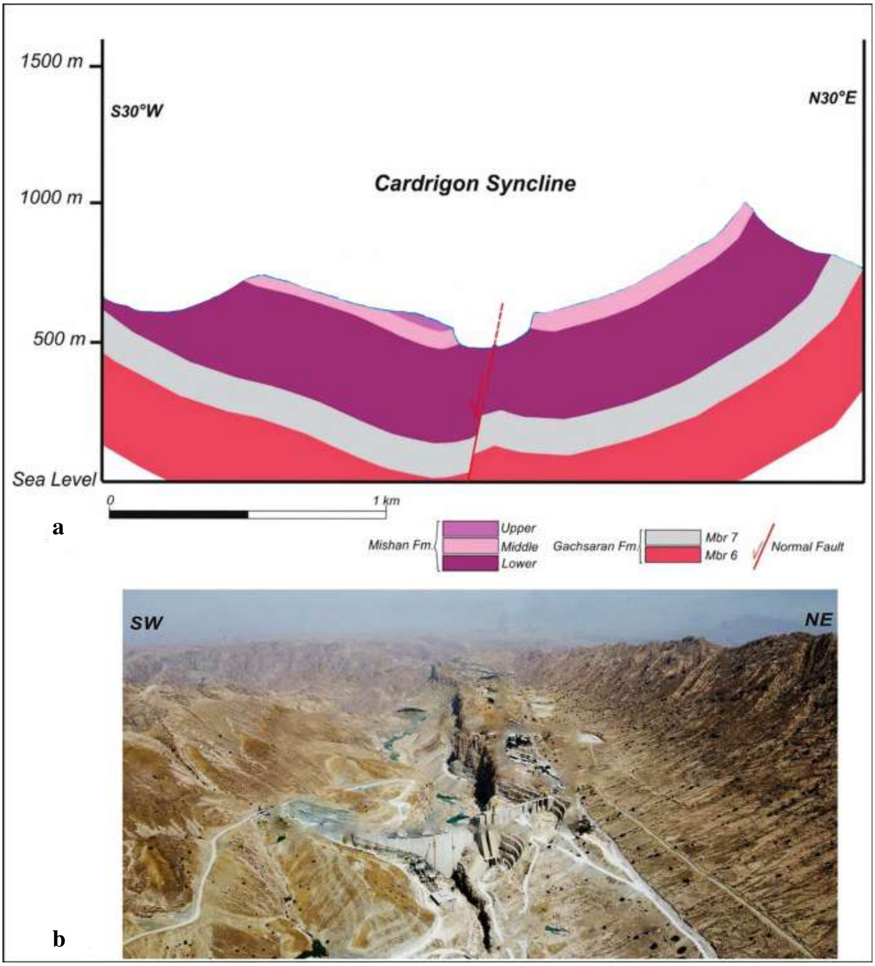


**Fig. 8** Cross-section of the Cardrigon syncline (**a**) and satellite image of this syncline (**b**) presented in this study

## *9.1 Anticline A9*

It is located in the vicinity of the northern wall of the Zohreh River. In this anticline, Members 5 and 6 of the Gachsaran Formation are exposed (Fig. 11). Member 6 of the Gachsaran Formation has been completely removed at the axial zone of the fold due to erosion, and Member 5 of the Gachsaran Formation crops out. In this asymmetric fold, the southwestern limb has a greater dip (38° towards the southwest) than the northeast one (20° towards the northeast). The trend of the axis of this anticline is 128E. Several small-scale folds occur in the axial zone and limbs.


**Fig. 9** SE end of the Cardrigon syncline (view to north). Here, Mishan Formation (Mn), Member 7 and Member 6 of the Gachsaran Formation are clearly distinguishable. Member 7 of the Gachsaran Formation consists of five zones (Z1 to Z5), anhydrite, grey marl, anhydrite, grey marl and anhydrite, respectively. Gs.6 and Gs.7 are Member 6 and Member 7 of the Gachsaran Formation, respectively. Z1–Z5: Zone 1–Zone 5

### *9.2 Anticline A18*

It is located in the NW part of the Chamshir area. In this anticline, Member 6 of the Gachsaran Formation is exposed (Fig. 12). Both the limbs and the axial zone of this anticline at the surface are composed of Member 6. This anticline is asymmetric that has a greater dip (60° to the northeast) than the southwest one (25° to the southwest). The trend of the axis of this anticline is 111E. The northeastern limb of this anticline is cut by a thrust (F4 with a dip towards the northeast). An unnamed smaller-scale anticline has been cut by this fault on the northeastern limb of the anticline A18.

### *9.3 Anticline A24*

It is located in the Gachsaran area. Members 5 and 6 of the Gachsaran Formation are exposed (Fig. 13). In this asymmetric anticline, the northeast limb has a greater dip (56° to the northeast) than the southwest limb (23° to the southwest). The trend of the axis of this anticline is 133E. In the axial zone and limbs of this anticline, several smaller-scale folds are observed.

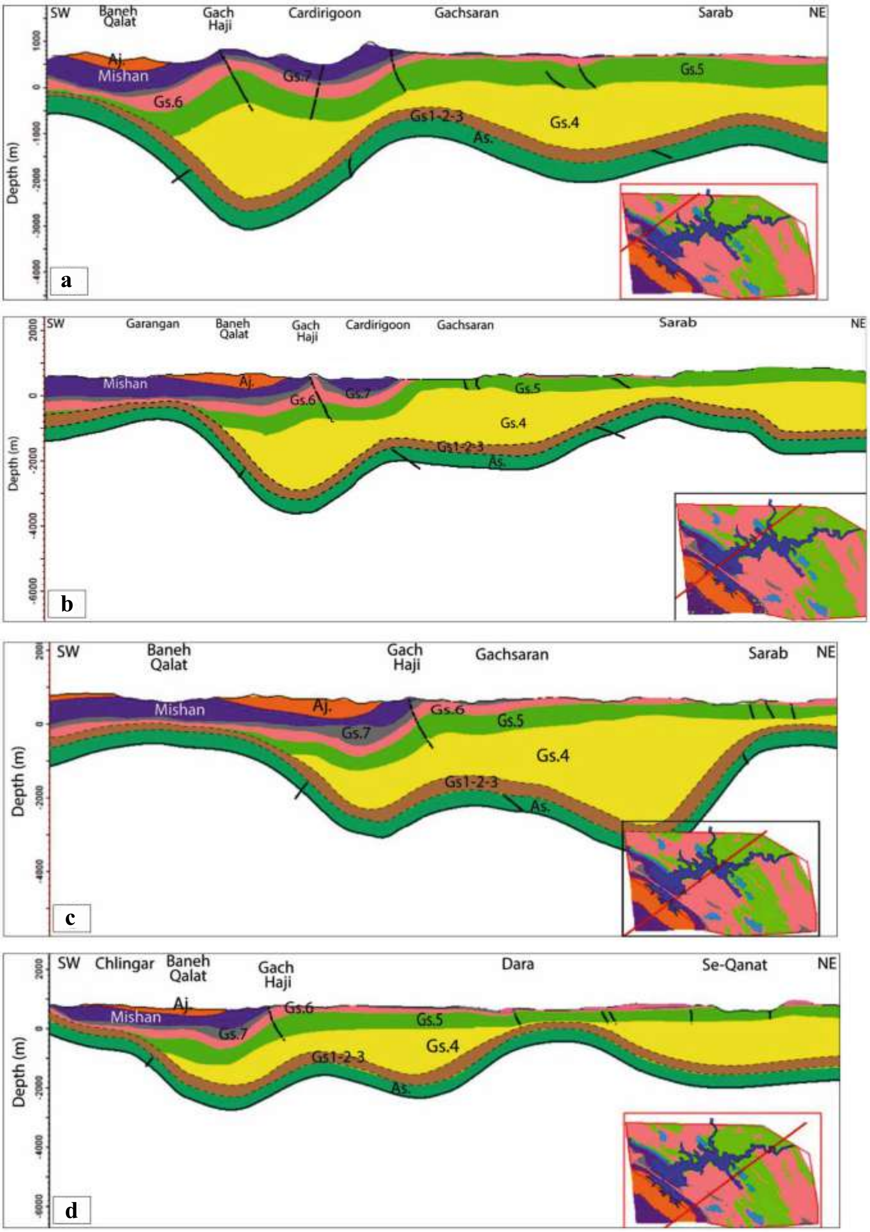


**Fig. 10** Cross-sections of the Chamshir area. The location of these cross-sections is shown by the red line in the right corner at the bottom of each cross-section on the geologic map. **a** Cross-section of Bane Qalat–Sarab anticlines, **b** Cross-section of Karangan–Sarab anticlines, **c** Cross-section of Bane Qalat–Sarab anticlines, **d** Cross-section of Chlingar–Se-Qanat anticlines. Aj: Aghajari Formation, Gs.1–Gs.7: members (1–7) of the Gachsaran Formation, As: Asmari Formation. Prepared by using fieldwork data, interpretation of seismic profiles, well data, geologic maps and Petrel software (version 2014). Gs.1-7: Members 1–7 of the Gachsaran Formation

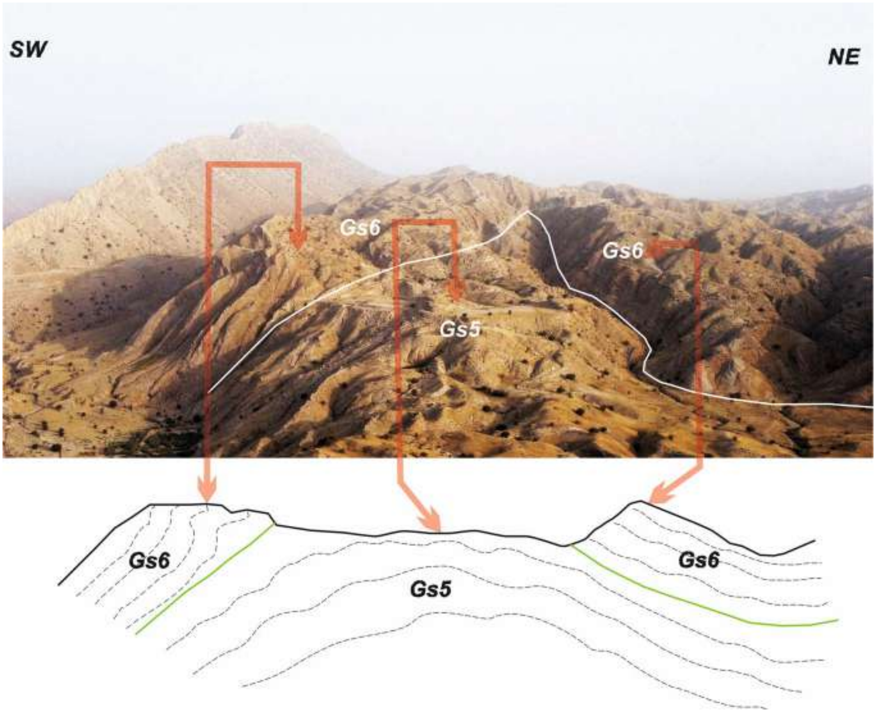


**Fig. 11** Anticline A9 in the vicinity of the northern wall of the Zohreh River (view to the northwest). Member 6 of the Gachsaran Formation (Gs.6) has been completely removed from the axial zone of the fold due to erosion, and Member 5 of the Gachsaran Formation (Gs.5) is visible at the surface. In the back side of the image, Member 6 of the Gachsaran Formation also occurs in the axial zone in addition to the limbs. Member 5 is not exposed along the anticline. Gs.5 and Gs.6 are Members 5 and 6 of the Gachsaran Formation

## *9.4 Anticline A70*

It is located in the southern part of the study area. Members 5 and 6 of the Gachsaran Formation are exposed (Fig. 14). At the surface, limbs are formed from Member 6 and the axial zone of the anticline is formed from Member 5 of the Gachsaran Formation. In other words, Member 6 has been removed from the axial zone of the anticline, but it remains on the limbs. In this relatively asymmetric anticline, the northeast limb has a greater dip (29° to the northeast) than the southwest edge (20° to the southwest). The trend of the axis of this anticline is 139E. In the axial zone and limbs of this anticline, several smaller-scale folds are observed.

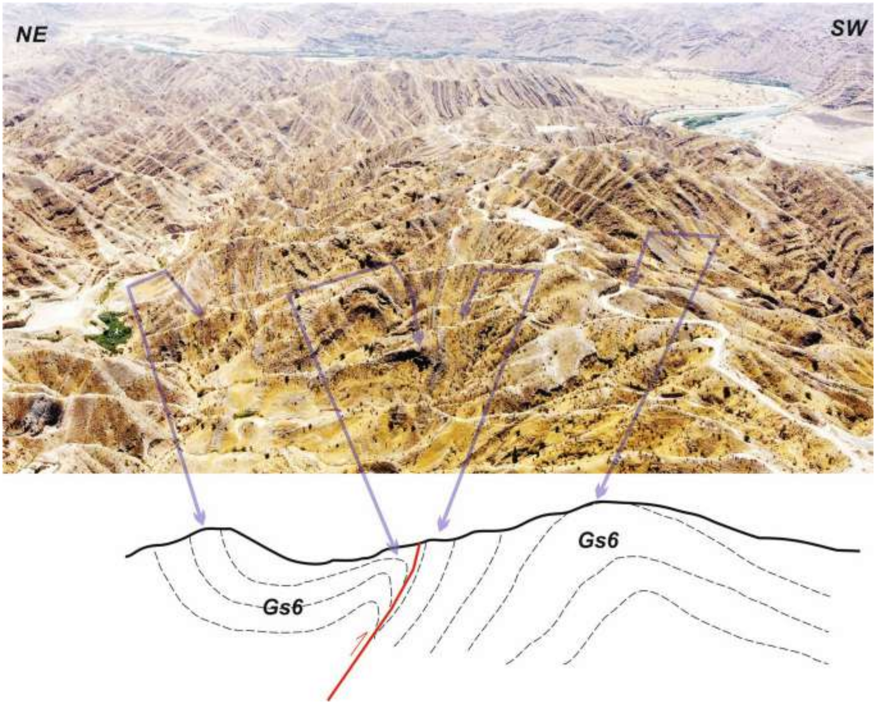


**Fig. 12** Anticline A18 (right side of the image), view to the southeast. Gs.6: Member 6 of the Gachsaran Formation

## *9.5 Anticlines A61 and A62*

Folds A61 and A62 are located in the northeast part of the studied area (south of Pakuh village). Only Member 5 of the Gachsaran Formation has been exposed at the surface in these two anticlines (Fig. 15). Both the limbs and the axial zone of both anticlines constitute Member 5. Between these two anticlines, the in between syncline cannot be distinguished, and the anticline (on the northeast side) is overthrust by a fault on the anticline on the southwest side. The trend of the axis of these anticlines is 110E.

## *9.6 Anticline A58 and Syncline S52*

Anticline A58 and syncline S52 are located in the northeast of the study area (south of the Pakuh village). Outcrop in the anticline is the Member 5 of the Gachasaran Formation and in the syncline is the Member 6 of the Gachesaran Formation (Fig. 16). In the anticline, Member 6 of the Gachsaran Formation has been completely eroded. The anticline is an asymmetric fold where the southwest limb is steeper (68° to

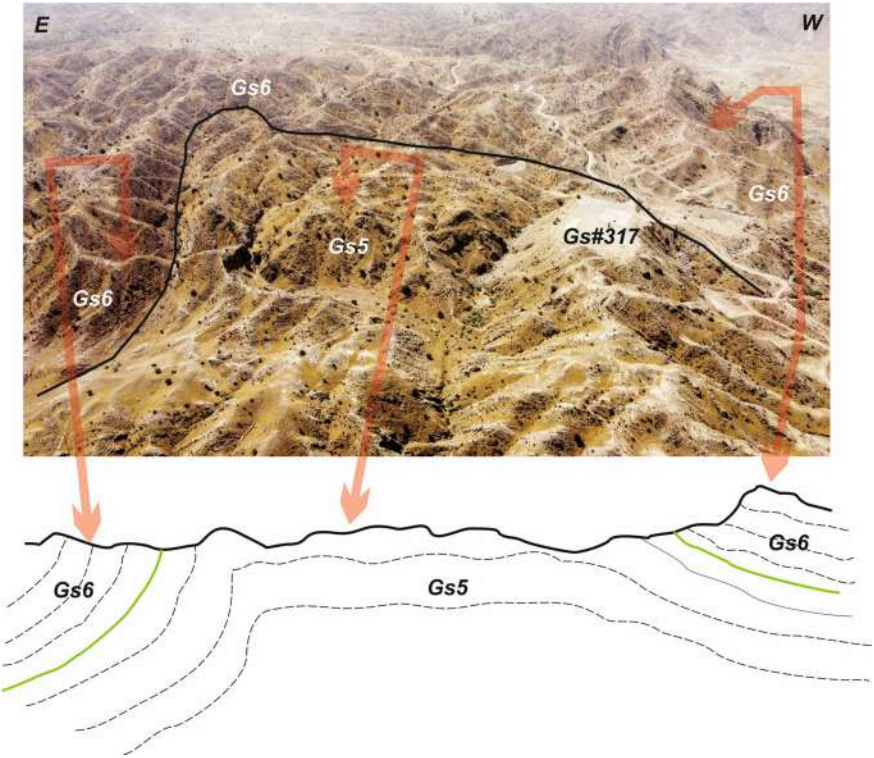


**Fig. 13** Anticline A24 in the Gachsaran area (view to the southeast). In front of the image, member 6 of the Gachsaran Formation has been completely removed from the axial zone of the fold due to erosion, and Member 5 of the Gachsaran Formation is visible on the surface, but in the back of the image, Member 6 of the Gachsaran Formation is also present in the axial zone in addition to the limbs, and Member 5 has not been exposed along the anticline. Gs $\neq$ 317 is a drilled well. Gs.5 and Gs.6 are Members 5 6 of the Gachsaran Formation, respectively

the southwest) than the northeast limb (39° to the northeast). The syncline, which is located in the northeast of the anticline, is almost asymmetric, and its southwest limb (32° to the northeast) is steeper than the northeast limb (18° to the southwest). The trend of the axis of this anticline and its adjacent syncline is 130E. In the southwestern limb of the anticline are observed several smaller-scale folds.

## *9.7 Anticline A43*

Anticline A43 is located near the intersection of the Delvar Haft Dasht drainage with the Zohreh River. Here, Member 5 of the Gachsaran Formation has a surface outcrop (Fig. 17). The fold is generally asymmetric, where the southwest limb is wavy but

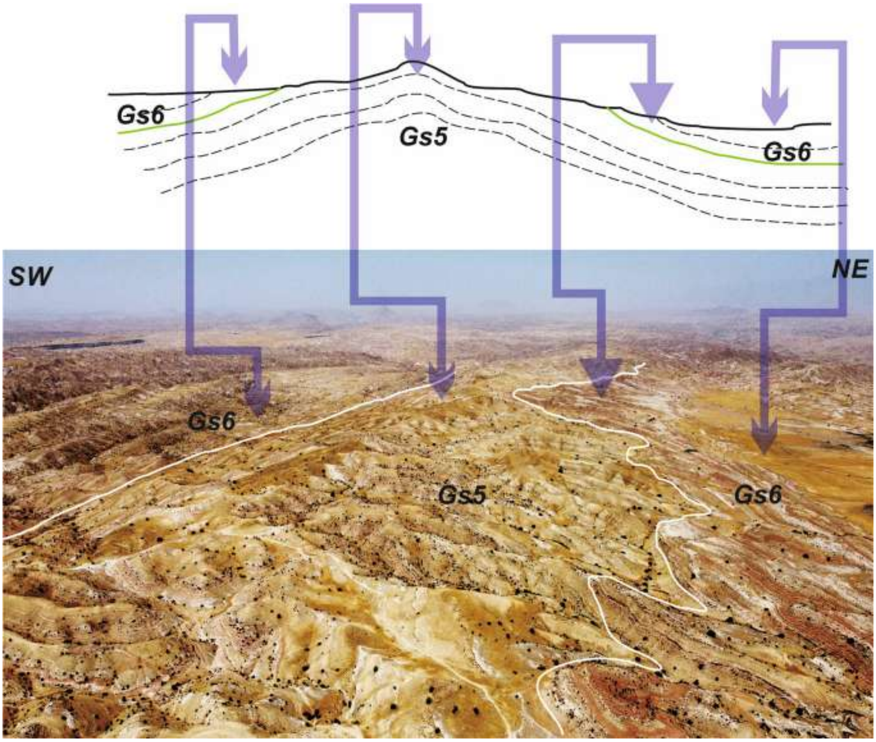


**Fig. 14** A70 fold at the southern part of the study area (view to the northwest). Among the stratigraphic units involved in folding, members 6 and 5 of the Gachsaran Formation (Gs.6 and Gs.5) are exposed here at the surface. Gs.5 and 6 are Members 5 and 6 of the Gachsaran Formation, respectively

overall sub-vertical, and the dip of the northeast limb is 48° to the northeast. With a closer look at all parts of this fold, smaller-scale folds can be recognized. In addition, thrust faults can be seen on the northeast limb of the anticline. The trend of the axis of this anticline is about 160E.

## *9.8 Folded Area in the Se-Qanat Area*

In a general view, a folded area in the Se-Qanat area can be considered a large-scale fold that contains several smaller-scale folds. In the northeast and the southwest limbs of this large-scale fold, Member 6 of the Gachsaran Formation is exposed at the surface. The middle part of the anticline is folded in a more intricate way. Member 6 has been completely removed due to erosion, and Member 5 of the Gachsaran Formation is exposed (Fig. 18). In Fig. 18, in the profile drawn, four smaller-scale anticlines can be recognized in the core consisting of the member 5 in the large-scale

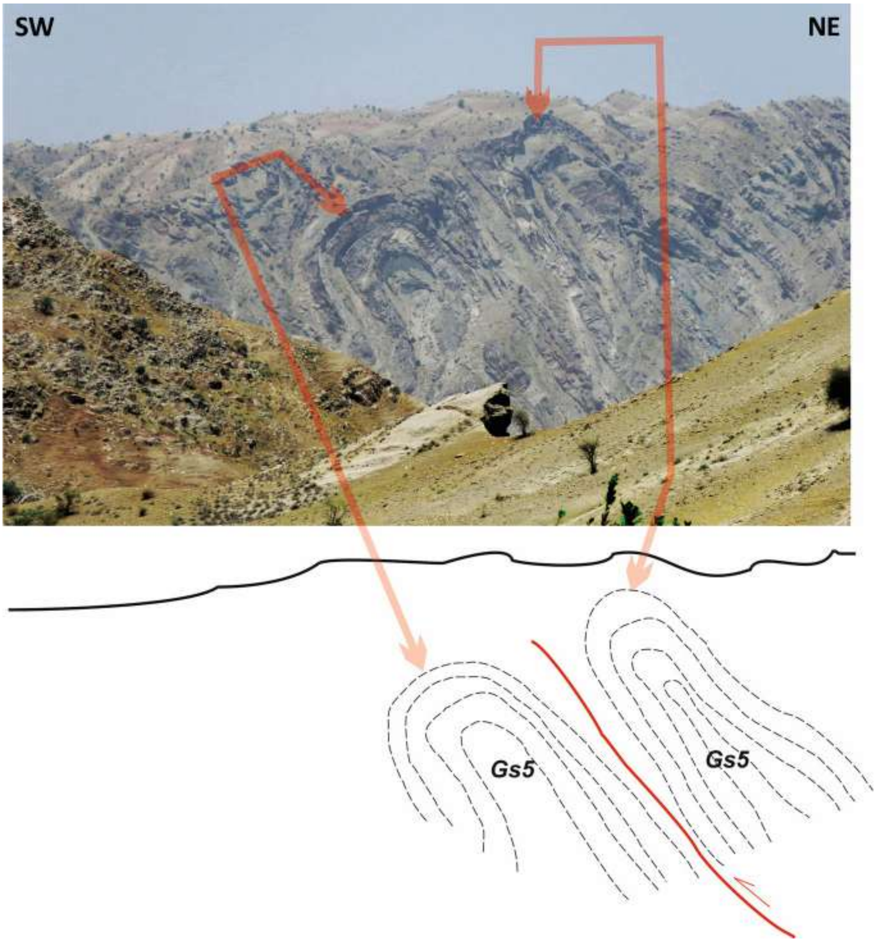


**Fig. 15** A photo of the two anticlines A61 and A62 in the northeast of the studied area, view towards the northwest. Gs.5: Member 5 of the Gachsaran Formation

anticlines. The anticline located at the end left (southwest) of the profile corresponds to the anticline A68, and the one located at the extreme right (northeast) of the profile corresponds to the anticline A66.

## *9.9 Anticline A12*

It is located in the north part of the study area around the Sarab drainage. In this anticline, the difference in colour tone between members 5 and 6 of the Gachsaran Formation, which are exposed at the surface, can be seen (Fig. 19). The axis trend

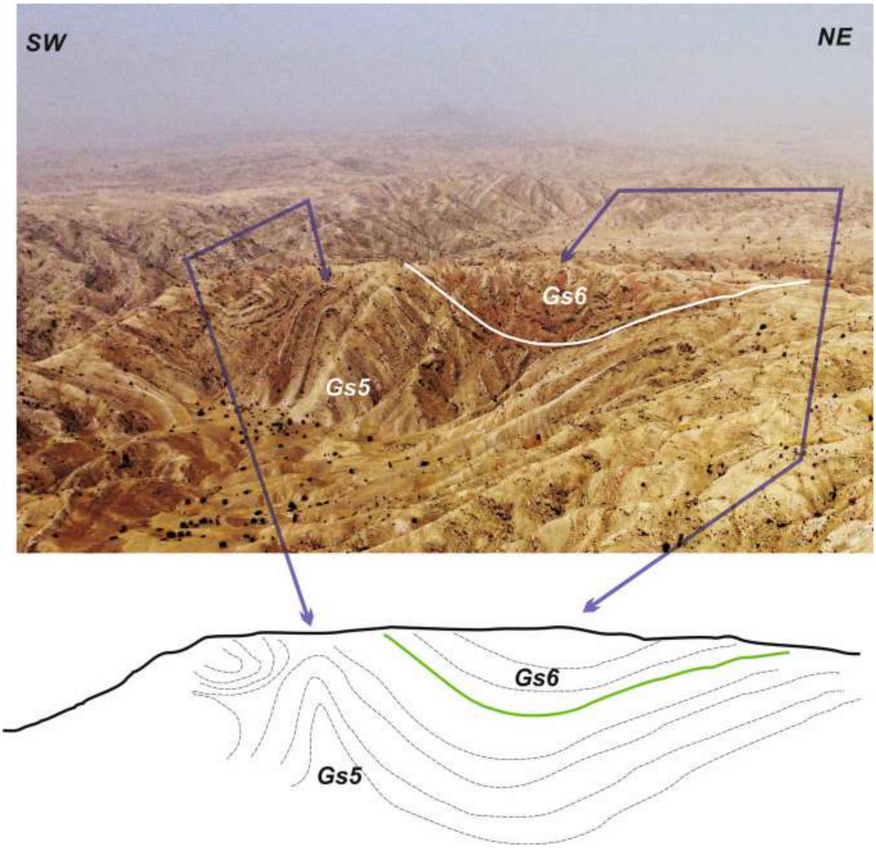


**Fig. 16** A photo of the anticline A58 and the syncline S52 in the northeast of the study area, view to the northwest. Gs.5 and Gs.6 are Members 5 and 6 of the Gachsaran Formation, respectively

of this anticline, unlike most of the anticlines of the folded-thrust zone in the study area, is NNE-SSW.

## *9.10 Small-Scale Faults*

The small-scale faults are observed in the northwest part of the study area. Figure 20 shows a normal fault. This normal fault is observed at the successive layers of grey marl, anhydrite and red marl belonging to Member 6 of the Gachsaran Formation. In this sequence, minute fractures can be recognized with the naked eye.

**Fig. 17** A43 near the intersection of the Delvar Haft Dasht drainage with the Zohreh River, view towards the northwest

## 10 Discussions

One of the requirements of the oil industry for the exploration and drilling of hydrocarbon reservoirs is to identify the geometric complexity of the structures and study the behaviour of the intermediate detachment horizons in the fold-thrust belts, such as the Zagros belt in Iran (O'Brien, 1957; Farzipour-Saein et al., 2009; Sherkati et al., 2006) and in Iraq (e.g. Aqrawi et al., 2010a, 2010b), and the Canadian Rocky Mountain (Cooper et al., 2004). The folding style is largely caused by changes in the mechanical characteristics of the sedimentary layers through the folding process (Cotton & Koyi, 2000; Spratt et al., 2004; Vergés et al., 2011).

The Chamshir area located in the Dezful Embayment has many structural complications that have been investigated in this research. In the studied area, the Gachsaran Formation (caprock of the Asmari reservoir) is a detachment horizon. In the Dezful Embayment, (thrust) faults are divided into two categories as per their locations. (i) Faults in the outcrop part of the studied area and often continue to the top of the Member 4 of Gachsaran, such as the Chamshir, Dezh Soleyman, F3 and F4 faults. The faults that have originated from the top of the Asmari Formation to the incompetent Triassic Formations. These deep faults have originated from older detachment surfaces. The same has been observed from the other parts of the Dezful Embayment (Sherkati & Letouzey, 2004; Tavakolian et al., 2022). In general, thicker incompetent units can create more effective structural detachments (Bahroudi & Koyi, 2004; Simpson, 2009; Stewart, 1996). The changes in the thickness of the Gachsaran Formation along the reflection seismic sections indicate the performance of the Gachsaran Formation as a detachment horizon.

Salt diapirs have flowed as salt masses, in a ductile style (Mukherjee et al., 2010), and they seem to penetrate the sedimentary cover disharmonically (Jackson & Talbot,

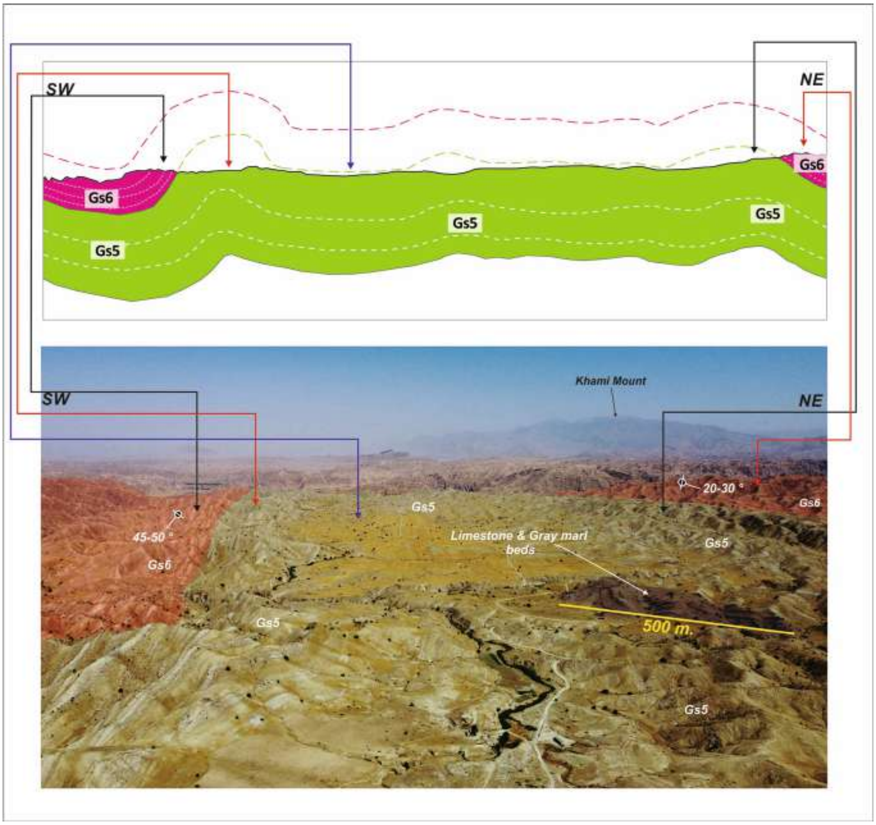


**Fig. 18** Folded terrain in the Se-Qanat area in the study area, view towards the northwest. The anticline located at the end left (southwest) of the profile corresponds to the anticline A68, and the one located at the extreme right (northeast) of the profile corresponds to the anticline A66. Gs.5 and 6: Members 5 and 6 of the Gachsaran Formation

1991). Between the two subsurface anticlines of Gachsaran and Garangan, due to compression and the movement of the Gachsaran Formation, the Gach Haji anticline is formed. This anticline is not formed in Formations older than Gachsaran. The Gachsaran Formation in the Gach Haji anticline has been squeezed and Member 6 is raised and therefore crops out. The anticline shows a salt wall structure affected by the Dezh Soleyman thrust fault. The presence of the Cardrigon and Bane Qalat synclines as mini basins on both sides of the Gach Haji anticline has caused insufficient space for salt emplacement of the Gachsaran Formation between these two synclines. This caused upward salt movement along the fault. Thus Member 6 of the Gachsaran Formation moves outward as a salt wall.

Based on the interpretation of seismic profiles, an outcrop of Members 5–7 of the Gachsaran Formation in the Chamshir area was observed at the surface. In the Chamshir, tectonics of the region folded, uplifted and cropped out Members 5 and 6

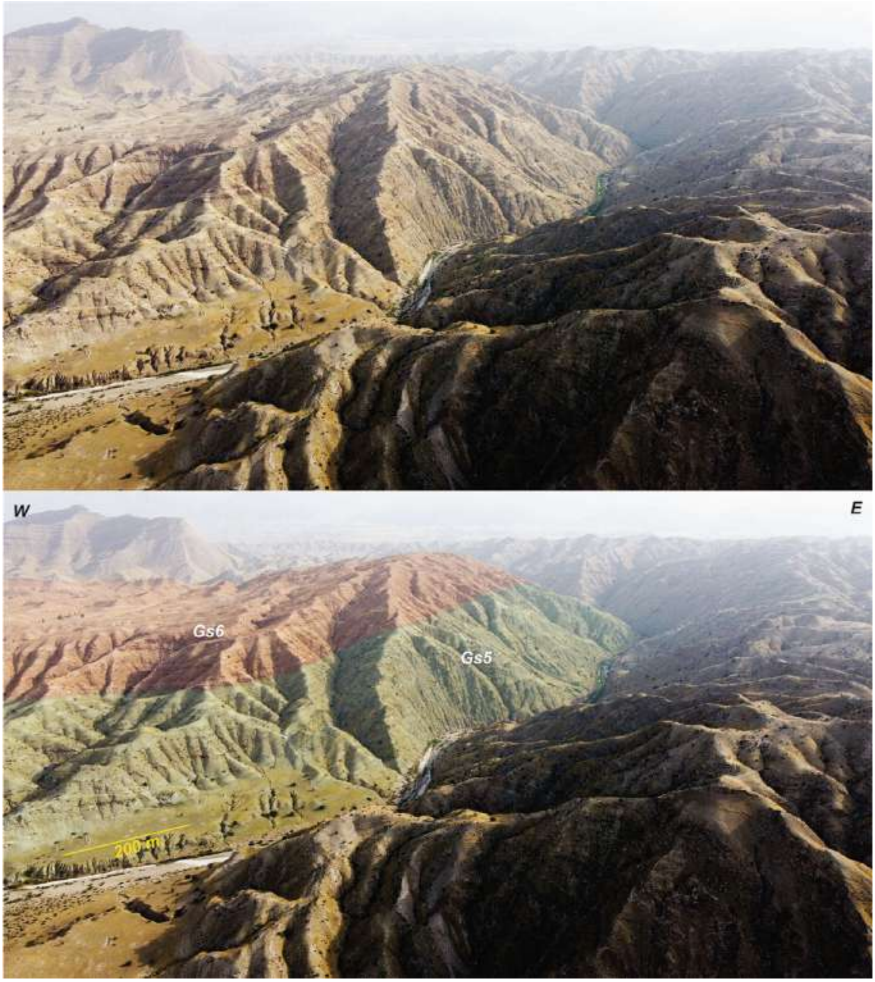


**Fig. 19** Northwest limb of the anticline A12 in the north part of the study area, view towards the north. Gs.5 and Gs.6: Members 5 and 6 of the Gachsaran Formation

of the Gachsaran Formation. Folding in the study area produced a series of anticlines and synclines. Towards the NE, younger portions of the Formation (Members 6, 7 and partly 5) have been removed.

Member 4 of the Gachsaran Formation had insignificant ductility and created a detachment level in the Gachsaran Formation, especially in the synclinal areas. Also, evidence of a large salt wall structure can be seen in seismic profiles in the Gach Haji anticline. This structure is formed by faulting and the rising of Members 5 and 6 salts of the Gachsaran Formation. Member 6 of the Gachsaran Formation was exposed.

In the NE of the Cardrigon syncline, the Gachsaran Formation has been folded and eroded due to shortening. This folding has appeared in a wide area, which includes

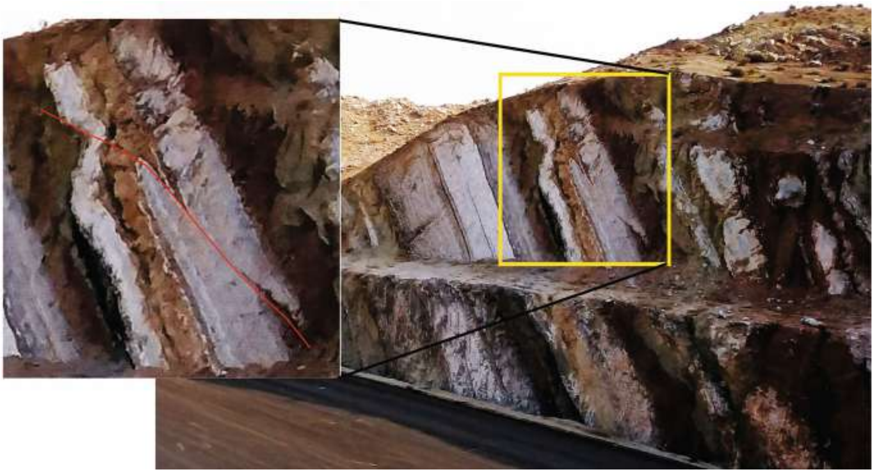

**Fig. 20** Close-up view of a small-scale (normal?) fault at the NW part of the study area

several large-scale anticlines and synclines and hundreds of disharmonic and small-scale folds, while the Gachsaran Formation in the Garangan anticline, like many anticlines of the Dezful Embayment, is deformed to folds of different shapes.

The faults seen in the exposed part of the studied area often continue to the top of the Member 4 (Gs.4) of the Gachsaran Formation, such as the Dezh Soleyman, Chamshir and along the F4 and F3 faults. A second category of faults developed from the top of the Asmari Formation to the approximate depth of the Triassic-Jurassic Formations. In other words, a thick layer of the evaporate Member of the Gachsaran Formation (Gs.4), as a detachment layer, has caused the structural style to be separated in the upper and lower layers (Fig. 21).

Based on the interpretation of seismic profiles and their correlation to the geological map and field data of the region, there is a good match between the surface and subsurface information in the Chamshir area, especially in relation to the spreading of different Members of the Gachsaran Formation at the surface (Fig. 22).

## 11 Conclusions

The Gachsaran Formation is the main detachment horizon in the Foreland basin of Zagros. As a detachment horizon, this Formation separates structural features and folding style in its overlaying and underlying units. The presence of a thick layer of Gachsaran Formation has affected the structural style in the Chamshir area. In the Chamshir area, Members Gs.5-7 of the Gachsaran Formation are exposed at the surface. The salt Members of the Gachsaran Formation are ductile and deformed to several secondary folds. Based on surface and subsurface data, the area has two

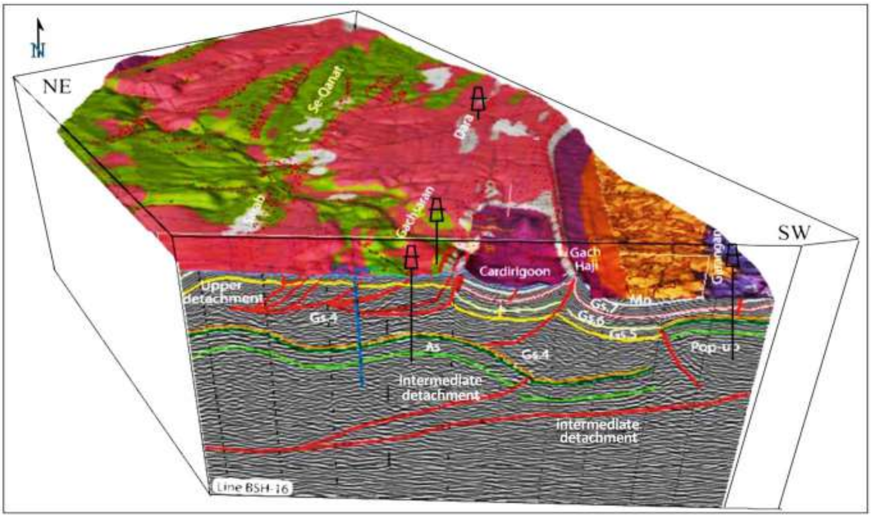


**Fig. 21** 3D model of the Chamshir area based on surface and subsurface data using Petrel software (v. 2014). Two categories of faults are shown—(1) those extending from the surface to the top of Member 4 (Gs.4) of the Gachsaran Formation and (2) those developed from the top of the Asmari Formation to the approximate depth of the Triassic-Jurassic Formations. Gs.4 to Gs.7 are Members 4 to 7 of the Gachsaran Formation, respectively

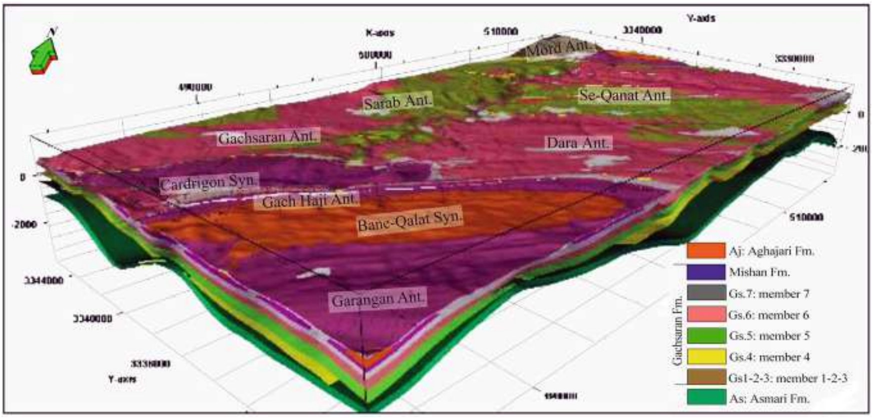


**Fig. 22** 3D model of the studied area in the Chamshira region from the base of the Asmari Formation to the surface

types of faults. The faults in the exposed part of the studied area often continue to the top of Member 4 (Gs.4) of the Gachsaran Formation, such as the Dezh Soleyman, Chamshir, F3 and F4 faults. The second category of faults developed atop the Asmari Formation to the approximate depth of the Triassic-Jurassic Formations. In other words, a thick layer of the evaporate member of the Gachsaran Formation (Gs.4), as a main detachment layer, has caused the structural style to be separated in the upper and lower layers in the Chamshir area.

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