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FORELAND PROPAGATION OF FOLDING AND STRUCTURE OF THE MOUNTAIN FRONT FLEXURE IN THE PUSHT-E KUH ARC (ZAGROS, IRAN)

Hadi Emami, 2008

Chapter 2

FOLD SHAPE ANALYSIS AND STRUCTURAL INTERPRETATION OF ZANGUL ANTICLINE IN PUSHT-E KUH ARC LURESTAN AREA (ZAGROS, IRAN)

2. FOLD SHAPE ANALYSIS AND STRUCTURAL INTERPRETATION OF ZANGUL ANTICLINE IN PUSHT-E KUH ARC LURESTAN AREA (ZAGROS, IRAN):

2.1 Introduction

The Zagros fold and thrust belt in Iran is known for spectacular anticlines that display whaleback geometries. In Pusht-e Kuh Arc these folds display a large variation of geometries and fold dimensions, whose interpretation at depth is difficult due to the little structural relief and the lack of the good seismic profiles. This mountain belt in Iran is formed by fold trains involving the Proterozoic to recent sedimentary cover with a thickness of 6-11 Km (Stöcklin, 1968; Colman-Sadd, 1978). Structural geologists have interpreted these folds as detachment folds (Colman-Sadd, 1978; Alavi, 1994; Mitra, 2003; McQuarrie, 2004; Molinaro et al., 2004; Sherkati and Letouzey, 2004; Sherkati et al., 2006) Recent works on the Zagros (Blanc et al., 2003; McQuarrie, 2004; Molinaro et al., 2004; Sherkati and Letouzey, 2004; Sherkati et al., 2006) have tried to understand the geometry, style of the fault-related folding and its relation to detachment levels across the Zagros fold belt through the construction of regional cross-sections based on field data, geological maps, seismic and well data. These interpretations are based on regional-scale reconstruction rather than on study of specific anticlines. Sherkati and Letouzey (2004) and Sherkati et al. (2006) attribute the complexity of the structural geometries to the role of the intermediate detachment horizons. In the stratigraphic succession of the Zagros fold and thrust belt there are different incompetent units, which work as detachment horizons during fold evolution. All of the present models postulate a basal detachment in Hormuz salt at the base of the thick sedimentary sequence of the Zagros fold belt. Sherkati et al. (2006) document different detachment levels in central Zagros using analogue models. These authors concluded that the position of the intermediate detachments is the main factor controlling both structural style and fold wavelength as also proved in Vergés et al. (in press). The anticlines in Pusht-e Kuh Arc are exposed at the level of different stratigraphic levels showing complicate geometries at their terminations. These exposed levels are the upper Cretaceous Sarvak Formation (Bangestan Group) and the Oligo-Miocene Asmari Formation, which are two important oil reservoirs in the Zagros fold and thrust belt (Hull and Warman, 1970; McQuillan, 1974).

2.2 Objectives

The main objectives of this chapter consist in the determination of the varying geometry of the Zangul anticline in the Pusht-e Kuh Arc of the Zagros Fold Belt in an area of 824 km^2. This anticline has been selected because: it changes from a single anticline at the level of the Ilam Formation (top Bangestan Group) to multiple anticlines in both terminations at the level of the Asmari Formation. We try to ascertain if this is the consequence of intermediate detachment levels that decouple the competent Asmari limestone or is related intrinsically to the differential growth of different trends of folds. We mostly used structural information from Iranian geological maps at 1/100,000 scale as well field data to complete the lack of information in some areas of the study region.

The analysis of the apparently simple Zangul anticline will help us to understand the geometry of different folds, which show contrasting amplitudes and wavelengths with an apparent irregular distribution.

The analysis of the 1/100,000 geological maps of Pul-e Dokhtar (Takin et al., 1970), Kuhdasht (MacLeod, 1972), Khorram-Abad (Fakhari, 1985) and Aleshtar (NIOC Sheet No 20809W) and the construction of cross-sections both across (11 cross sections) and along (3 longitudinal sections) the area permitted to determine:

1) The structure of the Zangul anticline.

2) The folding distribution at the terminations of the Zangul anticline.

3) The potential depths of detachment horizons and their relation to the mechanical stratigraphy.

4) The 3D geometry of the study region around the Zangul anticline at top of the upper Cretaceous Ilam Formation (at the top of the Bangestan Group) and at the base of the Oligo-Miocene Asmari Formation levels.

5) The extrapolation of these results to other areas of the Pusht-e Kuh Arc.

This study tries to understand the geometry and characteristics of the folds in Pusht-e Kuh Arc. It will help the planning of the new seismic acquisition in the same area (Khorramabad Block) by StatoilHydro Company.

2.3 The Zagros mountain belt

The Zagros mountain belt develops along the SW border of Iran and Iraq. It extends from east Turkey to the Oman Sea. Several structural units are identified parallel to the belt, which are the Urumieh-Dokhtar Magmatic Arc, the Sanandaj-Sirjan Metamorphic Zone, the Imbricate Zone or High Zagros, the Zagros Simply Folded belt and the Mesopotamian-Persian Gulf Foreland basin (Alavi, 1994), (**Fig. 2**). The Urumieh-Dokhtar Magmatic Arc interpreted to be an Andean type Magmatic Arc that has been active since the Late Jurassic through present (Alavi, 1980; Berberian et al., 1982; Berberian and King, 1981). The Sanandaj-Sirjan zone is a region of polyphase deformation, which reflects the collision between Arabia and Eurasia and the subsequent southwards propagation of the fold thrust belt (Alavi, 1994). The Imbricate Zone or High Zagros is a region that is characterized by highly deformed rocks by thrusting and folding. The Imbricate Zone is bounded to the SW by the High Zagros Thrust Fault (**Fig. 2** and **Fig. 13**).

The Zagros Simply Folded belt was further subdivided into 3 regional areas by (James and Wynd, 1965), who used the local names to define them. From NW to SE, the Lurestan Province (Pusht-e Kuh Arc), the Khuzestan Province (Dezful Embayment) in the centre and the Fars Province (Fars Arc) in the south. The Fars province includes Costal Fars and Interior Fars (**Fig. 2**). The width of the Zagros folded belt is about 250-300 km wide in the Fars area and 120-130 km wide in the Lurestan area. The Zagros Simply Folded is bounded to the northeast by the Zagros Main Thrust and separated by this fault from the Sanandaj-Sirjan metamorphic belt. The Zagros Main Thrust Fault is proposed as suture zone between Arabian and Eurasia plates (Dercourt et al., 1986; Dewey et al., 1973; Sengor, 1984). However, Alavi, 1994 proposed the boundary between Sanandaj-Sirjan and Urumieh-Dokhtar Magmatic Arc as the suture zone between these two plates. To the SW, the Zagros Simply Folded Belt is formed by Middle Cretaceous to late Tertiary sediments and is limited in the SW by the Mountain Front Flexure (MFF) that separates the folded belt from the Mesopotamian foreland basin and the Dezful Embayment, where most of the oil is concentrated. The Mountain Front Flexure (MFF) has an irregular trace, which is not completely parallel to the belt. Changes in its trend are represented by the Balarud fault and the Kazerun fault (**Fig. 2**).

The stratigraphy of the Lurestan area from Early Cretaceous to Pleistocene has been reported by James and Wynd (1965). The stratigraphy in this area consists of a 10-km thick succession of Late Palaeozoic and Mesozoic Arabian passive margin followed by sediments of the Cenozoic foreland deposits (**Fig. 14**). The Palaeozoic sequence is mostly cropping out in the Izeh Zone, where forms the hanging wall of the High Zagros Fault (O'B Perry and Setudehnia, 1967). Older rocks were only reported in Kabir Kuh and Samand wells where Permian units were drilled (Dalan and Fraghan formations). The Tertiary foreland succession is only exposed in few synclines in the Pusht-e Kuh Arc although it fills most of the Dezful Embayment. Magnetostratigraphy studies in the Agha Jari growth unit of the foreland basin succession in front of the Pusht-e Kuh Arc indicated that the deformation along this front started at 8.1-7.2 Ma (Homke et al., 2004). Folding in the Pusht-e Kuh Arc resulted in multiple anticline dimensions as observed in geological map in **Fig. 13**

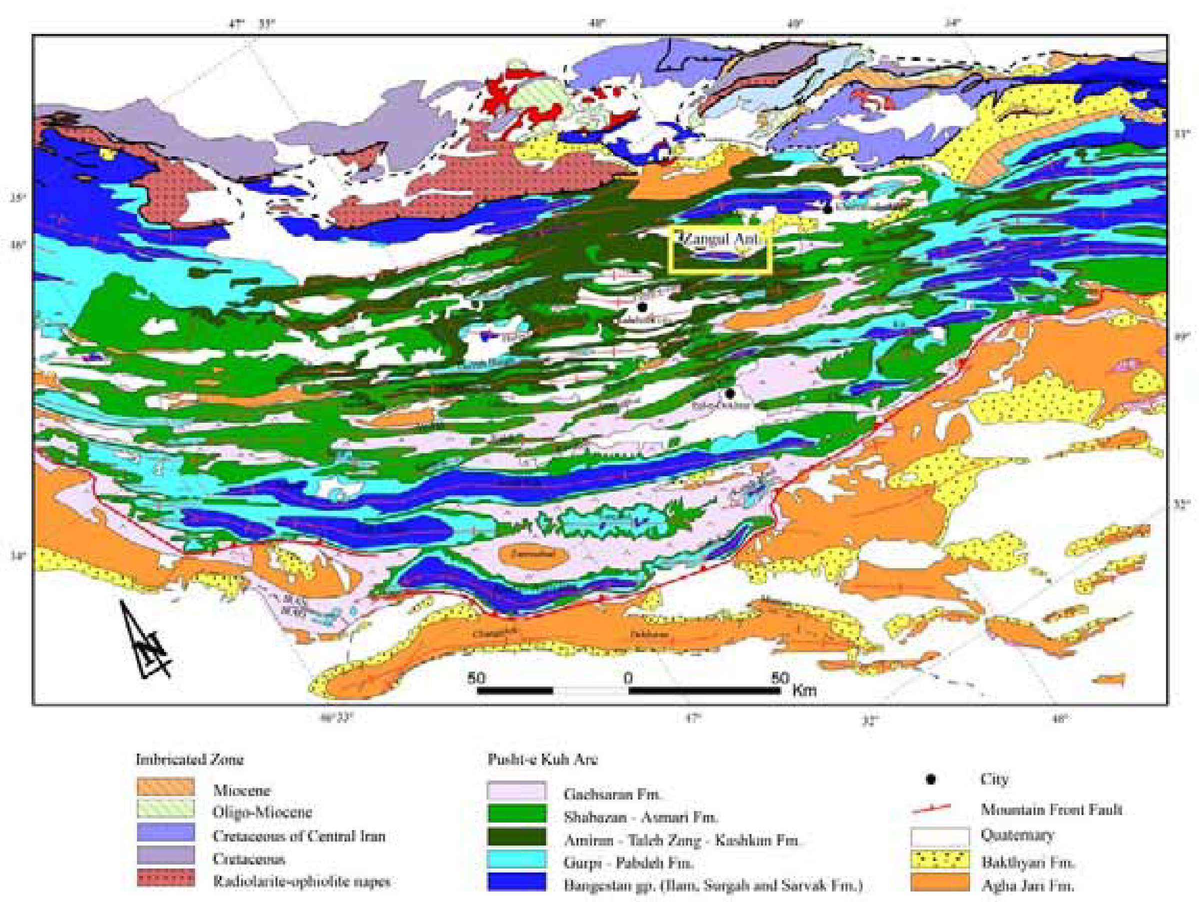


Fig. 13. *Geological map of the Pusht-e Kuh Arc and location of the Zangul anticline simplified from 1/1000,000 geological map of the Zagros(Iranian Oil Operating Companies, 1969).*

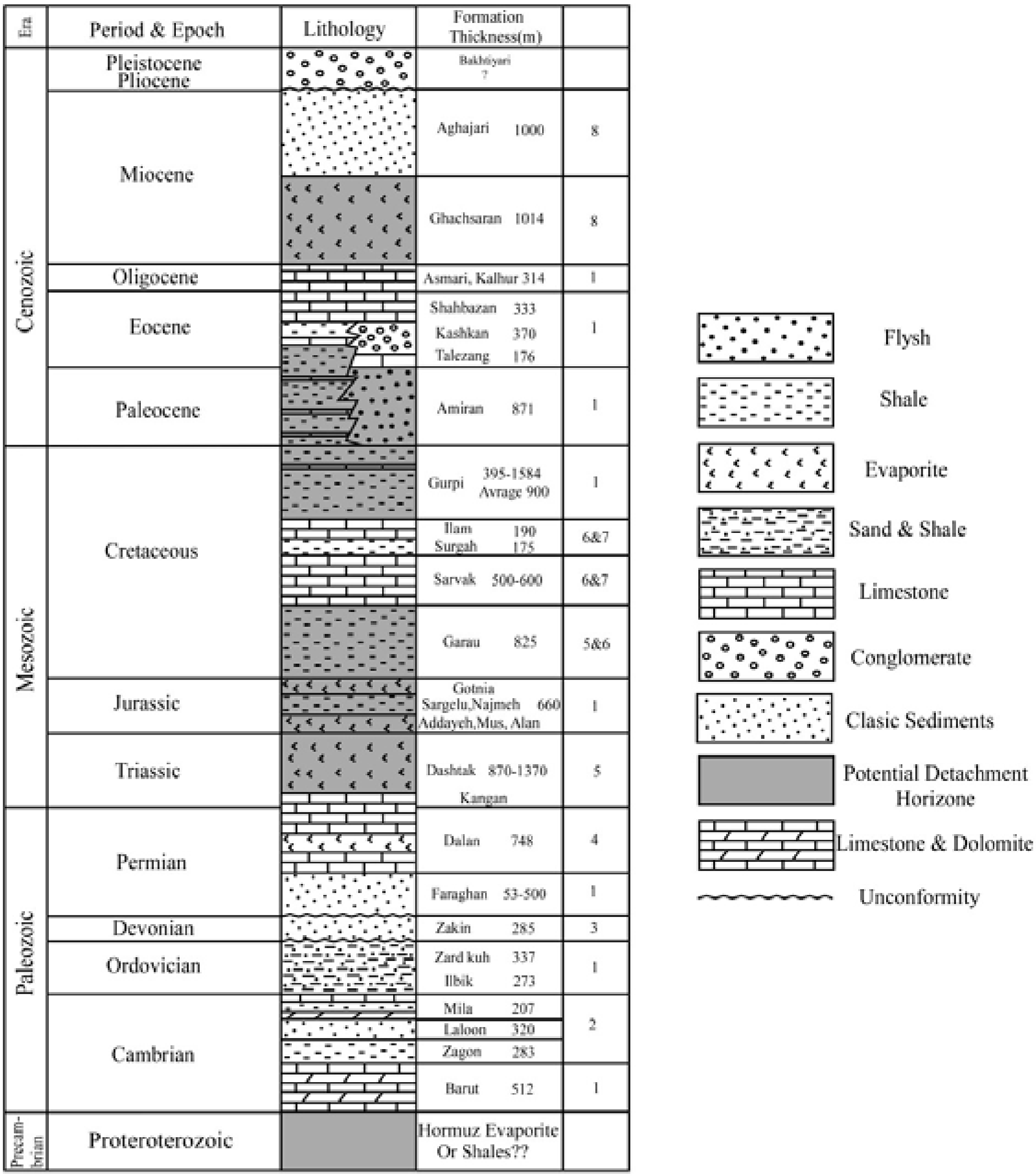


Fig. 14. *Simplified stratigraphic column of the Lurestan stratigraphy province from well and published data. The column has been provided in order to have thickness control of the units during the reconstruction of the geometry of the anticline. The numbers in the right side of the figure indicate the reference for the thicknesses, 1) Motiei (1994), 2) Setudehnia (1978), 3) Ghavidel-Syooki (1997), 4) Aghanabati (2004), 5) NIOC Samand and Kabir Kuh well data), 6) James and Wynd, J.D (1965), 7) NIOC different well data in Lurestan area and 8) Measured on the section across the Afrineh syncline.*

2.4 The Zangul anticline

2.4.1 Location

The Zangul anticline is located towards the NE side of the Pusht-e Kuh Arc (**Fig. 13**). The anticline is about 28 km to the east of Kuhdasht city and 41 km to the west of Khorramabad city. This Anticline is entirely presented in the 1/100,000 geological map of Kuhdasht sheet (MacLeod, 1972). However its SE termination is in the 1/100,000 geological maps of Pul-e Dukhtar (Takin et al., 1970) and Khorram-Abad (Fakhari, 1985). The Zangul anticline has a NW-SE direction and shows 15.5 km of length and 2.2 km of width at the top-Ilam level (**Fig. 15**). The study area is easily accessible through the main roads.

2.4.2 Morphology and geology

The area around the Zangul anticline is formed by topographic highs, which coincide with synclines (hanging synclines) whereas the anticlines are exposed along the valleys. Along these anticlines only the more resistant limestones of the Ilam and Sarvak formations resist to erosion.

The maximum topographic and structural relief of the anticline is about 400 m (level of the Kashkan River is ~1000 m in its NE flank). The Zangul anticline shows slightly oblique position with respect to the mean trend of nearby folding (**Fig. 15** and **Fig. 16**) The SE termination of the Zangul anticline is closer to the SW syncline whereas its NW termination is located 8 km away form the same syncline. Field observations do not support long displacement faulting or thrusting related to the Zangul anticline.

The geometry of the anticline presents a long central segment with box fold geometry and relatively steep flanks (**Fig. 16**). The anticline is asymmetric, formed by a forelimb with a mean dip of 70ºSW and average dip for the backlimb quite constant at 45ºNE as shown in the projections of the dip data (**Fig. 17).** The topography is more elevated in the SE flank, while in its northern side the Khashkan River is positioned parallel and along the outcrops of the Amiran Formation along the north-eastern flank of the anticline. The Khashkan River crosses the Zangul anticline at the contact of Ilam and Gurpi formations in its SE termination.

The Zangul anticline has been the focus of field work during November of 2004. Field data has been used in conjunction with data from NIOC geological maps (**Fig. 18**).

Pictures in **Fig. 18** show the structural data around the Zangul anticline (see their locations in **Fig. 15**). A reverse fault superposed Amiran Formation on top of Asmari Formation (**Fig. 18A**). To the NW side of the Zangul anticline **Fig. 18B** shows a profile view of the termination of the elevated syncline in the NW side of the anticline. **Fig. 18C** and **Fig. 18D** display the NW plunge of the Zangul anticline, as well as its subhorizontal crestal area. Internal deformation and several bend and kink band geometries have been observed in several places in the Amiran Formation (**Fig. 18E**). **Fig. 18F** and **Fig. 18G** show the profiles view of the NW plunge area and the asymmetric geometry of the fold in addition to vergence of the structure to the SW. observation from the hinge zone across the different lithology shows internal deformation, which is accommodated by fractures, short displacement faults and kink geometries (**Fig. 18H-K**).

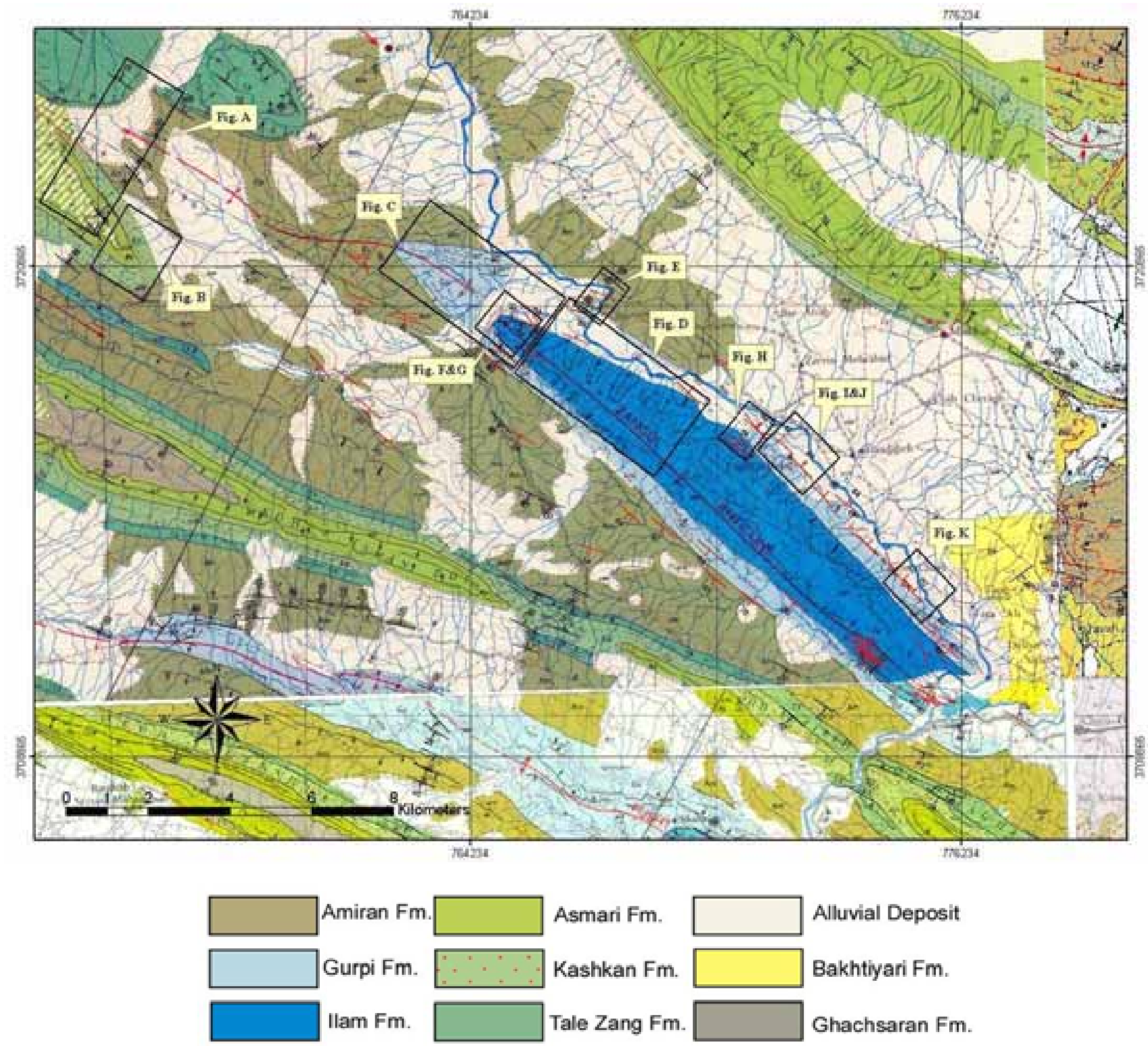


Fig. 15. *Geological map of the Zangul anticline modified from 1/100000 geological maps of the Pul-e Dokhtar (Takin et al., 1970), Kuhdasht (MacLeod, 1972), Khorram-Abad (Fakhari, 1985) and Aleshtar (NIOC Sheet No 20809W). Boxes show the location of the close view pictures in* ***Fig. 18.*** *Dip data from geological map and those, which are collected in the field, are marked by black and red symbols, respectively.*

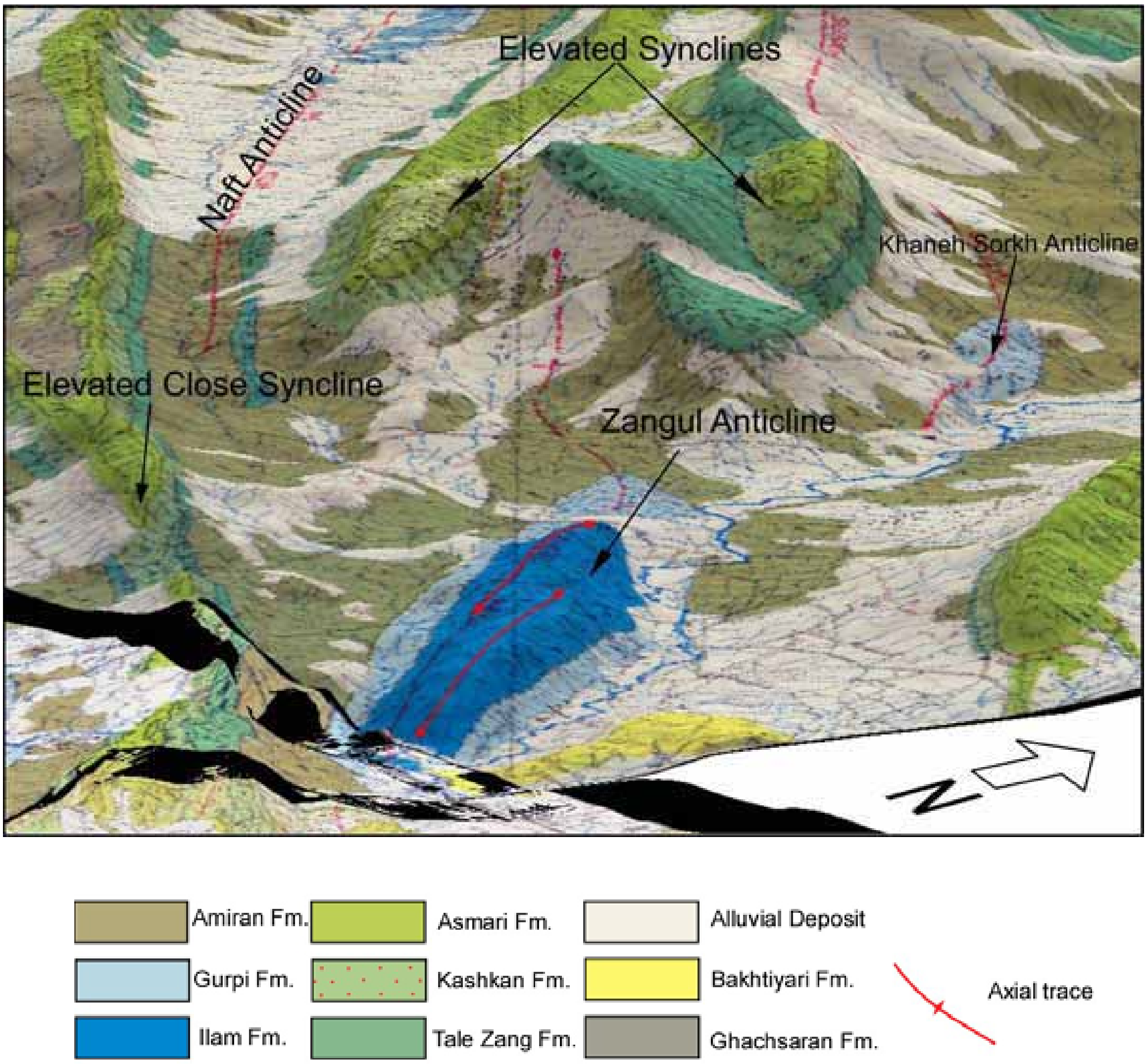


Fig. 16. *3D view of the Zangul anticline toward the NW. Note the two elevated synclines in the NW of the Zangul anticline. The 3D shows the differences of the elevation in forelimb and backlimb of the anticline. Two axial traces can be marked on top of the anticline, which are not continuous along entire length the anticline trace.*

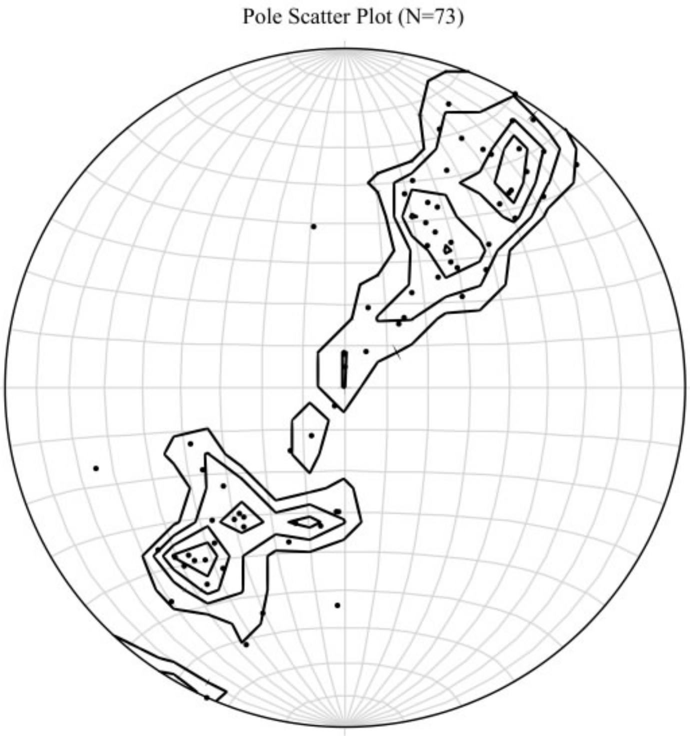


Fig. 17. *Equal area stereo plot of the bedding attitude of the Zangul anticline. The plotted dip data is from the core of the anticline where the Ilam Formation is exposed. The plot shows that the forelimb of the anticline includes a wider spectrum of dips from vertical to horizontal, while the backlimb is less scattered. This distribution shows that the anticline has an asymmetric geometry verging toward the SW.*

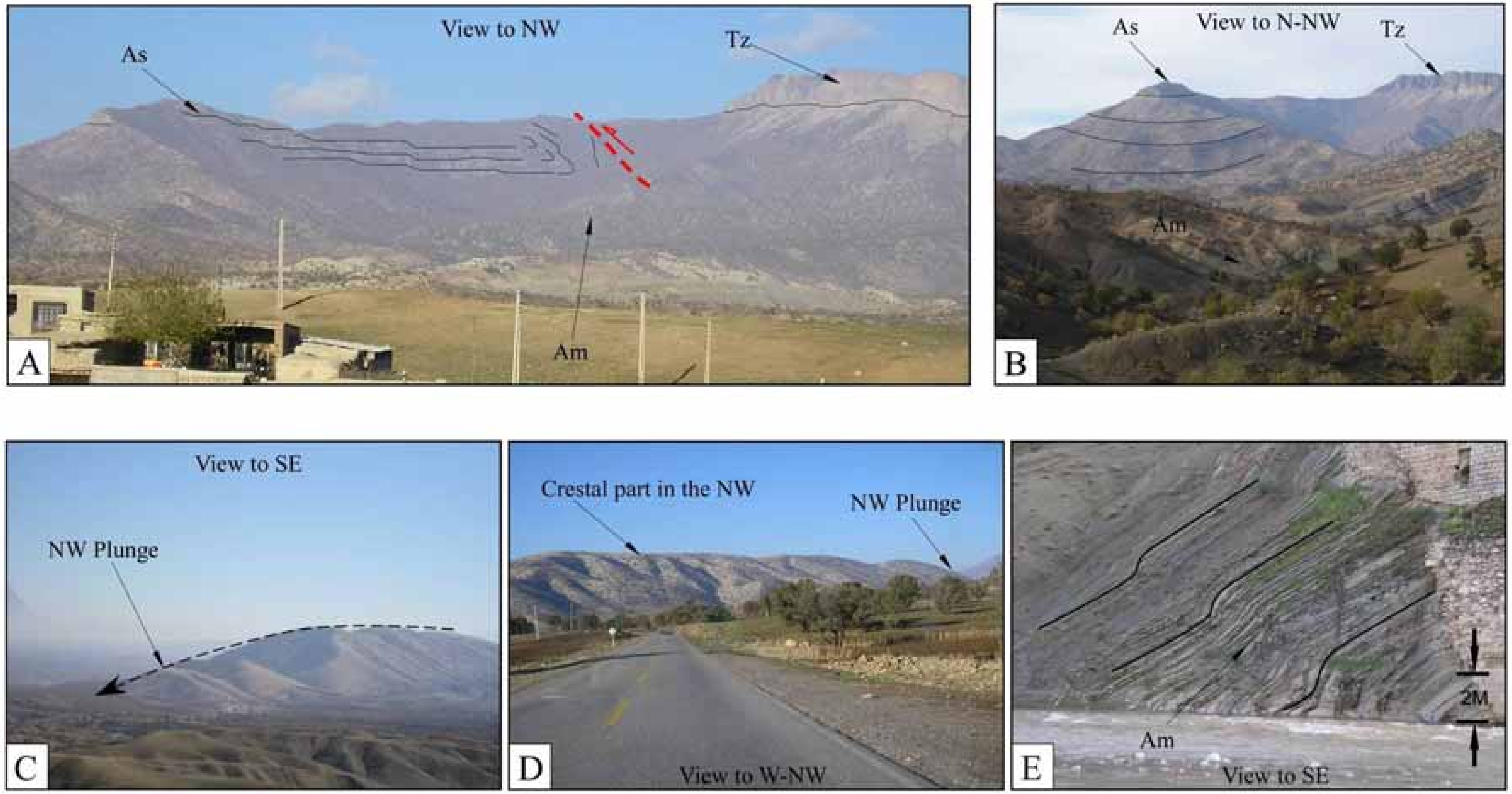
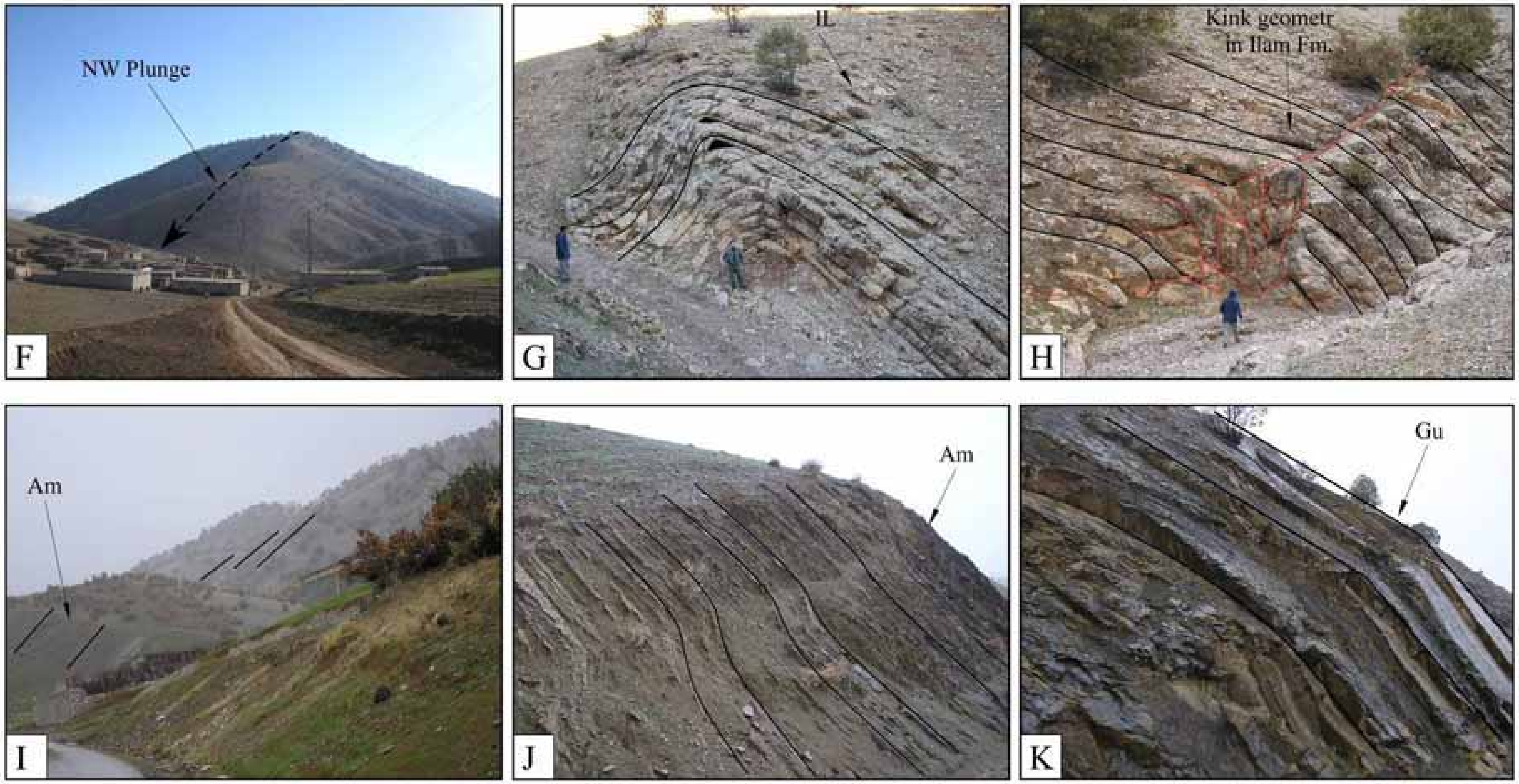


Fig. 18. *A-E Close view pictures of the Zangul anticline. A) superimposed of the Amiran on top of the Asmari Formation. B) SE profile view of the elevated syncline. C) NW plunge of the Zangul anticline. D) View to the backlimb and NW plunge of the Zangul anticline. E) internal deformation in Amiran Formation. Location of the pictures are shown in* ***Fig. 15****. As, Am, Tz, Kn, IL, Gu and Sav abbreviations are corresponded to Asmari, Amiran, Tale Zang, Kashkan, Ilam, Gurpi and Sarvak formations respectively in figures.*



Continue Fig. 18. *Close view pictures of the Zangul anticline. F) Showing the NW plunge of the anticline. G) Folding in the core of the anticline in Ilam Formation. H) Kink geometry in Ilam Formation characterized with highly fracterized zone I) Backlimb dip attitude in Amiran Formation (J & K) Internal deformation in hinge zone and dip domain changes in Amiran and Gurpi formations . Location of the pictures are shown in* ***Fig. 15***.

2.5 Cross-section construction (Methodology)

A cross-section or a set of them is a powerful tool for constraining the structure of a deformed area. The accurate interpretation of the cross-sections, internally consistent, provides a consistent geometry of deformed beds (Groshong, 1999).

In order to understand the geometry of the Zangul anticline and to reconstruct its 3D view, we constructed 11 cross-sections perpendicular to the regional trend of folds in the area as well as 3 longitudinal cross-sections that parallel the fold trend in the study area. These cross-sections are constructed along the Zangul anticline and along the two synclines to the SW and NE of the Zangul anticline. The length of the cross-sections varies from 16 km in section 6 to 21 km in section 11. The longitudinal section along the Zangul anticline is 44 km long and ends in the Asmari Formation outcrops in both terminations of the anticline (**Fig. 19**).

Cross-sections are constructed using data from 1/100,000 geological maps of the Kuhdasht, Alashtar, Pule-e Dokhtar and Khorramabad sheets (published by NIOC) as well as field data. We used 2DMove program from Midland Valley to construct the sections. To construct the section, the dip data near to the cross sections are projected to the same scale vertical and horizontal topographic profile. The outcrops of the Asmari and Ilam formations are also positioned along of the each section on topographic profiles. The topographic profile, dips data and outcrops data are used to construct the structural sections in 2DMove program using dip domain method (Groshong, 1999). The dip domain method is based on the assumption that beds bended at the planar segments separated by narrow hinge zones. For constant thickness beds, the axial surface bisects the interlimb angle between adjacent dip domains. In order to construct the section down to depth we have used the projection of the resulted geometry at surface down to depth by using constant thickness stratigraphy for each Formation. With this assumption we are able to geometrically define the position of potential detachment levels at depth (if any) where the parallel fold geometries are terminated in a horizon at depth. The thicknesses of the stratigraphic levels are controlled by published data as well as data from the field (**Fig. 14**).

2.5.1 NE-SW cross-sections

During the construction of the cross-sections we encountered difficulties to fit the geometry of the dip data while keeping a constant thickness for the Amiran Formation, and also during the reconstructing the geometry between the Zangul anticline and the synclines located to the NW. We have attempted different interpretations to find the best consistency between the available data and fold geometry. In some interpretations the geometry was consistent with the dip data, but the thickness of the Amiran Formation was extremely thick of about 4 km. Using the available dip data alone it was not possible to fit the thickness of the Amiran Formation as reported by Homke et al., (in press) and Motiei (1994) 850 m and 871 m, respectively. To reconcile this thickness problem we finally used a thicker Amiran Formation of about 1300 m as well as we modified the geometry of the anticline flanks accordingly.

The Zangul anticline shows open box fold geometry with interlimb angle of about 86º in the centre of the structure with amplitude of 1440 m and a half wavelength of 4460 m at the level of top of Ilam Formation (measured at cross-section 6). In sections 5, 7 and 8 the Zangul anticline preserved the box fold geometry (**Fig. 20**).

Geometry of the anticline at depth is reconstructed by projecting the geometry at surface. The axial patterns in cross-sections 5 to 8 show that the folded units are terminated in Dashtak Formation (**Fig. 20**). The fold termination is located on the top of the Dashtak Formation in cross-section 5, base of the Dashtak Formation in cross-section 6 and 7, and inside the Dashtak Formation in cross-section 8. These observations conclude that the geometry of the Zangul anticline at surface has been mostly controlled by the position and nature of the Dashtak Formation.

In the cross-section 9 and 10 the amplitude and wavelength of the anticline decrease towards the NW. In cross-section 9 the anticline is still preserved at the level of the Gurpi Formation but in cross-section 10 the anticline ends at the level of the Amiran Formation (**Fig. 20**). Finally in cross-section 11 a syncline in the Tale Zang and Asmari formations has formed in the NW termination of the Zangul anticline (**Fig. 20**). In cross-section 9 the surficial fold seems to terminate at depth at the level of the shallower Garau Formation while in cross-section 1 the Gurpi Formation seems to be the most significant detachment level.

Cross-sections 7, 8 and 9 (**Fig. 20**) show low amplitude anticlines at the level of the Asmari Formation, which are in close continuation to the Naft anticline to the SE. These anticlines show an overturned geometry at the level of the Tale Zang Formation with a

NE vergence. The SE termination of the Naft anticline along the cross-section 10 (**Fig. 15** and **Fig. 20**) shows a SW vergence and low amplitude fold, which terminates at the Gurpi Formation level. In cross-section 6 the Naft anticline displays a small fold in its SW flank that can be interpret as a rabbit-ear fold. Toward the SE, in cross-sections 6 to 9 the interaction between the synclines, Naft anticline and forelimb of the Zangul anticline resulted to an exceptional close syncline.

The depth projection of most of the presented cross-section shows that below the most significant detachment levels at Gurpi, Garau and Dashtak formations the Paleozoic units are also folded. The geometry of the deformation in Paleozoic units is generally characterized by wide and gentle folds with low amplitudes indicating that possibly a deeper detachment level at the level of the Precambrian Hormuz salt is active at the base of the stratigraphic pile as already documented in Vergés et al. (in press).

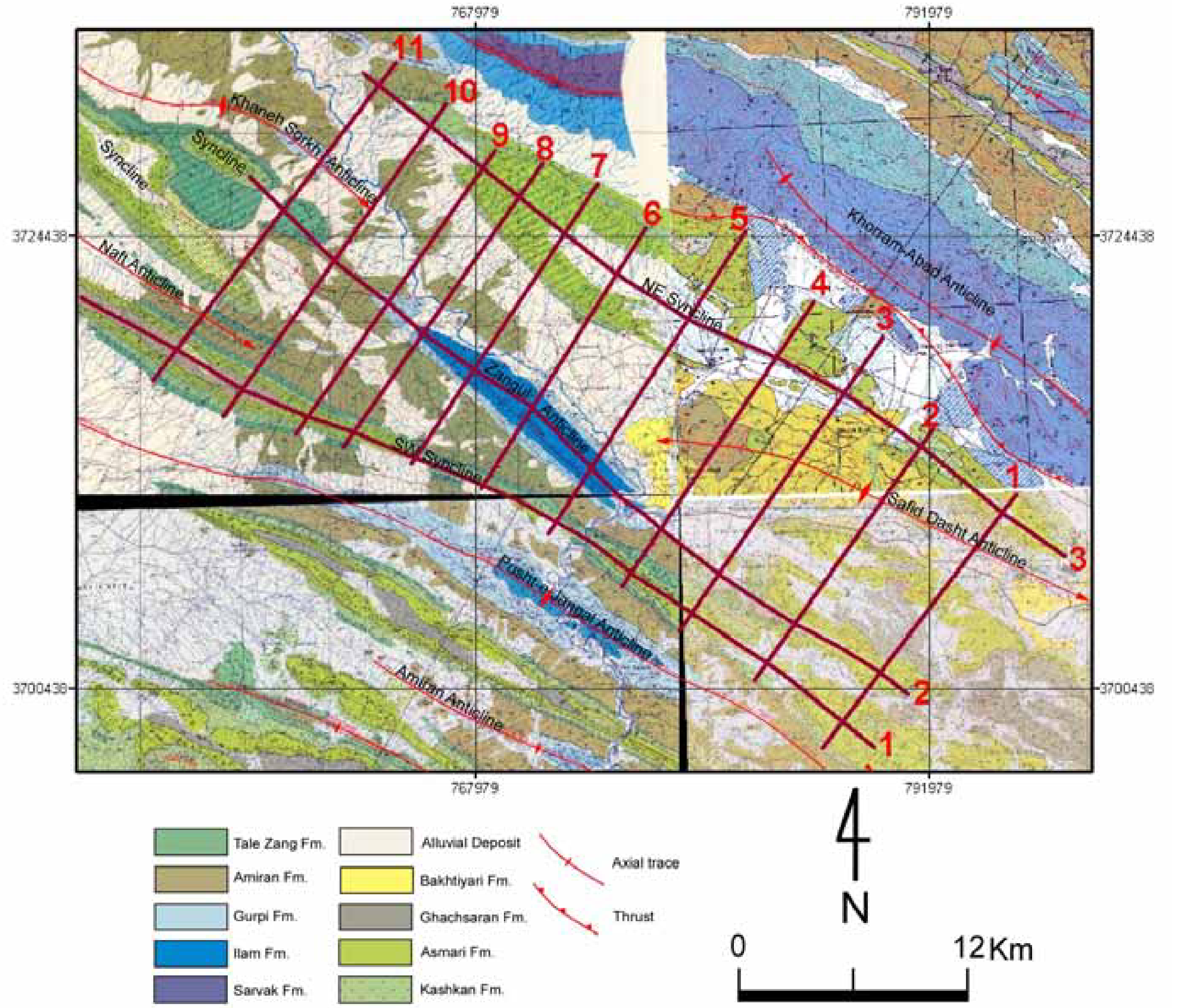


Fig. 19. *Geological map with location of the cross-sections and longitudinal sections. Based on the outcrop and dip data the sections have been constructed at approximately regular distance. Longitudinal sections are located along the major syncline-anticline structures. Geological map is modified from 1/100000 geological maps of the Pul-e Dokhtar (Takin et al., 1970), Kuhdasht (MacLeod, 1972), Khorram-Abad (Fakhari, 1985) and Aleshtar (NIOC Sheet No 20809W).*

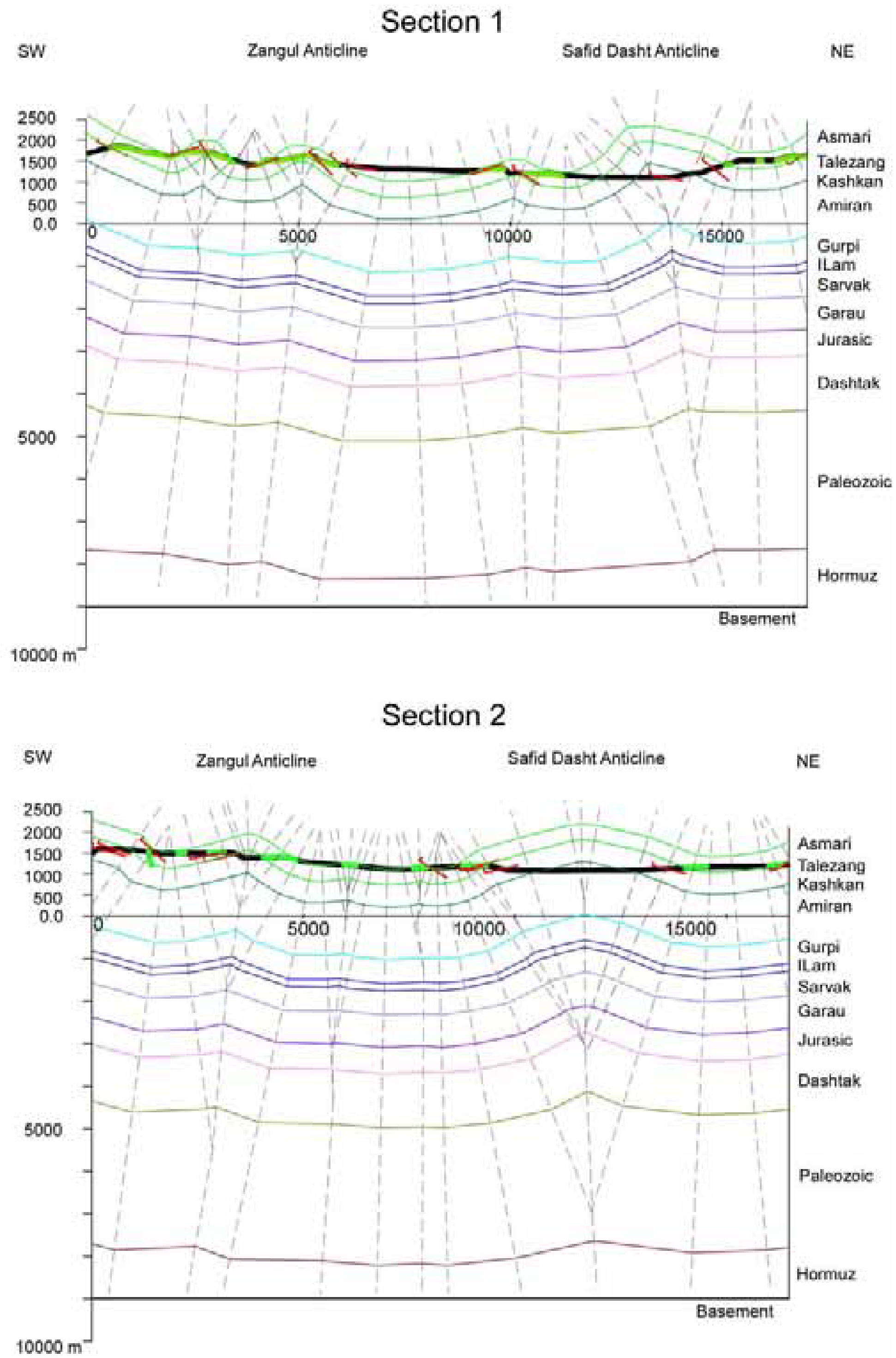
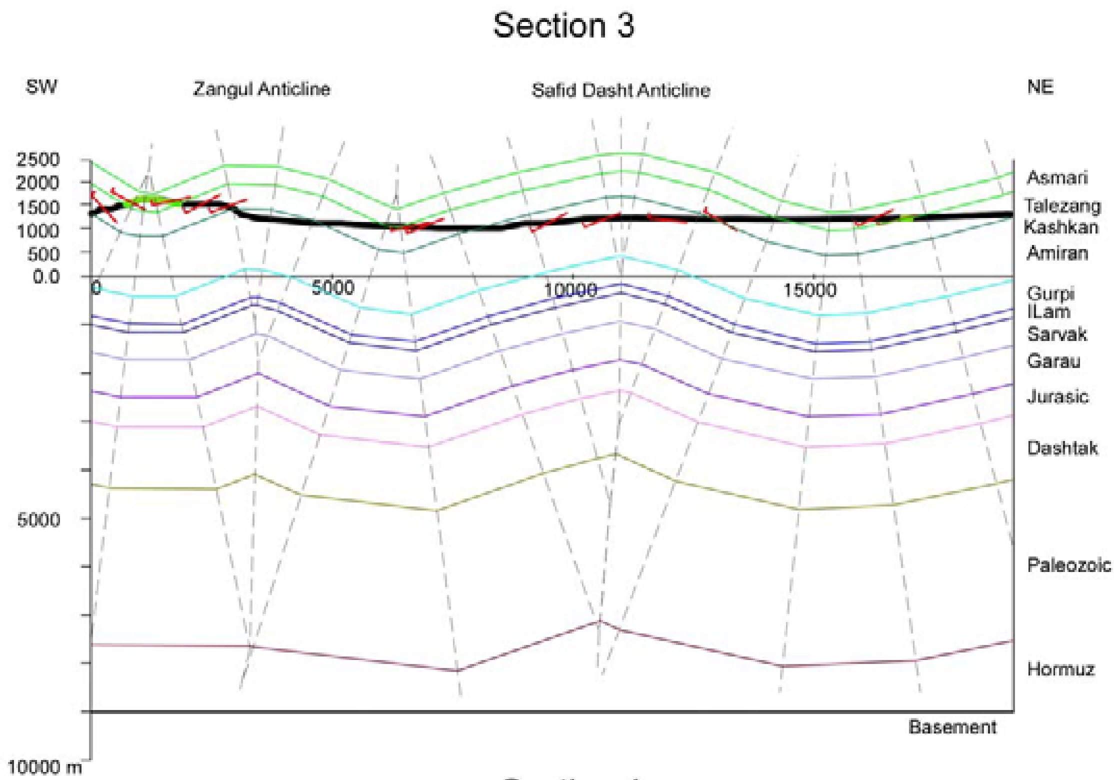
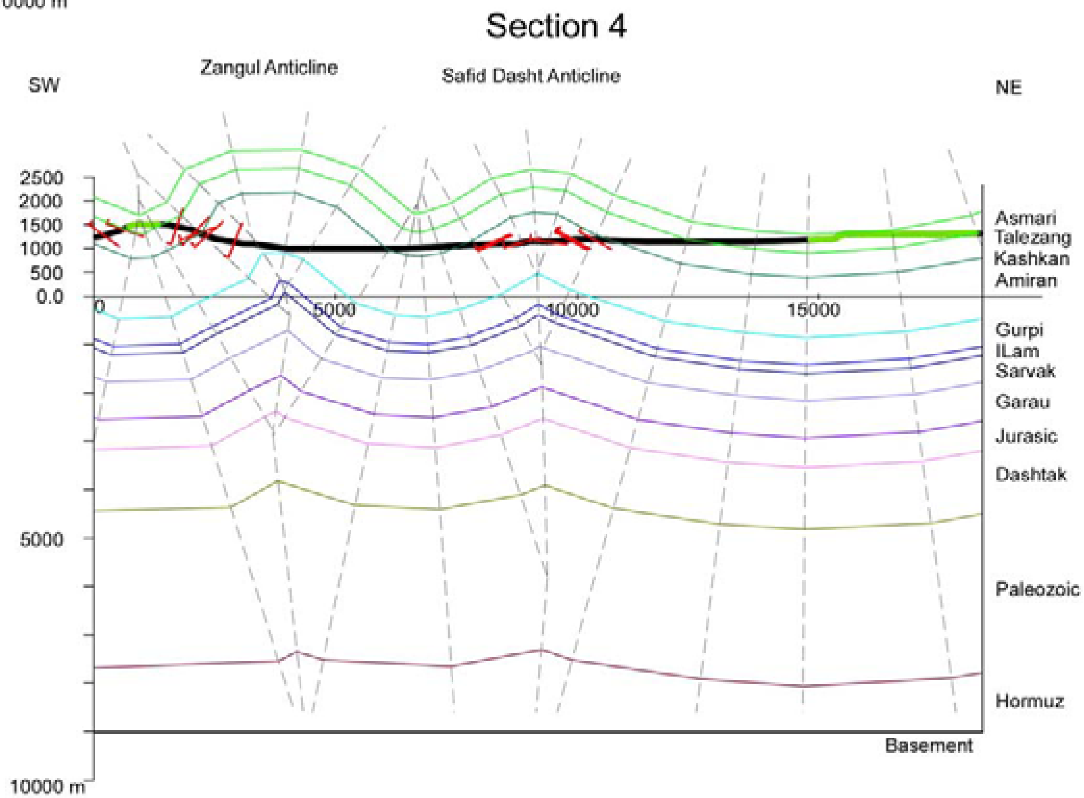
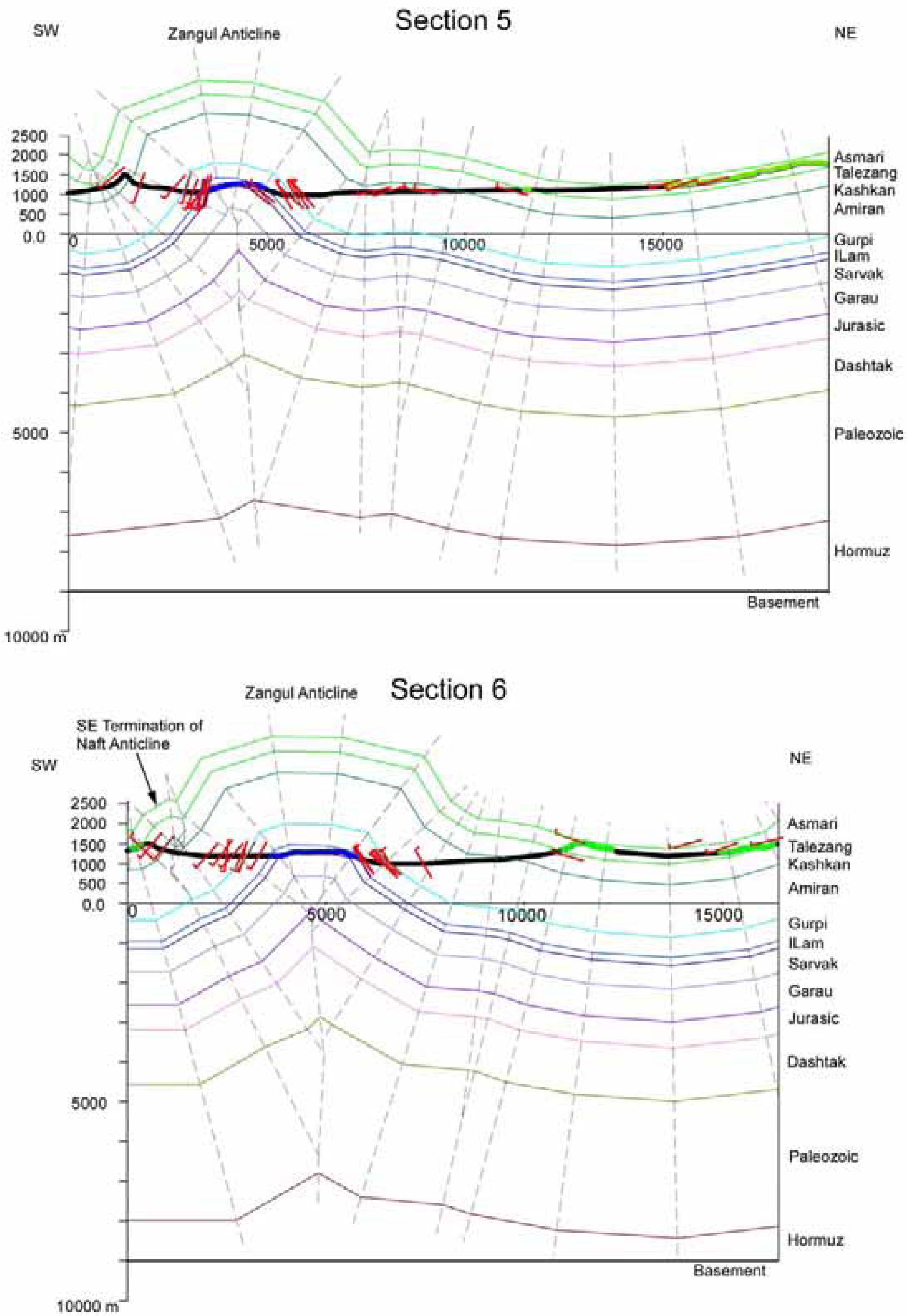


Fig. 20. *Serial cross sections (1 to 11) from SE to NW of the Zangul anticline. In order to have better control on the geometry reconstruction the remnants of the two most important units the Asmari and Ilam formations are marked by green and blue color respectively in the sections. Sections have the same vertical and horizontal scale. In section 1 and 2 the short amplitude-wavelength folds at the level of the Asmari formation displaying at surface but at the level of the Ilam Formation they form synformal geometry at depth.*

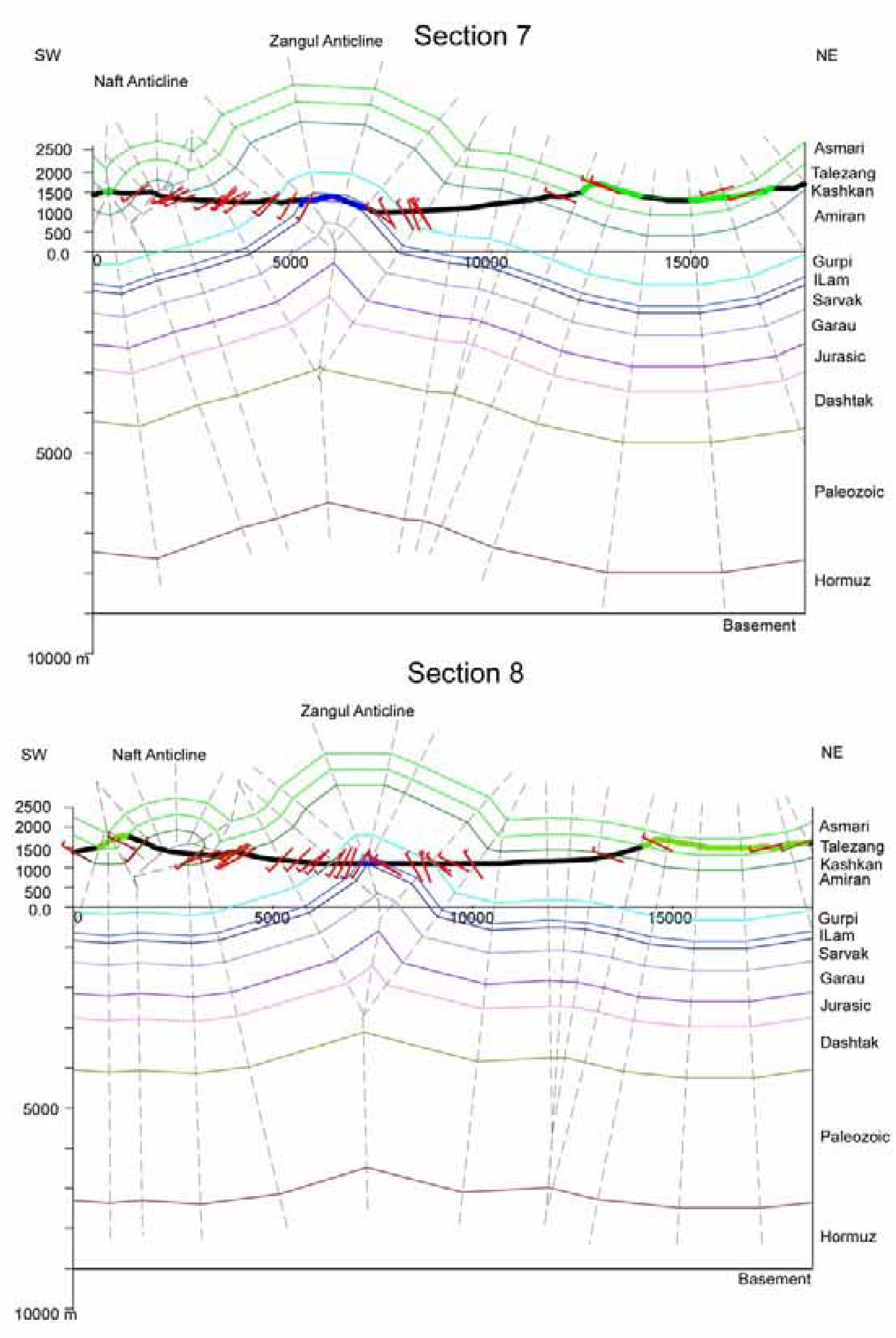




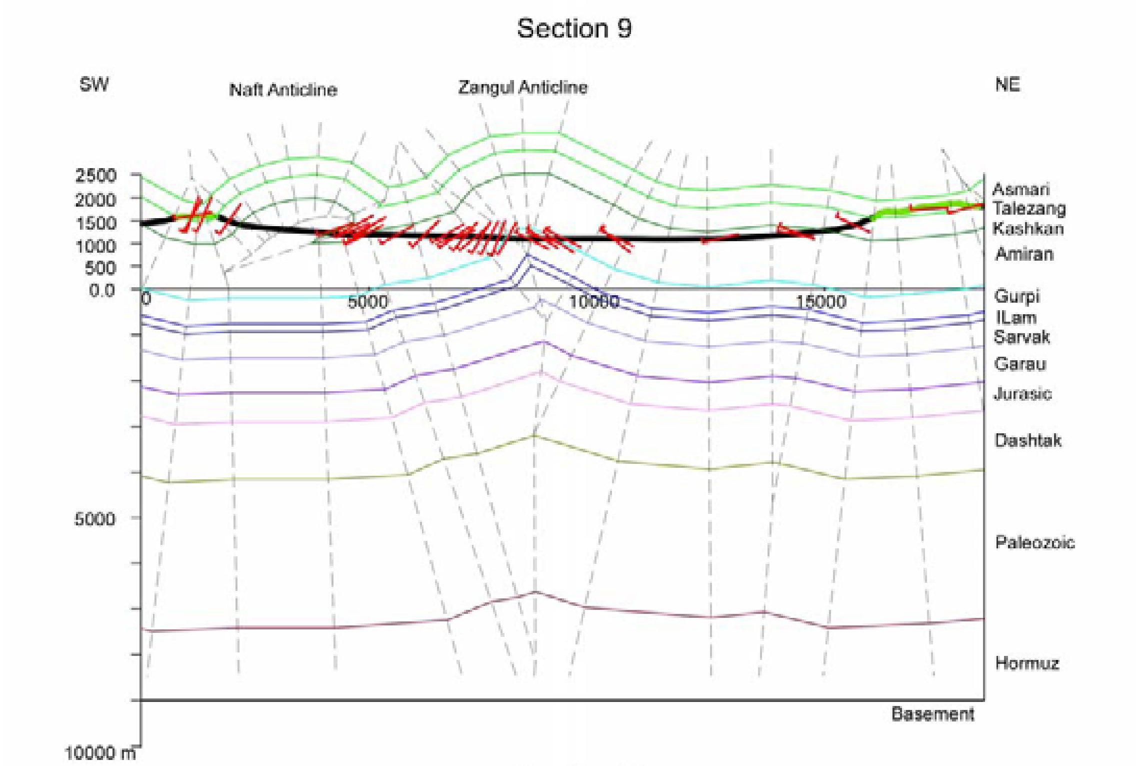
Continue Fig. 20. *Showing the wide wavelength folds in section 3 while moving to section 4 shows shorter wavelength and higher amplitude at both levels of Asmari and Ilam formations.*

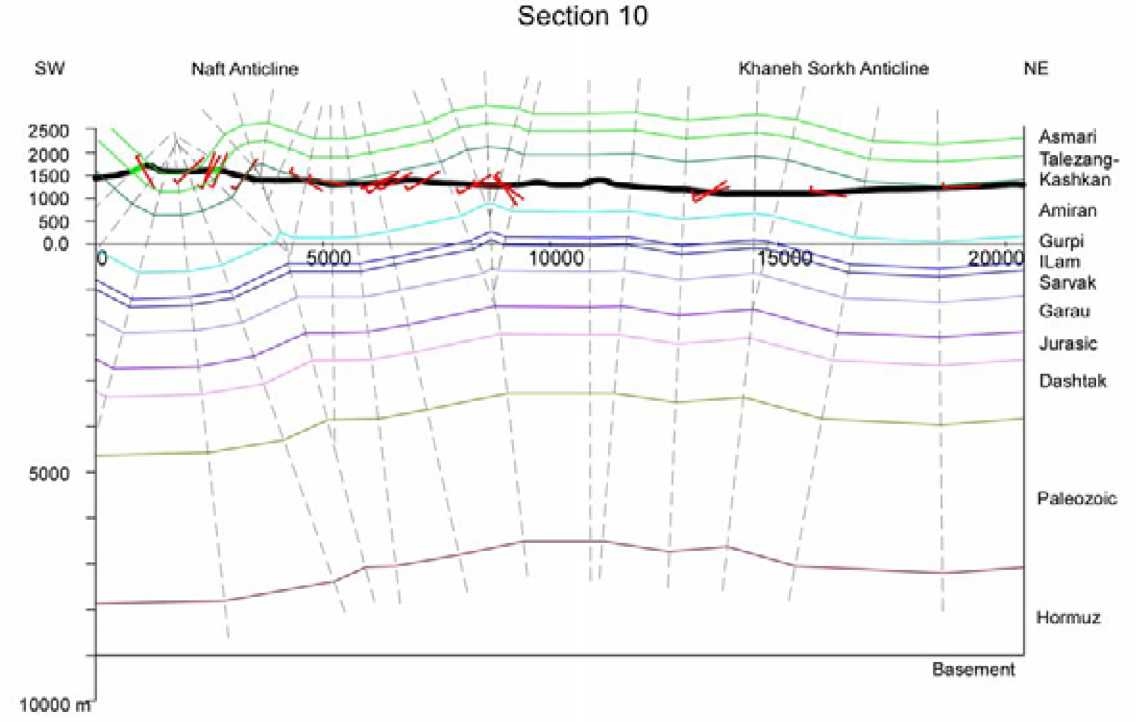


Continue Fig. 20. *Showing box fold geometry for Zangul anticline while the Safid Dasht anticline has been disappeared to these sections. The Naft anticline shows rabbit structure on the forelimb of the Zangul anticline.*

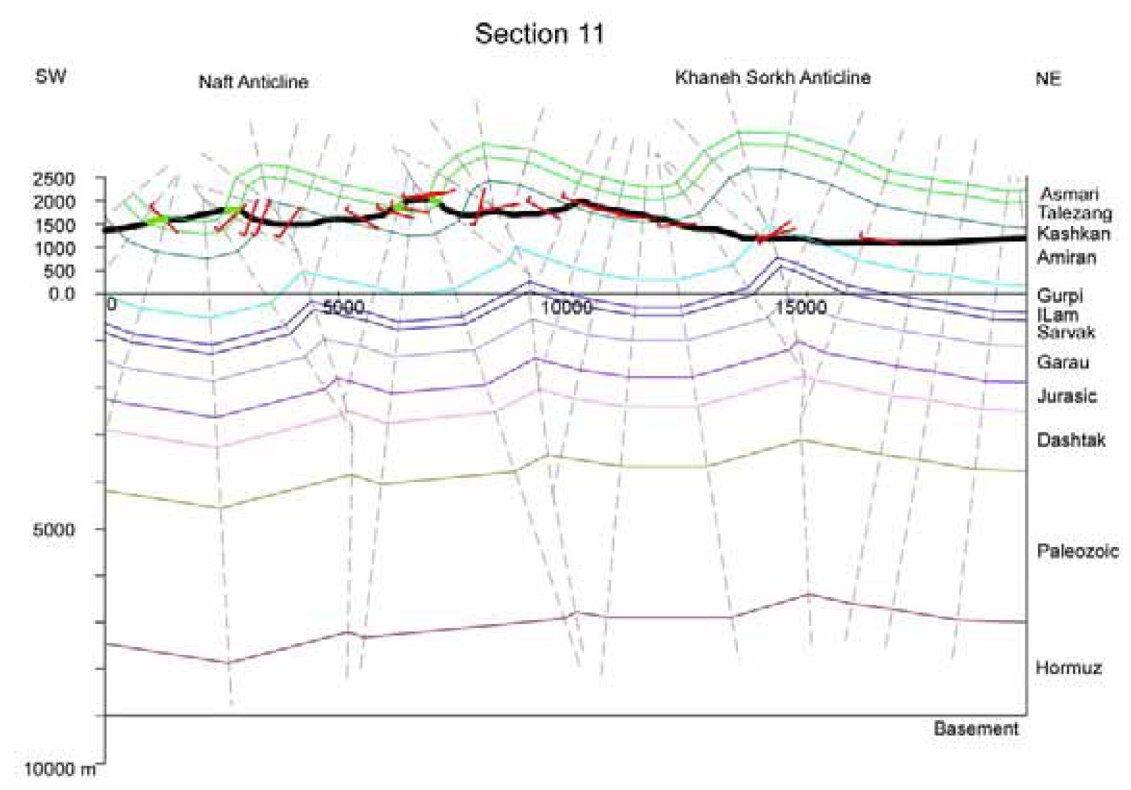


Continue Fig. 20. *The amplitude and wavelength of the Zangul anticline decrease in to section 7 & 8 but the Naft anticline has increased in amplitude and wavelength from section 7 to section 8. The geometry of the Naft anticline displaying a detachment fold and Amiran Formation works as detachment horizon in these sections.*





Continue Fig. 20. *The Zangul anticline disappeared to section 10 and also the Naft anticline decreased the amplitude and wavelength from section 9 to 10. The geometry at the level of the Ilam Formation involved making an antiform at depth with long wavelength of about 10 km. In the left side of the section the Khaneh Sorkh anticline appeared with very short amplitude.*



Continue Fig. 20. *In section 11 the elevated synclines are appeared and still the fold geometry at the level of the Ilam formation makes an antiform at depth. The amplitude and wavelength of the Khanh Sorkh anticline increased from section 10 to section 11.*

2.5.2 Longitudinal cross-sections

In order to control the consistency between the cross-sections across the folds it is necessary to construct the longitudinal cross-section along the structure. Three longitudinal sections have been constructed along the Zangul anticline and 2 bordering synclines (**Fig. 19**). The cross-section network will be used to produce a 3D visualization of the study area around the Zangul anticline.

At the Ilam Formation level the Zangul anticline displays a relatively flat crest limited by two axial surfaces, which are not continuous along the entire length of the anticline (**Fig. 15**). The anticline can be separated in at least 3-plunge domain based on the topographic profiles and field observations. The stereographic determination of the plunges for the terminations of the Zangul anticline is of 122/9.8˚ towards the SE and 303/12.8˚ towards the NW (**Fig. 21**). The central segment of the anticline is represented by a large and subhorizontal domain (132/2˚), which coincides with the culmination of the Zangul anticline. Integration between the topographic profile, calculated plunges and projections of the dip data to the fold terminations is presented in (**Fig. 21**).

The longitudinal cross-section along the Zangul anticline shows a long subhorizontal dip domain that terminates at both ends by the anticline terminations with complex geometry. The NW plunge is formed by two long dip domains, which are dipping 10˚ and 17˚ to SW. The SE plunge formed by short dip domains with maximum plunge of 29˚ to the SE.

Longitudinal cross-section along the NE syncline shows that subhorizontal dip domains control the geometry of the syncline except in the NW side of the section where there is one dip domain that dips 10˚ to the SE. The longitudinal cross-section along the SW syncline is formed by relatively large subhorizontally dip domains (**Fig. 21**).

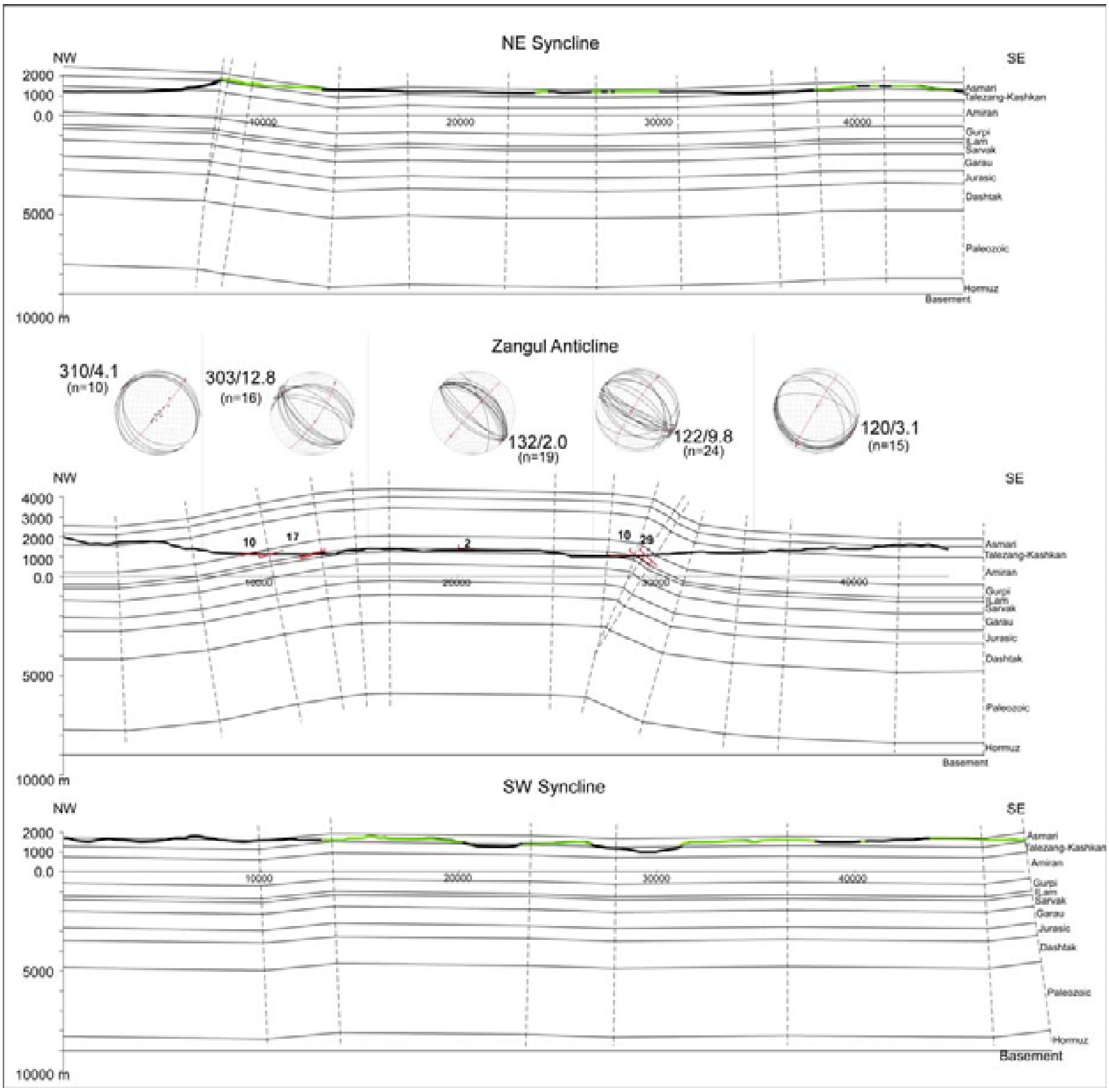


__Fig. 21.__ Longitudinal sections along the axial trace of the Zangul anticline and the synclines located to the SW and NE. In order to control the geometry of the structure along the synclines at the level of the Asmari Formation the Asmari outcrops along the synclines are marked by green color in topography profiles.

2.6 Zangul anticline 3D Visualization

Different methods have been developed in order to reconstruct a 3D structural model using fields and subsurface data. Except the 3D seismic survey most of the methods are based on 2D interpretation and interpolations of regular spaced two-dimensional data such as cross-sections and seismic profiles (Rowan, 1997). New 3D reconstruction method has been proved (Fernández et al., 2004) using a 3D dip domain technique. The advantage of their method is that they reconstruct the 3D geometries independent of the 2D reconstructions.

In this study, based on the results from the network of cross-sections, a 3D visualization of the Zangul anticline is made using ArcMap program capabilities. In order to provide the 3D view of the anticline all the cross sections and longitudinal sections are imported in to the ArcMap program in a format of the point data including (X, Y, Z) coordinates. In addition to this data set we also used the top-Ilam Formation and the base-Asmari Formation contour extracted from the geological map. An interpolation approach has been used to calculate the structural position of the anticline between the sections. Finally the results of the interpolation are demonstrated in a 3D environment. The visualization is made at the level of top of Ilam Formation and at the level of base of Asmari, which represent the two most important hydrocarbon reservoirs in the study area **(Fig. 22)**.

The 3D geometry of the study area shows an intricate system of folds with anticline merges and bifurcations that are typical of detached folds (**Fig. 22**). The geometry of the Zangul anticline is relatively simple whereas its terminations are more complex with the development of smaller amplitude folds at the level of the Asmari limestones. These anticlines, however, describe larger folds to describe an antiformal geometry at the NW termination of the Zangul anticline and synformal structures in its SE end (**Fig. 22**). Major structures close to the Zangul anticline as the Naft and Safid Dasht anticlines merge on its forelimb and backlimb, respectively.

Structural contours map calculated from the 3D interpolation shows the distribution of the culminations and saddles, which are very important to define the geometry and size of the structural traps in oil exploration as well as the structure and prospect evaluation, volume calculation and whole risk assessment. The structural contours indicate that the Zangul anticline closure is at sea level for the top of Ilam Formation and at 500 m below the sea level for the Safid Dasht anticline.

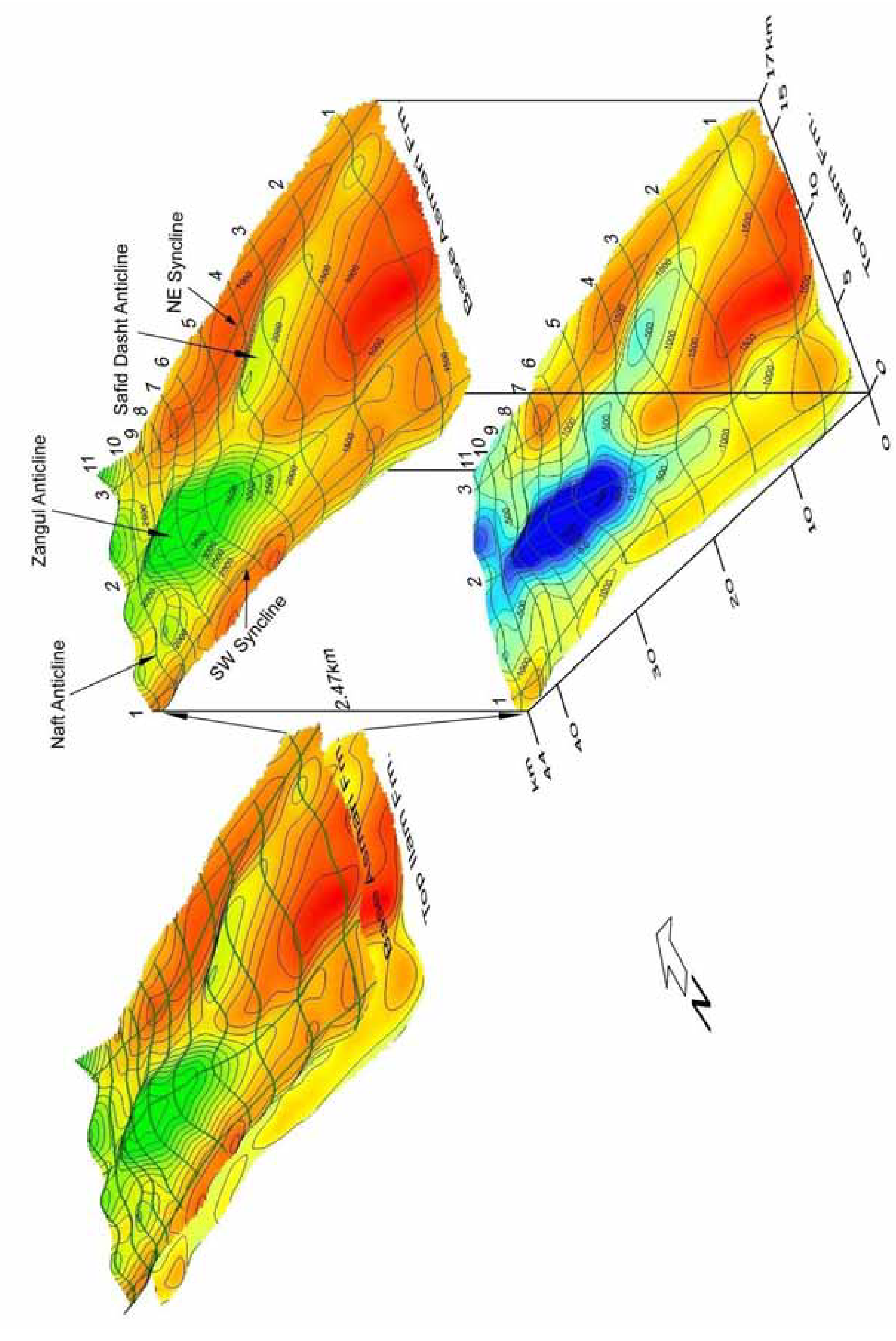


Fig. 22. *3D Geometry of the Zangul anticline for base Asmari and top Ilam formations. Structural contours are respect to the sea level. The distance between the Ilam and Asmari Formation is exaggerated.*

2.7 Discussion

The geometrical construction shows that the position of the significant intermediate detachment can be estimated by geometry of the anticline at surface. The pattern of the axial surfaces can help to estimate the position of the intermediate detachment horizon. The sections of Zangul anticline show that normally a wide wavelength fold underlined by the shorter wavelength fold on top. These two folds in profile view are separated where the axial surfaces in the upper structure show a convergence pattern at depth indicating the termination of the upper fold. The cross sections show that the intermediate detachment in sedimentary units is also involved in to folding. According to the resulted sections we can recognize 3 significant detachment horizons. The basal detachment in Hormuz evaporite or equivalent incompetent units, the intermediate detachments in Dashtak evaporite and finally the Gurpi, Amiran or Garau formations could work as a shallower detachment horizon for short amplitude and short wavelength folds.

The short wavelength folds especially at the level of Asmari Formation can have different indications. They can be formed at the termination of the big single structures, which are exposed at the level of the Bangestan group (Zangul, Sultan, Pusht-e Jangal anticlines). They could be located in the junction area between different structures to adopt the shortening from one structure to another or they can be as individual folds, which are detached in shallow depths and overlay the wide wavelength anticline or syncline at depth. The last case has a good signal in oil exploration in the area where the wide anticlines of Bangestan Group are hidden below the short wavelength Asmari folds.

The development of this kind of intermediate detachment can be explained in the way that the sequence of the folding has happened in two separate stages. In the first step the shortening taking place in the units located top of the intermediate detachment (Dashtak Formation) and later in the second step of shortening all the units are folded coevally. In this way the second step of the shortening taking place along the basal detachment and will result to amplification of the primary folded units and also producing a wide wavelength fold beneath the intermediate detachment horizon.

Sherkati et al. (2006) present different intermediate detachment in central Zagros by developing a kinematic model including different mechanical stratigraphy. In their model the displacement from the deep structures are moved to the intermediate detachment through the thrust faults in the same structure. Their kinematic evolution will produce anticlines, which are different in size and geometry in profile view presenting different detachment horizon. Sepehr, (2006) also interpreting the role of the mechanical stratigraphy in development of the fold above the intermediate detachment horizons in the central Zagros. In their cross sections the folds are limited to the units located on top of the horizontal intermediate detachment without affecting the units below the detachment horizon. These models clearly showing that occurrence of the intermediate detachment horizons are controlling the surface geometry as well as the size of the anticlines at surface. It is in agreement to the proposed evaporitic Dashtak Formation as intermediate detachment horizons for Zangul anticline while the geometry at depth should be proved by further subsurface data.

2.8 Conclusions

The Zangul anticline is about 15.5 km long and 2.2 km wide at the top of the Bangestan Group outcrop (top of upper Cretaceous Ilam Formation). This anticline constitutes the center of the study area of about 824 km^2. Eleven cross-sections across the study area and 3 longitudinal sections along the traces of the main anticline-syncline structures permitted to characterize the geometry of folding for the Zangul anticline as well as for its terminations where extensive outcrops of Oligo-Miocene Asmari limestones show different fold shapes.

The Zangul anticline is a four-closure fold with amplitude of 1440 m and a half wavelength of 4460 m at the level of top of Ilam Formation (measured at cross-section 6). Its aspect ratio amplitude / half wavelength is of 0.38±0.05. The northwestern termination plunges a maximum of 17ºNW whereas the maximum plunge of its southeastern termination is 29ºSE. The Zangul anticline is an open box fold (interlimb angle 86º in section 6 in the center of the structure) with long subhorizontal crestal segments. Its vergence is SW with a forelimb with a mean dip of 70ºSW. The average dip for the backlimb is quite constant at 45ºNE. The fold is limited between well-developed hinge zones represented by axial planes.

The relatively large Zangul anticline merges with several smaller anticlines at the level of the base of Asmari outcrop. These anticlines are symmetric to SW-verging showing in some cases NW-dipping thrusting with short displacement. These anticlines show amplitudes of few hundred meters and half wavelengths of 1-2 kilometers. Their aspect ratio, however, is very homogeneous and amounting 0.21±0.07 for the SE termination and 0.22±0.03 for its NW termination. These aspect ratio is about half of the one calculated for the Zangul anticline and thus implying a different deep structure.

The small displacement thrusts can affect the small Asmari folds are detached in the shales of the Paleocene Amiran Formation. However, the observed geometries of the folds in the study area are controlled by deeper detachments located beneath the Bangestan Group. Although not conclusive, the geometric construction of cross-sections across the study area suggests that most of the anticline axial surfaces intersections coincide at the Triassic evaporites corresponding to the Dashtak Formation This interpretation coincides with previous results across the Kabir Kuh anticline and regional stratigraphic observations (Vergés et al., in press), as well as with the characteristic detachment folding geometry of the folds in the study area documented in the 3D geometry.

The 3D geometry (2.5D according to Fernández et al., 2004), shows a relative parallelism between the top of the Ilam Formation and the base of the Asmari Formation levels and thus indicating that where there is a large anticline at depth (top of Bangestan Group) it continues towards shallower levels (Asmari limestones). On the contrary, where the base of Asmari shows smaller amplitude and wavelength anticlines, the folds at the top of the Ilam Formation are also small. Although small folds show similar characteristics at both ends of the Zangul anticline they group forming different tectonic structures. At the SE end the small amplitude folds form synformal geometry whereas they develop an antiformal geometry at the NW termination.

This study concludes that areas dominated by small amplitude and short wavelength folds at the level of Asmari Formation are also formed by small folding at deeper levels of the Bangestan Group except in the termination of the structures where one structure is terminated on the forelimb or backlimb of another. These conclusions can apply to the extensive regions of the Pusht-e Kuh Arc dominated by this type of folding. These are important result that must be evaluated during future field work and that can help to the seismic acquisition surveys to develop during the end of year 2008.