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Determine folding mechanism of Lali structure, northern Dezful, Zagros, Iran

Gholamreza Asgari[1], Farzin Ghaemi*[1], Bahman Soleimany[2], Behnam Rahimi[1], Mehrdad Maleki[2]

1. Department of Geology, Faculty of Science, Ferdowsi University of Mashad, Iran
2. Exploration Directorate of the National Iranian Oil Company (NIOC), Tehran, Iran

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Abstract

Lali sub-surface structure, with a NW-SE Zagros trending is located in Dezful Embayment. To determine the folding mechanism, structural geometric parameters including limbs dip, amplitude, wavelength, and crestal length were determined in four stages during deformation. In order to investigate the lateral folding mechanism, these geometric parameters were analyzed in three parts in the Lali structure including northwest, central and southeast. Lali structure in all three sections, show detachment folding mechanism. At the initial stage, due to the rheology of the region's stratigraphic units, the folding mechanism was fault-bend fold and due to the thickness of incompetent units, folding mechanism changes from the fault-bend fold to fault detachment fold and growth of this structure continues with this mechanism. As the deformation continues, detachment folding, the Dahlstrom type inclined to migration type. By identifying the folding mechanism of the Lali structure, determination of the detachment depth was necessary with two computational and graphical methods. Therefore, the depth of this surface was estimated at about 7500-8500 m for Lali structure. This amount is determined at the maximum thickness of the stratigraphic sequence of the region due to the migration of incompetent units to the core of the Lali structure.

Keywords: *Geometry parameters, Folding mechanism, Detachment depth, Dezful Embayment, Zagros*

1. Introduction

Characterization of geometric parameters and determination of folding mechanism in the exploration of hydrocarbon reserves is important because most of Iran`s hydrocarbon reserves have been discovered in the structural traps. The Lali structure with a NW-SE trending is one of the sub-surface structure located in Dezful Embayment (Fig 1). Most of Iran's oil fields are located in Dezful Embayment, which is limited to northwest the Lorestan mountains, to southeast the Fars area and to northeast the mountain front in the north of Khuzestan (Fig 1). In Dezful Embayment, evaporate units of Early Miocene Gachsaran Formation has controlled the folding style of sedimentary cover. These units are the boundary between the differentiation of surface and subsurface structures (e.g., O'Brien 1957; Sherkati et al. 2006; Carruba et al. 2006). In the seismic lines, the upper boundary of the Asmari Formation determines the distinction between surface and subsurface structures. The stratigraphy of the study area in the Lali structure can be divided into two sections of outcrops and subsurface (Fig 2). The outcrops belong to Neogene, Fars Group (Gachsaran, Mishan and Aghajari Formations) and Bakhtiari Formation.

These deposits are mostly syntectonic. Therefore, folding and uplifting of the Zagros fold-thrust belt has played an important role in the distribution of these formations. According to the data from the wells drilled on the Lali structure, the deepest unit of this structure is the Sarvak Formation with Cretaceous age (Cenomanian) (Fig 2).

In the maps and satellite imagery, the syncline structure is observed in the study area, but in the seismic lines, the anticline structure is observed in the depth. This represents a structural difference in surface and subsurface (Disharmonic Folding).

Considering the importance of geometric parameters and determining the folding mechanism in the exploration of hydrocarbon reserves, in this paper geometric parameters of the Lali anticline are measured and its mechanism has been determined from the time of formation until the present day. In the detachment folding mechanism, it is important to determine the detach surface and the detachment depth. This depth is necessary to provide tectonic models and structural studies because this surface causes a difference in the structural style of the upper and lower parts. An estimate detachment depth is effective for areas where there is no the outcrop structure. Hydrocarbon structures in the Zagros are deep and have no outcrops, determining the detachment depth of these structures is very important.

2. Methods

In this paper, based on geophysical studies, the National Iranian Oil Company (NIOC) obtained three seismic sections of the Lali structure. According to the data from wells drilled by the NIOC, stratigraphic sequences were

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*Corresponding author.
E-mail address (es): fghaemi@ferdowsi.um.ac.ir

adapted to the seismic lines. Using seismic sections and drilling wells, the Lali structure was interpreted in three sections. In each of the three sections, the geometric parameters of this structure were measured (Figs 3, 4 and 5). The A-A` section is about 32 km length and covers the northwestern part of the Lali structure (Fig 3). The amount of shortening in this section is 2350 meters. After removing the effect of the faults, this amount of shortening is reduced to 740 meters. The B-B` section is about 28 km length and covers the central part of the Lali structure (Fig 4). The amount of shortening during the brittle deformation is 1740 m and during the ductile deformation is 1920 m. The C-C` section is about 27 km length and covers the southeastern part of the Lali structure (Fig 5) and the amount of shortening is 4470 meters, 1830 meters is spent on ductile deformation. The location of these three sections is shown in Fig 1.

To determine the folding mechanism, determination of the geometric parameters of the fold during deformation Depending on the geological location, the folding mechanism may change over time. After determining is necessary. This not only shows the folding mechanism the geometric parameters of the Lali structure (includes deformation history reconstructed during several stages and in each step, geometric parameters of this structure of the present day, but it also shows the folding mechanism from the initial to the present day. The limbs dip, amplitude, wavelength, and crestal length), in order to determine these parameters, have been calculated. The folding mechanism is determined in the northwestern, the central and the southeastern parts of the Lali structure.

With the help of Move 2D and 3D, the Lali structure was restored and balanced in all the three sections (Figs 3, 4 and 5) and at each stage of reconstruction, the geometric parameters of the Lali structure were calculated, the results are presented in Tables 1, 2 and 3. This work is also motivated by the shortcomings in many of the existing kinematic models of fault-related folding that assume bed length is conserved, a stylized geometry in which folds are straight-limbed and sharp hinged (Suppe 1983; Contreras and Suter 1990, 1997; Hardy 1995; Suppe et al. 2004; Hardy and Connors 2006). A further criticism is that these models consider fault related folding as a steady state process (Poblet et al. 2004). Some of these assumptions are not physically realistic (e.g., Kwon et al. 2005) and appear to be unwarranted in the light of field data (Vergés et al. 1996; Poblet et al. 2004), experimental results (Biot 1961; Storti et al. 1997; Daëron et al. 2007).

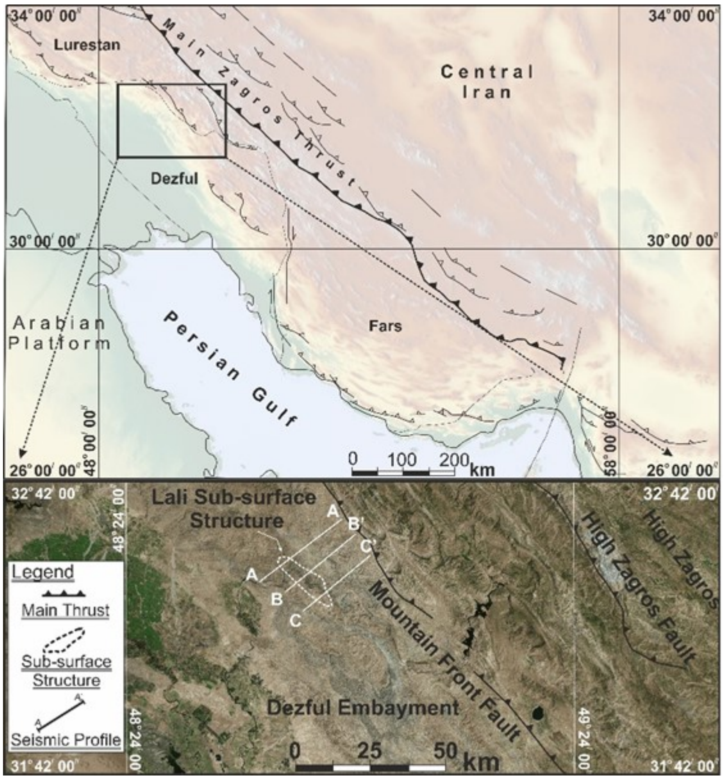

Fig 1. Location of the Lali structure relative to the Dezful Embayment and the boundaries.

Base on the folding mechanism diagrams (e.g., Suppe 1983; Suppe and Medwedeff 1990; Homza and Wallace 1995; Poblet and McClay 1996; Bulnes and Poblet 1999), the history of the folding mechanism of the Lali structure was obtained from the initial to the present time. Then these diagrams were interpreted for the Lali structure based on each section (Figs 6, 7 and 8). One of the folding mechanisms is fault-related folding that depending on the fault type is various. Fault propagation fold, detachment fold, and fault-bend fold are associated with thrust faults and en-echelon folds are associated with strike-slip faults (e.g., Suppe 1985; Jamison 1987; Mitra 1990; Suppe and Medwedeff 1990; Nemcok ea al. 2005). In the Zagros fold-thrust belt, most of the folds are associated with thrust faults (e.g., Sherkati et al. 2005; Verge´s et al. 2009; Soleimany et al. 2011; Soleimany et al. 2013).

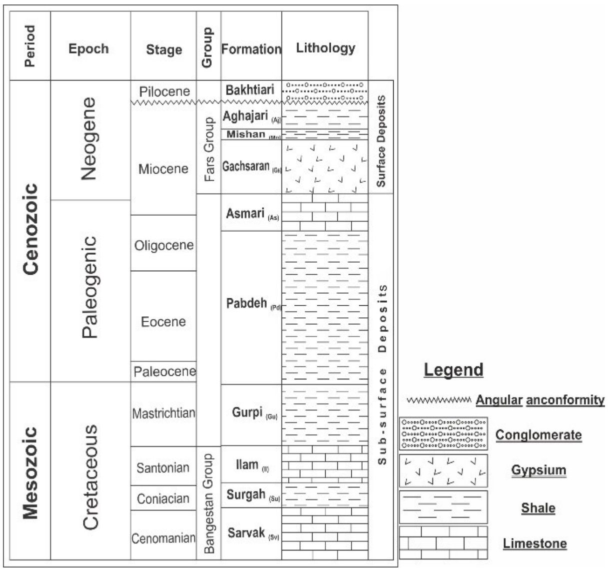

Fig 2. Simplified stratigraphy column of the Lali area, modified after (NIOC 2016).

Determining the depth of detachment was also necessary after the detachment folding mechanism of the Lali structure was determined.

One of the important features of the detachment folds is symmetry. These folds, especially in the initial of formation, have symmetric geometry and are usually formed in regions with difference rheological between stratigraphic units. In these folds, the base units, which is introduced as the detachment surface, is a layer with a low friction surface, such as evaporates and shale, that is covered with resistant layers such as carbonates and sandstones (Mitra 2003). Geometry and development of detachment folds depend on factors such as the thickness, the property of the ductility and the stratigraphic sequence of the region (Davis and Engelder 1985).

One of the methods for estimating the depth of detachment in detachment folds is the Chamberlin (1910, 1919) method (Fig 9). This method is based on the calculation and basis of the area-conservation principle, this method predicts that depth of detachment is equal the excess area beneath a particular horizon uplifted above the regional divided by the shortening undergone by this horizon. There is another method to estimate the depth of detachment base on the Chamberlin (1910), this method takes into account information at several stratigraphic horizons. This method is presented by Bulnes and Poblet (1999) (Fig 10). Because detachment folds often have a ductile core (shale, evaporation units, etc.) the migration of these units in different parts of folds increases the possibility of differences in cross-sections.

3. Results

By measuring the geometric parameters of the Lali structure in the seismic sections and calculating the geometric parameters obtained from the deformation stages, the folding mechanism of this anticline was determined from the initial to the present day in each section. In the A-A’ section, the folding mechanism of detachment fold is the Dahlstrom type but in some stages during the deformation, the Dahlstrom type changes to the migration or rotation types. In the early stages of the initial, the folding mechanism of the Lali structure changes from the fault-bend fold to detachment fold (Fig 6). In the B-B’ section folding mechanism is the detachment fold Dahlstrom type (Fig 7) that during stages of deformation inclined to the migration and rotation types. In the initial stages, due to the stratigraphic of the region, the folding mechanism was fault-bend fold (Fig 7). In the C-C section, the Dahlstrom type is oriented in periods of deformation to the migration and rotation types, and at the initial and the early stages of development, the folding mechanism was fault-bend fold. By increasing the amount of shortening and maturation of the structure, the folding mechanism is perfectly matched to the detachment fold (Fig 8). Due to the folding mechanism of the Lali structure, it was necessary to determine the depth of detachment. The amount of shortening, the excess area and finally the depth of detachment base on the Chamberlin (1910) method calculated for Asmari, Pabdeh, Gurpi and Ilam Formations and presented in Table (4). To calculate the detachment depth, only parts of the formations are considered that make the Lali structure. In the A-A` section, the depth of detachment is about 7795-8472 m. The higher detachment depth is related to the Asmari Formation and the lower detachment depth is related to the Ilam Formation (Table 4). It is clear that the younger formations show higher detachment depth due to their higher excess area. Therefore, the depth of detachment from the young formations to the old decreases. This process continues to the top of the main detachment horizon. In the B-B` section, the maximum and minimum detachment depths are 7518 and 7077 m respectively (Table 4). In the C-C` section, the depth of detachment for Asmari Formation is 8580 m and for the Ilam Formation is 7938 m (Table 4). In the Chamberlain (1910) method, the depth of detachment is calculated for a formation, and the interaction of formations on each other is neglected. In order to increase our accuracy, we calculated the depth of detachment based on each formation to better estimate the detachment depth.

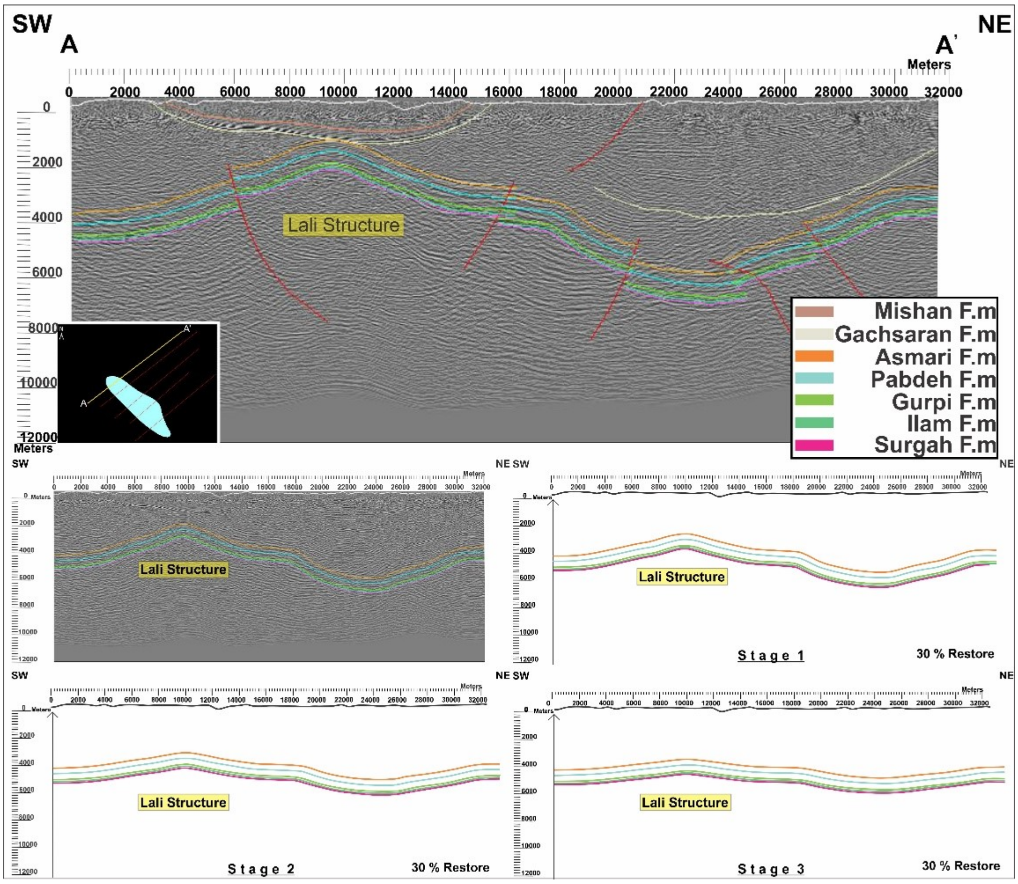

Fig 3. the A-A' seismic section and geometry of the Lali structure in the deformation stages. This profile located in the northwestern part on the Lali structure.

Table 1. The amount of shortening and geometric parameters of the Lali structure in the deformation stages of the A-A' seismic section.

Formations	Stages	Unfolded bed length (l0) meters	Deformed bed length (w) meters	Shortening (s) = l0-w meters	SW limb dip	NE limb dip	Amplitude meters	Half wavelength meters	Crestal length meters
Asmari	1	33430	32686	744	16	14	1148	6190	940
Asmari	2	33430	33085	345	10	10	687	6472	1014
Asmari	3	33430	33328	102	7	8	525	6562	1334
Pabdeh	1	33423	32686	737	16	15	866	6140	891
Pabdeh	2	33423	33085	338	10	12	599	6435	979
Pabdeh	3	33423	33328	95	8	9	480	6303	1167
Gurpi	1	33420	32686	734	15	15	768	5901	693
Gurpi	2	33420	33085	335	12	11	485	6068	807
Gurpi	3	33420	33328	92	8	8	450	5867	1075
Ilam	1	33418	32686	732	15	15	660	5595	627
Ilam	2	33418	33085	333	13	13	429	6040	670
Ilam	3	33418	33328	90	8	8	375	5785	908

After determining the depth of detachment base on Chamberlin (1910) method, the detachment depth was estimated by the Bulnes and Poblet (1999) method for Lali structure (Fig 11) because this method is based on the Chamberlin (1910) method, with the fundamental difference that this method is graphical and takes into account information at several stratigraphic horizons. In this graphical method, the vertical axis is the cumulative thickness of the stratigraphic units in the region and the horizontal axis is the depth of detachment obtained from the Chamberlain (1910) method for each formation (Fig 10). After plotting the points in the diagram, the best passing line, which crosses the horizontal axis and strikes the vertical axis, shows the depth of detachment for the stratigraphic units. Based on this method, the detachment depth for the A-A`, B-B and C-C` sections is 7400, 6800 and 7600 meters respectively (Fig 11).

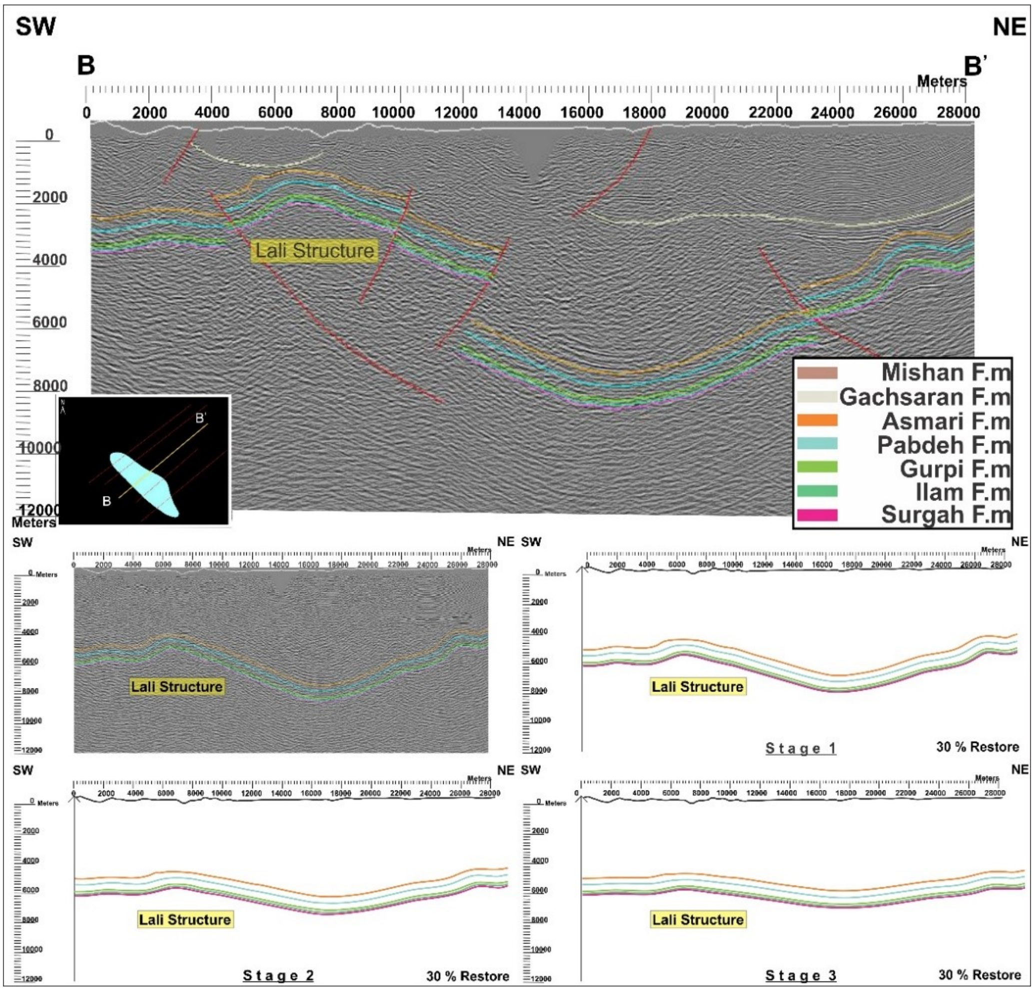

Fig 4. the B-B' seismic section and geometry of the Lali structure in the deformation stages. This profile located in the central part on the Lali structure.

Table 2. The amount of shortening and geometric parameters of the Lali structure in the deformation stages of the B-B' seismic section.

Formations	Stages	Unfolded bed length (l0) meters	Deformed bed length (w) meters	Shortening (s) = l0-w meters	SW limb dip	NE limb dip	Amplitude meters	Half wavelength meters	Crestal length meters
Asmari	1	30186	29272	914	17	17	542	3429	924
Asmari	2	30186	29736	450	14	11	436	3494	1132
Asmari	3	30186	29978	208	8	7	323	4180	1331
Pabdeh	1	30146	29272	874	20	16	514	3329	898
Pabdeh	2	30146	29736	410	16	11	383	3383	919
Pabdeh	3	30146	29978	168	11	8	281	3996	1148
Gurpi	1	30137	29272	865	23	17	823	3176	720
Gurpi	2	30137	29736	401	16	12	344	3247	723
Gurpi	3	30137	29978	159	10	7	225	3718	1063
Ilam	1	30134	29272	862	22	16	430	3120	672
Ilam	2	30134	29736	398	15	11	321	3139	704
Ilam	3	30134	29978	156	10	8	216	3375	988

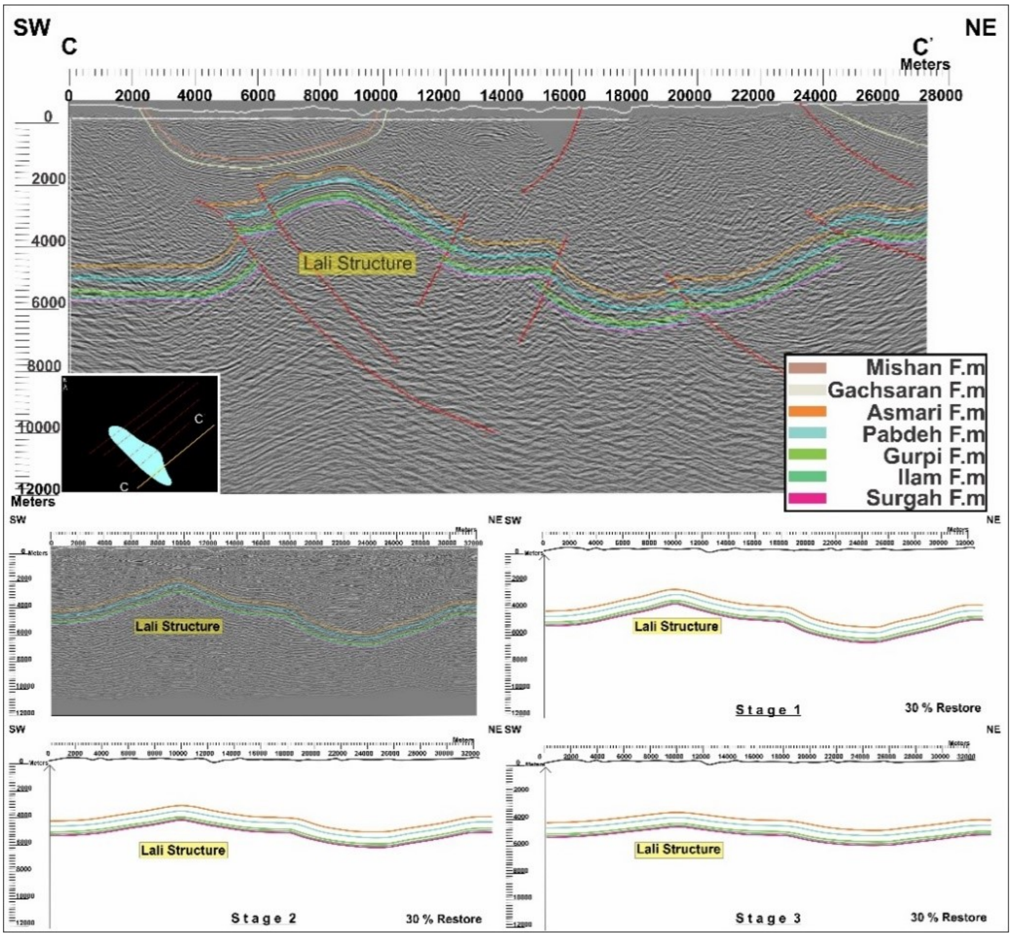

Fig 5. the C-C' seismic section and geometry of the Lali structure in the deformation stages. This profile located in the southeastern part on the Lali structure.

Table 3. The amount of shortening and geometric parameters of the Lali structure in the deformation stages of the C-C' seismic section.

Formations	Stages	Unfolded bed length (l0) meters	Deformed bed length (w) meters	Shortening (s) = l0-w meters	SW limb dip	NE limb dip	Amplitude meters	Half wavelength meters	Crestal length meters
Asmari	1	29243	28271	972	23	19	1194	5518	867
Asmari	2	29243	28708	535	16	14	729	5121	947
Asmari	3	29243	29039	204	12	9	494	5462	1041
Pabdeh	1	29146	28271	875	23	20	1066	5077	725
Pabdeh	2	29146	28708	438	15	13	729	4846	781
Pabdeh	3	29146	29039	107	13	10	455	5013	910
Gurpi	1	29177	28271	906	23	21	1066	4942	611
Gurpi	2	29177	28708	469	15	15	653	4827	653
Gurpi	3	29177	29039	138	11	9	455	4879	910
Ilam	1	29175	28271	904	22	21	1109	4856	597
Ilam	2	29175	28708	467	15	14	653	4718	601
Ilam	3	29175	29039	136	11	9	429	4854	767

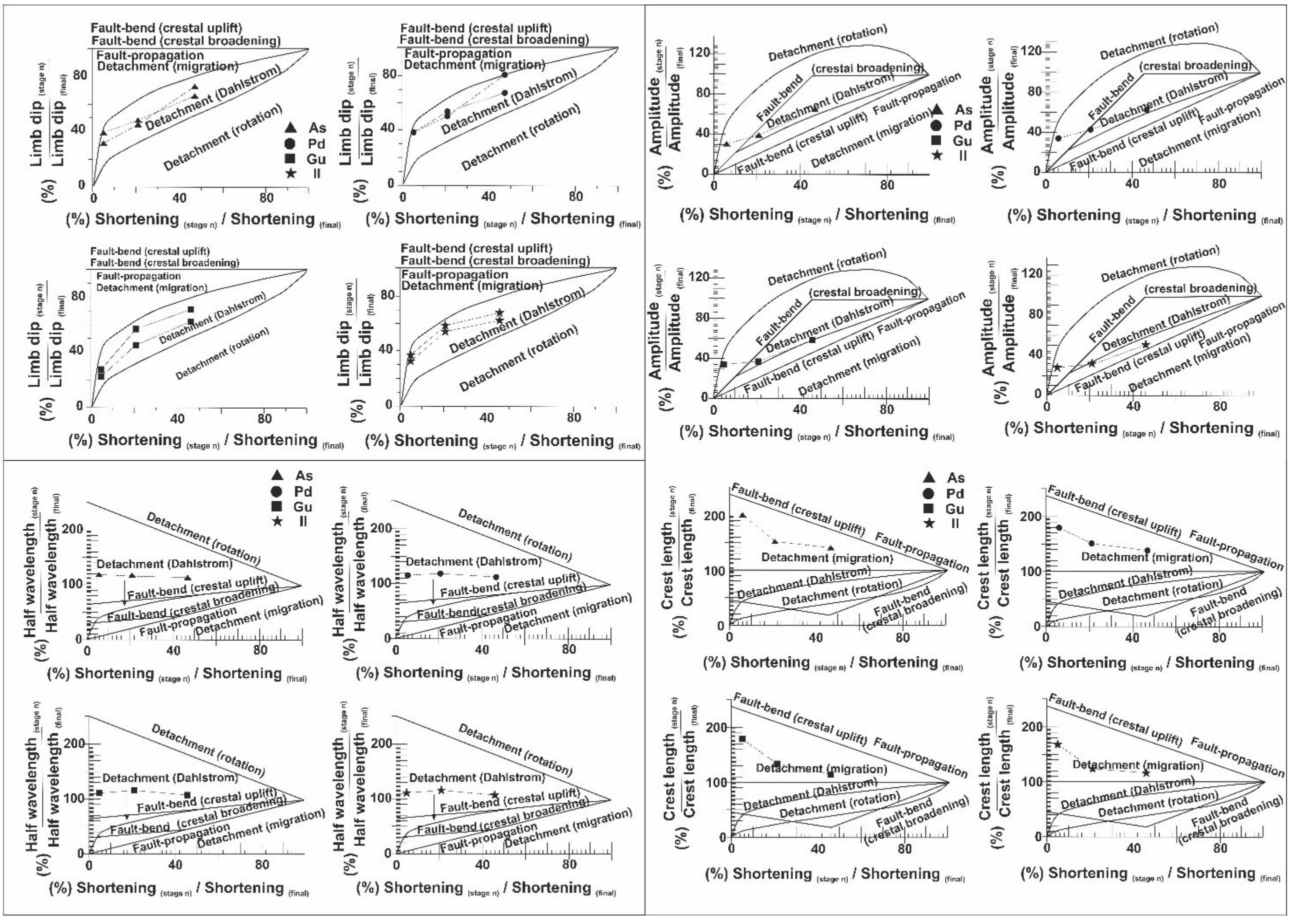

Fig 6. The folding mechanism history of the Lali structure in the A-A' section. Based on parameters of the limbs dip, amplitude, wavelength, and crestal length, the folding mechanism of the Lali structure is detachment fold.

4. Discussion

In the A-A` section, based on the geometric parameter of the dip of limbs, the history of the folding mechanism of the Lali structure was determined (Fig 6). Based on this parameter, the folding mechanism from the initial to the present day has always been the detachment fold Dahlstrom type. The Southwestern limb of the Lali anticline in this section shows a tendency to change more than the northeastern limb. In the early stages of deformation, the southwestern limb tends to the migratory type, with the continuation of the deformation, this limb adapted to the Dahlstrom type (Fig 6).

Based on the geometric parameter of the amplitude, the initial folding mechanism of the Lali structure has been the fault-bend fold. With the continuation of the deformation, the mechanism has changed and has become a detachment fold. The detachment fold Dahlstrom type has dominated the Lali structure until the final stages and in the present day tends to the migration type (Fig 6). The folding mechanism of Lali structure has always been fixed based on the geometric parameter of wavelength since the initial until the present day and shows that Lali structure is a detachment fold Dahlstrom type (Fig 6). Based on the geometric parameter of the crestal length, the folding mechanism of the Lali structure has always been the detachment fold migration type since the initial until the present day (Fig 6). In the B-B` section, based on the geometric parameter of dip of the limbs, the folding mechanism of Lali structure is a detachment fold Dahlstrom type (Fig 7). Based on the geometric parameter of the amplitude, the initial mechanism of the folding is the fault bend fold, with the continuation of the deformation, the mechanism has changed and the Lali structure has become a detachment fold Dahlstrom type (Fig 7).

Based on the geometric parameter of wavelength, the folding mechanism from the time of the formation to the present day has always been the detachment fold Dahlstrom type. Another geometric parameter used to determine the folding mechanism of the Lali anticline is the crestal length, according that the folding mechanism from the initial to the present day is the detachment fold migration type and tends towards the Dahlstrom type (Fig 7).

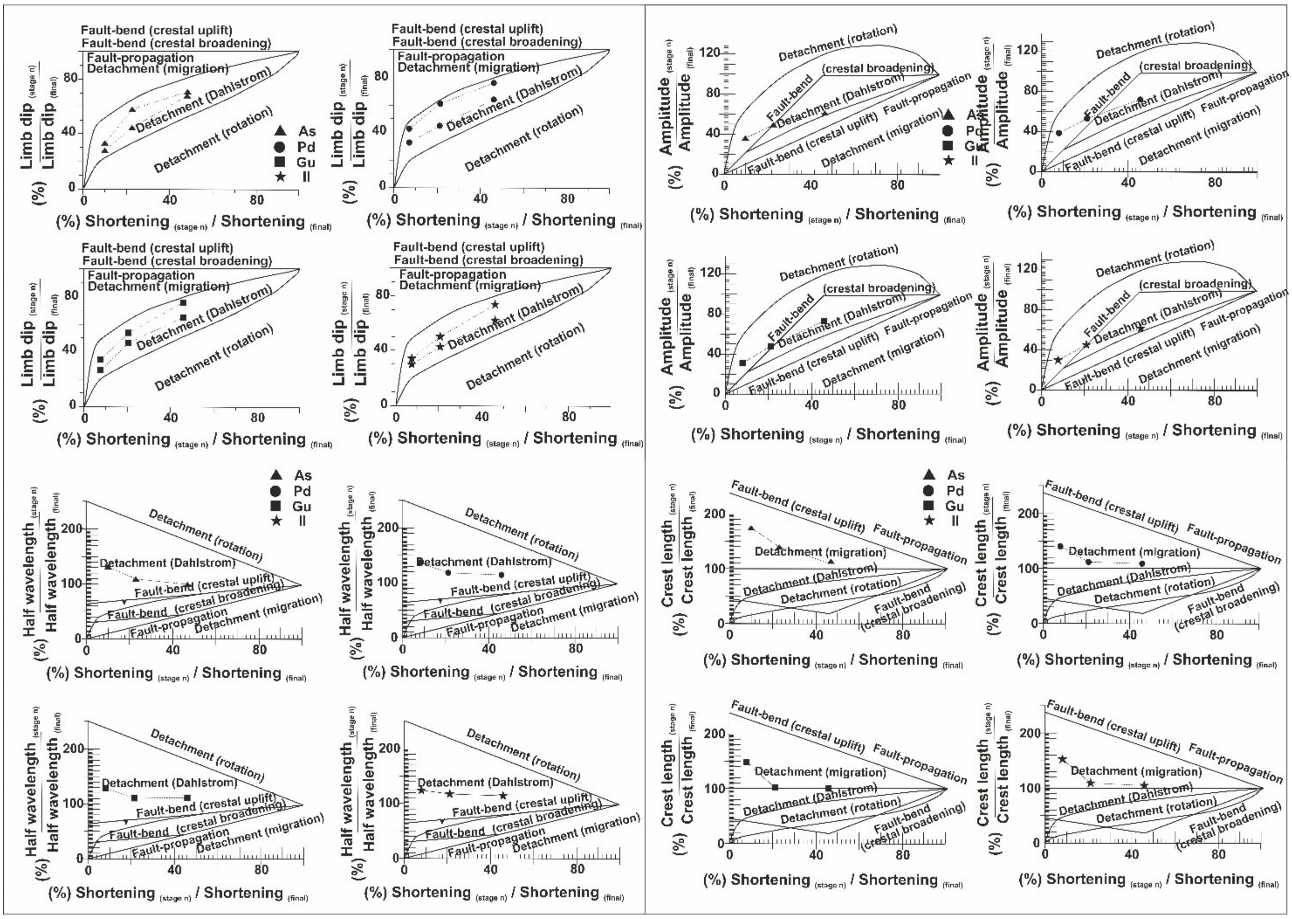

Fig 7. The folding mechanism history of the Lali structure in the B-B' section. Based on parameters of the limbs dip, amplitude, wavelength, and crestal length, the folding mechanism of the Lali structure is detachment fold.

In the C-C` section, the folding mechanism based on the geometric parameter of dip of the limbs has always been the detachment fold Dahlstrom type (Fig 8). The folding mechanism of the Lali structure in the early stage of deformation was the fault bend fold, based on the amplitude parameter. With the continuation of the deformation and growth of the fold, the Lali structure has become the detachment fold. The structure has a distinction between the Dahlstrom type and the migration type (Fig 8).

Based on the geometric parameters of the wavelength and the crestal length, the folding mechanism of the Lali structure has been the detachment fold from the initial to the present day. The detachment fold types are the Dahlstrom type and the migration type, respectively (Fig 8).

According to the history of the folding mechanism, the primary mechanism of the Lali structure has been the fault-bend fold. One of the most important reasons for that is the difference in the rheology of the stratigraphic units in the region (Fig 2). The stratigraphic units in the region is a periodic competent and incompetent layers. The different behavior of the stratigraphic units is the main factor in the formation of fault propagation fold, fault-bend fold and detachment fold types. This factor can lead to the formation of ramp, after the formation of the ramp, the continuity of the folding mechanism can be either fault-bend fold or detachment fold.

Due to the thickness of evaporate deposits in the Dezful Embayment (Fig 2), the continuation of the folding mechanism of the Lali structure coincides with the detachment fold. The Lali structure is a class of fault-related folds denominated low amplitude detachment folds. This anticline is a structure with a small amount of contraction.

The percentage of shortening in the A-A`, B-B` and C-C` sections is %2.2, %2.5 and %3.4, respectively (Tables 1, 2 and 3). These low values of shortening, regardless of the effect of faults, in the Lali structure also show that the anticline, in addition to the low amplitude visible in the geophysical sections, has also been compacted slightly. As the amount of shortening and deformation continue, detachment folds become disharmonic. Fig 12 shows the effect of increasing deformation on the detachment folds in the Jura Mountains, Switzerland, and the Tian Shan Piedmont, Central Asia (Contreras 2010).

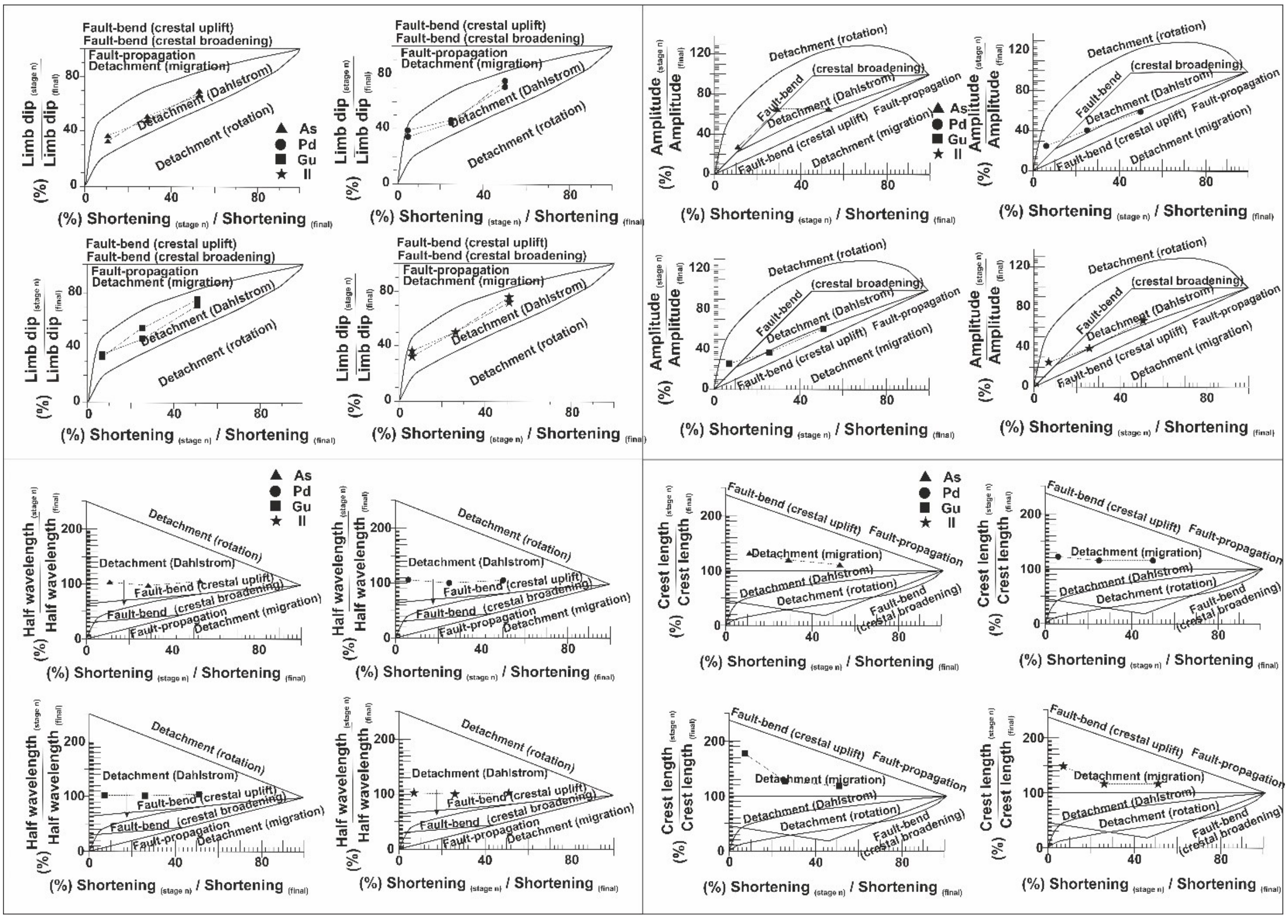

Fig 8. The folding mechanism history of the Lali structure in the C-C' section. Based on parameters of the limbs dip, amplitude, wavelength, and crestal length, the folding mechanism of the Lali structure is detachment fold.

Table 4. Calculation of the detachment depth for the Lali structure base on Chamberlin (1910) method.

Sections	Formations	Unfolded bed length (l0) meters	Deformed bed length (w) meters	Shortening (s) = l0-w meters	Excess Area (Af) sq meters	Detachment depth (z) = Af/s meters
A-A`	Asmari	6018	5657	361	3058556	8472
A-A`	Pabdeh	6019	5657	362	2993902	8270
A-A`	Gurpi	6019	5657	362	2879909	7955
A-A`	Ilam	6020	5657	363	2829910	7795
B-B`	Asmari	6768	6377	391	2939547	7518
B-B`	Pabdeh	6748	6377	371	2814567	7586
B-B`	Gurpi	6757	6377	380	2784842	7328
B-B`	Ilam	6761	6377	384	2717801	7077
C-C`	Asmari	10022	9036	986	8460761	8580
C-C`	Pabdeh	9957	9036	921	7604282	8256
C-C`	Gurpi	9953	9036	917	7370079	8037
C-C`	Ilam	9955	9036	919	7295362	7938

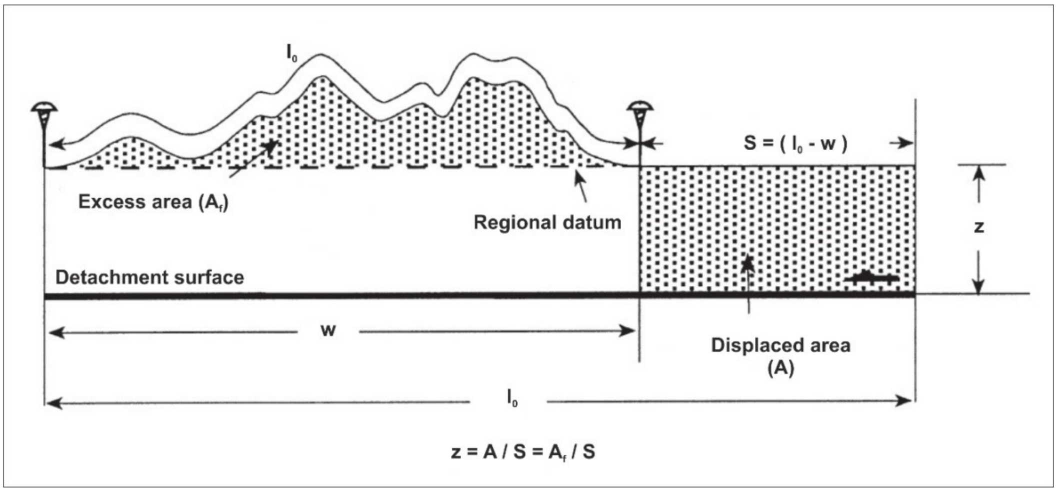

Fig 9. Relationship between excess area and depth of detachment in Chamberlin's method (1910). Abbreviations: z, depth of detachment; S, shortening; l_0, initial bed length; w, fold width; A_f, uplifted area in the anticline core; A, displaced area.

These changes can vary depending on the geological location and the structural and stratigraphic conditions. Considering the effects of faults on the Lali structure in the present day, in addition to the effect of brittle deformation on this anticline, this structure is progressing to increasing deformation. Previously, the difference between the amount of shortening with the effect of faults and without considering them was discussed. Detachment folds are divided into three types: migration, rotation, and Dahlstrom. Fold growth is achieved by changes in bed thickness, bed length, and rigid body rotation while maintaining the hinges fixed and the depth of the detachment constant (e.g., Epard and Groshong 1993; 1995). Due to these factors and the effect of deep faults on the limbs of this anticline during deformation, the folding mechanism varies between three types of Dahlstrom, migration, and rotation.

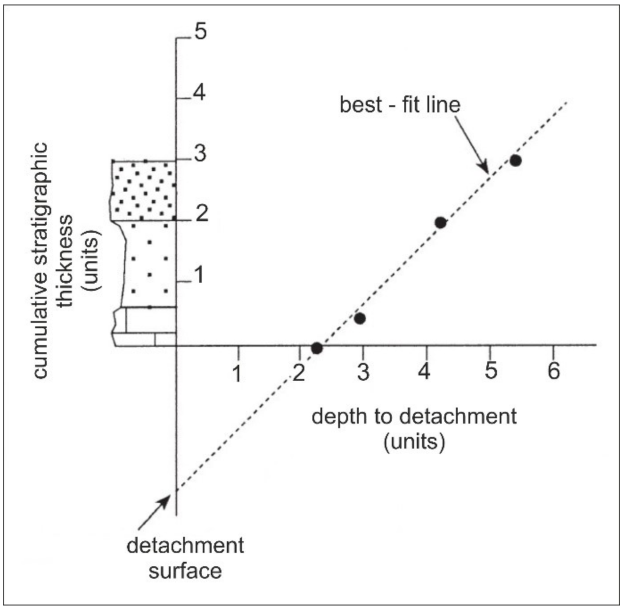

Fig 10. Graphical method to estimating detachment depth, this method is presented by Bulnes and Poblet (1999).

The depth of detachment was calculated by using the existing methods. The depth of detachment was determined for the Lali structure between 7500 and 8500 meters (Table 4 and Fig 11).

The calculated detachment depth for the Lali structure is different because the horizons of detachment show immobility behavior, it is expected that in the central parts of the Lali structure, the volume of accumulation will be higher than the northwestern and southeastern parts of the fold. In central parts of Lali structure, fold has shorter amplitude relative to the northwestern and southeastern parts, as a result, there is a difference in the thickness and depth of detachment horizon (Fig 11).

Stratigraphic rheology in the study area is another reason for that. In the study area, there can be seen several sequences of competent and incompetent layers in the stratigraphy column (Fig 2). In other words, between Asmari Formation and main detachment horizon has a different detachment horizon.

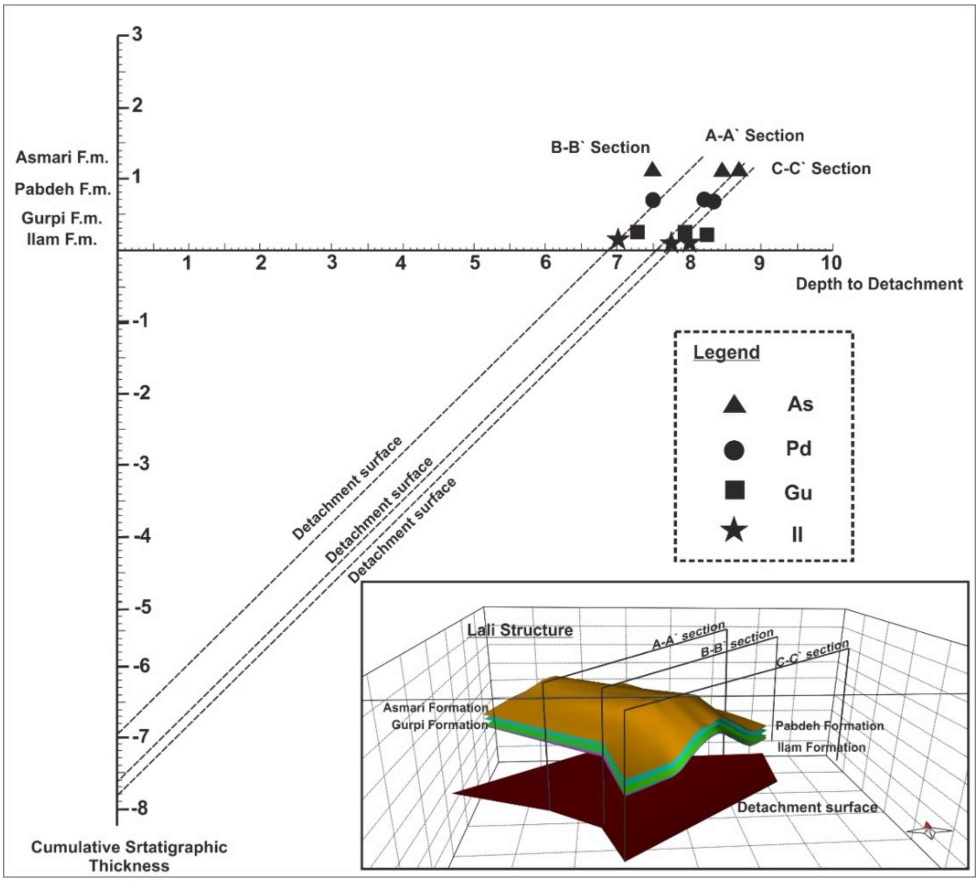

Fig 11. Estimate the detachment depth for the Lali structure base on Bulnes and Poblet (1999) method. For more details, see text.

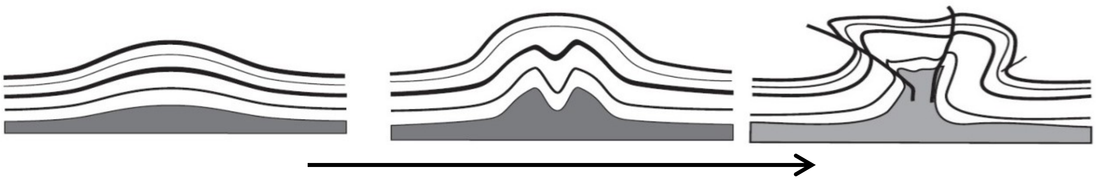

Fig 12. Progression of deformation in detachment folds based on observations in the Jura Mountains, Switzerland, and the Tian Shan Piedmont, Central Asia. The detachment surface lies at the base of the gray basal layer (Contreras, 2010).

5. Conclusion

Based on the study of the Lali structure, one of the most important subsurface anticline in Dezful Embayment, the following results were obtained. These results derive from the history of the folding mechanism of this structure from the initial to the present day and the determination of the detachment depth by two computational and graphical methods:

1- In the early stage of deformation, the folding mechanism of the Lali structure has been the fault-bend during deformation stages, the detachment folding mechanism varies between three types of Dahlstrom, migration, and rotation.

fold. The formation of the ramp due to the rheological difference of the stratigraphic units in the region caused this folding mechanism.

2- Due to the thickness of the stratigraphic units and with the continuation of the deformation, the mechanism has changed and the Lali structure has become a detachment fold.

3- Due to the bed thickness, the bed length, and the rigid body rotation factors and the effect of these factors on the geometric parameters of the Lali structure

4- The depth of detachment was determined for the Lali structure between 7500 and 8500 meters. Because the horizons of detachment show immobility behavior, there is a difference in the thickness and detachment depth

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