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

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Chapter 4

MAGNETOSTRATIGRAPHY AND TIMING OF DEFORMATION IN PUSHT-E KUH ARC, LURESTAN AREA, ZAGROS IRAN

4. TIMING AND SEQUENCE OF FOLDING IN THE NW ZAGROS, IRAN CONSTRAINED BY MAGNETOSTRATIGRAPHY

4.1 Introduction

Dating syntectonic sediments (growth strata) in foreland fold-and-thrust belts is a key point for understanding their evolution. The magnetostratigraphy is an appropriate technique for dating nonmarine deposits where other methods are not possible. Successful results of magnetostratigraphic studies have been published from most foreland basins in the World: Himalaya (e.g., Burbank and Raynolds 1988), Andes (e.g., Reynolds et al., 1990; Jordan and Alonso 1987), Alps (e.g., Schlunegger et al., 1997), Pyrenees (e.g., Burbank et al., 1992), Tien Shan (e.g., Heermance et al., 2007), and Zagros (Homke et al., 2004).

The closure of the Tethys realm between Arabian and Iranian plates produced the NW-SE trending Zagros fold and thrust belt. Deformation in the cover succession mostly occurred near the Suture Zone across the Imbricate Zone that is separated from the Zagros Fold Belt by the High Zagros Fault (**Fig. 36**). The Zagros collisional orogen is divided in four main tectonic domains (e.g., Alavi 1994; Berberian 1995) from which the Zagros Fold Belt (also named Simply Folded Belt) and the Mesopotamian foreland basin are the most important for the aim of this study. The Zagros Fold Belt tectonic unit is bounded along its most external limit by the Mountain Front Flexure (Falcon, 1961; Emami et al., in press). The Mountain Frontal Flexure shows an irregular geometry with salients (arcs) and re-entrants (embayments), which from SE to NW are: the Fars Arc, the Dezful Embayment, and the Pusht-e Kuh Arc (e.g., Dunnington, 1968; Alavi, 1994; Sattarzadeh et al., 2000) (**Fig. 36**). On the basis of lateral facies variations, the Zagros Simply Folded belt is divided into three different stratigraphic provinces: the Fars Province that coincides with the Fars Arc, the Khuzestan Province that fits with the Dezful Embayment and the Lurestan Province that matches the Pusht-e Kuh Arc (e.g,, Motiei 1994; 1995) (**Fig. 36**).

The Simply Folded Belt is formed by a large number of folds exhibiting a whaleback shape that are the traps of the largest foreland hydrocarbon province in the World (e.g., Bordenave and Hegre, 2005). Although the age of the observed folding was attributed to a young event occurring at about the Miocene-Pliocene boundary there is not consensus about the longer evolution of the Zagros Fold Belt. The age at which the

shortening was transferred to the front of the Pusht-e Kuh Arc to form folds was determined by means of magnetostratigraphy in the Changuleh growth syncline at 7.65 Ma (Homke et al., 2004). However, the longer term as well as the sequence of deformation is still unresolved.

For this reason, we investigate in this paper the timing of growth of two synclines showing syntectonic deposition in the centre of the Pusht-e Kuh Arc (Afrineh growth syncline) and in the Izeh Zone along the footwall of the High Zagros Fault (Chaman Goli growth syncline) by means of magnetostratigraphy. Their timing of growth together with additional recently published dating will constrain the large-scale evolution of folding across the Zagros Fold Belt defining the sequence of deformation from the footwall of the High Zagros Fault to the foreland basin (**Fig. 36**).

4.2 Timing of Zagros collision: a review

The Zagros orogeny took place along a protracted period of deformation. However, its complete evolution is difficult to ascertain because of the strong folding that occurred in Neogene times partially or totally masking previous folding history. Earlier evolution of Zagros collision is only partially recorded in the geological successions and thus different authors working in different areas reached different but certainly complementary results. In this short review we only try to summarize results based on constrained ages in the Zagros Fold Belt.

Gidon et al. (1974) concluded that deformation occurred in two major tectonic phases related to the closure of the Neo-Tethys Ocean. The first compressive deformation event started during the Late Cretaceous when the ophiolitic slices were obducted on top of the northeast border of the Arabian passive margin (Ricou, 1994; Ravaut et al., 1997). The second tectonic event was related to the final oceanic closure with an age lasting from Eocene (Braud, 1987; Sengör et al., 1993) to upper Miocene (Stoneley, 1981; McQuarrie et al., 2003).

Hessami et al. (2001) described several unconformities within the Cenozoic stratigraphy of the Simply Folded Zagros in both Dezful Embayment and Fars Arc and separated deformation pulses, which occurred at the end of the Eocene, in Early Miocene, in Middle-Late Miocene and during the Pliocene. They suggested that these pulses of deformation progressively propagated from northeast to southwest across the entire Zagros Simply Folded Belt (their figure 7).

Sherkati et al. (2005) interpreted two phases of folding for the Zagros, which are in relation to the Neogene and younger compressive event. They provided evidences, based on seismic interpretation from the Ab Tymure, Parsi and Karnj anticlines in the Dezful Embayment, for a first episode of deformation with a pre-upper Gachsaran Formation age (Middle Miocene) and a second episode during the Late Miocene based on magnetostratigraphic studies by Homke et al. (2004).

Ahmadhadi et al. (2007) based on fracture studies in the Central Zagros interpreted that the first stage of basement fault reactivation may have started as early as the Oligocene during the deposition of the Asmari Formation. They proposed that this early reactivation of basement blocks can mark the older age for the initial plate collision between Late Oligocene and Early Miocene (30 to 22 Ma).

Homke et al. (in press) determined new ages for initial folding in the Pusht-e Kuh Arc based on a multidisciplinary study combining magnetostratigraphy, biostratigraphy using large foraminifera and calcareous nanoplankton, strontium isotope dating and detrital fission track ages applied to the Amiran anticline. The about 2-My long hiatus during the Late Cretaceous-Paleocene boundary (lack of NP1 and NP2 zones) at the base of the Amiran Formation is interpreted as recording an early phase of folding previoulsy distinguished only along the Persian Gulf. The reconstruction of the Amiran-Taleh Zang-Kashkan succession in this north-eastern part of the Pusht-e Kuh Arc shows that the inner part of the Amiran basin was thrusted and uplifted synchronously to the flexural basin development. A second and longer sedimentary hiatus was identified in this region encompassing the Middle and Late Eocene that is inferred to be concomittnat of either stress migration to weaker areas of the large-scale Arabia-Iran collision or to deep seated processes as discussed in Homke et al. (in press).
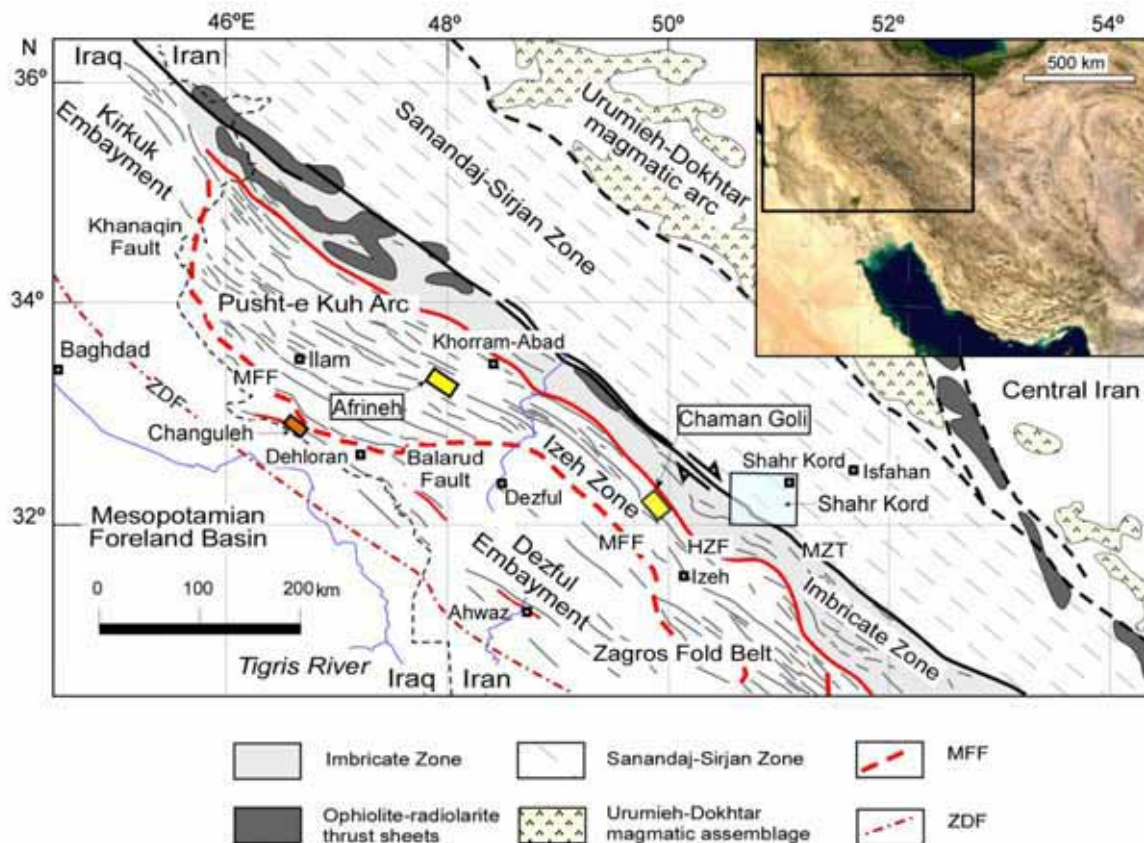
Fig. 36. *Tectonic map of NW Zagros to show the location of Afrineh and Chaman Goli growth synclines. Changuleh (Homke et al., 2004) and Shahr Kord (Fakhari et al., 2008) localities are also shown. MZT= Main Zagros Thrust, HZF=High Zagros Fault, ZDF= Zagros Deformation Front.*

4.3 Foreland stratigraphy and location study

The upper part of the thick Cenozoic sedimentary pile in Zagros Fold Belt corresponds to the foreland basin sequence on top of the passive margin sequence lasting from the Upper Palaeozoic to the Late Cretaceous (Colman-Sadd, 1978; James and Wynd, 1965). The 3-4 km thick Mesozoic succession, mostly formed by carbonates and marls, involves the major oil reservoirs in the upper part of the Bangestan Group (Sarvak Formation). The Cenozoic stratigraphic units record the evolution of the foreland basin and of its deformation history where the Paleocene and Early Eocene clastic successions filled up the early foreland basin (Homke et al., in press) (**Fig. 37**).

During the Paleocene, to the north of the Kabir Kuh anticline, a thick shallowing-upward siliciclastic succession was deposited, which includes the Amiran, Taleh Zang, and Kashkan formations (e.g., James and Wynd, 1965; Homke et al., in press) (**Fig. 37**).

The Shahbazan and Asmari formations, which correspond to the Tertiary main reservoir in the Zagros Oil Province, are Oligocene to Middle Miocene in age to the north of the Kabir Kuh anticline. Above the Asmari Formation, the about 1-km thick evaporites of the Gachsaran Formation correspond to the Lower Fars Group (e.g., Kashfi, 1980; Bahroudi and Koyi, 2004). These evaporites form an effective seal above the Asmari reservoir. The age of the top Gachsaran evaporites near the front of the Pusht-e Kuh Arc is constrained by magnetostratigraphy to be ~12.5 Ma, corresponding to the uppermost mid Miocene (Homke et al., 2004). Along the front of the Pusht-e Kuh Arc, the ~1650 m thick lower Agha Jari deposits encompasse the interval from 12.8-12.3 Ma to 5.5 Ma. Above these, the fine grained Lahbari Member (~825 m thick) ranges from 5.5 Ma to 3 Ma. The age of the conglomeratic Bakhtyari Formation is constrained to be from 3 Ma to at least 2.5 Ma, although its younger extrapolated age may correspond to ~1.5 Ma (Homke et al., 2004) (**Fig. 37**).
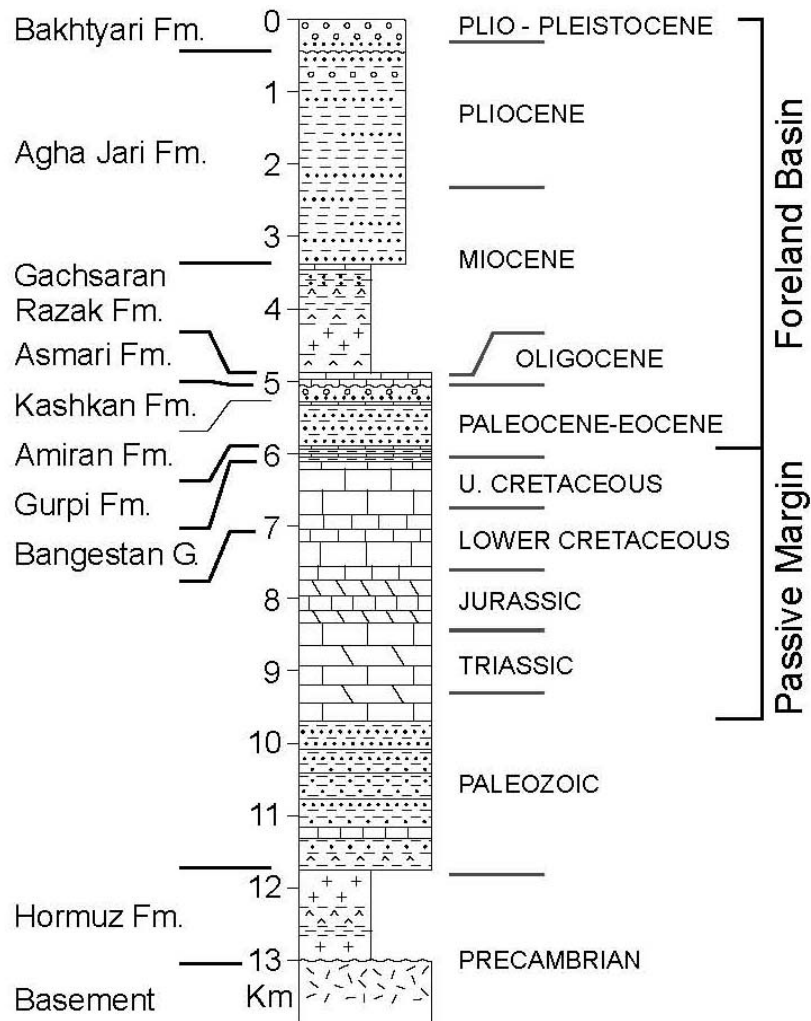
Fig. 37. *Simplified stratigraphy of the Lurestan Province (present Pusht-e Kuh Arc). This work refers to latest foreland deposits (after Vergés et al., in press).*
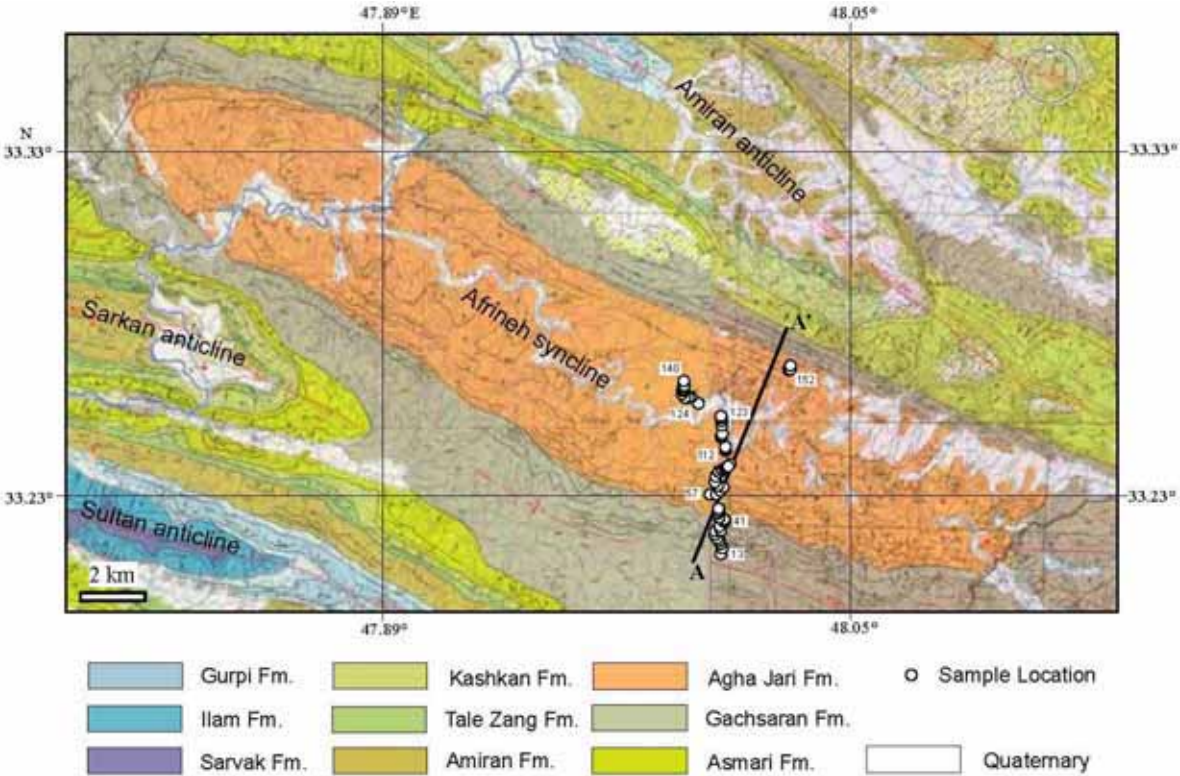
4.3.1 Afrineh syncline

The Afrineh syncline corresponds to one of the few synclines that remain in the Pusht-e Kuh Arc since the majority of them have been eroded away during uplift above the Mountain Front Fault (e.g., Emami et al., in press). The Afrineh syncline is about 31 km long and 5 km wide and is located between two relatively open anticlines: the Amiran anticline in the NE and the Sultan anticline in the SW (**Fig. 38**). The flanks of the syncline are steep (subvertical to overturned) above the ~1000 m of mean topography of the core of the syncline outcrops. These overturned flanks produced an irregular geometry for this syncline between two detached lift-off anticlines (in the sense of Mitra, 2003) but with a curved and open synclinal hinge domain where the

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studied Agha Jari section is gently folded (**Fig. 38** to **Fig. 41**). The syncline is asymmetric with a subvertical northeastern flank in which growth strata is well recognized (**Fig. 40A**). It is in its NE flank where the syncline shows growth strata patterns (**Fig. 40** and **Fig. 41**). A relatively thick section of Agha Jari deposits show subvertical dips and are overlaid by subhorizontal uppermost Agha Jari deposits above an angular unconformity (**Fig. 40**). Although at local scale the subhorizontal beds above the unconformity show a very abrupt change in dip from gently dipping to SW (~8º) to strongly dipping to SW (~85º), both the changes in thickness of each bed across this hinge zone as well as their oblique onlap attitude at larger scale clearly demonstrate that these uppermost beds are recording the growth of the syncline (**Fig. 40**). Below this unconformity no signs of growth strata patterns are observed and thus it is the contact limits pre-growth and growth strata units.

Sampled section starts 350 m stratigraphically below the Gachsaran-Agha Jari contact where nice levels of red-greenish mudstone and siltstone are interbeded with limestone and anhydrite (**Fig. 39**). The thickness of these clastic beds range between 0.5 and 9 m. The limestone beds decrease in thickness and number towards the Gachsaran-Agha Jari contact. The top of the last anhydrite bed, which seems to be quite continuous at the level of the SW flank of the syncline, is considered as the top of the Gachsaran Formation. The section also samples 850 m of Agha Jari deposits both pre-growth and growth. The greenish sand beds varying from 0.5 to 12 m in thickness, laminated reddish siltstone and mudstone, constitute the lower part of the Agha Jari Formation. Paleocurrent indicators at the base of the sand channels show main paleoflow direction to the N-114° and thus subparallel to the present trend of the syncline. The cross bedding and laminations within the sand and silt beds show a more variable trend ranging from N-80° to N-120° (**Fig. 39**).

The geological cross-section has been build using dip measurements along a relatively straight line following the sampling sites and connecting the growth strata locality in the NE flank of the syncline (**Fig. 41**). Pre-growth Agha Jari Formation shows the same thickness in both flanks of the syncline and thus the use of constant thickness construction for these ~550 m of succession seems reasonable. Along the wide hinge domain of the growth syncline the beds can be continued in map view as indicated in the cross-section as well as the contact between pre-growth and growth strata (depicted in dashed yellow line in **Fig. 40B** and **Fig. 41**).

Fig. 38. *Geological Map of the Afrineh syncline modified from 1/100000 geological maps of the Pul-e Dokhtar (Takin et al., 1970) and Khorram-Abad (Fakhari, 1985) to show the location of samples for magnetostratigraphy, and position of geological cross-section AA'.*
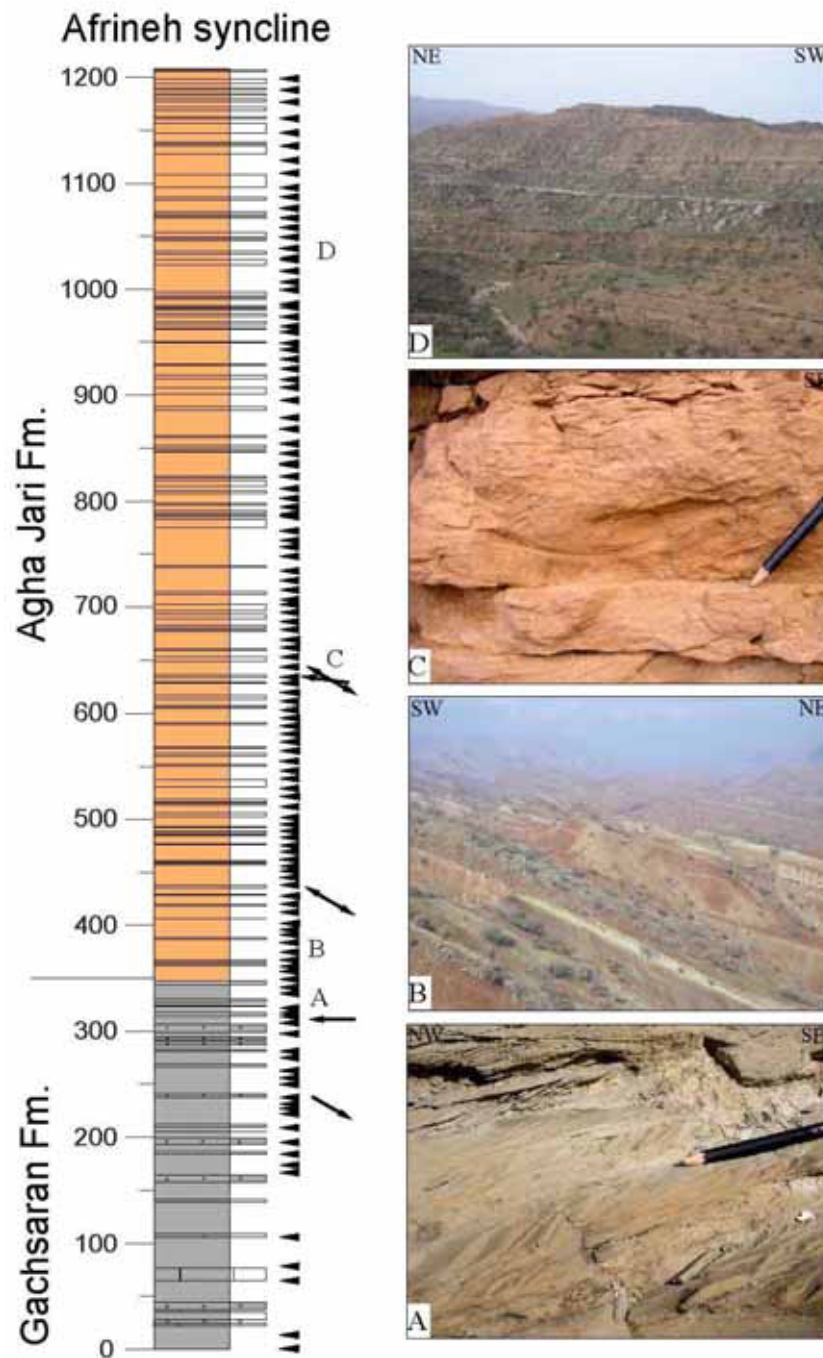
Fig. 39. *Stratigraphic section for top Gachsaran and Agha Jari formations in Afrineh syncline showing the position of samples for magnetostratigraphy, pictures (described in the text) and few measured paleocurrents.*
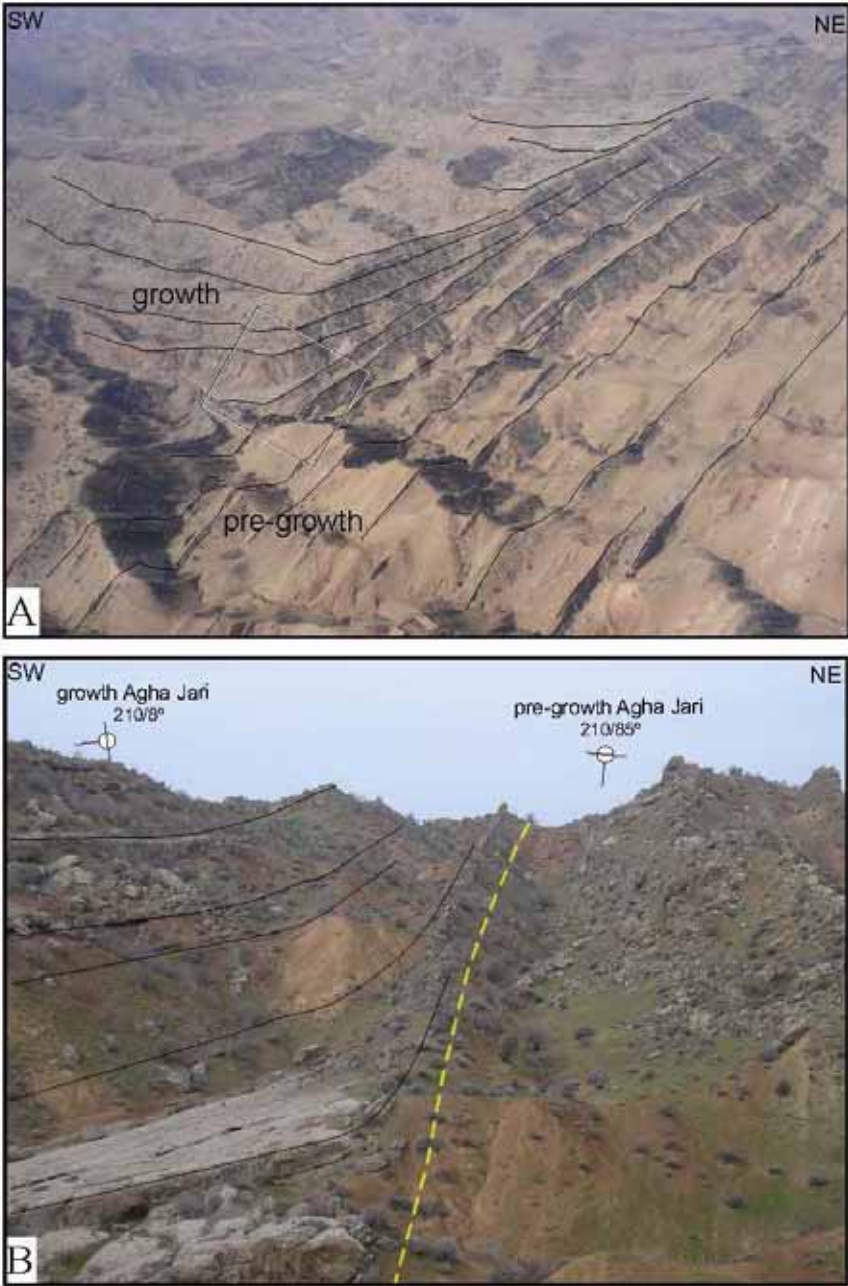
Fig. 40. *Helicopter and field views of the north-eastern limb of the Afrineh growth syncline where growth patterns show a major onlap of gently dipping beds against subvertical strata across a major unconformity depicted in dashed yellow line.*
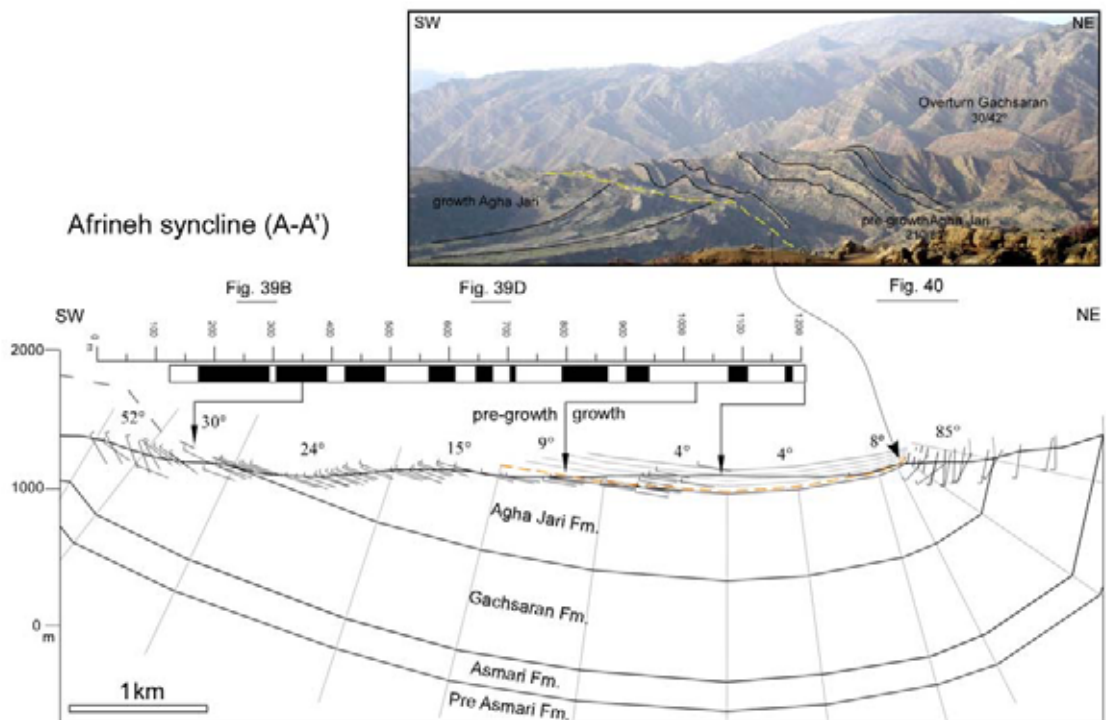
Fig. 41. *Geological cross-section AA' crossing the Afrineh growth syncline (see the location in* **Fig. 38**) *Agha Jari deposits are separated in pre-growth with uniform thickness and growth units.*

4.3.2 Chaman Goli syncline

The Chaman Goli syncline is located in the Izeh Zone along the footwall of the High Zagros Fault towards the SE of the Afrineh syncline (**Fig. 36** and **Fig. 42**). This syncline is located between the Keynow anticline with 3100 m of maximum altitude and the high Zard Kuh range to the NE, with 4220 m of elevation, and forming the hangingwall of the High Zagros Fault (**Fig. 43A** and **Fig. 43C-D**, respectively). The mean topography of the syncline is high and of about 1800 m above sea level. The High Zagros Fault in this area juxtaposed the lower Paleozoic rocks on top of the Agha Jari-Bakhtyari formations in its footwall (**Fig. 43C-D**).

The upper part of the foreland stratigraphy above the Asmari Formation in Chaman Goli syncline is different from previous one in Afrineh syncline and constituted by marl and limestone units of the Razak Formation. In more detail the Razak Formation is made of limestone beds, brown and gray marls, together with few gypsum beds. The Razak Formation deposited in the inner parts of the foreland system showing a highly variable thickness of about 200 m in the study region. This formation is time equivalent to the Gachsaran Formation towards the central and northeastern termination of the

folded zone (James and Wynd, 1965; Motiei, 1995). On top of this unit, more than 1.6-km thick nonmarine Agha Jari and Bakhtyari formations infill the Chaman Goli syncline (**Fig. 42A**). The ~800-m thick lower part of the Agha Jari succession is dominated by reddish silt and mudstone thick units with sand channel intervals. The passage from Agha Jari to Bakhtyari is not abrupt but progressive towards the top of the red beds succession. Thick conglomeratic (~10 m) units start to occur around 600 m above the base of the section and become predominant at about 1600 m indicating the interplay between distal (Agha Jari Formation) and proximal alluvial (Bakhtyari Formation) facies (e.g., Ramos et al., 2002; Vergés, 2007) (**Fig. 43** and **Fig. 44**). The only measured paleocurrent locality gives N-10º direction of flow. There is a gap in the stratigraphic section that corresponds to about 320 m because the difficulties on sampling rather than to the lack of outcrops. In this gap of measurements, however, there are indications of coarse conglomerates displaying growth strata patterns as maybe observed in **Fig. 43B**.

The Chaman Goli cross-section has been constructed using a large number of dips and strikes from bedding measured in the field during sampling collection. The SW side of the syncline shows a simple structure with beds decreasing their dip away from the steep flank of the Keynow anticline (**Fig. 43A** and **Fig. 45**). In the centre of the syncline subvertical beds with highly fractured limestones at the base of the succession seem to correspond to the hangingwall of a SW-directed thrust (**Fig. 45**). The highly fractured limestone unit at the base of the succession possibly corresponds to the upper part of the Razak Formation, which may correspond to an internal detachment level as depicted in geological cross-section.

The NE sector of the syncline shows multiple changes in dip that seem to correspond to small unconformities within the Agha jari-Bakhtyari units (**Fig. 43**). The uppermost part of the succession clearly shows a decrease in dip near the High Zagros Fault that is also indicative of growth strata (**Fig. 43C-D**). In this work we determine that growth strata geometries first occurred in the Agha Jari-Bakhtyari transition segment of the succession at about 1000-1200 m (**Fig. 44**).

The topmost part of the succession, in the footwall of the High Zagros Fault, is located below Palaeozoic strata gently dipping towards the NE. The geological map of the area shows few areas in which these topmost conglomerates seem to cover the High Zagros Fault trace and thus recording its fossilization. The gentle dips of the Palaeozoic strata above the High Zagros Fault probably are indicative of a low-angle thrust in contact with the NE flank of the Chaman Goli growth syncline (**Fig. 42** and **Fig. 43**). To

the NE, the topography as well as bedding of the High Zagros Fault hangingwall show steeper slopes that probably indicates ramp geometry at depth (**Fig. 42**).
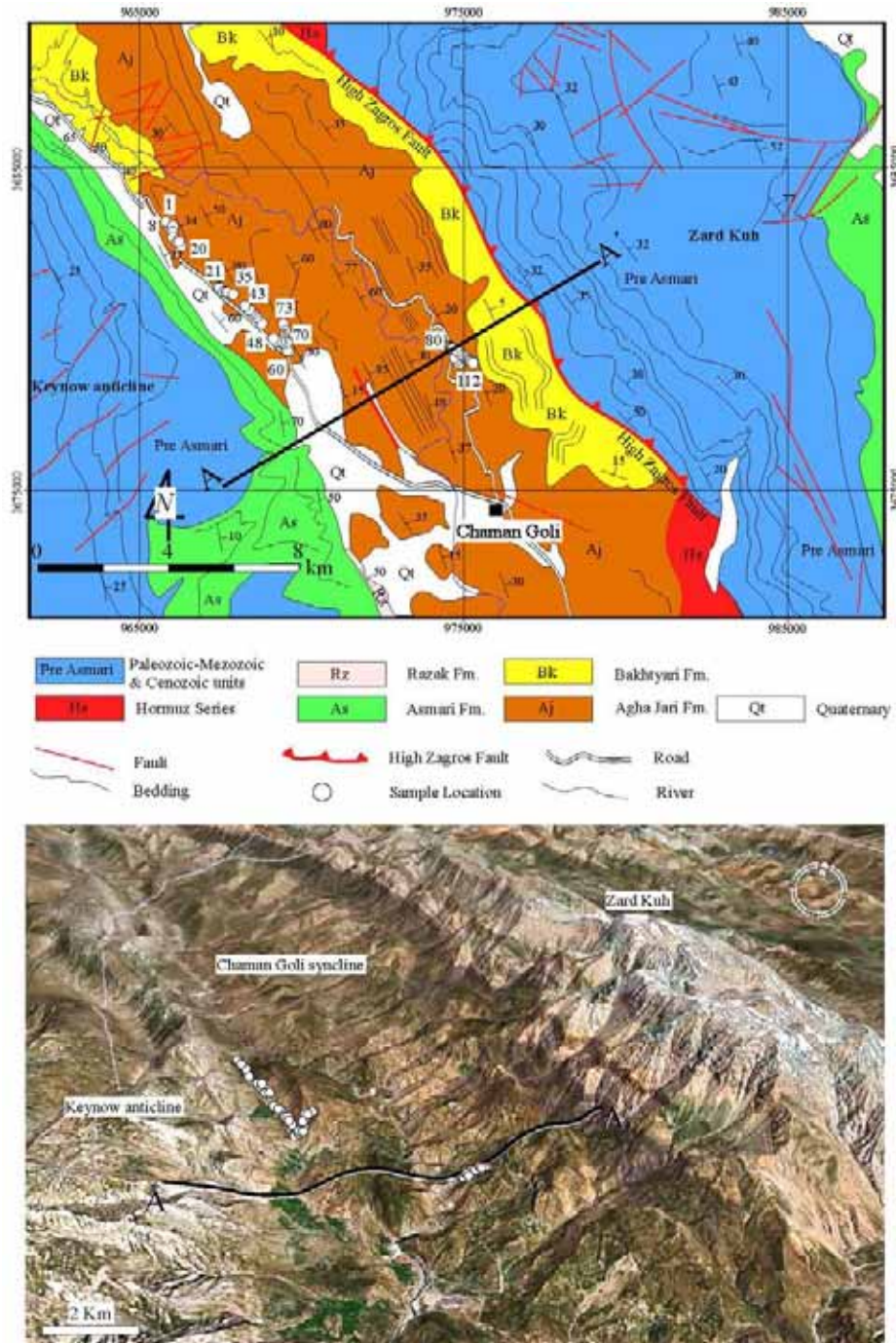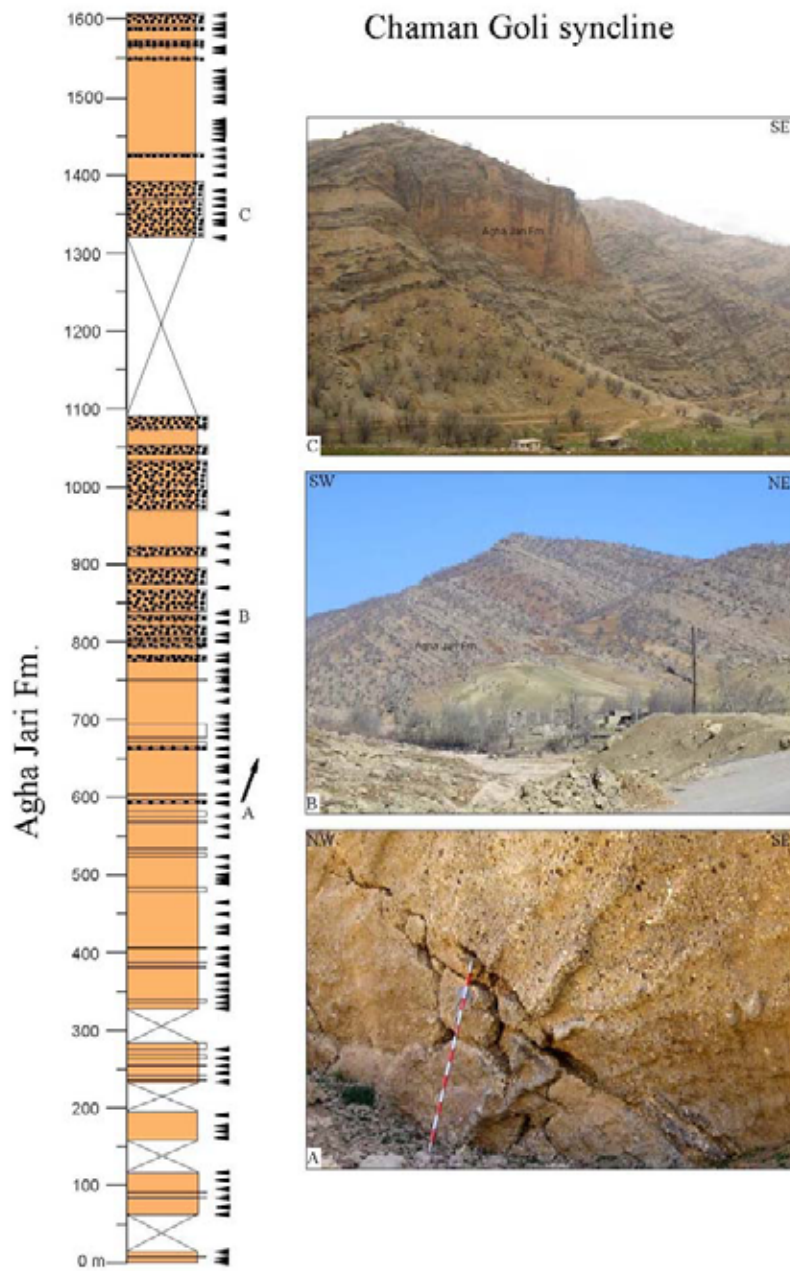

Fig. 42. Geological map of the Chaman Goli syncline in the footwall of the High Zagros Fault modified from 1/100000 geological maps of the Baba Heydar (Sheet No 20822W) and Kuh-e Kamestan (O'B Perry and Setudehnia, 1967) to show the position of samples for magnetostratigraphy and cross-section AA'. At the bottom 3D view from Google Earth showing the Chaman Goli syncline and location of the samples, section AA' is marked by balck line following the topography across the syncline.

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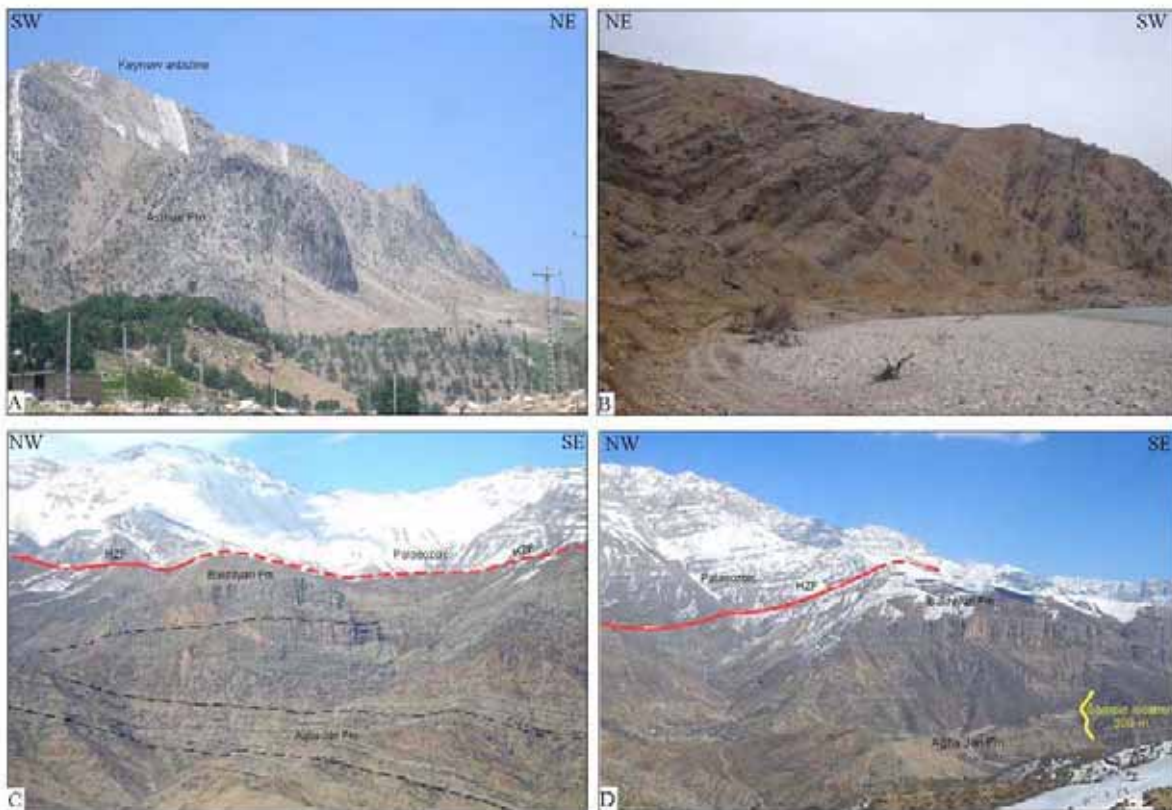
Fig. 43. *Field pictures showing the complex structure of the Chaman Goli syncline in the footwall of the High Zagros Fault. A) Subvertical north-eastern flank of the Keynow anticline at the level of Asmari Formation; B) Agha Jari deposits in the central part of the syncline showing growth patterns; C and D) views of the uppermost part of the section to show the contact relationships between the Agha Jari and Bakhtyari deposits in the footwall of the High Zagros Fault (HZF). In C these deposits show decreasing dips of the beds determined as growth pattern.*

Fig. 44. *Stratigraphic section for Agha Jari and Bakhtyari formations in Chaman Goli syncline showing position of samples for magnetostratigraphy, pictures and few measured paleocurrents.*
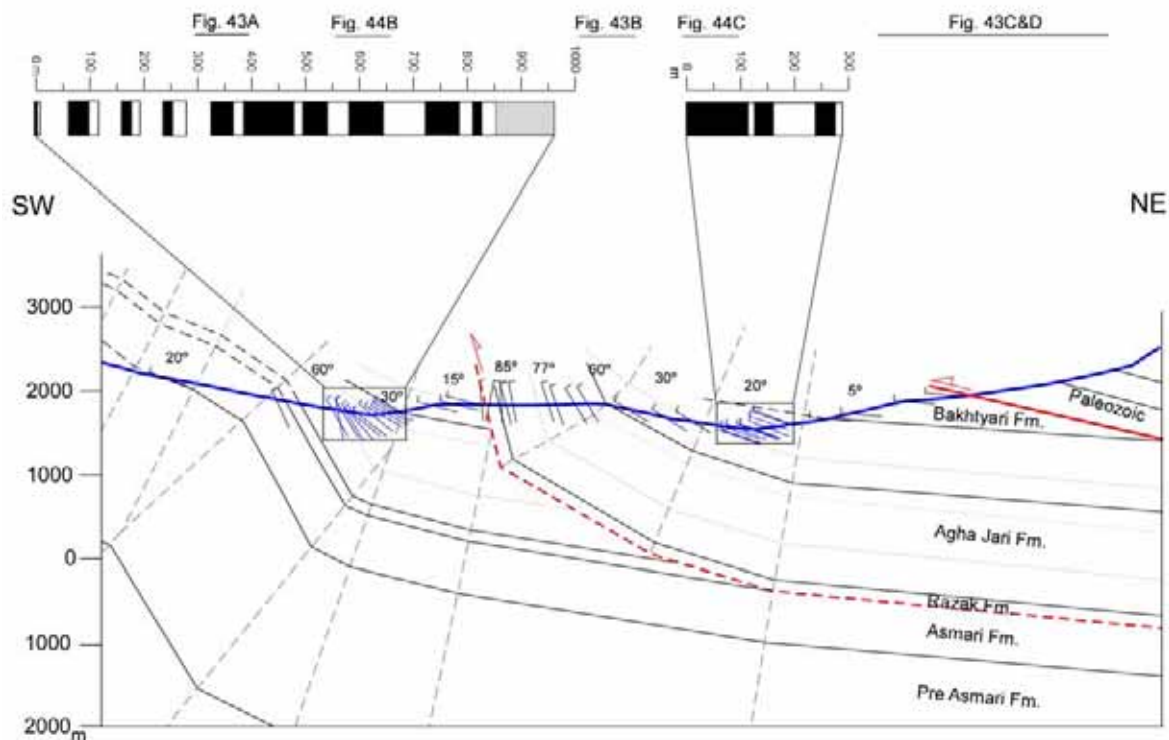
Fig. 45. *Geological cross-section across the Chaman Goli syncline. The samples have been collected in two separated sections. The High Zagros Fault (HZF) carries Paleozoic strata in its hangingwall.*

4.4 Magnetostratigraphy

4.4.1 Sampling strategy

Samples were collected in the field with a portable gas powered drill and oriented in situ with a magnetic compass coupled to a core orienting fixture. Favourable outcrop conditions and abundance of suitable lithologies allowed sampling of the Afrineh syncline section at regular intervals of about 10 meters. A total of 128 sites were drilled along the 1200 meters of the fine-grained red bed succession (**Fig. 39**). On the contrary, sampling of the Chaman Goli succession, located at altitudes above 2000 m was more complex due to both vegetation cover and climatologic conditions. Structural complexity also added difficulties in locating a best transect for sampling the Agha Jari Formation through the Chaman Goli syncline, which was eventually carried out along two different transects with a total of 107 sites for about 1300-m thick succession. Abundance of conglomerate intervals caused sampling gaps of tens of meters in the upper part of the section (**Fig. 44**). The average sampling interval of the Chaman Goli section is 12.5 m.

4.4.2 Paleomagnetic analysis

Paleomagnetic samples were analyzed at the Laboratory of Paleomagnetism of the CSIC-Serveis de Suport a la Recerca UB at the Institute of Earth Sciences "Jaume Almera" in Barcelona (Spain). The Natural Remanent Magnetization (NRM) was measured in a three axes superconducting rock magnetometer (2G Enterprises). In the Afrineh section, the average NRM intensity was of the order of $1500 \cdot 10^{-6}$ A/m, ranging from $37.4 \cdot 10^{-6}$ to $13620.4 \cdot 10^{-6}$ A/m. In the Chaman Goli section, the average NRM intensity was of the order of $1100 \cdot 10^{-6}$ A/m , ranging from $47.04 \cdot 10^{-6}$ to $13683 \cdot 10^{-6}$ A/m. In order to identify the different NRM components, routine stepwise thermal demagnetization was applied to the samples at 20º to 50ºC steps up to a maximum temperature of 680ºC. This technique permits to isolate paleomagnetic components of increasing thermal stability. The bulk susceptibility of the samples was measured after each thermal demagnetization step using a KLY-2 susceptibility bridge. Most of the samples showed a similar rapid increase of susceptibility at about 400-500°C, which is probably the result of magnetite growth upon heating. Neither remanence intensity increase nor directional change could be correlated with temperature intervals of the increasing susceptibility, indicating that the growth of the new magnetic minerals did not contribute to the magnetic remanence.

Stable Characteristic Remanent Magnetization (ChRM) for each sample was identified through visual inspection of vector endpoint diagrams of demagnetization data (Zijderveld, 1967) (**Fig. 46**). In most of the samples, thermal treatment revealed the presence of a low-temperature component parallel to the present north-directed magnetic field. This recent overprint was removed after heating to 200-300°C. Above this temperature, a ChRM was isolated, showing either normal or reverse polarity. The ChRM direction for each sample was calculated by means of Principal Component Analysis (Kirschvink and Chang, 1984). Maximum unblocking temperatures in the range of 630ºC-680ºC were typical of hematite, while a number of samples also showed sharp magnetization decays between 500-600°C, suggesting the co-occurrence of magnetite (**Fig. 46**).

Samples were grouped into three classes regarding the quality of the demagnetization analysis. The first class includes samples with ChRM components showing a liniar and complete decay towards the origin. Second class of samples show a satisfactory cleaning of the recent overprint but unstable behaviour at high temperatures. Finally, the third class of samples showed unstable directional data at temperatures within the range of the recent overprint, and were not further considered.

Our results from Afrineh show up to 59.5% class 1, 28.6% class 2 and 11.9% class 3 samples. The stratigraphic distribution of the three classes of samples is shown in **Fig. 48**. The results from Chaman Goli show 54.18% of first class, 29.61% of second class and 16.21% of third class samples (**Fig. 50**).

Stereographic projection of the ChRM directions of class 1 and 2 from both Afrineh and Chaman Goli synclines are shown in both geographic and bedding tilt corrected coordinates (**Fig. 47**). In the Chaman Goli section the angle between the mean normal and reverse directions is 12.6º, yielding a negative reversal test (McFadden and McElhinny, 1990). These results most likely indicate that ChRM components are not fully isolated from the north-directed recent overprint, which results in an apparent counterclockwise rotation of the reverse polarity directions. Results from the Afrineh section show an angle between the mean of normal and reverse polarity magnetizations of 5.7º, and yields a positive reversal test with (class C, critical angle of 12º). The overall mean direction of Afrineh (**Table I**) yields very small but significant CCW rotation of 7º.

In order to constrain the age of the magnetization a fold test was carried out in the Afrineh syncline. Six paleomagnetic cores were drilled along the steep south-dipping northern flank and compared with results from six magnetostratigraphic samples from the top of the magnetostratigraphic section along the south flank (**Fig. 47**). The precission parameter *kappa* increases from a 3.5 in geographic coordinates to 19 after bedding correction, and yields a positive fold test (McFadden, 1990). Testing for a synfolding magnetization, best *kappa* is obtained at 90% unfolding, but confidence bounds include 100% unfolding, which indicates that this result is indistinguisable from purely pre-folding age of magnetization.

In order to construct a Local Magnetic Polarity Stratigraphy (LMPS), the ChRM directions were used for calculating the Virtual Geomagnetic Pole (VGP) latitude at each site. The results show an Afrineh LMPS consisting of 21 magnetozones (**Fig. 48**). Similarly, the Chaman Goli LMPS shows 26 magnetozones (**Fig. 49**). Most of the magnetozones are determined by more than two consecutive sites averaging 80% magnetozones in Afrinen and 68% in Chaman Goli.
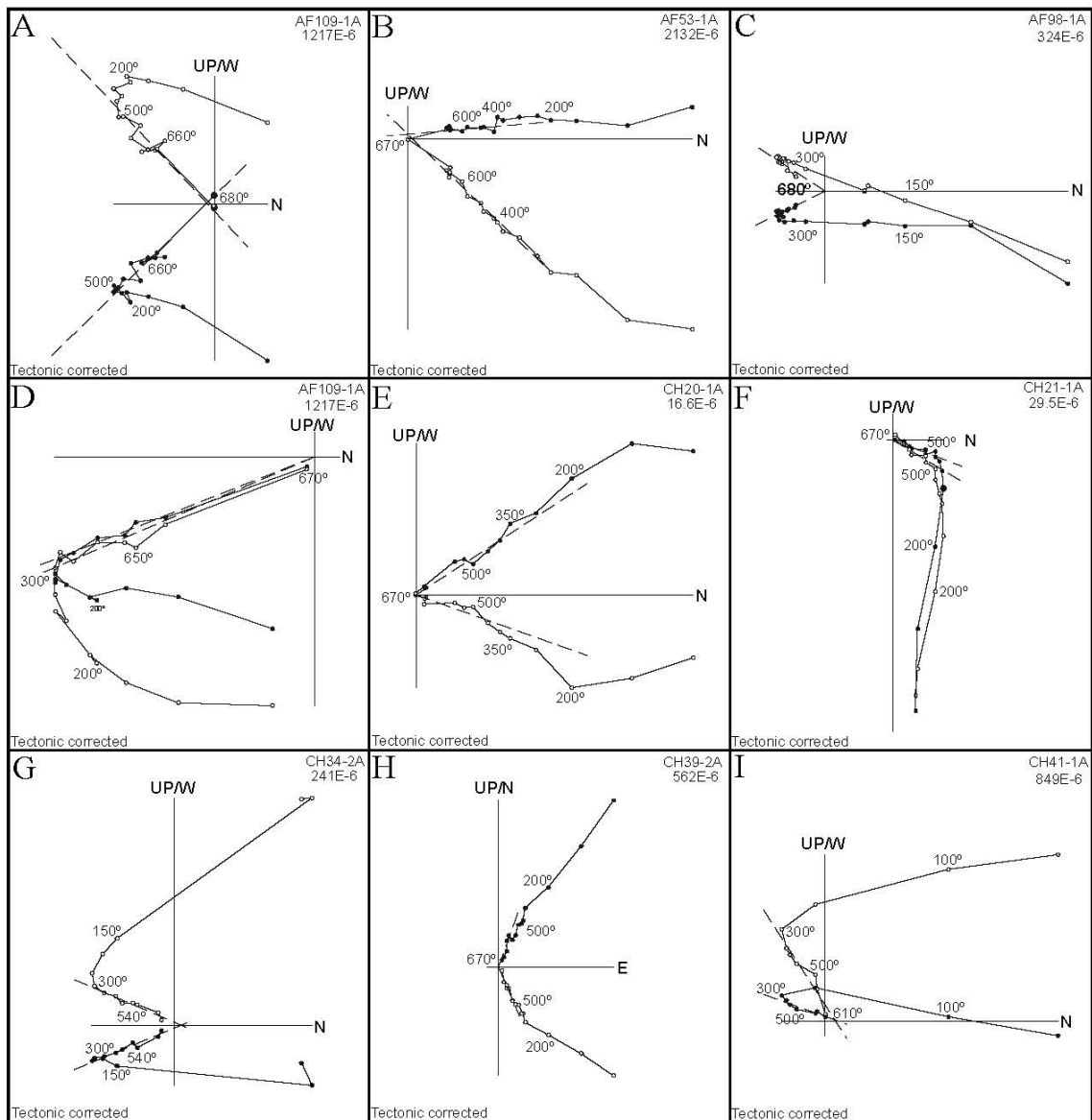
Fig. 46. *Demagnetization vector endpoint diagrams of representative samples from Afrineh (A-D) and Chaman Goli (E-I). Black and white dots in the graphs represent the projection of the magnetization vector on the horizontal and vetical planes respectively.*
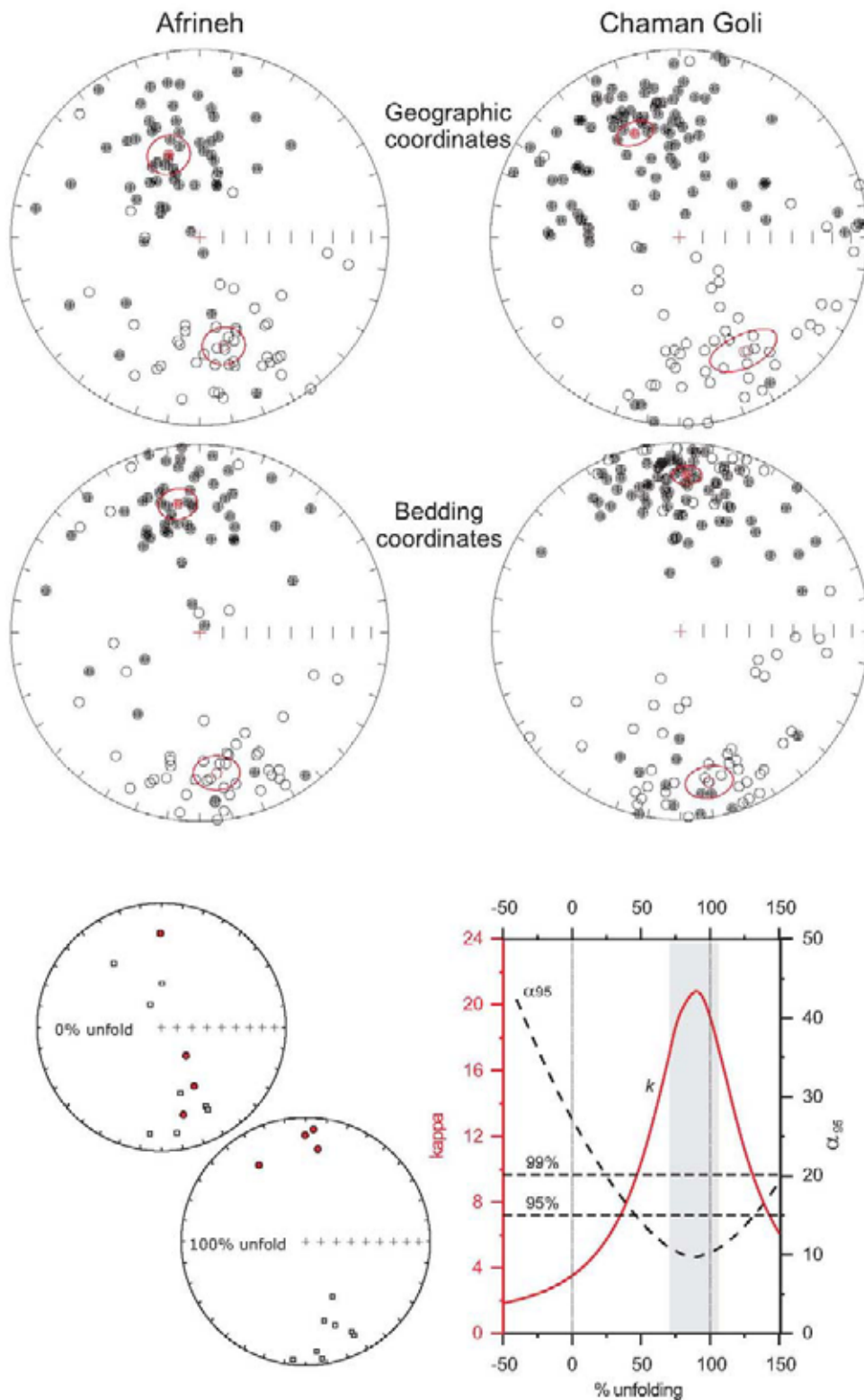
Fig. 47. *Equal Area stereographic projection of the ChRM directions of the Afrineh and Chaman Goli syncline sections. calculated in both geographic and tilt corrected (stratigraphic) coordinates. Normal and reverse polarity mean directions are plotted with their cone of confidence. Below, fold test of the Afrineh syncline. On the right, a test of synfolding magnetization shows a maximum kappa for a 90% unfolding with confidence bounds at 72-106% unfolding.*

	Polarity	N	geographic coordinates				bedding coordinates			
			Dec	Inc	*k*	a95	Dec	Inc	*k*	a95
Afrineh syncline										
	Reverse	48	169,3	-39,8	5,3	9,9	174,3	-25,0	5,4	9,8
	Normal	56	341,2	50,8	7,5	7,4	351,4	30,4	7,7	7,3
	All	**104**	**345,2**	**46,0**	**6,2**	**6,1**	**352,8**	**28,0**	**6,4**	**5,9**
Chaman Goli syncline										
	Normal	95	337,9	39,7	6,2	6,3	002,4	18,0	8,9	5,1
	Reverse	55	152,0	-31,0	4,3	10,5	169,2	-19,5	4,9	9,7
	All	**150**	**335,7**	**36,7**	**5,3**	**5,5**	**357,9**	**18,6**	**6,7**	**4,8**

Table I. *Mean directions and Fisher statistics from Afrineh and Chaman Goli sections.*
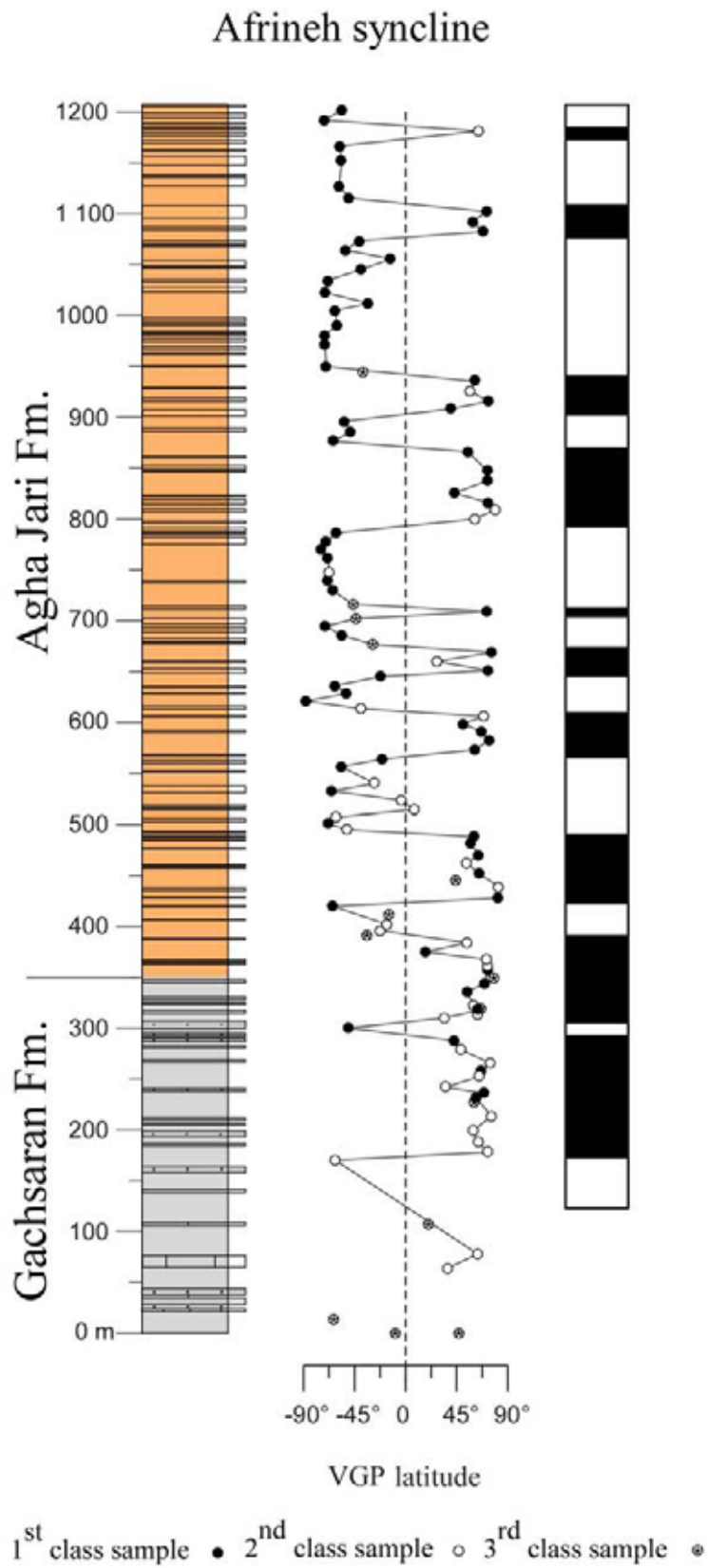
Fig. 48. *Local Magnetic Polarity Stratigraphy of the Afrineh syncline section.*
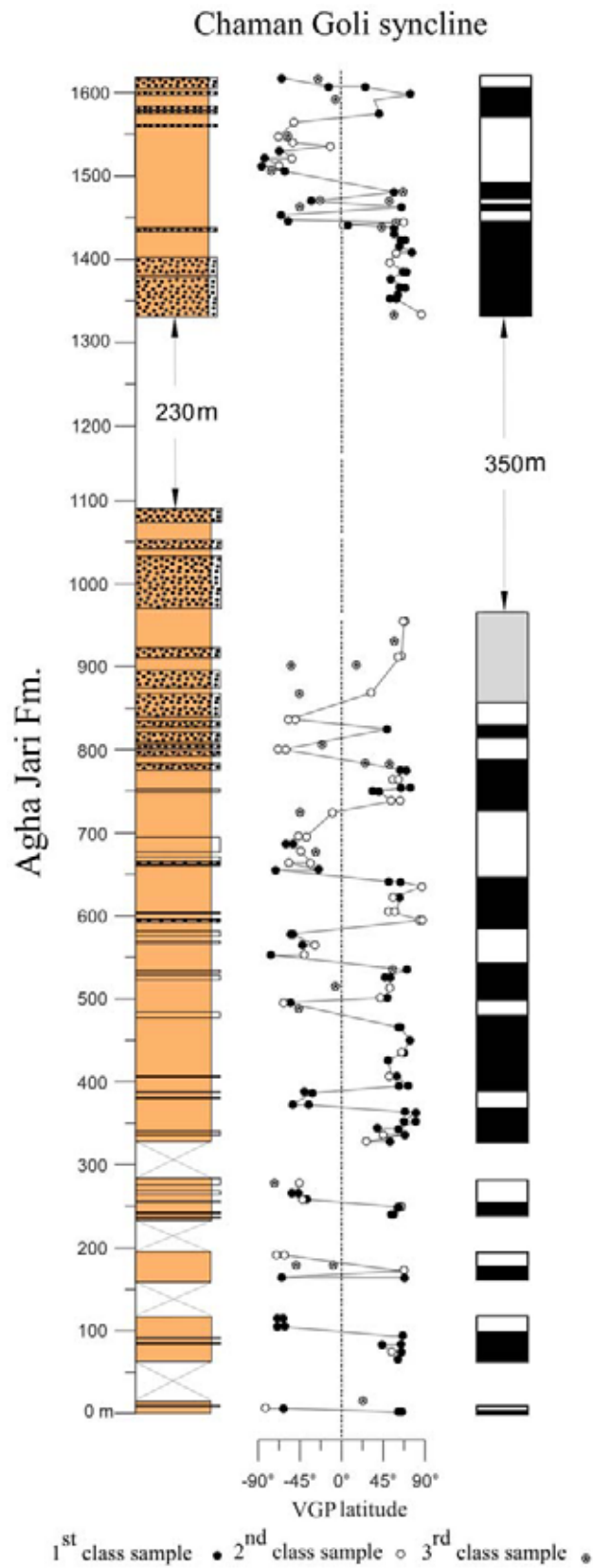
Fig. 49. *Local Magnetic Polarity Stratigraphy of the Chaman Goli syncline section*

4.4.3 Correlation with the Geomagnetic Polarity Time Scale.

Neither biostratigraphic nor radiometric age constrains are available for the Agha Jari Fm in the studied regions of the Zagros fold and thrust belt. A previous magnetostratigraphic study along the Mountain Front Flexure in the Changuleh and Zarrinabad synclines (**Fig. 36**) yielded a Late Miocene to Early Pliocene age for the most of the Agha Jari Fm (Homke et al., 2004). Assuming this constrain, a correlation of the Afrineh LMPS with the Late Miocene portion of the Geomagnetic Polarity Time Scale (Gradstein et al., 2004) would demand a correlation of the two lower thick normal magnetozones with the characteristic thick chron C5n (option 2 in **Fig. 50**). This correlation yields, however, a poor fit with the GPTS: a short reverse magnetozone is correlated with the long chron C4Ar, while a sequence of N-R-N of equal thickness magnetozones present a missmatch with the distinct chron C4n. In addition, for this correlation to work, as many as eight short chrons of the GPTS must be omitted.

An alternate correlation of the Afrineh LMPS with the GPTS (option 1 in **Fig. 50**) exists which is based solely on a best-fit between magnetozone thicknesses and chron durations. The two remarkably thick normal magnetozones of the base of the Afrineh LMPS correlate with chrons C5AC and C5AD, while the upper dominantly reverse part of the section nicely correlates with chrons C5An to C5r. This solution yields a very good fit with the GPTS, with steady sedimentation rates and no geomagnetic chrons being omitted from the correlation. Note that the pattern of reversals in the Afrineh LMPS is so characteristic that no other feasible correlation exists with the Miocene segment of the GPTS.

In summary, two alternate correlations with the GPTS are presented for the Afrineh LMPS. The two options yield very different ages: option 1 favours a correlation with the Middle Miocene while option 2 shows a correlation with the Late Miocene (**Fig. 50**). Despite the contrasting age for the Agha Jari Fm compared to a previous study in the Changuleh syncline (Homke et al., 2004), option 1 is our prefered correlation because it yields the best independent match with the time scale.
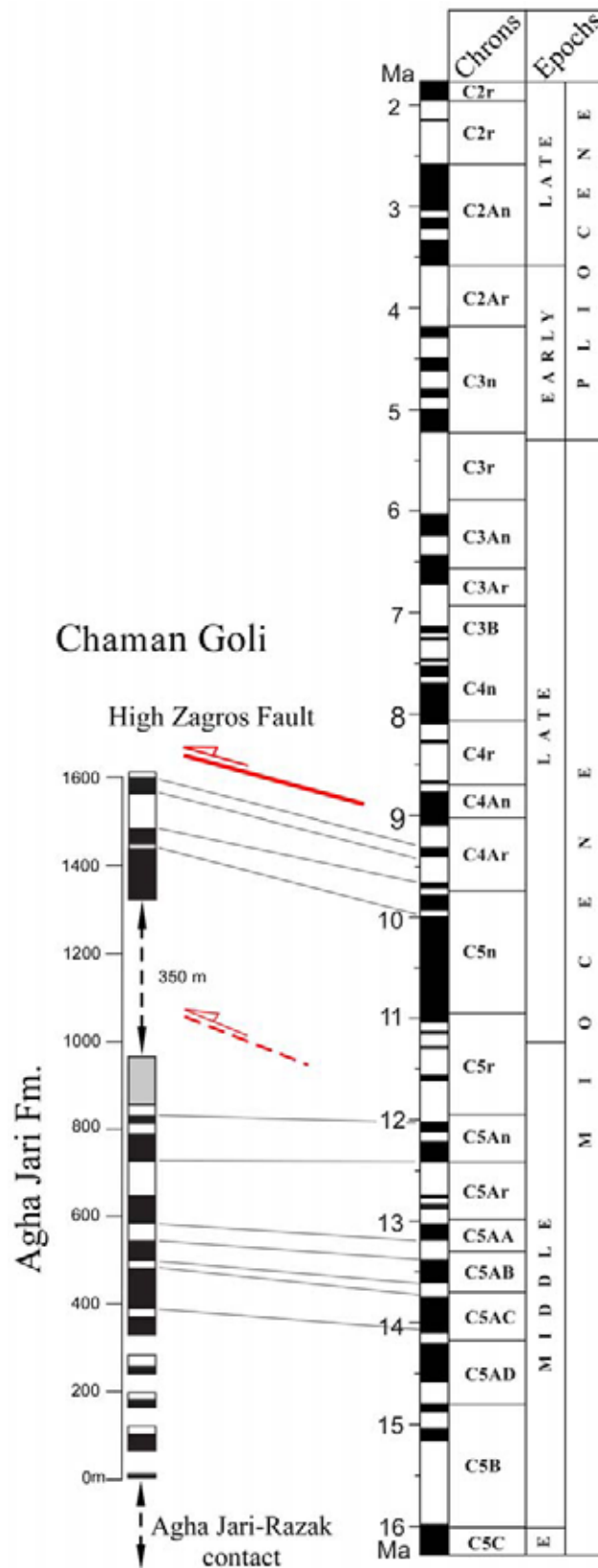
The correlation of the Chaman Goli LMPS with the GPTS shows a best fit that yields a Middle Miocene age of the Agha Jari Fm., similar to the above results from Afrineh syncline (**Fig. 51**). Nevertheless, this correlation is less robust than that from Afrineh due to the existence of multiple sampling gaps. We avoided stablishing a correlation of the lower part of the section because it was sampled along discontinuous otucrops. Conversely, the middle part of the section from 320-850 m shows continuous sample coverage. In this interval there is a good correlation with chrons C5AC to C5An.

The correlation means that the two short geomagnetic events within chron C5Ar are missing in the Chaman Goli section. The upper part of the Chaman Goli section was sampled on the hanging wall block of a north-dipping thrust fault and its stratigraphic position relative to the lower Chaman Goli section was estimated from a balanced cross section (**Fig. 45**). A 350 m stratigraphic gap was estimated from the two sampled transects and best correlation of the thick normal magnetozone of the upper Chaman Goli transect corresponds to chron C5n (**Fig. 51**).

The magnetostratigraphic age of both the Chaman Goli and Afrineh sections lead to similar conclusions regarding the age of pre-growth sedimentation, which is significantly older compared to the Changuleh syncline (Homke et al, 2004). The average sedimentation rates derived from magnetostratigraphy are 30.9 cm/ka in Afrineh syncline and 20.9 cm/ka in Chaman Goli (**Fig. 52**), values which do not differ significantly from earlier results in Changuleh.
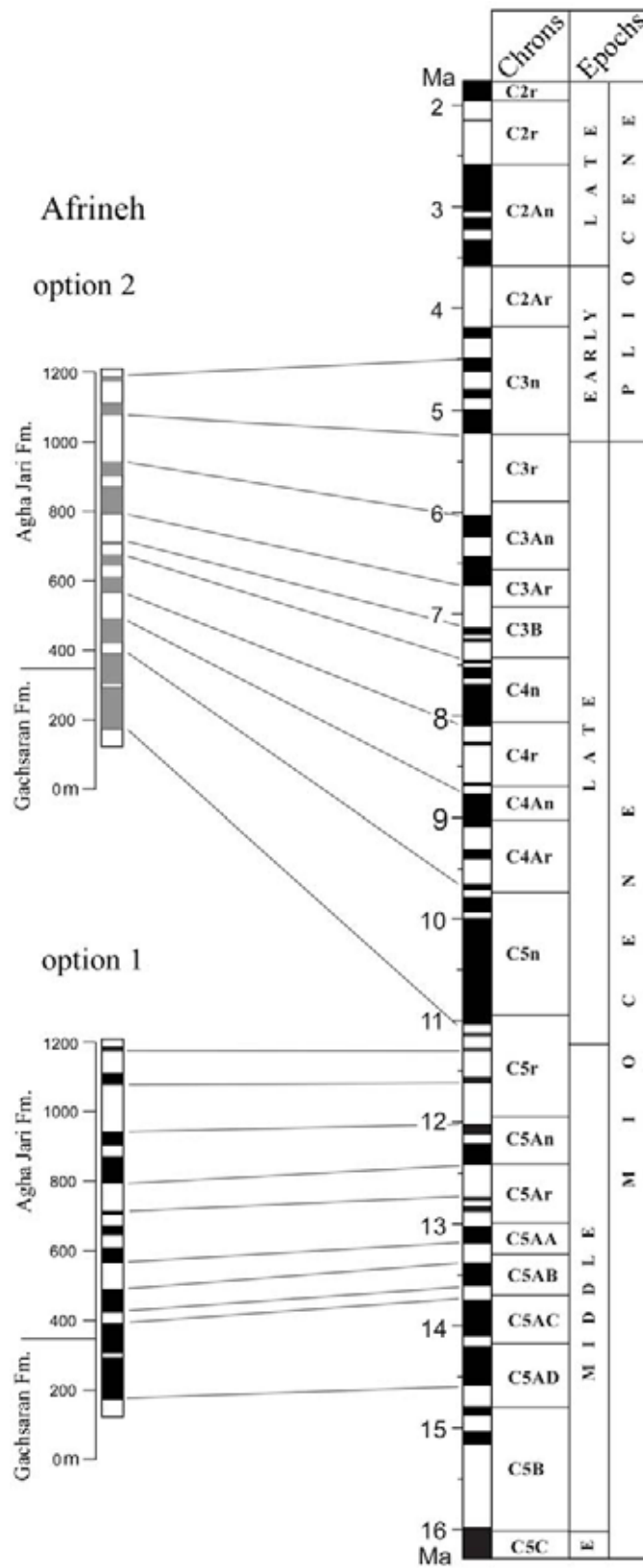
Fig. 50. *Correlation of the Afrineh Local Magnetic Polarity Stratigraphy with the GPTS. Option 1 represents the prefered correlation based on best fit with the GPTS. See the text for discussion.*

Fig. 51. *Correlation of the Chaman Goli Local Magnetic Polarity Stratigraphy with the GPTS. See text for discussion.*

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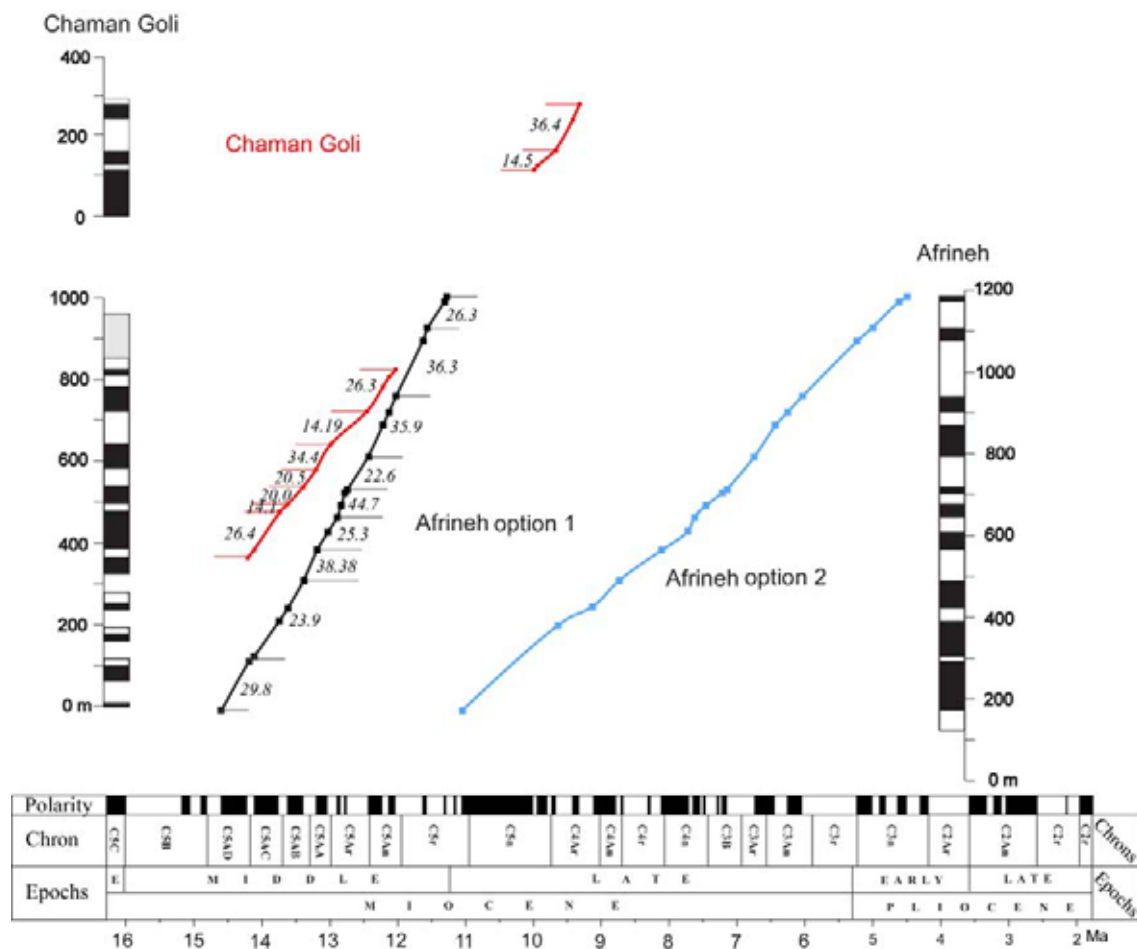
Fig. 52. *Rates of sediment accumulation derived from the correlation of the LMPS with the GPTS (Gradstein et al., 2004).*

4.5 Results

Age determination for sedimentary successions as well as dating growth strata units are the most important objectives of magnetostratigraphic studies.

4.5.1 Age of Gachsaran, Agha Jari and Bakhtyari formations

The age of the Gachsaran Formation is determined in the Afrineh section (**Fig. 53**). In this syncline located in the centre of the Pusht-e Kuh Arc, the lower part of the sampled Gachsaran Formation, 350 m below the Gachsaran-Agha Jari contact is of about 15.4 Ma using an extrapolated age. The Gachsaran-Agha Jari contact is dated as 13.9 Ma and the top of preserved Agha Jari Formation is dated at about 11.2 Ma (**Fig. 53**). Bakhtyari Formation is not represented in the Afrineh syncline but it certainly

would be younger than 11 Ma but possibly older than the same formation in the Changuleh growth syncline, dated as Pliocene (Homke et al. 2004).

In the Chaman Goli syncline the age of the Gachsaran-Agha Jari contact is not directly determined since the measured section starts in the lower Agha Jari succession. However, the top of the Gachsaran Formation is older than in Afrineh syncline. Our interpretation indicates that the base of the well-defined magnetic correlation, 370 m above the base of the succession has an age of 14.2 Ma (**Fig. 53**). The base of the Agha Jari-Bakhtyari transition at 660 m has an age of 12.4 Ma and the top of the lower continuous and well-calibrated succession is of about 12 Ma. The upper part of the succession is probably spanning from 10 to 9 Ma. The growth units may start at about 11 Ma although it is not totally sure that older growth exists in the syncline. Although totally speculative and only using regular constant rates of sediment accumulation we may try to define the age of the Agha Jari-Razak contact; which could be as old as 17.2 Ma (Early Miocene). This age, if correct, is older than equivalent boundary in the Afrineh syncline and much older than Gachsaran-Agha Jari contact in the Changuleh and Zarrinabad growth synclines.

Although highly speculative the Razak-Agha Jari contact can be as old as 17.2 Ma (late Early Miocene) using a long-term extrapolation with constant rates of sedimentation of 20.9 cm/ka. (James and Wynd, 1965) also reported an Early Miocene age for the Razak Formation.
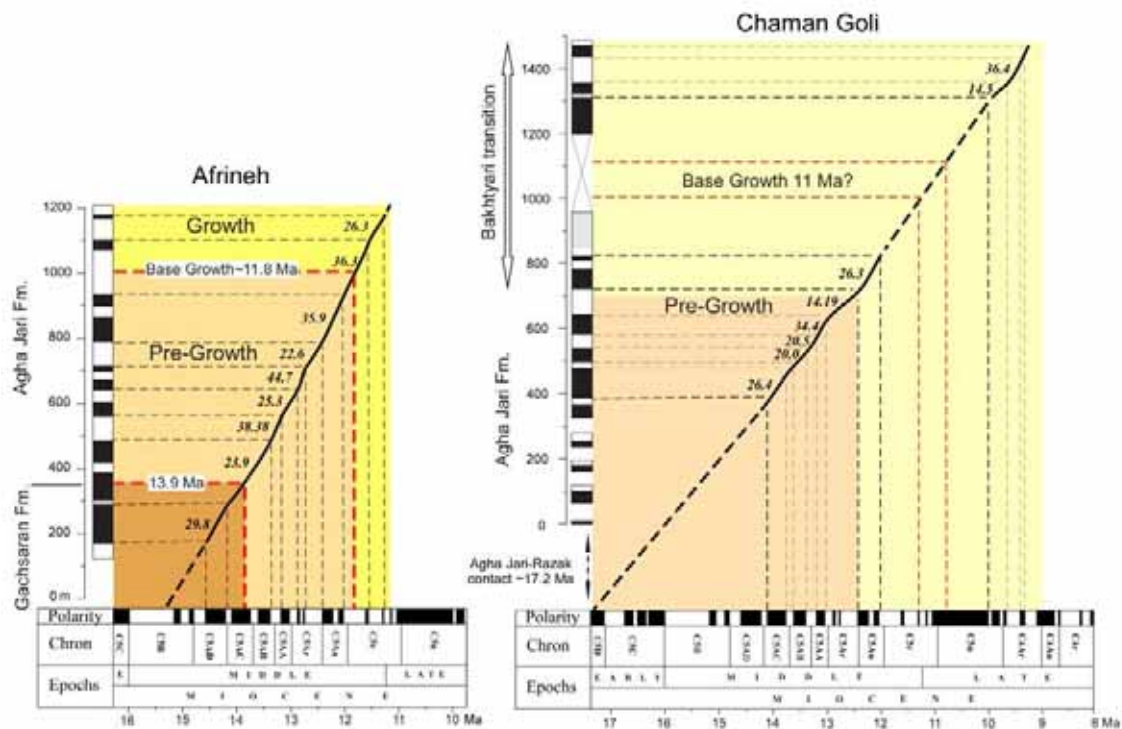
Fig. 53. *Plots showing the age of Gachsaran, Agha Jari and Bakhtyari formations as well as the ages of pre-growth and growth units that record the evolution of the growth synclines.*

4.5.2 Timing of deformation in Afrineh and Chaman Goli synclines

The Afrineh syncline shows unambiguous growth strata at about 656 m above the Gachsaran-Agha Jari contact with an age starting at 11.8 Ma (late Middle Miocene). The growth of the syncline was active for at least 1 My up to about 11 Ma although this is the top of preserved growth strata in this syncline (**Fig. 53**).

In the Chaman Goli syncline there are indications of growth starting at about 1000-1100 m above the initiation of the sampled succession. These growth units have an age of about 11 Ma and thus similar to the initial growth in Afrineh syncline. Younger units in the northeastern flank of the syncline also show growth patterns with younger ages (as young as 9 Ma) possibly related to the last emplacement of the High Zagros Fault (**Fig. 53**).

4.6 Discussion: Sequence of folding and foreland barn evolution in Zagros Fold Belt

A clear sequence of folding seems to emerge from existing well-calibrated growth strata units across the Central and NW Zagros Fold Belt (**Fig. 54**). The existing data supports both a foreland sequence of deformation in which both shortening and proximal to distal sedimentary facies belts migrate from the hinterland to the foreland of the foreland fold-and-thrust belt. This sequence of deformation includes the study region (Pusht-e Kuh Arc and High Zagros Fault) as well as more internal parts of the Zagros Fold Belt around the Main Zagros Thrust (Fakhari et al., 2008). Another interesting conclusion is the long term duration of the deformation in Zagros, which spans from Early Miocene to Pliocene times (**Fig. 54**). This Miocene long tectonic activity was little accounted for the Zagros deformation although it has been started to be mentioned in recent papers (e.g., Hessami et al., 2001; Sherkati et al., 2005; Fakhari et al., 2008).

Fig. 54 shows a summary of the sedimentary evolution and shortening migration through Miocene and Pliocene times from the Chaman Goli growth syncline in the footwall of the High Zagros Fault to the Changuleh growth syncline in the Mesopotamian plains but also in the Shahr Kord locality in the footwall of the Main Zagros Thrust (Fakhari et al., 2008). In this last locality, in the most hinterland position, the Agha Jari-Bakhtyari conglomerates are as old as Early Miocene (**Fig. 54**). In this position, several units of conglomerates (Bakhtyari facies) show growth patterns, possibly related to the emergence of the Main Zagros Thrust during Early Miocene. These coarse conglomerates indicate concomitant topographic growth and significant erosion in the back of the mountain chain grade into more distal Agha Jari Formation towards the foreland (Fakhari et al., 2008; their fig. 13) in front of the advancing thrust and fold belt.

This is observable in the Chaman Goli growth syncline where above more than 1000 m of Agha Jari deposits the contact with the Bakhtyari Formation seems transitional spanning from ~12.4 Ma to 9.3 Ma. The High Zagros Fault thrust over these uppermost conglomerates but the age of thrust initiation and displacement must be older.

Towards the foreland, the age of the base of the Bakhtyari Formation in the Changuleh syncline is of about 3 Ma. Deposition of these conglomerates are related to the emergence of limestone beds in the uplifted Pusht-e Kuh Arc above the Mountain Front Flexure after 5.5 Ma (Homke et at 2004; Emami et al. in press). The Agha Jari

Formation shows a similar distribution than the Bakhtyari Formation migrating and getting younger towards the foreland (**Fig. 54**). As stated before, there are no clear Agha Jari deposits in the Shahr Kord area in the footwall of the Main Zagros Thrust. In the footwall of the High Zagros Fault, initial Agha Jari deposits can be as old as Early Miocene (extrapolated age of 17.2 Ma) whereas these sediments are Middle Miocene in age in the Afrineh syncline (13.9 Ma) and in the Zarrinabad syncline (12.8 Ma) in the frontal regions of the Pusht-e Kuh Arc. The oldest Early Miocene age for the Agha Jari initiation fits with proposed older landbridge in Zagros foreland during Burdigalian times (Rögl, 1998; Harzhauser et al., 2007). The age of the contact Gachsaran-Agha Jari in Afrineh syncline correlates with the onset of the final closure of the Tethyan seaway (Harzhauser et al., 2007).

These ages for Gachsaran, Agha Jari and Bakhtyari show a migration of facies towards the foreland. This is also corroborated by the ages of the initiation of growth across the Pusht-e Kuh Arc. In Shahr Kord the growth units are already Early Miocene in age whereas in the footwall of the High Zagros Fault are Middle Miocene in both the Chaman Goli and Afrineh synclines. In the Chaman Goli syncline the growth units record both the folding of the syncline and the final emergence of the High Zagros Fault thrust on top of the preserved Bakhtyari conglomerates. In the Afrineh syncline, in the centre of the Pusht-e Kuh Arc and far away of the High Zagros Fault, folding seem to be as old as deformation in Chaman Goli that would imply a relatively fast migration of deformation across the relatively undeformed foreland basin. More than 3.5 My separates the initial folding in Afrineh and Changuleh growth synclines and thus suggesting a potential slower rate of shortening propagation during Late Miocene. On the contrary, the Changuleh growth strata indicate a long lasting duration for growth from 7.65 Ma to about 2.5-1.5 Ma (Homke et al., 2004), although encompassing both folding and Mountain Front Flexure uplift (Emami et al., in press).

Several conclusions can be drawn from presented foreland evolution. One of the most important is the diachroneity in foreland basin stratigraphic formations. It is now clear that Gachsaran, Agha Jari and Bakhtyari formations are laterally equivalent in age and represent different environments in the foreland basin from distal to proximal, respectively (**Fig. 54**). These belts of facies migrate from NE to SW as recently proposed by Fakhari et al. (2008). However, paleocurrent directions always suggest a longitudinal direction of flow from NW to SE towards the former Persian Gulf in Miocene times and thus paralleling the foreland basin axial trend (Vergés, 2007).

If our conclusions are correct the thrusting and folding have been active for the last 20 My that is much longer than normally though for the Zagros described as a very young orogen. Another important conclusion is that the foreland direction of shortening migration including the Main Zagros Thrust and the High Zagros Fault can be determined from dating foreland infill. The older ages of conglomerates in the footwall of these two major thrusts could invalidate proposed out-of-sequence thrusting as proposed towards the SE in Fars Arc (Molinaro et al., 2005; Mouthereau et al., 2007) but this needs to a re-valuation of sedimentary ages in this area that may differ from the Izeh Zone and Pusht-e Kuh Arc.

The results presented in this paper show the Miocene-Pliocene phase of folding that produced the marine to nonmarine transition of the Zagros foreland basin. This phase of folding, lasting for the last 17-20 My, corresponds to the most severe one creating present morphotectonics of Zagros folds. This older ages for initiation of Zagros Neogene collision was discussed in McQuarrie et al. (2003), based on Arabia-Eurasia plate reconstructions, concluding that the latest age for continental collision was 10 Ma but probably was much older (~20 Ma).

However, older phases of folding (Late Cretaceous to Eocene) have been detected in some of the anticlines of the Pusht-e Kuh Arc (see Homke et al., in press; Sherkati et al., 2005; Hessami et al., 2001; Fakhari and Soleimany, 2003). These early phases of folding are difficult to decipher and thus to quantify but certainly configure a more complex tectonic scenario than previously though when only a fast and recent folding event was taking in consideration. This longer and composite tectonic scenario is important for the comprehension of the relationships between folding trap formation and hydrocarbons history in the Pusht-e Kuh Arc.
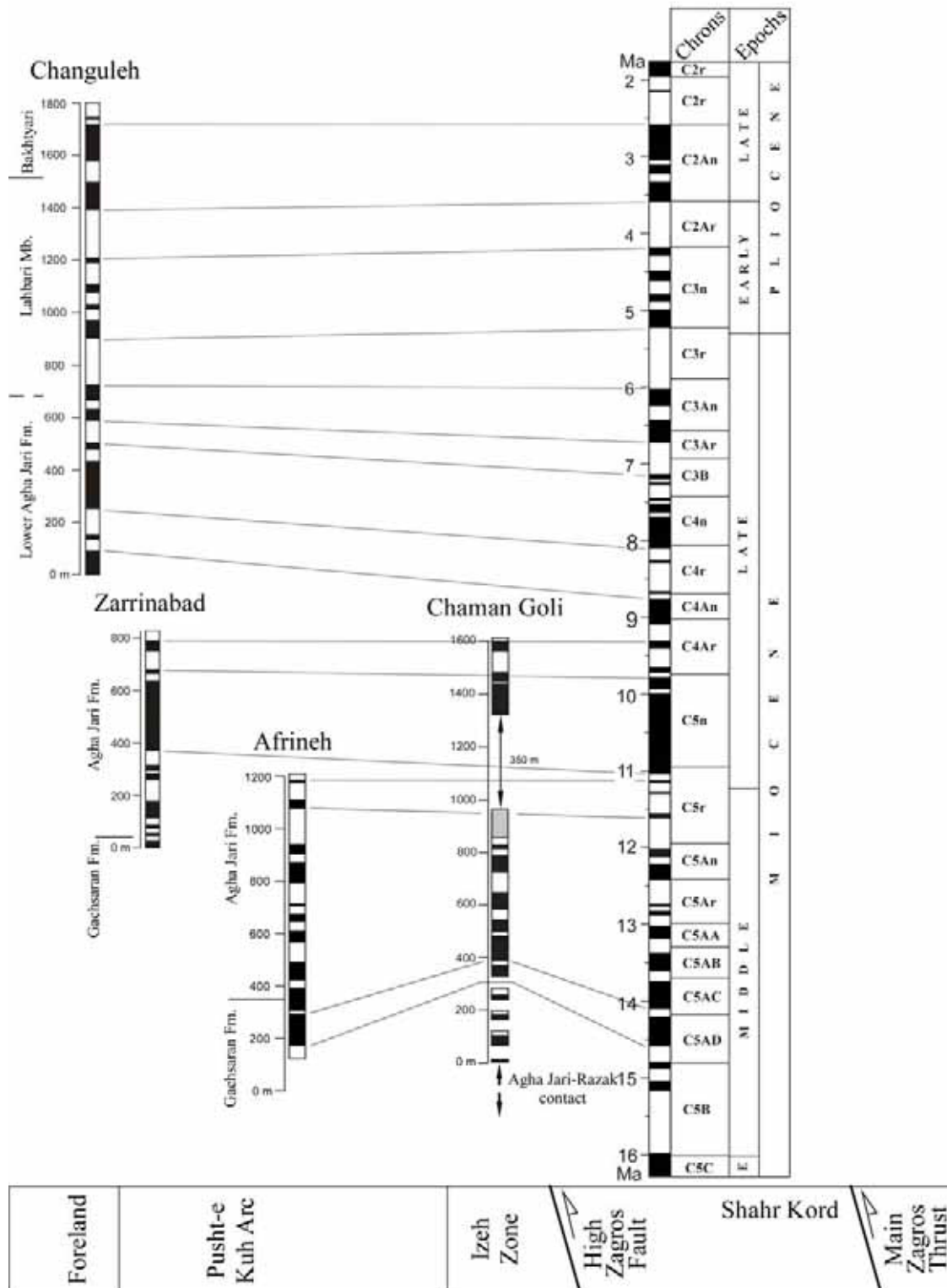
Fig. 54. *Magnetic polarity correlation for study successions to the GPTS in addition to Zarrinabad (Pusht-e Kuh Arc) and Changuleh (foreland) successions (Homke et al., 2004). The position of Shahr Kord (Fakhari et al., 2008) within the Zagros Belt tectonic frame is also included.*

4.7 Conclusions

Magnetostratigraphy of the two sections across the central part of the Pusht-e Kuh Arc (Afrineh syncline) and in front of the High Zagros Fault (Chaman Goli syncline) provides the ages of Gachsaran, Agha Jari and Bakhtyari formations as well the timing of growth of these two growth synclines.

Correlation of our results to the GPTS shows the Gachsaran-Agha Jari contact at ~13.9 Ma (Langhian-Serravallian boundary) in the Afrineh syncline. In this syncline the top of the 862-m thick Agha Jari Formation is slightly older than 11 Ma (Serravallian-Tortonian boundary). The long term sedimentation rates for the continuous succession in Afrineh syncline is of about 0.3 mm/yr.

In the Chaman Goli succession the contact between the fluvial Agha Jari and coarse alluvial conglomerates of the Bakhtyari formations is transitional and can be placed anywhere between 660 and 1600 m and thus spanning a period between 12.2 to 9.3 Ma. The age of the Razak-Agha Jari contact can be estimated at about 17.2 Ma (Late Burdigalian) using extrapolation of sedimentary rates. The long term sedimentation rates for the Chaman Goli succession is of about 0.21 mm/yr

The boundary between pre-growth and growth strata units is well defined in the Afrineh syncline and can be dated as 11.8 Ma. Although we do not see the top of the Agha Jari growth unit because erosion it must be younger than 11 Ma. According to proposed correlation for the Chaman Goli succession, growth units may have an age of about 11 Ma and thus of similar age to the initial folding in Afrineh growth syncline. This growth unit is located in the transition between Agha Jari-Bakhtyari sedimentary facies. The High Zagros Fault cuts the uppermost remaining Bakhtyari conglomerates and thus its final age of emplacement is as young as ~9.3 Ma (mid Tortonian). The duration of Chaman Goli syncline growth in the footwall of the High Zagros Fault is of about 1.7 My.

According to presented results deformation in Afrineh and Chaman Goli growth synclines initiated almost simultaneously at about 11.8 Ma and 11 Ma, respectively. This timing of deformation is, however, older than the one reported along the front of the Pusht-e Kuh Arc by Homke et al. (2004). These authors defined the onset of folding along the front at 7.65 Ma. Combining these ages we can define a sequence of deformation migrating towards the foreland, which was not confirmed before. Present distances between Chaman Goli and Afrineh growth synclines, in the direction of tectonic transport, is ~45 km whereas between Afrineh and Changuleh growth syncline

is ~85 km. This means that deformation progressed from Afrineh to Changuleh by 85 km in only about 4.1 My. In addition, deformation started in the Afrineh growth syncline at about 11.8 Ma and ended in the Changuleh growth syncline at about 2.5-1.5 Ma at the Pliocene-Pleistocene boundary (9.3-10.3 My duration).

Foreland basin deposits in front of advancing fold and thrust systems show migration of belts of sedimentary facies ahead of deformation front. In this way, the Gachsaran evaporitic units, the distal Agha Jari and more proximal Bakhtyari deposits migrated towards the Mesopotamian plains although the main direction of sediment flux was parallel to the NW-SE fold belt trend (Vergés, 2007). The base of the Bakhtyari Formation in the Changuleh growth syncline is 3 Ma in mid Pliocene time Homke et al. (2004) whereas it is 12.2 to 9.3 Ma (early Late Miocene times) in Chaman Goli growth syncline in the footwall of the High Zagros Fault. Interestingly, similar conglomerates in the footwall of the Main Zagros Thrust have an older age corresponding to the Early Miocene (Fakhari et al., 2008). These ages clearly fit a foreland propagation of both the fold and thrust system as well as the sedimentary facies belts. It is also documented a relatively old timing of deformation as well as relatively slow rates of shortening propagation across the Zagros Fold Belt (certainly older timing and slower rates than previously though). In addition, these ages close the existing apparent gap between older phases of deformation in the Zagros defined during Paleocene and Eocene times (Homke et al., in press) and recent Quaternary tectonic activity.