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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 1

GENERAL INTRODUCTION

1. GENERAL INTRODUCTION:

1.1 Tectonic setting of the Arabian plate

The Arabian plate displays different types of plate boundaries; rifting and sea floor spreading in the Red Sea and Gulf of Aden, collision belt along the Zagros-Bitlis, active subduction margin along the Makran belt and transform fault activity along the Dead Sea and Owen-Sheba fracture zones (**Fig. 1**). The Arabian plate (Nubian-Arabian Shield) generally displays two dominant tectonic fabrics: N-S and NW-SE trending (Stacey et al., 1984; Sten, 1985). The N-S trend is defined by foliations and upright folds which record the accretion of disparate terranes that were sutured major north-south lithological discontinuities during Pan African construction of Gondwanaland. Towards the north the Arabian plate is bounded by the NW-SE Zagros orogenic belt, which is part of the Alpine-Himalayan belt and extends for about 2000 km through Iran and Turkey. This orogenic belt is one of the richest oil provinces in the World and together with Arabian foreland, the Neoproterozoic to Neogene sequence of the Zagros fold thrust belt hosts two thirds of the World's proven oil reserves and one-third of the World's reserves of gas (Beydoun et al., 1992) (**Fig. 1**).

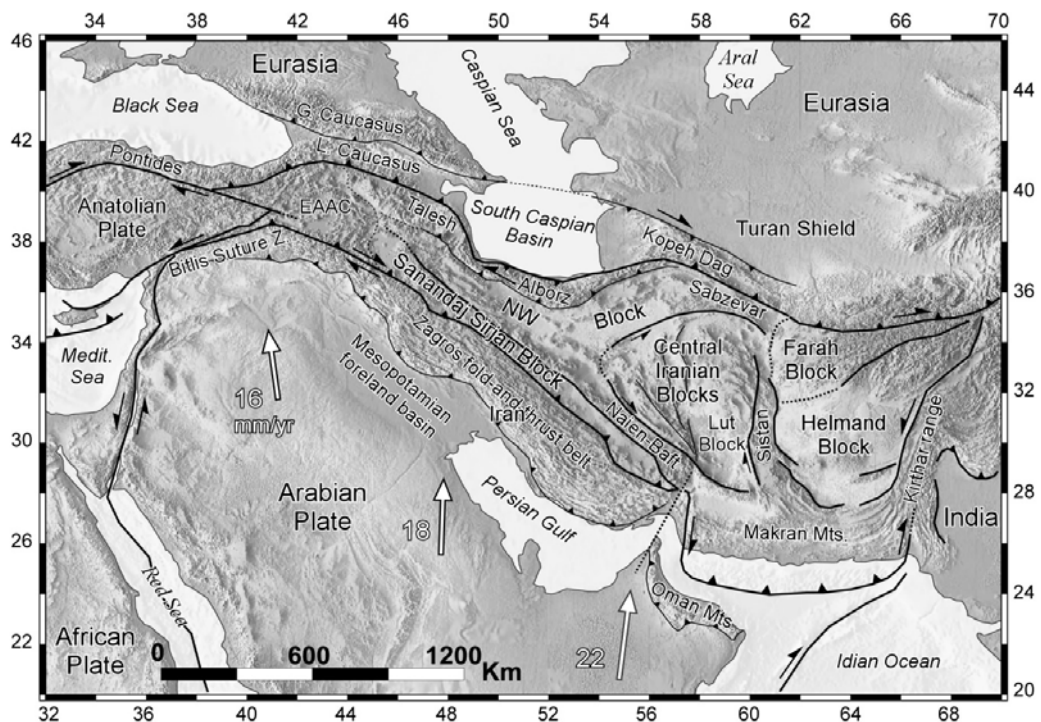


Fig. 1. Major tectonic elements of the Arabian and Iranian plates. Velocity movement in mm/y are from Sella et al., 2002. EAAC=East Anatolian Accretionary Complex.

1.2 Morpho-tectonic units of the Zagros orogenic belt

The over 2000-km long NW-SE trending Zagros Mountain belt extends from eastern Turkey to the Makran Mountains, forming a morphological boundary between the Iranian plateau and the Mesopotamian and Persian Gulf basins (**Fig. 1**). The Zagros Mountains are characterized by a mean topographic elevation of ~1200 m and the maximum elevation reaches at 4231 m in Zard Kuh peak near to Kuhrang city.

The Zagros orogenic belt can be subdivided in different ways. Geomorphologically it is divided in two adjacent belts: the High Zagros Belt and the Zagros Simply Folded Belt separated by the High Zagros Fault (Berberian and King, 1981; Falcon 1974; Stocklin, 1968). Based on the lateral facies variations the Zagros range has been classified into tectono-stratigraphic domains from SE to NW: the Fars province or eastern Zagros, the Izeh zone and Dezful Embayment or Central Zagros and The Lurestan province or Western Zagros (Motiei, 1994; Motiei, 1995; Talbot and Alavi, 1996) (**Fig. 2**). This classification is actually based on the subdivision proposed by James and Wynd (1965) in which they divided the Zagros Fold Belt in three stratigraphic provinces as the Fars province in SE of Zagros, The Khuzestan in the Center and the Lurestan province in NW of the Zagros. From tectonic point view five zones along the length of the orogen can be distinguished (e.g. Stöcklin, 1968; Falcon 1974; Sten, 1985; Berberian, 1995): The Zagros Imbricate Zone; the Zagros Simply Folded Belt; the Zagros Foredeep; the Mesopotamian and Persian Gulf foreland basin and finally the Arabian foreland.

However the most common subdivision of the Zagros orogene is the five structural zones parallel to the NW-SE trend of the belt. From the NE to the SW these are: the Urumieh Dokhtar Magmatic arc, the Sanandaj Sirjan metamorphic Zone, the High Zagros Zone (Imbricated or Crush zone), the Zagros Simply Folded Belt and the Mesopotamian-Persian Gulf foreland basin (**Fig. 2**).

The Urumieh Dokhtar Magmatic Arc, extended along the NE side of the belt, represents a calc-alkaline Arc that was mostly active from Eocene to Late Miocene, it formed in response to northeast ward subduction of the Neotethys Ocean beneath the Iranian plate (Berberian and Berberian, 1981; Berberian et al., 1982).

The Sanandaj Sirjan Zone is a ~150-200 km wide zone bounding to the SW the Urumieh-Dokhtar magmatic Arc and composed mainly of metamorphosed Paleozoic to Late Cretaceous rocks, intruded by calc-alkaline Jurassic to Early Eocene plutons (Alavi, 1994; Masoudi, 1997). Towards the SW the Main Zagros Thrust separates the

Sanangaj Sirjan and the Imbricated zones (Berberian and King, 1981; Berberian, 1995) and constitutes the suture between Arabian and Iranian plates. Although Alavi (1994) argue that the suture between the Arabian and Iranian plates is located between the Urumieh Doktor Magmatic Arc and the Sanandaj Sirjan Zone it is more generally accepted that the Main Zagros Thrust represents the Zagros suture (e.g. Berberian and King, 1981; Berberian, 1995; Agard et al., 2005) (**Fig. 2**).

The Imbricated Zone represents the inner-most part of the Arabian deformed margin, featuring radiolaritic-ophiolitic thrust sheets over the NE Arabian margin. The Kermanshah and the Neyriz complexes, in the NW and SE Zagros respectively, with metamorphic thrust sheets from Sanandaj Sirjan Zone are constitute the imbricated zone (Agard et al., 2005; Babaie et al., 2005) (**Fig. 2**).

The Imbricated Zone is separated from the Simply Folded Belt by High Zagros Fault (Berberian, 1995). The Simply Folded Belt is characterized by spectacular folds within the ~12-14 km-thick sedimentary cover of the Zagros basin (e.g. Falcon, 1974; Colman-Sadd, 1978). The Simply Folded Belt is separated from the Mesopotamian-Persian Gulf foreland basin by the Mountain Front Flexure (Falcon, 1961). This structural and topographic front defines the tectonic salients or arcs and re-entrants or embayments in the folded belt from SE to NW: the Fars Arc (Fars stratigraphic province), the Dezful Embayment (Khuzestan stratigraphic province), and the Pusht-e Kuh Arc (Lurestan stratigraphic province), respectively from the SE to the NW (**Fig. 2**). In front of the MFF, the inner-most part of the Mesopotamian foreland basin is affected by the Zagros deformation giving rise to NW-SE buried anticlines (Dunnington, 1968). These buried anticlines are containing the richest oil traps in frontal part of the Zagros Fold Belt.

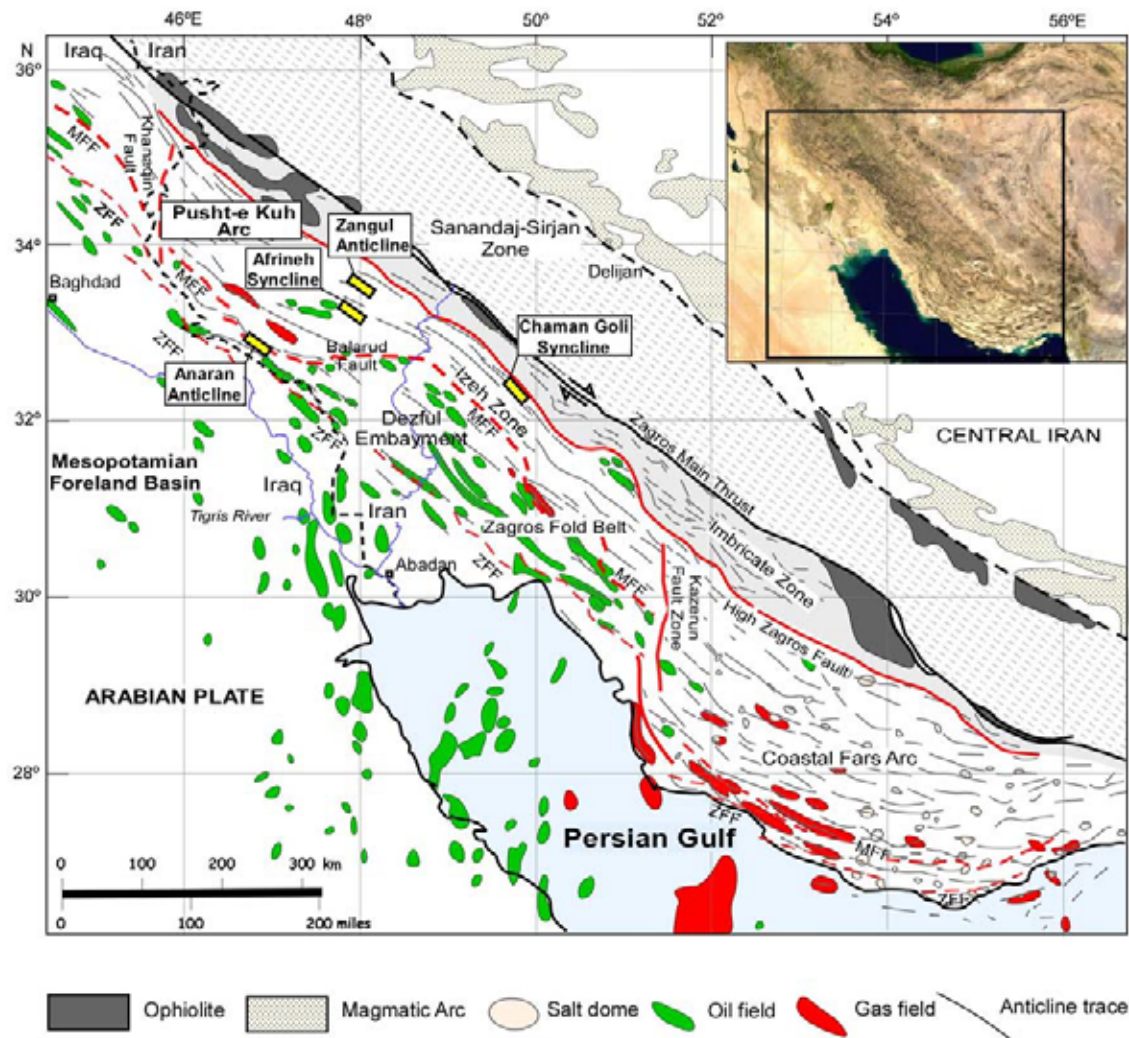


Fig. 2. Zagros Fold and Thrust Belt and structural divisions. Oil and Gas fields are marked by Green and red colour respectively after Vergés et al., (in press), MFF=Mountain Front Fault, ZFF=Zagros Frontal Fault. Locations of the different studied areas are shown in the map.

1.3 Geodynamic evolution and tectono-stratigraphic setting of the Zagros Fold and Thrust belt

The Zagros belt represents a segment of the large Alpine-Himalayan orogenic system formed in relation with the closure of the Neotethys Ocean and the collision between the Arabian and Eurasian plates (e.g. Talbot and Alavi, 1996; Stampfli and Borel, 2002; Golonka, 2004) (**Fig. 3**). The Zagros belt is often presented as a young collisional belt since the development of the spectacular Zagros fold-and-thrust belt took place mostly in Miocene-Pliocene times (e.g. Haynes and McQuillan, 1974; Berberian and King, 1981; Molinaro, 2004) (**Fig. 3** and **Fig. 4**).

During the Middle to Late Proterozoic (800-650 Ma) the Arabian plate formed the northeastern margin of the African craton, as part of the Gondwana super-continent (Beydoun, 1991). The Precambrian basement of the Arabian plate is exposed along its western margin (Falcon, 1967; Hussein, 1988; Konert et al., 2001). It is similar to the basement exposed in central Iran (Alavi, 1991). The Precambrian basement of the Zagros is known just based on the available air-magnetic data and fragments of the metamorphic basement, which brought to the surface by the Hormuz salt diapirs (Gansser, 1992; Kent, 1979).

During the Palaeozoic Iran, Turkey and the Arabian plate together with Afghanistan and India formed the wide passive margin of Gondwanaland bordering the Paleo-Tethys Ocean to the north (Berberian and King, 1981) (**Fig. 3**). The Early Palaeozoic deposits, which extend from the Zagros to central and northern Iran, were deposited during the stage of rifting (Berberian and King, 1981; Beydoun et al., 1992; Stöcklin, 1968). It is generally considered that the evaporites of the Hormuz Formation (latest Proterozoic-Early Cambrian) were deposited directly on the basement. In some parts of the Iranian Zagros seismic evidence suggests the existence of the pre-Hormuz Formation (Sherkati and Letouzey, 2004). The Hormuz salt plugs were originally deposited in evaporitic basins related to the north trending rifting which developed at that time in the Arabian plate (Edgell, 1996). The Hormuz Formation consists of anhydrite, dolomite, shale and volcanic rocks (Haynes and McQuillan, 1974).

Epicontinental deposits of Paleozoic age show some sedimentary gaps, thickness and facies changes linked to salt and epirogenic movements, basement faulting and eustatic sea level changes (Berberian and King, 1981). Deposition of Permian clastics and carbonates on a truncated Silurian to Cambrian surface underlines Hercynian unconformity, which is the most important sedimentary gap in the Zagros belt (Szabo and Kheradpir, 1978).

By the Late Triassic, the Neo-Tethys Ocean opened between Arabia and Iran with two different sedimentary basins on either side of the ocean (Berberian and King, 1981). Crustal thinning along the Main Zagros Fault is the evidence of the thermal arching, rifting and opening of the Neo-Tethys Ocean (Koop and Stoneley, 1982; Stampfli and Borel, 2004). Throughout the Late Triassic to Early Cretaceous, the Arabian platform was a stable shallow shelf dominated by carbonate and some evaporite deposition. Numerous transgression and regression during the Mesozoic explain the lateral variation in facies of carbonates from southeastern Zagros to the Lurestan Province in the northwest of the Zagros belt (Setudehnia, 1978; Van Buchem et al., 2003).

The configuration of the NE margin of the Arabian platform changed abruptly with the Early Coniacian-Late Santonian ophiolite obduction (Sherkati and Letouzey, 2004). To the northeast of the Arabian plate, especially along the NW part of the Zagros in Lurestan a flexural basin formed due to the overloading of continental crust by ophiolite obduction, in the Late Cretaceous to Pleistocene time (Agard et al., 2005). This basin is marked by accumulation of Campanian flysch supporting radiolaritic nappes. The nappe emplacement was followed by an uplift, which forced Palaeocene erosion in the High Zagros (Agard et al., 2005). That was followed by a relatively calm period during the Late Eocene. In Late Oligocene-Early Miocene time, basinal facies (turbidite) deposited in the northeast part of the High Zagros area whereas the limestone of the Asmari Formation were deposited in other places. This reveals the presence of a second flexural basin associated with the onset of continental collision during the Late Oligocene-Early Miocene (Agard et al., 2005)

The major angular unconformity between the Agha Jari and Bakhtyari formations is considered as Late Pliocene climax orogeny in the Zagros fold and thrust belt (Haynes and McQuillan, 1974). Growth strata within Agha Jari Formation indicate early movements before this major unconformity (Hessami et al., 2001; Homke et al., 2004; Sherkati et al., 2005). The base of the growth strata is dated at 7.6 ± 0.5 Ma in front of the Zagros Fold Belt by Homke et al. (2004). It seems that the Zagros folding started in the Middle Miocene and covered the entire belt by the Early Pliocene (Sherkati et al., 2005).

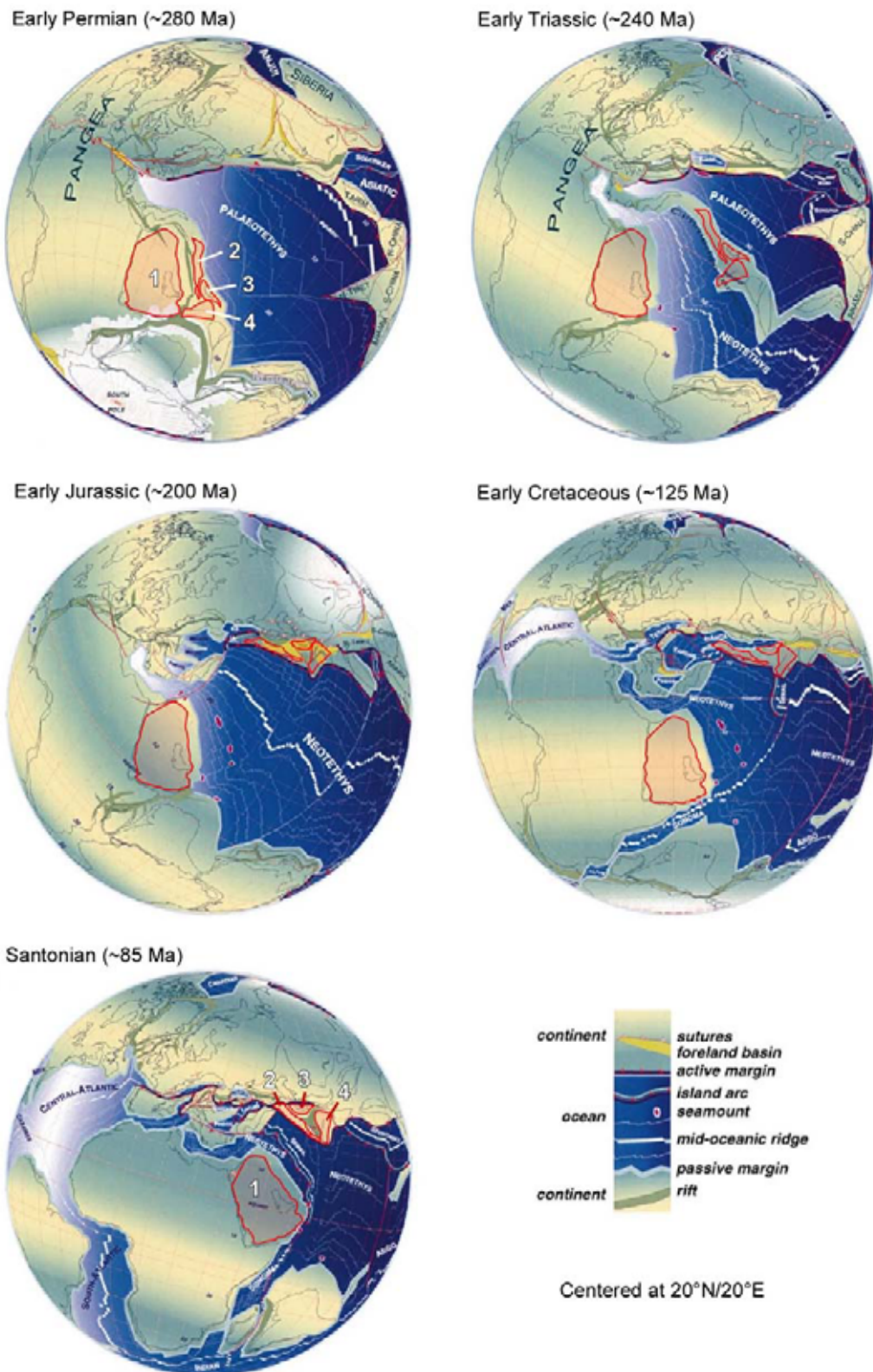


Fig. 3. Tectonic evolution of the Paleo-Tethys and Neo-Tethys as well as the Position of Arabian and Iranian plates during the Paleozoic-Mesozoic (Stampfli and Borel, 2002). 1 = Arabian plate, 2 = Sanandaj Sirjan block, 3 = NW Iranian block, 4 = Central Iranian block.

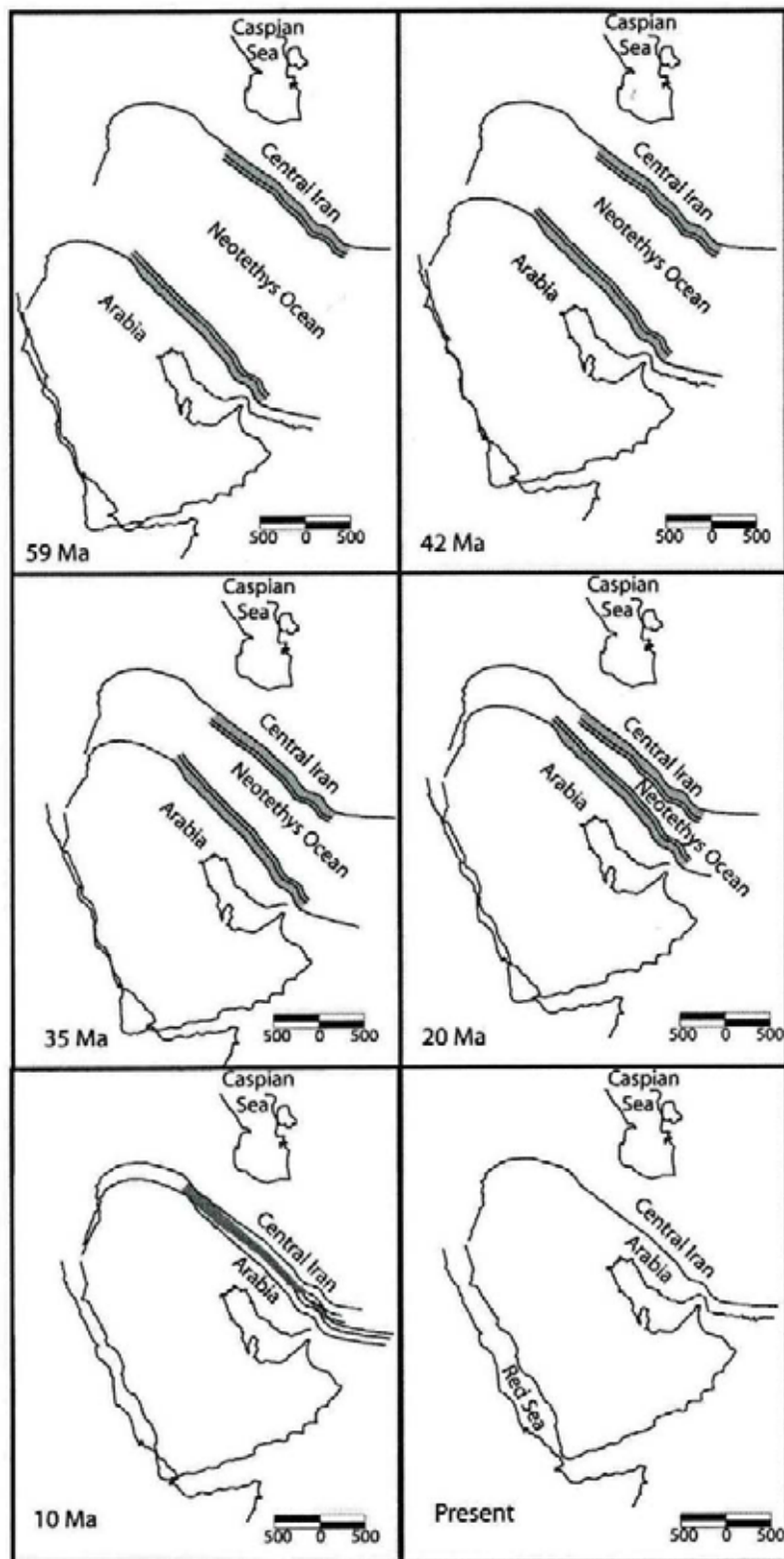


Fig. 4. Maps showing the evolution of the Neo-Tethys and relationship between the opening the Red sea and collision of Arabia and Eurasia (McQuarrie et al., 2003). The grey bands show the amount of shortened crust 70 km on Arabian plate and 80 km in Eurasia. The thin grey band inside shows the passive margins (50 km) in both sides of the Neo-Tethys.

1.4 Zagros orogeny and petroleum system

For the long time the Zagros fold and thrust belt has been focus of petroleum exploration as well as geological studies. The interest for this region started when the first major oil accumulation was discovered at Masjid Suleiman in the south west of the Zagros Fold Belt of Iran in 1908 by the DARCY exploration company (Beydoun et al., 1992). As much as 98.7% of oil and 92% of gas reserves in the Middle East are located along the NE Arabian plate margin, in the Iraq-Iran-Arabian basin (Beydoun 1991; Beydoun et al., 1992).

The timing of the orogenic events associated with the closure of the Neo-Tethys significantly influenced the generation, migration and entrapment of the hydrocarbons in the Zagros Fold Belt (Bordenave and Hegre, 2005). Two major structural trends control oil and gas reservoirs in this area. Within the Zagros belt oil fields are aligned with NW-SE trending folds (James and Wynd, 1965) while to the south of the Zagros Fold Belt, the main Arabian oilfields are aligned with north-south trend anticlines (Beydoun, 1991; McQuillan, 1991).

The influence of the tectonic events on petroleum entrapment is particularly important in the Dezful Embayment of the Zagros Fold Belt. Since this area is one of the world richest oil provinces, which contains about 8% of global oil reserves in an area of 60000 sq. Km (Bordenave and Hegre, 2005). In the Zagros Fold Belt and particularly in the Dezful Embayment hydrocarbons occur in two carbonate reservoirs: the Sarvak Formation Cenomanian to Turonian in age and the Oligocene-Early Miocene Asmari Formation (Beydoun, 1991; McQuillan, 1991). The two reservoirs are sealed by marls and shales of the Gurpi Formation and the evaporites of the Gachsaran Formation respectively. The hydrocarbons are trapped in large whaleback anticlines. The two reservoirs are constitute the Middle Cretaceous to Early Miocene Petroleum system, which is separated from two older systems (Paleozoic and Jurassic) by thick evaporite seals (Bordenave and Hegre, 2005) (**Fig. 5**). Two excellent source rocks, the Albian Kazhdomi Formation and the upper part of the Pabdeh Formation (Middle Cretaceous to Early Oligocene) supplied the Sarvak and Asmari reservoirs.

The Zagros folding commenced in the Dezful Embayment around the end of Middle Miocene (10 Ma) and continued throughout the Late Miocene and Pliocene (Sherkati et al., 2005). Oil expulsion from the Kazhdomi and Pabdeh source rocks occurred during deposition of the Aghajari Formation between 8 and 3 Ma depending on the location. Oil migrated over short distance from source rocks to nearby traps within well-defined drainage area (Bordenave and Hegre, 2005).

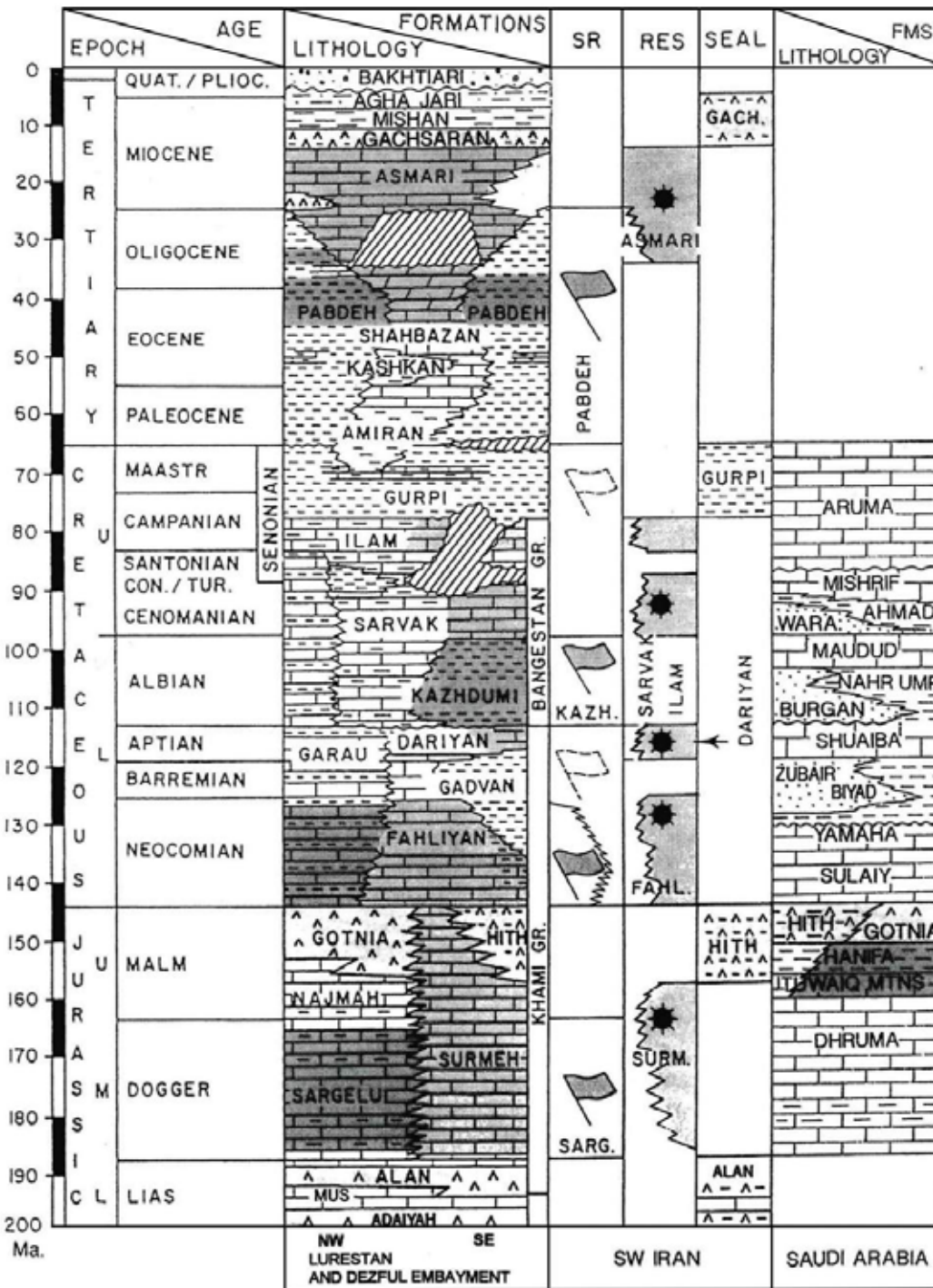


Fig. 5. Stratigraphy and source rocks-reservoir-seal relationships for the Dezful Embayment and the adjacent areas. Grey flags and white flags indicate principal and marginal source rocks respectively (Bordenave and Hegre, 2005).

1.5 The Pusht-e Kuh Arc, Lurestan stratigraphy Province,

The study area is located in the Pusht-e Kuh Arc northwestern part of the Zagros Fold and Thrust Belt. The use of the Pusht-e Kuh Arc name for this part of the belt probably is related to the some of the internal NIOC reports as well as the several authors (e.g. Alavi, 1994; Bahroudi and Talbot, 2003). The Pusht-e Kuh name is composed by two Persian words: *Pusht-e* (*behind*) and *Kuh* (*mountain*). Interestingly in the Lurestan area this name is used by the locals to refer to the area north of the Kabir Kuh anticline. They used another Persian word the *Pish Kuh*, which means *in front of the mountain*, for the area in front of the Kabir Kuh. Not surprisingly the Kabir Kuh anticline has the highest elevation >2500 m in Lurestan and represent a topography boundary (**Fig. 2**). From a geological point of view Pusht-e Kuh Arc refers to the entire Simply Folded of the NW Zagros belt.

In the Pusht-e Kuh Arc, rocks belonging to the later passive margin and early foreland basin stratigraphy are exposed in the core of the anticlines in this area. The younger rocks of the foreland basin succession are only exposed in the rare deep synclines. The stratigraphy of the Lurestan province is a 10-12 km thick succession, which consist of the Paleozoic and Mesozoic Arabian passive margin deposits followed by the sediments corresponding to the long lived Cenozoic Zagros orogenic phase. The thick sediments were probably deposited on top of the Proterozoic-Early Cambrian Hormuz evaporites although this fact is not proved in Lurestan (**Fig. 6**). James and Wynd (1965) described the Mesozoic and Cenozoic outcrops in this part of the Zagros Fold Belt.

The Paleozoic sequence is not exposed in the Pusht-e Kuh Arc but it is well documented in the hanging wall of the High Zagros Fault (O'B Perry and Setudehnia, 1967). Some information about the Paleozoic rocks has been obtained from exploration wells which are penetrated in to the Permian rocks in Kabir Kuh and Samand anticlines. In addition to that, the existence of deep folded reflectors in seismic lines across the north-west frontal regions of the Dezful Embayment strongly suggests that lower Paleozoic is present beneath the external parts of the Lurestan Province (Vergés et al., in press). The broad extent of the lower Paleozoic must be considered within the frame of the wide, stable and long-lived northern passive margin along the Paleo-Tethyan border of Gondwana (e.g., Beydoun et al., 1992).

The Mesozoic sequence of the north-eastern Arabian platform was stable up to the Late Cretaceous when oceanic obduction took place along this margin in the Pusht-e Kuh Arc. This succession is about 3 km thick and includes the Triassic Dashtak

Formation, the Khami Group (Jurassic-Aptian) and the Bangestan Group (Albian-Middle Campanian) (James and Wynd, 1965). During the Triassic, Jurassic and lower Cretaceous the region was shaped by a large carbonate platform (Khami group) with associated shallow basins filled with marls, shales, and argillaceous carbonates interbedded with episodic plugs of evaporites (upper Jurassic Gotnia Formation) providing several large areas of potential source rocks in Pusht-e Kuh Arc (Murriss, 1980; Stoneley, 1990). The Bangestan Group presents the continuation of the carbonate platform deposition including Kazhdomi, Sarvak, Surgah and Ilam formations. The thick rudist limestones of the Sarvak Formation correspond to the lower reservoir in the Zagros. In the northeast of the Kabir Kuh this group changes laterally to the more basinal dark carbonate shales of the Garau Formation, with a maximum thickness of 1000 m. The Bangestan Group is overlain by the shallow marine Middle Campanian of Gurpi Formation including two extensive fossiliferous carbonate members (James and Wynd, 1965). To the north of the Kabir Kuh anticline, a thick shallowing upward Paleocene siliclastic succession composed of the Amiran, Tale Zang and Kashkan formations is time equivalent to the upper part of the Gurpi and Pabdeh formations (Homke et al., in press). To the north of the Kabir Kuh anticline the Asmari Formation presents a Middle Miocene age suggests a very long sedimentary gap between the Asmari limestone and the underlying deposits (Homke et al., in press). These authors suggest that the Amiran Formation marks the initiation of the foreland deposition characterized by episodic in fill in the early stage (Amiran, Tale Zang and Kashkan formation) and over filled during the Late Miocene and Pliocene evolution (Gachsaran, Agha Jari and Bakhtyari formations).

Above the Miocene Asmari Formation the thick evaporites of the Gachsaran Formation corresponding to the Lower Fars Group (Bahroudi and Koyi, 2004; Kashfi, 1980) form an effective seal for hydrocarbon on top of the Asmari reservoir. The upper age of the Gachsaran evaporites is constrained by magnetostratigraphy near the front of the Pusht-e Kuh Arc with an age of 12.8-12.3 Ma corresponding to the uppermost Middle Miocene (Homke et al., 2004). Along the front of the Pusht-e Kuh Arc the thick 1650 m lower Agha Jari fluvial deposits encompasses from 12.8-12.3 Ma to 3 Ma. Above that the fine grained Lahbari Mb (825 m thick) has an age of 5.5-3 Ma and the overlying conglomerate of the Bakhtyari Formation has been dated at 3-1.5 Ma.

The mechanical behaviour of the sedimentary succession of Zagros Fold Belt and its response to the folding is discussed by O'Brien (1950) and Dunnington (1968). It is also has been discussed by several recent works (Sattarzadeh et al., 2000, Molinaro et al., 2004, Sherhati et al., 2004 and 2006). O'Brien (1950) and Dunnington (1968)

divided the succession of the fold belt in 5 structural units with relatively uniform characteristics (**Fig. 7**). From below to top of the units are: 1) The basement; 2) the Lower Mobile Group (Late Proterozoic-Early Cambrian Hormuz evaporites); 3) the Competent Group (Paleozoic and Mesozoic to Middle Tertiary passive margin and early foreland carbonates); 4) the Upper Mobile Group (Middle-Late Miocene Gachsaran evaporites); and 5) The Passive Group (Late Miocene-Pliocene foreland clastics). These groups of strata do not exactly correspond to the large-scale geodynamic cycles that modeled the NE margin of the Arabian plate, especially the Competent Group (**Fig. 7**). This group includes the full passive margin period as well as the early foreland basin period up to the Asmari Formation. Generally, the sedimentary pile is grouped in two stiff units and two weak detachments, whose position and limits are also important to define their different style of deformation (Vergés et al., in press). The Competent Group deformed between a basal and a roof detachments located in the Lower Mobile Group and the Upper Mobile Group respectively. The Passive Group is folded and thrust-disharmonically above the upper Mobile Group (Vergés et al., in press). The upper part of the Competent Group characterizes the architecture and geometry of the Pusht-e Kuh Arc. The Passive Group on the top preserved in some of the synclines across the Pusht-e Kuh Arc.

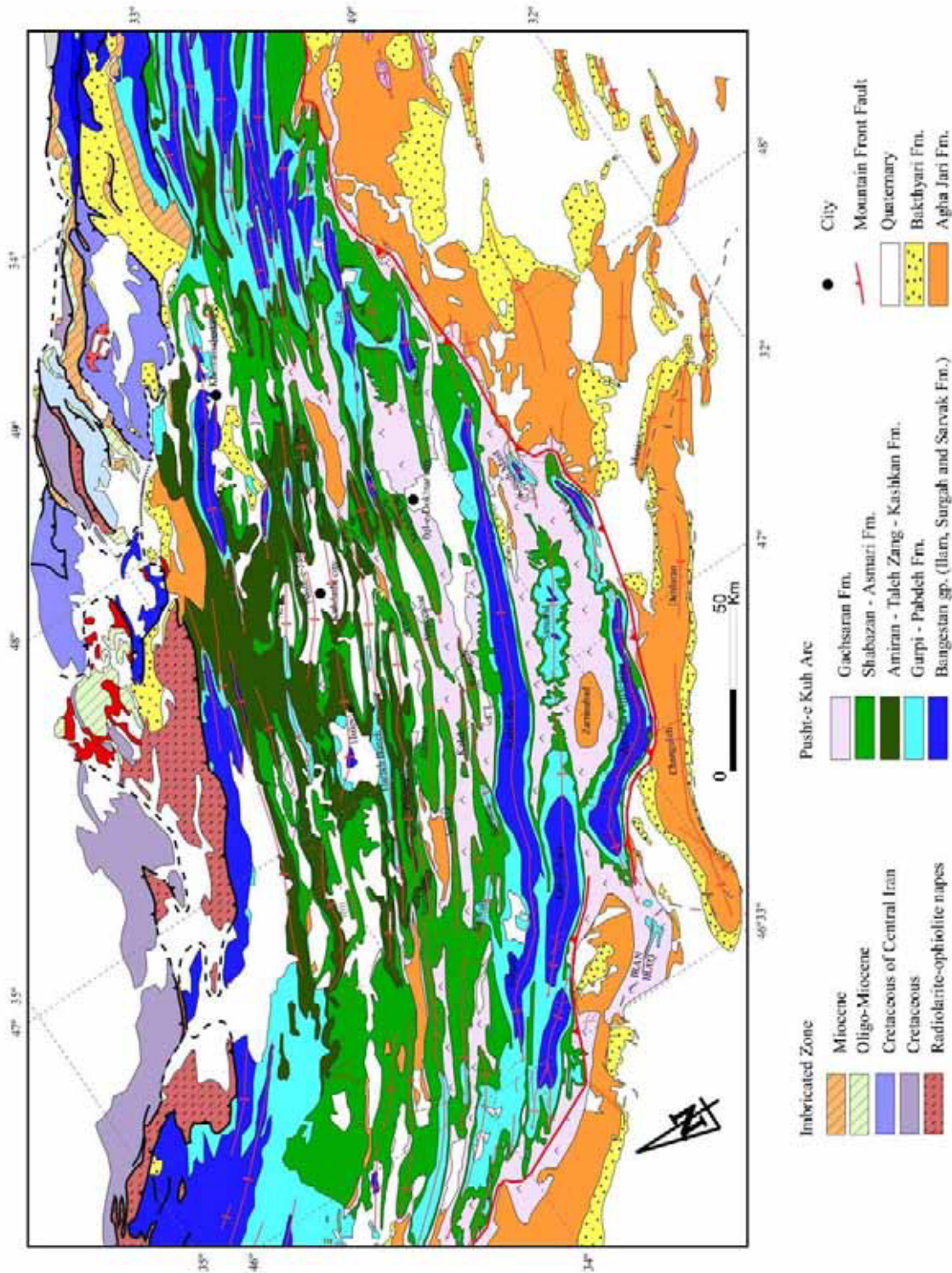


Fig. 6. Geological map of the Pusht-e Kuh Arc (modified from 1/1000000 geological map of the Zagros published by NIOC).

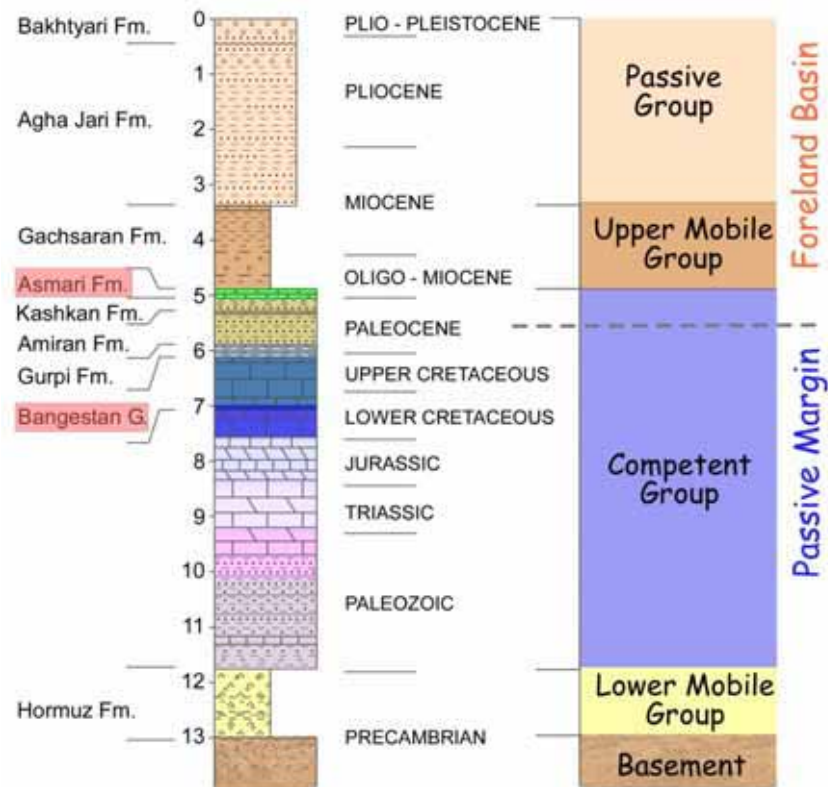


Fig. 7. Stratigraphy and mechanical units in the Pusht-e Kuh Arc. This panel is combined with the position of the Paleozoic-Mesozoic passive margin and Cenozoic foreland (Vergés et al., in press).

1.6 Objectives and Methodology

Several aspects of the Zagros Fold and Thrust Belt such as 1) lack of the good quality deep seismic profiles, 2) very thick sedimentary sequence (10-12 km), 3) unexposed deep structural geometries and 4) existence of the different incompetent units in the sedimentary pile makes that very complex to explain the characteristics of the Zagros Fold and Thrust Belt.

The objectives of this work are divided in three parts, which correspond to three chapters of this study (**Fig. 8**).

- 1) Defining the structural characteristics of the anticlines in the Pusht-e Kuh Arc as well as the potential depths of detachment horizons and their relation to the mechanical stratigraphy. This is accomplished by using available data

sets and by combining data from the field to construct a 3-D visualization of the Zangul anticline in the NE side of the Pusht-e Kuh Arc.

- 2) Determine the role of the basement structure of the Mountain Front Fault and the potential geometry of the Anaran anticline at depth using a combination of field geology and analogue modeling. That helps to understand the interaction of basement and cover structures, the geometry of normal faults and the role of erosion and syntectonic sedimentation during the evolution of the anticline.
- 3) Determining the age of the growth strata of the Agha Jari Formation as well as the sequence of the deformation across the NW part of the Zagros Fold Belt in the Pusht-e Kuh Arc.

In order to study these objectives in this study, the dissertation has been organized in five chapters. The chapters 2, 3 and 4 are the core of this work. The chapters 1 and 5 respectively are presenting the general introduction and summary of this work (**Fig. 8**).

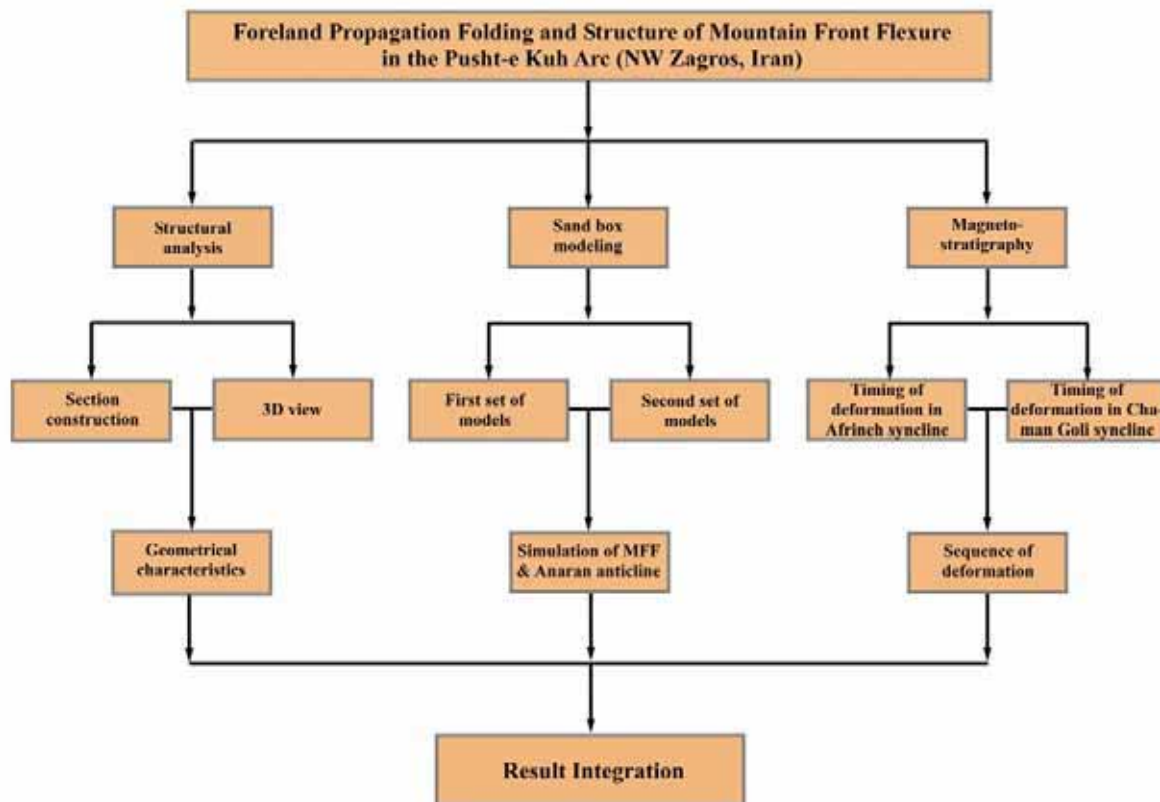


Fig. 8. Workflow shows the structure of the study, different objectives and methodology.

In chapter 2 we try to determine the variation of the geometry of the Zangul anticline along the strike; geometrical relation to the adjacent structures and also the potential intermediate detachments for this anticline is discussed. The result of this study can be extrapolated to the interpretation and study of other anticlines in Pusht-e Kuh and the Zagros Fold Belt. In this highlight these characteristics we provide a 3D view for Zangul anticline based on the surface geological data by helping of the construction of 11 seriated cross and 3 longitudinal sections. In order to do that a geological data base for this chapter is provided in GIS application. It is including published geological map, well data, digital elevation model and field data. From this data base the topography profiles across the sections and the formation tops (e.g. the Asmari and the Ilam formations) are provided in a format of the GIS for the further steps of the work. The dip data set from geological maps and field also are prepared for the 2D Move application. In this step of the work the appropriate dips data respect to the sections are projects to the sections along the strike of the dips data. In the next step all data (formation tops and contacts along the sections, topography profile and projected dip data) are combined in the graphic tools like Canvas application. In the next step in 2D Move application the geometry of the Zangul anticline has been reconstructed. It follows the kink method in which geometry of the structure is reconstructed by assuming constant thickness of the units bended in a narrow hinge zone (Groshong, 1999), the thicknesses of the units are provided from the published data as well as the several well data in Push-e Kuh Arc. In this step different geometry can be tested and also at the seam time a quality control of the data set along the sections can be done through the data base in GIS and 2D Move. Later the result can be presented as single reconstructed section of the anticline or the resulted section will use in GIS application to produce the 3D view of the structure by interpolation between the all the resulted section (**Fig. 9**).

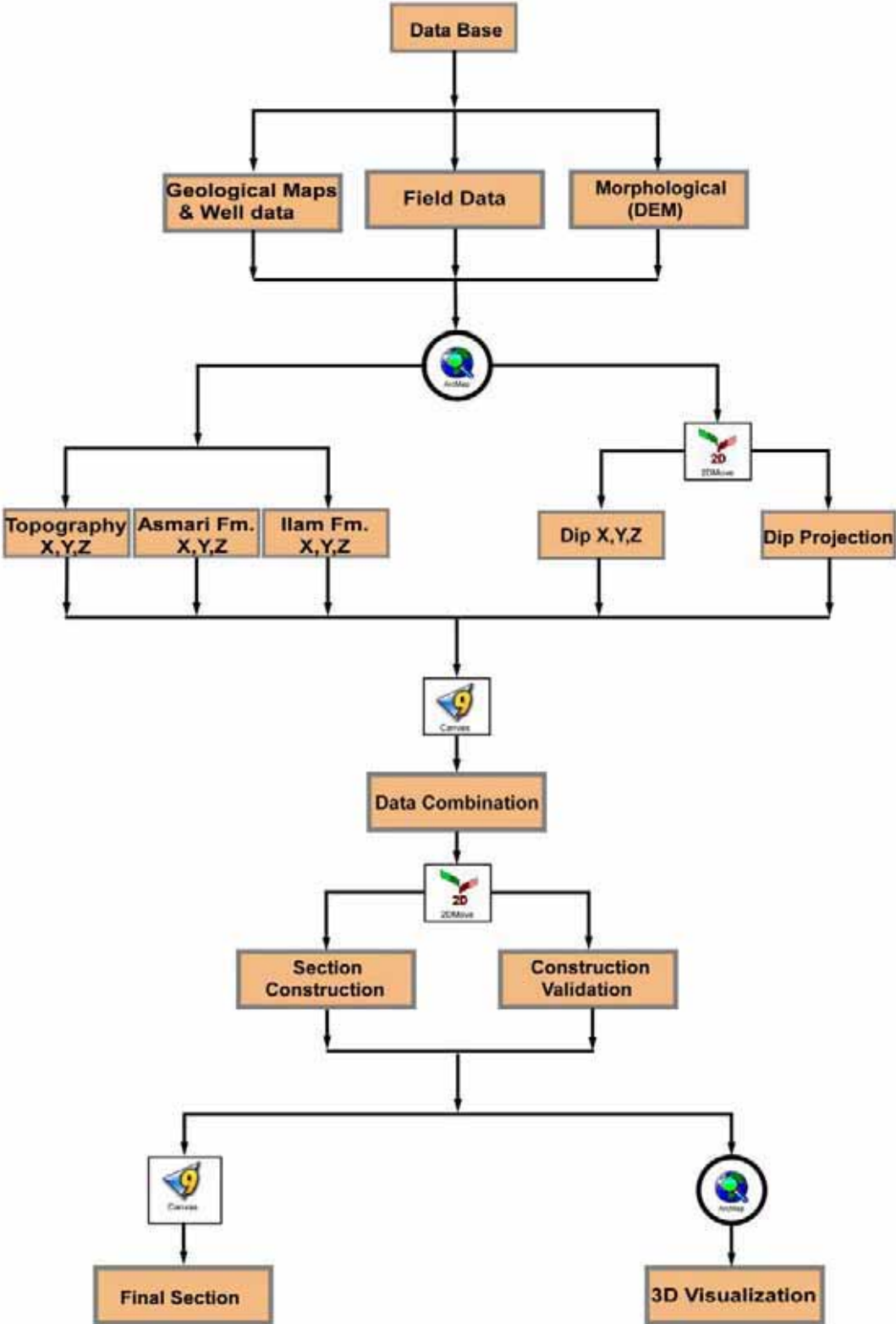


Fig. 9. Workflow showing the methodology has been used in Chapter 2 to study the structural characteristics of the Zangul anticline in NE side of the Pusht-e Kuh Arc.

The chapter 3 is particularly related to sand box modeling. The modeling has been done in Laboratory of Experimental Tectonics of Géosciences Rennes (Rennes University, France). In the sand box modeling technique the deformation is simulated by using an experimental apparatus, which is composed of a rigid mobile wall pushing the sand beds at a constant rate of compression velocity. The basement and brittle sediments (pre and synkinematic) are represented by sand, with an angle of internal friction close to 30° (Krantz 1991) and a density of $\rho = 1400 \text{ Kg/m}^3$. Weak ductile sediments such as shale, clay, marl or salt are represented by silicone putty with a viscosity of $\mu = 10^4 \text{ Pa.s}$ at 30°C and a density of $\rho = 1400 \text{ Kg/m}^3$ (e.g. Faugère and Brun 1984; Vendeville et al. 1987; Davy and Cobbold 1991).

In the this type of modeling different parameters like compression velocity and configuration of the models can be changed and also different process like erosion and role of the syntectonic sedimentation can be tested. At the end of the experiments the models should be covered with sand to protect the further deformation then the model has to be saturated by water to have enough cohesion for vertical sections. It is providing the internal structure across a series of cross-sections cut parallel to the compression direction.

In the chapter 3 the sand box modeling has been applied to understand how the basement fault and deformation at depth will control the surface structural characteristics of the Anaran anticline at the location of the Mountain Front Flexure. In this chapter we simulate 2 different groups of kinematics models. In order to analogue these two kinematics models we were using different configuration in our experiments to produce the different phase of shortening. By combination of the result from analogue models together with field data and also help of numerical and rock analogue models a geometrical model is presented for the Anaran anticline (**Fig. 10**)

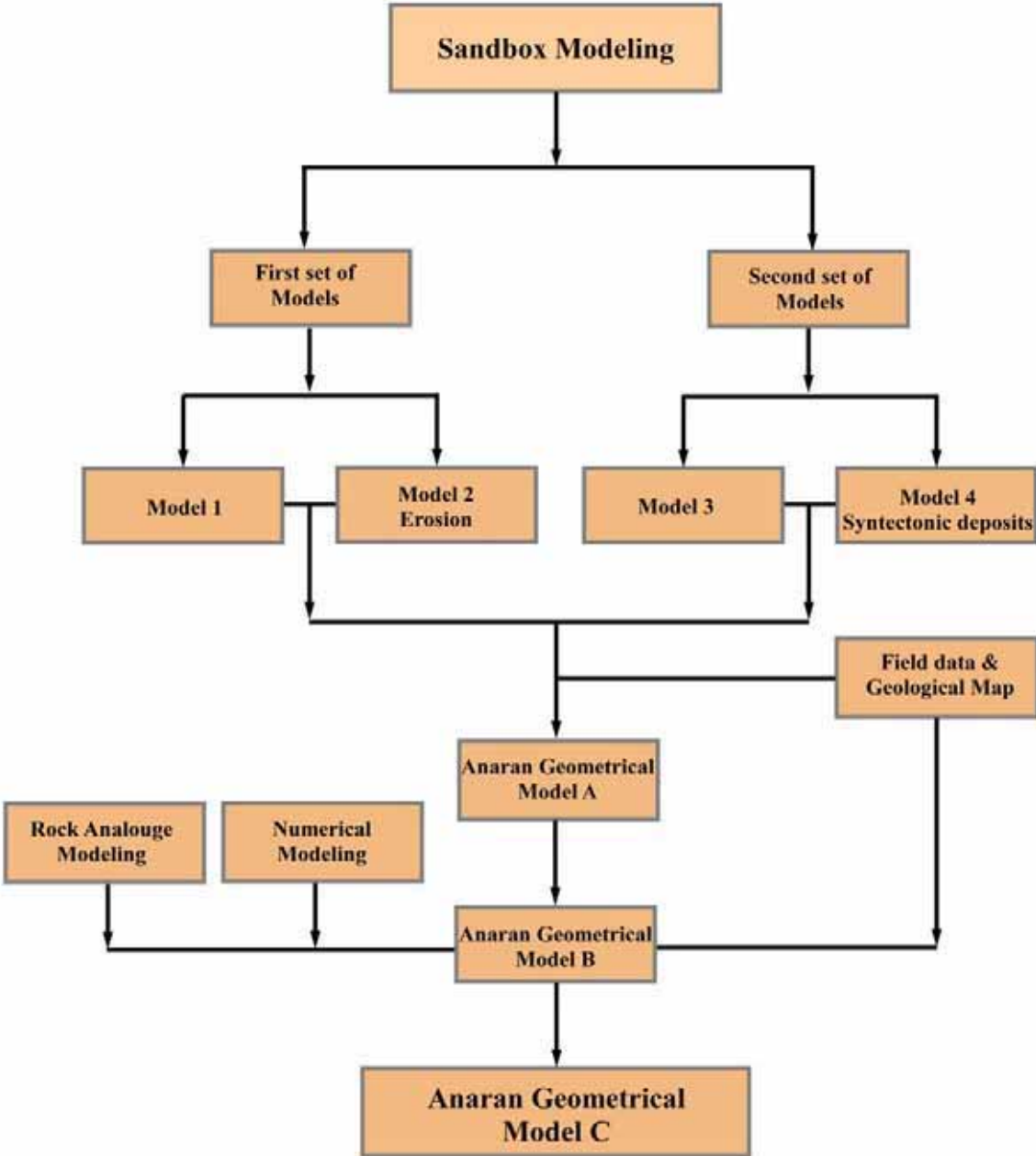


Fig. 10. Workflow showing the application of the analogue models as well as the combination of the different data set to provide the geometrical model for Anaran anticline.

The chapter 4 is related to the magnetostratigraphy and timing of the deformation across the Zagros Fold Belt at two sections (Afrineh and Chaman Goli synclines). The magnetostratigraphy is an appropriate technique to date the fine grain fluvial sediments where the other dating methods are not possible. The magnetostratigraphy dating method is based on the recording the earth's magnetic field direction during deposition and compaction of the fine grain detrital sediments. It depended to the alignment of the magnetic grains with the current earth's magnetic field (Irving 1964; Hailwood, 1989; Butler, 1992). The stable magnetic component acquired by depositing sediments, called the Detrital Remanent Magnetization (DRM). That is normally analyzed by a progressive stepwise demagnetization of sequence of the oriented samples. The stepwise demagnetization procedure permits to remove the viscous overprint of the recent magnetic field and finally to isolate the detrital remanent magnetization at the timing of the depositing the magnetic grains (**Fig. 11**).

The demagnetization method is a stepwise thermal or alternative-field demagnetization technique (Butler, 1992). Magnetic polarity measurements after demagnetization are generally analyzed using vector end point diagram, which referred as vector component, orthogonal projection, or Zijderveld diagram (Zijderveld, 1967) (**Fig. 11**). A magnetic polarity sequence will be provided by studied the sequential samples from a sedimentary profile. Correlation of the magnetic stratigraphy to the Geomagnetic Polarity Time Scale (Cande and Kent, 1992, 1995) will provide an absolute age for the studied samples.

Two sections across the Afrineh and Chaman Goli syncline have been sampled in this study. 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. Later 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).

In chapter 4 we present the detail methodology as well as the result of the two sections and their combination with the recent published data in Zagros fold and thrust belt (**Fig. 12**).

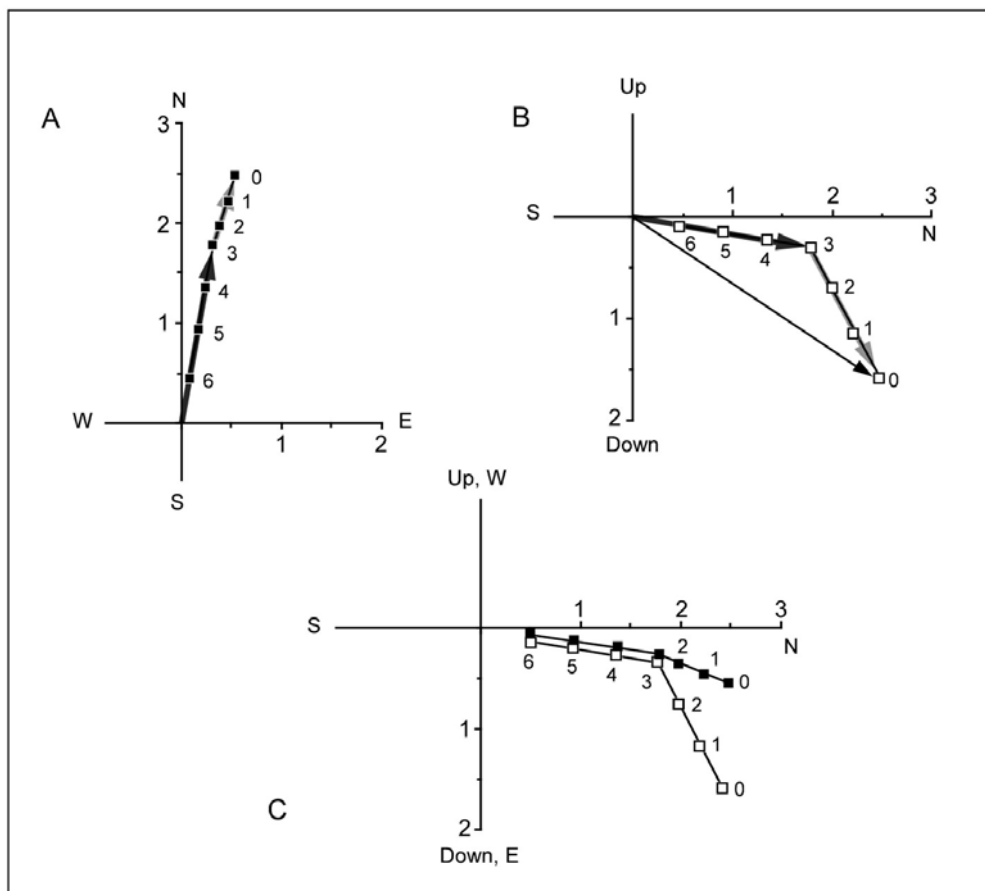


Fig. 11. Construction of vector component diagram, from Butler (1992). The low temperature magnetic component (recent magnetic overprint) is progressively removed from step 0 to 3. The stable component, the Natural Remanent Magnetization (NRM), is isolated after step 3. (A) Projection of the NRM vector onto the horizontal plane. The scale of axes is in A/m in the graphs. the light grey arrow represents the horizontal projection of the magnetic component vector removed during demagnetization from levels 1 to 3. The thick dark arrow represents the projection of the NRM vector remaining at level 3. (B) Projection of the NRM vector onto a vertical plane oriented north-south. The solid arrow represents the vertical projection of the NRM vector prior to demagnetization. (C) Horizontal and vertical projections combined into a single vector component diagram. Solid data points indicate vector-end points projected onto the horizontal plane. Open data points indicate vector-end points projected onto the vertical plane.

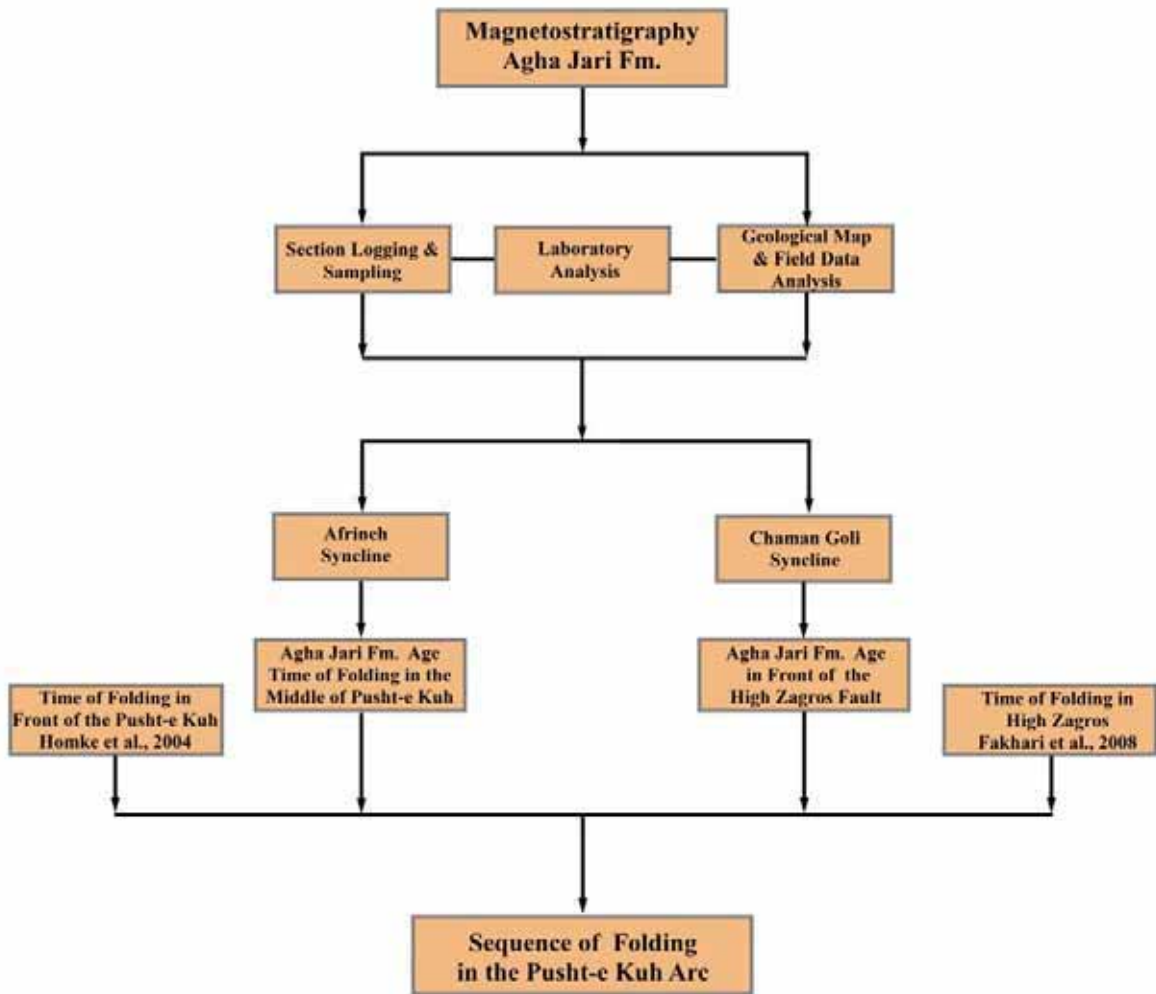


Fig. 12. Workflow showing the application of the magnetostratigraphy in chapter 4.

