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Revised age of proximal deposits in the Zagros foreland basin and implications for Cenozoic evolution of the High Zagros

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Abstract

The regionally extensive, coarse-grained Bakhtiyari Formation represents the youngest synorogenic fill in the Zagros foreland basin of Iran. The Bakhtiyari is present throughout the Zagros fold-thrust belt and consists of conglomerate with subordinate sandstone and marl. The formation is up to 3000 m thick and was deposited in foredeep and wedge-top depocenters flanked by fold-thrust structures. Although the Bakhtiyari concordantly overlies Miocene deposits in foreland regions, an angular unconformity above tilted Paleozoic to Miocene rocks is expressed in the hinterland (High Zagros).

The Bakhtiyari Formation has been widely considered to be a regional sheet of Pliocene–Pleistocene conglomerate deposited during and after major late Miocene–Pliocene shortening. It is further believed that rapid fold growth and Bakhtiyari deposition commenced simultaneously across the fold-thrust belt, with limited migration from hinterland (NE) to foreland (SW). Thus, the Bakhtiyari is generally interpreted as an unmistakable time indicator for shortening and surface uplift across the Zagros. However, new structural and stratigraphic data show that the most-proximal Bakhtiyari exposures, in the High Zagros south of Shahr-kord, were deposited during the early Miocene and probably Oligocene. In this locality, a coarse-grained Bakhtiyari succession several hundred meters thick contains gray marl, limestone, and sandstone with diagnostic marine pelecypod, gastropod, coral, and coralline algae fossils. Foraminiferal and palynological species indicate deposition during early Miocene time. However, the lower Miocene marine interval lies in angular unconformity above ~150 m of Bakhtiyari conglomerate that, in turn, unconformably caps an Oligocene marine sequence. These relationships attest to syndepositional deformation and suggest that the oldest Bakhtiyari conglomerate could be Oligocene in age.

The new age information constrains the timing of initial foreland-basin development and proximal Bakhtiyari deposition in the Zagros hinterland. These findings reveal that structural evolution of the High Zagros was underway by early Miocene and probably Oligocene time, earlier than commonly envisioned. The age of the Bakhtiyari Formation in the High Zagros contrasts significantly with the Pliocene–Quaternary Bakhtiyari deposits near the modern deformation front, suggesting a long-term (>20 Myr) advance of deformation toward the foreland.

Keywords: Arabia–Eurasia collision; Bakhtiyari Formation; Foreland basins; Iran, Zagros fold-thrust belt

1. Introduction

Dating foreland-basin fill is fundamental to identifying the onset and tempo of deformation in orogenic systems. In collisional settings, the age, provenance, and structural relationships of the oldest foreland-basin deposits are commonly used to define the record of initial continental collision. An accurate chronology of foreland sedimentation has proven critical for assessing the geologic evolution of the Indo-Asian collision (e.g., Beck et al., 1995; Rowley, 1996) and Alpine collision (e.g., Sinclair, 1997; Schlunegger et al., 1997). However, in the case of the Arabia–Eurasia collision, a precise chronostratigraphy remains elusive due to a lack of diagnostic fossils and

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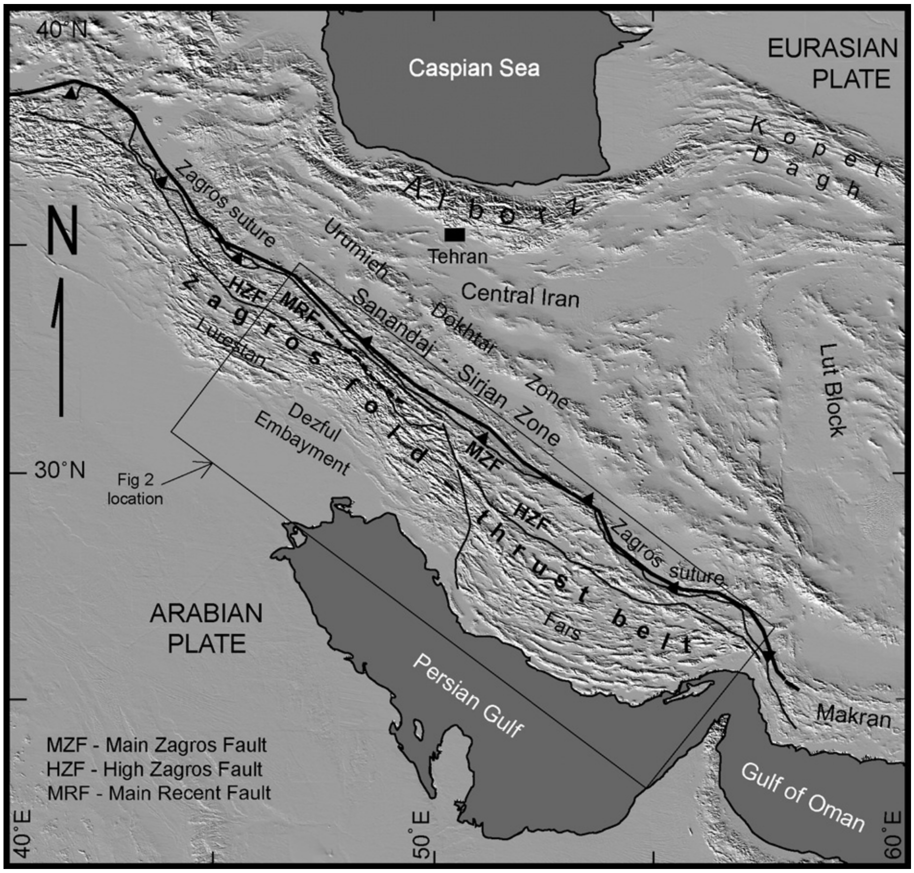

Fig. 1. Shaded relief map showing the Zagros fold-thrust belt and foreland basin within the Arabia–Eurasia collision zone (after Guest et al., 2006).

volcanic horizons within the principally nonmarine foreland-basin succession.

The Zagros foreland basin was produced by construction of the Zagros fold-thrust belt during the Arabia–Eurasia collision (Koop and Stoneley, 1982; Beydoun et al., 1992; Alavi, 2004). The fold-thrust belt (Fig. 1) consists of a hinterland zone of emergent SW-directed thrust faults near the suture (High Zagros and "Crush Zone") (Fig. 2), (Wells, 1969) and a frontal belt of large, regularly spaced, NW-trending folds with few exposed thrusts (Simply Folded Zone) (Falcon, 1969; Wells, 1969; Falcon, 1974; Haynes and McQuillan, 1974; Sepehr and Cosgrove, 2004). A regional sheet of coarse-grained basin fill consistently mapped as the Bakhtiyari Formation covers large areas of the foreland and fold-thrust belt (Fig. 2). This deposit is regarded as the stratigraphic

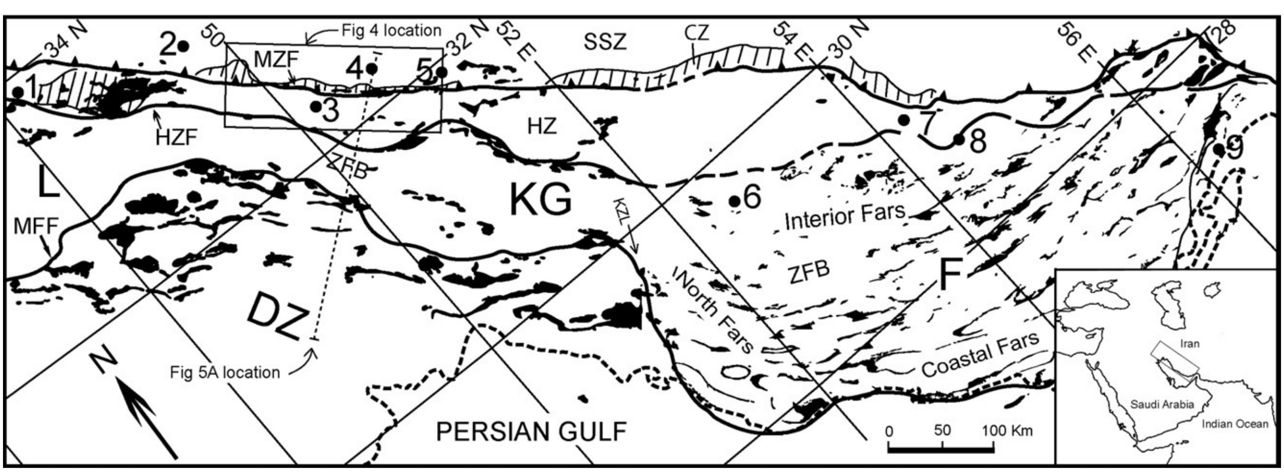

Fig. 2. Map of major structural units and surface exposures of the Bakhtiyari Formation (black) in the Zagros fold-thrust belt. L—Lurestan; KG—Kuh-giluyeh; DZ—Dezful Embayment and Khuzestan; F—Fars; SSZ—Sanandaj–Sirjan Zone; ZFB—Zagros Folded Belt; MFF—Mountain Front Flexure; HZF—High Zagros Fault; MZF—Main Zagros Fault; HZ—High Zagros; CZ—Crush Zone; KZL—Kazerun Line; 1—Aleshtar; 2—Aligoodarz; 3—Kuhrang; 4—Shahr-kord; 5—Borujen; 6—Shiraz; 7—Neyriz; 8—Darab; 9—Bandar Abbas.

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signature of Zagros uplift induced by the Arabia–Eurasia collision (James and Wynd, 1965; Stocklin, 1968; Falcon, 1974; Berberian and King, 1981). Although direct dates are lacking, fossil age control for underlying units led James and Wynd (1965) and the official stratigraphic lexicon of Iran (Setudehnia, 1972) to propose a late Pliocene and younger age for the Bakhtiyari Formation (Fig. 3). Confirmation of this age has only been provided for the frontalmost structures of the fold-thrust belt, where magnetic polarity stratigraphy defined an ~3 Ma age for the base of Bakhtiyari exposures (Homke et al., 2004). Direct age control is still lacking for the vast majority of Bakhtiyari outcrop belts, notably the deposits farther NE toward the hinterland.

The goal of this paper is to evaluate the structural, stratigraphic, and chronologic context of Bakhtiyari deposits exposed in the High Zagros. We first present a regional overview of the Bakhtiyari Formation throughout the Zagros fold-thrust belt, then focus on the sedimentology, provenance, and new age control for the study region in the hinterland of the Dezful Embayment (Fig. 2). Finally, we consider the implications of our findings for the tectonic evolution of the High Zagros and timing of initial collision between Arabia and Eurasia.

2. Geologic setting

The Zagros fold-thrust belt (Figs. 1 and 2) consists of a well-known frontal belt Zagros folded belt (also known as simply folded belt) of large NW-trending folds and a hinterland region (High Zagros and Crush Zone) of SW-directed thrust faults (Falcon, 1974; Colman-Sadd, 1978; Sepehr and Cosgrove, 2004; Sherkati and Letouzey, 2004). The High Zagros are bounded on the NE by two faults, the reverse Main Zagros Fault (MZF) and the dextral Main Recent Fault (MRF), which together approximate the Zagros (Neotethys) suture zone between the Arabian and Eurasian plates (Berberian, 1995; Bosold et al., 2005; Authemayou et al., 2006). To the SW, the high-angle reverse-dextral High Zagros Fault (Fakhari, 1996b) defines the boundary between the High Zagros and Simply Folded Zone (Fig. 1). The Zagros deformation front (the SW margin of the Simply Folded Zone) is defined by the so-called Mountain Front Flexure (Koop and Stoneley, 1982; McQuarrie, 2004) or Mountain Front Fault (Berberian, 1995; Sepehr and Cosgrove, 2004).

The Iranian portion of the ~2000-km-long Zagros fold-thrust belt is divided into three segments, from SE to NW: the Fars salient, Dezful Embayment, and Lurestan salient (Fig. 2). The Kazerun Line (Fig. 2), a N-striking dextral fault, defines the boundary between the Dezful and Fars segments (Berberian, 1995; Authemayou et al., 2006; Lacombe et al., 2006). Most structural restorations suggest 45 to 85 km of NE–SW shortening across the Zagros (Falcon, 1969, 1974; Blanc et al., 2003; McQuarrie, 2004, Molinaro et al., 2005; Sherkati et al., 2006). Total NE–SW shortening in the Fars, Dezful, and Lurestan segments was estimated by McQuarrie (2004) to be 67 km, 85 km, and 57 km respectively. The uniform wavelength and amplitude of parallel folds in the Simply Folded Zone suggests a common regional décollement in the Cambrian Hormuz salt near the basement-cover interface at ~10 km depth (Falcon, 1969, 1974; Colman-Sadd, 1978; McQuarrie, 2004). Alternatively, some cross sections show varying degrees of basement involvement (Blanc et al., 2003; Sherkati and Letouzey, 2004; Molinaro et al., 2005; Sherkati et al., 2006; Mouthereau et al., 2006), consistent with earthquake hypocenter depths (Jackson, 1980; Talebian and Jackson, 2004).

The timing of shortening within the Zagros has been directly associated with late Cenozoic deposition of coarse-grained basin fill of the Bakhtiyari Formation (Figs. 2 and 3) (Stocklin, 1968; Falcon, 1974; Berberian and King, 1981). Despite limited age control, a general consensus has emerged that growth of individual Zagros fold-thrust structures across the belt was roughly

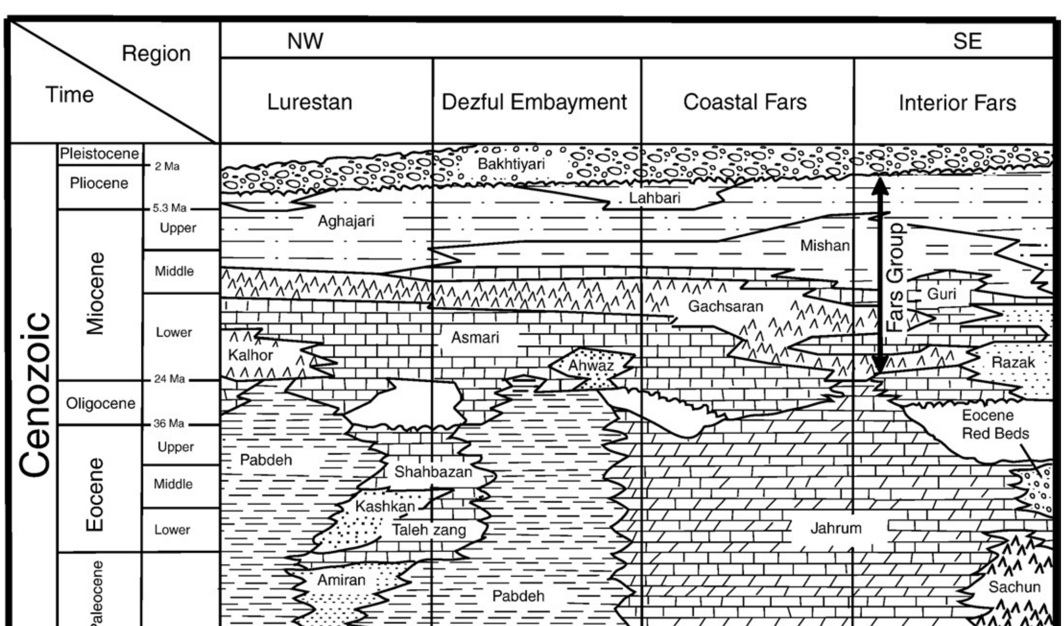

Fig. 3. Cenozoic stratigraphy of the Zagros basin, after James and Wynd (1965) and Setudehnia (1972) showing the Bakhtiyari Formation as Plio-Pleistocene.

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synchronous, with varying degrees of out-of-sequence deformation (Molinaro et al., 2004, 2005; Mouthereau et al., 2006). However, some studies have proposed a hinterland to foreland progression of deformation (Alavi, 1994, 2004). Discrimination between these kinematic scenarios depends on whether the Bakhtiyari Formation was deposited in either a series of individual piggyback (intermontane) depocenters NE of the present deformation front (James and Wynd, 1965; Haynes and McQuillan, 1974; Bahroudi and Koyi, 2004; Sepehr and Cosgrove, 2004) or in a regional foreland basin that was progressively incorporated into the fold-thrust belt during encroachment of fold-thrust structures from NE to SW (Hessami et al., 2001; Alavi, 2004; Sherkati and Letouzey, 2004). To shed light on the kinematic evolution of the Zagros, we focus on an outcrop belt of proximal basin fill preserved in the hinterland (NE) zone of the Zagros fold-thrust belt (Fig. 4). Our study in the High Zagros centers on coarse-grained deposits near Shahr-kord that have been mapped consistently as the Bakhtiyari Formation by the British Petroleum Company, National Iranian Oil Company and Geological Survey of Iran (e.g., British Petroleum Company, 1963; Iranian Oil Operating Companies, 1969; Zahedi et al., 1999).

3. Methods

This study builds upon a regional synthesis of the Bakhtiyari Formation (Fig. 2) which serves as a framework for a detailed investigation of Bakhtiyari exposures in the High Zagros near the city of Shahr-kord (Fig. 4). We first present a regional survey of Bakhtiyari relationships, largely derived from structural and stratigraphic investigations by the Oil Service Company of Iran (e.g., Evers et al., 1977; Fakhari et al., 1977) and the National Iranian Oil Company (e.g., Fakhari, 1979, 1996a). The regional summary is followed by presentation of the results of field structural mapping, sedimentological observations, provenance studies, and fossil identification for the study region. Identification of macroscopic marine fossil assemblages was followed by determination of foraminiferal and palynological species from 34 thin sections and 3 processed samples studied in collaboration with the National Iranian Oil Company (Hosseini, 2004; Ghavidel-Syooki, 2004; Fakhari et al., 2005). The significance of these ages is considered in the context of the tectonic evolution of the High Zagros and regional chronostratigraphic relationships across the Zagros foreland basin.

4. Regional overview of the Bakhtiyari Formation

4.1. Stratigraphic definition

Terrigenous clastic deposits of the synorogenic Bakhtiyari Formation compose the uppermost strata of the Mesozoic–Cenozoic Zagros basin. The definition of the formation has evolved in the ~100 years since it was first recognized. The Bakhtiyari Formation was originally named by Pilgrim (1908) after the Bakhtiyari Mountains and applied to limestone- and chert-clast conglomerates and interbedded sandstones that lie unconformably on the Fars Group of Lurestan and Khuzestan (Figs. 2 and 3). Subsequently, the Anglo-Persian Oil Company (Harrison et al., 1932) included additional underlying sandstones, siltstones, and conglomerates of the Fars Group within the lower Bakhtiyari. On the geological map of Isfahan (British Petroleum Company, 1963), a Miocene age was assigned to the silty and marly sandstone facies of the lower Bakhtiyari (so-called Upper Fars facies) that lie conformably on marine carbonates of the Asmari Formation (Fig. 3). Younger Bakhtiyari conglomerate that lies unconformably above this unit was shown as Mio-Pliocene on that map, but no diagnostic fossils were reported. Following this work, James and Wynd (1965) restricted the Bakhtiyari Formation to the original unit designated by Pilgrim (1908) and extended the definition to include similar conglomerate sequences in the Fars province to the SE (Fig. 2). On the 1:1,000,000 regional geological map of the Zagros (Iranian Oil Operating Companies, 1969), the Bakhtiyari Formation was considered to be middle to upper Pliocene. A Pliocene age has also been proposed for Iraq, consistent with reported *Hipparion* sp. fossils (Kukal and Al-Jassim, 1971).

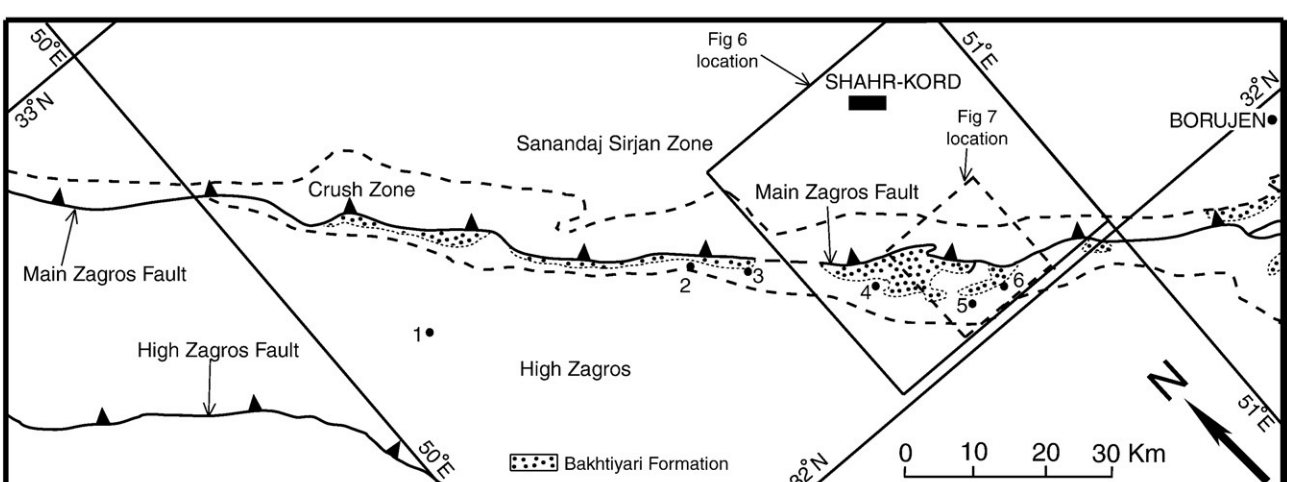

Fig. 4. Location map and geological setting of study area. BK—Bakhtiyari Formation exposures of High Zagros; 1—Kuhrang; 2—Baba-Heydar; 3—Farsan; 4—Juneghan; 5—Dastana; 6—Shalamzar.

For over 30 years, the regularly accepted chronology for the Bakhtiyari Formation has been based on the official stratigraphic lexicon of Iran (Setudehnia, 1972), which followed the stratigraphic nomenclature of James and Wynd (1965). In this classification, the Bakhtiyari is represented by 1 m to >2400 m of coarse conglomerate interbedded with sandstone and marl of presumably late Pliocene and younger age. As defined, this unit unconformably overlies the Agha Jari Formation or locally older formations. The unit was divided into members by Evers et al. (1977) and Fakhari et al. (1977); they introduced and mapped three subunits of Bakhtiyari Formation in the High Zagros and Fars province as Bk1, Bk2, and Bk3.

The geologic provinces of Fars, Bandar Abbas, Dezful Embayment, Lurestan, Kuh-giluyeh, and the High Zagros (Fig. 2) show significant differences in the geographic distribution, thickness, basal contact, clast composition, depositional history, and presumably the age of the Bakhtiyari Formation. These variations, likely due to spatial changes in deformation kinematics, source area composition, and river drainage patterns, make precise regional lateral correlations difficult. Therefore, we present an overview of the regional context for the Bakhtiyari Formation in these different regions, proceeding from SE to NW.

4.2. Fars province and Bandar Abbas region

The Bakhtiyari Formation is more widespread in the Fars province and Bandar Abbas region than in the rest of the Zagros (Fig. 2). The thickness of the Bakhtiyari, exposed in synclines and along flanks of anticlines, varies from a few meters in the coastal Fars (Fig. 2) to over 1200 m in the interior Fars (Fig. 2) and Bandar Abbas regions (Heybrock et al., 1968). The assigned age of the Bakhtiyari in the interior Fars region is Miocene–Pliocene (Fig. 3), but toward the south and in coastal regions, it is Pliocene–Pleistocene (Wynd et al., 1968; Shepherd and Khosravi Saeed, 1968; Molinaro et al., 2004).

In the North Fars and Bandar Abbas regions (Fig. 2), three distinct subunits (or members) of the Bakhtiyari are present (Bk1, Bk2, and Bk3) (Fakhari et al., 1977). Although their lithofacies are similar, clear angular unconformities exist between these subunits. The lower subunit (Bk1) in the Fars and Bandar Abbas regions is usually conformable or disconformable above the underlying Agha Jari Formation, whereas the upper subunits (Bk2 and Bk3) rest unconformably on the Agha Jari and lower Bakhtiyari (Bk1). Examples of these units are exposed along the southern flanks of North Fars (Fig. 2) anticlines (Evers et al., 1977). The intraformational unconformities indicate several periods of deformation during progressive shortening. In some localities, the angular unconformities merge down-dip into conformable strata (so-called progressive unconformities); elsewhere growth strata on fold limbs record uplift of adjacent anticlines (e.g., Kuh-e-Pazanan and Dasht-e-Palang anticlines) (Fakhari, 1982; Bakhtari et al., 1998).

Clasts in Bakhtiyari conglomerates are dominantly derived from formations exposed in nearby anticlines. There are also significant amounts of igneous clasts in the High Zagros north of Bandar Abbas. Cretaceous ophiolites of the Zagros suture zone and plutonic rocks of the Sanandaj–Sirjan and Makran Zones (Figs. 1 and 2) represent the principal sources of igneous grains in the region. Chert clasts observed in the Interior Fars (Fig. 2) and Bandar Abbas regions are recycled from erosion of chert–pebble conglomerates in Eocene red beds and/or the Oligocene–Miocene Razak Formation (Fig. 3). Bakhtiyari deposits surrounding salt plugs in the Fars province contain clasts of Cambrian carbonates and sparse igneous components of late Proterozoic origin that were carried to the surface in salt originating from the Cambrian Hormuz salt.

4.3. Dezful Embayment

The Bakhtiyari Formation in the Dezful Embayment (Fig. 2) is a thick sheet of conglomeratic fill that covers a large area and has experienced less deformation than most other Bakhtiyari exposures. The type section of the Bakhtiyari Formation is located in the Dezful Embayment and contains an interval 518 m thick (James and Wynd, 1965). Within the embayment, the Bakhtiyari ranges from a few meters up to 1000 m thick (Hamzepour et al., 1999). It sits on upper Miocene deposits in the Dezful Embayment and is thought to be Pliocene in age (Fig. 3) (Hulstrand, 1962; James and Wynd, 1965). Within broad synclines and near low-relief anticlines, the Bakhtiyari conformably overlies the Agha Jari Formation. However, younger beds of the Bakhtiyari onlap the Agha Jari and/or Mishan formations in angular unconformity along the southern flanks of anticlines.

In the Dezful Embayment, Bakhtiyari clasts mainly consist of carbonates and radiolarian cherts produced by erosion of different Cenozoic successions exposed during initial uplift of anticlines in the Simply Folded Zone. Many of the chert clasts in this region are probably recycled from chert–pebble conglomerates of the Paleocene–Eocene Amiran and Kashkan formations (Fig. 3).

4.4. Lurestan and Kuh-giluyeh

There are only a few isolated outcrops of the Bakhtiyari Formation in the Simply Folded Zone of the Lurestan and Kuh-giluyeh provinces (Fig. 2). In contrast, there are significant Bakhtiyari exposures in these same provinces adjacent to the High Zagros. The thickness of the Bakhtiyari in the Simply Folded Zone is about 300–500 m, but it thickens sharply northward, exceeding 2400 m near Aleshtar (Fig. 2) (British Petroleum Company, 1963). The Bakhtiyari Formation lies conformably on the Agha Jari and Razak formations over most of the Lurestan and Kuh-giluyeh provinces (e.g., Elmore and Farrand, 1981). Adjacent to the High Zagros, however, the formation rests in angular unconformity on older Cenozoic, Mesozoic, and even Paleozoic rocks (O' B Perry and Setudehnia, 1967).

The Bakhtiyari of the Simply Folded Zone in Lurestan and Kuh-giluyeh (Fig. 3) has been considered to be of latest Miocene age based on its stratigraphic position above the middle to upper Miocene Agha Jari Formation. New age constraints from magnetic polarity stratigraphy along the Changuleh anticline, the frontal structure of the Lurestan salient, confirm a middle to late Miocene age for the Agha Jari but reveal an ~3 Ma age for the basal Bakhtiyari (Homke et al., 2004). Our new age results

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(discussed below) indicate a substantially older age for the Bakhtiyari Formation in the High Zagros.

Clasts of the northern Bakhtiyari exposures are derived from Cenozoic and Mesozoic carbonates and Paleozoic sandstones, demonstrating significant erosional exhumation of the High Zagros and Crush Zone (Figs. 4, 6 and 7). In contrast, Bakhtiyari clasts of the southern exposures are limited to carbonates and cherts of Mesozoic and Cenozoic formations. The Bakhtiyari outcrops near Aleshtar have a high amount of ophiolitic clasts and various other plutonic clasts probably derived from the Zagros suture and Sanandaj–Sirjan Zone to the NNE (Fig. 2). The location and composition of these deposits suggest they were generated by activation of the High Zagros Fault and uplift of the adjacent High Zagros and Crush Zone.

4.5. High Zagros

The High Zagros in the footwall of the Main Zagros Fault (Fig. 2), south of the Crush Zone contain few exposures of coarse-grained basin fill. However, an elongate, NW-trending belt of Bakhtiyari strata ~150 km long occurs in the hinterland of the Dezful Embayment. This belt, the focus of our investigation, is ~10 km wide south of Shahr-kord, narrows to less than 100 m NW of Kuhrang and south of Aligudarz, and is ultimately cut out beneath the hanging wall of the Main Zagros Fault (Figs. 4 and 5). Scattered Bakhtiyari exposures along the fault south of Aligudarz show that the original basin may have been continuous and wider to the west, where it is now buried structurally. The Bakhtiyari Formation in the High Zagros sits in angular unconformity on the Oligocene–Miocene Razak Formation (Fig. 3). The Bakhtiyari thickness varies from a few hundred meters to 2000 m. Growth strata are present and there are 3 subunits separated by angular unconformities, suggesting shortening and uplift during sedimentation.

The Bakhtiyari Formation has been considered to be late Pliocene and younger in age (James and Wynd, 1965; Setudehnia, 1972), but it lacks age-diagnostic fossils. Its

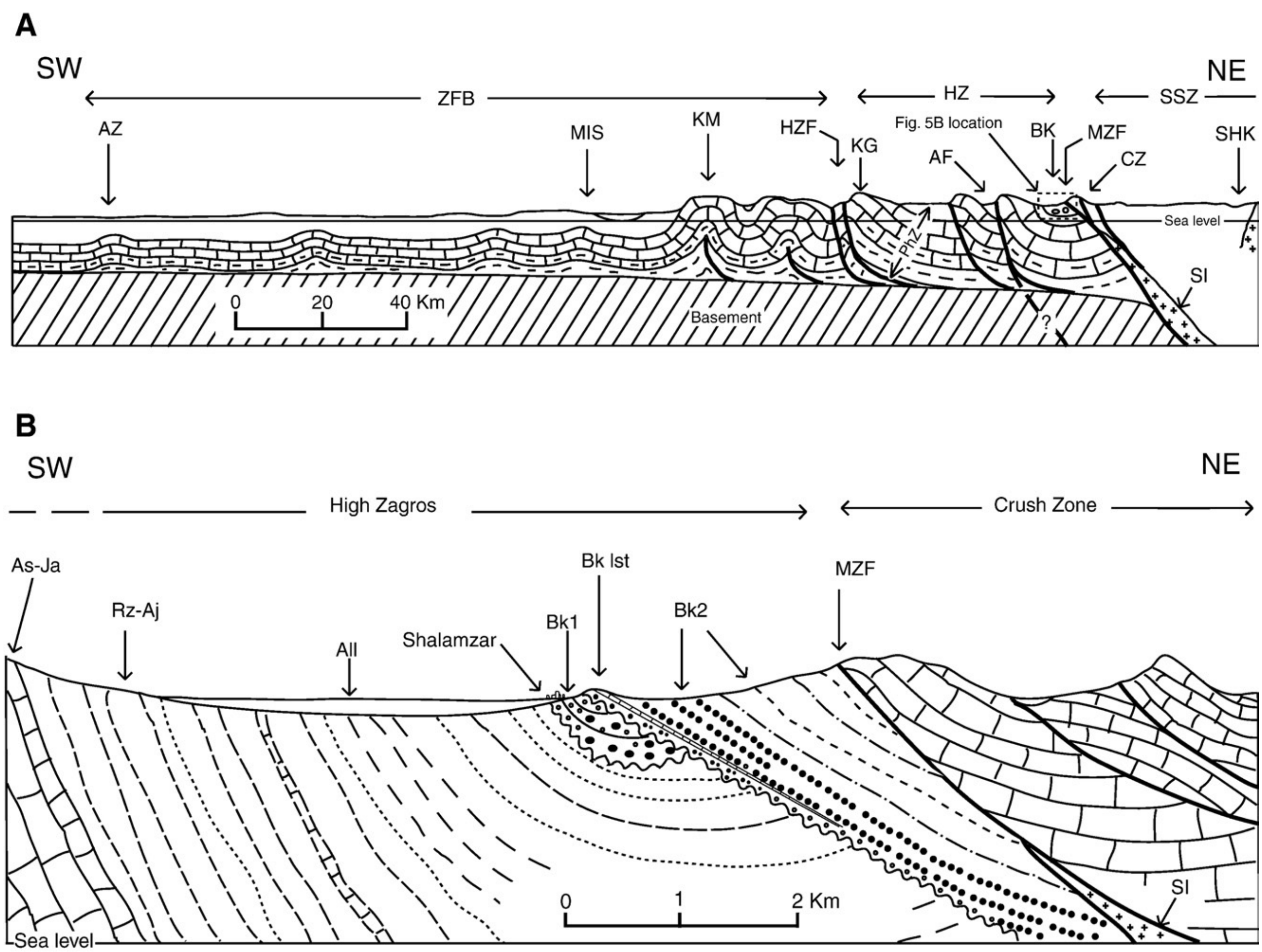

Fig. 5. (A) Regional cross section through Zagros Folded Belt, High Zagros Fault, High Zagros, Main Zagros Fault, Crush Zone, Sanandaj–Sirjan Zone, and structural position of Lower Miocene Bakhtiyari Formation (after Fakhari, 1992). ZFB—Zagros Folded Belt; HZ—High Zagros; SSZ—Sanandaj–Sirjan Zone; AZ—Ahwaz; MIS—Masjed-I-Soleyman; KM—Kuh e Mongasht; HZF—High Zagros Fault; KG—Kuh e Gereh; AF—Ardal Fault; BK—Miocene Bakhtiyari Fm; MZF—Main Zagros Fault; CZ—Crush Zone; SHK—Shahr-kord; PhZ—Phanerozoic sequence; SI—Zagros Suture Intrusive. (B) Cross section through High Zagros Bakhtiyari Formation exposure, Crush Zone, and Main Zagros Fault near Shalamzar south of Shahr-kord. As–Ja-Asmari-Jahrum formations; Rz–Aj-Razak–Aghajari formations; All—Alluvium; Bk1—Bakhtiyari 1, the lowermost conglomerates; Bk lst—lower Miocene marine beds at the base of Bk2; Bk2—Bakhtiyari-2 conglomerates and marls; MZF—Main Zagros Fault; SI—Suture Intrusive.

stratigraphic position above presumed upper Miocene strata has generally been used to define its age. As discussed below, discovery of marine fossil assemblages and pollen species in the Bakhtiyari Formation of the High Zagros shows that Bakhtiyari deposition in this proximal location started by early Miocene, and probably Oligocene, time.

Bakhtiyari clasts in the High Zagros are composed mainly of Mesozoic carbonates, radiolarian cherts, and rare ophiolite grains

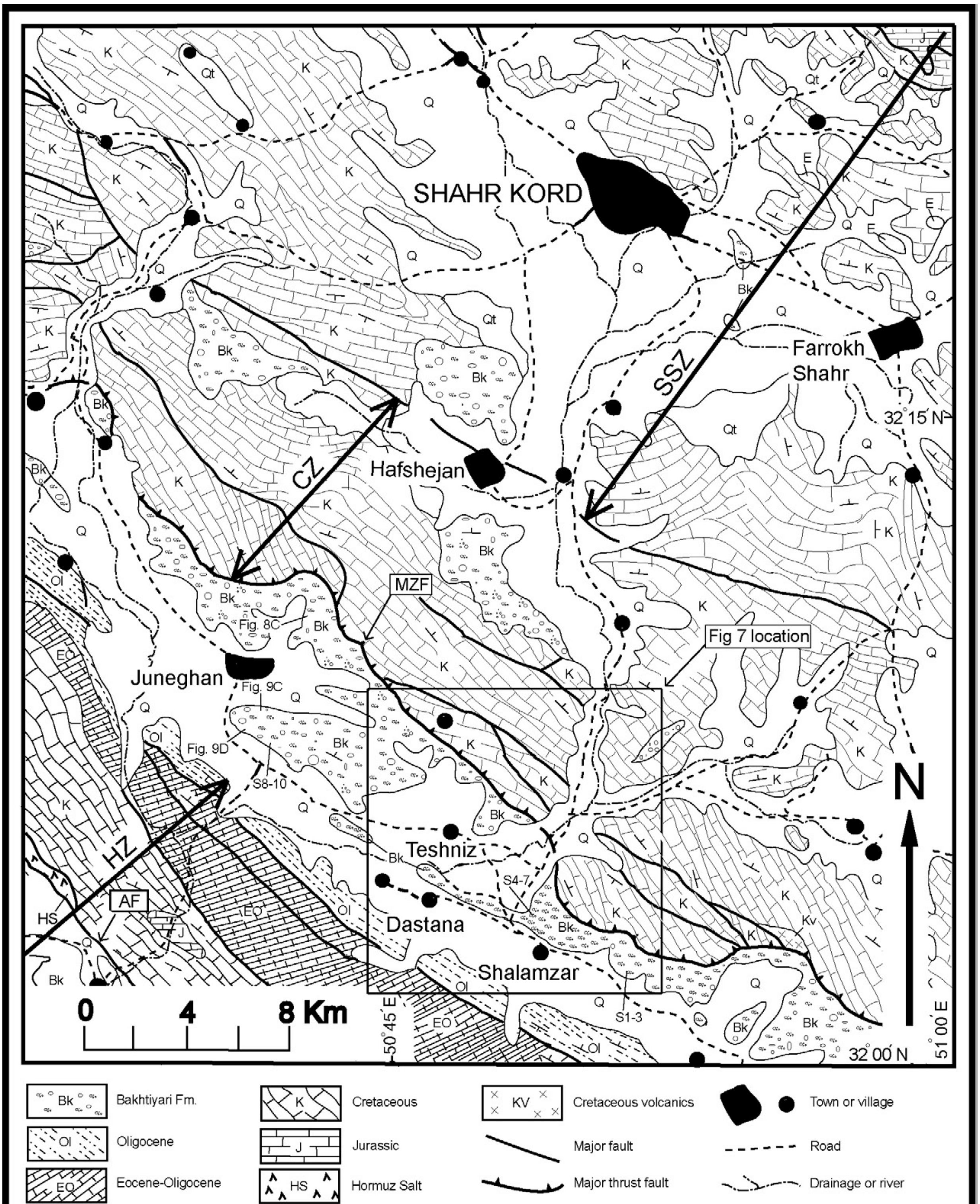

Fig. 6. Geologic map of Shahr-Kord and Shalamzar (modified after Geological Survey of Iran, 1999). J—Jurassic; K—Cretaceous; KV—Cretaceous volcanics of suture zone; E—Eocene limestone; EO—Eocene–Oligocene Jahrum–Asmari formations; Ol—Oligocene Razak Formation; Bk—Miocene Bakhtiyari Formation; Qt—Quaternary terraces; Q—Quaternary alluvium. Also shown are clast count stations S1–3, S4–7, S8–10 (Fig. 11) and photo locations Figs. 8 C, 9 C and D.

derived from localities north of the High Zagros Fault, including the Zagros suture zone, and Sanandaj–Sirjan Zone (Figs. 1 and 2). Clasts of the Eocene Jahrum and Oligo-Miocene Asmari limestones (Fig. 3) are present only in younger Bakhtiyari beds, suggesting the introduction of a younger source, probably due to uplift of structures farther SW toward the foreland.

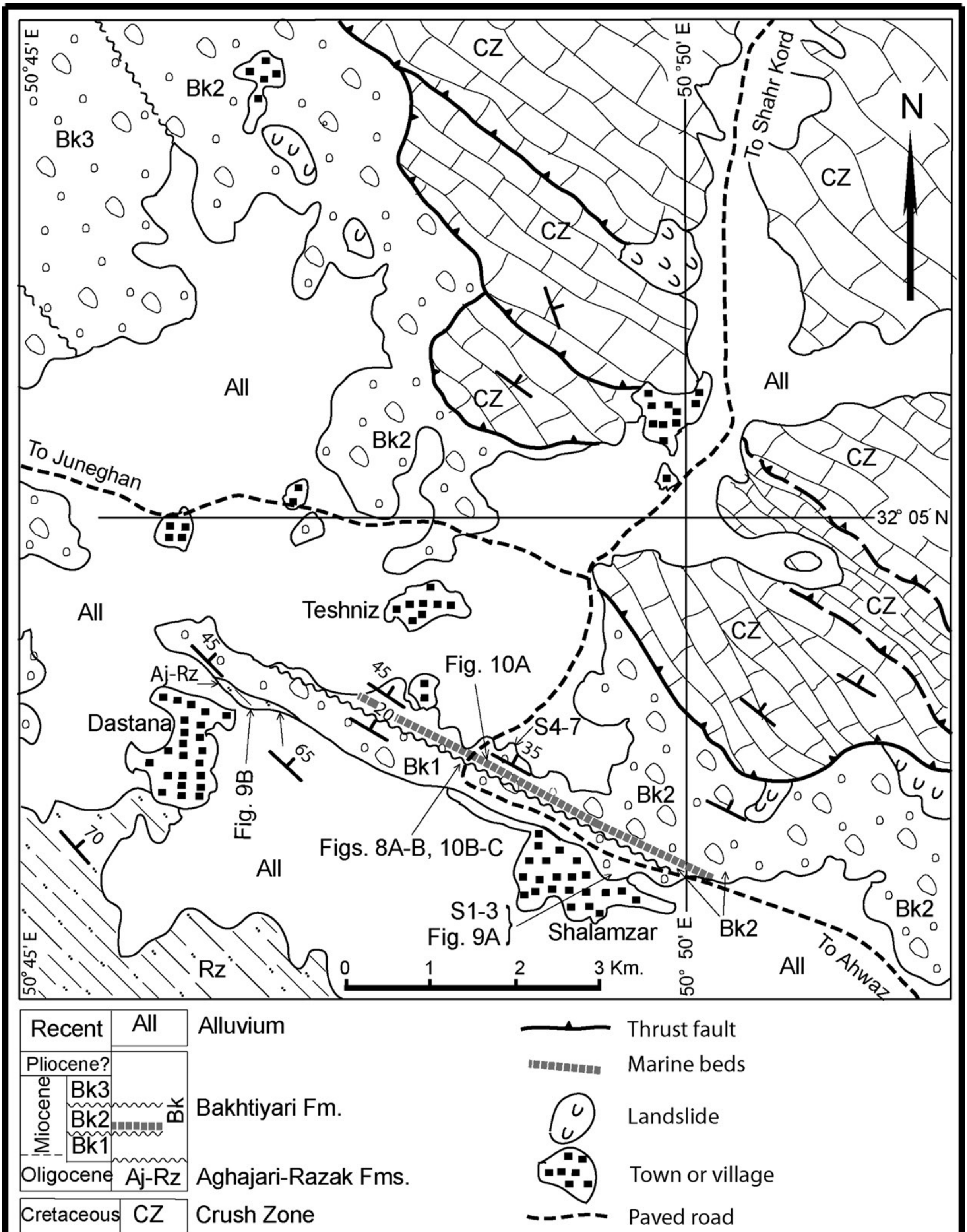

Fig. 7. Geology map of the Shalamzar area displaying Bk1, Bk2, Bk3 and lower Miocene marine beds at the base of Bk2. Also shown are photo locations Figs. 8 A, B, 9A, B and 10A–C and clast count stations S1–3 and S4–7 (Fig. 11).

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5. Bakhtiyari Formation in the High Zagros

5.1. Structural context

The focus of our study is a belt of coarse-grained deposits assigned to the Bakhtiyari Formation ~30 km south of Shahr-kord, in the region north and west of Shalamzar (Figs. 6, 7, and 8A). The outcrop belt is 5–10 km wide by 20 km long and occurs in the footwall of the Main Zagros Fault (Fig. 4). This belt is situated in the High Zagros and lies directly SSW of the Crush Zone and Sanandaj–Sirjan Zone. Although not well exposed in this region, the Zagros (Neotethys) suture between the Arabian and Eurasian plates is situated along the NE margin of the 10–15-km-wide Crush Zone.

Within the outcrop belt, Bakhtiyari beds strike NW–SE and dip generally NE except in a few minor folds around Juneghan (Figs. 4, 6, and 8C). The basal strata of the mapped Bakhtiyari Formation dip 40–45° NE and rest unconformably on Razak–Agha Jari sandstone and marl dipping 65° NE (Fig. 9B). Only a few meters of Razak–Agha Jari sandstone are exposed in the section, and the rest of the upper Razak section is covered under alluvium around Dastana village (Figs. 6 and 7) west of Shalamzar.

The upper part of the Bakhtiyari Formation is truncated by the Main Zagros Fault, which carries Cretaceous carbonates of the Crush Zone in its hanging wall. The upper portion of Bakhtiyari is largely buried by the thrust, but is well exposed along strike in the Juneghan syncline (Figs. 9C and D) NW of Shalamzar. A succession of growth strata consisting of upper Bakhtiyari levels is preserved in Juneghan syncline as >600 m of cliff-forming conglomerate and sandstone beds (Fig. 9C).

5.2. Stratigraphic relationships

Detailed field analysis of the Bakhtiyari Formation near Shalamzar (Fig. 6) reveals the stratigraphic setting, provenance, and depositional environments of the High Zagros. The Bakhtiyari overlies the Razak–Agha Jari formations in angular unconformity. The conglomerates in this region have been assigned to the Bakhtiyari Formation by previous studies of the Geological Survey of Iran and the National Iranian Oil Company (British Petroleum Company, 1963; Iranian Oil Operating Companies, 1969; Zahedi et al., 1999; Bosold et al., 2005). Moreover, the recognition of three subunits (or members) within the Bakhtiyari Formation and its stratigraphic position above the Razak and/or Agha Jari formation are consistent with the regional lithostratigraphy of the Bakhtiyari in the Simply Folded Zone and High Zagros.

Field study in the region shows that most of the Razak–Agha Jari section is comprised of Razak facies, with <20 m of Agha Jari facies exposed at the top of the section directly beneath the basal Bakhtiyari. It is likely that the Agha Jari was locally absent

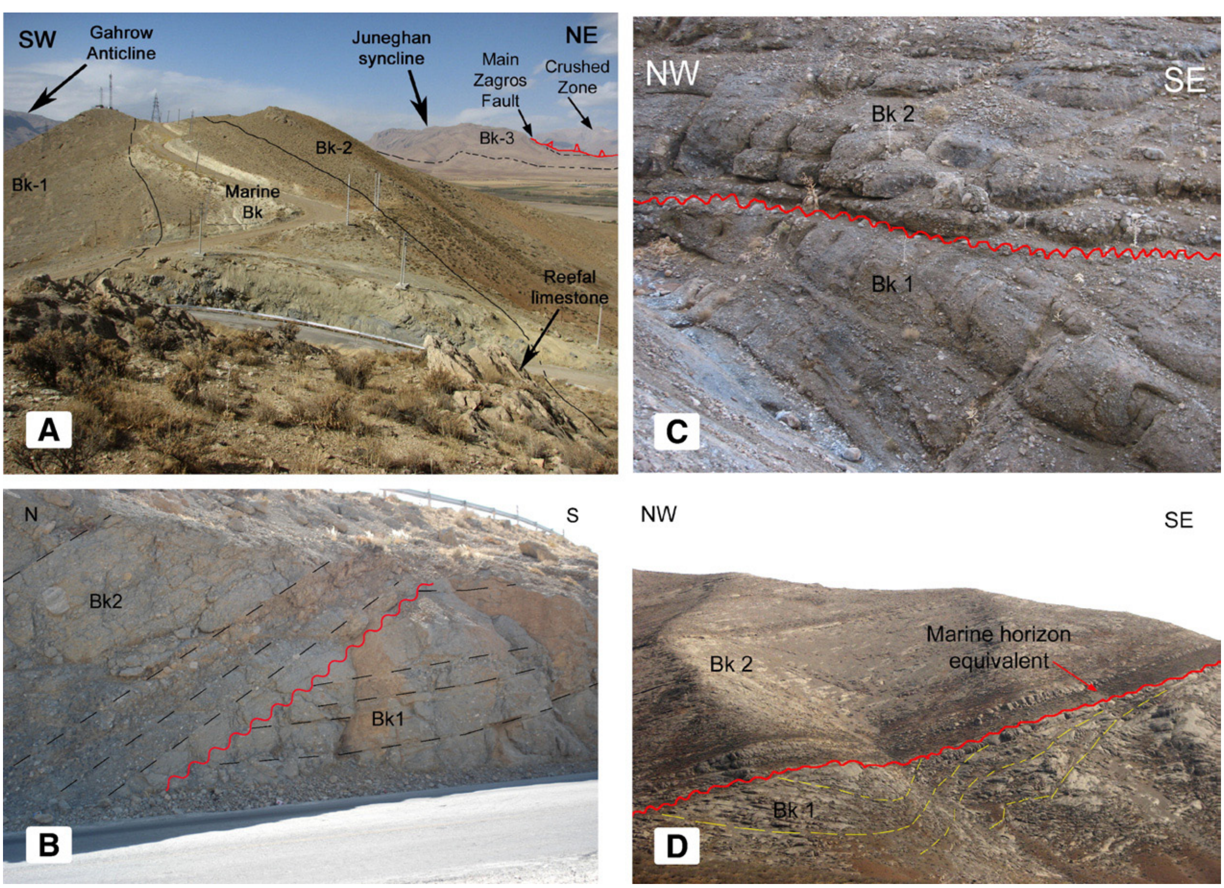

Fig. 8. (A) Exposures of marine Bakhtiyari interval at Shalamzar pass (view to NW). Angular unconformity between Bk1 and Bk2 in locations (B) north of Shalamzar, (C) north of Juneghan, and (D) north of Kuhrang. See Figs. 6 and 7 for locations.

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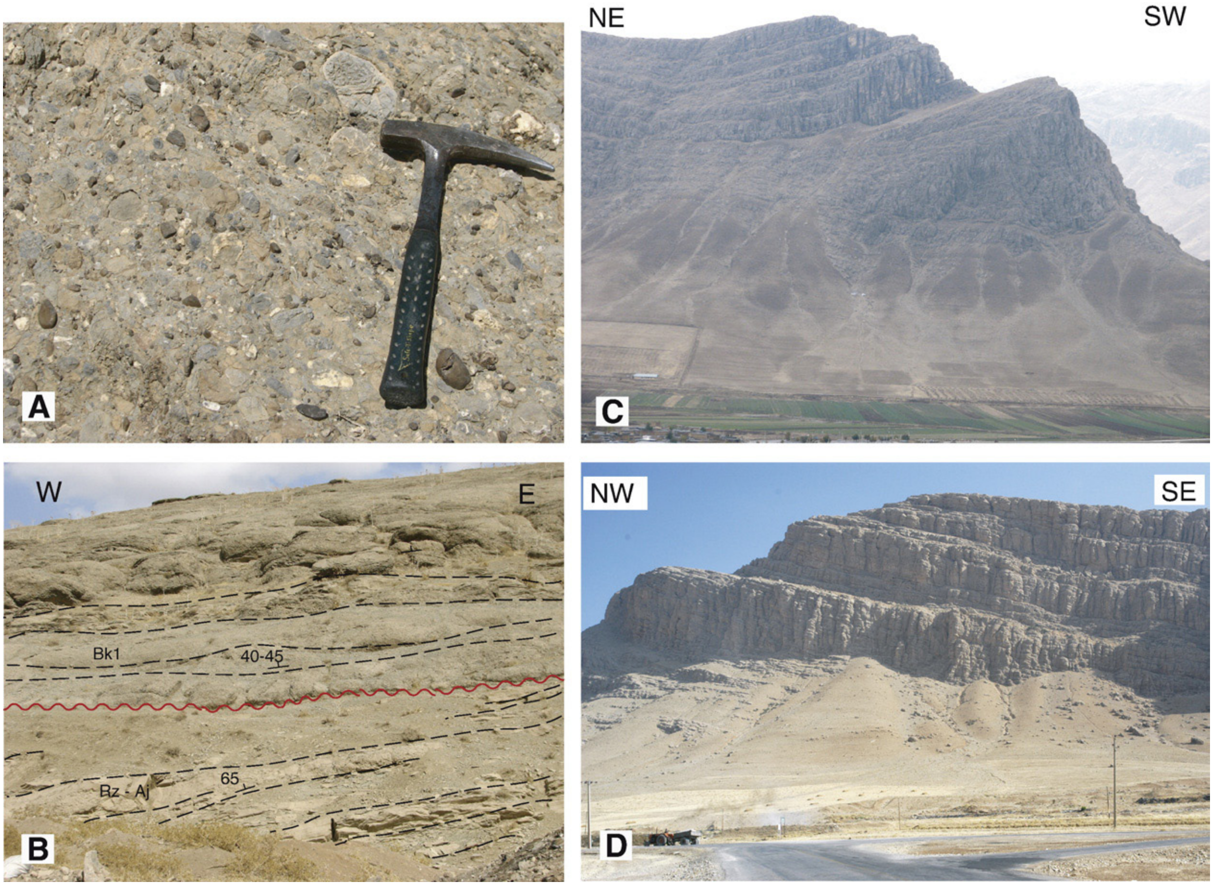

Fig. 9. (A) Lowermost Bakhtiyari conglomerate (Bk1) NE of Shalamzar with gray and light brown clasts of Cretaceous formations and dark brown igneous and chert clasts. (B) Angular unconformity between the Razak–Agha Jari and Bakhtiyari formations north of Dastana. (C) Growth strata and rapid thickness variation of the Bakhtiyari conglomerate (Bk3) in Juneghan syncline (view to SE). (D), Cliff-forming upper Bakhtiyari conglomerate (Bk3) at the western hinge zone of the Juneghan syncline (view to northeast). See Figs. 6 and 7 for locations.

in the High Zagros with the Bakhtiyari deposited directly on the Razak Formation (Fig. 9B).

In the Shalamzar region, the lowermost Bakhtiyari beds consist of 154 m of well-cemented, medium-bedded conglomerate (Fig. 9A) with rounded pebbles. Cross-bedded sandstones and multiple conglomeratic channel fills at the base of the Bakhtiyari record deposition in a delta or fan-delta environment. The overlying conglomeratic beds (Bk1) were deposited in fluvial, and locally, alluvial fan environments (Fig. 9B). West of Shalamzar and north of Dastana village, the dip of Bk1 conglomerates decreases upsection from 45° to 20° NE (Figs. 6 and 7). The top of the lower Bakhtiyari subunit (Bk1) is truncated by an erosional surface and overlain in angular unconformity by a younger conglomerate (Bk2) dipping 45° NE.

At Shalamzar pass (Figs. 6, 7, and 8A), only the upper part of the lower conglomerate (Bk1) is exposed and it dips 13° NE (Fig. 8B). These beds were erosionally truncated and overlapped in angular unconformity by Bk2 conglomerates that dip 35° NE (Fig. 8B). The lower levels of Bk2 are marked by a marine sequence 43 m thick (Fig. 8A) composed of fossiliferous gray marl (Fig. 10B), coralline limestone (Fig. 10A and C), and fossiliferous calcarenite beds that pass laterally into rubbly and reefal limestone (Fig. 10A). A variety of in-situ corals, coralline algae (Fig. 10C), small gastropods, and pelecypods are present in these beds, revealing a shallow marine depositional environment. Within this marine sequence, there is ~10 m of conglomerate that pinches out laterally into coarse-grained sandstone.

The Shalamzar section has the thickest identified marine layers of the Bakhtiyari Formation, and they thin rapidly to the east. However, some thinner coralline limestone beds and marine marly layers were deposited to the northwest and north of Juneghan, Farsan, Baba-Heydar, and Kuhrang (Figs. 4 and 8D). Facies changes and the lack of coarse-grained components in the marine interval may suggest a local sea-level rise and/or diminished uplift. At some locations where the marine facies pinch out (e.g., NW of Kuhrang), only the younger conglomerate (Bk2) sits on the lower Bakhtiyari Formation (Bk1) (Fig. 8D). At Shalamzar pass, Bk1 is capped by the marine fossiliferous interval, 290 m of younger conglomerate (lower Bk2) and, finally, a few hundred meters of nonresistant marl, silty calcareous sandstone, and conglomerate (upper Bk2).

Field observations of the Bakhtiyari exposures in the High Zagros show that marine Bakhtiyari strata are mainly limited to the region south of Shahr-kord, including Shalamzar, Juneghan and Farsan (Fig. 4). In Bakhtiyari exposures west of Farsan, north of Baba-heydar and near Kuhrang, there are only a few

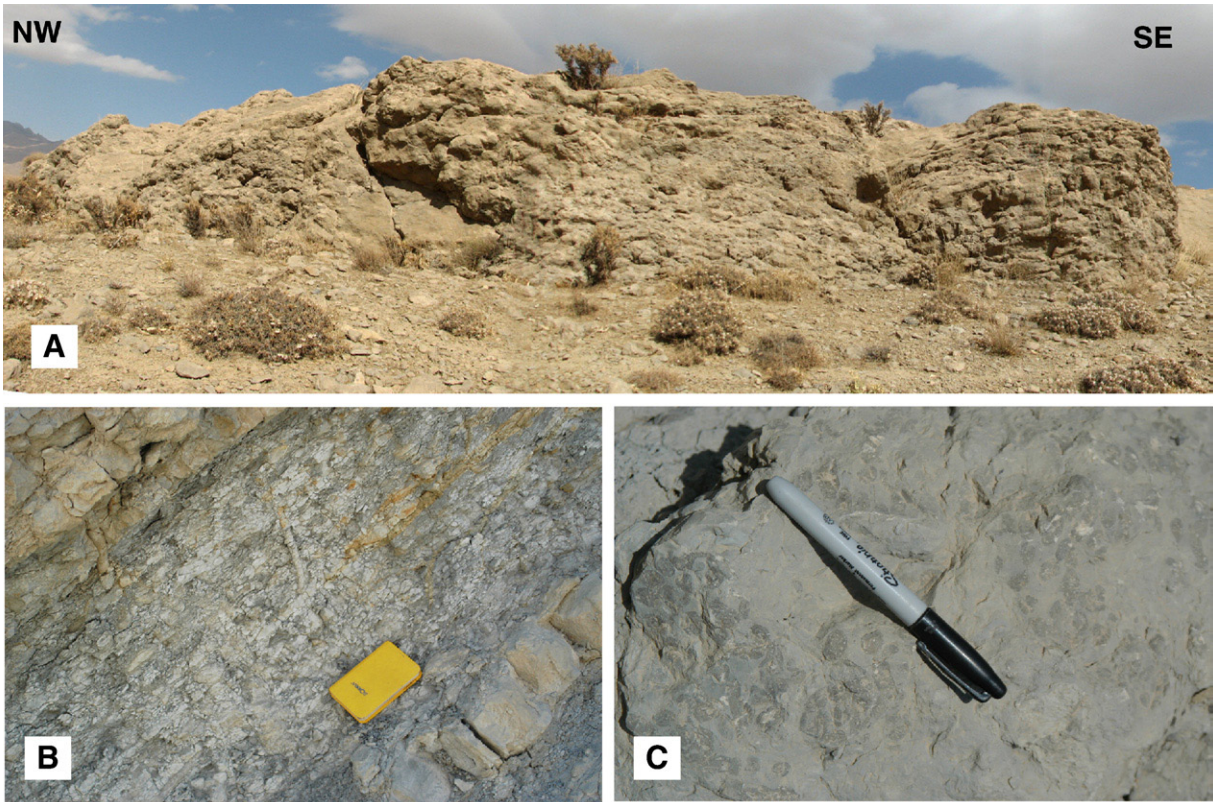

Fig. 10. (A) Reefal limestone beds of marine Bakhtiyari north of Shalamzar and south of Shahr-kord (view to NE). (B) Alternation of marine gray marl and fossiliferous limestone within the marine Bakhtiyari interval at Shalamzar pass (view to west). (C) In-situ corals of marine Bakhtiyari Formation at Shalamzar pass (view to east). See Fig. 7 for locations.

meters of marine limestone and 10–30 m of marly facies. However, in the other Bakhtiyari exposures of the High Zagros that lack marine beds entirely, there are commonly 2 angular unconformities similar to those expressed in the study region.

5.3. Conglomerate clast compositions

A total of 10 stations were selected for conglomerate clast counts within the three subunits (Bk1, Bk2, and Bk3) of the Bakhtiyari Formation. Three stations in Bk1 and four stations in Bk2 were selected north of Shalamzar (Figs. 6 and 7), along with three stations in Bk3 on the south limb of the Juneghan syncline (Figs. 6 and 9D). Each clast count consisted of identification of ~100 clasts. The major clast categories are as follows: Cenozoic limestones, Cretaceous limestones, Cretaceous radiolarian cherts, Jurassic carbonates, Jurassic sandstones and quartzites, and igneous intrusive rocks.

The results of the 10 conglomerate clast counts (Fig. 11) show that the Bk1 and Bk2 clasts are derived from Cretaceous and Jurassic formations of the Crush Zone and Sanandaj–Sirjan Zone. This pattern reveals uplift and erosion of these two zones to the NNE. In contrast, Bk3 conglomerates in the Juneghan syncline are composed mainly of Cenozoic and Cretaceous clasts derived from sedimentary fill of the Zagros basin. This clast assemblage suggests later uplift of the High Zagros farther south as a source of Bk3 clasts. Small amounts of radiolarian chert and igneous intrusive clasts are present in the conglomerates and show that a few ophiolitic slices of suture-zone rocks (Fig. 6) were exposed in the Crush Zone north of the Main Zagros Fault during deposition of Bk1, Bk2 and Bk3. Jurassic clasts are only observed in stations 3–10 and are most likely derived from exhumation of deeper structures of the Crush Zone and Sanandaj–Sirjan Zone.

5.4. Age control

Paleontological analyses were conducted for microfossil samples (including 34 thin sections and 3 processed samples)

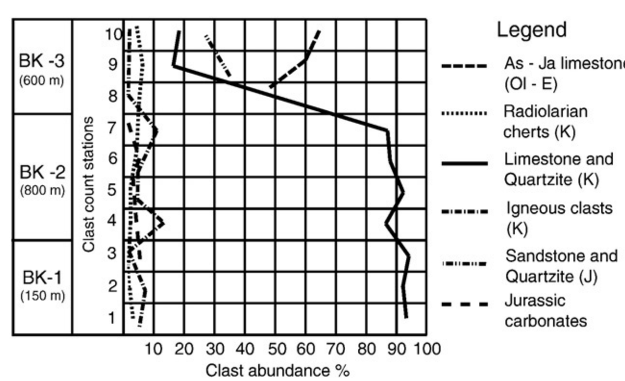

Fig. 11. Conglomerate clast compositions in the Bakhtiyari exposures of the High Zagros near Shalamzar and Juneghan. Thicknesses shown not to scale. J–Jurassic, K–Cretaceous, Ol-E–Oligocene-Eocene. See Figs. 6 and 7 for locations.

collected from the marine beds of the Bakhtiyari Formation exposed at Shalamzar Pass (Hosseini 2004; Ghavidel-Syooki, 2004; Fakhari et al., 2005). The following age-diagnostic microfossils were identified: *Miogypsinoides complanata*, *Miogypsinoides* sp. (Schlumberger 1900), *Ammonia beccarii*, *Lithophyllum* sp., and *Subterranophyllum thomasi* (Fig. 12) (Elliott 1957). Regional correlations of these fauna with marine fossil assemblages (Adams and Bourgeois, 1967; Wynd, 1965) from other parts of the Middle East indicate that these beds belong to the lower Miocene. Pollen, spores and dinoflagellate cysts were identified from palynological analyses of 3 samples (Ghavidel-Syooki, 2004) collected from the same marine beds: *Slowakipollenites* sp., *Periporopollenites* sp., *Monoporopollenites* sp., *Compositae type-pollen*., *Saxosporis* sp., *Verucatosporites* sp., and *Homotrydium oceanicum*, *Hystrichokolpoma rigaudiae*, *Spiniferites mirabilis*, *Cleistosphaeridium placacanthum*, *Fibrocysta* sp., and *Deflandrea* sp. This pollen assemblage also reveals an early Miocene (Aquitanian) age for these beds. It is important to note that these age assignments pertain to the Bakhtiyari conglomerate subunit Bk2. Therefore, the older Bakhtiyari conglomerate (Bk1) below the intraformational unconformity is likely Oligocene in age and can be no younger than early Miocene.

6. Discussion

6.1. Structural and sedimentation history of the High Zagros

Structural and stratigraphic relationships described for the Bakhtiyari Formation in the High Zagros indicate initial foreland-basin conditions and coeval deformation near the Zagros suture zone by Oligocene–early Miocene time. These observations allow for a sequential reconstruction of depositional and deformational events. During earliest development of the foreland basin, the region NE of the Main Zagros Fault experienced initial uplift as Cretaceous carbonates of the Crush Zone (between the Sanandaj–Sirjan Zone and Main Zagros Fault; Figs. 1, 2, 4–6) were exposed for the first time. To the SW, in the present-day footwall of the Main Zagros Fault, up to several hundred meters of the Razak and Agha Jari formations

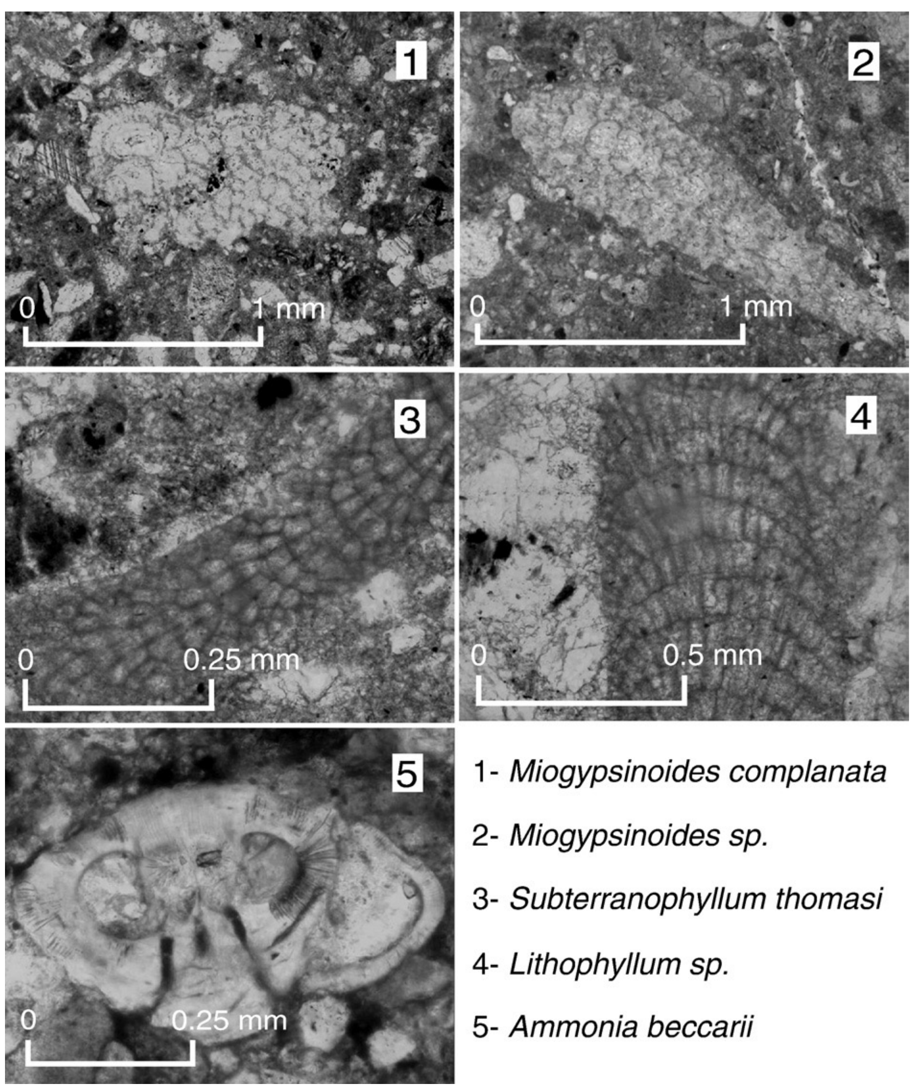

Fig. 12. Diagnostic microfossils from the marine Bakhtiyari interval in the High Zagros. All samples were recovered from outcrops at Shalamzar pass south of Shahr-kord.

were deposited in the adjacent basin, and tilted ~20° NE during folding. This tilting preceded deposition of the lowest Bakhtiyari conglomerate (Bk1), which consists principally of Cretaceous carbonate clasts eroded from the Crush Zone. Subsequently, this entire package of Razak–Agha Jari silty sandstone and lower Bakhtiyari (Bk1) conglomerate was uplifted and tilted ~25° to the SW. The tilted and beveled succession was then overlapped by the marine Bakhtiyari unit (base of Bk2) during a marine incursion SW of the still eroding Crush Zone. Observations of the Bk1 and Bk2 erosional contacts and internal structural geometries (Figs. 8C and D) reveal that Bk1 conglomerates were involved in several NW-trending anticlines before deposition of Bk2 marine beds.

A critical relationship in this region is the recognition of angular unconformities in older clastic fill that is overlapped depositionally by a marine succession yielding early Miocene fossil assemblages. Such cross-cutting and overlapping relationships in foreland-basin systems are essential for evaluating temporal and spatial linkages between fold-thrust deformation and basin evolution (e.g., DeCelles and Giles, 1996; Horton, 1998). These cross-cutting relationships indicate that foreland-basin sedimentation and synchronous deformation had commenced prior to early Miocene time.

Accumulation of fossiliferous carbonate and marl (Fig. 10B) recorded a transgression related to sea-level rise or reduced surface uplift in the High Zagros. The presence of a coralline limestone layer at the top of the marine interval (within Bk2) indicates a regression marking the southwestward retreat of the marine environment away from the High Zagros. Above the coralline limestone beds at the top of the marine Bakhtiyari interval there are 290 m of coarse conglomerate beds (lower Bk2) and 800–1500 m of silty marl and sandstone (upper Bk2). These thick clastic successions (lower and upper Bk2) recorded another deformational episode and continued erosion of the Crush Zone.

The uppermost portion of the Bakhtiyari Formation (Bk3) exposed in the Juneghan syncline consists of >600 m of cliff-forming conglomerate (Figs. 9C and D) with growth stratal geometries. These beds sit on the marly facies of Bk2 and demonstrate further tectonic activity in the region. The abundance of Cenozoic clasts derived from Jahrum Formation in the upper Bakhtiyari (Bk3) indicates that fold-thrust structures in parts of the High Zagros to the SSW were subjected to initial uplift and exhumation at this time. Finally the entire Shalamzar nonmarine and marine succession, including the Razak–Agha Jari formations, lowest Bakhtiyari conglomerate (Bk1), unconformably overlapping fossiliferous marine interval and younger nonmarine sequences (Bk2 and Bk3), were folded along the north flank of the Gahrow anticline (Fig. 8A).

6.2. Evolution of the Zagros foreland basin and Arabia–Eurasia collision

We propose major revision of the regional stratigraphy of the Zagros foreland basin (Fig. 13) on the basis of structural relationships and newly discovered marine fossil assemblages within the coarse-grained Bakhtiyari Formation of the High Zagros. An early Miocene (Aquitanian) fossil assemblage was recovered from Bakhtiyari deposits that unconformably overlie a nonmarine sequence of lower Bakhtiyari, Razak, and Agha Jari formations, demonstrating deposition synchronous with early Zagros shortening. We therefore conclude that initial shortening in the Zagros had commenced by Oligocene–early Miocene time. This age is therefore considered to be a minimum age for the Arabia–Eurasia collision. Our estimate is considerably earlier than some estimates for the timing of collision (e.g., Dewey et al., 1973; McQuarrie et al., 2003) and precedes major shortening and exhumation in the Alborz Mountains of northern Iran by >10 Myr (Axen et al., 2001; Guest et al., 2006, 2007).

Some previous researchers have also recognized evidence for an earlier collision. Partially on the basis of a low-angle unconformity below the Asmari Formation west of Shiraz, Hessami et al. (2001) argued for a late Eocene to early Oligocene

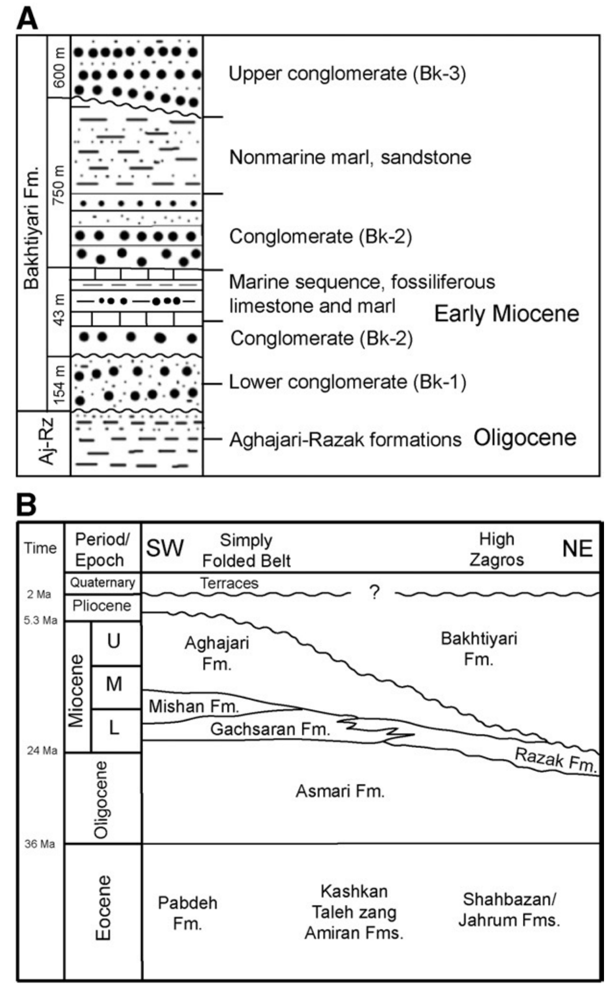

Fig. 13. (A) Cumulative stratigraphic column for the Bakhtiyari Formation and underlying units in the High Zagros. Thicknesses shown not to scale. (B) Revised regional stratigraphic profile for the Bakhtiyari Formation and underlying units across the Zagros. Note the pronounced time-transgressive character from NE to SW, indicating accumulation of the Bakhtiyari in the High Zagros synchronous with deposition of the Asmari, Razak, Gachsaran, Mishan and Agha Jari formations of the Simply Folded Zone to the SW.

onset of deformation in Zagros, earlier than we infer from the Bakhtiyari deposits near Shalamzar. They propose a zone of late Eocene–early Oligocene deformation in the NE part of the Simply Folded Belt adjacent to the High Zagros and SE of the Kazerun Line. Although there is a widespread depositional gap below the Asmari, including the region NW of the Kazerun Line, it is generally not angular (Farshadfar et al., 1960; Gray, K. W., 1962; Eshghi et al., 1970; James and Wynd, 1965; O' B Perry and Kheradpir, 1969, and Wynd, 1965); therefore, we view the low-angle unconformity emphasized by Hessami et al. (2001) as a localized phenomenon not indicative of widespread shortening. However, their inference of southwestward propagation of deformation and facies belts from late Oligocene through Pleistocene time is in general agreement with our data and conclusions.

Perhaps the most intriguing implication of our study is the remarkable age range exhibited by the Bakhtiyari Formation, from early Miocene (and probably Oligocene) in our hinterland study region to Pliocene (~3 Ma) at the front of the fold-thrust belt (Homke et al., 2004). At face value, these relationships suggest a >20 Myr duration of conglomerate progradation from NE to SW, a restored distance of ~200 km. We rule out the possibility of misidentification of stratigraphic units for the following reasons. First, the same outcrop belt has been consistently identified as the Bakhtiyari Formation in multiple studies by the Geological Survey of Iran and the National Iranian Oil Company. Second, facies analysis leads to straightforward identification of lithostratigraphic units underlying the Bakhtiyari Formation. Third, the three subunits (or members) recognized elsewhere within the Bakhtiyari Formation are found within the study area. It is possible that the entire Zagros foreland basin may be characterized by deposition of lithostratigraphic units displaying similarly dramatic time-transgressive qualities. Clearly, extreme caution must be exercised in utilizing the middle to late Cenozoic stratigraphic record of the Zagros foreland basin to identify the kinematic history of deformation in the Zagros fold-thrust belt.

Nevertheless, the Bakhtiyari deposits near Shalamzar represent the earliest record of deposition within the Zagros foreland basin in close proximity to the hinterland of the fold-thrust belt. The location of the outcrop belt within ~20 km of the Zagros (Neotethys) suture provides a considerable level of confidence that the Oligocene–early Miocene onset age reported here represents a robust estimate for the earliest collision-related shortening and foreland-basin evolution in the Iranian segment of the Arabia–Eurasia collision zone. We emphasize that the time-transgressive character of the Bakhtiyari Formation suggests southwestward advance of the foreland basin, and by inference, forward advance of the fold-thrust belt. In the broadest sense, this pattern is suggestive of a foreland-ward migration of contractional deformation throughout the middle to late Cenozoic. However, the age resolution and local structural records for foreland-basin deposits are not sufficient at a regional scale to identify the precise kinematic history of individual structures which may have involved shorter term pulses of deformation along with important strike–slip deformation.

7. Conclusions

New age constraints for the oldest known synorogenic succession within the Zagros hinterland provide a critical step toward estimating the onset of foreland-basin conditions and initial deformation of the Zagros fold-thrust belt during the early stages of the Arabia–Eurasia collision. Conglomerates of the regionally extensive Bakhtiyari Formation have long been considered to be upper Pliocene and younger, even though the unit lacks age-diagnostic fossils. Our structural and stratigraphic observations and discovery of a marine interval containing a lower Miocene fossil assemblage within the Bakhtiyari Formation of the High Zagros indicate that shortening and foreland-basin deposition had commenced in the hinterland by early Miocene time.

The Lower Miocene marine interval rests in angular unconformity above a lower Bakhtiyari conglomerate, which in turn overlies clastic basin fill of the Razak and Agha Jari formations in angular unconformity. It is likely that these older clastic deposits beneath the lower Miocene marine sequence of the Bakhtiyari Formation represent the distal, finer-grained parts of a prograding clastic wedge. Therefore, the best estimate for the onset of the Arabia–Eurasia collision may be considered to be Oligocene, as recorded by the Razak–Agha Jari succession in the High Zagros.

Growth stratal relationships and clast provenance data reveal a foreland-ward progression of deformation during Bakhtiyari deposition. The lower Bakhtiyari is dominated by Cretaceous carbonate clasts derived from the Crush Zone in the hanging wall of the Main Zagros Fault, directly SSW of the Zagros (Neotethys) suture zone. An abundance of Cenozoic carbonate clasts in the upper part of the Bakhtiyari section suggests uplift and unroofing of a younger fold-thrust structure toward the foreland to the SW. Although the regional kinematic history is not known, these observations require that earliest shortening, uplift, and exhumation during the Eurasia–Arabia collision was focused near the suture zone, with a long time span (>20 Myr) required before the Zagros deformation front reached its present location.

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