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Provenance evolution of Oligocene–Pliocene foreland deposits in the Dezful embayment to constrain Central Zagros exhumation history

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Abstract

This paper presents a detailed provenance analysis of the 6.5-km thick Oligocene–Pliocene foreland succession in the north Dezful embayment in Zagros, Iran. Using petrography, geochemistry, and paleoflow analysis, we determined three provenance shifts during the exhumation of Zagros orogen. Above the Ahwaz sandstones, sourced from the Arabian craton, a sharp decrease in $\text{SiO}_2/\text{Al}_2\text{O}_3$, Zr/Sc, Th/Sc, Th/Co and Th/Cr within the Gachsaran Fm., and the appearance of first-cycle sands derived from metamorphic and volcanic rocks at the base of Aghajari Fm., characterize the onset of exhumation, rising topography and denudation of the Zagros orogenic system during latest Oligocene and constitute the first shift. The second shift, in middle Aghajari Fm., is marked by a distinct increase in radiolarian cherts and compatible/incompatible elements, indicating the exhumation of Neo-Tethyan radiolarite-ophiolite allochthonous slices in the High Zagros Zone during Tortonian (~9 Ma). A vast number of carbonates derived from nearby growing Izeh Zone anticlines characterize the Messinian (~7 Ma) Bakhtyari conglomerates marking the third shift. In conclusion, a detailed hands-on provenance analysis of the clastic sedimentary sequences in the north Dezful embayment enabled us to determine catchment areas and shifts hitherto unstudied thus contributing to the exhumation history of the Central Zagros orogenic system.

Supplementary material: Details of the petrography and geochemistry results are presented in 7 tables and 4 figures <https://doi.org/10.6084/m9.figshare.c.4905558>.

The Zagros Mountain belt is a large segment of the Alpine–Himalayan orogenic system formed by the progressive closure of the Neo-Tethys and the opening of the Red Sea driving the onset of continental collision between Arabian and Eurasian plates. But the timing of

Zagros orogenic building, exhumation and erosion of tectono-topographic reliefs is still little known.

The integration of petrographic and geochemical techniques represents a powerful tool to study provenance history of foreland basins adjacent to orogenic systems in order to determine catchment areas and their exhumation history as a result of tectonic evolution (e.g., Garzanti *et al.* 2000, 2004, 2007; White *et al.* 2002; Najman 2006; Decelles 2012; Baral *et al.* 2017; Ramos-Vázquez & Armstrong-Altrin 2019).

The Zagros Mountains and their coupled foreland basin evolved during a multi-episodic orogeny lasting from Late Cretaceous to Recent. The Late Cretaceous obduction of the Neo-Tethys ophiolites resulted in the Late Cretaceous–Eocene Amiran–Kashkan early foreland flexure restricted in front of the emplaced ophiolite slices in Neyriz and Kermanshah regions (Fig. 1) (Braud 1987; Homke *et al.* 2009; Saura *et al.* 2011; Farahpour & Hessami 2012; Gholami-Zadeh *et al.* 2017). The proposed ages for Neo-Tethys closure and Arabian-Eurasian collision vary from middle Eocene-early Oligocene to latest Miocene (Gavillot *et al.* 2010; Homke *et al.* 2010; Zhang *et al.* 2017; Koshnaw *et al.* 2018). During the Miocene and Pliocene, a combination of cover folding and thick-skinned blind thrusting produced the SW-propagation of deformation towards the foreland shaping the present Zagros Fold Belt (e.g. Homke *et al.*, 2004; Khadivi *et al.*, 2010; Ruh *et al.*, 2012; Vergés *et al.*, 2019). Syntectonic Mesopotamian foreland depositional environments also migrated in front of the deforming fold belt (Hessami *et al.* 2001; Pirouz *et al.* 2015, 2017a; Pirouz 2018).

Recent growing interest in provenance analysis and thermochronological studies of the synorogenic Oligocene–Pliocene deposits in the Zagros foreland basin, as well as the hinterland domains, has provided an incipient database in both the Zagros of Iran and the Iraqi Kurdistan, which in most cases has been used to interpret the initial age of the collision (Fig. 1). Gholami-Zadeh *et al.* (2017) examined the sandstone petrographic modals along the footwall of the Zagros suture zone in the Neyriz area to correlate the Arabian-Eurasian initial collision with the first arrival of metamorphic hinterland sediments to the northeastern margin of the Arabian plate. Detrital zircon U-Pb dating carried out by Koshnaw *et al.* (2018) dated these first deposits at late Oligocene (~26 Ma) in the Kurdistan region. In contrast, Zhang *et al.* (2017) suggest a late Miocene–early Pliocene time for the onset of continental collision, using U-Pb detrital zircon dating from syntectonic sediments from the Lurestan Arc.

Most of the above-mentioned studies were carried out in the Kurdistan, Lurestan and Fars regions, but not in the Dezful embayment where the largest accumulations of foreland basin syntectonic deposits are preserved (Fig. 1). The continuous 6.5-km-thick post-Asmari syntectonic succession in the SW flank of the Azanak syncline-minibasin in the northern region of the Dezful embayment (Najafi *et al.* 2018) is analyzed here in this provenance study. For our study we combined fieldwork and petrographic and geochemical analyses in mudrocks, sandstones and conglomerate clasts from Gachsaran, Mishan, Aghajari and

Bakhtyari formations. To complement these results, the Asmari Fm. including the Ahwaz sandstones were also analyzed using the Cheshmeh-Khosh and Marun oil wells data to establish the Mesopotamian foreland basin provenance history at the base of the Asmari Formation (wells located several tens of kilometers to the SW of the Azanak sedimentary succession).

The two main objectives in this study are: 1) to analyze the provenance history of the Zagros foreland clastic deposits in the northern Dezful embayment recorded in the late Oligocene–early Miocene Asmari Fm., the Miocene Gachsaran, Mishan and Aghajari formations, and the late Miocene–Pliocene Bakhtyari Fm.; and 2) to determine the exhumation history of the Central Zagros Belt.

Tectonic framework of the Central Zagros

The Central Zagros is divided into five NW-trending tectonic domains based on different structural styles and rock assemblages (Fig. 1). The Urumieh-Dokhtar magmatic arc and the Sanandaj-Sirjan metamorphic zone are located in the hinterland side of collision, on the SW margin of the Eurasian plate, while the High Zagros, Izeh zone and Dezful embayment form the foreland fold belt on the NE edge of the Arabian plate.

The Urumieh–Dokhtar arc contains Andean-type subduction-related Eocene calc-alkaline igneous rocks that were intruded by Oligo–Miocene shoshonitic and alkaline magma (Omrani *et al.* 2008; Moghadam *et al.* 2010; Honarmand *et al.* 2013).

The Sanandaj-Sirjan zone constitutes the metamorphic core of the Zagros orogenic belt (Figs. 2a and b), which is chiefly made up of Paleozoic–Cretaceous sedimentary and low-to-medium grade metamorphic rocks intruded by Jurassic–Oligocene Plutons. These metamorphic rocks, including slate, phyllite, greenschist, and amphibolite, were intruded by various plutons ranging in composition from gabbro to granite (Alavi 1994). The area has extensively deformed by ductile flow and has mylonitic shear zones and folds that record multiple deformational events (Mohajjel & Fergusson 2013). The metamorphic belt overrides the High Zagros zone along the Main Zagros Thrust as the boundary between the Arabian and the Eurasian tectonic plates (McQuarrie 2004; Motaghi *et al.* 2017) (Fig. 2). Furthermore, toward the NW end of the High Zagros, the Main Zagros Thrust has been overprinted by an active dextral fault since Pliocene, referred to as the Main Recent Fault (Tchalenko & Braud 1974; Talebian & Jackson 2002).

The High Zagros zone is characterized by a south-verging fold-and-thrust system involving different detachment levels in the sedimentary cover (Tavakoli-Shirazi *et al.* 2013; Sadeghi *et al.* 2016). The High Zagros is marked by the exposure of ophiolite and radiolarite oceanic remnants in the core of several anticlines. The ophiolite slices were initially over-thrusted as

tectonic nappes on the NE margin of the Arabian plate in the Late Cretaceous. They were then unconformably covered by the Paleogene sedimentary successions, and started to expose again with the folding of the High Zagros zone during Neogene. The Zagros ophiolites contain complete mantle and crustal sequences, which include harzburgite, rare ultramafic–mafic cumulates, gabbros, sheeted dykes and pillowed lavas (Moghadam & Stern 2011; Monsef *et al.* 2019), accompanied by Jurassic–Upper Cretaceous pelagic limestones and radiolarites. The highly folded radiolarites constitute more than 500 m of thin-bedded sediments made up predominantly of the microscopic remains of radiolarians. To the south, the High Zagros zone is separated from the Izeh zone along the ‘High Zagros Fault’, involving crystalline basement at depth (Fig. 2).

The Izeh zone is a 50-km width domain displaying south-verging anticlines, accompanied by reverse faults on their southern flank. The anticlines of the Izeh zone are mostly exposed at the level of resistant Oligo–Miocene Asmari Fm. limestones, however, several are incised to the level of the Jurassic Khami Group (Figs. 2a and b) (Sherkati & Letouzey 2004). The southern limit of the Izeh zone is characterized by an abrupt decrease at structural and topographic levels (5 and 1 km, respectively) towards the southwest. This limit marks the front of the Central Zagros Mountains and occurs along the Mountain Front basement fault (Berberian 1995; Sepehr & Cosgrove 2004; Emami *et al.* 2010).

The current study area is located in the footwall of the Mountain Frontal Fault, in the north Dezful embayment (Figs 2a and b) in which a thick and continuous syntectonic succession is well-preserved. This large sedimentary succession was deposited during both active shortening and as salt tectonics developed over the 1.5-km thick Gachsaran salt-bearing deposits in the Azanak growth syncline-minibasin. This syncline-minibasin is thrust by the Gachsaran evaporitic extrusion along the Azanak thrust-weld located only 10 km to the SW of the large Gurpi anticline aligned above the Mountain Frontal Fault (Fig. 2b).

Stratigraphy of the Zagros foreland succession in the Dezful embayment

The 6500-m locally thick foreland stratigraphy of the Oligocene–Pliocene in the northern Dezful embayment is shown in Figure 3 (Najafi *et al.* 2018). It is composed of the Asmari, Gachsaran, Mishan, Aghajari (including the Lahbari Mb.), and Bakhtyari formations. The age of the Zagros foreland deposits is well constrained by magnetostratigraphic and Sr-isotopic studies (Homke *et al.* 2004; Ehrenberg *et al.* 2007; Khadivi *et al.* 2010; Ruh *et al.* 2012; Pirouz *et al.* 2015, 2017a; Vergés *et al.* 2019; Lashgari *et al.* 2020). Most of these studies concern to the Lurestan and Fars structural salients, but a study of the Dezful embayment was recently published by Lashgari *et al.* (2020). The dated succession is located in the NE flank of the Jarik growth anticline, about 80 km to the SE of Azanak, along the NW–SE folding direction, but in a similar structural position regarding the Mountain Frontal Fault position

(Fig. 2a). In the present study we used the Sr-isotopic ages determined for the Asmari Formation in the Ahwaz and Marun oil fields (Ehrenberg *et al.* 2007), and magnetostratigraphic ages determined for the Mishan–Bakhtyari formations in the Jarik anticline (Lashgari *et al.* 2020) (Fig. 2a for locations).

Asmari Formation

The Oligo-Miocene Asmari Fm., which is the main reservoir in SW Iran, is 326-m thick, and is located in well no. 10 of the Cheshmeh-Khosh (CK) oil field. It consists of bedded, loose, fine-grained sandstones, green-to-dark grey mudrocks, and brown crystalline dolomites. The Ahwaz sandstone Mb., in the lower part of the Asmari Fm., is 150-m thick and forms siliciclastic tongues that pinch out towards the northeast. Whereas the Ahwaz sandstones correspond to shallow marine-to-delta environments (Motiei 1993; Daraei *et al.* 2015), the Asmari limestones show proximal open marine and tidal environments (Ehrenberg *et al.* 2007; Jafarzadeh & Hosseini-Barzi 2008; Honarmand & Amini 2017). In the Dezful embayment, the Asmari Fm. has an age between 32 and 18 Ma, which corresponds to earliest Oligocene–middle early Miocene (Ehrenberg *et al.* 2007). In Ahwaz, the base of the Asmari is younger —27–26 Ma— due to the progradation of the carbonate platforms. The original depositional thickness of the Gachsaran evaporites is estimated as being about 1500 meters by restoring a well-calibrated cross-section, based on combined field and seismic datasets, in the northern Dezful embayment (Sherkati *et al.* 2006; Najafi *et al.* 2018).

Gachsaran Formation

The Gachsaran Fm. is characterized by interbedded mudrocks, halite, gypsum, anhydrite, and thin-bedded carbonates, which were deposited in sabkha, supratidal to restricted shallow marine environments (Pirouz *et al.* 2015; Pirouz 2018). Strontium isotope dating shows that the base of the Gachsaran Fm. has an age of about 18 Ma (Burdigalian) in the Dezful embayment (Ehrenberg *et al.* 2007). The magnetostratigraphic ages indicate 14.1 Ma (Langhian) for the end of the Gachsaran deposition (Lashgari *et al.* 2020). The Gachsaran evaporites thin to the NE grading laterally to the Razak Fm. towards the Izeh and High Zagros domains.

Mishan Formation

The Mishan Fm. overlays the Gachsaran Fm. and has an age of 14.1–13.6 Ma (middle Miocene) in the north Dezful embayment (Lashgari *et al.* 2020). This formation consists predominantly of 50 to 200 m green-grey mudrocks intercalated with well-bedded yellowish-grey fossiliferous carbonates, which were deposited in a shallow open marine environment (Najafi *et al.* 2018).

Aghajari Formation

The 3-km siliciclastic deposits of the Aghajari are divided into lower Aghajari and Lahbari units. The lower part of the Aghajari Fm. consists of interbedded light-grey to reddish medium-thick sheet-like sandstone beds and red mudrocks. It contains a variety of sedimentary structures such as bi-directional cross-stratification, round-crested symmetrical and current-ripple marks, microbially induced sedimentary structures, and also trace fossils such as *Skolithos* and *Cruziana* ichnofacies, which indicate that they were deposited in a clastic shoreline environment (Najafi *et al.* 2018; Pirouz 2018). The magnetostratigraphic ages show 13.6 Ma (Serravallian) for the onset of the Aghajari deposition in the north Dezful embayment. The Lahbari Mb. (upper part of the Aghajari Fm.) is marked by the lenticular matrix- and clast-supported conglomerates and sandstone layers intercalated with laminated or massive mudrocks. It contains basic architectural elements of meandering fluvial deposits such as channels and scours, lateral accretion, gravel bars, sand bedforms, floodplain mudrocks, and fining-up sequences produced by lateral migration of a meandering system (Najafi *et al.* 2018). The transition from the lower Aghajari to the Lahbari Mb. occurred ~9 Ma (Tortonian) in the northern Dezful embayment.

Bakhtyari Formation

The Bakhtyari Fm. unconformably overlies older strata in the north Dezful embayment starting at ~7 Ma during early Messinian. It consists of about 200 m of clast-supported polymictic conglomerates intercalated with cross-stratified sandstones deposited in a proximal gravel-dominated braided fluvial system (Pirouz *et al.* 2017a; Najafi *et al.* 2018; Pirouz 2018).

Materials and methods

A combination of petrographic and geochemical analysis was performed to determine the composition of conglomerates, sandstones and mudrocks in the late Oligocene–Pliocene sediments in north Dezful embayment. A total number of 200 siliciclastic samples were systematically collected in order to represent the variations in stratigraphy, lithology and composition through the Gachsaran, Mishan, Aghajari, and Bakhtyari formations along the log of the SW flank of the Azanak growth syncline-minibasin. In addition, 50 samples were studied from the Oligo-Miocene Asmari Fm. in cuttings from drills of the Cheshmeh-Khosh oil field. The logged section and the position of selected samples for different analyses are given in the stratigraphic column (Fig. 3).

The lithology, size and roundness of conglomerate clasts were assessed at 10 locations in the Aghajari Fm. (Lahbari Mb.) and 5 locations in the Bakhtyari Fm. (Fig. 3). In addition, 30 thin sections were examined to determine the composition of selected lithic fragments in conglomerates (Najafi *et al.* 2018). Conglomerate clasts were counted in the study succession for six sites of the Lahbari Mb. and one site at the base of the Bakhtyari Fm.,

using the area method defined by Howard (1993). We added three other sites and counted at least 200 individual clasts using the same approach in the middle and upper parts of the Bakhtyari Fm. (Table S.1). Locations of the clast counts and various lithological types at each site are shown in the stratigraphic column (Fig. 3).

A detailed petrographic study of sandstones was performed on 117 thin sections, examining texture, fabric, composition as well as diagenetic modifications. Modal petrographic analysis was carried out on 40 selected medium-coarse-grained sandstones of the well-exposed Aghajari Fm., including 27 samples from the lower Aghajari, and 13 samples from the Lahbari Member. At least 300 framework sand grains were recognized and counted in each thin section according to the Gazzi-Dickinson point-counting method (Ingersoll *et al.* 1984).

To study the provenance of the Ahwaz sandstone Mb., 29 thin sections were selected for point counting, from the drilled cuttings of well no.10 in the Cheshmeh-Khosh oil field. Since the studied thin sections of the Ahwaz Mb. contained small portions of sandstones, only about 100 framework grains were counted in each sample. Most attention focused on identifying rock fragments to define the fabric, texture, and lithology of parent rocks. Counted parameters are given in Table S.2 and point-count data and calculated Quartz-Feldspar-Rock fragment (QFR) parameters for each of the 69 samples are listed in Table S.3.

Whole rock geochemical analysis, including major and trace elements, was done at the MS Analytical laboratory in Canada. This consisted of 43 mudrock samples including 4 samples from the Gachsaran Fm., 4 samples from the Mishan Fm., 18 samples from the lower Aghajari Fm., and 17 samples from the Lahbari Mb (Fig. 3 for sample locations). After sample preparation and cleaning, all samples were crushed and powdered to less than 200 mesh (<75 μm). Major and trace elements were measured using Inductively Coupling Plasma Atom Emission Spectrum (ICP-AES) and Inductively Coupling Plasma Mass Spectrometry (ICP-MS) through the Lithium Metaborate fusion method. Powder samples were fused with a lithium metaborate flux within graphite crucibles, melted at 900 °C in a muffle furnace, and then digested in a 10% nitric acid solution for major element analysis by ICP-AES. For trace elements, powdered samples were digested in a hydrofluoric and perchloric acid mix, and then diluted with de-ionized water, and analyzed by ICP-MS. Concentrations of major and trace elements for individual samples are available in Tables S.4, S.5, and S.6.

To reconstruct the organization of flow direction during the foreland basin evolution in the study area, 84 new paleocurrent data were measured on the NE limb of the Aghajari anticline (Fig. 2a for location), and combined with 64 paleocurrent measurements recently published from the Azanak syncline (Najafi *et al.* 2018). The orientation data were corrected for tectonic tilt effects following the method of Tucker (2003) and then plotted on rose diagrams (Fig. 3).

Results and interpretations

The results are explained in four different sections, combining description and a first interpretation whenever possible: 1) clastic petrography of sandstones; 2) clastic petrography of conglomerates (Lahbari Mb. and Bakhtyari Fm.); 3) geochemistry of mudrocks; and 4) paleocurrent directions.

Clastic Petrography: Framework composition in sandstones

The Ahwaz sandstone Mb. of the Asmari Fm. is dominantly fine-grained, moderately to well sorted, sub-mature to mature, with sub-angular to sub-rounded grains (Fig. 4a) corresponding to quartzarenite with minor proportion of subarkose ($Q_{96}F_{3.5}RF_{0.5}$) according to classification by Folk (1974), (Fig. 5a). Quartz is the predominant detrital grain, constituting an average of 96% of rock volume, with a high monocrystalline to polycrystalline quartz ratio ($Q_m/Q_p = 43.9$). Orthoclase and plagioclase are the most common type of detrital feldspars and the K-feldspar to plagioclase ratios (K/P) have a mean of 1.4. Feldspars are mostly replaced by sericite and carbonate minerals. Rock fragments are ~0.5% on average of the modal composition and are mostly sedimentary and chert grains. Silica and carbonate are the dominant cements. The Ahwaz sandstone composition determined in this study matches the findings by Avarjani et al. (2014), that is, 97.5% quartz grains, 1.6% feldspar and 0.9% rock fragments.

The Mineralogical Index of Alteration (MIA) (Johnsson 1993), given by the ratio between Qtz and the sum of Qtz+Kf+Plg, ranges between 88.5 and 100 (avg. 96.3; Table S.3). According to QFL tectonic provenance diagrams (Dickinson 1985), the Ahwaz sandstones are quartzose (Qtz-rich) with high Q_m/Q_p and K/P ratios (average as $Qt_{96}F_{3.5}L_{0.5}$ and $Qm_{94}F_4Lt_2$), and plot in the 'Craton interior provenance' field (Fig. 5b, c). The main sources for craton-derived quartzose sands are crystalline basement terranes composed of granites and gneisses in continental interiors, passive continental margins, or cratonic margins of foreland basins (Dickinson 1985). The Arabian craton provenance is also in accordance with spatial distribution of Ahwaz sandstone fans in the passive margin of the incipient Zagros foreland basin. These siliciclastics are overlain by shallow marine carbonate platform towards the north (Daraei et al. 2015).

The medium- to coarse-grained sandstones of the Aghajari Fm. are mostly moderately to well sorted, sub-mature to mature, and contain rounded to angular grains (Fig. 4b-d), corresponding to litharenite according to Folk (1974) classification ($Q_{27}F_8RF_{65}$ for the lower Aghajari and $Q_{23}F_6RF_{71}$ for the Lahbari Mb.). Almost all litharenites are further subdivided into sedarenites based on rock fragment types (Fig. 5a).

Framework clasts are dominated by a wide variety of lithic fragments comprising about 67% of the total mode (Fig. 6). The lithic fragments are mostly composed of extra-basinal carbonate (37.9%), metamorphic (19.7%), and volcanic grains (7.9%) in the lower Aghajari (Fig. 4b, c). In the Lahbari Mb. the lithic fragments are chert (40.3%), extra-basinal carbonate

(37%) and siltstone grains (15.3%) (Fig. 4d). Metamorphic grains (Lm) largely consist of slate/phyllite and quartz-sericite to quartz-mica lithic fragments and show low to intermediate metamorphic ranks (Figs. 4b, 6). Among the volcanic rock fragments (Lv), intermediate and mafic volcanic grains are common with microlitic and lathwork textures (Figs. 4c, 6). Calcareous grains include mudstone to bioclastic wackestone/packstone (Dunham 1962), most of them with benthic foraminifers (Figs. 4b, 6). Chert grains contain evidence of radiolarian microfossils (Figs. 4d, 6). On average quartz grains comprise 26% of the total mode and are dominated by plutonic monocrystalline quartz ($Q_m/Q_p = 1.7$ in the lower Aghajari and $Q_m/Q_p = 1.8$ in the Lahbari Mb.). Polycrystalline quartz grains are primarily composed of more than three sub-grains with straight to slightly undulose extinction and are mostly recrystallized metamorphic quartz. The feldspar content of the Aghajari sandstones is on average ~7% of the modal composition. Feldspars are chiefly K-feldspar with an average K/P ratio of 3.3 in the lower parts of the Aghajari Fm. that slightly decreases to 3.1 in the upper parts (Lahbari Mb.). K-feldspars are dominated by orthoclase and display a low degree of alteration. These sandstones are cemented by carbonates.

The MIA values in the lower Aghajari sample range between 57.1 and 91.8 (avg. 76.9) and in the Lahbari sandstone samples range between 53.6 and 89.7 (avg. 79.1; Table S.3). The average grain composition of the Aghajari sandstones is $Qt_{39}F_8L_{53}$, $Qm_{17}F_8Lt_{75}$, $Qp_{29}Lv_7Ls_{64}$ and $Lm_{23}Lv_{10}Ls_{67}$, for the lower Aghajari, and $Qt_{52}F_6L_{42}$, $Qm_{15}F_6Lt_{79}$, $Qp_{46}Lv_2Ls_{52}$ and $Lm_9Lv_3Ls_{88}$ for the Lahbari Member. In the provenance ternary diagrams (Ingersoll & Suczek 1979; Dickinson 1985) the majority of the Aghajari sandstones plot within the 'orogenic provenance' field (Fig. 5b-e). The key source rocks in this tectonic provenance are subduction complexes, suture belts, and foreland uplifts (Dickinson 1985).

The basal part of the Aghajari sandstone, above the Gachsaran evaporites, shows an abrupt change in the nature of the lithic fragments to the basin evidencing source rock change (provenance shift 1 in Fig. 3). From the base of the Aghajari Fm. (1550 m in log of Fig. 3) to its middle part (3400 m), metamorphic and volcanic clast composition characterizes the unroofing and erosion of the Sanandaj-Sirjan tectonic domain. During the middle Aghajari deposition (3400 m in log of Fig. 3), an increase of radiolaritic clasts and a concomitant decrease of metamorphic and volcanic lithic fragments occur (provenance shift 2 in Fig. 3). This increase in radiolarite fragments is associated with the unroofing of the radiolaritic series within the Imbricated Zone after the erosion of the overriding Sanandaj-Sirjan tectonic domain on the hangingwall of the Main Zagros Thrust. The third significant change of lithic compositions is observed around point 5600 m on the stratigraphic column (provenance shift 3 in Fig. 3). This shift is characterized by a decrease in fragments of chert in favor of carbonate fragments. It is interesting to note that this change is also observed in conglomerates, starting at the base of Lahbari Member.

Clastic petrography: Framework composition in conglomerates

The Lahbari conglomerates are polymictic, matrix- to clast-supported, and moderately to well sorted (Fig. 4e). Conglomerate clasts range from very fine to cobble in size and sub-angular to rounded in shape. Preferred orientation is also observed in some clasts. Clasts are mainly sub-angular radiolarian cherts (59%; Fig. 4e, f), and sub-rounded to rounded fossiliferous carbonates (35%). Evaporite (4%) and low-grade metamorphic clasts (2%) have also been detected (Fig. 4e).

The Bakhtyari Fm. contains well to very well sorted, clast-supported, polymictic conglomerates with clasts up to 40 cm (Fig. 4g). Clasts mainly consist of fossiliferous carbonates (83.8%), but also include litharenite (calclithite) sandstones, conglomerates (less than 0.3%), and cherts (15.7%; Fig. 4h). Carbonate clasts in both Lahbari and Bakhtyari units contain well preserved fossils, mainly benthic foraminifera, including diverse Cenozoic macrofauna such as *Dendritina rangi*, *Neoalveolina pygmaea*, *Rotalia*, *Miliolia*, *Nummulites vascus*, and *Eulepidina dilatata* (Fig. S.1a-h), planktonic foraminifera (e.g., *Miogypsinoidea complanata*) and *Lithophyllum* coralline algae. Lahbari Mb. and Bakhtyari Fm. conglomerate clasts show a decrease in radiolaritic in favor of carbonate clasts sourced from the nearby growing anticlines of the Asmari Fm. The change in clast composition occurs gradually at the beginning (between 4600 and 5600 m in Lahbari Mb and referred to as provenance shift 3 in Fig. 3), but is more abrupt towards the top of the Bakhtyari succession where carbonates and radiolarites are the only components and metamorphic and volcanic clasts derived from the Sanandaj-Sirjan Zone no longer appear. It is interesting to note that there is a small but persistent proportion of evaporite clasts from 4600 to 5850 m in the Lahbari Mb., indicating either the dismantling and erosion of already structured Gachsaran beds or their extrusion and erosion along diapiric salt walls as seen in the northern Dezful embayment (Najafi et al. 2018).

Geochemistry of mudrocks

The use of Geochemical approaches in fine-grained sediments complement the information obtained from petrographical methods (e.g., McLennan *et al.* 1993; Armstrong-Altrin *et al.* 2018, 2019; Etemad-Saeed & Najafi 2019). Since thick layers of mudrock remain well preserved in the study section, we analyzed the bulk chemical composition of these fine-grained siliciclastics in order to collate them with our petrographic results. Although geochemistry provides a powerful tool for tracking the sediment provenance mudrocks represent more homogeneously mixed sources than coarse-grained clastics (McLennan *et al.* 1993). Major and trace element concentrations of 42 analyzed samples are presented in Tables S.4 and S.5; locations of samples are shown along the stratigraphic column in Figs. 3 and 7.

Compared with the Post Archean Australian Shales (PAAS), as a composition reference to the upper continental crust (Taylor & McLennan 1985), our studied mudrocks have similar to slightly lower values of SiO_2 , Al_2O_3 , Fe_2O_3 , Na_2O , K_2O , and P_2O_5 , while they show

significantly higher CaO and MgO values (Fig. S.2a). This strong enrichment in CaO shows a high concentration of carbonates. And although they indicate similar concentrations in most trace elements, they are slightly depleted in Rb and Ba mobile lithophile elements (Fig. S.2b).

The Rare Earth Elements (REE) values also fall within the reference range, although their chondrite-normalized REE patterns are highly fractionated (Fig. S.2c). The La_n/Yb_n equals 7.43, 7.28, 7.67, 7.34 for the Gachsaran, Mishan, lower Aghajari, and Lahbari mudrocks, respectively. These patterns are characterized by light rare earth elements enrichment (La_n/Sm_n), large negative Eu anomaly ($Eu/Eu^* = 2Eu_n/(Sm_n + Gd_n)$) and flat heavy rare earth elements (Gd_n/Yb_n). The La_n/Sm_n values for all studied samples are higher than 3, with an average of 3.50, 3.34, 3.48, and 3.38 for the Gachsaran, Mishan, lower Aghajari, and Lahbari mudrocks. The Eu/Eu^* values range from 0.71 to 0.76 (avg. 0.73) in the Gachsaran mudrocks, 0.67 to 0.72 (avg. 0.69) in the Mishan mudrocks, 0.65 to 0.83 (avg. 0.72) in the lower Aghajari mudrocks, and 0.65 to 0.87 (avg. 0.74) in the Lahbari mudrocks. The Gd_n/Yb_n values for each of these samples is near 1, with an average of 1.69, 1.63, 1.71, and 1.68 for the Gachsaran, Mishan, lower Aghajari, and Lahbari mudrocks, respectively. These REE patterns and the Eu anomaly are similar to those of PAAS.

The SiO_2/Al_2O_3 ratio in the Gachsaran mudrocks ranges from 3.71 to 4.77 (avg. 4.25). In the Mishan mudrocks the ratio ranges from 3.64 to 5.01 (avg. 4.32), in the Aghajari mudrocks from 3.54 to 8.82 (avg. 5.16), and in the Lahbari mudrocks from 4.36 to 7.29 (avg. 5.69) (Table S.4; Fig. 7).

The Chemical Index of Alteration (CIA) is defined as molecular proportions of $Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O) \times 100$, where CaO^* represents Ca of silicates only (Nesbitt & Young 1982). In our study, CaO values were corrected based on the method of McLennan (1993), in which, if $CaO > Na_2O$ then CaO equals Na_2O (Table S.4). Calculated CIA values are shown along the stratigraphy in Fig. 7, for Gachsaran mudrocks (65.53–70.19, avg. 68.54), Mishan mudrocks (64.41–70.64, avg. of 68.05), Aghajari mudrocks (59.90–70.62, avg. 65.90), and Lahbari mudrocks (61.97–71.22, avg. 66.36).

The index of chemical variability (Cox *et al.* 1995) was calculated using equation $ICV = (Fe_2O_3 + K_2O + Na_2O + CaO + MgO + MnO + TiO_2)/Al_2O_3$. Variations in ICV are indicated through stratigraphy (Fig. 7 and Table S.4): Gachsaran (1.43–1.88, avg. 1.64); Mishan (1.10–1.58, avg. 1.38); Aghajari (0.98–1.77, avg. 1.40); Lahbari (1.16–2.19, avg. 1.54).

Since we did not have access to the drill cuttings of the Ahwaz sandstones for geochemical measurements, we used published geochemical data from the Marun oil field in the Dezful embayment (Fig. 2 for location), reported by Avarjani *et al.* (2014), to compare with our geochemical measurements in the rest of the succession (Gachsaran–Lahbari) (Figs. 7 and 8; Table S.7). The La/Sc , La/Co , Th/Sc , Th/Co , Th/Cr , Eu/Eu^* , and La_n/Lu_n ratios in the studied mudrocks are shown in Table S.7. These elemental ratios show a sudden decrease from Ahwaz Mb. to the Gachsaran Fm. (e.g., decreasing La/Sc from 5.91 to 1.75), which strongly

suggests that the Ahwaz Mb. had more felsic source rocks than our studied Neogene mudrocks. This change in sediment compositions can also be seen in provenance discrimination diagrams, including Th/Co versus La/Sc (Cullers & Podkovyrov 2002), Cr/Th versus Th/Sc (Condie & Wronkiewicz 1990), and La-Th-Sc (Cullers 1994) (Fig. 8b-d).

Moreover, throughout this change, the concentration of Cr also increased from the Ahwaz, with low concentration of Cr (10–40, avg. 21.94 ppm), to the Gachsaran with very high concentration (122–256, avg. 177.5 ppm). A similar rise is observed in MgO concentration from the Ahwaz Mb. (0.04–1.65, avg. 0.4%) to the Gachsaran Fm. (5.02–8.73 %, avg. 6.61 %). Because the concentration of Cr and Mg is high in mafic and ultramafic rocks and low in felsic rocks (Armstrong-Altrin *et al.* 2004; Mohammedyasin & Wudie 2019), this change could reflect the initiation of the contribution of mafic-ultramafic sources in the composition of sediments. These variations imply a significant change in provenance from more felsic to intermediate-felsic sources (provenance shift 1 in Fig. 7; 300 m).

On the Ti/Zr-La/Sc, Th-Sc-Zr/10 and Th-Co-Zr/10 tectonic discrimination diagrams based on trace elements with relatively low mobility (Bhatia & Crook 1986), the Ahwaz Mb. plots in the passive margin field. Nevertheless, nearly all of the Gachsaran–Lahbari mudrocks are located in the field of active continental margin setting (Fig. 8e-g), which represent sedimentary basins adjacent to magmatic arcs in convergent plate margins in which sediments are mainly derived from felsic volcanic rocks (Bhatia 1983). Major element data for studied low-silica mudrocks (with $(\text{SiO}_2)_{\text{adj}} = 35\%–63\%$) were also plotted in a recently published discriminant-function multi-dimensional diagram by Verma and Armstrong-Altrin (2013). This diagram confirms the continental collision setting for the Gachsaran to Lahbari sediments (Fig. 8h).

Upward variations of the chemical composition throughout the succession further support two of the provenance shifts obtained by petrographic modal analysis (shifts 1 and 2). As seen in Fig. 7, there is a sharp increase in Cr, MgO and decrease in Zr/Sc, $\text{SiO}_2/\text{Al}_2\text{O}_3$, Th/Sc, Th/Co, and Th/Cr values from Ahwaz Mb. to the Gachsaran Fm. (300 m; according to provenance shift 1). In addition, there is a decrease in CIA, Rb/Sr, Th/U, Th, and LREE, and an increase in Sc, Co, and Cr in the middle of the Aghajari Fm. (2700–3400 m interval; according to provenance shift 2).

Paleocurrent directions

Along the analyzed Azanak and Aghajari stratigraphic columns, only few stratigraphic levels expose unambiguous paleocurrent directions, determined from cross-bedding and clast imbrications (Figs 3 and S.3). In the lower part of the Aghajari Fm., a total number of 84 cross-bedding and herringbone structures were measured in 16 sandstone levels, in both the Azanak and Aghajari sections (Figs 3 and S.3a). Paleocurrents show a bimodal distribution with ENE and SSW directions, likely developed naturally along the paleo-shoreline, with an asymmetry and stronger southward direction (rose diagrams in Fig. 3). In the Lahbari Mb., 43 cross-stratification were measured from 9 sandstone and pebble

conglomerate layers mostly showing SW direction of paleo flow (Fig 3 and S.3b). In the Bakhtyari Fm. paleocurrents were identified by the orientation of 21 either fluvial channels or pebble imbrications from 6 conglomerate beds. Most paleocurrents show a southward paleoflow direction varying from SSE to SW (Figs 3 and S.3c).

Discussion

Two major issues are addressed in this study: a) Recycling and past weathering conditions, and b) Provenance evolution of the foreland sediments and its implications for the exhumation history of the central Zagros Mountains.

Recycling and past weathering conditions

Prior to any tectonic interpretation of the Zagros orogen, the influence of recycling and paleo-weathering on the sediment composition must be assessed. We examined recycling and paleoweathering effects using reliable sandstone petrographic (MIA) and mudrock geochemical indicators (ICV, CIA $\text{SiO}_2/\text{Al}_2\text{O}_3$, Th/U and Zr/Sc). These indicators are defined based on the ratio of stable residual constituents over labile grains and mobile cations, which increase during recycling and chemical weathering (Fedo *et al.* 1995).

Petrographic observations showed that unstable lithic grains like carbonate rock fragments, which are not resistant to abrasion and recycling, are abundant in the Aghajari and Lahbari sandstones while they are absent in the Ahwaz sandstones. This indicates a lower degree of recycling in the composition of the Aghajari Fm. compared with the Ahwaz Mb. However, it should be noted that part of the well-rounded radiolarian chert grains in the Aghajari and Lahbari sediments can be recycled from Amiran and Kashkan formations exposed to the NW of our studied section in Lurestan Arc in the footwall of the High Zagros Fault (Fig. 2a for location). The Amiran-Kashkan coarse-grained sandstones and conglomerates were derived from radiolarite-ophiolite complexes during Paleocene-Eocene soon after the Late Cretaceous obduction of Neo-Tethys oceanic remnants (Homke *et al.* 2009; Saura *et al.* 2011). This early foreland flexure was restricted, forming a narrow elongated trough along the front of the emplaced ophiolite slices in Neyriz and Kermanshah regions (Fig. 1) (Braud 1987; Homke *et al.* 2009; Saura *et al.* 2011; Gholami-Zadeh *et al.* 2017).

In general, there is a substantial enrichment in quartz content (SiO_2) relative to clay materials (Al_2O_3) with increase in sedimentary recycling, that results in an elevation of the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio (McLennan *et al.* 1993). Our geochemical measurements also indicated a low $\text{SiO}_2/\text{Al}_2\text{O}_3$ (<10) ratio in the Gachsaran–Lahbari mudrocks (avg. 4.2–5.6), suggesting their chemical immaturity and a very low degree of recycling. This contrasts with the Ahwaz sandstones, which show a high $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio (avg. 74) as reported by Avarjani *et al.* (2014). In addition, the index of compositional variability (ICV) of all mudrocks (Gachsaran to Lahbari formations) shows values higher than one (avg. 1.38–1.64), supporting their

deposition as mostly first cycle sediments during incipient chemical weathering (Cox *et al.* 1995) (Fig. S.4a).

The Th/U ratio is about 3.5 to 4.0 for most upper crustal rocks (McLennan *et al.* 1993). Weathering and sedimentary recycling processes increase this ratio due to the oxidation of U^{4+} to more soluble U^{6+} . While, Th is mostly controlled by bulk composition of the source rocks and not affected by the sedimentary processes. The studied mudrocks have a Th/U ratio below 3.5 (avg. 2.4–2.6), indicating no significant weathering and/or sedimentary recycling (Fig. 7).

The Zr/Sc ratio also reflects the degree of sedimentary sorting and recycling characterized by the enrichment of zircon content due to the addition of zircon heavy mineral (McLennan *et al.* 1993). The Zr/Sc ratio in the Gachsaran-Lahbari mudrocks ranges between 10.2 and 13.7 (avg. 12.4) and in the Ahwaz sandstone between 62.9 and 264.9 (avg. 149.7). A bivariate plot of Th/Sc versus Zr/Sc of the studied mudrocks does not follow the sediment recycling trend and plot parallel to the igneous differentiation in the source rock as the primary control in an active margin setting (Fig. 8a). The concentration of these elements in the analyzed samples is similar to, or lower than, those of the PAAS suggesting that enrichment in zircon and recycling was minor. In contrast, the Ahwaz sandstone samples (Avarjani *et al.* 2014) plot along the zircon concentration trend (trend 2), indicating that they are enriched in zircon due to a high degree of sediment sorting and recycling (Fig. 8a).

Based on the mineralogical index of alteration (Johnsson 1993), the Aghajari and Lahbari sandstones with low MIA (average 77 and 79, respectively) show lower chemical weathering in their source regions than the Ahwaz sandstones with higher MIA (average 96). In accordance, the chemical index of alteration (Nesbitt & Young 1982) in the studied mudrocks of Gachsaran–Lahbari sequence (average CIA=66–69) is notably lower than the CIA values for average mudrocks (70–75), supporting low intensity chemical weathering in their source area. Plotting these CIA values on the A-CN-K (Al_2O_3 -CaO+Na₂O-K₂O) ternary diagram (Nesbitt & Young 1984; Fedo *et al.* 1995) indicates that a large part of the studied samples parallel to A-CN bind, which suggests the leaching of CaO and Na₂O under low to moderate weathering conditions (Fig. S.4b). Furthermore, low Rb/Sr (<0.5) in the Gachsaran (avg. 0.23), Mishan (avg. 0.26), Aghajari (avg. 0.22) and Lahbari (avg. 0.17) mudrocks also agrees with low chemical weathering in their source areas, as proposed by McLennan *et al.* (1993).

A high degree of recycling hinders a conclusive interpretation of climate from the composition of the Ahwaz sandstone. The first cycle and immature sediments of the Gachsaran–Lahbari sequence are robust indicators of a dry climate during their deposition. On the global scale, perturbations on $\delta^{18}O$ suggest a warming trend from the late Oligocene (27–26 Ma) until the early-middle Miocene with a peak in the middle Miocene climatic optimum (17–15 Ma) (e.g., Zachos *et al.* 2001) (Fig. 9). The deposition of Gachsaran and Mishan sedimentary units was coeval with this middle Miocene climatic optimum and show

the highest chemical alteration and Rb/Sr ratio among studied mudrocks. A generally warm and dry climate during this time is also consistent with the deposition of the thick Gachsaran evaporitic layers in a sabkha environment (Pirouz 2018). Moreover, regional scale paleoclimate reconstructions based on stable isotope ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) and clay minerals in synorogenic sedimentary rocks from the Fars Arc and southern Alborz, have demonstrated warm and arid climate during late Oligocene–early Miocene with some variations in aridity in response to the topographic evolution of the region (Ballato *et al.* 2010; Khadivi *et al.* 2012) (Fig. 9).

A closer inspection of the chemical index of alteration and Rb/Sr ratio in the mudrocks shows that there is a slight decrease upward, from Gachsaran to Lahbari sedimentary units (Fig. 7). This reduction fits with the reported gradual cooling from ~15 Ma until present-day based on the $\delta^{18}\text{O}$ analysis (Zachos *et al.* 2001) consistent with the long-term cooling of global climate, from early Cenozoic greenhouse to the late Cenozoic icehouse (Molnar & England 1990; Raymo & Ruddiman 1992; Zachos *et al.* 2001; Allen & Armstrong 2008).

Our paleo-weathering results, combined with published global and regional climate conditions, illustrate that there was no significant or sudden change in climate during the period ranging from the Gachsaran to the Bakhtyari deposition, spanning from middle Miocene to Pliocene. It is therefore significant to note that our detected compositional shifts are little influenced by climate and thus mostly related to tectonics and large-scale erosion (shifts 1 to 3, in Figs. 3, 9).

Implications for the exhumation history of the central Zagros Mountains

Using the modal analysis for sandstones and conglomerates together with whole-rock geochemical measurements we were able to determine the provenance evolution of a thick stratigraphic succession within the northern Dezful embayment and three significant provenance shifts (Fig. 9). These shifts are separated by four periods characterized by different compositions attributed to changes in denudation areas: the first in the Arabian craton; the other three in the Zagros hinterland.

The Arabian provenance for Ahwaz sandstones is known by their map distribution of deltaic tongues sourced from the SW (Daraei *et al.* 2015) and by published provenance studies by Avarjani *et al.* (2014) and Jafarzadeh and Hosseini-Barzi (2008). Our modal analysis indicates that the Ahwaz Mb. of late Oligocene age (Ehrenberg *et al.* 2007) is mainly quartzose ($\text{Qmnu}_{74.59}\text{Qmu}_{23.18}\text{Qp}_{2-30.76}\text{Qp}>3_{1.47}$; abbreviations as in Table S.2). This composition strongly proposes crystalline basement terranes of granitic and gneissic composition in a craton as the sediment source for Ahwaz sandstones (Fig. 5b, c) (Dickinson 1985).

Our geochemical data, based on provenance ratios of immobile elements (Table S.7 and Figs 8b-d), along with Cr and MgO concentrations, show that the Ahwaz Mb. has more felsic source rocks than the younger Gachsaran–Lahbari sediments. This provenance shift is also indicated in the tectonic setting discrimination diagrams (Fig. 8e-h). These diagrams suggest

a switch from a craton to an active continental margin based on both immobile trace elements including Ti/Zr versus La/Sc, Th-Sc-Zr/10, and Th-Co-Zr/10 (Bhatia & Crook 1986), as well as DF1-DF2 major element functions (Verma & Armstrong-Altrin 2013).

The Ahwaz sandstone is partially coeval with the deposition of the Razak Fm. and equivalent Red Bed sediments with maximum depositional age of late Oligocene (~26 Ma) (Koshnaw *et al.* 2019) in the inner part of the Zagros in Kurdistan (Fig. 9). These sedimentary units already contain metamorphic detrital components derived from the Sanandaj-Sirjan domain (Gholami-Zadeh *et al.* 2017; Moallemi *et al.* 2017) and thus sourced from the Zagros in latest Oligocene times as observed in diagram a, Figure 10. The Razak Fm. grades laterally towards the foreland to shallow water carbonates of Asmari Fm. and to the evaporitic systems of Gachsaran Fm. in the Dezful embayment (Fig. 9).

The first siliciclastic sediments within the study area are in the Aghajari Fm., above the shallow marine Mishan Fm. (Najafi *et al.* 2018; Pirouz 2018), which show a distinct compositional record with respect to the Ahwaz sandstones. The composition of the lower Aghajari quartzolithic sandstones indicate the arrival of immature and first-cycle igneous and low to medium grade metamorphic sand-size detritus from the Sanandaj-Sirjan Zone transported by the orogen-transverse river network characterized by SSW-paleoflow. The recent thermochronologic studies show a rapid exhumation of the metamorphic and magmatic Sanandaj-Sirjan domain, from Burdigalian to Serravallian (19–13 Ma) (Wrobel-Daveau 2011; Barber *et al.* 2018), and building topography above sea level (Francois *et al.* 2014) (Figs. 9 and 10b). A previous detrital apatite fission track study suggests older cooling ages of 22 ± 5 Ma (Homke *et al.* 2010), that indicate tectonic processes within the Sanandaj-Sirjan domain were already active in the hinterland of the Zagros starting several million years before 19 Ma.

Well-calibrated structural reconstructions based on a wealth of data collected from the Lurestan Province show the advance of the Sanandaj-Sirjan domain and its frontal Gaveh Rud accretionary system on top of the allochthonous slices of Kermanshah Complex corresponding to the Late Cretaceous–Paleocene obduction event (Vergés *et al.* 2011; Saura *et al.* 2015). Barber *et al.* (2018) improved these published Lurestan reconstructions adding new time steps supported by their Sanandaj-Sirjan thermochronologic results. In these restorations, the emplacement of the continental Sanandaj-Sirjan block over the Arabian continent occurred in a kind of out-of-sequence thrusting event during the late Oligocene (28–23 Ma) (Mouthereau *et al.* 2012; Barber *et al.* 2018).

A new significant compositional change occurred in the middle of the Aghajari Fm., with an early Tortonian age (Lashgari *et al.* 2020) indicated by provenance shift 2 (Figs. 9 and 10c). This compositional change is characterized by the increase of radiolarian chert grains and the substantial decrease of metamorphic and volcanic clasts (Fig. 3). In early Tortonian this provenance variation is also evidenced by a slight decrease in incompatible elements (Th, LREE) over compatible elements (Sc, Co, Cr) (Fig. 7). This geochemical variation indicates that possibly subordinate mafic rocks were exposed in the source areas during the

deposition of the upper part of the Aghajari Fm. (including the Lahbari Mb.). The combination of both the composition of the upper Aghajari sandstones and mudrocks and their NE to SW orogen-transverse paleocurrent direction, strongly indicates that these sediments derived from the radiolarite-ophiolite outcrops forming the Kermanshah Complex (Fig. 9). The Kermanshah Complex is part of the long Neo-Tethyan ophiolite belt that extends from the Balkans to northern India (Ricou *et al.* 1977; Coleman 1984), obducted on top of the NE margin of the Arabian plate during Late Cretaceous-Paleocene times (Agard *et al.* 2005; Homke *et al.* 2009; Saura *et al.* 2011; Mohajjel & Fergusson 2014). These Kermanshah allochthonous slices, thrust during the late Oligocene by the Sanandaj-Sirjan and its frontal accretionary prism, show a rapid exhumation between 11 and 8 Ma during Tortonian (Gavillot *et al.* 2010; Koshnaw *et al.* 2017; Barber *et al.* 2018). This exhumation brought important masses of radiolarites and mafic rocks to the surface causing them to become the source of the upper Aghajari sequences in the northern Dezful embayment (Fig. 10c). On the other hand, part of the well-rounded stable chert grains could have been recycled from the Paleocene-Eocene Amiran and Kashkan formations deposited in the early foreland basin in front of ophiolite slices (Homke *et al.* 2009; Saura *et al.* 2011), as discussed earlier in the recycling section. At the base of the Lahbari Mb., conglomerates were still dominated by radiolarian cherts, accompanied by subordinate carbonate, metamorphic and gypsum clasts (Fig. 3), indicating that the High Zagros (Imbricated Zone) was the main supply of clastic fragments (Figs 9 and 10d). The evaporitic unstable clasts were likely derived from local salt anticlines and salt walls formed by the diapiric flow of Gachsaran evaporites (Najafi *et al.* 2018). In any case, a marked decrease in radiolaritic coeval with an increase of carbonatic contributions towards the upper part of the Lahbari and lower Bakhtyari sedimentary successions is observed and identified as provenance shift 3 (Figs 3 and 9).

Shift 3 is coeval with a distinct change in depositional environment from meandering to braided fluvial systems (Najafi *et al.* 2018) that increased the gradient and power of the transverse rivers raising the capacity of erosion (Einsele 2013). The unstable carbonate clasts had shorter transport distance and were likely derived from proximal sources such as growing anticlines. The microfossil assemblages in the Bakhtyari carbonate clasts are similar to reported microfauna from the upper Oligocene–lower Miocene Asmari Fm. (Adams & Bourgeois 1967). The Asmari Fm. is exposed in the large Gurpi anticline uplifted along the hangingwall of the Mountain Frontal Fault (Fig. 2). Tectonic reconstructions indicate that the Mountain Frontal Fault, involving crystalline basement at depth, would have been most active during the upper Lahbari and Bakhtyari syntectonic depositions, as observed along the front of the Izeh zone (Najafi *et al.* 2018) as well as in the Lurestan arc (Homke *et al.* 2004; Emami *et al.* 2010; Lashgari *et al.* 2020). Thermochronologic data confirm the coeval exhumation of the Izeh Zone, across the Mountain Frontal Fault, at the Messinian-Pliocene boundary (5.8–4.4 Ma) (Wrobel-Daveau 2011; Koshnaw *et al.* 2017; Barber *et al.* 2018). The Izeh Zone could supply large quantities of carbonate clasts into the northern Dezful embayment, especially considering that the total structural relief across the Mountain Frontal Fault is 9.3 km (Najafi *et al.* 2018).

Geochemistry and petrography data presented in this study indicate that the provenance shift from the Arabian craton to the Zagros orogenic system took place between Ahwaz Mb. and Gachsaran Fm. with late Oligocene–early Miocene ages (between ~25 and 18 Ma). The base of the Aghajari Fm. clearly indicates the first arrival of Zagros provenance in the study area, which in turn agrees with the metamorphic provenance of the Razak Fm. and equivalent Red Beds along the footwall of the Main Zagros Thrust (Gholami-Zadeh *et al.* 2017) (Fig. 9), with documented late Oligocene age (~25–26 Ma) using magnetostratigraphic and detrital zircon U-Pb ages (Pirouz *et al.* 2017a; Koshnaw *et al.* 2018). These late Oligocene–early Miocene ages of initial Zagros building, predate the folding amplification and propagation across the Zagros Simply Fold Belt starting in lower Miocene in both Lurestan and Fars Arcs (e.g., Vergés *et al.* 2019). The ages of both the onset of the Zagros provenance and the propagation of folding towards the foreland make it difficult to justify the beginning of the collision as late as late Miocene–early Pliocene as proposed by Zhang *et al.* (2017), based on detrital zircon signature in NW Zagros. Instead, these young ages could be explained by an out of sequence basement thrusting, as suggested earlier by Koshnaw *et al.* (2017), and also indicated in this study by the provenance shift 3 along the Mountain Frontal Fault.

The first foreland sediments with Zagros provenance were deposited in late Oligocene (~25–26 Ma) along the suture zone (Pirouz *et al.* 2017a; Koshnaw *et al.* 2018), and arrived to the Dezful embayment during late Oligocene–early Miocene times (~25–18 Ma) (this study). These data suggest a late Oligocene age for the onset of Zagros orogenic building. However, the rising of tectono-topographic reliefs in the Zagros can be linked to either the onset of continental collision (similar to soft-collision) or to a more advanced stage of orogenic evolution (hard-collision; Ballato *et al.* 2018). A recent Thermochronologic study in Alborz Mountains supports soft-collision and slow exhumation in latest Oligocene (~27–23 Ma), followed by an accelerated exhumation in the middle Miocene (~12 Ma) due to hard-collision (Madanipour *et al.* 2017).

The sediments were transported to the basin across a well-developed river system crossing the different tectonic-topographic barriers created during the orogenic building of the Zagros. Our findings indicate that during Aghajari and Bakhtyari deposition, the northern Dezful embayment was dominated by transverse rivers flowing SSW into the longitudinal paleo-Tigris towards the foreland as proposed in Vergés (2007) and Koshnaw *et al.* (2019). The modern fluvial system displays a similar drainage pattern, constituted by the orogen-transverse Zab, Aqsu, Karun, and Karkheh rivers flowing into the longitudinal and orogen-parallel Euphrates and Tigris rivers. Their present-day composition is similar to that existing during the sedimentation of Aghajari and Bakhtyari formations (Garzanti *et al.* 2016).

It is interesting to compare the timing of the Zagros events since late Oligocene described in this study and the rifting and spreading evolution of the Red Sea determined in two recent articles (Schettino *et al.* 2016, 2019) (Fig. 9). Accordingly, the onset of thrusting of the continental Sanandaj-Sirjan domain over the Arabian continental crust (at ~26 Ma) show an

almost coeval or slightly younger age than the initiation of the Red Sea rifting (at ~27 Ma) in late Oligocene. The tectonic emplacement of the Sanandaj-Sirjan above the Main Zagros Fault, the High Zagros and the Izeh Zone and their corresponding exhumation events occurred during a Red Sea rift extension at constant rates of 11 mm/yr in a NE-SW direction from late Oligocene to early Pliocene (27–4.6 Ma) (Schettino *et al.* 2019). The oceanization of the Red Sea in early Pliocene doubled the rate of opening to 25 mm/yr. This 11–25 mm/yr of extension rate is remarkably greater than the rate of shortening determined during the Zagros folding, which is only of about 2 mm/yr across the Lurestan in NW Zagros, and 4 mm/yr across the Fars Arc in SE Zagros (e.g., Vergés *et al.* 2019). Part of this difference is accommodated by the tightening of several fold and thrust belts shaping interior Iran, including Alborz Mountains, Central Iran and Sanandaj-Sirjan domain.

Conclusions

1. Above and partly coeval to the Ahwaz sandstones sourced from the Arabian craton, the sandstones of the Razak Formation along the NE margin of the foreland basin show the first arrival of Zagros sediments and thus the first provenance shift during the latest Oligocene (~26 Ma). This shift is indicated in the Dezful embayment by geochemical variations and petrographic changes in Gachsaran evaporites and basal Aghajari sandstones, respectively. The sharp rise in Cr and MgO concentrations, and a concurrent drop in Zr/SC, SiO₂/Al₂O₃, Th/Sc, Th/Co, Th/Cr ratios, together with the tectonic setting discrimination diagrams, and the appearance of metamorphic and volcanic clast composition shows the unroofing of the Sanandaj-Sirjan tectonic domain through the Gachsaran–lower Aghajari deposition. Catchments within the Sanandaj-Sirjan domain, above the Main Zagros Thrust, supplied a large volume of metamorphic and igneous clasts subsequently deposited in the north Dezful embayment in sand size during the Serravallian (~13.6 Ma). Immature and mostly first cycle signature for the Gachsaran, Mishan, and Aghajari sediments, indicates deposition in a dominantly arid climate during the Miocene.
2. The second provenance shift occurred in Tortonian (~9 Ma) after 1850 m of Aghajari deposition, and is characterized by an increase in radiolarian chert grains (from 18% to 40%), and by a substantial decrease in metamorphic and volcanic clasts (from 20% and 8% to 5% and 2%, respectively). A coeval reduction in the ratio of incompatible (Th, LREE) over compatible elements (Sc, Co, Cr) suggests exposure of subordinate mafic rocks in the source area derived from the exhumed Neo-Tethyan radiolarite-ophiolite allochthonous slices from the Kermanshah Complex in the High Zagros zone.
3. The third provenance shift took place during the Messinian (~7 Ma) in the north Dezful embayment, after ~4000 m of Aghajari and Lahbari deposition. An increasing contribution of carbonate clasts (up to 85%) and a decrease of radiolarian cherts (to 15%) is characteristic of the upper Lahbari and Bakhtyari conglomerates. This significant volume of proximal

carbonate clasts was supplied by the large anticlines growing in the hanging wall of the Mountain Front Fault involving crystalline basement at depth.

4. The Zagros foreland succession shows three distinct compositional variations in the north Dezful embayment, attributed to the exhumation and erosion of rising topographic reliefs related to the Arabian-Eurasian collision. The Zagros orogenic building initiated slightly later than the onset of the Red Sea continental rifting in the latest Oligocene and produced the Razak basin at the footwall of the Main Zagros Thrust. The development of tectono-topographic reliefs in Zagros configured the source areas supplying Dezful embayment during late Oligocene–early Miocene just before the propagation of cover folding and basement thrusting across the Zagros Fold Belt during early Miocene–Pleistocene.

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Figure captions:

Fig. 1. Regional tectonic map showing the divisions of the Zagros fold-thrust belt and location of the north of Dezful embayment along the footwall of Mountain Front Fault (modified after Berberian 1995; Sepehr & Cosgrove 2004).

Fig. 2. (a) Geological map showing the main tectonic domains (modified after Nogol-e-Sadat 1993), the location of the regional cross-section, the position of the Azanak and Aghajari successions, and the position of Cheshmeh-Khosh and Marun wells. (b) The regional cross-section constructed in this study shows the crustal geometry across 4 tectonic domains in the Central Zagros, including the Sanandaj-Sirjan, High Zagros, Izeh and Dezful embayment.

Fig. 3. Stratigraphic column of the studied foreland succession in the northern Dezful embayment, indicating the position of analyzed samples, and upward compositional variations in sandstones and conglomerates. Ages are based on magnetostratigraphic (Lashgari *et al.* 2020) and Sr isotope data (Ehrenberg *et al.* 2007; Pirouz *et al.* 2015).

Fig. 4. Field photos and Photomicrographs of representative framework clasts in the Aghajari and Bakhtyari formations. (a) Photomicrographs of framework grains in the sandstone of Ahwaz Member, (b, c) lower Aghajari unit, and (d) Lahbari Member. Qm: monocrystalline quartz; Qp: Polycrystalline quartz; Lm: metamorphic lithic; Lv: volcanic lithic; Lc: carbonate lithic; Cht: chert lithic. (e) Field photo showing the dominated presence of the angular to sub-angular radiolarian chert (red clasts), few Gypsum clasts, (f) and photomicrographs of hematitic radiolarian chert grains in the Lahbari conglomerates. (g) Field photo showing the common presence of the rounded fossiliferous carbonate, few angular cherts and (h) conglomerate clasts in the Bakhtyari conglomerates.

Fig. 5. Plots of studied sandstones on triangular (a) QFRF, (b) QtFL, (c) QmFLt, (d) QpLvLs, and (e) LmLvLs discrimination diagrams (Folk 1974; Ingersoll & Suczek 1979; Dickinson 1985). Data and definitions are given in Tables S.2 and S.3.

Fig. 6. Photomicrographs of major lithic fragments in the lower Aghajari and Lahbari sandstones displaying source rocks lithology.

Fig. 7. Upward variations of the CIA, Rb/Sr, Th/U, SiO₂/Al₂O₃, Zr/Sc, MgO (%), Cr (ppm), Th/Sc, Th/Co, Th/Cr, and LREE in the studied section. Geochemical data of the Ahwaz sandstone in the Marun Oil Field in the Dezful embayment from Avarjani *et al.* (2014).

Fig. 8. (a) Plot of Th/Sc versus Zr/Sc indicating minimal effect of sediment recycling in the composition of the studied Gachsaran–Lahbari mudrocks. In contrast, Ahwaz sandstone data from Avarjani *et al.* (2014) are concentrated in the trend of sediment recycling. (b) Th/Co versus La/Sc (Cullers & Podkovyrov 2002), (c) Cr/Th versus Th/Sc (Condie & Wronkiewicz 1990), and (d) La-Th-Sc (Cullers 1994) provenance discrimination diagrams to recognize the composition of source regions of the studied mudrocks. The Ahwaz sandstone data (Avarjani *et al.* 2014) are shown for comparison. (e-g) Tectonic setting discrimination diagrams for the studied mudrocks based on immobile trace elements: Ti/Zr versus La/Sc, Th-Sc-Zr/10, and Th-Co-Zr/10 (Bhatia & Crook 1986). (h) Discriminant-function low-silica diagram is based on major elements. For discriminant function 1 and discriminant function 2 equations, see the original reference (Verma & Armstrong-Altrin 2013).

Fig. 9. Chronostratigraphic panel across the Central Zagros for the Oligocene to Pleistocene foreland deposits. Our detected geochemical and petrographic variations in the Dezful embayment are integrated with published thermochronometric ages from source areas (Gavillot *et al.* 2010; Homke *et al.* 2010; Wrobel-Daveau 2011; Koshnaw *et al.* 2017; Barber *et al.* 2018), as well as with the magnetostratigraphic and isotopic ages of syntectonic sediments (Homke *et al.* 2004; Ehrenberg *et al.* 2007; Pirouz *et al.* 2015, 2017b; Koshnaw *et al.* 2018; Vergés *et al.* 2019; Lashgari *et al.* 2020), in order to define exhumation history during the foreland basin evolution. This figure also shows late Cenozoic global climate changes based on deep-sea oxygen isotope records (Zachos *et al.* 2001) and regional paleoclimate reconstructions in Miocene synorogenic sediments from the Fars and Alborz (Ballato *et al.* 2010; Khadivi *et al.* 2012).

Fig. 10. Schematic block diagrams illustrating exhumation history of the Central Zagros Fold Belt, and tectono-sedimentary evolution of its foreland basin.

d) Bakhtyari Fm. (Messinian–Pliocene)

provenance shift 3

c) upper Aghajari Fm. (Tortonian)

provenance shift 2

b) lower Aghajari Fm. (Serravallian)

provenance shift 1

a) Ahwaz Mb. (late Oligocene)