



# The geologic configuration of the Zagros Fold and Thrust Belt: an overview

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## Abstract

The Zagros Fold and Thrust Belt (ZFTB) is an outstanding orogen running from eastern Turkey to the Makran area. It is formed as a consequence of the convergence between the Arabian and the Eurasian plates that occurred in the Neogene. This still active and long-lasting process generated a topographic configuration dominated by a series of parallel folding structures which, at places, isolate internal basins. The topographic configuration has, in turn, profoundly influenced the river network evolution, which follows a trellis pattern with the main valleys developed in the synclines and rivers that occasionally cut into anticlines. The peculiar climate, characterised by arid and semi-arid conditions, makes most of the rivers ephemeral, alimented only by short rainfall events. For this reason, the sediments are transported over short distances and deposited in huge alluvial fans. Although the Zagros is one of the most studied belts in the world, its tectonic evolution is far from being fully understood. Debated, for example, are the beginning of collision, the primary deformation mechanism, the evolution of the drainage system, the formation process of the alluvial fans, and the interrelations between landscape, tectonics, and climate. This paper, focusing on the geodynamic, geological, stratigraphic, and topographic configuration of the Zagros belt, is intended to be a compendium of the most up-to-date knowledge on the Zagros and aims to provide the cognitive basis for future research that can find answers to outstanding questions.

**Keywords** Zagros Mountains · Iran · Topography · Geodynamics

## 1 Introduction

The Zagros Mountains are a ~2000 km long SW-verging orogen, extending from eastern Turkey to the Makran area (Fig. 1a), produced by the Neogene collision between Arabia and central Iran after the northward subduction of the Neotethys Ocean (Ballato et al. 2011; Bigi et al. 2018; Sarkarinejad and Goftari 2019; Karasozen et al. 2019). The geologic history of the Zagros Belt began ~600 Ma when Iran was part of a continental magmatic arc extending along the northern margin of the supercontinent Greater Gondwana or Pannotia. During the Late Palaeozoic, this arc separated

from Gondwana and migrated northward until the collision with the Eurasian plate. This collision caused the closure of the Paleotethys seaway and formed the Permian–Triassic suture along Iran-Anatolia’s northern margin. In the Jurassic–Early Cretaceous period, a rifting event formed the Neotethys Ocean and weakened the lithosphere along the SW margin, determining the formation of an N-dipping subduction zone. The convergence of the Arabian–Eurasian plates started with the obduction of the Neotethyan oceanic crust at the northeastern margin of the Arabian plate between the Late Cretaceous and Early Paleocene, followed by the closure of the Neotethyan Ocean (Agard et al. 2011). Afterwards, the collision between Arabia and Eurasia began, and the enormous amount of sediment involved led to the initial growth of the Zagros Fold-and-Thrust Belt against the ophiolitic forearc backstop (Stern et al. 2021).

Based on topography, geomorphology, exposed stratigraphy, and seismicity, the Zagros Range can be divided into three main parallel tectonic units (Berberian and King 1981; Berberian et al. 1982; Alavi 2007; Mouthereau 2011). From the northeast to the southwest: the Urumieh–Dokhtar

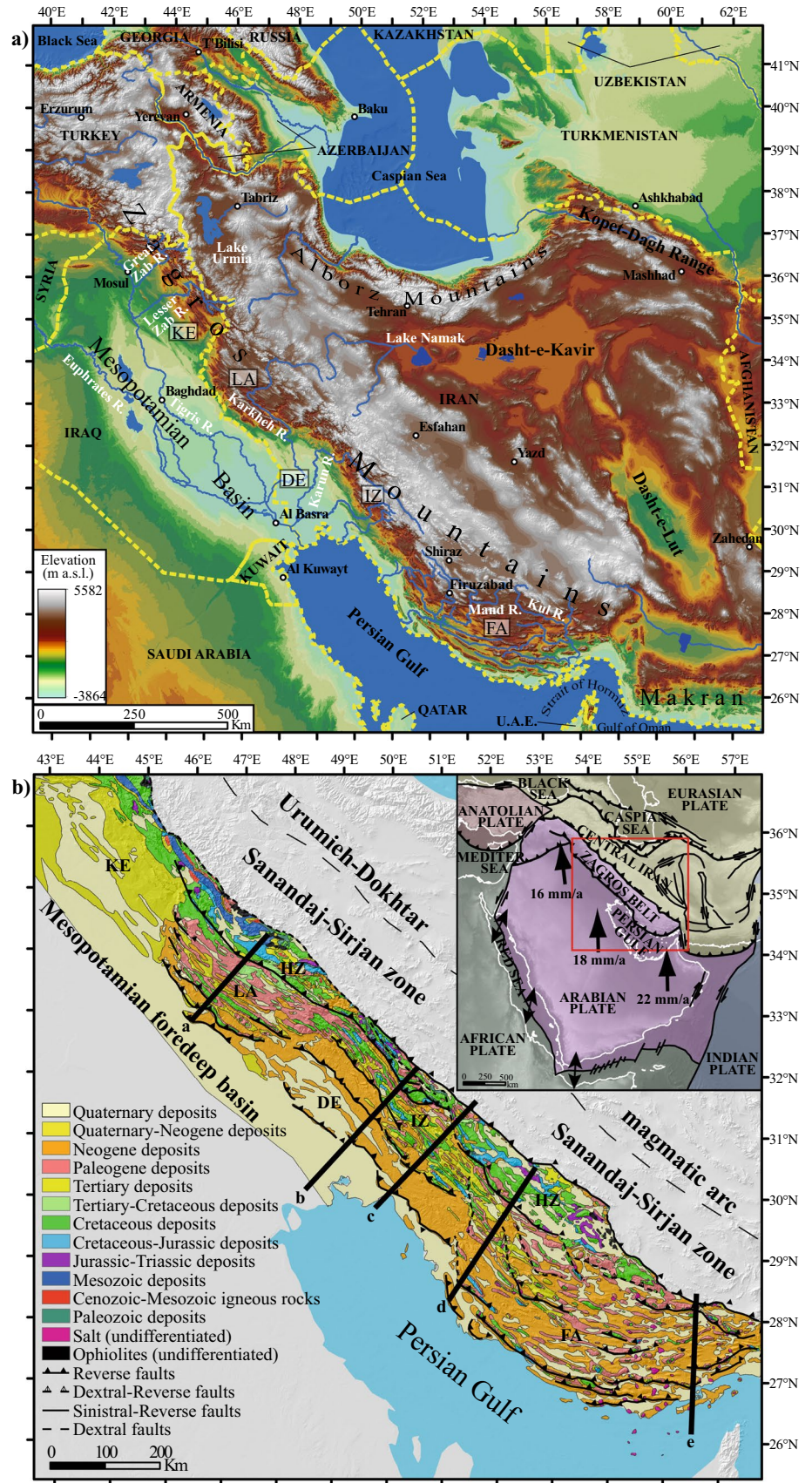
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**Fig. 1 a** Topography of Iran draped on hillshade (ETOPO1 DEM with a resolution of ~460 m). The solid blue lines indicate rivers; dashed yellow lines represent national borders; white points locate the principal cities. **b** Geological map of the Zagros Fold and Thrust Belt (from Pollastro et al. 1997, 1999). The principal tectonic lineaments are from Styron and Pagani (2020). Thick, solid black lines indicate the traces of the geologic sections of Fig. 4. The plate tectonic context of the Arabian–Eurasian collision zone is shown in the inset. Velocities of movement of Arabia with respect to Eurasia are from Sella et al. (2002) (modified after Soleimany and Sabat 2010). *KE* Kirkuk embayment, *LA* Lorestan Arc, *DE* Dezful embayment, *IZ* Izeh zone, *FA* Fars Arc.



Magmatic Arc (UDMA), the Sanandaj–Sirjan Zone (SSZ), and the Zagros Fold-and-Thrust Belt (ZFTB) (Fig. 1b). The latter, located in the frontal part of the Zagros orogen, contains a wide fold and fault system showing a general NW–SE trend, apart from the northwestern (north of  $\sim 36^\circ\text{N}$ ) and the southeastern (Fars region) portions of the belt where it shows an E–W trend (Fig. 1a, b). The structure of the belt is affected by different factors including mechanical stratigraphy (i.e., the existence of different detachment levels; McQuarrie 2004; Sherkati et al. 2006; Mouthereau et al. 2007; Oveisi et al. 2009; Yamato et al. 2011; Yeats 2012; Najafi et al. 2014, 2020; Gurbuz and Saein 2018), basement faults (Jackson and Fitch 1981; Berberian 1995; Talebian and Jackson 2004; Mouthereau et al. 2006, 2007; Homke et al. 2010; Leturmy et al. 2010; Teknik and Ghods 2017; Najafi et al. 2018; Karasözen et al. 2019; Pash et al. 2021), and diapirism (Kent 1979; Murriss 1980; Edgell 1991; Jahani et al. 2009, 2017; Hassanpour et al. 2018, 2021; Najafi et al. 2018; Najafi and Lajmorak 2020; Taghikhani et al. 2024). In turn, the structure of the belt, together with the peculiar climatic condition, control the drainage system and the coastal morphology along the Persian Gulf (Vita-Finzi 1979, 1980; Reyss et al. 1999; Pirazzoli et al. 2004; Oveisi et al. 2009; Wood et al. 2012; Lokier et al. 2015; Pourkerman et al. 2020). It is clear, therefore, that a proper characterisation of the evolution and present configuration of the Zagros Fold and Thrust Belt requires a multidisciplinary approach.

Putting together the articles published, the total number can be estimated at more than 500 (Fig. 2). Nearly a third of the papers have as their main topic the study of tectonic lineaments and folds and how they interact to determine the current topographic configuration of the Zagros. In this sense,

the earliest published work goes back to Falcon (1961). Since then, more than 140 studies have been published on the subject (Fig. 2).

The study of tectonics went in parallel with that related to diapirism (i.e., salt tectonics). On the subject, publications have been started since 1929 (De Böckh et al. 1929), totalling more than 50 papers (11%; Fig. 2).

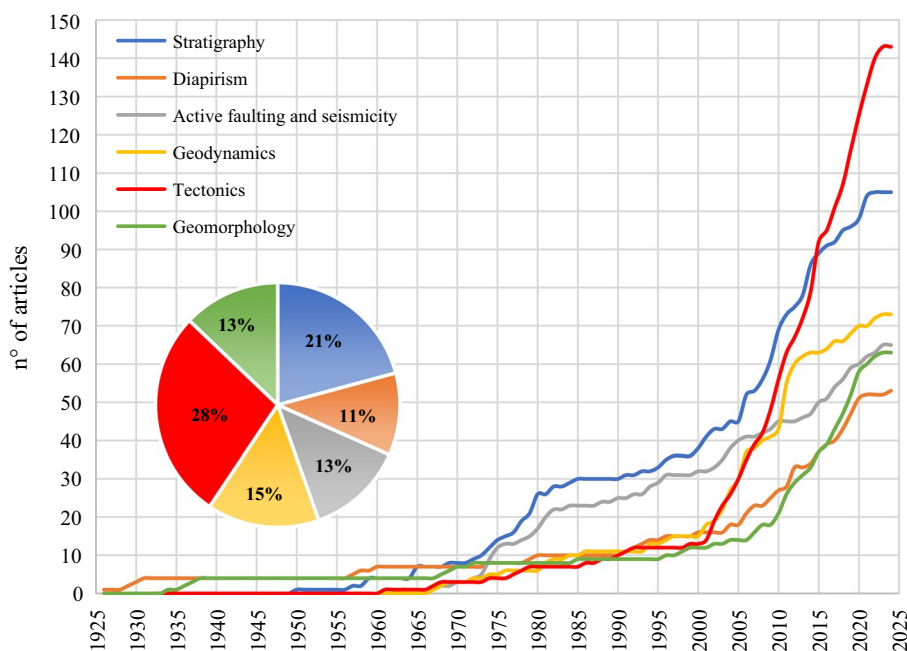
Stratigraphy is the main topic of more than 100 articles (21%; Fig. 2). The first published work is by O'Brien (1950), who divided the stratigraphic column of the Dezful embayment into five parts. However, this subdivision, which was too generalised and not responsive to the belt's heterogeneous geological configuration, was taken up and modified in subsequent articles.

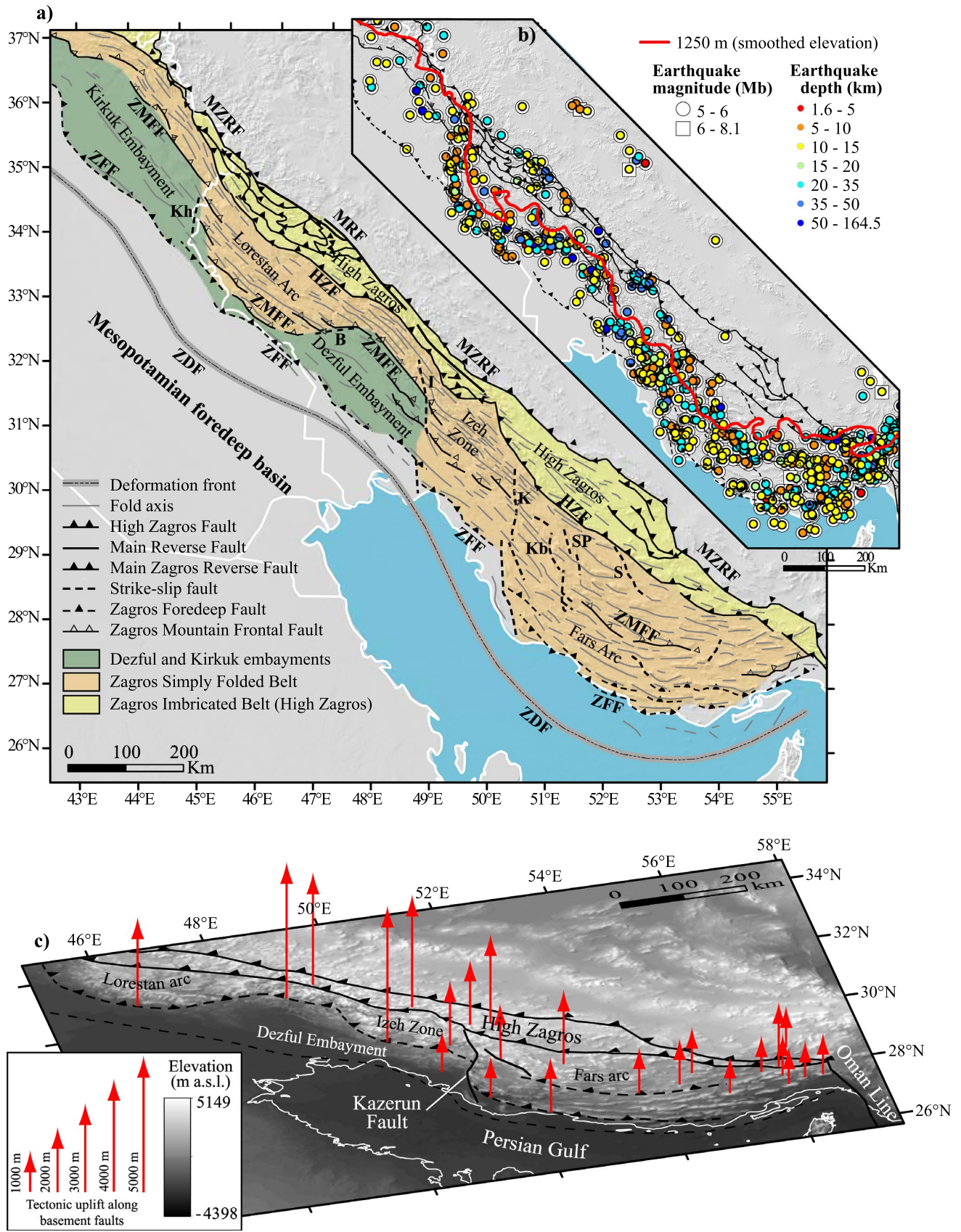
More than 70 papers (15%; Fig. 2) have been published on the geodynamic context of the Zagros, beginning with the work of Falcon (1967) and Stocklin (1968) tracing the geologic evolution of Iran. More than 60 papers (13%; Fig. 2) have covered active faulting and seismicity. The first paper collecting all the data on Iranian active faulting was by Tchalenko and Ambrayseys (1970), while the first earthquake catalogue was published by Berberian (1994), collecting more than 30 previous papers. Since then, more than 30 papers have been produced.

Finally, geomorphology, or the study of surface processes and their interaction with crustal processes, was addressed by more than 60 papers (13%; Fig. 2). The first published work is that of Harrison and Falcon (1934) in which collapse structures in southwestern Iran are observed and described.

Analysing the cumulative results of the studies published in the various fields, we can see that the number of studies investigating the Zagros belt has greatly increased since the

**Fig. 2** Cumulative curves showing the number of articles on the Zagros Fold and Thrust Belt published in scientific journals from 1926 to 2024 differentiated according to the topic covered. The percentage distribution of the various topics is shown in the pie chart in the inset





**Fig. 3** **a** Structural setting of the Zagros Fold and Thrust Belt with the major tectonic lineaments: *ZDF* Zagros Deformation Front, *ZFF* Zagros Foredeep Fault, *ZMFF* Zagros Mountain Front Fault, *HZF* High Zagros Fault, *MZRF* Main Zagros Reverse Fault, *MRF* Main Reverse Fault, *B* Bala Rud Fault, *I* Izeh Fault, *K* Kazerun Fault, *Kb* Karebas Fault, *SP* Sabz Pushan Fault, *S* Sarvestan Fault, *Su* Surmeh Fault (modified after Pirouz et al. 2011); **b** distribution of the earthquakes with  $M_b > 5$  occurred in the period 1900–2021 (from <https://earthquake.usgs.gov>). Solid red line indicates the smoothed 1250 m regional elevation contour (derived from a circular low-pass filter 20 km-in-radius) above which thrust-related earthquakes drastically diminished (Nissen et al. 2011); **c** Synthesis of tectonic uplift linked with the main basement faults in the Zagros. Data are from published sections (Letouzey et al. 2002; Molinaro et al. 2004, 2005; Sherkati and Letouzey 2004; Mouthereau et al. 2007; Jahani et al. 2009; Leturmy et al. 2010) (modified after Leturmy et al. 2010).

early 1980s with a substantial increase in the production of petroleum and natural gas (US—Energy Information Administration).

Despite many studies on the Zagros Fold and Thrust Belt, its evolution is far from completely understood. In fact, it is still unclear when the collision between Arabia and Eurasia occurred, what the main deformation mechanism which formed the fold system was, how the drainage system evolved, and what the main formation process of the alluvial fans was. Nor have the interrelations among landscape, tectonics, and climate been thoroughly investigated.

This paper combines the main results from the geological, geodynamical, stratigraphical, and geomorphological studies on the Zagros to understand the belt's development and evolution and provides a base for future studies that deepen and clarify aspects not yet fully understood.

## 2 Geodynamic setting

From morphological point of view, the ZFTB is characterised by two main portions extending parallel to the Arabian–Eurasian plate boundary: the Mesopotamian–Persian Gulf foredeep basin and the deformed wedge-top sediments of the High Zagros and Simply Folded Belt (Pirouz et al. 2011; Fig. 3). The northward motion of the Arabian plate relative to the Central Iran during Tertiary has been considered by several studies as the main cause of the recent evolution of the Zagros Mts. (e.g., Falcon 1967; Stoecklin 1968; Wells 1969; Ricou 1970; Nowroozi 1972; Haynes and McQuillan 1974; Alavi 1980, 1994, 2004; Berberian and King 1981; Jackson et al. 1981; Ni and Barazangi 1986; Farzipour-Saein et al. 2013; Jafari et al. 2023; Nouri et al. 2023; Fig. 1b). Because of this convergence the uppermost Arabian plate sediments were progressively scraped off and added to the outermost Zagros Fold and Thrust Belt: the oldest additions have been found in the northeast and the

youngest ones in the southwest (Stern et al. 2021; Jafari et al. 2023).

Despite the general consensus on the geologic evolution of the Zagros Mts., the beginning of compression is still debated. The initial continental collision is considered to be Late Cretaceous (Haynes and McQuillan 1974; Berberian and King 1981; Alavi 1994; Mazhari et al. 2009), Eocene–Oligocene (Hooper et al. 1994; Agard et al. 2005; Allen and Armstrong 2008; Ballato et al. 2011; Perotti et al. 2016), Oligocene–Miocene (Berberian et al. 1982; Mouthereau et al. 2012; McQuarrie and van Hinsbergen 2013; Saura et al. 2015), Early Miocene (Fakhari et al. 2008; Okay et al. 2010), Mid/Late Miocene (Homke et al. 2004; Guest et al. 2007), Late Miocene (Stoneley 1981; McQuarrie et al. 2003), Early Pliocene (Falcon 1961; Berberian and King 1981). Several recent studies infer the beginning of collision in the Late Oligocene and the Zagros folding inception at the Early/Mid Miocene (Khadivi et al. 2010; Pirouz et al. 2017; Vergés et al. 2019; Lashgari et al. 2020; Najafi et al. 2020). Provenance studies performed from Iraqi Kurdistan to Fars indicated an Eocene–Oligocene minimum age for the beginning of collision based on the sedimentary arrival in Arabia from Iran at this time (Horton et al. 2008; Gholami Zadeh et al. 2017; Koshnaw et al. 2019, 2021; Cai et al. 2021). Conversely, a new provenance study by Sun et al. (2023) fixed the collision initiation in a period before the Eocene. Based on several unconformities, Hessian et al. (2001) proposed a pulsed deformation since the Late Eocene, which reached the front of the belt during the end of the Pliocene. Direct support for this migration came from GPS and geochronological data indicating that shortening in central Fars is concentrated within 100 km of the Persian Gulf coastline (Walpersdorf et al. 2006; Oveisi et al. 2009). Documented Holocene anticline growth (Mann and Vita-Finzi 1988; Vita-Finzi 2001; Oveisi et al. 2007, 2009; Collignon et al. 2019) and recent seismicity (Jackson and McKenzie 1984; Karasözen et al. 2019; Pilia et al. 2020) point to a still active deformation in the Zagros belt, especially at deep crustal levels.

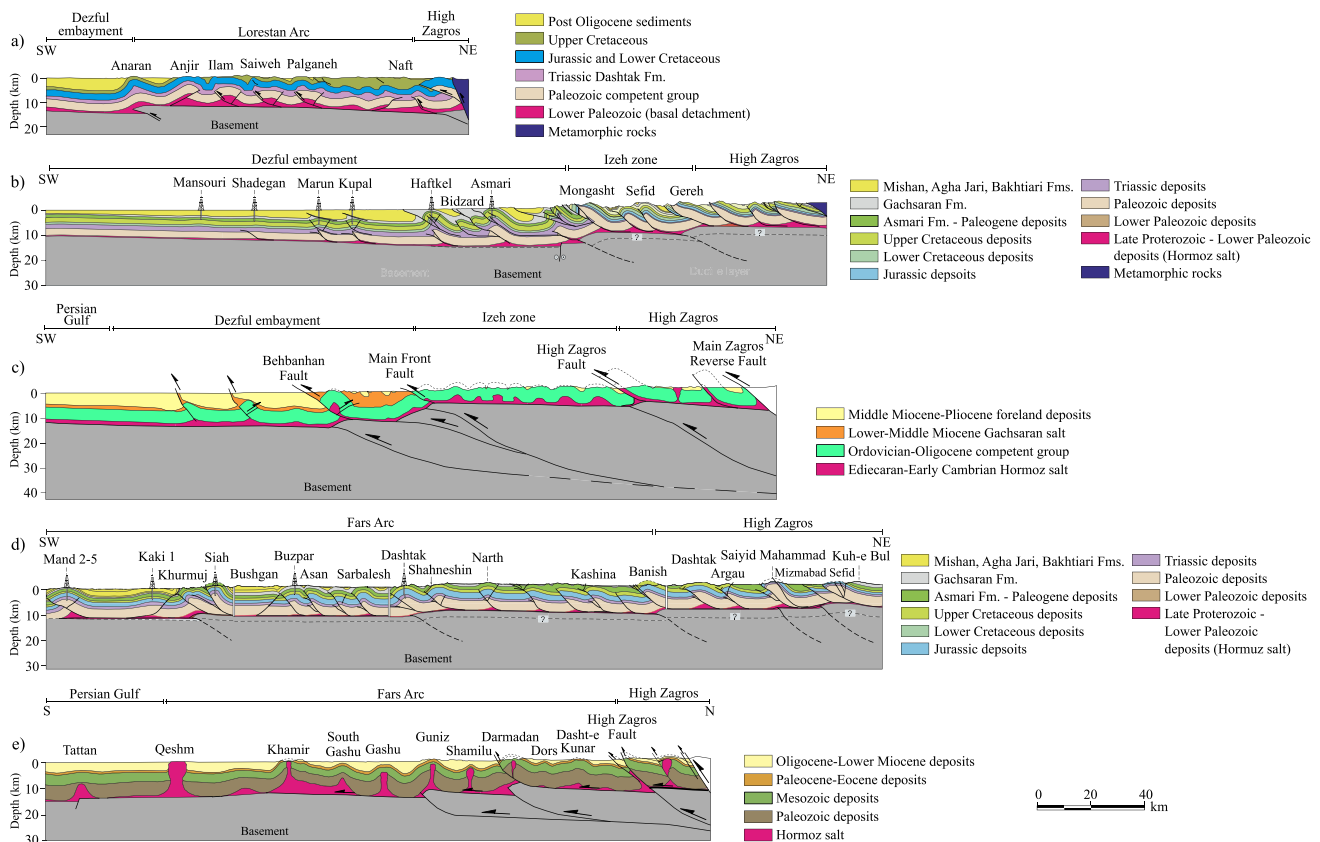
At present, the convergence trends N–S to NNE, with a velocity increasing eastwards from 16 mm/year at the northernmost portion of the Arabian promontory to 26 mm/year in eastern Iran (DeMets et al. 1990; Sella et al. 2002; Tatar et al. 2002; Bayer et al. 2003; Vernant et al. 2004; Walpersdorf et al. 2006; Palano et al. 2018; Zamani 2023; Fig. 1b). The shortening along the Zagros belt is estimated to be 30–85 km (Falcon 1974; Blanc et al. 2003; McQuarrie et al. 2003; Agard et al. 2005; Molinaro et al. 2005; Sherkati et al. 2006; Mouthereau et al. 2007; Jahani et al. 2009; Vergés et al. 2011a). A recent estimation of shortening based on the reconstruction of Moho geometries (Pirouz et al. 2017) gave ~30 km in the western sector and 75 km in the Fars (average value of  $45 \pm 13$  km) in good agreement

with the studies cited above. Active shortening rates from GPS change from 3 to 6 mm/year in the western portion to 6–10 mm/year in the eastern part (Hessami et al. 2006; Walpersdorf et al. 2006).

### 3 Tectonic setting

The ZFTB represents the active accretionary wedge of the Zagros collision zone (Beydoun et al. 1992; Alavi 1994, 2007; Berberian 1995; Mouthereau 2011; Nissen et al. 2011) and currently accommodates almost half of the present-day shortening between Arabia and Eurasia (Vernant et al. 2004). The northeastern limit of the ZFTB is marked by the Main Zagros Thrust, or Main Zagros Reverse Fault (MZRF), which represents the suture between Arabia and Eurasia (Fig. 3a). To the southwest of the MZRF, the belt is usually divided into two main tectonic domains whose boundaries and nomenclature change from one study to another: the High Zagros (HZ) and the Simply Folded Belt (SFB; also known as the Simply Folded Zone or just the Folded Belt; Fig. 3a).

The HZ is confined between the MZRF and the High Zagros Fault (HZF; Fig. 3a), which is currently seismically active along a few segments (Berberian 1995). This region is a narrow (80 km wide) NW–SE-trending thrust belt (average elevation of 1.5–2 km) characterised by several imbricated thrusts and by the exposure of Cambrian and Precambrian lithologies (Allen and Talebian 2011; Figs. 1b, 3a, 4). The HZ does not extend continuously along the Zagros orogen but is restricted to two distinct locations: the Western and Eastern High Zagros (Tavakoli-Shirazi et al. 2013; Fig. 3a). This discontinuity may arise from the original geometry of the Arabian plate margin or by differential erosion (Tavakoli-Shirazi et al. 2013). Thermochronology and structural data indicate that thrust activity in the area initiated between the Early and Late Miocene (Navabpour et al. 2007; Gaviillot et al. 2010), in agreement with palaeontological dates which fix the onset of syn-tectonic deposition at the Early Miocene (Fakhari et al. 2008). Several salt diapirs outcrop in the High Zagros zone, especially along the strike of the HZF (Taghikhani et al. 2024 and references therein; Fig. 1b), which, according to structural and stratigraphic observations, have been related to a long-term passive diapirism from Palaeozoic to Early Miocene (Taghikhani et al. 2024).



**Fig. 4** Regionally balanced cross sections across **a** Lorestan Arc (Farzipour Saein et al. 2009), **b, c** Dezful Embayment (from Pirouz et al. 2017 and Najafi and Lajmorak 2020, respectively), and **d, e** Fars Arc (from Pirouz et al. 2017 and Snidero et al. 2019, respectively)

The SFB extends 100–200 km from the HZF to the coast of the Persian Gulf and exposes Palaeozoic strata (Figs. 1b, 3a). The domain is characterised by the whaleback succession of folds whose deformation mechanism is still debated. In particular, two main processes are taken into consideration: the “detachment folding” along decollements within the sedimentary cover (mainly Hormoz and Gachsaran formations—see Sect. 5; Stocklin 1968; Falcon 1969; Colman-Sadd 1978; Jackson 1980; Sherkati and Letouzey 2004; Sephehr et al. 2006; Mouthereau et al. 2007; Casciello et al. 2009; Koyi and Mansurbeg 2021) and the “forced folding” where the growth of each anticline is associated to the activity of a buried blind thrust (Berberian 1995; McQuarrie 2004; Alavi 2007). Some studies explain the formation of folds as a combination of the two folding mechanisms (e.g., Sattarzadeh et al. 1999; Hessami et al. 2001; Blanc et al. 2003; Sephehr et al. 2006) or suggest a change in the folding mechanism through time (Molinaro et al. 2005; Sherkati and Letouzey 2004; Sherkati et al. 2005; Koshnaw et al. 2020). For example, footwall synclines, high-angle thrusts, limb rotation and reduction in anticlinal wavelength during fold evolution led Sherkati and Letouzey (2004) to hypothesise a transition from detachment folding to progressive fault propagation in central Zagros. In the SFB, the only major faults cutting the surface are in the western sector of the Fars Arc and consist of N–S-trending right-lateral faults (Kazerun, Karebas, Sabz Pushan, and Sarvestan faults; Nissen et al. 2011; Fig. 3a). According to GPS data the combined right-lateral slip-rate is 6 mm/year (Walpersdorf et al. 2006; Tavakoli et al. 2008), with ~4 mm/year accommodated by the Kazerun fault alone (Authemayou et al. 2009). These lateral fault zones accommodate the change in shortening between the western-central Zagros (NE–SW) and the eastern Zagros (roughly N–S; Talebian and Jackson 2004; Authemayou et al. 2005; Lacombe et al. 2006). At the surface, this shortening resulted in trains of anticlines and synclines (Figs. 1b, 3a).

The analysis of the patterns of crustal stresses indicates that deformation in the ZFTB can be associated with a dextral transpressional tectonic model where thrusting controls the MZRF and strike-slip system results in a transpressional tectonic regime (Palano et al. 2018; Zamani 2023). In addition, more than half of the crustal deformation in the northern Zagros occurs seismically, while in the southern Zagros, aseismic strain, probably related to the presence of the weak Hormoz Formation, dominates (Palano et al. 2018).

### 3.1 The Simply Folded Belt

The SFB can be further subdivided along-strike into three mountainous areas named Lorestan, Izeh and Fars and two low-elevated regions called Kirkuk and Dezful embayments (Figs. 1a, b, 3a). Each region differs from the other according to its structural style and sedimentary history

(Stocklin 1968; Falcon 1974; Berberian and King 1981; Motiei 1994; Fig. 4). Such a segmented geometry seems to reflect a different distribution of strain along the strike of the range (McQuarrie et al. 2003; Vernant et al. 2004) and the influence of inherited N–S faults within the Pan-African basement (Falcon 1974; Kent 1979; Furst 1990; McQuillan 1991; Moitei 1994; Berberian 1995; Hessami et al. 2001; Sherkati and Letouzey 2004; Sherkati et al. 2006), among which the pre-collisional basement structures of the Oman line (O’Brien 1957; Kadinski-Cade and Barazangi 1982; Molinaro et al. 2004; Talebian and Jackson 2004) and of the Kazerun fault (Sephehr and Cosgrove 2004; Authemayou et al. 2005, 2006) play a major role in accommodating the deformation (Fig. 3c).

The Kirkuk Embayment (KE) contains the southwestern limit of deformation in the Zagros and a large proportion of the hydrocarbon reserves in Iraq (Fig. 3a). It is characterised by a shift from a thin-skinned, basement-detached fold-thrust belt to a hybrid thin- and thick-skinned during Late Miocene with most of the anticlines resulted from the inversion of normal faults with a long history of episodic extension (Aqrabi et al. 2010; Kent 2010; Le Garzic et al. 2019; Koshnaw et al. 2020; Zebari et al. 2020). In addition, lateral changes in depositional facies deeply influenced the mechanical behaviour of the lithologies and the folding style (Le Garzic et al. 2019; Koshnaw et al. 2020). According to isopach maps, subsidence curves, and reconstructions of flexural profiles, Koshnaw et al. (2020, 2024) related the buildup of the orogen wedge in this sector to the combined effect of flexural and dynamic subsidence. The extraction of geomorphic indices in the region indicates different degrees of landscape maturity related to a non-conventional evolution (not proceeding from northeast to southwest) of the belt over time (Obaid and Allen 2017). In particular, the study evidences the presence of mature anticlines to the southwest (foreland) and less mature ones in the inner portion of the belt. The authors related this configuration to the activity of the NW–SE-trending basement faults, which promote out-of-sequence reactivation (Obaid and Allen 2017). Late Cenozoic horizontal shortening in the KE is small (5–25 km) with respect to the other zones (Obaid and Allen 2017; Koshnaw et al. 2020; Zebari et al. 2020).

The Lorestan domain (LA) extends between the HZF to the northeast and the ZMFF to the southwest (Fig. 3a) and shows several detachment horizons (Vergés et al. 2011a) uplifted above a basement thrust system (e.g., Emami et al. 2010; Vergés et al. 2011b, 2024). It is characterised by seventeen major *en echelons*, “whale-back” anticlines (Farzipour Saein et al. 2009; Fig. 4a). Palaeozoic rocks record shortening by tectonic wedging or fishtail low-angle thrusting, while Mesozoic lithologies are folded in anticlines at greater wavelength, followed by limb thrusting (Najafj et al. 2014; Fig. 4a). Moreover, as in the case of KE, differences in

lithology facies across the whole Lorestan province caused changes in anticlinal wavelength from north to south and facilitated forelimb thrusting (Casciello et al. 2009; Farzipour Saein et al. 2009; Vergés et al. 2011a, 2024; Davoidi et al. 2023; Figs. 1b, 4a).

The Dezful Embayment (DE) is a trapezoidal-shaped region bounded by the Bala Rud and Kazerun faults, respectively in the northwest and in the southeast (Alavi 1994; Berberian 1995; Sepehr and Cosgrove 2004; Allen and Talebian 2011; Fig. 3a). It is separated from the Izeh zone to the northeast by the Mountain Front Fault (ZMFF), a segmented master blind thrust (Berberian 1995; Fig. 3a). The structural style of the Dezful embayment has been controlled by the Miocene evaporites (Gachsaran Formation; see Sect. 5) and consists of disharmonic NW–SE-trending folds (O'Brien 1957; Sherkati et al. 2006; Carruba et al. 2006; Najafi et al. 2014; Tavakolian and Pash 2022; Tavakolian et al. 2022; Fig. 4b, c). The deeper structure of the anticlines is complicated by the same Gachsaran Formation which decouples the structure above and below their level (Sherkati and Letouzey 2004; Sherkati et al. 2005; Carruba et al. 2006; Derikvand et al. 2018; Yaghoubi et al. 2021; Tavakolian and Pash 2022; Tavakolian et al. 2022; Fig. 4b, c). A basal detachment horizon in the Lower Palaeozoic strata and several intermediate detachments between the basal and the upper ones are also suggested to affect the geometry of the folds (Sherkati et al. 2004, 2006; Abdollahi Fard et al. 2006; Derikvand et al. 2018). The region was flexed after the uplift of the ZFTB to the northeast of the ZMFF, and a post-Oligocene foredeep basin formed with an accumulation of more than 5000 m of Cenozoic strata, predominantly Miocene to Quaternary non-marine clastic deposits (Falcon 1974; Koop and Stoneley 1982; Motiei 1995; Berberian 1995; Bahroudi and Talbot 2003; Carruba et al. 2006; Sherkati et al. 2006; van Buchem et al. 2010; Allen and Talebian 2011; Saura et al. 2015; Pirouz et al. 2017). Surrounding areas present thinner successions over the same time interval, demonstrating that the embayment represented a depocenter and an indenter in the framework of the Arabia–Eurasia collision (Najafi et al. 2014; Malekzade et al. 2016; Kolahi-Azar and Gorliz 2018). In particular, the DE is considered the thickest part of the Mesopotamian foredeep basin. Its origin has been related to the pre-continental collision of the Arabian Plate margin and the irregular distribution of Cretaceous ophiolites upon it (Allen and Talebian 2011). The DE is one of the world's richest oil provinces, with 8% of global oil reserves in 60,000 km<sup>2</sup> (Bordenave and Hegre 2005).

The Izeh zone is located to the northeast of the Dezful embayment and shows a dramatic change in structural elevation and a more intense folding and thrusting (Sherkati and Letouzey 2004; Fig. 3a). It is comprised between the HZF to the northeast and the ZMFF to the southwest (Fig. 3a). This zone is subdivided into northern and southern

subzones (Sepehr et al. 2006). In the northern portion, the folds have box and chevron geometries formed above Albian and Eocene detachment horizons (Sherkati and Letouzey 2004; Sepehr et al. 2006). In the southern part, the folds have formed over deeper detachment (Triassic in age; Sepehr et al. 2006) and are larger than those in the northern portion (Sepehr et al. 2006; Fig. 4b, c). A structural section from IZ to DE indicates a drop in shortening from approximately 16% in IZ to 6% in DE, suggesting a shift of sedimentary depocenter to the southwest from Middle to Post Miocene (Sherkati and Letouzey 2004). This caused rapid subsidence in DE contemporary to the folding, uplift, and erosion in the inner portion of the belt (Sherkati and Letouzey 2004).

The Fars domain extends for ~700 km from the east of the Kazerun Fault to the eastern limit of the range (Bayer et al. 2003; Mouthereau et al. 2007; Fig. 3a). This region has been intensely exploited over the years, being the subject of the highest number of publications. It has an arc shape and represents the largest tectonic domain of the Zagros Belt, with ~280 km of width and ~65 km of total shortening (Najafi et al. 2020; Fig. 3a). The landscape is characterised by regular NW–SE- and W–E-trending concentric folds with homogenous wavelengths of ~15 km, composed of 10–12-km-thick pile of Phanerozoic sedimentary cover (Mouthereau et al. 2007; Figs. 1b, 3a, 4d, e). ~2 km salt-bearing evaporites of the Hormuz series (see Sect. 5), located at the base of the succession, decouples the deformation from the Precambrian crystalline basement (McQuarrie 2004; Sherkati et al. 2006; Alavi 2007; Mouthereau et al. 2007; Oveisi et al. 2009; Yamato et al. 2011; Yeats 2012; Najafi et al. 2014, 2020; Gurbuz and Saein 2018; Fig. 4d, e). For this reason, detachment folding is the main deformation mechanism (Mouthereau et al. 2006; Farzipour Saein et al. 2013; Najafi et al. 2020; Nabiei et al. 2021). In general, the structural style of the Fars domain was influenced by several factors (Motamedi and Gharabeigli 2019 and references therein): the variations in the thickness and distributions of the major tectonostratigraphic units across the Fars paleo-high (the northern prosequence of the Qatar Arc), the Hormoz salt tectonics, and the interaction between salt diapirism and tectonics associated with the Zagros orogen. It has been seen that the thickness of the Lower Palaeozoic succession on the eastern side of the structural high is 40–50% thicker than on the summit of the high (Motamedi et al. 2012). Such a variation, together with changes in the thickness of the Hormoz salt related to the underlying basement geometry, probably controlled differences in folding style in central Fars and justifies the larger crustal width of the folded structures in this region (Motamedi and Gharabeigli 2019). Moreover, analogue models indicate the importance of low-viscosity decollement and preexisting diapirs on the localisation, shape, size, and orientation of the folds (Callot et al. 2007, 2012; Ruh et al. 2017). A significant contribution



to the folding process was also provided by the activity of the basement reverse faults (Jackson and Fitch 1981; Berberian 1995; Talebian and Jackson 2004; Mouthereau et al. 2006, 2007; Homke et al. 2010; Leturmy et al. 2010; Teknik and Ghods 2017; Najafi et al. 2018; Karasözen et al. 2019). Paleomagnetic studies detected vertical axis rotations during the Late Cenozoic deformation (Bakhtari et al. 1998; Smith et al. 2005; Aubourg et al. 2008, 2010). These rotations are generally clockwise in the western part of the Fars Arc and counterclockwise to the east. Edey et al. (2020) attribute these structural patterns to deformation restricted at the Zagros/Makran transition zone and at the Kazerun Fault, which marks a pre-collisional basement structure within the Zagros (Talbot and Alavi 1996; Aubourg et al. 2010). Magnetostratigraphy data fix the beginning of folding in Fars at ~3.8 Ma, 10 Ma later with respect to the HZF area; this supports a progressive folding instead of a contemporaneous one in the SFB (Ruh et al. 2014). The shifting of the main frontal flexure from northeast to southwest in the Fars during the Late Miocene occurred with a rate of ~1 cm/a (Ruh et al. 2014) and determined changes from foredeep/wedge-top to foreland sedimentation toward southwest (Gharabeigli and McClay 2014). Based on these changes, the Fars Arc is further subdivided into interior Fars to the north and coastal Fars to the south (Stoecklin 1968; Falcon 1974; Berberian and King 1981; Alavi 1994).

Because of this peculiar geologic configuration, the Fars area is one of the main targets for gas exploration, containing 15% of the world's gas reserves (Bordenave and Hegre 2010; Motamedi et al. 2012).

## 4 Seismicity and main tectonic lineaments

The Zagros Fold and Thrust Belt is considered the most seismic sector of Iran (Sarkarinejad et al. 2017). Historical earthquake catalogues compiled by several authors through the years (Ambraseys and Melville 1982; Berberian 1994) and recent data (Bachmanov et al. 2004; Tatar et al. 2004; Hatzfeld et al. 2010; Nissen et al. 2011; Karazosen et al. 2019) indicate mainly reverse focal mechanisms with nodal planes dipping between 30° and 60° (Karazosen et al. 2019; Fig. 4), possibly due to the reactivation of normal basement faults inherited from the stretched passive margin of Arabia (Jackson 1980; Berberian 1995; Talebian and Jackson 2004). The focal depth seems to fall between 4 and 25 km, with a peak at 10–13 km, (Karasözen et al. 2019; Pilia et al. 2020; Fig. 3b), that is beneath the sedimentary cover and within the upper part of the basement (Tatar et al. 2004; Hatzfeld et al. 2010; Pilia et al. 2020; Fig. 3b). However, recent studies demonstrated that moderate earthquakes ( $M_w$  5–6) cluster around the major transverse faults, salt domes, and blind thrusts (Sahrei et al. 2023; Yang et al. 2023) involving

also the deposits above the Hormoz salt (e.g., Lohman and Simons 2005; Roustaei et al. 2010; Barnhart et al. 2013; Fig. 3b). In particular, Nissen et al. (2011) identify a marked cut-off in thrust seismicity at an elevation of 1250 m, below which the majority of thrust events occur, and distinguished two types of reverse fault earthquakes: (1) moderate events ( $M_w$  5–6), with focal depths of 5–10 km, produced above the Hormuz salt; and (2) large earthquakes ( $M_w > 6$ ), with focal depths > 10 km and ten-year return period (Sahraei et al. 2023), sourced from basement faults (Fig. 3b). Despite some studies (Jackson and McKenzie 1984; Ni and Barazangi 1986; Talebian and Jackson 2004; Hatzfeld et al. 2010) claim an apparent non-correlation between earthquakes with body wave magnitude ( $M_b$ ) higher than 5 and the main faults, there are several geoarchaeological evidences of the past and present activity of the main active tectonic lineaments which seem to refute this statement (i.e. Kazerun Fault; Tchalenko and Ambrayseys 1970; Berberian 1994; Berberian et al. 2014 and references therein).

In the Zagros, the faults can be classified according to their trend into (1) belt-parallel fault zones and (2) belt-oblique fault zones (Sepehr and Cosgrove 2007; Fig. 3a).

### 4.1 Belt-parallel fault zones

The belt-parallel fault zones consist of NW–SE trending reverse or thrust faults mainly identified by the present morphotectonics and seismicity of the belt (Berberian 1995). Their activity formed zones of uplift (between 1 and 5 km; Letouzey et al. 2002; Molinaro et al. 2004, 2005; Sherkati and Letouzey 2004; Mouthereau et al. 2007; Jahani et al. 2009; Leturmy et al. 2010; Fig. 3c) which gave the belt a typical stepped morphology, down stepping to the SW. The most important tectonic lineaments are the Main Recent (MRF), the High Zagros (HZF), the Mountain Front (ZMFF), and the Zagros Foredeep (or Frontal) faults (ZFF) (Fig. 3a).

The MRF is in the NW sector of the High Zagros and consists in an active NW–SE-trending right-lateral strike-slip fault generated by the oblique collision of the Arabian plate with Iranian micro-continent (Authemayou et al. 2006; Nissen et al. 2011; Mohajjel and Rasouli 2014; Dashti et al. 2020; Ghanbarian and Derakhshani 2022; Fig. 3a). According to some studies its active slip-rate ranges from 2–3 mm/year to 3.5–12.5 mm/year (Vernant et al. 2004; Walpersdorf et al. 2006; Authemayou et al. 2009), accommodating much of the right-lateral component of Arabia–Iran motion in NW Zagros (Talebian and Jackson 2002).

The HZF represents the boundary with the SFB and becomes blind in the region northeast of Shiraz where folding is gentle as well as in the SFB (Nissen et al. 2011; Fig. 3a). This fault is considered as a deep-seated and segmented fault system rooted in the basement and inverted

into a NW-trending reverse fault during the Zagros orogeny (Morris 1977; Berberian 1995; Bahroudi and Talbot 2003; Fig. 4c, e). Compared to the other thrusts, this fault presents the greatest stratigraphic displacement, placing Cambrian strata over Cretaceous or Tertiary rocks (Fig. 4c, e). The HZF also has a minor dextral strike-slip movement in addition to the thrust kinematics, according to the available field data and earthquake focal mechanisms (Berberian 1995; Talebian and Jackson 2002; Bachmanov et al. 2004; Sepehr and Cosgrove 2005; Molinaro et al. 2005; Authemayou et al. 2006; Yamini-Fard et al. 2006; Nissen et al. 2011). This kinematics is mainly due to the north-northeast oblique convergence between Arabia and Eurasia and the NW–SE orientation of the faults (Gavillot et al. 2010).

The ZMFF is located under a large and complex anti-form composed of different anticlines in which strata of various ages are present (Lashgari et al. 2020; Fig. 4c). From a topographic point of view, this line separates the inner highlands, where the deeper parts of the anticlines crop out, from the outer lowlands, where most structures are either hidden under Quaternary sediments or show only the youngest Neogene lithologies (Alavi 2007; Fig. 3a). According to Tavani et al. (2020) the ZMFF developed in front of a series of inverted Jurassic extensional faults. In particular, the sinusoidal shape of the ZMFF in the NW portion of the Zagros (Fig. 3a) is related to the original segmentation of the inverted Jurassic rift system. The throw of the tectonic lineament changes from 2 to 4 km in the Lorestan and Fars domains (Blanc et al. 2003; Molinaro et al. 2005; Emami et al. 2010) to ~6 km in the Dezful Embayment (Berberian 1995; Sherkati et al. 2006). Depositional ages of river terraces along the Greater Zab River (see Fig. 1a) and kinematic modelling of the fault-related fold belt provided an average slip rate of the ZMFF of  $\sim 1.46 \pm 0.6$  mm/year (Zebari et al. 2021).

The ZFF represents the boundary between the present alluvial basin of the Zagros and the SFB (Fig. 3a). It is marked by a relatively long linear fold alignment in Lorestan, Dezful, and Fars regions associated with thrust faults (Fig. 3a). Seismically, this front is not as active as the ZMFF (Talebian and Jackson 2004; Fig. 3b).

## 4.2 Belt-oblique fault zones

Belt-oblique fault zones are characterised by N–S to NNE–SSW and E–W tectonic lineaments (Fig. 3a). The formation of these fault zones occurred in the Palaeozoic, with a major pulse of activity during the Cretaceous (Sepehr and Cosgrove 2004; Sherkati and Letouzey 2004), and has been related to the presence of the Hormoz salt deposits at depth (Shams et al. 2020). The most important fault zones are the Bala Rud, Izeh, Kazerun, and Karebas ones, which coincide with areas of high seismicity and significant topographic

relief (Fig. 3a, b). Their activity caused the formation of paleo-highs and thickness/facies variations of the Cretaceous sediments in the Dezful Embayment and the Persian Gulf (Fig. 4b, c). Since the faults do not crosscut the anticlines, Sepehr and Cosgrove (2007) suggested that these tectonic lineaments were active simultaneously with the folding.

The Kazerun Fault Zone trends N–S and consists of four segments named, from north to south, Sisakht, Yasuj, Kamarij and Burazjan (Sepehr and Cosgrove 2005; Fig. 3a). Except for the Yasuj segment, all act as transfer faults or lateral ramps, linking the different segments of the Zagros deformation fronts (i.e. HZF and ZMFF). Its surface expression is represented by a transverse valley extending from the HZF to the Persian Gulf coast for about 300 km. The Kazerun Fault Zone is seismically active, with the most earthquakes occurring at the junction of this fault zone with the ZMFF (Authemayou et al. 2005; Sepehr and Cosgrove 2007; Tavakoli et al. 2008; Faghih and Nourbakhsh 2014; Eftekhari et al. 2021; Fig. 3b). The focal mechanisms suggest a strike-slip movement at a depth of 4–10 km (Baker et al. 1993; Maggi et al. 2000; Talebian and Jackson 2004; Authemayou et al. 2005; Yamini-Fard et al. 2006; Tavakoli et al. 2008; Berberian et al. 2014; Eftekhari et al. 2021). This indicates that most fault zones are within the sedimentary cover and not in the basement, which, in this part of the Zagros, is at 10 km of depth (Sepehr and Cosgrove 2005). Along the Kazerun Fault Zone, several Hormuz salt diapirs crop out (Fig. 1b). According to Aghanbati (2016), the Kazerun fault shifted to the west on the right side of the ZMFF by a strike-slip movement of 140–150 km with a vertical offset of 6 km (Fig. 3a).

The Izeh Fault Zone is another N–S-trending system that outcrops to the west of the Kazerun Fault (Motiei 1995; Sherkati and Letouzey 2004; Fig. 3a). Sepehr and Cosgrove (2007) interpreted this tectonic lineament as a lateral ramp linking two segments of the ZMFF. Stratigraphic evidence indicates that the Izeh and Kazerun faults were active during the Mid-Cretaceous up to the Tertiary (Motiei 1994).

The Bala Rud Fault Zone trends E–W and represents the northwestern limit of the Dezful Embayment (Fig. 3a). Pattinson and Takin (1971) estimated a vertical displacement of about 3–5 km with a downthrow to the south. The presence of *en echelon* folds above the fault zone indicates a left-lateral kinematics confirmed also by focal mechanisms (Talebian and Jackson 2004; Fig. 3a). Similar to the Izeh Fault Zone, the Bala Rud one acts as a lateral ramp linking two segments of the ZMFF. Its activity influenced the sedimentation from the Late Cretaceous to the Early Miocene (Pattinson and Takin 1971; Sepehr and Cosgrove 2004).

The Karebas Fault Zone, together with the minor Sabz Pushan and Sarvestan fault zones, trends NNW–SSE and outcrops to the east of the Kazerun Fault in the Fars region (Berberian 1995; Fig. 3a). The fault has a right-lateral

kinematics and terminates at the ZMFF. Even if it is comprised among the belt-oblique fault zones, it has no significant vertical displacement, and the anticlines do not terminate against it (Hassanpour et al. 2018).

## 5 Stratigraphy

In general, the thick sedimentary cover of the Zagros belt has a total thickness ranging between ~ 10 and ~ 14 km (e.g., Colman-Sadd 1978; Hatzfeld et al. 2003; Molinaro et al. 2005; Sherkati et al. 2005; Casciello et al. 2009), with a near continuous deposition since Late Precambrian (e.g., O'Brien 1957; James and Wynd 1965; Stoecklin 1968; Falcon 1969; Colman-Sadd 1978; Fig. 5).

O'Brien (1950) divided the stratigraphic column of the Dezful embayment into five parts: (1) basement group (Precambrian); (2) lower mobile group (Hormoz salt); (3) competent group (Cambrian to Lower Miocene); (4) upper mobile group (Miocene); (5) incompetent group (Lower Miocene to Plio-Pleistocene). However, this classification has been considered too general and recent researches have shown that subdivision of multiple mechano-stratigraphic levels may vary at different localities (Bahroudi and Koyi 2003; Sherkati and Letouzey 2004; Molinaro et al. 2005; Abdollahi Fard et al. 2006, 2011; Sepehr et al. 2006; Sherkati et al. 2006; Carruba et al. 2006; Farzipour-Saein et al. 2009; Jahani et al. 2009; Casciello et al. 2009; Vergés et al. 2011a, b; Motamedi et al. 2012; Najafi et al. 2014). The Late Precambrian–Cambrian Hormoz salt is the oldest exposed unit, even if seismic data from western Fars show the presence of pre-Hormoz sediments (Letouzey and Sherkati 2004; Jahani et al. 2009; Fig. 5). It never outcrops as a complete stratigraphic sequence, but it is brought to the surface in diapirs (e.g., O'Brien 1957; Kent 1979). High-resolution earthquake tomography in SW Iran allowed the Hormoz layer to be located at a depth of 8–12 km (Kianimehr et al. 2023). Two distinct scenarios have been proposed for the Hormoz salt diapirism in the Zagros. In the first one, the salt diapirism is attributed to the Miocene–Recent activity of pull-apart zones at extensional relays along the strike-slip faults or at the intersection between salt walls and the deformation fronts (Talbot and Alavi 1996; Hessami et al. 2001; Lacombe et al. 2006; Mouthereau et al. 2006; Yas-saghi 2006; Gavillot et al. 2010; Shams et al. 2020). In the second scenario, the Hormoz salt diapirs formed before the Zagros orogen (Jahani et al. 2007; 2009; 2017; Hassanpour et al. 2018; Najafi et al. 2018). In this scenario, the evacuation and inflation of the mobile Hormoz salt were initiated in the Palaeozoic times through a differential loading mechanism (e.g., Jahani et al. 2007; Perotti et al. 2016). The contractional deformation events since the Late Cretaceous (Pirouz et al. 2017; Koshnaw et al. 2019) later squeezed

these precursor Hormoz salt structures (Callot et al. 2012; Hassanpour et al. 2018; 2021; Snidero et al. 2019). The eastern Fars Arc and the High Zagros have the highest diapir density. Kent (1979) inferred an original thickness of Hormoz salt of at least 1 km, but it is unclear how much salt remains in place at depth.

During the Early Palaeozoic, shallow-marine and fluvial sandstone, siltstone, and shale were deposited on the Precambrian basement or the Hormoz Formation (Jahani et al. 2007; Fig. 5). Data from provenance studies indicate the Neoproterozoic crystalline basement and the related sedimentary cover of the Arabian-Nubian Shield as the most plausible sources of the Upper Palaeozoic strata of the Zagros Belt (Horton et al. 2008; Mohammadi et al. 2023). Epirogenic movements during Variscan orogeny caused a large sedimentary gap in the Silurian–Carboniferous period which drove a general emergence of the region (“Hercynian unconformity”; Jahani et al. 2007; Fig. 5). During Permian, a regional shallow marine transgression with coastal deposits at its base (Faraghan Formation) covered the whole area (Berberian and King 1981; Fig. 5).

The end of the Paleozoic and the beginning of the Mesozoic in the Zagros region were characterised by marine carbonate sedimentation (Setudehnia 1978; Koop and Stoneley 1982). In the Middle–Late Triassic, an evaporitic platform formed (Dashtak Formation; Murriss 1980; Fig. 5). At this time, the region was connected to the newly formed Neotethys Ocean as evidenced by the replacement of evaporites by dolomite in the northern tip of the basin (Setudehnia 1978; Szabo and Kheradpir 1978; Murriss 1980). Between Early Jurassic and Mid Cretaceous, vertical movements and flexure along major basement faults caused subsidence in the basin (Berberian and King 1981), proved by lateral change from platform sediments in the southeast to the basinal ones in the northwest (Setudehnia 1978; Fig. 5). During Early Coniacian–Late Santonian period, the compression phase began on the northeastern edge of the Arabian Plate (Ricou 1971; Falcon 1974) and consequently the Campanian–Maastrichtian sediments (deep water marls, shales, marly limestones, and turbidites) were deposited in front of the ophiolitic nappes (Fig. 5).

In the Cenozoic, the northeastern portion of Arabia was characterised by NW–SE-trending marine troughs, partially separated by ridges (Henson 1951; James and Wynd 1965; Koop and Stoneley 1982; Motiei 1994). A NW–SE-trending high, which later formed the High Zagros, separated these troughs from the Neotethys (Stoneley 1981). The stratigraphic column of this period starts with a Paleocene marine transgression, which caused the deposition of marls, shales and limestones (Pabdeh Formation; Fig. 5) along the main troughs (Hessami et al. 2001). At the same time, the dolomite of the Jahrom Formation sedimented mainly on shallow ridges until the end of Eocene (Fig. 5). The area

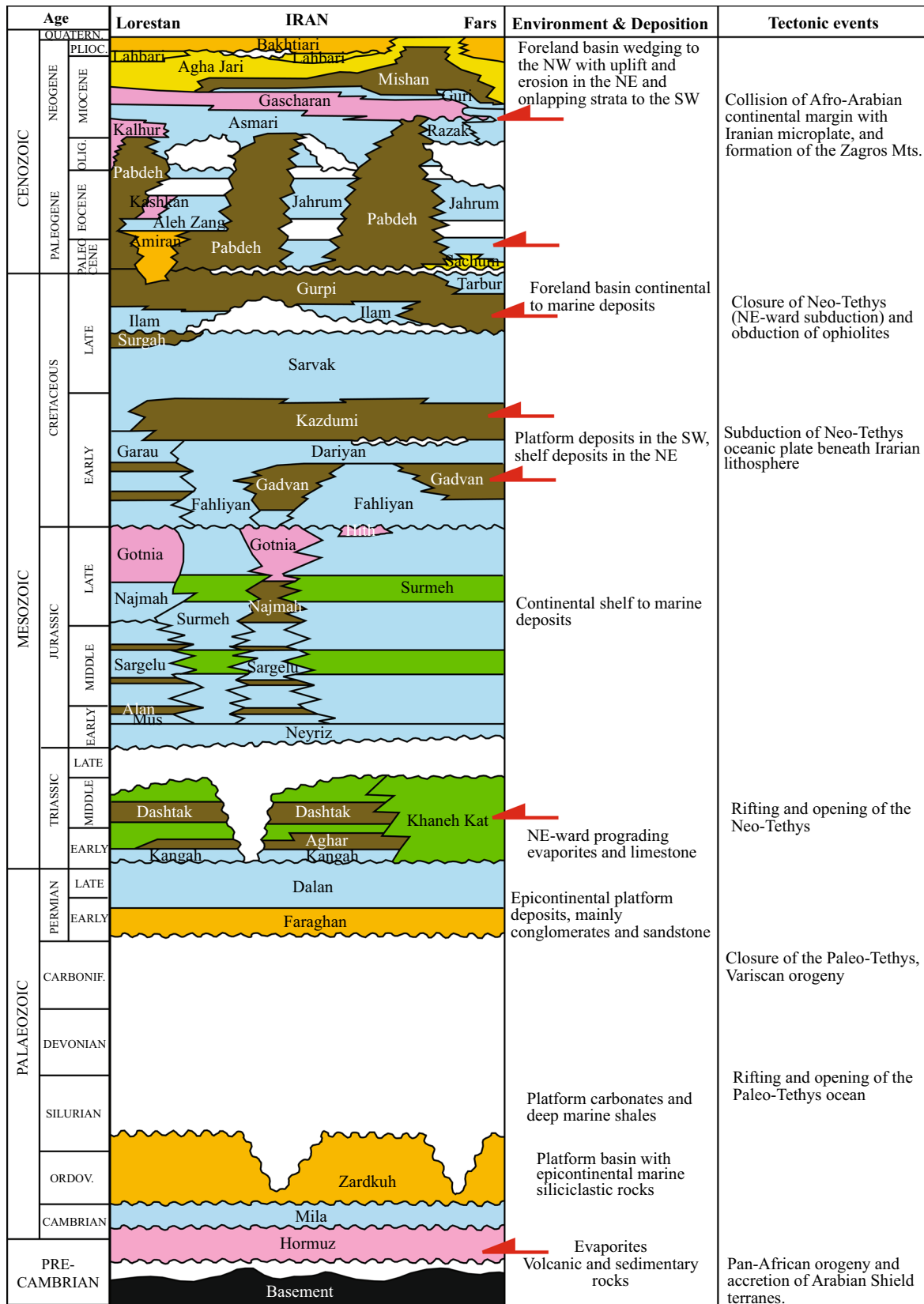


Fig. 5 Chronostratigraphic chart of the Zagros Fold and Thrust Belt. Potential decollement horizons are represented by red arrows (modified after Gines et al. 2019)

was then exposed to subaerial weathering by a regional regression (James and Wynd 1965; Mina et al. 1967; Koop and Stoneley 1982; Motiei 1994). Between the Eocene and Oligocene, clastic sediments accumulated to the SW of the Zagros (Mina et al. 1967; Motiei 1994). In the Early–Middle Miocene (Ehrenberg et al. 2007; Saura et al. 2011), a second marine transgressive cycle began with the deposition of shallow-marine limestone (Asmari Formation; Fig. 5) until Early Miocene (Hessami et al. 2001). Such formation unconformably overlies the older lithologies to the north (Homke et al. 2009) and becomes younger toward the foreland (James and Wynd 1965). These characteristics indicate a migration of basin depocenters with the propagation of thrust loading (Mouthereau et al. 2007) and a syn-collisional nature of the Asmari Formation (van Buchem et al. 2010). The subsequent regressive cycle began in the Early Miocene, depositing the Gachsaran, Razak, Mishan and Agha Jari formations (James and Wynd 1965; Fig. 5).

The overlying Bakhtyari Formation (Fig. 5) is composed of coarse conglomerates resulting from the uplifting range's initial erosion. It has been widely studied to understand the timing of continental collision (Nissen et al. 2011 and references therein). According to bio- and magneto-stratigraphic data, the age of the Bakhtyari Formation becomes younger and younger from northeast (High Zagros) to southwest (active foreland), passing from Oligocene to Plio-Pleistocene (Homke et al. 2004; Fakhari et al. 2008; Khadivi et al. 2010). This trend reflects the southwesternward propagation of the deformation front and foreland basin as confirmed by recent Sr isotope stratigraphy on 31 samples of marine macrofossils from the Neogene Mishan Formation (Pirouz et al. 2015). The results show a strong diachrony between western deposits (Dezful Embayment; ~ 17 Ma) and southeastern ones (Fars Arc; ~ 1 Ma). This means that the Zagros foreland basin migrated perpendicular to the orogen at rates ranging between 17.5 and 50 mm/year, much faster than the Alps, Pyrenees, Apennines and Himalayan foreland basins (Pirouz et al. 2015). The authors explain this rapid rate by the reactivation of major basement faults.

## 6 Topography

The Zagros belt is characterised by different topographic regions: to the east and northeast, the high-elevated low-relief Turkish-Iranian Plateau; to the west and southwest, the lowlands of the Zagros foreland (Mesopotamian basin), which includes the Euphrates and Tigris rivers, and the high relief areas of the Zagros Fold and Thrust Belt between the plateau and the foreland (Fig. 1a).

Gurbuz and Saein (2018) investigated the topographic configuration of the Zagros belt by dividing it into three morphotectonic subzones: Lorestan, Izeh and Fars (see

Figs. 1a, 3a). Hypsometric analysis and swath profiles show marked differences between subzones. In particular, the Lorestan and the southeastern Fars show stable landscapes, while the Izeh subzone and northern Fars present a youthful and unstable landscape (Gurbuz and Saein 2018). Moreover, despite the overall stability in the southeastern Fars, flattened S-shaped or more linear hypsometric curves speak to a still developing landscape (Willgoose and Hancock 1998). This is confirmed by the high amount of seismic activity and strain registered in southeastern Fars with respect to the Lorestan subzone, which is considered quiescent (Nissen et al. 2011; Fig. 3b). The hypsometric analysis also evidences the presence of tectonically active landscape features mainly in the middle part of the orogen (Gurbuz and Saein 2018). This is due to several transverse fault zones (i.e., Kazerun and Sabze Pushan faults; Fig. 3a), which probably act as transfer zones between the southern half of the Fars and Lorestan (Gurbuz and Saein 2018).

Balanced sections constructed across the entire width of the Zagros folded belt (between the Persian Gulf and the MZRF; McQuarrie 2004; Sherkati and Letouzey 2004) point out to a constant distance between two successive folds ( $\lambda = 20\text{--}25$  km) with the shape of folds outlined mainly by the geometry of the Asmari limestones (Fig. 4). However, despite the apparent continuity of structures, morphology, and surface geology, it is possible to recognise topographic steps along the landscape which indicate the presence of important structural features (Fig. 4). In Fars, for example, Mouthereau et al. (2006) evidenced the presence of two topographic steps coinciding with the ZMFF and the Surmeh Fault (Figs. 3a, 4). These tectonic lineaments are still active, as evidenced by the extensive seismotectonic analyses performed by Berberian (1995). The topographic step of the ZMFF is ~ 700 m high, while the one coinciding with the Surmeh Fault registers an offset of ~ 500 m (Mouthereau et al. 2006).

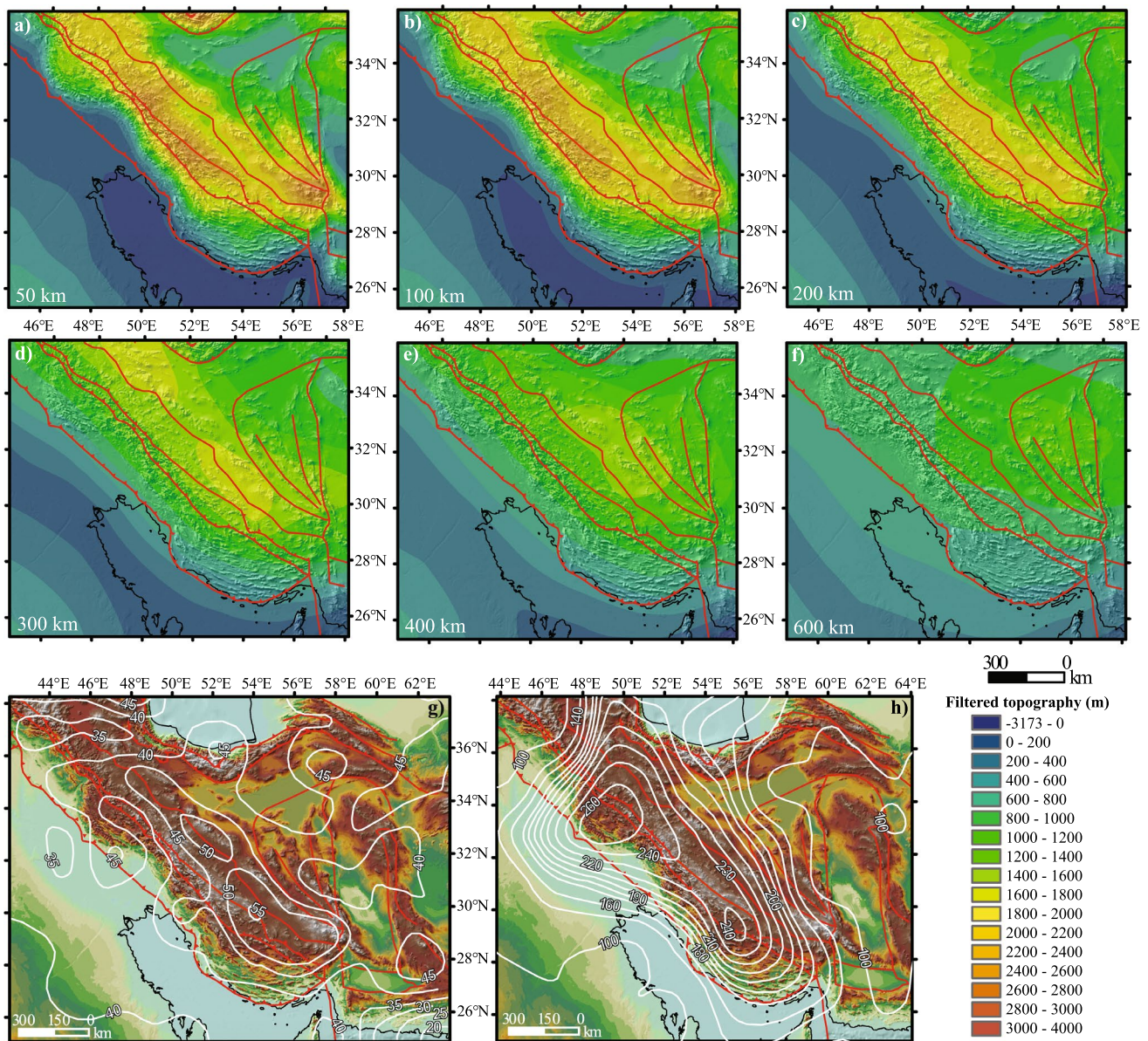
In general, the topographic configuration of most of the Zagros belt seems to be the result of the superimposition of a local short-wavelength signal (< 40 km) related to the periodic (almost sinusoidal) succession of folds on a larger scale signal (> 40 km) derived from differential uplift at the regional scale (Mouthereau et al. 2006). The same progressive decrease in elevation to the SE and the location of topographic steps seem to be strongly correlated to the activity of the transpressive strike-slip faults, which may have accommodated significant vertical offsets (Mouthereau et al. 2006).

Conversely, Leturmy et al. (2010) infer no correlation between basement uplift and topographic steps and associate the latter with the difference between mean elevations of valleys on both sides of the basement fault. For these reasons, the difference between the topographic steps and the basement uplift is the mean incision in valleys after the basement uplift. This mean incision systematically increases

northward, reflecting the forward propagation of basement faulting from north to south (Leturmy et al. 2010).

Beyond the possible influence of basement tectonics on the present topographic configuration of the Zagros, filtering of topography with a circular low-pass filter (see Molin et al. 2023 and references therein for methodology) at longer wavelengths than those used in Mouthereau et al. (2006) highlights how some components of the topography are related to crustal and subcrustal processes (Fig. 6). In particular, the filtered topography at 50 and 100 km (Fig. 6a, b) mimic quite well the configuration of the Moho (Amini

et al. 2012; Fig. 6g) where the highest values (50–56 km) are concentrated in a strip of land straddling the two major thrust faults. In the same way, the topographies resulted from filtering process at 200 and 300 km (Fig. 6c, d) seem to resemble the lithosphere configuration partially (Priestley et al. 2012; Fig. 6h). Conversely, the filtered topographies at 400 and 600 km (Fig. 6e, f) present a completely different configuration with the highest values (1600–1800 and 1400–1600 m respectively) shifted to the northeast of the major tectonic lineaments where crust and lithosphere are thinner (35–40 km and 100–180 km respectively; Fig. 6g,



**Fig. 6** a–f Topographic configurations of the study area obtained by filtering the topography with a low pass filter at wavelength 50, 100, 200, 300, 400, and 600 km. Solid red lines indicate the major tectonic lineaments; solid black lines represent the coastline. **g** Map of the

Moho depth with values in km (modified after Amini et al. 2012). **h** Map of the thickness of lithosphere with values in km (modified after Priestley et al. 2012)

h). Such a pattern seems to be correlated to negative P-wave velocity anomalies in the upper mantle (Shad Manaman et al. 2011; Koulakov 2011; Shomali et al. 2011; Amini et al. 2012; Koulakov et al. 2016; Talebi et al. 2020) that some studies interpret as being related to an upwelling of hot asthenospheric material (Koulakov et al. 2016; Talebi et al. 2020).

## 7 Drainage system

The drainage network of the Zagros can be divided into two main watersheds (Maghsoudi 2021): the Central Plateau and the Persian Gulf–Oman Sea watersheds (Fig. 1a). The Central Plateau basin contains most of the playas and desert areas and is characterised by rivers flowing into closed depressions and seasonal water bodies (Fig. 1a); the low annual precipitation makes most of the watercourses ephemeral. The Persian Gulf–Oman Sea watershed involves most of the Zagros belt and includes some of the longest rivers in Iran: the Tigris, Greater Zab, Lesser Zab, Karkheh, Karun rivers to the north, and the Mand and Kul rivers to the southeast (Figs. 1a, 7a). The northern rivers are part of the Tigris River network and drain the Kirkuk Embayment (Greater Zab and Lesser Zab rivers) and the Dezful Embayment (Karkheh and Karun rivers), while the southeastern ones (Mand and Kul rivers) pass through the Fars province to finally flow into the Persian Gulf (Figs. 1a, 7a).

In addition to these two main watersheds, there are three internally drained areas within the Fars region: Niriz, Shiraz, and a collection of smaller basins located between the Mand and the Kul drainage basins for a total area of ~ 10,000 km<sup>2</sup> (Mouthereau et al. 2007; Walker et al. 2011; Lee 2015; Fig. 7a, c). These regions may have formed because of fold growth (i.e. Walker et al. 2011).

In general, the river network in the Zagros is relatively young. It developed during the last few million years when the fold and thrust belt emerged from a marine environment and adapted to terrestrial conditions (Leturmy et al. 2010). This was a diachronic process advancing to the SW by shifting the deformation front and embedding foreland sediments (Hessami et al. 2001; Mouthereau et al. 2007; Koshnaw et al. 2017). The drainage divides between basins with outlets in the Persian Gulf and those developing northward coincides with the MZRF (Fig. 7a). This means that such a structure represented a topographic barrier for the river network development.

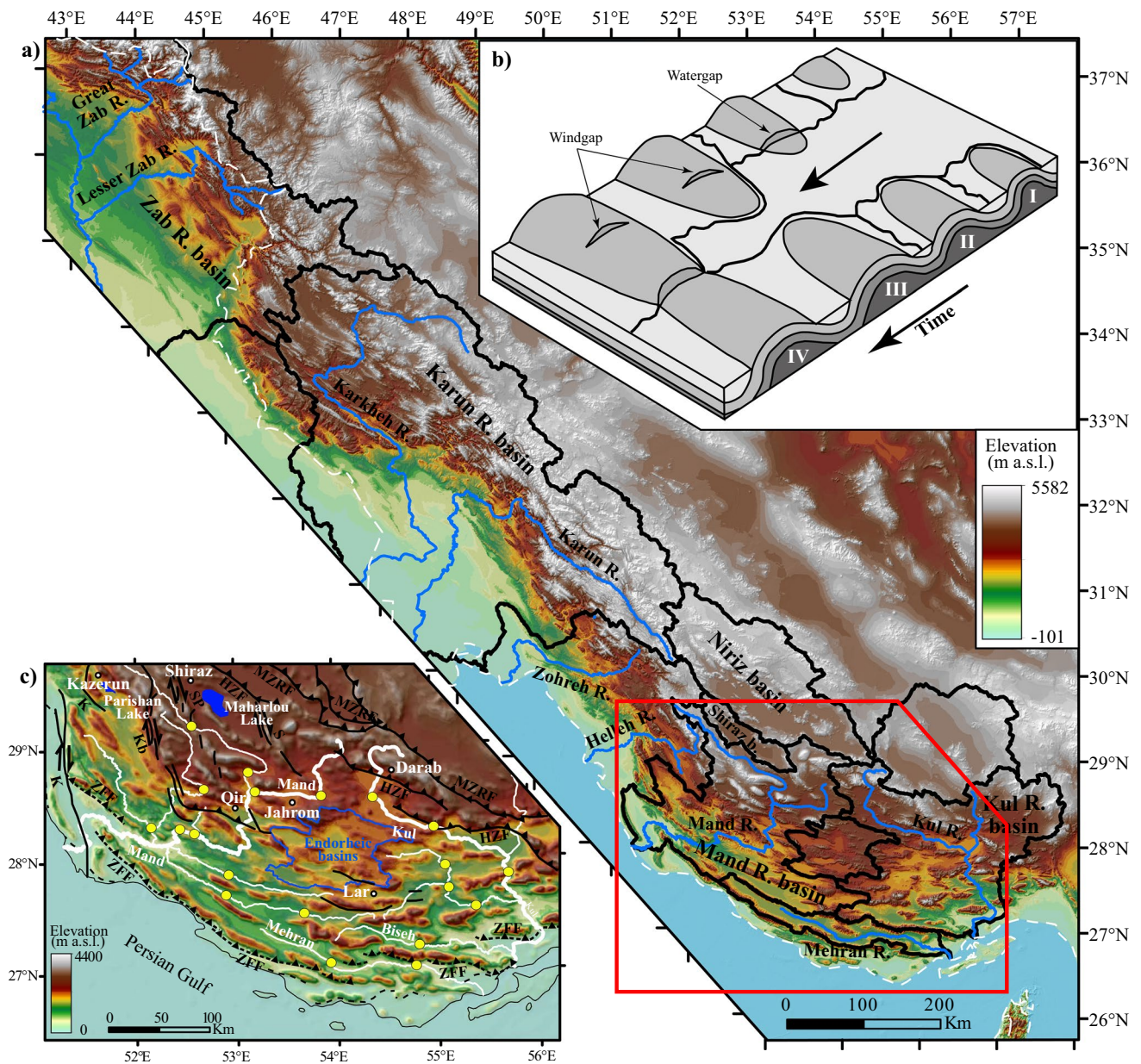
Generally, the rivers form a trellis pattern that is controlled by structural and lithological weaknesses (Fig. 7). The main rivers form long valleys that follow synclines, whereas small parallel tributaries flow from the slopes of the anticlines joining the main river segments at a sharp angle. This drainage configuration could correspond to a

newly formed network (Leturmy et al. 2010) or a pre-existing drainage deflected by the uplift and lateral propagation of anticlines (Mouthereau et al. 2007; Ramsey et al. 2008; Bretis et al. 2011). When rivers cross anticlines, they form water gaps (Fig. 7b). The development of a water gap can be related to the continuous incision of a river through a growing anticline or to an inactive anticline that is increasingly more exposed by erosion of younger rocks above it (Ramsey et al. 2008). Wind gaps, or dry water gaps, are remnant water gaps abandoned as the anticline grows or its exposure increases (Oberlander 1985; Burberry et al. 2008, 2010; Collignon et al. 2016; Fig. 7b).

The study of river-fold interaction in the Zagros has been dealt with by local studies without comparisons between different regions along the strike of the Zagros (e.g., Burberry et al. 2008, 2010; Ramsey et al. 2008; Bretis et al. 2011; Walker et al. 2011; Bahrami 2013, 2022; Zebari and Burberry 2015). The first attempt in this direction was made by Obaid and Allen (2019), who investigated the response of landscape to tectonics and climate using geomorphic indices. The results show a strong influence of seismogenic thrusting (occurring below 1250 m a.s.l. according to Nissen et al. 2011) on the trends of the principal geomorphic parameters. Clear differences have been evidenced between the northwestern Zagros and the Fars region: the northwestern Zagros shows both rivers crossing anticlines and rivers diverting or exploiting the relay zones between anticlines, while the Fars region is characterised by a general tendency of river deflection. The authors justify this discrepancy by the different climates of the two areas: wetter conditions and vigorous drainage systems in the northwestern Zagros retard orogenic plateau growth and make the rivers capable of incising the anticlines; drier climate and low power rivers in the Fars region promote plateau growth and river deflection.

Knickpoints are located over limestones, mostly where rivers cross relay zones between folds (Ramsey et al. 2008; Obaid 2018; Fig. 7c). According to Ramsey et al. (2008), this suggests that at these locations, rivers are being narrowed between two anticlines. Indeed, when a river does not have sufficient stream power to incise across, a propagating anticline is deflected away from its path. The river will join with any transverse drainage and flow through the topographic low between the two-fold noses. As uplift continues, the fold segments begin to merge. If the river does not have enough stream power to incise, it will flow parallel to the fold axes. However, the increase in drainage area related to the amalgamation of different river segments increases the stream power, making the river capable of balancing the tectonic uplift. In this case, the river will incise the anticline, forming a water gap (Fig. 7b).

Some authors (Ramsey et al. 2008; Walker et al. 2011; Gines et al. 2019) hypothesised that, before the exposure



**Fig. 7** a ETOPO1 topography of the Zagros Fold and Thrust Belt with the main drainage basins (solid black lines) and river network (solid blue lines). The red polygon indicates the location of c. **b** Possible evolutionary model of the river network according to Ramsey et al. 2008: (I) two folds propagate towards each other and two rivers start to be pinched between fold tips; (II) one of the two rivers is able to keep pace with uplift and carves a gorge at the nose of the fold;

(III) the river is defeated and diverted leaving behind a dry valley (windgap); (IV) the two rivers join together and cut a gorge between the merging fold tips. **c** ETOPO1 topography of the southeastern Zagros Mts. with rivers represented in white. Knickpoints (yellow circles) are from Ramsey et al. (2008) and Gines et al. (2019) (modified after Ramsey et al. 2008).

of the resistant Asmari-Jahrom limestones, southward-flowing rivers maintain their courses by downcutting through the soft Pliocene and Miocene sediments uplifted by folding. An example is the Mand River in Fars, which flows along reaches parallel and transverse to structure displaying several drainage diversions and gorges between two coalescing folds (Ramsey et al. 2008; Fig. 7c). Once

the resistant limestones were exposed, the river incision was no longer able to balance the tectonic uplift and the outlets were abandoned (Ramsey et al. 2008). On most of the Zagros anticlines, the soft sediments have been completely stripped away from the fold flanks, thus eradicating all evidence of early stages of growth (Gines et al. 2019).



An alternative explanation for the drainage evolution was suggested by Oberlander (1968, 1985), who hypothesised a strong influence of regional stratigraphy. In particular, the alternation of the hard Asmari limestone and the easily erodible Pabdeh–Gurpi marls determined the formation of a low-relief landscape and an ancestral drainage system. Such a drainage system was then superposed on the Mesozoic limestone, which was exhumed in the meanwhile by continued fold growth.

## 8 Alluvial fans

Another common characteristic of the Zagros landscape is the presence of huge alluvial fans. They consist of ‘depositional landforms that occur where confined stream channels emerge from mountain catchments into zones of reduced stream power’ (Harvey 2011). The size of these landforms depends mainly on the watershed area and the sediment characteristics (Maghsoudi 2021). In the Zagros, the values range from 0.2 to 10,000 km<sup>2</sup>, with the highest concentration registered in Fars (Maghsoudi 2021; Fig. 8). In many cases, the alluvial fans coalesce together to form typical *bajadas* (Fig. 8).

The formation processes of alluvial fans in Iran are debated. Despite it is widely recognised that the transition between tectonically active relief (providing voluminous sediments supply) and adjacent subsiding lowlands (allowing the stacking of thick fan successions) is the optimal tectono-geomorphic setting for fan development (Ventra and Clarke 2018 and references therein), it seems that the sensitive balance between aridity and humidity resulting from changes in the climate regime was able to influence the nature of fan sequences and how they interrelate to associated facies (Jones et al. 2014).

Few studies about alluvial fans in Iran have been carried out in the Zagros Belt. The only work focusing on the entire mountain range is from Allen et al. (2013). In particular, they found that in the active thrusting part of the SFB, anticlines may be characterised by discrete or merged (*bajadas*) alluvial fans on their flanks according to the geologic configuration (lithologic control). These fans are drained by a braided river network, which, in places, may incise the sediments. Conversely, the margins of the internally drained basins lack transverse alluvial fans for most of their length. Here, the axial rivers aggrade, filling the basin and burying the anticlines. This difference in alluvial fan configuration between endorheic and exoreic basins is interpreted as two distinct evolutionary steps of the Zagros landscape (Allen et al. 2013). The alluvial fans are prone to tilting, incision, and cannibalisation by active river channels in the exoreic basins, characterised by active folding and uplift. As thrust-related activity wears off, the basin is smoothed out

by erosion, driving the merging of the fans and, finally, the formation of wide valleys without axial fans on the flanks of the semi-buried anticlines.

Walstra et al. (2010) investigated the western side of the belt, characterised by a series of large alluvial fans extending into the Mesopotamian plains at the outlets of the major rivers (Beateman et al. 2004; Heyvaert 2007). Archaeological evidence coupled with geological data and satellite image analysis indicates that human intervention had an essential impact on the evolution of alluvial fans by influencing the natural avulsion processes and the development of the earlier fans (Walstra et al. 2010).

A strong interaction between active tectonics and alluvial fans has been evidenced in the northwesternmost sector of the ZFTB (Bahrami 2013). In particular, the study highlights that, in addition to the climate, active uplift along anticlines may have a long-term impact on the morphometric characteristics of alluvial fans.

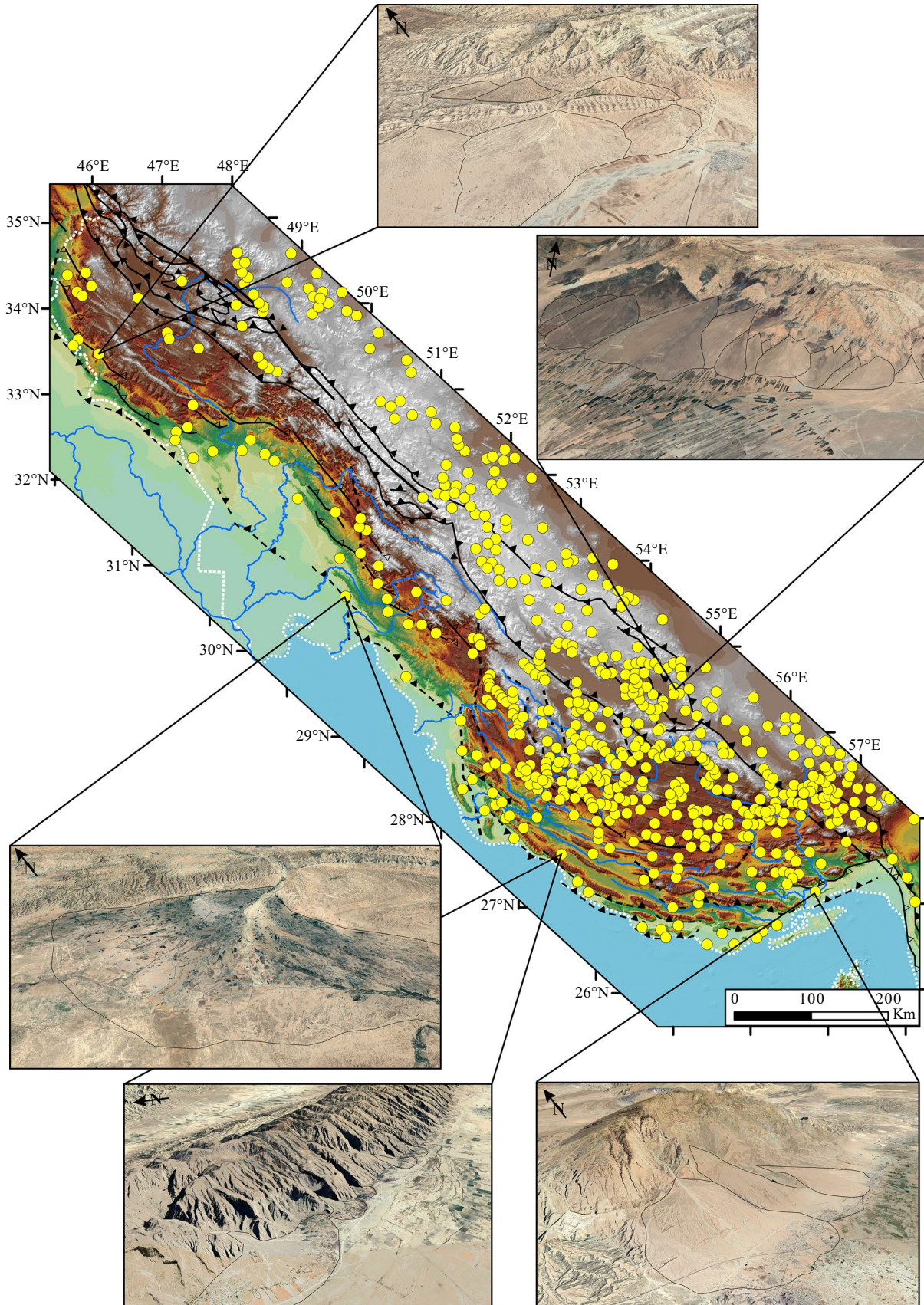
## 9 Summary and future perspectives

The Zagros Fold and Thrust Belt is the result of a long and complex history of tectonic convergence between the Arabian and Eurasian plates. The beginning of the compressional phase, based on the numerous studies on the geodynamics of the Zagros, ranges between the Late Cretaceous and Early Pliocene. Shortening in the Zagros belt varies from West to East between ~30 km and 75 km with an average value of  $45 \pm 13$  km. Similarly, the active shortening rates from GPS show an increase from 3 to 6 mm/year in the western portion to 6 to 10 mm/year in the eastern part.

Recent seismicity recorded in the area testifies that the deformation of the Zagros is still ongoing. The majority of earthquakes occurred at depths between 10 and 13 km, with focal mechanisms mainly related to reverse kinematics, capable of producing earthquakes with magnitudes higher than the Mw 5.

The Zagros belt is characterised by two tectonic domains separated by numerous tectonic lineaments. The High Zagros is a narrow NW–SE trending region close to the suture zone (Main Zagros Reverse Fault), characterised by imbricate thrusts and a long-term passive diapirism from Palaeozoic to Early Miocene along its northern boundary. The Simply Folded Belt, separated from the High Zagros by the High Zagros Fault, consists of a whaleback succession of folds formed by (1) “detachment folding” along décollements within the sedimentary succession or (2) “forced folding” linked to the activity of buried blind thrusts, or (3) a combination of detachment and forced folding.

The Simply Folded Belt is further divided into subdomains (from northwest to southeast: the Kirkuk Embayment, the Lorestan Arc, the Dezful Embayment, the Izeh Zone,



**Fig. 8** Map of the major alluvial fans (area from 0.2 to 10,000 km<sup>2</sup>) of the Zagros Fold and Thrust Belt (data from Maghsoudi 2021). The five images accompanying the map are from Google Earth

and the Fars Arc) that differ in both structural style and sedimentary history. The tectonic configuration of each region is characterised by the presence of thrusts and strike-slip faults, the most important of which are the Zagros Mountain Front Fault and the Zagros Foredeep Fault for the former and the Bala Rud, Izeh, Kazerun, Karebas, Sabz Pushan, Sarvestan faults for the latter. The strike-slip faults accommodate the shortening variation between the belt's western and eastern parts.

Another factor that heavily influences the tectonic style of the belt is diapirism. This phenomenon is related to different evaporitic horizons in the sedimentary succession, including the Late Precambrian–Cambrian Hormoz Fm, which turns out to be the most important in thickness (at least 1 km). Several studies demonstrate the importance of diapirs in the location, shape, size, and orientation of the Zagros folds. Two processes are suggested to explain diapirism in the Simply Folded Belt: (1) the recent activity of pull-apart zones at extensional relays along the strike-slip faults; (2) differential loading mechanisms prior to the Zagros orogen and later squeeze due to the orogenesis-related compression.

Despite the apparent continuity of structures, morphology, and surface geology, topographic steps have been recognised in the Zagros landscape. These features have been associated with the activity of blind thrusts at depth or with the difference between mean elevations of valleys on both sides of a basement fault.

In general, the topographic configuration of the Zagros can be defined as the result of low-wavelength processes (< 40 km), mostly related to crustal tectonics, and high-wavelength processes (> 40 km) related to subcrustal dynamics. In particular, long-wavelength topographic signals could be related to mantle dynamics.

The drainage pattern of the Zagros is strongly affected by differences in tectonic configuration and climate regime along the belt. In particular, clear differences have been highlighted between the northwest sector, where a wetter climate and a vigorous drainage system retard the orogenic plateau uplift and allow rivers to cut the anticlines, and the southeast, where an arid environment promotes orogenic plateau growth and river deflection. The general evolution of the Zagros river network has been explained by two models: (1) the existence of a paleo-drainage system that, flowing southwards, carved the soft Mio-Pliocene sediments and, once the resistant limestone was exhumed, deflected because no longer able to balance the tectonic uplift; (2) a strong influence of the alternation of the hard Miocene limestone and the soft Paleogene marls which determined the formation of a low-relief landscape and a paleo-drainage

system successively superposed on the exhumed Mesozoic limestone.

Alluvial fans in the Zagros belt are concentrated mainly in the Fars Arc since, in this arid region, most of the rainfall events are flash floods promoting the deposition of large amounts of material at the foot of the mountain fronts. Different patterns of fans in the endorheic basins, with the river's tendency to bury the anticlines and a general lack of transverse alluvial fans, and the exoreic basins characterised by discrete fans or bajadas, are dictated by the different tectonic settings. In the exoreic basins, where active folding and uplift occur, the fans are tilted, incised, and cannibalised by active river channels. In endorheic basins, by terminating the tectonic activity, the fans start to merge. When the basin is smoothed due to continuous erosion, the valleys are enlarged, and no axial fan is formed.

In summary, the interaction between surface and deep processes shaped the current topographic configuration of the Zagros Fold and Thrust Belt. The complexity of such an interaction has resulted in different or even opposite opinions, for example, about the precise onset of the collision between the Eurasian and Arabian plates, the deformation mechanism underlying the “whaleback” structure in the Simply Folded Belt, the evolution of the drainage network, and the formation and evolution of alluvial fans.

With this article, we provided a cognitive reference to thoroughly investigate the interaction between landscape, tectonics, and climate in shaping the present configuration of the Zagros Fold and Thrust Belt and summarise the possible answers to the main open questions.

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## Declarations

**Conflict of interest** On behalf of all authors, the corresponding author states that there is no conflict of interest.

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