UNIVERSITY
OF WOLLONGONG
AUSTRALIA

University of Wollongong
Research Online

Faculty of Science, Medicine and Health - Papers

Faculty of Science, Medicine and Health

2014

Jurassic to cenozoic tectonics of the zagros orogen in northwestern Iran

M Mohajjel

Tarbiat Modares University, mohajjel@uow.edu.au

C L. Fergusson

University of Wollongong, cferguss@uow.edu.au

Publication Details

Mohajjel, M. & Fergusson, C. L. (2014). Jurassic to cenozoic tectonics of the zagros orogen in northwestern Iran. *International Geology Review*, 56 (3), 263-287.

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library:
research-pubs@uow.edu.au

Jurassic to cenozoic tectonics of the zagros orogen in northwestern Iran

Abstract

The Zagros Mountains of Iran formed by continental collision from closure of the Neo-Tethyan Ocean. The Zagros Orogen underlying the mountain range reflects a much longer history with the Pan-African basement and Phanerozoic successions. New mapping, radiometric ages, and stratigraphic analyses have enabled advances in our understanding of the Jurassic to Cenozoic tectonic history. The northwestern Zagros Orogen consists of three belts: (1) the Zagros Fold and Thrust Belt, divided into the outer Zagros Simply Folded Belt and the inner High Zagros Belt; (2) the Zagros Suture Zone including radiolarite, ophiolite, and Bisotun limestone thrust sheets; and (3) the Sanandaj-Sirjan Zone, which contains abundant metamorphic rocks. Late Cretaceous ophiolites of the Kermanshah region are part of the outer ophiolite belt of the Zagros Orogen and have formed in passive margin and supra-subduction zone settings. Major events include early Mesozoic rifting, Jurassic subduction followed by a more cryptic interval of subduction in the Cretaceous, multiple ophiolite emplacement on the Arabian margin in the Late Cretaceous to Eocene, and collision of central Iran and the Arabian margin in the Oligocene with final closure of the shallow Tethyan seaway in the mid-Miocene. A Middle to Late Jurassic plutonic belt, the Qorveh-Aligodarz Plutonic Belt, formed a magmatic arc with subdued topography related to a moderately NE-dipping subduction zone under the Sanandaj-Sirjan Zone. An Early Cretaceous unconformity reflects limited uplift followed by widespread marine deposition with intercalated volcanic rocks in the Sanandaj region. Subduction continued with a low-lying arc that underwent trenchward advance. In the Late Cretaceous to Oligocene interval, the Neo-Tethyan Ocean closed with ophiolite obduction over the Arabian Peninsula margin and major shortening affected the Sanandaj-Sirjan Zone with uplift and plutonism. Much of the forearc of the Jurassic to Cretaceous arc system has been lost by tectonic erosion along a low-angle Eocene subduction zone prior to collision. Flattening of the subducting slab in the Late Cretaceous and Palaeogene explains the inland retreat of the arc to central Iran. Continental collision initiated in the Oligocene but the Tethyan seaway remained open until the mid-Miocene.

Keywords

northwestern, orogen, iran, zagros, jurassic, tectonics, cenozoic

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

Publication Details

Mohajjel, M. & Fergusson, C. L. (2014). Jurassic to cenozoic tectonics of the zagros orogen in northwestern Iran. *International Geology Review*, 56 (3), 263-287.

Jurassic to Cenozoic tectonics of the Zagros Orogen in northwestern Iran

M. Mohajjel^a and C. L. Fergusson^{b*}

^a*Department of Geology, Tarbiat Modares University, PO Box 14115-175, Tehran, Iran*

Telephone: +98-21-82883434

Fax: +98-21- 8809730

E-mail: mohajjel@Modares.ac.ir

Web Address:

http://www.modares.ac.ir/enpage/systems/index/Schools/sci/Academic_Staff/~mohajjel

^b*School of Earth & Environmental Sciences, University of Wollongong, Wollongong, New South Wales 2522, Australia*

*Corresponding author. Tel.: +61 242213860; fax: +61 242214250.

E-mail address: cferguss@uow.edu.au (C. Fergusson).

The Zagros Mountains of Iran formed by continental collision from closure of the Neo-Tethyan Ocean. The Zagros Orogen underlying the mountain range reflects a much longer history with the Pan-African basement and Phanerozoic successions. New mapping, radiometric ages and stratigraphic analyses have enabled advances in our understanding of the Jurassic to Cenozoic tectonic history. The northwestern Zagros Orogen consists of three belts: (1) the Zagros Fold and Thrust Belt, divided into the outer Zagros Simply Folded Belt and the inner High Zagros Belt, (2) the Zagros Suture Zone including radiolarite, ophiolite and Bisotun limestone thrust sheets, and (3) the Sanandaj–Sirjan Zone, which contains abundant metamorphic rocks. Late Cretaceous ophiolites of the Kermanshah region are part of the outer ophiolite belt of the Zagros Orogen and have formed in passive margin and supra-subduction zone settings. Major events include early Mesozoic rifting, Jurassic subduction followed by a more cryptic interval of subduction in the Cretaceous, multiple ophiolite emplacement on the Arabian margin in the Late Cretaceous to Eocene and collision of central Iran and the Arabian margin in the Oligocene with final closure of the shallow Tethyan seaway in the mid Miocene. A Middle to Late Jurassic plutonic belt, the Qorveh–Aligodarz Plutonic Belt, formed a magmatic arc with subdued topography related to a moderately NE-dipping subduction zone under the Sanandaj–Sirjan Zone. An Early Cretaceous unconformity reflects limited uplift followed by widespread marine deposition with intercalated volcanic rocks in the Sanandaj region. Subduction continued with a low-lying arc that underwent trenchward advance. In the Late Cretaceous to Oligocene interval, the Neo-Tethyan Ocean closed with ophiolite obduction over the Arabian Peninsula margin and major shortening affected the Sanandaj–Sirjan Zone with uplift and plutonism. Much of the forearc of the Jurassic to Cretaceous arc system has been lost by tectonic erosion along a low-angle Eocene subduction zone prior to collision. Flattening of the subducting slab in the Late Cretaceous and Paleogene explains the inland retreat of the arc to central Iran. Continental collision initiated in the Oligocene but the Tethyan seaway remained open until the mid-Miocene.

Keywords: continental collision, Northwestern Iran, Sanandaj–Sirjan Zone, subduction, Zagros Orogen

Introduction

The Zagros Mountains are part of the Alpine–Himalayan belt and formed from continental collision by closure of the Neo-Tethys. Collision is ongoing with the Arabian and Eurasian plates converging at $\sim 22 \text{ mm yr}^{-1}$ in a nearly northerly direction (Agard *et al.* 2011). To the NW, the Iranian collision zone merges into a complex pattern of former oceanic domains and continental blocks that presently occur in Anatolia (Robertson *et al.* 2012). To the east, the Zagros Mountains have a narrow transition into the convergent margin along the Makran (Regard *et al.* 2010). Much farther NE, the Indian–Eurasian collision zone displays a more advanced stage of development as shown by the widespread involvement of basement in thrust slices in the collision zone and formation of the Tibetan Plateau (Hatzfeld and Molnar 2010; Yin 2010).

The Zagros Orogen underlies the Zagros Mountains and consists of Pan–African metamorphic basement overlain by a thick Phanerozoic succession along with remnants from Neo-Tethys (Berberian and King 1981; Alavi 1994, 2004, 2007; Hassanzadeh *et al.* 2008). In this account, the Zagros Orogen is subdivided into the Zagros Fold and Thrust Belt, the Zagros Suture Zone that includes the Main Zagros Thrust, and the Sanandaj–Sirjan Zone, and the Late Cretaceous ophiolite belt (Figure 1). The Zagros Fold and Thrust Belt is subdivided into the inner High Zagros Belt (or imbricate thrust belt) and the outer Zagros Simply Folded Belt. Widespread metamorphic rocks are characteristic of the Sanandaj–Sirjan Zone, but very low-grade to weakly metamorphosed rocks and sedimentary rocks are also common (Mohajjel *et al.* 2003). The Sanandaj–Sirjan Zone is also known as the Sanandaj–Sirjan metamorphic belt (Sarkarinejad and Azizi 2008) although we prefer the former term because many rock units display minimal metamorphism. Development of the Zagros Orogen in the Cenozoic is closely related to the southwestern margin of the central Iran block including the Urumieh–Dokhtar Magmatic Arc.

Since our earlier review (Mohajjel *et al.* 2003), many advances in the understanding of the NW Zagros Orogen have occurred. Abundant new radiometric ages and geochemical analyses have been published on igneous rocks in the Sanandaj–Sirjan Zone and indicate a mid to Late Jurassic (150–175 Ma) timing for intrusions of subduction-related affinity (Ahmadi Khalaji *et al.* 2007; Shahbazi *et al.* 2010; Mahmoudi *et al.* 2011). These intrusions were previously regarded as Late Cretaceous to Paleogene. The timing and magmatic affinities of the Cretaceous and younger igneous rocks have also been clarified especially for the northwestern part of the Zagros Orogen around Sanandaj (Jahangiri 2007; Azizi and Jahangiri 2008; Azizi and Moinevaziri 2009; Azizi *et al.* 2011a; Omrani *et al.* 2008). Robust radiometric ages are beginning to be reported for Late Cretaceous ophiolites (Shafaii Moghadem *et al.* 2013) and we have learned much about the tectonic setting of Late Cretaceous ophiolites from their geochemical compositions. Stratigraphic data and radiometric ages from the Lurestan Arc of the Zagros Fold and Thrust Belt have also more closely bracketed ophiolite emplacement in the NW Zagros Orogen as well as placing tighter constraints on the Cenozoic uplift history (Homke *et al.* 2009, 2010; Saura *et al.* 2011).

Over the last 20 years, many 1:100,000 and regional-scale maps have been published covering all or part of the Zagros Orogen by the Geological Survey of Iran and a summary geological map of all of Iran is given by Sahandi and Soheili (2005). Additionally, publications in Farsi contain data on the structure of the High Zagros Belt and Sanandaj–Sirjan Zone but are usually not accessed by an international readership (Moinevaziri *et al.* 2009; Sadr *et al.* 2010; Elyaszadeh and Mohajjel 2011; Mohajjel and Biralvand 2011). Dextral transpression has been documented as common in the development of the Sanandaj–

Sirjan Zone (Mohajjel and Fergusson 2000; Sarkarinejad 2007; Sarkarinejad and Azizi 2008; Sarkarinejad *et al.* 2008, 2009). Seismic receiver function analysis has provided data on the deep crust under the Zagros Mountains and it has been inferred that Arabian crust has underthrust central Iran (Paul *et al.* 2010). These seismic results in addition to constraints from seismic tomography have formed the basis for several crustal-scale cross sections for the northwestern Zagros Orogen (Agard *et al.* 2011; Vergés *et al.* 2011).

In the last decade, and especially in the last several years, much data and detailed analyses have been published on the Cenozoic tectonic development of the Zagros collision zone (Alavi 2004, 2007; Vernant *et al.* 2004; Agard *et al.* 2005, 2011; Authemayou *et al.* 2006; Hatzfeld *et al.* 2010; Hatzfeld and Molnar 2010; Nemati and Yassaghi 2010; Wrobel-Daveau *et al.* 2010; Mouthereau 2011; Vergés *et al.* 2011; Mouthereau *et al.* 2012; McQuarrie and van Hinsbergen 2013). Syntheses by Agard *et al.* (2011) and Mouthereau *et al.* (2012) concentrated on Late Cretaceous to Cenozoic development reviewing constraints on the stratigraphic and deformation history and examining the geodynamics of the system in regard to slab break-off and crustal thickening during collision.

We have several aims in presenting this review. Firstly, we present an updated account of structure of the Sanandaj–Sirjan Zone, Zagros Suture Zone, and the High Zagros Belt of the Zagros Fold and Thrust Zone in northwestern Iran between Kermanshah and Shahrekord (Figure 2). We only briefly address the Late Cretaceous ophiolites of Zagros, which have recently been reviewed by Shafaii Moghadam and Stern (2011). Aspects of the stratigraphy and chronological data relevant to structure and tectonic history are included but readers are referred to original sources for lithological and stratigraphic detail. Secondly, a revised tectonic history for the Jurassic to Paleogene is presented with an emphasis on the nature of the magmatic arcs, associated deformation and their related subduction zones. Thirdly, we also briefly discuss the timing of continental collision in the Zagros using constraints from within the NW Zagros Orogen. As for the age of collision in the Himalayan Orogen (Aitchison *et al.* 2007), timing of the Arabian–Iranian continental collision has also been difficult to establish with estimates ranging from the Late Cretaceous (Alavi 2004, 2007) to the Late Miocene (McQuarrie *et al.* 2003).

Rock units and structure of the collision zone in the northwestern Zagros of Iran

Zagros Simply Folded Belt

The structure of this belt is only briefly treated here as it has been dealt with in numerous publications (e.g. Molinaro *et al.* 2005; Sherkati *et al.* 2005, 2006; Sepehr and Cosgrove 2004; Sepehr *et al.* 2006; Alavi, 2007; Casciello *et al.* 2009; Farzipour-Saein *et al.* 2009a, b). It is dominated by elongate anticlines and synclines along with associated thrust and reverse faults. In the northwestern Zagros, the Mesozoic to mid Cenozoic history of convergence and ophiolite emplacement is well documented from the Amiran and Kashkan formations that represent foreland basin deposits overlying the Arabian passive margin succession (Farzipour-Saein *et al.* 2009a; Homke *et al.* 2009). Both units are characterised by ophiolitic and radiolarite detritus and are diachronous spanning the Campanian to Early Eocene interval with accompanying regional tilting, erosion and growth folding (Hessami *et al.* 2001; Saura *et al.* 2011). Ophiolite emplacement and accompanying deformation along the Arabian margin in the northwestern Zagros Mountains has therefore lasted >30 Ma prior to continental collision. Deformation has migrated from the High Zagros Belt to the SW across the Zagros Simply Folded Belt from the Late Cretaceous to Pliocene (Alavi 1994; Hessami *et al.* 2001; Saura *et al.* 2011).

High Zagros Belt

The High Zagros Belt consists of an imbricate fault system that varies from a more deeply eroded level exposing Paleozoic rocks around Shahrekord adjacent to the Dezful Embayment to less deeply eroded mainly Mesozoic rocks around Kermanshah in the Lurestan Arc (also known as the Pusht-e Kuh Arc). It is the more deformed, inner part of the Zagros Fold and Thrust Belt. Note that in some papers the High Zagros Belt is equated with thrust sheets of radiolarites and Bisotun limestones which we regard as part of the Zagros Suture Zone rather than being part of the proximal Arabian margin.

In the Shahrekord region, the High Zagros Belt has a NE-dipping imbricate stack of early Paleozoic to early Cenozoic rocks locally intruded by Cambrian Hormoz Salt plugs (Figures 3 and 4) (Nemati and Yassaghi 2010). These authors also pointed out that the structure is typical of the internal part of an orogen with a duplex style controlled by detachment along the Hormoz Salt. From the minimum undeformed length of the Mesozoic–Paleozoic contact shown in Figure 4, between the SW end of the cross section and the Main Zagros Thrust, and using the formula for shortening (s) (modified from Marshak and Mitra 1988, p. 325):

$$s = \frac{[l_i - l_d]}{l_i} \times 100\%$$

l_i = initial length, l_d = deformed length, we calculated a minimum shortening of 37% for the High Zagros Belt and part of the adjoining Zagros Simply Folded Belt. The Bakhtiari Formation to the south of Shahrekord (Figure 3) has two units separated by an angular unconformity; the unit above the unconformity consists of Early Miocene conglomerate and shallow marine rocks and the unit below the unconformity is Oligocene(?) conglomerate (Fakhari *et al.* 2008). The age of thrusting in this part of the High Zagros Belt is further constrained by apatite (U–Th)/He thermochronometry that shows most cooling in the High Zagros Belt as Early Miocene with deformation continuing into the Late Miocene (Gavillot *et al.* 2010).

SW of Azna, the High Zagros Belt contains weakly deformed conglomerate of the Bakhtiari Formation that extends 50 km parallel to regional strike (Figure 5). These synorogenic deposits mostly formed during Pliocene deformation. Several footwall synclines occur below NE-dipping thrusts and are interpreted as fault-propagation folds (Sadr *et al.* 2010, in Farsi) (Figure 6). NW of Dorud, the High Zagros Belt is covered by a large thrust sheet of Bisotun limestone (the Kuh-e Farangui tectonic unit of Homke *et al.* 2010) and some Mesozoic volcanic rocks (Figure 2) (Mohajjel *et al.* 2003). The structure of this thrust sheet is poorly known as it has only been mapped at 1:250,000 and 1:100,000 scales. Its map distribution indicates a minimum horizontal thrust displacement to the WSW of 40 km assuming that it has been derived from the Zagros Suture Zone and has overridden the radiolarites (Figure 5). It predates the upper part of the Bakhtiari conglomerates generally considered Pliocene (Homke *et al.* 2010, p. 663).

The High Zagros Belt, 30–40 km SE of Kermanshah (Figure 7), has a 2000 m thick Cretaceous to Eocene succession of competent cliff-forming limestone interbedded with shale and clastic rocks of the Sarvak, Ilam, Gurpi, Amiran and Kashkan formations. These rock units are strongly folded about ENE trending axes. Detailed cross sections based on mapping of excellent exposures are given by Elyaszadeh and Mohajjel (2011, in Farsi) and are redrawn and reinterpreted in Figure 8. Overturned folds are associated with NE-dipping imbricate thrust faults and are typical of fault-propagation folds. From the method of Marshak and Mitra (1988, p. 324–325), wavelengths (<2–5 km) of the fold train have been used to determine the depth to décollement at 2–3 km below the surface within the Garau Formation below the Sarvak Formation (Figure 8). To the SW, Casciello *et al.* (2009) have

shown that décollements occur at several stratigraphic horizons (see also Farzipour-Saein *et al.* 2009b), including in weak shale and marl of the Garau Formation. In one area in the cross section (Figure 8), 4 km SW of the Kuh-e Sefid Fault, a small-scale imbricate thrust system soles into a décollement developed along the base of the upper Sarvak Formation; thus décollements occur locally at two levels. Shortening of 33% has been calculated for the cross section in Figure 8 based on the minimum undeformed length of a competent limestone in the upper Sarvak Formation (Sv(u)) between the thrust fault labelled A and the Kuh-e Sefid Fault (see shortening formula given above). As expected this shortening is much greater than in the adjoining Zagros Simply Folded Belt where shortening ranges 11.5 to 17.5% (Vergés *et al.* 2011). The timing of deformation in this part of the High Zagros Belt is poorly constrained. Farther to the SE near Khorramabad (Figure 2), the Cehel Taghi Syncline shows syndepositional growth with development of a syncline with a steeply NE-dipping limb during the Campanian to Maastrichtian (Saura *et al.* 2011).

The Kuh-e Sefid Fault forms a 200 m wide zone exposed in a new highway cutting south of Kermanshah and consists of fault breccia with blocks of limestone, shale and thin-bedded folded radiolarian chert. Shear fabrics in the fault zone indicate an overall dip of 50°NE and down-dip striations indicate up-dip slip. The dip of the fault is steeper than most faults in the radiolarites to the NE and the High Zagros Belt to the SW (Figure 9). It is therefore possible that the Kuh-e Sefid Fault is an out-of-sequence reverse fault similar to those of the Zagros Simply Folded Belt (Molinaro *et al.* 2005; Vergés *et al.* 2011) and cuts across the thin-skinned structures.

Zagros Suture Zone

The Zagros Suture Zone includes radiolarites, Bisotun limestones and ophiolites that are widely exposed in the Kermanshah region (Figures 7 and 10) as described by Braud (1987) and Saccani *et al.* (2013). Radiolarites form a major belt NE of the Kuh-e Sefid Fault (Figure 7) and are dominated by thin-bedded radiolarian chert and shale but also include beds of pelagic limestone, limestone nodules and blocks of limestone. Prominent limestone horizons have been mapped NE of the Kuh-e Sefid Fault and also 10 km west of Harsin (Bavandpur and Hajihoseini 1999). The stratigraphy and structure of the radiolarite succession has been examined in detail 30 km ESE of Kermanshah (Figure 7) where detailed sampling and radiolarian biostratigraphy was undertaken along numerous sections by Gharib and De Wever (2010). They documented a 250–300 m thick succession of shale and radiolarite overlain by massive limestone with an age span of Early Jurassic to early Late Cretaceous (early Pliensbachian to Turonian) whereas previously, these limestone horizons were considered Triassic (Bavandpur and Hajihoseini 1999).

Tight folds associated with thrust faults abound in the detailed sections (Figure 11) sampled by Gharib and De Wever (2010) as has been documented by Mohajjel and Biralvand (2011, in Farsi). The thin-bedded nature of the succession has promoted chevron folding and formation of fault accommodation structures in fold hinges as illustrated by the model of Ramsay and Huber (1987, p. 423). The folds are SW-verging with overturned limbs cut by thrust faults indicative of fault-propagation structures although at much smaller scales than in the High Zagros Belt to the SW (see above). It is clear from stratigraphic duplications shown by Gharib and De Wever (2010) that the succession has been repeated in numerous thrust slices across the belt (Figure 11). The abundant mesoscopic folds, common chevron fold style, the thinly bedded nature of the succession, and closely spaced faults are consistent with greater shortening than encountered in the High Zagros Belt. For example, Ramsay and Huber (1987, p. 423) indicated shortening in excess of 50% for chevron folding in rocks with

a bed thickness to limb length ratio of <0.01 where fold interlimb angles are $<60^\circ$ (i.e. comparable to interlimb angles in the cross sections shown in Figure 11).

North and NE of Kermanshah, the mountainous terrain is formed by thick Bisotun limestones of Late Triassic to Middle–Late Cretaceous age (Braud 1978). Structural trends change from northwesterly to the NW of Kermanshah to an ENE trend north of the Bisotun Fault, which truncates the underlying NW-trending radiolarites over at least 20 km (Figure 7). The radiolarites trend to the NW from Kermanshah for over 100 km and are structurally overlain to the NE by the Bisotun limestones and the ophiolites in a SW-verging imbricate thrust stack (Figure 2). The radiolarites are considered to have been deposited in a deep basin along the Arabian passive margin with the Bisotun limestones formed in an outer shallow continental platform on the margin of Neo-Tethys represented by the ophiolites (Kazmin *et al.* 1986).

North of Kermanshah around Kamyaran, the extent of the Late Cretaceous and Eocene assemblages is unclear with different map distributions of similar units given by Sadeghian and Delavari (2007), Shafaii Moghadam and Stern (2011) and Azizi *et al.* (2011a). Inferred Late Cretaceous ophiolites consist of crustal and mantle tectonites with interfingering island arc tholeiites, calc-alkaline lavas and abundant sheeted dyke complexes including common late-stage felsic rocks (Shafaii Moghadam and Stern 2011). West of Kamyaran, basalt mixed with Eocene sedimentary rocks has a U–Pb zircon age of 55 ± 2 Ma and is considered part of a supra-subduction zone ophiolite (Azizi *et al.* 2011a). These ophiolitic mélanges are the highest thrust sheets exposed below the Sanandaj–Sirjan Zone metamorphic rocks to the NE. Cretaceous and Cenozoic ophiolitic assemblages are found along the Zagros suture in Iraq and its extension into Turkey (Elmas and Yilmaz 2003; Aswad *et al.* 2011; Robertson *et al.* 2012).

In the Harsin district, the ophiolitic rocks include basalts with island arc and alkaline affinities (Ghazi and Hasanipak 1999) and abundant mantle sections and crustal elements with N-MORB and E-MORB magmatic affinities (Allahyari *et al.* 2010; Saccani *et al.* 2013). Cretaceous ophiolites are considered to form a flat-lying thrust sheet overlying the Bisotun limestones (Agard *et al.* 2005), whereas Wrobel-Daveau *et al.* (2010) showed that Bisotun limestones are thrust over the Cretaceous ophiolite. Ultramafic units around Harsin have been interpreted by Wrobel-Daveau *et al.* (2010) as continental sub-lithospheric mantle exposed by extensional detachments and subsequently obducted onto the Arabian margin. Eocene igneous rocks include mafic pillow lavas, deep-marine turbidites, pelagic limestone, and gabbro and are interpreted as part of an island arc assemblage thrust over the Cretaceous ophiolites (Braud 1987; Shahidi and Nazari 1997; Agard *et al.* 2005; Wrobel-Daveau *et al.* 2010). These ophiolitic assemblages have their thrust contacts sealed by a Late Oligocene to Miocene sedimentary succession indicating a potential upper constraint on continental collision (Agard *et al.* 2005).

The ophiolites of the Kermanshah region are part of the outer ophiolite belt of the Zagros Orogen which also includes ophiolites at Neyriz and elsewhere SE of Sirjan along the Main Zagros Thrust (Shafaii Moghadam and Stern 2011). An inner ophiolite belt is recognised along the NE boundary of the southeastern part of the Sanandaj–Sirjan Zone (Figure 1). Although the exposures of ophiolite are discontinuous, the inner belt is regarded as linked with ophiolites in the Nain region NE of the Urumieh–Dokhtar Magmatic Arc and thus extending into central Iran (Shafaii Moghadam *et al.* 2009). No ophiolite has been found along the NE boundary of the Sanandaj–Sirjan Zone between Esfahan and Sanandaj and we consider that the inner ophiolite belt is therefore restricted to the SE. In an earlier synthesis, Alavi (1994) argued that the inner ophiolite belt represented the main suture of the Zagros Orogen and that the ophiolites of the outer belt, such as at Neyriz and Kermanshah, are derived from this belt rather than being upthrust along the Main Zagros Thrust. We, however,

along with others (e.g. Agard *et al.* 2005, 2011; Wrobel-Daveau *et al.* 2010) recognise that the outer ophiolite belt has been emplaced along the Main Zagros Thrust rather than being a klippe isolated from the inner belt. Alavi's (1994) suggestion was based on the premise that the Sanandaj–Sirjan Zone consisted of a stack of thrust slices including Cretaceous rocks thrust over units such as the Hamadan Phyllite which we previously rejected (Mohajjel *et al.* 2003; see below).

Another thrust sheet containing radiolarites, similar to those of the Kermanshah region, is thrust against late Mesozoic units of the High Zagros Belt south of Azna (Figures 5 and 6). These radiolarites are strongly folded with sub-vertical to steeply dipping axial planes, a SW vergence and are cut by thrust faults (Sadr *et al.* 2010, in Farsi). A syn-orogenic sedimentary breccia unit with mostly radiolarite pebbles and boulders, 100 m wide, is exposed along the SW side of the radiolarite thrust sheet. Bedding within the radiolarites is sub-vertical to steeply NE-dipping and they are unconformably overlain by gently dipping Oligocene–Miocene sedimentary, shallow marine rocks indicating that the strong folding in the radiolarites predated the Oligocene.

Sanandaj–Sirjan Zone

The Sanandaj–Sirjan Zone occurs between the Zagros Suture Zone and the southwestern boundary of the Urumieh–Dokhtar Magmatic Arc (Figure 2). It includes a range of stratigraphic successions, volcanic rocks, multiply deformed metamorphic rocks, intrusive igneous complexes, and common brittle faults. U–Pb data from granites and related intrusive rocks in a belt from Qorveh to Aligodarz (Figure 2) indicate Jurassic ages (Ahmadi-Khalaji *et al.* 2007; Shahbazi *et al.* 2010; Mahmoudi *et al.* 2011; Esna-Ashari *et al.* 2012) rather than Late Cretaceous to Paleogene as previously considered (Mohajjel *et al.* 2003). We refer to these intrusive rocks as the Qorveh–Aligodarz Plutonic Belt (Figure 2).

Precambrian rocks along the Sanandaj–Sirjan Zone occur in the Lake Urumieh region (Hassanzadeh *et al.* 2008; Azizi *et al.* 2011b), and also east and north of Golpaygan (Figure 2). Late Neoproterozoic Pan–African U–Pb zircon ages have been determined from granitic rocks and gneissic basement near the Muteh Gold Mine (Hassanzadeh *et al.* 2008). $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages and low-angle mylonitic foliation in these rocks are consistent with extensional tectonics during the Eocene between 56 and 39 Ma (Moritz *et al.* 2006) similar to central Iran (Verdel *et al.* 2007). A unit of Precambrian metamorphic rocks occur between Shahrekord and Aligodarz (Sahandi and Soheili 2005) and include eclogites 40 km north of Shahrekord (Davoudian *et al.* 2008). No definitive radiometric ages on these rocks have been published; they are a basement metamorphic complex of pre-Cretaceous age.

In the Muteh Gold Mine area, NE of Golpaygan (Figure 2), the Neoproterozoic metamorphic and granitic rocks and overlying Paleozoic succession (Moritz *et al.* 2006) are typical of the basement and stratigraphic succession in central Iran. Farther north in the Mahallat area (Figure 12), the succession consists of Neoproterozoic carbonates, Cambrian sandstone and shale, Permian–Triassic carbonates, Jurassic shale and sandstone, Cretaceous dominantly carbonate succession including Aptian–Albian limestone and Cenozoic units (Thiele *et al.* 1968; Sheikholeslami 2008). The pre-Pliocene succession lacks any angular unconformities although time breaks are indicated by missing Ordovician to Devonian rocks and disconformities occur at the base of the Cretaceous and Eocene units. An unconformity is also widely developed in central Iran at the base of the Cretaceous succession (Berberian and King 1981, p. 240), although the Jurassic and Cretaceous successions have no angular discordance (Radfar 1993). A Permian A-type granite also occurs in this part of the Sanandaj–Sirjan Zone (Figure 2) (Alirezai and Hassanzadeh 2012). Eocene and older units

are folded and uplifted along a NE-trending thrust fault that has been reactivated after the Pliocene (Figure 12; Sheikholeslami 2008). Most of the shortening is pre-Pliocene given that flat-lying Pliocene units unconformably overlie tilted Eocene rocks and thus the folding and most of the thrusting was probably Miocene. The unusual NE trend of these structures may reflect reactivation of extensional faults formed in the Eocene like those near the Muteh Gold Mine (Moritz *et al.* 2006).

Metamorphic rocks include the widespread Late Triassic to Early Jurassic Hamadan Phyllite (Figure 2) dominated by black phyllite and less abundant sandstone and carbonate. These rocks are metamorphosed up to greenschist and locally amphibolite facies conditions and have horizontal schistosity (Berberian and Alavi-Tehrani 1977; Sepahi *et al.* 2004; Agard *et al.* 2005). Medium pressure to medium temperature metamorphism affected these rocks (Agard *et al.* 2005), and predated intrusion of the Middle to Late Jurassic plutons and is therefore of Early to Middle Jurassic age. SW of the Hamadan Phyllite, more varied metamorphic rocks include Permian metacarbonates, widespread marble, schist, quartzite, and amphibolite (Figure 5). These rocks are known in the Dorud district as the June Complex that has been intruded by strongly foliated granite west of Azna but their age is poorly documented (Mohajjel and Fergusson 2000).

In the Azna region, these metamorphic rocks form several thrust duplexes overlying Late Jurassic–Early Cretaceous volcanic rocks (Figures 5 and 6) consistent with S/C fabrics in fault zones showing a NE over SW shear sense (Sadr *et al.* 2010, in Farsi). Several nappes containing the June Complex and Permian metacarbonate reflect frontal rolling and nappe emplacement during gravitational spreading of the thrust wedge during continental collision (Merle 1998). Elsewhere, such as in the Harsin region, metamorphic rocks of the Sanandaj–Sirjan Zone have been thrust over units of the adjacent Zagros Suture Zone (Agard *et al.* 2005).

Granitic plutons of the Qorveh–Aligodarz Plutonic Belt (Figure 2) include the Alvand plutonic complex around Hamadan (Shahbazi *et al.* 2010), plutons east of Borujerd (Ahmadi-Khalaji *et al.* 2007), plutons near Aligodarz (Esna-Ashari *et al.* 2012) and the Gorveh pluton (Mahmoudi *et al.* 2011). Their ages all fall in the range 172–149 Ma with the oldest plutons near Borujerd at 172–168 Ma. They are typically massive and post-date major deformation and metamorphism in the Hamadan Phyllite and June Complex. Plutons with similar ages of 173–147 Ma have also been found in the Neyriz region in the SE Sanandaj–Sirjan Zone (Fazlnia *et al.* 2007, 2009) and Jurassic granite, its age determined from field relationships, is found 40 km SSE of Esfahan (Zahedi 1976).

Late Jurassic to Cretaceous volcanic rocks and interbedded shallow marine carbonate and clastic rocks are common NE of the Zagros Suture Zone (Figures 2, 5, 10 and 13) in the NW Sanandaj–Sirjan Zone with a prominent belt occurring SW of the metamorphic rocks (the marginal subzone of Mohajjel *et al.* 2003). The Late Jurassic volcanic rocks are of intermediate composition and are the same age as younger plutons in the Qorveh–Aligodarz Plutonic Belt. Cretaceous units consist of carbonates, including abundant Orbitolina-bearing limestone, clastic and volcanic rocks. Locally, such as 45 km SW of Golpaygan (Mohajjel *et al.* 2003), the Cretaceous rocks overlie Jurassic rocks above an angular unconformity indicating folding in the Early Cretaceous.

For over 300 km along strike from Hamadan SE to beyond Golpaygan, Cretaceous clastic and carbonate rocks non-conformably overlie the Hamadan Phyllite with the hiatus encompassing the age range of the Qorveh–Aligodarz Plutonic Belt (Mohajjel *et al.* 2003; Mahmoudi *et al.* 2011). The unconformity at the base of the overlying Cretaceous succession of the Sanandaj–Sirjan Zone indicates that uplift and erosion must have occurred in the Late Jurassic to earliest Cretaceous. Nowhere does the unconformity overlie the Jurassic plutonic rocks indicating that they remained at depth despite the uplift. In the Mahallat district, the

Triassic–Jurassic units are unmetamorphosed and have no angular discordance with the overlying Cretaceous succession (Figure 12) as is typical of central Iran.

The Cretaceous units between Hamadan and Shahrekord are folded in tight synclines and the deformation was considered latest Cretaceous because massive Late Cretaceous to Paleogene plutons of the Qorveh–Aligodarz Plutonic Belt were considered to have post-dated the folding (Mohajjel *et al.* 2003). These plutons have been shown to be Middle to Late Jurassic (see above) and thus predate the deformation. Nevertheless, a latest Cretaceous age for the deformation is consistent with relationships in the Sonqor region, where the Cretaceous succession is overlain by an angular unconformity at the base of a weakly folded Paleocene to Eocene volcanic to sedimentary succession (Eshragi *et al.* 1996). In contrast, in the Sanandaj region, a conformable succession of Late Jurassic, Cretaceous and Paleocene units are unconformably overlain by Oligocene–Miocene rocks indicating folding in the Late Eocene (Zahedi and Hajian 1985). The Cretaceous succession consists of 2000–3000 m of alternating clastic, carbonate and volcanic units (Figure 10) (Zahedi and Hajian 1985). Fission track cooling ages of 45–35 Ma from both bedrock samples and detrital apatite grains found in Miocene and younger clastic successions indicate uplift in the Sanandaj–Sirjan Zone in the Middle to Late Eocene (Homke *et al.* 2010). In the Mahallat area, a major deformation has produced NE-trending thrust faults and overturned folds that affect the Eocene and older units and predate flat-lying Pliocene units, although minor post-Pliocene fault reactivation has probably occurred (Figure 12) (Sheikholeslami 2008).

NE of the Zagros Suture Zone, within the Sanandaj–Sirjan Zone west of Sanandaj, the Cretaceous to Eocene succession is intruded by Eocene gabbroic to dioritic plutons and granitic dykes with zircon ages of 36–35 Ma (Azizi *et al.* 2011a). One of these Eocene plutons at Taa–Baysaran, SW of Sanandaj (Figure 2), has intruded the Eocene succession but is non-conformably overlain by Oligo–Miocene clastic and carbonate rocks (Sadeghian and Delavari 2007). These Oligo–Miocene rocks are equivalents of the Lower Red and Qom formations of central Iran and these relationships indicate Late Eocene folding, uplift and erosion. The Eocene ophiolite of the Zagros Suture Zone and the Eocene igneous rocks in the Sanandaj–Sirjan Zone (Figures 2 and 7) were referred to as the Early Tertiary Magmatic Domain by Agard *et al.* (2011). We prefer to treat these two assemblages as separate units consistent with the nearly 20 Ma age difference between them (Azizi *et al.* 2011a). Another small pluton, the Gosheh–Tavandasht Complex, has a U–Pb zircon age of 35 Ma SE of Borujerd (Mahmoudi *et al.* 2011).

Main Recent Fault and related structures

The Main Recent Fault is associated with topographic depressions and valley-fill sediments but in many areas the fault is not accurately mapped, such as between Sahneh and Nahavand (Figure 2). Offsets of drainage basins and mis-alignments of wind gaps with major rivers indicate dextral strike-slip displacement of ~50 km along the Main Recent Fault mainly in the last 3–5 Ma (Talebian and Jackson 2002). In contrast, on the basis of displaced ophiolite contacts north of Kermanshah, a much lower maximum dextral offset of 16 km has been found by Alipoor *et al.* (2012). In the Nahavand region, the fault has two overlapping strands (Figure 2) resulting in a contractional overlap zone, with development of a zone of E–W to ESE aligned ridges formed mainly by upthrust Jurassic Bisotun limestones (Mohajjel and Behyari 2010). These are back-thrust to the north over Miocene limestone (Figures 13 and 14) that forms Kuh-e Garin with peaks over 3600 m high. Miocene limestone is structurally overlain to the north by a north-dipping thin thrust slice of Oligocene–Miocene sandstone,

marl and limestone. SE of Dorud the Main Recent Fault is developed along steepened thrusts of the High Zagros Belt (Figure 5).

Central Iran and the Urumieh–Dokhtar Magmatic Arc

The central Iran block has Pan–African metamorphic and granitic basement overlain by a Phanerozoic stratigraphic succession with the Eocene Urumieh–Dokhtar Magmatic Arc in the SW containing abundant mafic to intermediate volcanic and intrusive rocks, with calc-alkaline to shoshonitic chemistry (Berberian and King 1981; Alavi 1994, 2007; Hassanzadeh *et al.* 2008). New U–Pb zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ ages show that peak volcanism lasted 17 Ma from 55 to 37 Ma (Verdel *et al.* 2011). Late Miocene to Quaternary igneous rocks includes adakites and alkaline rocks (Jahangiri 2007; Omrani *et al.* 2008; Azizi and Moeinevaziri 2009). The Urumieh–Dokhtar Magmatic Arc is the southwestern part of a wide domain of Eocene igneous activity throughout much of Iran and adjoining regions (Vincent *et al.* 2005; Allen and Armstrong 2008). Volcanic rocks are overlain by a thick, Late Oligocene to Recent, clastic succession with a prominent carbonate unit (Qom Formation) in the Late Oligocene to Early Miocene (Morley *et al.* 2009). Deformation synchronous with sedimentation has developed strike-slip faults, thrust faults and folds in a transpressional phase that overlapped sedimentation in the last 10 Ma (Morley *et al.* 2009).

Tectonic History

A revised tectonic history of the High Zagros Belt, Zagros Suture Zone and Sanandaj–Sirjan Zone is presented. The Sanandaj–Sirjan Zone and adjacent parts of central Iran formed part of the Late Neoproterozoic orogenic belt along the Arabian margin of Gondwana (Hassanzadeh *et al.* 2008; Horton *et al.* 2008). The overlying sedimentary succession is consistent with a setting as part of the Gondwana craton with widespread continental deposition (Berberian and King 1981). In most reconstructions of Neo-Tethys, the Sanandaj–Sirjan Zone is attached to at least part of central Iran and rifted away from the Arabian margin (Ricou 1994; Stampfli and Borel 2002; Bagheri and Stampfli 2008). Alternatively, the Sanandaj–Sirjan Zone has been shown as separated from central Iran by a wide Neo-Tethyan Ocean in the Early Jurassic (Golonka 2004), thereby implying the existence of a suture along the NE boundary of the Sanandaj–Sirjan Zone (i.e. the inner ophiolite belt which occurs along the SW margin of the Urumieh–Dokhtar Magmatic Arc in the SE Zagros at Dehshir and Baft, Shafaii Moghadam *et al.* 2010; Shafaii Moghadam and Stern 2011). This reconstruction is not followed here because in the Golpaygan region, Jurassic shale overlies Paleozoic rocks and Neoproterozoic basement consistent with a connection to central Iran. The Jurassic shale thickens westwards towards the Hamadan Phyllite with no evidence for a suture. Additionally, the inner ophiolite belts are thought to have formed during closure of small ocean basins developed by rifting in the Jurassic to Late Cretaceous (Bagheri and Stampfli 2008; Shafaii Moghadam *et al.* 2009; Agard *et al.* 2011).

Permian–Triassic rifting

Part of central Iran and the Sanandaj–Sirjan Zone were rifted from Gondwana and the Arabian margin in the Permian to Triassic to form Neo-Tethys (Stampfli *et al.* 1991; Ricou 1994; Alavi 1994, 2004). Direct evidence of this rift event is poorly documented in the

Zagros Fold and Thrust Belt apart from a seismic section in the Dezful Embayment showing inversion of a half-graben with a thick section of Permian–Triassic growth strata in the Rag-e Sefid Anticline (Sepehr and Cosgrove 2004). An unconformity between Triassic evaporite, dolomite and limestone and overlying Jurassic to Cretaceous continental deposits of the Zagros Simply Folded Belt is also attributed to this event (Alavi 2004, p. 5). Some basalts of Permian age occur in the High Zagros Belt and syn-depositional normal faulting has been documented in the Triassic Khaneh Kat Formation west of Neyriz (Navapour *et al.* 2010). Evidence for rifting in the Sanandaj–Sirjan Zone was outlined in Mohajjel *et al.* (2003) and includes deposition of Permian metacarbonate rocks and Triassic clastic, carbonate and mafic igneous rocks of the June Metamorphics. The Early Permian A-type Hasanrobat granite near Golpaygan has also been related to this rift event (Alirezaei and Hassanzadeh 2012).

Jurassic convergent margin along the Sanandaj–Sirjan Zone

Elongate plutons form a belt over 350 km along the trend of the northwestern Sanandaj–Sirjan Zone and are of Middle to Late Jurassic age (172–149 Ma) with a subduction-related magmatic arc geochemical affinity (Ahmadi-Khalaji *et al.* 2007; Mahmoudi *et al.* 2011; Esna-Ashari *et al.* 2012). In the Qorveh region, mafic rocks of the northern Qorveh–Aligodarz Plutonic Belt have been locally related to an island arc setting followed by collision with part of the Sanandaj–Sirjan Zone (Azizi and Asahara 2013). However, this suggestion is based on the magmatic affinity of the inferred island arc rocks and their localised NNE–SSW trend compared to the dominant NW–SE trend of the Qorveh–Aligodarz Plutonic Belt. No suture zone has been identified associated with this collision and more data are required on the metamorphic rocks of the Qorveh area to test this hypothesis. South of the Lake Urmieh region of NW Iran, the Qorveh–Aligodarz Plutonic Belt has not been identified. 500 km beyond the SE termination of the Qorveh–Aligodarz Plutonic Belt in the Neyriz region, anorthosite, S-type granite, gabbro and trondjemite have U–Pb zircon ages in the range 173–147 Ma with a subduction-related magmatic arc affinity (Fazlnia *et al.* 2007, 2009). Between Shahrekord and Neyriz, this belt is either underlying Cretaceous rocks (as evident 40 km SSE of Esfahan) or the spacing of plutons is variable along the belt with large parts having no magmatic activity. Additional to the Jurassic plutonic rocks, Late Jurassic intermediate volcanic rocks are interbedded with shallow marine limestones developed along the NE side of the Zagros Suture Zone (Figure 2).

The paleogeography is of a continental margin with a subdued, largely submerged volcanic arc with deeper levels in the arc affected by plutonic activity that are presently exposed due to younger events (Figure 15). Uplift occurred with erosion forming the sub-Cretaceous unconformity but granitic rocks of the Qorveh–Aligodarz Plutonic Belt were not uplifted to the surface in this interval. In the Golpaygan region, deformation decreases to the NE consistent with adjacent central Iran forming a stable cratonic block at this time. The succession shows no clastic influx consistent with a lack of significant topography along the adjoining active continental margin arc.

Triassic and Early Jurassic rocks in the Sanandaj–Sirjan Zone have been metamorphosed and deformed prior to intrusion of the typically massive mid to Late Jurassic plutons. The cause of this deformation and metamorphism is unclear. Presumably they are related to development of a convergent margin along the southwestern side of the Sanandaj–Sirjan Zone after sea-floor spreading in Neo-Tethys formed a wide ocean basin (Stampfli and Borel 2002). Initiation of subduction along a newly developed Eurasian margin has followed closure of Paleo-Tethys by collision of central Iran and Eurasia (Golonka 2004). A minimum constraint on the timing of collision is indicated by the youngest U–Pb ages of detrital zircons

at 213 ± 5.8 Ma in the overlapping Shemshak Formation of northern Iran (Horton *et al.* 2008). Given that the depositional age of the Hamadan Phyllite extends into the Jurassic (Braud 1987; Soheili *et al.* 1992), it is apparent that subduction was initiated no earlier than 190–180 Ma, at least 20 Ma after the collision along the Paleo–Tethyan suture.

Cretaceous tectonic setting

Eurasian margin

The main indicator of the Cretaceous tectonic setting in the NW Sanandaj–Sirjan Zone is the marine succession containing intercalated, basaltic to andesitic basaltic, calc-alkaline rocks with a continental arc geochemical signature (Azizi and Jahangiri 2008; Azizi and Moinevaziri 2009). These rocks are most widely developed in the Sanandaj region and extend northwestwards towards Lake Urumieh. Towards the SE the volcanic rocks are much less common and the succession consists dominantly of Aptian–Albian limestone overlying conglomerate and sandstone (Figure 10) with minor intermediate volcanic rocks (Mohajjel *et al.* 2003). In some areas, such as 45 km SW of Golpaygan, a volcanic succession ranges from the Jurassic into the Early Cretaceous (Mohajjel *et al.* 2003). The Cretaceous volcanic arc (Figure 16) developed farther west of the preceding Qorveh–Aligodarz Plutonic Belt and overlapped exposed Jurassic volcanic rocks. It appears that the Cretaceous arc is truncated southeastwards along the Main Zagros Thrust although it is possible that the arc dies out to the SE (Figures 2 and 16). Additionally, Cretaceous volcanic rocks occur in northern Iran north of Tehran (Figure 1) (Annells *et al.* 1975) and are also scattered elsewhere in northern Iran (Verdel *et al.* 2011). By analogy with western North America in the Laramide Orogeny, Verdel *et al.* (2011) inferred an episode of flat slab subduction for the Cretaceous in central and northern Iran. Late Cretaceous shortening affected Cretaceous units and underlying rocks of the Qorveh–Aligodarz Plutonic Belt in the arc to backarc region and is related to an inferred flattening of the subducting slab. This deformation is synchronous with ophiolite generation and emplacement throughout the Zagros.

Cretaceous ophiolites are widely developed in and neighbouring central Iran including the inner ophiolite belt of the Zagros Orogen extending to the Nain ophiolite, the Sistan Suture Zone of eastern Iran and ophiolites in northern Iran. A supra-subduction zone affinity has been documented for the inner ophiolite belt (Shafaii Moghadam *et al.* 2010; Shafaii Moghadam and Stern 2011) and also for part of the Sistan Suture Zone (Saccani *et al.* 2010). One explanation for these ophiolites is that they developed after Cretaceous rifting in a backarc setting followed by closure with generation of Late Cretaceous supra-subduction zone ophiolite (Shafaii Moghadam *et al.* 2009; Saccani *et al.* 2010; Agard *et al.* 2011).

Arabian margin

In the Kermanshah region, initiation of ophiolite obduction is no better constrained than Campanian from the age of the Amiran turbidites reflecting flexural subsidence in front of the advancing ophiolite (Alavi 2004; Homke *et al.* 2009). Diachronous advance of the clastic wedge across the Zagros Simply Folded Belt indicates that ophiolite obduction extended from the Late Cretaceous into the Eocene (Saura *et al.* 2011). As for Oman, obduction was driven by subduction of the Arabian passive margin northeastwards under this newly initiated arc. This contrasts with the idea that both the inner and outer ophiolite belts of the Zagros Orogen developed as part of a single coherent forearc lithosphere near the SW Eurasian margin of

Neo-Tethys (Shafaii Moghadam and Stern 2011; Shafaii Moghadam *et al.* 2013). Others show that the Kermanshah ophiolite includes older elements in addition a supra-subduction zone component formed in a newly initiated subduction zone adjacent to the Arabian passive margin and distant from the ophiolites of the inner Zagros belt and Central Iran (Allahyari *et al.* 2010; Agard *et al.* 2011; Saccani *et al.* 2013). Complicated relationships east of Harsin reflect a long history of convergence with repeated episodes of thrusting, out-of-sequence thrusting and back-thrusting (Agard *et al.* 2005, 2011; Wrobel-Daveau *et al.* 2010).

Early Cenozoic magmatic arc

The broader context for the northwestern Zagros Orogen in the Paleogene was the intermediate igneous activity in the Urumieh–Dokhtar Magmatic Arc and more widely throughout central Iran and in the Caucasus (Allen and Armstrong 2008; Verdel *et al.* 2011). Eocene igneous activity and accompanying extensional tectonics, such as in the Saghand region of central Iran, has been considered a response to rollback and slab steepening in a largely continental region (Verdel *et al.* 2007, 2011). This was unaccompanied by formation of either new ocean floor or infant arc crust that in contrast was widely formed in the Late Cretaceous in the contracting Tethyan Ocean.

Limited igneous activity with granitic to gabbroic rocks at ~35 Ma affected the Sanandaj–Sirjan Zone adjacent to the Zagros Suture Zone (Azizi *et al.* 2011a; Mahmoudi *et al.* 2011). These plutons reflect anomalous igneous activity in the forearc as occurs in the Early Cenozoic convergent margin in southern Alaska (Gasser *et al.* 2012) and adjacent to the Nankai Trough in SW Japan (Kimura *et al.* 2005). In both cases the anomalous near-trench magmatism is related to subduction of active oceanic spreading centres. The backarc basin magmatic affinity of the gabbroic pluton SW of Sanandaj (Azizi *et al.* 2011a) is consistent with subduction of an actively spreading backarc basin. These plutonic rocks were rapidly uplifted following intrusion as shown by apatite cooling ages of 45–35 Ma for the Sanandaj–Sirjan Zone (Homke *et al.* 2010) and the unconformably overlying Oligocene–Miocene succession (Sadeghian and Delavari 2007).

Closure of Neo-Tethys and timing of collision

Global reconstructions show that a wide but continuously closing seaway existed along the Zagros Orogen until the mid to late Cenozoic (Ricou 1994; Şengör and Natal'in 1996; McQuarrie *et al.* 2003; Golonka 2004; Seton *et al.* 2012; McQuarrie and van Hinsbergen 2013). A Paleocene to Early Eocene timing of collision was favoured by Ghasemi and Talbot (2006) and also argued by Mazhari *et al.* (2009) on the basis of Eocene bimodal plutonic rocks considered to be post-collisional. However, it has been argued that collision was no earlier than Late Eocene based on the cessation of regional Eocene volcanism across Iran and in the Talysh (Vincent *et al.* 2005; Allen and Armstrong 2008). Collision must have also followed development of minor Eocene ophiolite fragments preserved in the suture zone near Kermanshah (Wrobel-Daveau *et al.* 2010; Azizi *et al.* 2011a).

Constraints on the timing of collision based on stratigraphy and structure in the High Zagros Belt, Zagros Suture Zone and Sanandaj–Sirjan Zone in the NW Zagros Orogen are scarce. For example, shortening in the Zagros Suture Zone involving the radiolarites around Kermanshah is impressive (Figure 11) but is presumably related to emplacement of the Cretaceous ophiolite during passive margin – island arc collision rather than being related to the continental collision (Vergés *et al.* 2011). Similarly, much of the deformation in the

Harsin district in northwestern Iran reflects ophiolite emplacement with accretion of the Eocene island arc related to the continental collision. On the basis of structural and stratigraphic relationships in the Harsin district, Agard *et al.* (2005) argued for collision prior to 23–25 Ma. This is consistent with the Oligocene(?) age of syn-orogenic conglomerate in the High Zagros Belt near Shahrekord (Figure 3) documented by Fakhari *et al.* (2008). It seems likely that collision preceded widespread deposition of Oligocene–Miocene units along the suture zone and in central Iran and the Zagros. In a scaled reconstruction utilising plate tectonic constraints using GPlates, McQuarrie and van Hinsbergen (2013) showed that continental collision most likely occurred at 27 Ma. Thus collision followed the 35 Ma shut-down of widespread magmatic activity.

After continental collision, the Tethyan seaway still remained in existence although presumably only as a wide epeiric sea following subduction of all the oceanic crust. Closure of this epeiric sea connecting the widening Indian Ocean with the Mediterranean Sea occurred in the Miocene around 15 Ma based on isotopic evidence for warm and saline water entering the Indian Ocean up until this time (Woodruff and Savin 1989). Along the suture, folding of Oligocene–Miocene successions and incorporation of Pliocene conglomeratic wedges into thrust slices shows that deformation was widespread in the Late Neogene, although many of the thrust faults are clearly reactivated structures from earlier ophiolite emplacement. Comprehensive treatments of the Neogene tectonic history of the Zagros Orogen are given by Agard *et al.* (2011) and Mouthereau *et al.* (2012).

Discussion

Jurassic to Eocene subduction zones

Most tectonic reconstructions for the Jurassic to Paleogene history of the Zagros show active subduction occurring along the SW margin of the Sanandaj–Sirjan Zone. Much less agreement exists about the nature of those subduction zones. For example, Agard *et al.* (2011) show a steeply dipping slab in the northwestern Zagros Orogen in the Late Cretaceous that steepens in the Paleogene followed by slab breakoff associated with Eocene magmatic activity in the Zagros Suture Zone. Alternatively, Verdel *et al.* (2011) proposed a Laramide-style, gently-dipping slab for the Late Cretaceous followed by slab rollback associated with formation of the Eocene Urumieh–Dokhtar Magmatic Arc. Shafaii Moghadam and Stern (2011) argued that Zagros ophiolites reflect an important episode of subduction initiation along the SW margin of Eurasia. For the Eocene, Mouthereau *et al.* (2012) show a steeply dipping slab that at depth bends to an almost flat, stagnant slab.

From the mid Jurassic to the Cretaceous, the paleogeography of the Zagros Orogen around Sanandaj is consistent with trenchward advance of the arc (Figures 15 and 16). A subducting slab with a moderate dip to the NE, with either rollback or net accretion occurring in the forearc from growth of a subduction complex, can account for this at least locally. For the Cretaceous subduction zone, it has been argued by comparison with the Laramide Orogeny of the western United States that the dip angle of the subduction zone must have been relatively low to account for shortening and for Cretaceous igneous activity in northern Iran (Verdel *et al.* 2011). This does not explain the continuing Cretaceous magmatic activity in the Sanandaj region nor is it consistent with widespread shallow marine sedimentation in the Sanandaj–Sirjan Zone and central Iran in the Cretaceous (Berberian and King 1981). An explanation for co-existing magmatic activity in the Sanandaj region and northern Iran is that the slab is segmented so locally it is steeper adjacent to Sanandaj and elsewhere has a low-angle dip (cf. the segmented Laramide slab of Saleeby 2003). A reduction in slab dip in the

Late Cretaceous accounts for cessation of volcanism around Sanandaj and explains the Late Cretaceous shortening in the Qorveh–Aligodarz Plutonic Belt. Such low-angle subduction may have also pre-conditioned the backarc in central Iran prior to the Eocene flare-up of igneous activity (Verdel *et al.* 2011). We suggest that relocation of the magmatic arc to the Urumieh–Dokhtar Magmatic Arc accompanied a minimal change in slab dip angle after the shallowing of the slab in the Late Cretaceous and/or Paleocene (Figure 17). Thus repositioning of the arc well inboard of the trench reflects a new slab depth at 125 km or so, suitable for magma generation in subduction zones (Stern 2002).

In active subduction zones, the arc-trench gap is usually 160 ± 60 km (Stern 2002), whereas the Qorveh–Aligodarz Plutonic Belt and the Cretaceous arc succession in the Sanandaj region presently lie adjacent to the Zagros Suture Zone indicating that much of the forearc crust is missing. While some of the forearc must have been removed during erosion associated with the collision, the make-up of the leading edge of the Sanandaj–Sirjan Zone with a varied assemblage of medium grade to very-low grade metamorphic rocks indicates a lack of pervasive deep erosion and implies that some other mechanism operated. Two possibilities are that the forearc has been removed by either strike-slip transport during oblique convergence or by an episode of intense subduction erosion in the Eocene. Subduction erosion is a widespread process and is occurring along more than half of the presently active subduction zones (Clift and Vannucchi 2004; Stern 2011) and we consider this process the most likely explanation for the loss of the Jurassic–Cretaceous forearc. We note that Shafaii Moghadam and Stern (2011) identify Late Cretaceous Zagros ophiolites as representing the forearc but find their arguments unconvincing.

The Late Cretaceous Neo-Tethys was characterised by widespread development of infant arc crust generated at newly formed subduction zones that have been related to increased convergence rates (Agard *et al.* 2011). Ophiolite emplacement has resulted especially where these infant arc assemblages have developed near passive margins resulting in island arc – passive margin collisions as is well documented for the Lurestan Arc (Allahyari *et al.* 2010; Saccani *et al.* 2013). Continuing closure of Neo-Tethys in the Late Cretaceous to Paleogene was probably associated with subduction of a more topographically heterogeneous oceanic plate involving infant island arcs, backarc basins as indicated by the Eocene ophiolitic rocks north of Kermanshah (Azizi *et al.* 2011a), and various ribbon microcontinents such as must have formed basement to the Bisotun limestones. This oceanic assemblage would have been more conducive to subduction erosion than less topographically varied oceanic crust (Clift and Vannucchi 2004; Stern 2011) and therefore may have played a significant role in the removal of the missing Jurassic to Cretaceous forearc.

Crustal Structure

A cross section of the crustal structure of the northwestern Zagros Orogen has been constructed from radial receiver function records and crustal velocity models (Paul *et al.* 2010). This shows a Moho depth of about 42 km across the Zagros Fold and Thrust Belt that deepens into the Sanandaj–Sirjan Zone where the Moho reaches a maximum depth of 56 ± 2 km. A low-velocity zone that crosses the whole crust, and occurs at the surface coincident with the Main Zagros Thrust, has been interpreted as a major thrust fault with central Iran and the Sanandaj–Sirjan Zone thrust over Arabian crust (Paul *et al.* 2010; Agard *et al.* 2011, figure 9). Thus in this interpretation Arabian crust wedges out to the NE under central Iran with the contact between the plates having a relatively low-angle dip of $10\text{--}15^\circ$. This amount of underthrusting is markedly less than that thought to occur in the Indian–Eurasian collision zone (Hatzfeld and Molnar 2010).

An alternative interpretation based on seismic tomography showed the Main Zagros Thrust changing from a low-angle dip ($\sim 10^\circ$) in the uppermost crust to a fault with a 50° NE dip through most of the middle and lower crust (Vergés *et al.* 2011). The tomographic sections show broad features in the crust and mantle and are a reflection of changing physical properties rather than necessarily reflecting different plates, especially for the crust. For both central Iran and the Arabian plate the crust is compositionally similar and consists of crystalline rocks formed by Pan-African orogenesis and overlain by a thick Phanerozoic succession. It is possible that the crustal variations in seismic tomography reflect variations in physical properties, such as thermal state, that are now independent of structures that were initiated with ophiolite emplacement over 70 Ma and culminated in collision in the mid-Cenozoic.

Our interpretations of shallow crustal structures are based on exposed structures as shown in the regional cross sections (Figures 4, 6, 9, and 14) and highlight development of low-angle structures related to thrusting and associated fault-propagation folding in the High Zagros Belt and in the radiolarities. Low-angle thrusting is also evident along the eastern boundary to the Zagros Suture Zone where metamorphic rocks of the Sanandaj–Sirjan Zone have thrust over the former during the Miocene phase of collision (Agard *et al.* 2005, 2011). Subduction erosion during the Eocene has presumably also thinned the Sanandaj–Sirjan Zone. We therefore favour the interpretation of crustal structure presented by Paul *et al.* (2010) for the NW Zagros Orogen. We suggest that the mismatch between basement length at 150 km and the 180 km length of undeformed shallow crustal rocks found by Vergés *et al.* (2011) is more consistent with a lower, rather than a steeper, dip of the Main Zagros Thrust in the middle and lower crust.

Conclusions

The Zagros Orogen in northwestern Iran between Shahrekord and Sanandaj consists of a Cenozoic zone of continental collision that has developed after more-or-less continuous subduction since the mid Jurassic. Subduction was apparently initiated after the closure of Paleo-Tethys by accretion of the Cimmerian blocks to Eurasia and is associated with mid Jurassic metamorphism and deformation in the Hamadan Phyllite and other units of the Sanandaj–Sirjan Zone. A moderately NE-dipping subduction zone was associated with mid to Late Jurassic plutonic rocks of the Qorveh–Aligodarz Plutonic Belt and related volcanic rocks that formed in a mainly marine environment indicating that the arc was topographically subdued. Some uplift in the latest Jurassic to Early Cretaceous resulted in some erosion but the Jurassic plutonic rocks remained below the surface. The arc advanced trenchward in the Cretaceous in the Sanandaj region but remained a mainly marine topographically subdued feature.

The Late Cretaceous was an interval of rapid change in the Middle East with increased convergence rates associated with ophiolite obduction along the Arabian passive margin (Agard *et al.* 2011). In the Kermanshah region, ophiolite obduction was associated with a prolonged episode of foreland basin migration across the Zagros Fold and Thrust Belt (Homke *et al.* 2009; Saura *et al.* 2011) with imbrication and widespread fault-propagation folding in the radiolarites and the High Zagros Belt. The higher convergence rates are associated with Late Cretaceous shortening in the Qorveh–Aligodarz Plutonic Belt. Some uncertainty exists about the dip of the subducting slab in the Cretaceous; for the Sanandaj region the slab appears to have remained moderately dipping to the NE whereas Verdel *et al.* (2011) argued the slab was almost flat to account for magmatic activity in northern Iran. By the Paleogene, a subducting flat slab must have existed and was followed by development of

the Urumieh–Dokhtar Magmatic Arc along the southwestern margin of central Iran. Island arc and backarc basin development in Neo-Tethys continued in the Early Eocene. Thus subduction of a much more topographically irregular underthrusting plate occurred under the Sanandaj–Sirjan Zone that promoted tectonic erosion of the overriding plate and loss of the forearc associated with the Jurassic and Cretaceous subduction zones. Continental collision followed shut-down of volcanic activity along the Urumieh–Dokhtar Magmatic Arc in the Oligocene consistent with stratigraphic constraints from the NW Zagros Orogen (McQuarrie and van Hinsbergen 2013). Development of the Main Recent Fault and its association with shortening across the Zagros Mountains in the last 15 Ma or so remains poorly understood.

Acknowledgements

M. Mohajjel acknowledges joint work undertaken with students including A. Babaahmadi, M. Behyari, M. Biralvand, R. Elyaszadeh, and A.H.Sadr. Field activities were supported by the Tarbiat Modares University. C. Fergusson acknowledges support from the GeoQuEST Research Centre at the University of Wollongong. We thank the referees Drs Khalil Sarkarinejad, Charles Verdel and the Editor Professor Bob Stern for constructive reviews that have significantly improved the final manuscript.

References

- Agard, P., Omrani, J., Jolivet, L., and Mouthereau, F., 2005, Convergence history across Zagros (Iran): constraints from collisional and earlier deformation: *International Journal of Earth Sciences Geologische Rundschau*, v. 94, p. 401–419.
- Agard, P., Omrani, J., Jolivet, L., Whitechurch, H., Vrielynck, B., Spakman, W., Monie, P., Meyer, B., and Wortel, R., 2011, Zagros orogeny: a subduction-dominated process: *Geological Magazine*, v. 148, p. 692–725.
- Ahmadi Khalaji, A., Esmaeily, D., Valizadeh, M.V., and Rahimpour-Bonab, H., 2007, Petrology and geochemistry of the granitoid complex of Boroujerd, Sanandaj–Sirjan Zone, Western Iran: *Journal of Asian Earth Sciences*, v. 29, p. 859–877.
- Aitchison, J.C., Ali, J.R., and Davis, A.M., 2007, When and where did India and Asia collide? *Journal of Geophysical Research*, v. 112, B05423, doi:10.1029/2006JB004706, 19 p.
- Alavi, M., 1994, Tectonics of the Zagros Orogenic belt of Iran: new data and interpretations: *Tectonophysics*, v. 229, p. 211–238.
- , 2004, Regional stratigraphy of the Zagros fold-thrust belt of Iran and its proforeland evolution: *American Journal of Science*, v. 304, p. 1–20.
- , 2007, Structures of the Zagros fold-thrust belt in Iran: *American Journal of Science*, v. 307, p. 1064–1095.
- Alavi, M., and Mahdavi, M.A., 1994, Stratigraphy and structure of the Nahavand region in western Iran and their implications for the Zagros tectonics: *Geological Magazine*, v. 131, p. 43–47.
- Alirezai, S., and Hassanzadeh, J., 2012, Geochemistry and zircon geochronology of the Permian A-type Hasanrobat granite, Sanandaj–Sirjan belt: a new record of the Gondwana break-up in Iran: *Lithos*, v. 151, p. 122–134.
- Alipoor, R., Zaré, M., and Ghassemi, M.R., 2012, Inception of activity and slip rate on the Main Recent Fault of Zagros Mountains, Iran: *Geomorphology*, v. 175–176, p. 86–97.
- Allahyari, K., Saccani, E., Pourmoafi, M., Beccaluva, L., and Masoudi, F., 2010, Petrology of mantle peridotites and intrusive mafic rocks from the Kermanshah ophiolitic complex

- (Zagros belt, Iran): implication for the geodynamic evolution of the Neo-Tethyan oceanic branch between Arabia and Iran: *Ofioliti*, v. 35, p. 71–90.
- Allen, M.B., and Armstrong, H.A., 2008, Arabia–Eurasia collision and the forcing of mid-Cenozoic global cooling: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 265, p. 52–58.
- Annells, R.N., Arthurton, R.S., Bazley, R.A., and Davies, R.G., 1975, Explanatory text of the Qazvin and Rasht quadrangles map, Quadrangles E3 and E4: *Geol. Surv. of Iran Geol.*, Tehran, 94 p.
- Aswad, K.J.A., Aziz, N.R.H., Koyi, H.A., 2011, Cr-spinel compositions in serpentinites and their implications for the petrotectonic history of the Zagros Suture Zone, Kurdistan Region, Iraq: *Geological Magazine*, v. 148, p. 802–818.
- Authemayou, C., Chardon, D., Bellier, O., Malekzadeh, Z., Shabanian, E., and Abbassi, M.R., 2006, Late Cenozoic partitioning of oblique plate convergence in the Zagros fold-and-thrust belt (Iran): *Tectonics*, v. 25, TC3002, doi:10.1029/2005TC001860, 21 p.
- Azizi, H., and Jahangiri, A., 2008, Cretaceous subduction-related volcanism in the northern Sanandaj–Sirjan Zone, Iran: *Journal of Geodynamics*, v. 45, p. 178–190.
- Azizi, H., and Moinevaziri, H., 2009, Review of the tectonic setting of Cretaceous to Quaternary volcanism in northwestern Iran: *Journal of Geodynamics*, v. 47, p. 167–179.
- Azizi, H., and Asahara, Y., 2013, Juvenile granite in the Sanandaj–Sirjan Zone, NW Iran: Late Jurassic–Early Cretaceous arc–continent collision: *International Geology Review*, v. 15, p. 1523–1540.
- Azizi, H., Tanaka, T., Asahara, Y., Chung, S.L., and Zarrinkoub, M.H., 2011a, Discrimination of the age and tectonic setting for magmatic rocks along the Zagros thrust zone, northwest Iran, using the zircon U–Pb age and Sr–Nd isotopes: *Journal of Geodynamics*, v. 52, p. 304–320.
- Azizi, H., Chung, S-L., Tanakac, T., and Asaharad, Y., 2011b, Isotopic dating of the Khoy metamorphic complex (KMC), northwestern Iran: A significant revision of the formation age and magma source: *Precambrian Research*, v. 185, p. 87–94.
- Babaahmadi, A., Mohajjel, M., Eftekhari, A., and Davoudian, A.R., 2012, An investigation into the fault patterns in the Chadegan region, west Iran: Evidence for dextral brittle transpressional tectonics in the Sanandaj–Sirjan Zone: *Journal of Asian Earth Sciences*, v. 43, p. 77–88.
- Bagheri, S., and Stampfli, G.M., 2008, The Anarak, Jandaq and Posht-e-Badam metamorphic complexes in central Iran: New geological data, relationships and tectonic implications: *Tectonophysics*, v. 451, p. 123–155.
- Bavandpur, A.K., and Hajihoseini, A., 1999, Geological map of Kermanshah quadrangle 5458: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Berberian, M., and Alavi-Tehrani, N., 1977, Structural analyses of Hamadan metamorphic tectonites, *in* Berberian, M., ed., *Contribution to the Seismotectonics of Iran (part 3)*: Geological Survey of Iran, Report 40, p. 239–260.
- Berberian, M., and King, G.C., 1981, Towards a palaeogeography and tectonics evolution of Iran: *Canadian Journal of Earth Sciences*, v. 18, p. 210–265.
- Braud, J., 1978, Geological map of Kermanshah quadrangle C6: Geological Survey of Iran, scale 1:250,000, 1 sheet.
- , 1987, *Paleogéographie, magmatique et structurale de la region Kermanshah, Iran [Thèse de étate]*: Université de Paris, 430 p.
- Casciello, E., Vergés, J., Saura, E., Casini, G., Fernández, N., Blanc, E., Homke S., and Hunt, D.W., 2009, Fold patterns and multilayer rheology of the Lurestan Province, Zagros Simply Folded Belt (Iran): *Journal of the Geological Society, London*, v. 166, p. 947–959.

- Clift, P., and Vannucchi, P., 2004, Controls on tectonic accretion versus erosion in subduction zones; implications for the origin and recycling of the continental crust: *Reviews of Geophysics*, v. 42, RG2001, doi:10.1029/2003RG000127, 31 p.
- Davoudian, A.R., Genser, J., Dachs, E., and Shabanian, N., 2008, Petrology of eclogites from north of Shahrekord, Sanandaj-Sirjan Zone, Iran: *Mineralogy and Petrology*, v. 92, p. 393–413.
- Elmas, A., and Yilmaz, Y., 2003, Development of an Oblique Subduction Zone – Tectonic Evolution of the Tethys Suture Zone in Southeast Turkey: *International Geology Review*, v. 45, p. 827–840.
- Elyaszadeh, R., and Mohajjel, M., 2011, Structural Style of High Zagros Zone Based on Thrust Fault System in Southeast Kermanshah: *Scientific Quarterly Journal, Geosciences (Iran)*, v. 20, p. 61–68 (in Farsi).
- Eshragi, S., Jafarian, M.B., and Eglimi, B., 1996, Geological map of the Songhor quadrangle, 5559: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Esna-Ashari, A., Tiepolo, M., Valizadeh, M.-V., Hassanzadeh, J., and Sepahi, A.-A., 2012, Geochemistry and zircon U–Pb geochronology of Aligoodarz granitoid complex, Sanandaj-Sirjan Zone, Iran: *Journal of Asian Earth Sciences*, v. 43, p. 11–22.
- Fakhari, M.D., Axen, G.J., Horton, B.K., Hassanzadeh, J., and Amini, A., 2008, Revised age of proximal deposits in the Zagros foreland basin and implications for Cenozoic evolution of the High Zagros: *Tectonophysics*, v. 451, p. 170–185.
- Farzipour-Saein, A., Yassaghi, A., Sherkati, S., and Koyi, H., 2009a, Basin evolution of the Lurestan region in the Zagros fold-and-thrust belt, Iran: *Journal of Petroleum Geology*, v. 32, p. 5–20.
- Farzipour-Saein, A., Yassaghi, A., Sherkati, S., and Koyi, H., 2009b, Mechanical stratigraphy and folding style of the Lurestan region in the Zagros Fold–Thrust Belt, Iran: *Journal of the Geological Society, London*, v. 166, p. 1101–1115.
- Fazlnia, A.N., Moradian, A., Rezaei, K., Moazzen, M., and Alipour, S., 2007, Synchronous activity of anorthositic and S-type granitic magmas in the Chah-Dozdan batholith, Neyriz, Iran: Evidence of zircon SHRIMP and monazite CHIME dating: *Journal of Sciences, Islamic Republic of Iran*, v. 18, p. 221–237.
- Fazlnia, A.N., Schenk, V., van der Straaten, F., and Mirmohammad, M., 2009, Petrology, geochemistry, and geochronology of trondhjemites from the Qori Complex, Neyriz, Iran: *Lithos*, v. 112, p. 413–433.
- Gasser, D., Rubatto, D., Bruand, E., and Stüwe, K., 2012, Large-scale, short-lived metamorphism, deformation, and magmatism in the Chugach metamorphic complex, southern Alaska: a SHRIMP U–Pb study of zircons: *Geological Society of America Bulletin*, v. 124, p. 886–905.
- Gavillot, Y., Axen, G.J., Stockli, D.F., Horton, B.K., and Fakhari, M.D., 2010, Timing of thrust activity in the High Zagros fold–thrust belt, Iran, from (U–Th)/He thermochronometry: *Tectonics*, v. 29, TC4025, doi:10.1029/2009TC002484, 25 p.
- Gharib F., and De Wever P., 2010, Mesozoic radiolarians from the Kermanshah Formation (Iran): *Comptes Rendus Palevol*, v. 9, p. 209–219.
- Ghasemi, A., and Talbot, C.J., 2006, A new tectonic scenario for the Sanandaj–Sirjan Zone (Iran): *Journal of Asian Earth Sciences*, v. 26, p. 683–693.
- Ghazi, A.M., and Hassanipak, A.A., 1999, Geochemistry of subalkaline and alkaline extrusives from the Kermanshah ophiolite, Zagros Suture Zone, Western Iran: Implications for Tethyan plate tectonics: *Journal of Asian Earth Sciences*, v. 17, p. 319–332.
- Golonka, J., 2004, Plate tectonic evolution of the southern margin of Eurasia in the Mesozoic and Cenozoic: *Tectonophysics*, v. 381, p. 235–273.

- Hajmolla-Ali, A., Husseini, M., Farhadian, M.B., and Sedagat, E., 1989, Geological map of the Borujerd quadrangle 5757: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Hassanzadeh, J., Stockli, D.F., Horton, B.K., Axen, G.J., Stockli, L.D., Grove, M., and Schmitt, A.K., 2008, Douglas Walker U–Pb zircon geochronology of late Neoproterozoic–Early Cambrian granitoids in Iran: Implications for paleogeography, magmatism, and exhumation history of Iranian basement: *Tectonophysics*, v. 451, p. 71–96.
- Hatzfeld, D., and Molnar, P., 2010, Comparisons of the kinematics and deep structures of the Zagros and Himalaya and of the Iranian and Tibetan Plateaus and geodynamic implications: *Reviews of Geophysics*, v. 48, RG2005, doi:10.1029/2009RG000304, 48 p.
- Hatzfeld, D., Authemayou, C., Van Der Beek, P., Bellier, O., Lavé, J., Oveisi, B., Tatar, M., Tavakoli, F., Walpersdorf, A., and Yamini-Fard, F. 2010, The kinematics of the Zagros Mountains (Iran), in Leturmy, P., and Robin, C., eds., *Tectonics and Stratigraphic Evolution of Zagros and Makran during the Mesozoic–Cenozoic*: Geological Society, London, Special Publication 330, p. 19–42.
- Hessami, K., Koyi, H.A., Talbot, C.J., Tabasi, H., and Shabanian, E., 2001, Progressive unconformities within an evolving foreland fold-thrust belt, Zagros Mountains: *Journal of the Geological Society of London*, v. 158, p. 969–981.
- Homke, S., Vergés, J., Serra-Kiel, J., Bernaola, G., Sharp, I., Garcés, M., Montero-Verdu, I., Karpuz, R., and Goodarzi, M.H., 2009, Late Cretaceous–Paleocene formation of the proto-Zagros foreland basin, Lurestan Province, SW Iran: *Geological Society of America Bulletin*, v. 121, p. 963–978.
- Homke S., Vergés, J., van der Beek, P., Fernández, M., Saura, E., Barbero, L., Badics, B., and Labrin, E., 2010, Insights in the exhumation history of the NW Zagros from bedrock and detrital apatite fission-track analysis: Evidence for a long-lived orogeny: *Basin Research*, v. 22, p. 659–680.
- Horton, B.K., Hassanzadeh, J., Stockli, D.F., Axen, Gillis, G.J., Guest, B., Amini, A., Fakhari, M.D., Zamanzadeh, S.M., and Grove, M., 2008, Detrital zircon provenance of Neoproterozoic to Cenozoic deposits in Iran: Implications for chronostratigraphy and collisional tectonics: *Tectonophysics*, v. 451, p. 97–122.
- Hossaini-Doust, J., and Mahdavi, M.A., 1992, Geological map of Nahavand quadrangle 5658: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Jahangiri, A., 2007, Post-collisional Miocene adakitic volcanism in NW Iran: Geochemical and geodynamic implications: *Journal of Asian Earth Sciences*, v. 30, p. 433–447.
- Kazmin, V.G., Ricou, L.F., and Sbertshikov, I.M., 1986, Structure and evolution of the passive margin of the eastern Tethys: *Tectonophysics*, v. 123, p. 153–179.
- Kimura, J.-I., Stern, R.J., and Yoshida, T., 2005, Re-initiation of subduction and magmatic responses in SW Japan during Neogene time: *Geological Society of America Bulletin*, v. 117, p. 969–986.
- Mahmoudi, S., Corfu, F., Masoudi, F., Mehrabi, B., and Mohajjel, M., 2011, U–Pb dating and emplacement history of granitoid plutons in the northern Sanandaj–Sirjan Zone, Iran: *Journal of Asian Earth Sciences*, v. 41, p. 238–249.
- Marshak, S., and Mitra, G., 1988, *Basic methods of structural geology*: New York, Prentice-Hall, 446 p.
- Mazhari, S.A., Bea, F., Amini, S., Ghalamghash, J., Molina, J.F., Montero, P., Scarrow, J.H., and Williams, I.S., 2009, The Eocene bimodal Piranshahr massif of the Sanandaj–Sirjan Zone, NW Iran: A marker of the end of the collision in the Zagros orogen: *Journal of the Geological Society, London*, v. 166, p. 53–69.

- McQuarrie, N., and van Hinsbergen, D.J.J., 2013, Retrodeforming the Arabia-Eurasia collision zone: Age of collision versus magnitude of continental subduction: *Geology*, v. 41, p. 315–318.
- McQuarrie, N., Stock, J.M., Verdel, C., and Wernicke, B.P., 2003, Cenozoic evolution of Neotethys and implications for the causes of plate motions: *Geophysical Research Letters*, v. 30, doi:10.1029/2003GL017992, 4 p.
- Merle, O., 1998, Emplacement mechanisms of nappes and thrust sheets: Dordrecht, Kluwer Academic Press, 169 p.
- Mohajjel, M., and Behyari, M., 2010, Young transpressive positive flower structure along the Zagros collision zone, Nahavand area, west Iran, *in* Buckman, S., and Blevin, P., eds., *New England Orogen 2010: Proceedings of a conference held at the University of New England, Armidale, New South Wales, Australia, November 2010*, p. 242–251.
- Mohajjel, M., and Biralvand, M., 2011, Folding style in Kermanshah radiolarites and its significance in collision tectonic of NW Iran: *Scientific Quarterly Journal Geosciences (Iran)*, v. 19, 75–82 (in Farsi).
- Mohajjel, M., and Fergusson, C.L., 2000, Dextral transpression in Late Cretaceous continental collision, Sanandaj–Sirjan Zone, western Iran: *Journal of Structural Geology*, v. 22, p. 1125–1139.
- Mohajjel, M., Fergusson, C.L., and Sahandi, M.R., 2003, Cretaceous-Tertiary convergence and continental collision, Sanandaj–Sirjan Zone, western Iran: *Journal of Asian Earth Sciences*, v. 21, p. 397–412.
- Moinevaziri, H., Azizi, H., Mehrabi, B., and Ezadi, F., 2009, Oligocene magmatism in Zagros thrust zone (Sahneh-Marvan): Neo-Tethys subduction in Paleocene: *Science Magazine, the University of Tehran*, v. 34, 113–122 (in Farsi).
- Molinario, M., Leturmy, P., Guezou, J.-C., and Frizon de Lamotte, D., 2005, The structure and kinematics of the southeastern Zagros fold-thrust belt, Iran: From thin-skinned to thick-skinned tectonics: *Tectonics*, v. 24, TC3007, doi:10.1029/2004TC001633, 19 p.
- Moritz, R., Ghazban, F., and Singer, B.S., 2006, Eocene gold ore formation at Muteh, Sanandaj–Sirjan tectonic zone, western Iran: A result of late-stage extension and exhumation of metamorphic basement rocks within the Zagros Orogen: *Economic Geology*, v. 101, p. 1497–1524.
- Morley, C.K., Kongwung, B., Julapour, A.A., Abdolghafourian, M., Hajian, M., Waples, D., Warren, J., Otterdoorn, H., Srisuriyon, K., and Kazemi, H., 2009, Structural development of a major Cenozoic basin and transpressional belt in central Iran: The central basin in the Qom-Saveh area: *Geosphere*, v. 5, p. 325–362. Doi: 10.1130/GES00223.1.
- Mouthereau, F., 2011, Timing of uplift in the Zagros belt/Iranian plateau and accommodation of late Cenozoic Arabia–Eurasia convergence: *Geological Magazine*, v. 148, p. 726–738.
- Mouthereau, F., Lacombe, O., and Vergés, J., 2012, Building the Zagros collisional orogen: Timing, strain distribution and the dynamics of Arabia/Eurasia plate convergence: *Tectonophysics*, v. 532–535, p. 27–60.
- Navapour, P., Angelier, J., and Barrier, E., 2010, Mesozoic extensional brittle tectonics of the Arabian passive margin, inverted in the Zagros collision (Iran, interior Fars), *in* Leturmy, P., and Robin, C., eds., *Tectonics and Stratigraphic Evolution of Zagros and Makran during the Mesozoic–Cenozoic*: Geological Society, London, Special Publication 330, p. 65–96.
- Nemati, M., and Yassaghi, A., 2010, Structural characteristics of the transitional zone from internal to external parts of the Zagros orogen, Iran: *Journal of Asian Earth Sciences*, v. 39, p. 161–172.

- Omrani, J., Agard, P., Whitechurch, H., Benoit, M., Prouteau, G., and Jolivet, L., 2008, Arc-magmatism and subduction history beneath the Zagros Mountains, Iran: A new report of adakites and geodynamic consequences: *Lithos*, v. 106, p. 380–398.
- Paul, A., Hatzfeld, D., Kaviani, A., Tatar, M., and Péquignat, C., 2010, Seismic imaging of the lithospheric structure of the Zagros mountain belt (Iran), *in* Leturmy, P., and Robin, C., eds., *Tectonics and Stratigraphic Evolution of Zagros and Makran during the Mesozoic–Cenozoic*: Geological Society, London, Special Publication 330, p. 5–18.
- Radfar, J., 1993, Geological map of Kashan quadrangle 6257: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Ramsay, J.G., and Huber, M.I., 1987, *The techniques of modern structural geology*, Volume 2, folds and fractures: London, Academic Press, 700 p.
- Regard, V., Hatzfeld, D., Molinaro, M., Aubourg, C., Bayer, R., Bellier, O., Yamini-Fard, F., Peyret, M., and Abbassi, M., 2010, The transition between Makran subduction and Zagros collision: Recent advances in its structure and active deformation, *in* Leturmy, P., and Robin, C., eds., *Tectonics and Stratigraphic Evolution of Zagros and Makran during the Mesozoic–Cenozoic*: Geological Society, London, Special Publication 330, p. 43–64.
- Ricou, L.E., 1994, Tethys reconstructed: Plates, continental fragments and their boundaries since 260 Ma from Central America to South-eastern Asia: *Geodinamica Acta* (Paris), v. 7, p. 169–218.
- Robertson, A.H.F., Parlak, O., and Ustaömer, T., 2012, Overview of the Palaeozoic–Neogene evolution of Neotethys in the Eastern Mediterranean region (southern Turkey, Cyprus, Syria): *Petroleum Geoscience*, v. 18, p. 381–404.
- Saccani, E., Delavari, M., Beccaluva, L., and Amini, S., 2010, Petrological and geochemical constraints on the origin of the Nehbandan ophiolitic complex (eastern Iran): Implication for the evolution of the Sistan Ocean: *Lithos*, v. 117, p. 209–228.
- Saccani, E., Allahyari, K., Beccaluva, L., and Bianchini, G., 2013, Geochemistry and petrology of the Kermanshah ophiolites (Iran): Implication for the interaction between passive rifting, oceanic accretion, and OIB-type components in the Southern Neo-Tethys Ocean: *Gondwana Research*, v. 24, p. 392–411.
- Sadeghian, M., and Delavari, S.T., 2007, Geological map of Kamyaran quadrangle 5359: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Sadr, A.H., Mohajjel, M., and Yassaghi, A., 2010, Structural analysis of Zagros collision zone, West Aligodarz: *Scientific Quarterly Journal Geosciences* (Iran), v. 19, p. 149–158 (in Farsi).
- Sahandi, M.R., and Soheili, M., 2005, Geological map of Iran: Geological Survey of Iran, scale 1:1,000,000, 1 sheet.
- Saleeby J., 2003, Segmentation of the Laramide Slab—evidence from the southern Sierra Nevada region: *Geological Society of America Bulletin*, v. 115, p. 655–668.
- Sarkarinejad, K., 2007, Quantitative finite strain and kinematic flow analyses along the Zagros transpression zone, Iran: *Tectonophysics*, v. 42, p. 49–65.
- Sarkarinejad, K., and Azizi, A., 2008, Slip partitioning and inclined dextral transpression along the Zagros Thrust System, Iran: *Journal of Structural Geology*, v. 30, p. 116–136.
- Sarkarinejad, K., Faghih, A., and Grasemann, B., 2008, Transpressional deformations within the Sanandaj–Sirjan metamorphic belt (Zagros Mountains, Iran): *Journal of Structural Geology*, v. 30, p. 818–826.
- Sarkarinejad, K., Godin, L., and Faghih, A., 2009, Kinematic vorticity flow analysis and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology related to inclined extrusion of the HP–LT metamorphic rocks along the Zagros accretionary prism, Iran: *Journal of Structural Geology*, v. 31, p. 691–706.

- Saura, E., Vergés, J., Homke, S., Blanc, E., Serra-Kiel, J., Bernaola, G., Casciello, E., Fernández N., Romaine, I., Casini, G., Embry, J.C., Sharp, I.R., and Hunt, D.W., 2011, Basin architecture and growth folding of the NW Zagros early foreland basin during the Late Cretaceous and early Tertiary: *Journal of the Geological Society, London*, v. 168, p. 235–250.
- Şengör, A.M.C., and Natal'in, B.A., 1996, Paleotectonics of Asia: Fragments of a synthesis, *in* Yin, A., and Harrison, T.M., eds., *The Tectonic Evolution of Asia*: Cambridge, Cambridge University Press, p. 486–640.
- Sepahi, A.A., Whitney, D.L., and A. A. Baharifar, A.A., 2004, Petrogenesis of andalusite–kyanite–sillimanite veins and host rocks, Sanandaj–Sirjan metamorphic belt, Hamadan, Iran: *Journal of Metamorphic Geology*, v. 22, p. 119–134.
- Sepehr, M., and Cosgrove, J.W., 2004, Structural framework of the Zagros Fold–Thrust Belt, Iran: *Marine and Petroleum Geology*, v. 21, p. 829–843.
- Sepehr, M., Cosgrove, J., and Moieni, M., 2006, The impact of cover rock rheology on the style of folding in the Zagros fold-thrust belt: *Tectonophysics*, v. 427, p. 265–281.
- Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., and Chandler, M., 2012, Global continental and ocean basin reconstructions since 200 Ma: *Earth-Science Reviews*, v. 113, p. 212–270.
- Shafaii Moghadam, H., Corfu, F. and Stern, R.J., 2013, U–Pb zircon ages of Late Cretaceous Nain–Dehshir ophiolites, Central Iran: *Journal of the Geological Society, London*, v. 170, p. 175–184.
- Shafaii Moghadam, H., and Stern, R.J., 2011, Geodynamic evolution of Upper Cretaceous Zagros ophiolites: Formation of oceanic lithosphere above a nascent subduction zone: *Geological Magazine*, v. 148, p. 762–801.
- Shafaii Moghadam, H., Stern, R.J., and Rahgoshay, M., 2010, The Dehshir ophiolite (central Iran): Geochemical constraints on the origin and evolution of the Inner Zagros ophiolite belt: *Geological Society of America Bulletin*, v. 122, p. 1516–1547.
- Shafaii Moghadam, H., Whitechurch, H., Monsef, I., and Rahgoshay, M., 2009, Significance of Nain–Baft ophiolitic belt (Iran): Short-lived, transtensional Cretaceous back-arc oceanic basins over the Tethyan subduction zone: *Comptes Rendus Geoscience*, v. 341, p. 1016–1028.
- Shahbazi, H., Siebel, W., Pourmoafae, M., Ghorbani, M., Sepahi, A.A., Shang, C.K., and Vousoughi Abedini, M., 2010, Geochemistry and U–Pb zircon geochronology of the Alvand plutonic complex in Sanandaj–Sirjan Zone (Iran): New evidence for Jurassic magmatism: *Journal of Asian Earth Sciences*, v. 39, p. 668–683.
- Shahidi, A.R., and Nazari, B., 1997, Geological map of Harsin quadrangle 5558: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Sheikholeslami, M.R., 2008, Geological map of Mahallat quadrangle 6057: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Sherkati, S., Molinaro, M., Frizon de Lamotte, D., and Letouzey, J., 2005, Detachment folding in the Central and Eastern Zagros fold-belt (Iran): Salt mobility, multiple detachments and late basement control: *Journal of Structural Geology*, v. 27, p. 1680–1696.
- Sherkati, S., Letouzey, J., and Frizon de Lamotte, D., 2006, Central Zagros fold-thrust belt (Iran): New insights from seismic data, field observation, and sandbox modelling: *Tectonics*, v. 25, TC4007, doi:10.1029/2004TC001766, 27 p.
- Soheili, M., Jafarian, M.B., and Abdollahe, M.R., 1992, Geological map of Aligudarz quadrangle 5956: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Soheili, M., 1993, Geological map of Khorramabad quadrangle D7: Geological Survey of Iran, scale 1:250,000, 1 sheet.

- Stampfli, G.M., and Borel, G.D., 2002, A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones: *Earth and Planetary Science Letters*, v. 196, p. 17–33.
- Stampfli, G., Marcoux, J., and Baud, A., 1991, Tethyan margins in space and time: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 87, p. 373–409.
- Stern, R.J., 2002, Subduction zones: *Reviews of Geophysics*, v. 40, RG1012, doi:10.1029/2001RG000108, 38 p.
- Stern, C.R., 2011, Subduction erosion: Rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle: *Gondwana Research*, v. 20, p. 284–308.
- Talebian, M., and Jackson, J., 2002, Offset on the Main Recent Fault of NW Iran and implications for the late Cenozoic tectonics of the Arabia–Eurasia collision zone: *Geophysical Journal International*, v. 150, p. 422–439.
- Thiele, O., Alavi-Naini, M., Assefi, R., Houshmandzadeh, A., Seyed-Emami, K., and Zahedi, M., 1968, Explanatory text of the Golpaygan quadrangle E7: Geological Survey of Iran, scale 1:250,000, 24 p.
- Verdel, C., Wernicke, B.P., Ramezani, J., Hassanzadeh, J., Renne, P.R., and Spell, T.L., 2007, Geology and Thermochronology of Tertiary Cordilleran-style metamorphic core complexes in the Saghand region of central Iran: *Geological Society of America Bulletin*, v. 119, p. 961–977.
- Verdel, C., Wernicke, B.P., Hassanzadeh, J., and Guest, B., 2011, A Paleogene extensional flare-up in Iran: *Tectonics*, v. 30, TC3008, doi: 10.1029/2010TC002809, 20 p.
- Vergés, J., Saura, E., Casciello, E., Fernández, M., Villaseñor, A., Jiménez-Munt, I., and García-Castellanos, D., 2011, Crustal-scale cross-sections across the NW Zagros belt: implications for the Arabian margin reconstruction: *Geological Magazine*, v. 148, p. 739–761.
- Vernant, P., Nilforoushan, F., Hatzfeld, D., Abbassi, M.R., Vigny, C., Masson, F., Nankali, H., Martinod, J., Ashtiani, A., Bayer, R., Tavakoli, F., and Chéry, J., 2004, Contemporary crustal deformation and plate kinematics in Middle East constrained by GPS measurements in Iran and northern Oman: *Geophysical Journal International*, v. 157, p. 381–398.
- Vincent, S.J., Allen, M.B., Ismail-Zadeh, A.D., Flecker, R., Foland, K.A., and Simmons, M.D., 2005, Insights from the Talysh of Azerbaijan into the Paleogene evolution of the South Caspian region: *Geological Society of America Bulletin*, v. 117, p. 1513–1533.
- Woodruff, F., and Savin, S.M., 1989, Miocene deepwater oceanography: *Paleoceanography*, v. 4, p. 87–140.
- Wrobel-Daveau, J.-C., Ringenbach, J.-C., Tavakoli, S., Ruiz, G.M.H., Masse, P., and Frizon de Lamotte, D., 2010, Evidence for mantle exhumation along the Arabian margin in the Zagros (Kermanshah area, Iran): *Arabian Journal of Geosciences*, v. 3, p. 499–513.
- Yin, A., 2010, Cenozoic tectonic evolution of Asia: A preliminary synthesis: *Tectonophysics*, v. 488, p. 293–325.
- Zahedi, M., 1976, Geological map of Shahreza quadrangle 6354: Geological Survey of Iran, scale 1:100,000, 1 sheet.
- Zahedi, M., and Hajian, J., 1985, Geological map of Sanandaj quadrangle C5: Geological Survey of Iran, scale 1:250,000, 1 sheet.

Figure Captions

Figure 1. Map showing the distribution of the Zagros Fold and Thrust, Eocene rocks of the Urumieh–Dokhtar Magmatic Arc and the Sanandaj–Sirjan Zone in western Iran. Also shown are the outer (Nain–Dehshir–Baft) and inner (Kermanshah–Neyriz) Zagros ophiolite belts and Cretaceous volcanic rocks northwest of Tehran and north of Sanandaj. The Zagros Orogen consists of the Sanandaj–Sirjan Zone and the Zagros Fold and Thrust Belt.

Figure 2. Regional map of the Zagros Orogen in NW Iran. See Figure 1 for location. Abbreviations: CTS–Cehel Taghi Syncline, HZRF–High Zagros Reverse Fault, KSF–Kuh-e Sefid Fault, MRF–Main Recent Fault, MZT–Main Zagros Thrust, QAPB–Qorveh–Aligodarz Plutonic Belt. Also shown are location of cross sections AA', BB' and CC' from Alavi (2007), the Zagros03 seismic experiment from Paul *et al.* (2010) and the crustal cross section from Vergés *et al.* (2011). The toe line showing the northeastward extent of Arabian crust in the subsurface is also shown (from Paul *et al.* 2010). For cross sections aa', bb', cc', and dd' see Figures 4, 6, 9 and 14 respectively. Ages of granites in the Sanandaj–Sirjan Zone are from Ahmadi-Khalaji *et al.* (2007), Mahmoudi *et al.* (2011), and Esna-Ashari *et al.* (2012). Extent of the QAPB (Qorveh–Aligodarz Plutonic Belt) shown by dotted line. U–Pb zircon ages on granites from the Muteh Gold Mine and on gneiss from farther west are from Hassanzadeh *et al.* (2008). The age of the Permian granite at Hasanrobat is from Alirezaei and Hassanzadeh (2012)

Figure 3. Geological map of the Shahrekord region compiled and reinterpreted from Fakhari *et al.* (2008), Nemati and Yassaghi (2010), and Babaahmadi *et al.* (2012). For location see Figure 2. Note that Bakhtiari Formation south of Shahrekord consists of Oligocene(?) and Early Miocene parts (Fakhari *et al.* 2008). Abbreviations: AT–Ardal Thrust, BT–Ben Thrust, BZT–Bazoft Thrust, KT–Kuhrang Thrust, MS–Mili Splay, MT–Mafaroon Thrust, MZT–Main Zagros Thrust.

Figure 4. Cross section aa' to the NW of Shahrekord. For location see Figures 2 and 3. See Figure 3 for a key to geological units. Structure of the Zagros Fold and Thrust Belt is redrawn and reinterpreted from Nemati and Yassahi (2010). The high-grade rocks (including eclogites) of the Sanandaj-Sirjan Zone form the core of an antiform.

Figure 5. Geological map of the Azna region compiled and reinterpreted from the Aligodarz 1:100,000 geological map of Soheili *et al.* (1992), the Khorramabad 1:250,000 geological map (Soheili 1993), and Sadr *et al.* (2010). For location see Figure 2. Abbreviations: CNT–Cheshmeh–Narges Thrust, GGT–Galeh–Ghorchak Thrust, MRF–Main Recent Fault, MZT–Main Zagros Thrust, RT–radiolarite thrust.

Figure 6. Cross section bb' from the Azna region. For location see Figures 2 and 5. See Figure 5 for a key to geological units. Movement of blocks either side of Main Recent Fault: A-away, T-towards.

Figure 7. Geological map of the Kermanshah and Harsin 1:100,000 geological map areas simplified and reinterpreted from Shahidi and Nazari (1997) and Bavandpur and Hajihoseini (1999) respectively. Locations of detailed cross sections are given across the High Zagros Belt (Figure 8) and the radiolarites (Figure 11). For location of this map see Figure 2.

Figure 8. Cross section of the High Zagros Belt redrawn and reinterpreted from Elyaszadeh and Mohajjel (2011). See Figure 7 for location. Abbreviations: Am–Amiran Formation, Ga–Garau Formation, Gu–Gurpi Formation, Il–Ilam Formation, Ka–Kashkan Formation, Sv(l)–lower Sarvak Formation, Sv(u)–upper Sarvak Formation, fz–fault zone.

Figure 9. Cross section cc' from the Kermanshah region. See Figure 2 for location. The Kuh-e Sefid Fault is interpreted a reverse fault moderately dipping to the NE that has cut thin-skinned structures in the adjoining units. The Bisotun limestones are shown thrust over the Cretaceous ophiolite (Wrobel-Daveau *et al.* 2010). Abbreviations: Bl–Bisotun limestone, Oph–ophiolite. Shaded layer SW of the Kuh-e Sefid Fault is a limestone marker in the upper Sarvak Formation (see Figure 8).

Figure 10. Time-space plot for Permian and younger rocks from the SW to NE across the Zagros Orogen in the Kermanshah region.

Figure 11. Cross sections across the radiolarites redrawn and reinterpreted from Mohajjel and Biralvand (2011). See Figure 7 for locations. Thrust faults shown by slightly thicker lines with half arrow heads. Abbreviations: Apt-Alb = Aptian-Albian, Apt-Tur = Aptian-Turonian, Baj-Ber = Bajocian-Berriasian, Haut-Tur = Hauterivian-Turonian, Pliens-Apt = Pliensbachian-Aptian, Val-Apt = Valanginian-Aptian.

Figure 12. Geological map and cross section of the northern half of the Mahallat 1:100,000 geological map. Simplified and redrawn from Sheikholeslami (2008). See Figure 2 for location

Figure 13. Geological map of the region west of Borujerd. Compiled and reinterpreted from the Nahavand 1:100,000 geological map of Hossaini-Doust and Mahdavi (1992), the Borujerd 1:100,000 geological map of Hajmolla-Ali *et al.* (1989), Alavi and Mahdavi (1994) and Mohajjel and Behyari (2010). For location see Figure 2. Abbreviation: MRF–Main Recent Fault. Thrust faults shown as thicker lines with black triangles on hanging wall.

Figure 14. Cross section dd' from the Nahavand region. For location see Figures 2 and 13. Redrawn and reinterpreted from Hossaini-Doust and Mahdavi (1992) and Mohajjel and Behyari (2010). Offset across the Main Recent Fault is conjectural and under alluvial cover. Abbreviations: A-away, T-towards, Kv-Cretaceous volcanics, JI-Jurassic limestone, Ks-Cretaceous sedimentary rocks, MI-Miocene limestone, SSZ-Sanandaj-Sirjan Zone, ZFTB-Zagros Fold and Thrust Belt.

Figure 15. Map and cross section of Middle to Late Jurassic elements of the southwestern Eurasian margin in the northwestern Sanandaj–Sirjan Zone. The subduction zone is interpreted as having a moderately dipping slab. Crust of the Sanandaj–Sirjan Zone is simplified with upper crustal metamorphic rocks overlying Pan-African crust. The forearc is no longer preserved in the collision zone and has been removed by a combination of tectonic erosion along the early Cenozoic subduction zone, erosion during Late Eocene continental collision and strike-slip faulting.

Figure 16. Map and cross section of Early Cretaceous elements of the southwestern Eurasian margin in the NW Sanandaj-Sirjan Zone. A moderately dipping subduction zone to the NE is shown but note that this only applies to the region NW of Dorud. The Cretaceous magmatic arc has migrated trenchward accompanying growth of a hypothetical subduction complex so that the axis of the Jurassic arc is now in a backarc setting. The arc is still topographically subducted. The arc is apparently truncated to the SE along the Main Zagros Thrust or alternatively it dies out to the SE which may be related to segmentation of the slab (see text).

Figure 17. Cross section of Eocene elements of the southwestern Eurasian margin in the northwestern Sanandaj–Sirjan Zone. Location of cross section is the same as that for the Jurassic subduction zone (see Figure 15). In the Late Cretaceous shallowing of the subducting slab caused deformation in the backarc and igneous activity was driven away from its former location to be re-established as the Urumieh–Dokhtar Magmatic Arc in the Eocene. Closer to the trench anomalous Eocene plutons are adjacent to the Jurassic magmatic arc. The forearc has been lost presumably mainly from tectonic erosion along the Late Cretaceous to Eocene subduction zone along with uplift and erosion during the early stages of continental collision in the Late Eocene. Strike-slip displacement of forearc crust may also have occurred although this crust has yet to be identified in the Zagros Orogen.