Tectono-stratigraphy and general structure of the northwestern Zagros collision zone across the Iraq-Iran border

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Abstract

Tectono-stratigraphic units within the Zagros Orogen in northeast Iraq (foreland) and northwest Iran (hinterland) are correlated to provide an integrated map along the collision zone. Access to this part of Iraq during the past four decades has been limited due to geopolitical situation. Structural cross-sections across the Zagros Suture Zone in this area reveal the relationships between the tectonic terranes of various ages and different origins. Terranes of oceanic affinity have accreted onto the Arabian plate during collision-accretion events that started in the Late Cretaceous. The collision resulted in closure of the Neotethys Ocean and the construction of a structurally complex suture zone. Jurassic-Cretaceous deep ocean radiolarites of the Qulqula-Kermanshah terrane and ophiolitic mélange serpentinites were structurally accreted against the Arabian passive margin during an ophiolite arc-continent collision event in the Late Cretaceous. The overthrust radiolarites and ophiolitic mélange terranes initiated the development of the foreland basin overlapping flysch (turbidites) and molasse assemblages on the now active Arabian margin. Eocene-Oligocene volcano-sedimentary rocks of the Walash-Naopurdan-Kamyaran terrane developed as an intra-oceanic island-arc within the intervening Neotethys Ocean. They now structurally overlie the older ophiolite mélange and radiolarite terranes as a result of continued convergence onto the margin of the Arabian Plate. These younger thrust sheets and nappes have been transported over the Miocene molasse unit of the Tertiary Red Beds in the flexural foreland basin and covered the Late Cretaceous accretionary complex terranes and foreland basin assemblages. The Qulqula-Kermanshah terrane is exposed in a tectonic window in the northeastern part of the mapped area indicating that the Late Cretaceous accreted terranes occur below the Walash-Naopurdan-Kamyaran thrust sheet. A Late Cretaceous ophiolite-bearing terrane named the "Upper Allochthon" (i.e. Gemo-Qandil nappe, 97-118 Ma) was emplaced by younger thrust sheets over the Eocene-Oligocene Walash-Naopurdan-Kamyaran terrane by out-of-sequence thrusting. Mesozoic metamorphic rocks from the hinterland, including volcanic and intrusive rocks of the active Iranian continental margin (Sanandaj-Sirjan zone), were emplaced during continent-continent collision and occur in the youngest nappes and klippes along the Zagros Suture Zone.

Keywords: Iraq; Iran; Neotethys; Tectonic; Zagros

1. Introduction

The Zagros Suture Zone passes along the border of northeast Iraq and southwest Iran. Tectonic units in the Zagros Orogen have been exposed in both countries in several thrust sheets and nappes. Parts of these tectonic units have been described by a number of researchers in both Iran (e.g. Stocklin, 1968; Berberian and King, 1981; Alavi, 1994; Mohajjel et al., 2003; Agard et al., 2005, 2011) and Iraq (Aswad, 1999; Jassim and Goff, 2006). In spite of regional works on the geodynamic evolution of the Zagros Orogen (Agard et al., 2011) and timing of the collision events (Mouthereau et al., 2011, 2012) that produced a unified tectonic story for the whole Zagros collision zone, the structural relationships between the tectonic units in northeast Iraq and northwest Iran have not previously been combined. Recent field observations in both countries have resulted in new structural, geochemical and radiometric age data (e.g. Moinevaziri et al., 2009; Mohajjel and Biralvand, 2010; Ali et al., 2012; Aziz et al., 2011; Azizi et al., 2011). The timing and magmatic affinities of Cretaceous and younger igneous rocks have also been clarified, especially for the northwestern Zagros (Jahangiri, 2007; Azizi and Jahangiri, 2008; Azizi and Moinevaziri, 2009; Azizi et al., 2011). Stratigraphic data and radiometric ages from the arc in the northwestern Zagros Orogen (Azizi and Asahara, 2013) have more effectively constrained the timing of ophiolite emplacement as well as placing tighter constraints on the Cenozoic uplift history (Homke et al., 2009, 2010; Saura et al., 2011). These new observations enable us to correlate the tectonic units along a

poorly known part of the Zagros Suture Zone.

In this study we present a simplified compilation of the regional geological map of both Iraq and Iran along the northwestern part of the Zagros. This is the first effort to correlate the tectonic units across this area. Detailed geological information has been compiled for the first time across the Iraq-Iran border by using the published larger scale geological maps from both regions to correlate the tectonic units across the border. The tectono-stratigraphic map presented here will serve as important building block for further studies in this part of the Zagros collision zone. Tectonic terranes in the Zagros Suture Zone are identified and named according to the methodology outlined by Coney et al. (1980). Structural cross-sections are presented to demonstrate the thrust sheet relationships and relative ages of convergent tectonic events due to collision along the northeast Iraq and west Iran border.

2. Zagros Orogen

The Zagros Mountains in northeastern Iraq and southwestern Iran are located in the Alpine–Himalayan mountain range that extends in a NW–SE orientation (Fig. 1a). The Zagros Orogen consists of several main parallel tectonic zones: 1) the Urumieh-Dokhtar magmatic arc (UDMA); 2) the Sanandaj-Sirjan zone (SSZ); 3) the Zagros fold and thrust belt (ZFB); and 4) the Mesopotamian foreland basin (Fig. 1b; Berberian and King, 1981; Alavi, 1994; Jassim and Goff, 2006).

The Urumieh-Dokhtar magmatic arc contains intrusive and extrusive rocks of Eocene-Quaternary age that form a zone approximately 50 km wide and up to 4 km thick (Berberian and Berberian, 1981). The southeastern part of the Urumieh-Dokhtar magmatic arc is still active and is associated with ongoing subduction of Indian Ocean crust (McCall, 2002). Calc-alkaline magmatic activity from Eocene to present occurred in this arc, and it represents an Andean-type arc in the Zagros Orogen (e.g., Berberian and Berberian, 1981).

The Sanandaj-Sirjan zone contains intensely deformed and metamorphosed rocks in the hinterland of the Zagros Orogen. It is separated from the Zagros fold and thrust belt by the Main Zagros Thrust in the southwest, and is bordered by the Urumieh-Dokhtar magmatic arc in the northeast (Fig. 1b). It has a length of 1500 km, is 150-250 km wide from southeastern Iran to northeastern Iraq and joins the Taurus belt in Turkey. The rocks in Sanandaj-Sirjan zone are mostly of Mesozoic age and it is characterised by metamorphic and complexly deformed rocks associated with abundant deformed and undeformed Mesozoic plutons, in addition to widespread Mesozoic volcanic rocks (Mohajjel et al., 2003). The northern Sanandaj-Sirjan zone is dominated by Triassic-Jurassic rocks but in places Cretaceous turbidites, deposited in deep submarine fans, are preserved and intruded by plutonic activity. Greenschist facies metamorphism was accompanied by the intrusion of felsic granitoid plutons, including the Borojerd and Alvand plutons. Late Cretaceous and/or younger pyroclastic-volcaniclastic rocks were also found in the northern Sanandaj-Sirjan zone (Alavi, 1994). Late Jurassic-Early Cretaceous events in the Sanandaj-Sirjan zone were followed by the deposition of continental clastic rocks (Stocklin, 1968; Berberian and King, 1981) overlain by Early to Middle Cretaceous carbonate rocks. During the Late Oligocene-Early Miocene the marine carbonates of the Qom Formation accumulated along the northwestern Sanandaj-Sirjan zone. The Sanandaj-Sirjan zone is divided into an outer belt of imbricate thrust slices that includes the Zagros Suture, and an inner belt of Paleozoic-Mesozoic metamorphic rocks (Mohajjel et al., 2003). Regional deformation of the Sanandaj-Sirjan zone in Late Jurassic produced pervasive southwest-verging, northwesterly trending fold structures and accompanying greenschist facies metamorphism (Mohajjel and Fergusson, 2000; Mohajjel et al., 2003). This convergent deformation is related to crustal thickening along the active margin of the northeastern Sanandaj-Sirjan zone. The complexities in adjoining low grade metamorphic rocks and deformed silicic igneous rocks in the Dorud-Azna region indicate that this deformation was produced during an episode of dextral transpression with low obliquity (Mohajjel and Fergusson, 2000).

The Zagros fold and thrust belt is contained between the Main Zagros Thrust to the northeast and the Mountain Front Fault to the southwest, with some extension of folding beyond this area (Fig. 1b). This belt contains huge, elongated anticlines, penetrated by salt plugs from the Hormoz Salt in the Zagros Mountains. The salt diapirs formed via solution processes associated with compression of buried evaporitic deposits, especially in the Hormuz Formation, or from localized deformation associated with strike-slip faulting in basement rocks. The development of anticlines in the competent cover-rock, combined with minor strike-slip faults and horizontal displacements of parts of folded structures, strongly point to the presence of these basement faults (Bahroudi and Talbot, 2003). Cooling and exhumation of thrust sheets and salt plugs in the High Zagros continued from Middle to Late Miocene time (Gavillot et al., 2010). The Eocene-Oligocene Asmari Limestone and Mesozoic formations dominate the topography. Structures change from NW-SE trending in northwest to E-W trending in central and

ENE-WSW trending in the southeastern parts of the fold belt. The Phanerozoic sedimentary column in the belt is estimated to be up to 12 km thick (James and Wynd, 1965). The belt was faulted and folded during continent-continent collision. The Cambrian-Miocene strata were folded, while different detachment surfaces affected the folding (Berberian, 1995; Sherkati et al., 2005; Molinaro et al., 2005).

The Cretaceous Mesopotamian proto-foreland basin contains erosional products from the accretionary complex terranes. In the Iraqi segment of the Zagros Suture Zone, this flexural foreland basin is partitioned into a foredeep (i.e., Shiranish Formation), forebulge or "peripheral bulge" (i.e., Aqra Formation), and marine flysch trough (Tanjero Formation; Aswad et al., 2013; fig.15a). Therefore, the Tanjero Formation is equivalent in age to the Amiran Formation in Iran, and they are considered to represent typical peripheral foreland deposits. The Tanjero Formation was deposited where deeper water marine conditions were present. The emplacement of the ophiolitic serpentinite mélange was probably synchronous with late turbidite sedimentation (Maastrichtian) in the Tanjero Formation since the latter contains serpentinite-rich terrigenous sediments derived from the mélange (Aziz et al., 2011). Through the Paleogene, however, the flexurally deformed proto-foreland basin changed in stratal architecture with molasse deposits replacing the turbidite sedimentation of the Tanjero Formation. The Paleocene-Miocene molasse successions in the Tertiary Red Beds record the filling of a complex non-marine flexural foreland basin. Unconformities separate the different units in the Tertiary Red Beds and represent migration of the flexural basin as convergence proceeded. The terrigenous sediment accommodation was proportional to flexural subsidence driven by the topographic load of the accretionary complex terrane and advancing nappes. Field relationships confirm that the Tanjero and Tertiary Red Beds assemblages documented a transition from early deep-marine foreland sedimentation (turbidites) to later coarse-grained, non-marine and shallow-marine flexural foreland sedimentation ('molasse'). The volcaniclastic deposits in the Walash succession and the Nummulites-bearing carbonates in the Naopurdan sequence were still accumulating on the remaining oceanic lithosphere farther to the northeast and were, in part, coeval with the molasse sedimentation on the foreland basin in the southwest.

3. Tectonic units of the Zagros Orogen in northeastern Iraq and southwestern Iran

Several terranes of the Zagros Orogen were accreted to the Arabian plate during closure of the Neotethys. In the study area they include the Late Jurassic to Early Cretaceous metamorphic and igneous rocks of the hinterland (Sanandaj-Sirjan zone), Late Triassic to Middle/Late Cretaceous Bisotun-Avroman carbonates, Jurassic-Cretaceous radiolarites of the Qulqula-Kermanshah terrane, Late Cretaceous ophiolitic mélanges, Eocene-Oligocene Walash-Naopurdan-Kamyaran island-arc to back-arc complexes and ophiolite-bearing nappes. The synorogenic Eocene- Oligocene Red Bed series were deposited in the adjacent foreland basin (Fig. 2).

3.1 Metamorphic and igneous rocks of the hinterland

Mesozoic metamorphic rocks (Gimo and Qandil Groups) come from the Iranian hinterland and occur in several thrust sheets NE of the Zagros Suture and in the youngest nappes in the Mawat area of the foreland basin. The Shalair zone in northeastern Panjween mainly comprises thrust sheets consisting of Cretaceous metapelite and carbonates. These thrust sheets contain imbricate slices of Triassic carbonate (Jassim and Goff, 2006). To the southeast in the Marivan area the Cretaceous rocks are described as low grade metamorphic rocks, including phyllite, with minor meta-limestone, and are turbiditic in places (Nogole Sadat and Houshmandzadeh, 1993). Cretaceous andesitic volcanic rocks occur within this succession. Similar rocks exist in several thrust sheets in the Baneh-Sardasht-Piranshahr area (Eftekharnedjad, 1984).
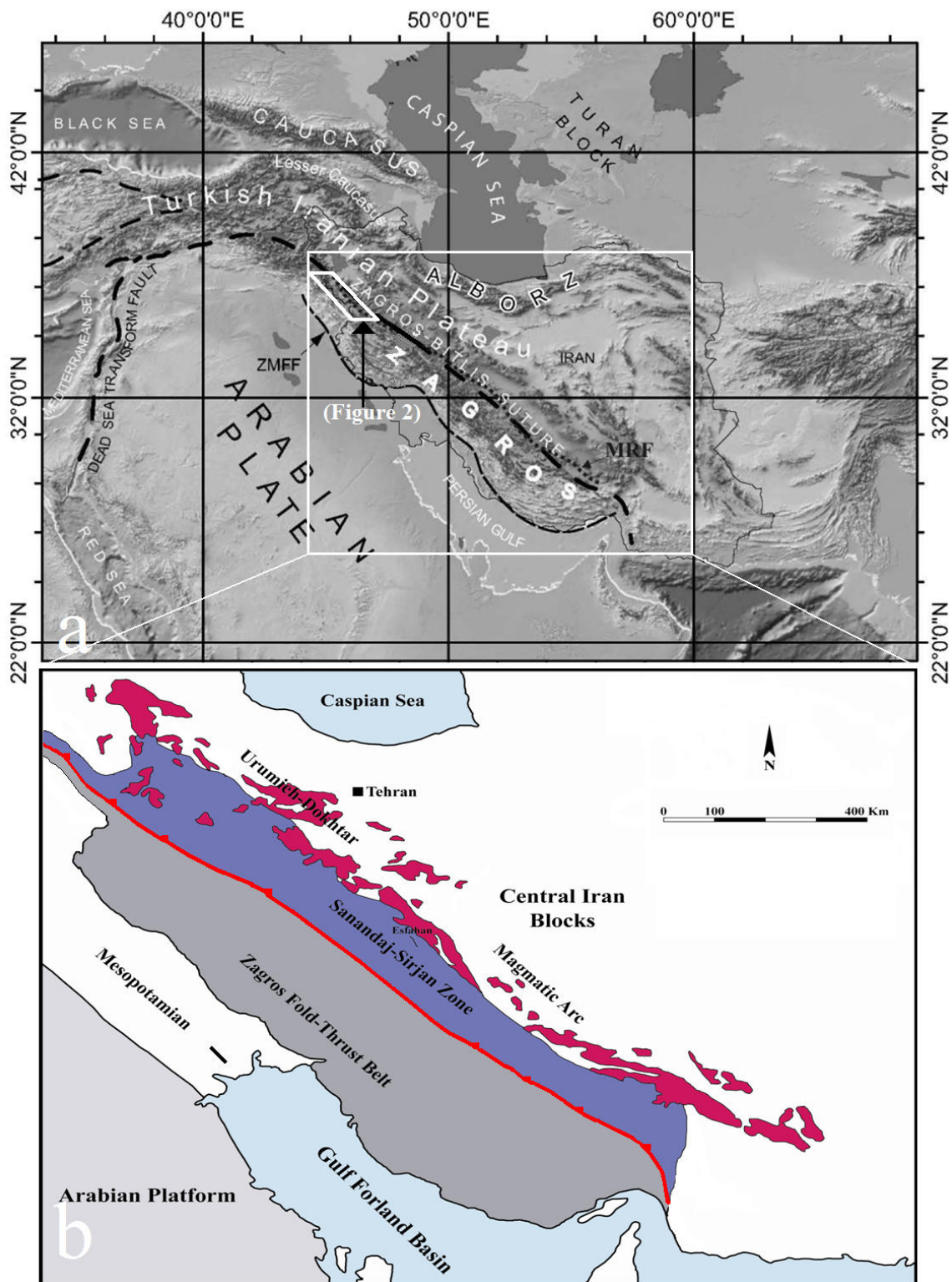
Figure 1. Zagros Orogen, a part of the Alps-Himalaya orogenic belt. Location of the study area
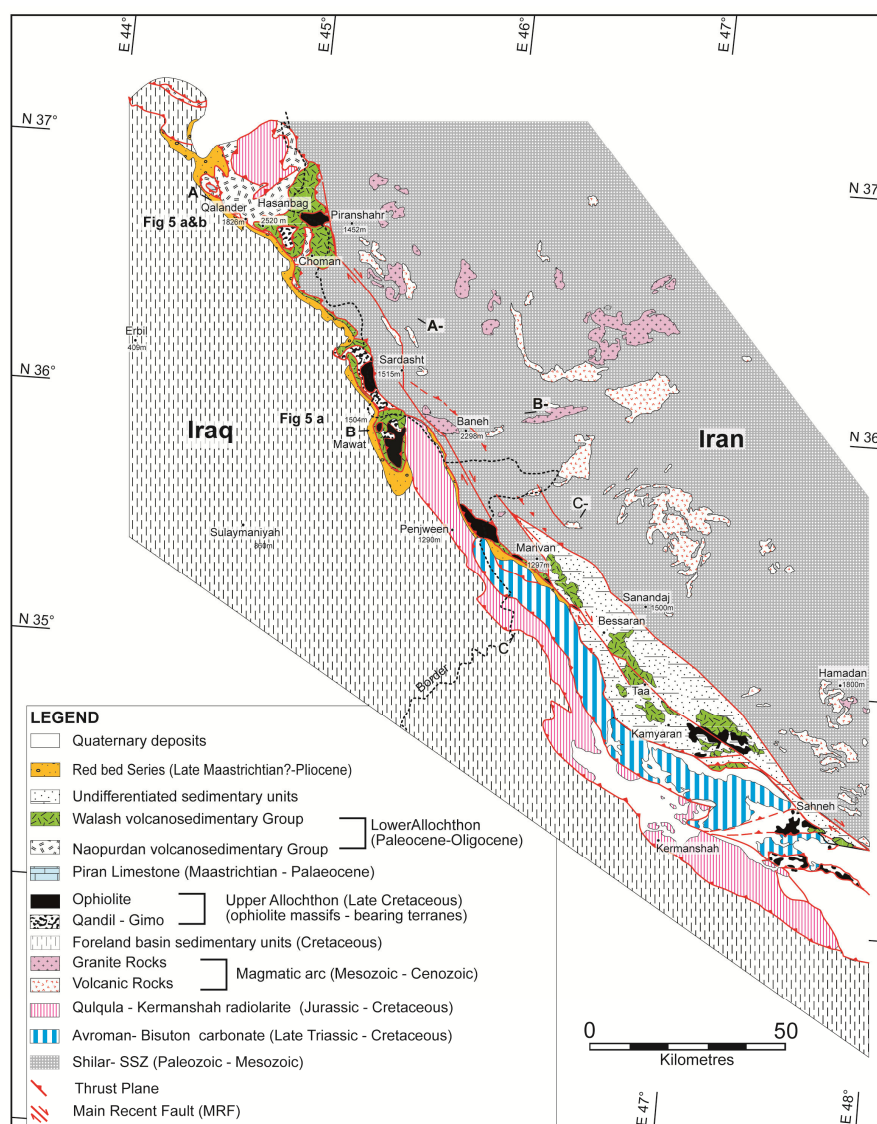
Figure 2. Simplified geological map of the Zagros collision zone along the Iraq-Iran border

(after Ali, 2012).

3.2 Mesozoic-Cenozoic continental magmatic arc

A Mesozoic-Cenozoic continental magmatic arc (Berberian and King, 1981; Mohajjel et al., 2003; Azizi and Moinevaziri, 2009) is located on the northeastern side of the Zagros Suture Zone (Fig. 2) and has been produced by subduction of the Neotethys Ocean since Late Jurassic (Berberian et al., 1982; Alavi, 1994). During most of the second half of the Mesozoic, calc-alkaline magmatic activity along this Andean-like margin progressively shifted northward (Berberian and King, 1981; Mohajjel et al., 2003). The Mesozoic magmatic arc includes Eocene granitoids that intrude Cretaceous sediments on the southwestern side of the Sanandaj-Sirjan zone (cross-section BB́ in Fig. 3) in the west Baneh area (Nogole Sadat and Houshmandzadeh, 1993) and southeast of Piranshahr (Mazhari et al., 2009), indicating that subduction-related magmatism associated with the Iranian continental arc continued into the Cenozoic before the final continent-continent collision occurred.

The magmatic arc plutons are accompanied by Late Jurassic to Early Cretaceous volcanic and shallow marine successions (Mohajjel et al., 2003). The volcanic rocks are unconformably overlain by a Cretaceous (Albian-Aptian-Cenomanian) terrestrial succession (Braud, 1987; Shahidi and Nazari, 1997). Geochemical characteristics of the andesites presented by Azizi and Moeinevaziri (2009) indicate that they are calc-alkaline volcanics typical of continental arcs. The age of this volcanic arc became younger to the northwest where a belt of Cretaceous volcanic rocks occurs northeast of Sanandaj city. It is 5-15 km wide and 80-120 km long, striking NW–SE

parallel to the Zagros Suture (Fig. 2). Cretaceous sequences in the Sanandaj region are locally different to those in other parts of the Sanandaj-Sirjan zone. They consist of a thick (2000–3000 m) sequence of shallow-marine detrital sediments overlain by marine sediments inter-bedded with volcanic rocks. This sequence is repeated over at least three cycles. The high rate of subsidence in the Sanandaj region led to a short interval during which pelagic sediments were deposited in the basin (Zahedi et al., 1985). The belt appears to be the northern extention of the marginal sub-zone of the Sanandaj-Sirjan zone proposed by Mohajjel et al. (2003), which is characterized by Late Jurassic-Early Cretaceous volcanic rocks and shallow-marine sediments. These volcanic rocks on the southwestern side of the Sanandaj-Sirjan zone were interpreted to represent successions that were tectonically dislocated and transported by thrusts from the Urumieh-Dokhtar magmatic arc (Alavi, 1994). However, the age of this magmatic activity is different from the Urumieh-Dokhtar magmatic arc (Mohajjel et al., 2003). These volcanic rocks are interbedded with detrital sediments such as shale, sandstone and sandy limestone (Braud, 1987). Abundant subduction related granitoids were intruded into the Sanandaj-Sirjan zone ranging in age from Late Jurassic (Ahmadi Khalaji et al., 2007; Shahbazi et al., 2011) to Cretaceous (Mahmoudi et al., 2012; Masoudi et al. 2002; Ghalamghash et al., 2009). Mazhari et al. (2009) reported undeformed Eocene (~41 Ma) alkaline, bimodal, A2-type gabbros and granitiods from the Piranshahr massif in the Sanadaj–Sirjan Zone, west Iran, and interpreted them to have formed in an extensional, post-orogenic setting and, therefore, post-dating the final continent-continent collision by up to 10 Ma. Allen (2009) made the point that A-type magmas do not necessarily exclude subduction settings and that some form of back-arc extension could account for the alkaline Piranshahr massif. The existence of the Neo-Tethys Ocean after the Eocene is confirmed by recent dating of calc-alkaline, island-arc intrusions (Dargahi, 2007; Dargahi et al., 2010) indicating that the final collision could not have occurred before the Miocene (Jackson et al. 1995; Mohajjel et al., 2003). An important aspect of this paper is to emphasise that the Eocene island-arc volcanic and intrusive equivalents of the Walash-Naopurdan-Kamyaran terrane (see below) are not related to the Jurassic-Cretaceous continental arc rocks that developed within the Sanandaj-Sirjan zone.

3.3 Bisotun- Avroman carbonates

Bisotun-Avroman carbonates extend sub-parallel to the northeastern side of the Qulqula-Kermanshah radiolarites (Figs 2 and 3b). These thick limestones are folded, affected by imbricate thrust faulting and range in age from Late Triassic to Middle/Late Cretaceous (Cenomanian). The Bisotun-Avroman carbonates were also referred to as the 'inner carbonate platform' by Kazmin et al. (1986). Differences between these carbonates and the Zagros fold belt deposits in terms of facies and thickness suggest that Bisotun-Avroman limestone was deposited in a distinct palaeogeographic domain, separate from the Arabian platform and the radiolarites (Braud, 1987; Mohajjel et al., 2003).

3.4 Qulqula-Kermanshah terrane

Radiolarites are exposed in two separate domains in southeastern (Kermanshah) and northwestern (north of Hasanbag Mountain) parts of the Iraq-Iran border, with a small outcrop in the Qulqula area in the central part. The main exposure of the radiolarites occurs from east of Mawat and extends 450 km to the southeast terminating in the Kermanshah area inside Iran (Fig. 2). The radiolarites range in age from Triassic to Cretaceous and form a 10-40 km wide exposure in the Kermanshah area (Braud, 1987). The Kermanshah radiolarites were recently dated using radiolarian biostratigraphy producing an age range from Early Pliensbachian to Turonian for the youngest (Gharib and De Wever, 2010). The age of radiolarite sequences in northeastern Iraq is controversial and has not yet been precisely determined. Here the cherts are structurally repeated by isoclinal folding and thrust faulting (Buday, 1980), which is typical of ocean floor cherts being accreted into a sediment-starved trench.

Abundant well-bedded radiolarian cherts in different colours, inter-bedded with thick to medium-bedded limestone and shale, are exposed in the Kermanshah area. Chevron folds were produced in well-bedded thin layers of radiolarian cherts But no volcanic rocks are included in the radiolarites in the Kermanshah area. Olistoliths from the Zagros continental carbonates are found along the southwestern margin of the radiolarites (Braud 1987; Mohajjel, 1997). The geometry and style of folding indicates southwest vergence. Folded radiolarites were cut by thrust faults and displaced several times in different areas (Mohajjel and Biralvand, 2010). Radiolarite fragments exist in the Amiran-Tanjero turbidites of Paleocene age in the Zagros foreland. This indicates Late Cretaceous thrusting of the radiolarites in this area (Braud, 1987).

Radiolarites in Qulqula gorge are unconformably overlain by Tertiary clastics of Maastrichtian-Pliocene age. They are also thrust over the Zagros platform carbonates containing Tithonian-Cenomanian sediments of deep

marine facies, including radiolarian chert, mudstone and limestone with basic volcanic rocks and conglomerate in the upper parts. The whole sequence is strongly isoclinally folded and cut by reverse faults. The Qulqula Radiolarites and serpentinite mélange were shed as flysch deposits into the Tanjero Formation (Campanian-Maastrichtian age). Therefore, their emplacement and exhumation may be synchronous with the flysch sedimentation Radiolarites to the northwest at the triple junction of the Iran, Iraq and Turkey borders are associated with volcanic and ultramafic rocks (Jassim and Goff, 2006). Radiolarites are also exposed in the Azna (Mohajjel et al., 2003) and Neyriz areas (Ricou et al., 1977) in the southeastern Zagros Suture Zone. The radiolarite sequences, were deposited in an extensive ocean basin (para-autochthonous basin) that extended from the Hawasina series (Oman) in the south, and continued northward into the successions at Pichakun in the Neyriz area (SE Iran), Kermanshah (western Iran) and Qulqula (NE Iraq) ending with the Kocali series in Turkey. The radiolarites bordered the Arabian platform foredeep carbonates (e.g. Balambo Formation, Albian-Cenomenian). Hence, the sequences clearly define the oceanic crust adjacent to the continental margin of the Arabian plate and are preserved within the Zagros Suture Zone (Kazmin et al., 1986; Dercourt et al., 1986).

The presence of these rock types is consistent with many intra-oceanic accretionary complexes. The rock group which is referred to as radiolarite comprises radiolarite mudstone, shale and chert, as well as foraminiferal limestone (biomicrite). These rocks are strongly deformed and thrust onto the Mesopotamian fore-deep carbonate of the Balambo Formation (Albian-Cenomanian). The Qulqula-Kermanshah terrane was accreted against the Zagros supra-subduction zone ophiolite/arc complexes in the Late Campanian-Maastrichtian. Later both the ophiolite and the accretionary complex were emplaced onto the Arabian platform carbonate (Balambo Formation) was accompanied by widespread development of a serpentinite-matrix melange. Radiolarite (and the serpentinite mélange) in the Qulqula area represents the Qulqula Rise (i.e. accretionary complex terrane) in northeastern Iraq that marks the transition from a passive margin into a foreland basin setting.
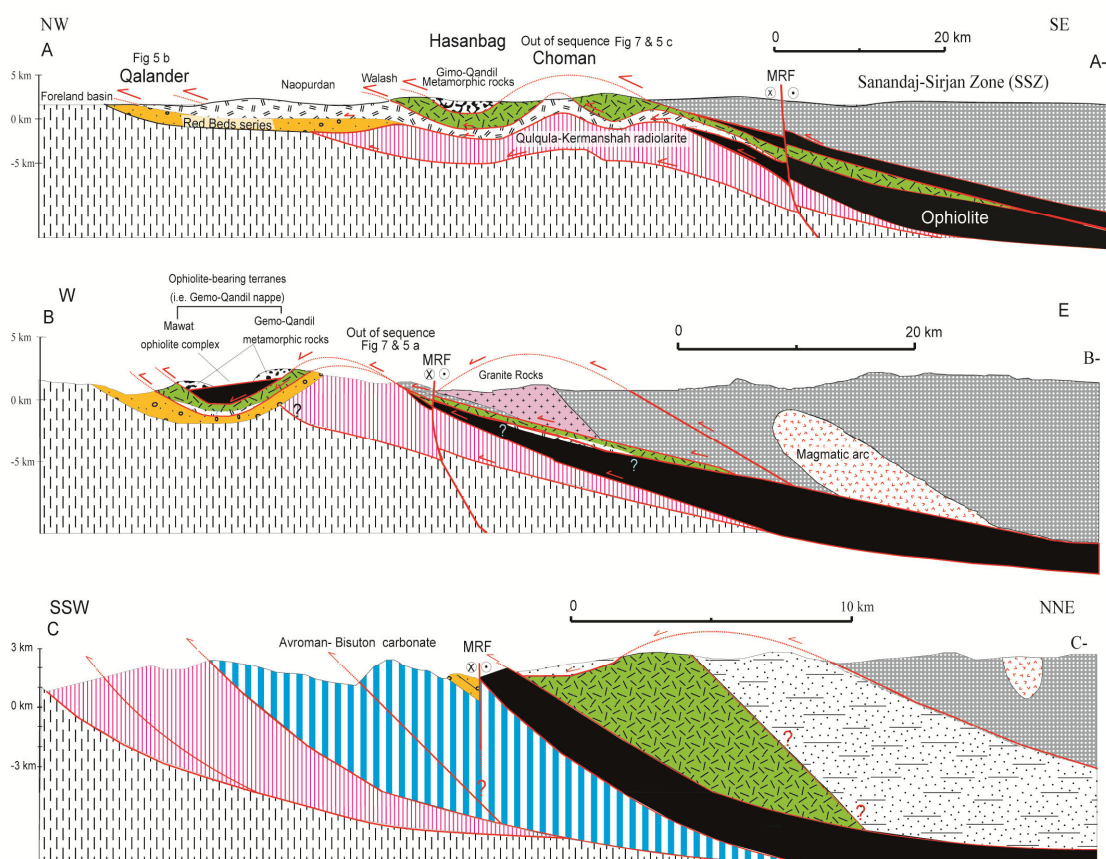

Figure 3. Three structural cross-sections across the Zagros collision zone along the Iraq-Iran border

(for locations and legend see Figure 2).

3.5 Ophiolite massifs and ophiolitic mélanges

Lithospheric mantle components of the ophiolites (i.e. ophiolite massifs and ophiolitic mélanges) in the Zagros

collision zone along the Iraq-Iran border are exposed in several areas. The ophiolite massif, containing mantle and oceanic crustal sequences, includes peridotite, gabbro, diorite, plagiogranite and mafic and felsic volcanic differentiates (including mid ocean ridge basalt, MORB). In contrast the ophiolitic mélanges are related subduction-accretion units that were generated by subduction-driven viscous flow within ``channels'' at the base of the accretionary wedge before the closing stages of the Neotethyan oceanic basins in the Late Cretaceous. Ophiolitic mélange serpentinites show sporadic or chaotic blocks of exotic origin embedded in a serpentinite matrix. (Aziz et al., 2011; Aswad et al., 2011). The exposed ophiolite massifs could be divided into two groups including the Kermanshah-Penjween ophiolites in the southeast (Figs 2 and 4) and the Mawat, Baneh-Bulfat and Piranshahr-Hajomran ophiolites in the northwest. The southeastern group is associated with a metamorphic sole beneath the Late Cretaceous obducted ophiolites. In contrast, the northwestern group is not associated with sole metamorphism and always occurs in nappes sitting on top of Walash magmatic rocks and fore-arc sediments.

The Kermanshah ophiolite has K-Ar mineral ages on hornblende of 86.3±7.8 Ma from a leucodiorite and 81.4±3.8 Ma from a diabase dyke cutting the same leucodiorite (Braud, 1987). K-Ar age determinations based on hornblende from spilitic diabases in the Mawat ophiolite sequence assign an age of the tectono-thermal event ranging 97-118 Ma (Aswad and Elias, 1988). These igneous sequences in the Mawat ophiolite are unconformably overlain by an epi-ophiolitic volcano-sedimentary cover of
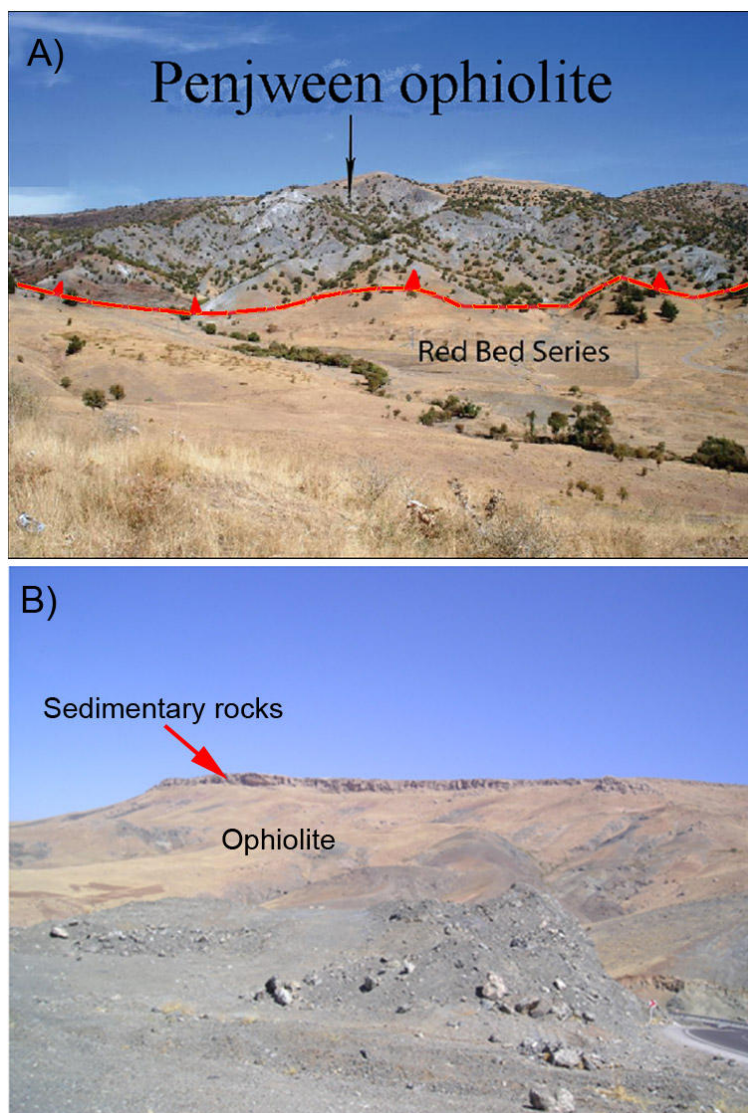

Figure 4. Penjween ophiolites thrust over the Red Bed Series in foreland basin 2 km southeast of Penjween city (after Ibrahim, 2009).

Albian-Cenomenian age. The volcano-sedimentary sequence is referred to the Gemo Group (Jassim and Goff,

2006). The term "ophiolite bearing terrane" (Gemo-Qandil nappe) is used in this paper to represent the distinctive rock association stated above (i.e. an imbricate stack of thrust sheets of ophiolitic massif and related sedimentary, igneous and locally-metamorphosed rocksas defined by Aziz et al., 2011). The stated ophiolitic massifs in the Mawat-Baneh-Bulfat group nappes contain almost all the characteristic members of an ophiolite suite with the highly sheared basal serpentinites. The ophiolitic massifs and associated epi-ophiolitic volcano-sedimentary cover are the main constituents of the Gemo-Qandil nappe (ophiolite bearing terrane) that was juxtaposed onto Walash-Naopurdan nappe (32-42 Ma; Koyi, 2006; Aziz et al., 2011). The Gemo-Qandil nappe and Walash-Naopurdan nappe are referred in this paper as the Upper Allochthon and Lower Allochthon thrust sheets respectively. These allochthonous thrust sheets have been thrust over the Miocene Red Bed Series (Aswad, 1999; Jassim and Goff, 2006). The Lower Allochthon is sealed from earlier rocks by imbricate serpentinite wedges of ophiolitic origin (i.e. ophiolitic mélange serpentinite). Serpentinite is the most abundant lithology in the ophiolitic mélange and contains blocks of highly dismembered oceanic lithosphere and old crustal rocks forming a serpentinite–matrix mélange. The latter also occur along thrust faults which juxtapose the Qulqula-Kermanshah terrane with the overlying Tertiary volcano-sedimentary segment of the Lower Allochthon which is referred to as the GQR (Galalah, Qalander and Rayat) serpentinite-matrix melange (Aziz, 2008; Aziz et al., 2011). In comparison with the highly sheared basal serpentinites, the GQR serpentinite-matrix melange (ophiolitic mélange) has drastically different petrogenesis, age and regional field relationships, consisting of exotic blocks of mixed age (150 and 770 Ma; Aziz et al., 2011), and has initial $(\varepsilon Nd)i$ values down to -30 (Aziz, 2008). The low $(\varepsilon Nd)i$ values are indicative of maximal incorporation of old continental crustal rocks into the serpentinite-matrix mélange.

At the very front of the Mawat allochthonous thrust sheets, the 'Mawat klippe' lies on Tertiary molasse (Tertiary Red Beds, TRB) whose age limits tightly overlap with nappe outcrops, suggesting a close relationship between the TRB deposition and progressive Mawat allochthonous thrust sheet emplacement (Aswad, 1999). The emplacement process in the Mawat nappe has been interpreted as a gravity sliding mechanism by Aswad (1999). The Mawat nappe probably detached after collision from main Kermanshah-Penjween ophiolitic body and its emplacement probably started in the Late Oligocene (ca. 25 Ma).

3.6 Walash-Naopurdan-Kamyaran terrane

Paleocene-Eocene volcanosedimentary rocks occur in the Walash-Naopurdan (Aswad, 1999; Jassim and Goff, 2006) and Kamyaran (Moinevaziri et al., 2009; Azizi et al., 2011) regions. They represent intra-oceanic, island arc and back-arc volcanic rocks that are collectively named the Walash-Naopurdan-Kamyaran terrane. They occur close to the suture zone on the southwestern side of the Sanandaj-Sirjan zone but are not observed in the southeastern part of the Zagros Orogen in Iran.

The Walash-Naopurdan-Kamyaran terrane is exposed along the Zagros Suture Zone close to the Cretaceous ophiolitic mélanges (Fig. 2). It contains abundant mafic-intermediate intrusive rocks including gabbro and diorite cut by minor felsic dykes. In the Kamyaran area of northwest Iran, Braud (1987) reported that gabbro intruded into the Late Cretaceous ophiolite complex. Abundant intrusive phases occur along the Sahneh-Marivan line (Moinevaziri et al., 2009), with minor mafic volcanic equivalents. These Late Eocene-Oligocene calc-alkaline to tholeitic rocks imply a heterogeneous genesis in an intra-oceanic setting (Moinevaziri et al., 2009). Azizi et al. (2011) proposed that this complex may have been part of the Cretaceous supra-subduction zone ophiolite. However, field, petrographic and geochemical comparisons between the Kamyaran volcanic/subvolcanic rocks and the Walash-Naopurdan volcanic/subvolcanic rocks in Iraq (Ali et al., 2012) indicate they are equivalent units unrelated to the Cretaceous ophiolite.
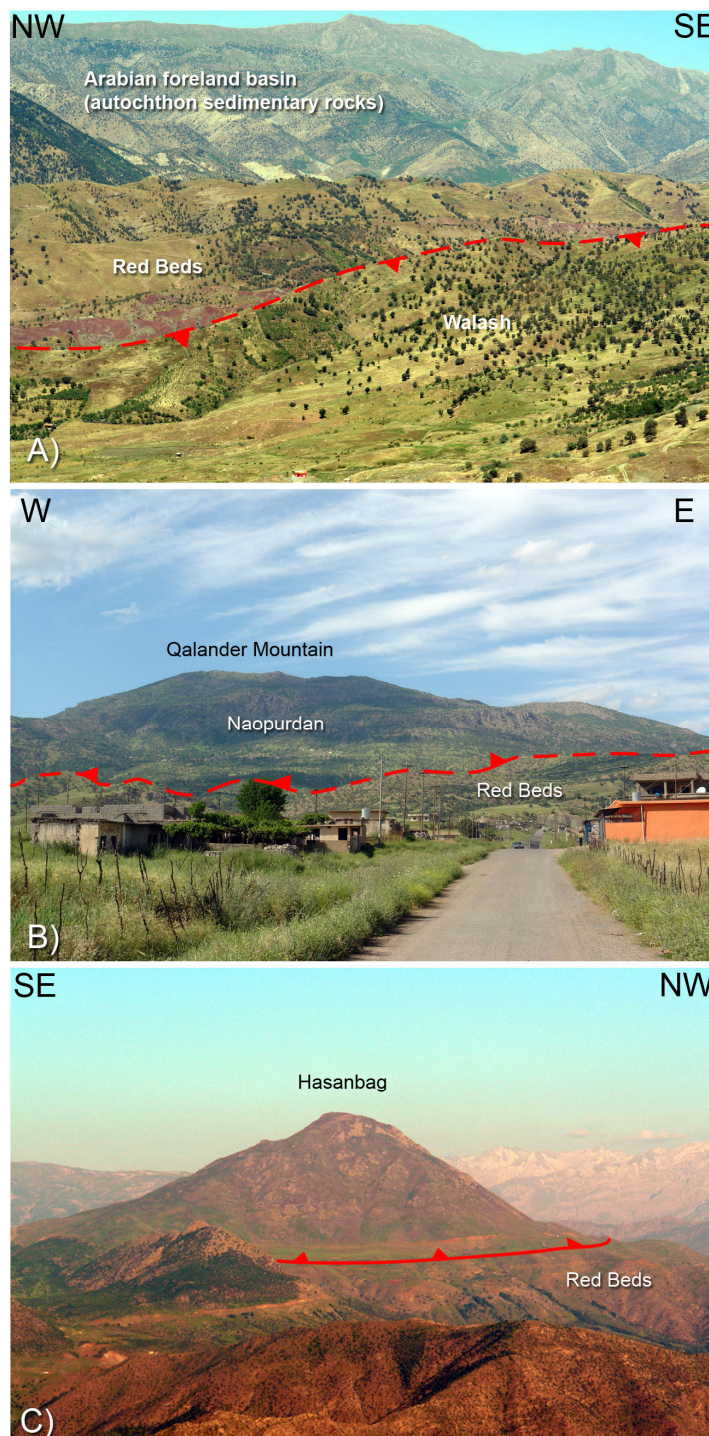
Figure 5. Walash-Naopurdan-Kamyaran volcano-sedimentary rocks are thrust over the Red Beds at **a)** Mawat, **b)** Qalander, and **c)** Hasanbag areas (after Ali, 2012).

The Walash is thought to have formed in a Paleogene back-arc setting to the Naopurdan island-arc that developed in the Neotethys after the obduction of the ophiolite in the Late Cretaceous. In the Walash-Naopurdan magmatic arc in Iraq the volcanic components are more abundant and are exposed as nappes thrust over the Red Beds, whereas Walash-Naopurdan equivalents along the Sahneh-Marivan line (Minevaziri, et al., 2009) are exposed as thrust sheets in the Sanandaj-Sirjan active continental margin (Fig. 5; see geological maps in

Moinevaziri et al. (2009) and Azizi et al. (2011) for more detail). The Walash-Naopurdan components can be divided vertically into two main thrust sheets according to Buday and Suk (1978) as follows: a) the lower Naopurdan (Paleocene-Miocene) consists of turbidites, nummulitic limestone and cycles of volcanic rocks that sometimes loses identity with Walash volcanic; and b) the upper Walash (Paleocene-Oligocene) is composed of basic spilitic diabases, pyroxene bearing spilitic basalts and spilites with some intermediate dykes, lava flows and pyroclastic rocks.

The subduction signature of volcanic rocks in the Walash-Naopurdan nappe has been confirmed by many researchers who show that almost all the studied rocks in these nappes fall into the compositional field of arc-related rocks (Aziz, 1986; Aswad, 1999; Ali, 2002; Koyi, 2006; Aziz et al., 2011). Recent studies carried out by Ali et al. (2013) and Aswad et al. (2013) show that the Walash-Naopurdan volcanic suites display a wide range in composition from early tholeiite, through calc-alkaline to late alkaline domains, with an incredibly broad arc tectonic setting with a long time span (~19 Myr). The isotope compositions of andesites in the Walash-Naopurdan volcanic suites have 143Nd/144Nd=0.51073 and 87Sr/86Sr=0.706679. These low Nd and high Sr isotope ratios undoubtedly have a subduction-related signature characteristic of a melt component input from cratonically derived sediments. Furthermore, SHRIMP U-Pb dating of inherited zircons confirms the Palaeoproterozoic crustal assimilation of Late Paleogene Walash-Naopurdan calc-alkaline magma (Ali and Aswad, 2013).

3.7 Synorogenic foreland rocks

The foreland Maastrichtian flysch (turbidites) and Tertiary Red Bed sediments were shed from orogenic highlands and advancing nappes formed during continental convergence. In particular, the Miocene Red Beds (i.e., Merga Red Beds) are composed mainly of a Paleogene and Cretaceous polymictic clast assemblage from the overlying nappes (Aswad et al., 2013). The synorogenic flysch and molasse deposits in the thrust wedge-foreland basin system continued to deform due to protracted continental convergence. The sustained convergence provided a structural high to facilitate gravity sliding of the nappes and hence structurally controlled the mollasse deposition in adjacent troughs (Aswad, 1999). Therefore, a huge thickness of Paleocene-Miocene flysch (turbidites) and molasse sediments crop out mainly within the imbricate zone and foreland of the thrust sheets and nappes in northeastern Iraq (Fig. 2). The basin extends as narrow northwest-southeast belt (Al-Mehaidi, 1975; Jassim and Goff, 2006) and the Red Beds mainly consist of alternations of thick beds of clastic red claystone, sandstone and conglomerate (Al-Barzinjy, 2005). Many authors (Bolton, 1958b; Buday and Jassim, 1987; Al-Barzinjy, 2005; Jassim and Goff, 2006) have studied the tectono-stratigraphy and petrography of the Tertiary Red Bed series. According to a recent study by Jassim and Goff (2006) the Red Beds can be divided into three groups, the lower Maastrichtian?-Oligocene Suwais Red Beds, the Early-Middle Miocene Lailuk Limestone (Govanda Limestone) and the upper Miocene-Pliocene Merga Red Beds. The Suwais Red Beds (marine and continental foredeep) are partly similar in composition to the Naopurdan Group in the Penjween-Walash zone and their outcrop is narrow because of overthrusting by the Naopurdan Group. The Suwais Red Beds comprise both turbidites and molasse-type clastic rocks alternating with neritic nummulitic limestone deposited in a trough (see Jassim and Goff, 2006, for more details).These Oligocene-Miocene molasse units consists of polygenic conglomerate and sandstone overlain by calcirudite to calcarenite limestone, marl and sandstone deposited conformable over the Qulqula-Kermanshah radiolarites about 15 km southwest of Marivan (Nogole Sadat and Houshmandzadeh, 1993). These rocks are exposed along a narrow basin from east of Mawat in northwest to west of Bessaran in the southeast (see Fig. 2). Patches of ophiolite and Walash-Naopurdan-Kamyaran magmatic arc rocks are exposed along the Zagros suture to the northeast of the Oligocene-Miocene narrow basin (see cross-section CC- in Fig. 3).

4. Structure and tectonic history of the Zagros collision zone along the Iraq-Iran border

Rifting along the present Zagros fold and thrust belt took place during Permian to Triassic time, resulting in the opening of the Neotethys Ocean (Saidi et al., 1997). Reconstructions of Tethys by numerous authors (e.g. Stampfli et al., 1991; Alavi, 1994; Ricou, 1994; Sengör and Natalin, 1996; Glennie, 2000; Mohajjel et al., 2003; Agard et al., 2005) show that the Neotethys was initiated in the Permian, with extension along both passive margins in the Late Triassic, followed by Jurassic-Miocene subduction along the northeastern margin, Late Cretaceous arc-continent collision and ophiolite obduction along the northeastern margin of the Arabian plate and finally collision with Central Iran (Fig. 6). Subduction of the Neotethyan oceanic crust under the southwestern border of Central Iran (Sanandaj-Sirjan zone) caused development of the Late Jurassic-Cretaceous

magmatic arc (Mesozoic magmatic arc, see above). The northward movement of the Arabian plate closed the remnant basin of the Neotethys Ocean in southwestern Iran (Mohajjel et al. 2003) and southern Turkey (Yilmaz et al., 1993) in the Miocene. After Arabia and Central Iran were sutured, large scale post-orogenic strike-slip faulting (Main Recent Fault) occurred (Talebian and Jackson, 2002).

The location of and relationship between the different tectonic units situated in several thrust sheets across the Zagros Suture Zone in the study area are presented along three structural cross-sections (Fig. 3). The transport direction of all thrust sheets was towards the west and southwest. The first detritus from the Neotethys oceanic rocks, including the ophiolites and radiolarites, have been found in Tanjero Formation and its equivalent Amiran Formation in the foreland basin of the Zagros Orogen. The presence of clasts of Neotethys oceanic rocks derived solely from the serpentinite-matrix mélanges in the Tanjero turbidites does not necessarily constrain the end of subduction. The Late Cretaceous ophiolites, including the Kermanshah-Penjween ophiolites, were obducted over the northeastern margin of the Arabian plate in this area (Mohajjel at al., 2003; Agard et al., 2005, 2011; Jassim and Goff, 2006) due to collision of an island arc and the Arabian passive margin. Island arc remnants have been found in the Zagros Suture Zone in the Neyriz area (Babaie et al., 2001). The obduction of the Late Cretaceous ophiolites and deformation of the Qulqula-Kermanshah radiolarites and Avroman-Bisotun carbonates all occurred during the Late Cretaceous collision of an island arc with the Arabian passive margin. Fragments of this island arc are not observed in the Penjween area but a remnant of the ophiolite arc (Hasanbag) has been recognized for the first time in the Sidekan area in northeastern Iraq (Ali, 2012; Ali et al., 2012). Late Cretaceous ophiolites exposed in the Mawat, Bulfat and Pushtashan areas are found in thrust sheets overlying the Red Bed series (Aswad, 1999; Jassim and Goff, 2006). The Mawat ophiolites were thrust over the Walash-Naopurdan magmatic arc thrust sheet (Fig. 6). Late Cretaceous serpentinite has been observed in the sole of the Mawat ophiolite nappe (Aziz et al., 2011).

The exposed radiolarites from the northwestern part of the suture near the Turkish border to Kermanshah in southeast (Fig. 2) show that the radiolarite basin was a long ocean basin along the northeastern margin of the Arabian plate (Kazmin et al., 1986). In the northwestern part near the Iraq-Turkey border the radiolarites are exposed in a tectonic window. Therefore, in cross-section AA', radiolarite is present in the lowest thrust sheets of the collision zone. The Avroman-Bisotun carbonates are exposed along the suture zone in southeastern part (Fig. 2) and are not exposed in thrust sheets farther to the northwest.

The Red Beds contain components from different tectonic units in the collision zone and unconformably overlie the autochthonous Cretaceous sedimentary units of the Tanjero/Shiranish Formations in the foreland (see above). The Red Beds are overlain by different thrust sheets in the collision zone. In northern part of the collision zone, in the Sheikhan-Qalander area, they are overlain by the Naopurdan (island-arc) thrust sheet (Figs 3, 7) but in the Mawat area they are overlain by the Walash (back-arc) thrust sheet (Figs 3, 7).

A) Permo-Triassic, ~250 Ma : Eurasia-ward subduction in Paleo-Tethys

B) Cretaceous, 106-92 Ma : After closure of Paleo-Tethys, establishment of the Hasanbag arc in Neo-Tethys

C) Late Cretaceous: emplacement of Hasanbag arc onto Arabian margin, initiation of the Walash-Naopurdan arc systme

D) Miocene, 23-16? Ma: Emplacement of Walash-Nopurdan arc onto Arabian margin

E) Middle Miocene-Present; Ongoing Arabian-Eurasian Continental collision
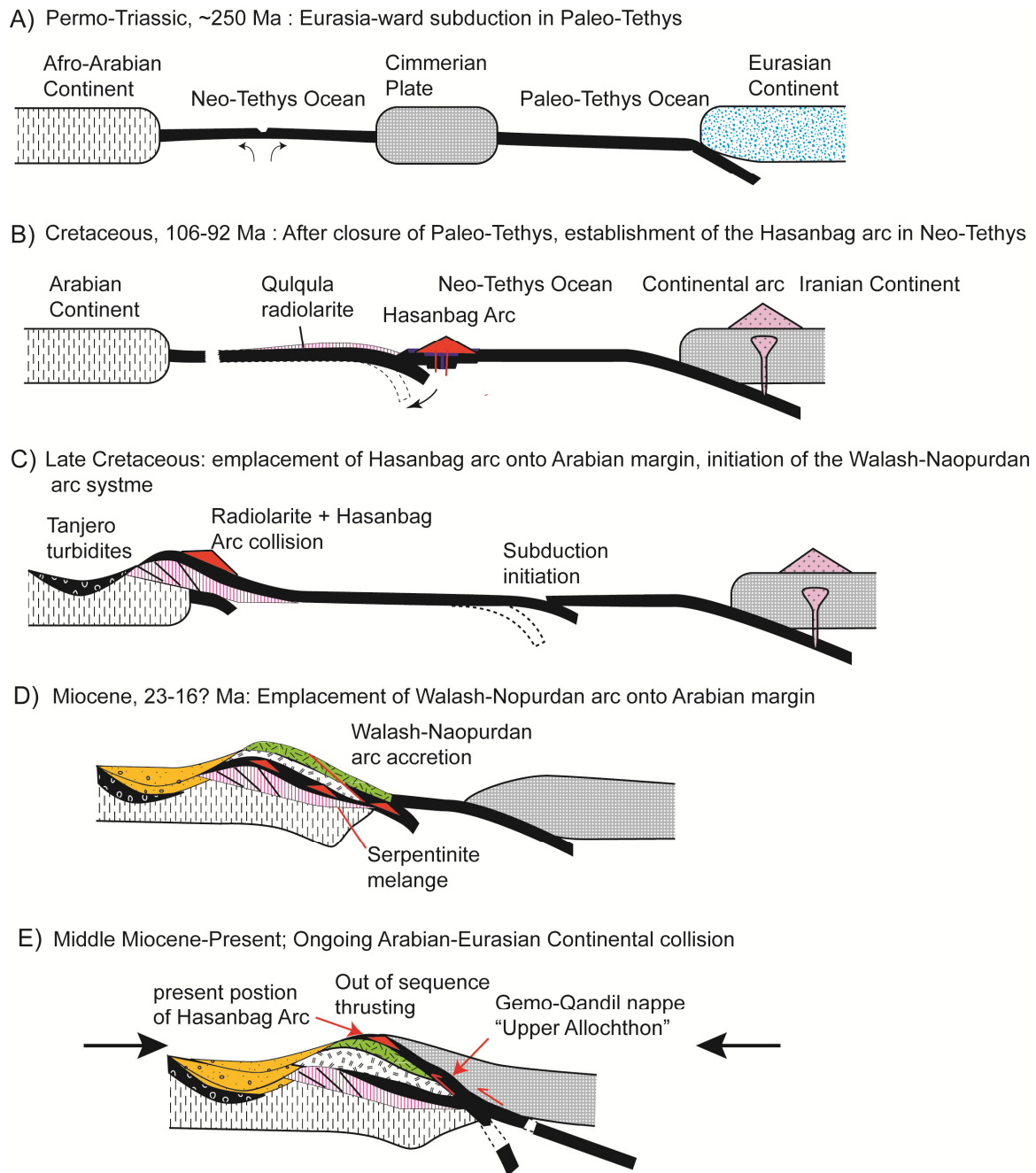
Figure 6. Schematic diagram presenting a tectonic evolution model for the Zagros collision zone along the Iraq-Iran border (after Ali et al., 2012).
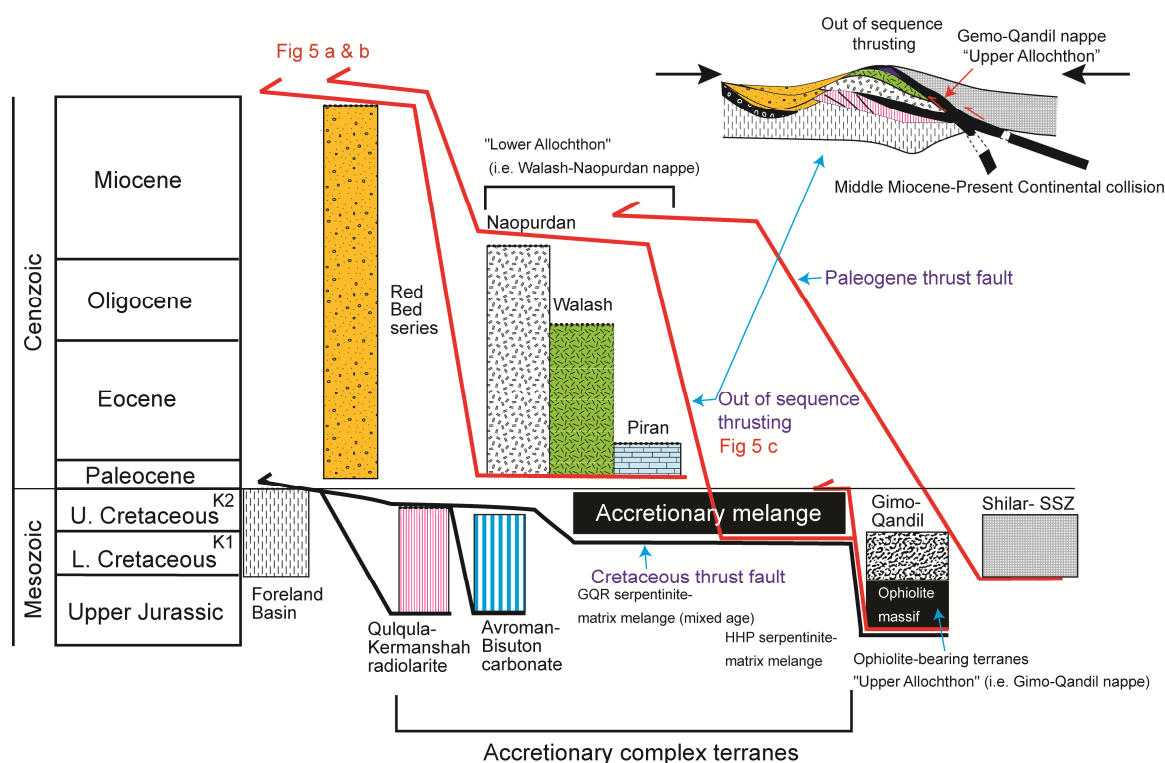
Figure 7. Schematic diagram of the tectono-stratigraphy of the Zagros collision zone along the Iraq-Iran border. Thrusts associated with the Late Cretaceous collision are shown in black and the Miocene thrusts are shown in red. GQR (Galalah, Qalander, Rayat), HHP (Halsho, Hero, Pushtashan; see Aziz et al., 2011, for additional details).

The Naopurdan thrust sheet is not exposed southwest of Mawat Mountain but it is thought that in cross-section BB' it is overlain by the Walash thrust sheet. The marine-dominated Naopurdan Group passed laterally into the volcano-sedimentary Walash Group forming the Walash-Naopurdan nappe (Lower Allochthon; Jassim and Goff, 2006). Later, this was locally dismembered into the Naopurdan and Walash thrust sheets. The structure of the collision zone shown in the cross-sections indicates that the Naopurdan and Walash magmatic arc to back-arc sequences were transported from their original locations in the suture zone over the foreland basin to the southwest by thrust sheets. In the Mawat area, these thrust sheets are sitting on Miocene Red Beds indicating that this tectonic emplacement happened during Late Miocene.

The Eocene-Oligocene Walash-Naopurdan volcano-sedimentary complex was thrust over the Miocene Red Beds and overlain by the Late Cretaceous ophiolitic mélange. The ophiolitic mélange serpentinite had already been accreted onto the Arabian margin during the Late Cretaceous, whereas the Mawat ophiolite-bearing nappe was thrust over the younger (Late Miocene) accreted Walash-Naopurdan magmatic arc nappe (Ali et al., 2013). This contradicts the out-of-sequence thrust in the southwestern Zagros Suture Zone, which has also been mentioned in another area of the Zagros Suture Zone by Alavi (1994). The Gimo-Qandil thrust sheet containing metamorphic rocks from the hinterland (Sanandaj-Sirjan zone, Figs 3, 7) is the top thrust sheet in the Mawat area sitting over the Mawat ophiolite complex.

5. Conclusions

Two tectonic terranes (i.e. ophiolitic mélanges and ophiolite massif-bearing terranes) were accreted onto the Arabian passive margin during the closure of the Neotethys along the Zagros Suture Zone in northeastern Iraq and southwest Iran. The first terrane belongs to a Late Cretaceous ophiolite mélange/arc-continent collision, instigated during the Late Maastrichtian and continued through the Paleocene, which marks the transition from a passive margin to a foreland basin setting. The Qulqula-Kermanshah radiolarites and Avroman-Bisotun carbonates were deformed and accreted over the Arabian passive margin and Late Cretaceous ophiolitic melange was emplaced on these accreted terranes along the Arabian margin (Figs 3-7). The erosional products from the

Qulqula radiolarite and serpentinite mélange were shed as flysch deposited in the Tanjero Formation, which is equivalent in age to the Amiran Formation in Iran, and it is considered to be a typical peripheral foreland deposit on the Arabian passive margin. The continuous tectonic activity ultimately produced the Walash-Naopurdan island-arc and back-arc series (island-arc tholeiite and calc-alkaline to alkaline rocks) that developed in an intra-oceanic setting bordering the Arabian continent during the Paleogene. The second collision event involved the accretion (obduction) of the Walash-Naopurdan island-arc and back-arc terranes onto the Arabian margin during the Miocene (Fig. 7).

The continent-continent collision event is documented by abundant allochthonous thrust sheets and nappes transported in front of the advancing hinterland rocks over the previously mentioned accretionary complex terranes and foreland basin assemblages. This collisional tectonic event in the Late Miocene is identified by thrust sheets of the Eocene-Oligocene Walash-Naopurdan magmatic arc overlying the Red Beds in the flexural foreland basin (Fig. 7).

It is concluded that the arc-continent collision in Late Cretaceous was completely eroded or covered by later continent-continent collision-related thrust sheets in the Late Miocene apart from a small window of ophiolite arc preserved at Hasanbag Mountain. Continent-continent collision resulted in the Late Cretaceous ophiolite being cut by a younger generation of thrusts and re-emplaced as out-of-sequence thrusts on top of the Walash-Naopurdan magmatic arc on Mawat Mountain. Thrust sheets of metamorphic rocksfrom the hinterland were also transported as still younger nappes that are situated above the earlier accreted thrusts and nappes.

Acknowledgements

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*, 94, 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*,148, 692-725.

Ali, S.A. (2002). Petrography and geochemistry of Walash Volcanics in HajOmran and Sidekan Provinces, NE Iraq. MSc thesis, *Mosul University*, Iraq (unpublished), 110 pp (in Arabic).

Ali, S. A. (2012). Geochemistry and geochronology of Tethyan-Arc related igneous rocks, NE-Iraq. NE Iraq. (PhD thesis), *University of Wollongong*, 326 p (unpublished).

Ali, S. A., Buckman. S., Aswad, K. J., Jones, B. G., Ismail, S. A., and Nutman, A. P. (2012). Recognition of Late Cretaceous Hasanbag ophiolite-arc rocks in the Kurdistan region of the Iraqi Zagros Thrust Zone: A missing link in the paleogeography of the closing Neo–Tethys Ocean. *Lithosphere* 4, 395–410. doi: 10.1130/L207.1.

Ali S.A. and Aswad, K.J. (2013). SHRIMP U-Pb dating of zircon inheritance in Walash arc volcanic rocks (Paleogene age), Zagros Suture Zone, NE Iraq: new insights into crustal contributions to trachytic andesite generation. *Iraqi National Journal of Earth Sciences*, 13, 45-58.

Ali S.A., Buckman, S., Aswad, K.J., Jones, B.G., Ismail, S.A. and Nutman, A.L.(2013). The tectonic evolution of a Neo-Tethyan (Eocene–Oligocene) island-arc (Walash and Naopurdan Groups) in the Kurdistan region of the northeast Iraqi Zagros Suture Zone. *Island Arc*, 22, 104-125.

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*, 29, 859-877.

Alavi, M.(1994). Tectonics of the Zagros orogenic belt of Iran: new data and interpretation. *Tectonophysics*, 229, 211-238.

Al-Mehaidi, H. (1975). Tertiary nappe in Mawat range, NE Iraq. *Journal of the Geological Society of Iraq*, 5, 31-44.

Al-Barzinjy, Sh.T. (2005). Stratigraphy and basin analysis of the Red Series from NE Iraq, Kurdistan region. PhD thesis, *University of Sulaimaniya*, Iraq (unpublished), 149 pp.

Aswad, K.J. and Elias, E.M. (1988). Petrogenesis, geochemistry and metamorphism of spilitized subvolcanic rocks of the Mawat ophiolite complex, NE Iraq. *Ofioliti*, 13, 95-109.

Aswad, K.J. (1999). Arc-continental collision in northeastern Iraq as evidence by the Mawat and Penjween ophiolite complex. *Rafidain Journal of Science*, 10, 51-61.

Aswad, K.J., Aziz, N.R.H. and Koyi, H. (2011). Cr-spinel compositions in serpentinites, and their implications for the petrotectonic history of the Zagros Suture Zone, Kurdistan region, Iraq. *Geological Magazine*, 148, 802-818.

Aswad, K.J., Al.Sheraefy, R.M. and Ali, S.A. (2013). Pre-collisional intrusive magmatism in the Bulfat Complex, Wadi Rashid, Qala Deza, NE Iraq: geochemical and mineralogical constraints and implications for tectonic evolution of granitoid-gabbro suites. *Iraqi National Journal of Earth Sciences*, 13, 103-137.

Aziz, N.R.H. (1986). Petrochemistry, petrogenesis and tectonic setting of spilitic rocks of Walash volcanic sedimentary group in Qala Diza area, NE Iraq. MSc thesis, *Mosul University*, Iraq (unpublished), 164 pp (in Arabic).

Aziz, N.R.H. (2008). Petrogenesis, evolution, and tectonics of the serpentinites of the Zagros Suture Zone, Kurdistan region, NE Iraq. PhD thesis, *University of Sulaimaniya*, Iraq (unpublished), 250 pp.

Aziz, N.R.H., Aswad, K.J. and Koyi, H. (2011). Contrasting of serpentinite bodies in northwestern Zagros Suture Zone serpentinites, Kurdistan region, Iraq: tracing a "subduction signature" in serpentinite-matrix mélanges. *Geological Magazine*, 148, 819-837.

Azizi, H. and Jahangiri, A. (2008). Cretaceous subduction-related volcanism in the northern Sanandaj-Sirjan Zone, Iran. *Journal of Geodynamics*, 45, 178-190.

Azizi, H. and Moinevaziri, H. (2009). Review of the tectonic setting of Cretaceous to Quaternary volcanism in northwestern Iran. *Journal of Geodynamics*, 47, 167-179.

Azizi, H., Tanaka, T., Asahara, Y., Chung, S.L. and Zarrinkoub, M.H. (2011). 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*, 52, 304-320.

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*, http://dx.doi.org/10.1080/00206814.2013.782959.

Babaie, H.A., Ghazi, A.M., Babaei, A., La Tour, T.E. and Hassanipak, A.A. (2001). Geochemistry of arc volcanic rocks of the Zagros Crush Zone, Neyriz, Iran. Journal of Asian Earth Sciences, 19, 61-76.

Bahroudi, A. and Talbot, C.J. (2003). The configuration of the basement beneath the Zagros Basin. *Journal of Petroleum Geology*, 26, 257-282.

Berberian, M. (1995). Master blind thrust faults hidden under the Zagros folds: active basement tectonics and surface morphotectonics. *Tectonophysics*, 241, 193-224.

Berberian, F., Muir, I.D., Pankhurst, R.J. and Berberian, M. (1982). Late Cretaceous and Early Miocene Andean-type plutonic activity in northern Makran and Central Iran. *Journal of the Geological Society of London*, 139, 605-614.

Berberian, F. and Berberian, M. (1981), Tectono-plutonic episodes in Iran. In : Gupta HK, Delany FM (eds) Zagros Hindu Kush Himalaya Geodynamic Evolution. *American Geophysical Union*, Washington DC, pp 5-32.

Berberian, M. and King, G.C.P. (1981), Towards a paleogeography and tectonic evolution of Iran. *Canadian Journal of Earth Sciences*, 18, 210-265.

Bolton, C.M.G. (1958a). Geological map - Kurdistan series, scale 1/ 100,000 sheet K4, Rania. Manuscript report No. 276, *GEOSURV*, Baghdad.

Bolton, C.M.G. (1958b). The Geology of Ranya area. Manuscript report No. 271, *GEOSURV*, Baghdad.

Braud, J. (1987). La suture du Zagros au niveau de Kermanshah (Kurdistan Iranien): reconstitution paléogéographique, évolution géodynamique, magmatique et structurale. Thése, *Université Paris-Sud*, France (unpublished), 489 pp.

Buday, T. (1980). The Regional Geology of Iraq, Volume I, Stratigraphy and Paleogeography. Publication of *GEOSURV*, Baghdad, 445 pp.

Buday, T. and Suk, M. (1978). Report on the geological survey in north-eastern Iraq between Halabja and Qala-Diza. *SOM Library*, Baghdad, 950 pp.

Buday, T. and Jassim, S.Z. (1987). The Regional Geology of Iraq, Vol. 2, Tectonism, Magmatism and Metamorphism. Publication of *GEOSURV*, Baghdad, 352 pp.

Coney, P.J., Jones, D.L. and Monger, J.W.H. (1980). Cordilleran suspect terranes. *Nature*, 288, 329-333.

Dargahi, S. (2007). Post-collisional Miocene magmatism in the Sarcheshmeh-Shahrebabak region, NW of Kerman: isotopic study, petrogenetic analysis and geodynamic pattern of granitoid intrusives and the role of adakitic magmatism in development of copper mineralization. Unpublished Ph.D. thesis, Shahid Bahonar *University of Kerman*, (in Persian), 310 pp.

Dargahi, S., Arin, M., Pan, Y. and Babaei, A. (2010). Petrogenesis of post-collisional A-type granitoids from the Urumieh–Dokhtar magmatic assemblage, southwestern Kerman, Iran: constraints on the Arabian-Eurasian continental collision. *Lithos*, 115, 190-204.

Dercourt, J., Zonenshain, L.P., Ricou, L.E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet, C., Sbortshikov, I.M., Geyssany, J., Lepverier, C., Pechersky, D.H., Boulin, J., Sibuet, J.C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M.L., Lauer, L.P. and Biju-Duval, B. (1986). Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. *Tectonophysics*, 123, 241-315.

Eftekharnedjad, J. (1984). Geological Map of Mahabad, 1:250000. *Geological Survey of Iran*, Tehran, Iran.

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*, 29, TC4025, doi:10.1029/2009TC002484.

Ghalamghash, J., Nédélec, A., Bellon, H., Vousoughi Abedini, M. and Bouchez, J.L. (2009). The Urumieh plutonic complex (NW Iran): a record of the geodynamic evolution of the Sanandaj–Sirjan zone during Cretaceous times – Part I: petrogenesis and K/Ar dating. *Journal of Asian Earth Sciences*, 35, 401-415.

Gharib, F. and De Wever, P. (2010). Mesozoic radiolarians from the Kermanshah Formation (Iran). *Comptes Rendus*, 9, 209-219.

Ghazi, A.M. and Hassanipak, A.A. (1999). Geochemistry of subalkaline and alkaline extrusives from Kermanshah ophiolite, Zagros Suture Zone, western Iran: implications for Tethyan plate tectonics. *Journal of Asian Earth Sciences*, 17, 319-332.

Glennie, K.W. (2000). Cretaceous tectonic evolution of Arabia's eastern plate margin: a tale of two oceans, in Middle East models of Jurassic/Cretaccous carbonate systems. SEPM (*Society for Sedimentary Geology*) Special Publication, 69, 9-20.

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*, 22, 659-680.

Ibrahim, A.O. (2009). Tectonic style and evolution of the NW segment of the Zagros fold and thrust belt, Sulaimani governorate, Kurdistan region, Iraq. PhD thesis, *Sulaimani University* (unpublished).

Jackson J, Hains J, and Holt, W. (1995). The accommodation of Arabia- Eurasia plate. *Journal of Geophysical Research*, 100, 15205-15219.

Jahangiri, A. (2007). Post-collisional Miocene adakitic volcanism in NW Iran: geochemical and geodynamic implications. *Journal of Asian Earth Sciences*, 30, 433-447.

Jassim, S.Z. and Goff, J.C. (2006). Geology of Iraq. Dolin, Prague and Moravian Museum, Brno, *Czech Republic*, 341 pp.

James, G.A. and Wynd, J.G. (1965). Stratigraphical nomenclature of Iranian Oil Consortium agreement area. *American Association of Petroleum Geologists Bulletin*, 49, 2182-2245.

Kazmin, V.G., Ricou, L.F. and Sbortshikov, I.M. (1986). Structure and evolution of the passive margin of the eastern Tethys. *Tectonophysics*, 123, 153-179.

Koyi, A.M. (2006). Petrochemistry, petrogenesis and isotope dating of Walash volcanic rocks at Mawat-Chowarta area, NE Iraq. MSc thesis, *Unversity of Mosul*, Iraq (unpublished), 226 pp. (in Arabic).

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*, 41, 238-249.

Masoudi, F., Yardley, B.W.D. and Cliff, R.A. (2002). Rb-Sr geochronology of pegmatites, plutonic rocks and a hornfels in the region southwest of Arak, Iran. Islamic Republic of Iran *Journal of Sciences, 13, 249-254.*

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 of London*, 166, 53-69.

McCall, G.J.H. (2002). A summary of the geology of the Iranian Makran. *Geological Society of London Special Publication*, 195, 147-204.

Mohajjel, M. (1997). Structure and tectonic evolution of Palaeozoic-Mesozoic rocks, Sanandaj-Sirjan zone, western Iran. PhD thesis, *University of Wollongong*, Wollongong, Australia (unpublished).

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*, 21, 397-412.

Mohajjel, M. and Fergusson, C.L. (2000). Dextral trasnpression in Late Cretaceous continental collision Sanandaj-Sirjan zone, western Iran. *Journal of Structural Geology*, 22, 1125-1139.

Mohajjel, M. and Biralvand, M. (2010). Folding style in Kermanshah radiolarites and its significance in collision tectonics of NW Iran. *Scientific Quarterly Journal of Geosciences*, 19, 75-82.

Moinevaziri, H., Azizi, H., Mehrabi, B. and Ezadi, F. (2009). Oligocene magmatism in Zagros thrust zone (Sahneh-Marvan); Neo-Tethys subduction in Paleocene. *Science*, 34, 113-122 (in farsi).

Molinaro, 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*, 24, TC3007, doi:10.1029/2004TC001633, 19 p.

Mouthereau, F. (2011).Timing of uplift in the Zagros belt/Iranian plateau and accommodation of late Cenozoic Arabia-Eurasia convergence. *Geological Magazine*, 148, 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*, 532-535, 27-60.

Nogole Sadat, M.A.A. and Houshmandzadeh, A. (1993). Geology map of Marivan-Baneh, Scale 1:250000. *Geological Survey of Iran*, Tehran, Iran.

Ricou, L.E., Braud, J. and Brunn, J.A. (1977). Le Zagros. Mémoire Societe Géologique de France, *Hors-Série*, 8, 33-52.

Ricou, L.E. (1994). Tethys reconstructed: plates continental fragments and their boundaries since 260 Ma from Central America to southeastern Asia. *Geodinamica Acta*, 7, 169-218.

Saidi, A., Brunet, M.-F. and Ricou, L.-E. (1997). Continental accretion of the Iran Block to Eurasia as seen from Late Paleozoic to Early Cretaceous subsidence curves. *Geodinamica Acta* (Paris), 10, 189-208.

Sabzehi, M. and Eshragi, S. (1995). Geological map of Neyriz area 6848. 1:100000, *Geological Survey of Iran*, Tehran, Iran.

Shahbazi, H., Siebel, W., Pourmoafee, M., Ghorbani, M., Sepahi, A.A., Shang, C.K. and Vousoughi Abedini, M. (2011). 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*, 39, 668-683.

Shahidi, A.R. and Nazari, B. (1997). Geological map of the Harsin area 5558. 1:100000, *Geological Survey of Iran*, Tehran, Iran.

Sherkati, S., and Letouzey, J. (2004). Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment), Iran. *Marine and Petroleum Geology*, 21, 535 -554.

Sengör, A.M.C. and Natal'in, B.A. (1996). Paleotectonics of Asia: fragments of a synthesis. In: Yin, A., Harrison, T.M. (eds.), The Tectonic Evolution of Asia. Cambridge University Press, pp. 486-640.

Stampfli, G.M., Marcoux, J. and Baud, A. (1991). Tethyan margins in space and time. *In*: Channell, J.E.T., E.L. Winterer, E.L., Jansa, L.F.. (eds.), Paleogeography and paleoceanography of Tethys. Palaeogeography, Palaeoclimatology, Palaeoecology, 87, 373-410.

Stocklin, J. (1968). Structural history and tectonics of Iran: a review. *American Association of Petroleum Geologists Bulletin* 52, 1229-1258.

Talebian, M. and Jackson, J. (2002). Offset on the Main Recent Fault of NW Iran and implications for late Cenozoic tectonics of the Arabia-Eurasia collision zone. *Geophysical Journal International*, 150, 422-439.

Tchalenko, J. S., and Braud, J. (1974). Seismicity and structure of the Zagros: the Main Recent Fault between 33º and 35ºN. *Philosophical Transactions of the Royal Society of London* A, 277, 1-25.

Yilmaz, Y., Yigitbas, E. and Genc, S.C. (1993). Ophiolitic and metamorphic assemblages of southeast Anatolia and their significance in the geological evolution of the orogenic belt. *Tectonics*, 12, 1280-1297.

Zahedi, M., Hajian, J. and Blourchi, H. (1985). Geology Map of Sanandaj (Scale1:250000). *Geological Survey of Iran*, Tehran, Iran.