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A new tectonic scenario for the Sanandaj–Sirjan Zone (Iran)

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Abstract

Recent geochemical studies of volcanic rocks forming part of the ophiolites within the Zagros and Naien-Baft orogen indicate that most of them were developed as supra-subduction ophiolites in intra-oceanic island arc environments. Intra-oceanic island arcs and ophiolites now forming the Naien-Baft zone were emplaced southwestward onto the northeastern margin of the South Sanandaj–Sirjan Zone, while those now in the High Zagros were emplaced southwestward onto the northern margin of Arabia. Thereafter, subduction continued on opposite sides of the remnant oceans. The floor of Neo-Tethys Ocean was subducted at a low angle beneath the entire Sanandaj–Sirjan Zone, and the floor of the Naien-Baft Ocean was subducted beneath the Central Iranian Micro-continent. The Naien-Baft Ocean extended into North-West Iran only temporarily. This failed ocean arm (between the Urumieh-Dokhtar Magmatic Assemblage and the main Zagros Thrust) was filled by thick Upper Triassic–Upper Jurassic sediments. The Naien-Baft Ocean finally closed in the Paleocene and Neo-Tethys closed in the Early to Middle Eocene. After Arabia was sutured to Iran, the Urumieh-Dokhtar Magmatic Assemblage recorded slab break-off in the Middle Eocene.

Keywords: Neo-Tethyan ocean; Zagros orogenic belt; Supra-subduction ophiolite; Slab breakoff

1. Introduction

The subduction of the Neo-Tethyan ocean floor beneath Iran sutured Iran to Arabia (e.g. Takin, 1972; Berberian and King, 1981; Alavi, 1980, 1994), and the subsequent continental convergence built the Zagros Orogenic Belt. This orogenic belt (Fig. 1) consists of four NW-SE trending parallel zones: (1) Urumieh-Dokhtar Magmatic Assemblage (UDMA); (2) Sanandaj–Sirjan Zone (SSZ); (3) High Zagros; and (4) Zagros Simply Folded Belt (ZSFB).

The SSZ is a narrow band lying between the towns of Sirjan and Esfandagheh in the southeast, and Urumieh and Sanandaj in the northwest (Mohajjel and Fergusson, 2000). The rocks in this zone are the most highly deformed in the Zagros orogen and share the NW-SE trend of its structures. One of the main problems concerning the geological history of the Zagros Orogeny is the tectonic setting of the SSZ. We follow most geologists who have worked in Iran (e.g. Berberian and King, 1981; Stöcklin, 1968, 1974; Takin, 1972) and take the SSZ to lie along the southern edge of the Iranian Plate.

In the Golpaygan area The SSZ can be subdivided into two parts (Eftekharnejad, 1981) (Fig. 1): (1) The southern part (South SSZ) consists of rocks deformed and metamorphosed in Middle to Late Triassic; (2) The northern part (North SSZ), deformed in the Late Cretaceous, contains many intrusive felsic rocks (such as the Alvand, Borojerd, Arak and Malayer plutons).

Central Iran, which is separated from the SSZ by a belt of steep and straight faults, consists of two distinct provinces (Sengör, 1990). The North-West Iranian Plate (NWIP) comprises the region north of the Darouneh Fault and south of the Alborz Mountains and extends to the towns of Nakhichevan, Armania and Svanetia (Sengör, 1990). The Central Iranian Micro-continent (Takin, 1972) comprises terrain delimited by the Sistan, Naien-Baft and Makran ophiolitic belts, plus the Darouneh Fault (Fig. 1) and the Sabzevar Ophiolites (Sengör, 1990) (Fig. 2). The Central Iranian Micro-continent is divided into three major blocks

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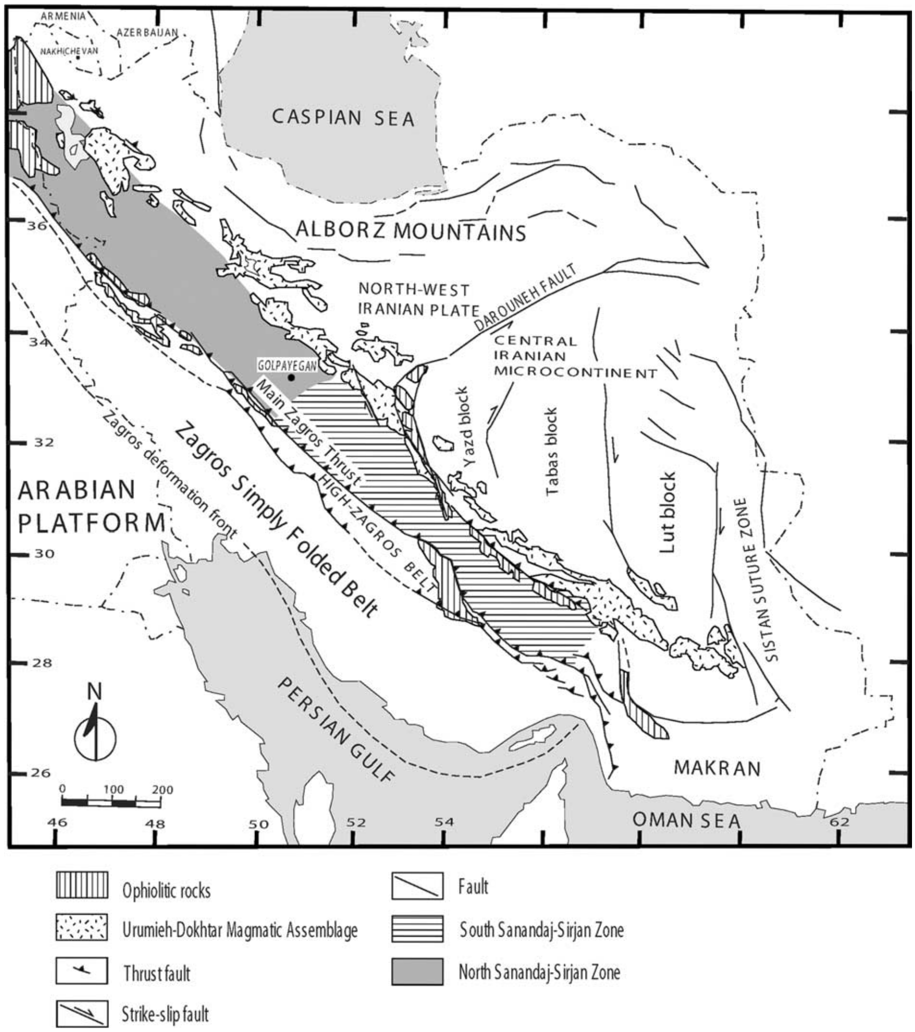

Fig. 1. Main tectonic units of Iran.

(Yazd, Tabas and Lut) by long, generally N-S, right-lateral, strike-slip faults, concave to the east (Sengör, 1990) (Fig. 1). In this paper the North and South Sanandaj–Sirjan zone is considered to form the edge of both the North-West Iranian Plate and the Central Iranian Micro-continent.

The main aim of this paper is to reconstruct, from a review of the literature, the tectonic evolution of the Zagros Orogenic Belt, and particularly of the Sanandaj–Sirjan Zone.

2. Data and their sources

2.1. Permo-Triassic time

Prior to the Late Paleozoic, the whole of Iran formed a relatively stable continental platform covered conformably by epeiro-continental shelf deposits, with no evidence of major magmatism or folding (Berberian and King, 1981; Stöcklin, 1968). Deformation commenced in the Zagros Basin during Permian time (Koop and Stoneley, 1982; Sengör, 1990; Kazmin, 1991; Grabowski and Norton, 1994; Stampfli et al., 1991, 2001). This was a phase of rifting, which flanked the Sanandaj–Sirjan Zone and was associated in the Upper Permian with basic (basalt, diabase, and some intermediate) volcanic activity. Permian rocks, which are predominantly calcareous sediments, overlie Cambrian and Ordovician rocks unconformably in southern Azarbaijan (NW Iran), a different level of Cambrian rocks in the Soltanieh Mountain, northern Golpaygan (Stöcklin, 1968) and other levels of Lower Paleozoic rocks in the Sanandaj–Sirjan Zone. Permian to Middle Triassic sequences are remarkably uniform throughout most of Iran and are composed mainly of shallow water limestones and dolomites associated locally with anhydrite.

In Arabia, Permo-Carboniferous clastic rocks filled topographic lows, and Upper Permian to Triassic rocks overlie Silurian and locally Ordovician or Devonian rocks unconformably, after overstepping the entire Arabian platform (Grabowski and Norton, 1994).

West of Sirjan in the southern SSZ (Fig. 2), metamorphosed basic and ultra-basic rocks containing widespread Barrovian-type metamorphic assemblages are thrust into imbricate slices (Berberian and King, 1981). These metamorphic rocks are overlain by unmetamorphosed Jurassic volcanic detritus and flysch-type deposits above a basal conglomerate (Sabzai et al., 1997). The Sikhoran basic and ultrabasic complex east of Hajiabad (South SSZ, Fig. 2) is probably of Triassic age. This complex represents a sequence of layered intrusive rocks (dunite, harzburgite, pyroxenite, and gabbro) from a magma source of tholeiitic composition capped by unconformable Jurassic sediments (Berberian and King, 1981).

2.2. Jurassic–Cretaceous

In the South Sanandaj–Sirjan Zone (Dehsard region) (Fig. 2), Berberian and King (1981) noted Late Jurassic to Early Cretaceous diabasic andesitic and pyroxene diabasic lavas. Significantly, the Jurassic rocks of west Sirjan below the *Orbitolina* limestone display an important schistosity recording a Late Jurassic phase of tectonism (Ricou, 1974). Along the South SSZ, low- to medium-pressure metamorphism was accompanied by coeval Jurassic andesitic intrusions and volcanism ranging from gabbro to granite with K/Ar ages between 118 ± 10 and 164 ± 4 Ma (Berberian and Berberian, 1981). Later silicic to intermediate plutonic activity and further deformation occurred in the North SSZ during the Late Cretaceous (Berberian and King, 1981). To the southwest of Arak town (North SSZ) (Fig. 2), the metamorphic rocks of the Borojerd Complex were intruded by Early Cretaceous and Late Cretaceous–Paleocene granitoid rocks, which have yielded Rb/Sr ages of 120 and 52–70 Ma, respectively (Masoudi, 1997; Masoudi et al., 2002).

Central Iran and the Alborz Mountains were uplifted by NE-SW shortening during the Late Jurassic when many continental areas emerged from the sea (Stöcklin, 1968). A Late Jurassic–Early Cretaceous granite intrusion is documented in the Shirkuh area (west of the Central Iranian Micro-continent, Sengör, 1990) (Fig. 2). Late Jurassic–Early Cretaceous events in the SSZ were followed by the deposition of continental red beds (Stöcklin, 1968; Berberian and King, 1981) overlain by Lower to Middle Cretaceous carbonate rocks. The whole zone underwent strong deformation towards the end of the Cretaceous. Through most of the Jurassic and Early Cretaceous, the Arabian platform remained a broad, stable, shallow shelf, dominated by carbonate deposition (Koop and Stoneley, 1982). Upper Maastrichtian–Paleocene Amiran flysch accumulated along a linear trough in the High Zagros area.

In the Late Cretaceous, greenschist facies metamorphism was accompanied by the intrusion of felsic granitoid plutons along the North SSZ (Berberian and Berberian, 1981). During Maastrichtian–Paleocene time, Central Iran underwent strong folding, magmatism and uplift. These rocks were eroded and covered by the Late Paleocene–Eocene rocks beneath a pronounced transgressive unconformity. An important phase of Late Cretaceous volcanism is known along the 'Colored Mélange zone' (Naien, Baft and Shahr Babak ophiolites, Stöcklin, 1968). The beginning of the main compressional deformation in the Alborz Mountains also occurred in the Late Cretaceous, although the major deformation was Paleocene (Sengör, 1990).

2.3. Cenozoic

Cretaceous and/or younger pyroclastic–volcanoclastic rocks are found near Nahavand (northern SSZ) and adjacent areas (Alavi, 1994). In the SSZ, syn-tectonic conglomerates indicate episodes of Late Cretaceous–Paleocene, Eocene, Miocene, Pliocene and Pliocene-Quaternary fault activity (Alavi, 1994). In the Urumieh Dokhtar Magmatic Assemblage (UDMA), extensive volcanism in the Eocene, with a wide range of composition (generally calc-alkaline), climaxed in the Middle Eocene. Eocene rocks everywhere overlie various older formations with pronounced angular unconformity (Stöcklin, 1968). The Kharzahre Diorite (Braud, 1987) and Panjvein, Kamyaran and Kolah-Sar mafic plutons in the North SSZ have been assigned to the Eocene–Oligocene (Aghanabati, 1990). Widespread regression affected most of the Zagros Basin during Late Eocene movements when the limestone of the Asmari Formation (Oligo-Miocene, James and Wynd, 1965) transgressed southward over Paleocene–Eocene rocks.

The paleogeographic reconstruction of Iran for Oligocene–Miocene times shows the marine carbonate of the Qom Formation (Upper Oligocene–Lower Miocene) accumulating along the SSZ and over the North Western Iranian Plate, as igneous rock intruded the South SSZ (Berberian and King, 1981). Stable conditions were re-established in the Oligocene, allowing a return to deposition of the carbonates of the Asmari Formation over most of the Arabian Platform. The Qom Formation consists of bioclastic carbonates about 300 m thick, with, like the Asmari limestone, a large proportion of organic debris. The flat-lying Qom Formation overlies older rocks along the SSZ unconformably. Saline anhydrite beds in the uppermost Asmari limestone provide cap-rocks for oil in the Zagros Basin and also cap the Qom reservoir in Central Iran. The deltaic-river channel sands (Upper Red Formation in North Western Iran) are time equivalent to the Aga-jari clastic rocks in the Zagros Basin (Kashfi, 1988).

3. Ophiolitic rocks in the Zagros orogen

Ophiolitic rocks in the Zagros orogen can be divided into two groups: the Naien-Shahr Babak-Baft Ophiolite Belt is a remnant of the Naien-Baft Paleo-ocean along the northern margin of the South SSZ (Fig. 1); the Neyriz-Kermanshah Ophiolite Belt is a remnant of the Neo-Tethys ocean that was obducted along the main Zagros Thrust bounding the southern margin of the SSZ (Stöcklin, 1974) (Fig. 1).

Each of these ophiolitic suites is described briefly below.

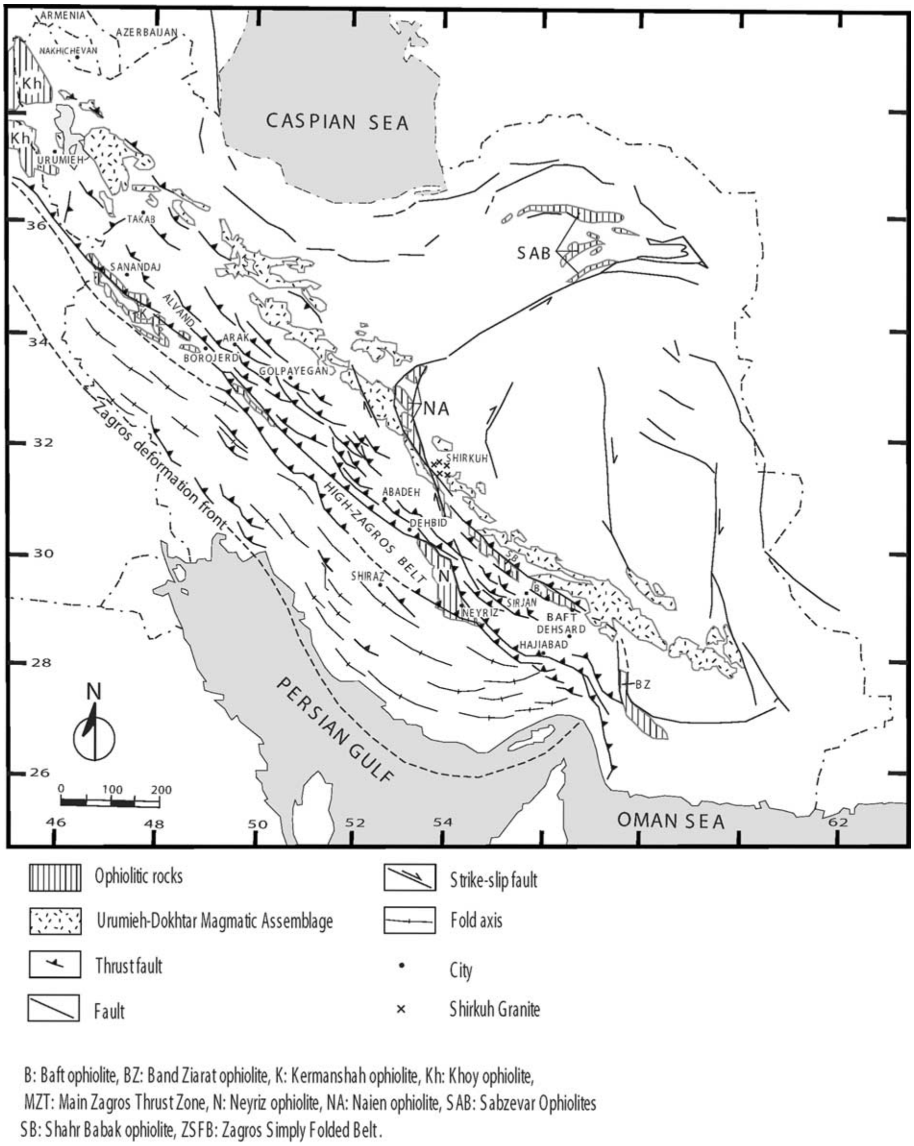

Fig. 2. Simplified structural map of Zagros Orogenic Belt (derived from Alavi, 1994).

3.1. Naien-Shahr Babak-Baft ophiolitic belt

This group has been already referred to as the Colored Mélange Complex (Stöcklin, 1974; Stoneley, 1974; Berberian and King, 1981). Rocks along this belt are strongly imbricated and sheared by closely spaced sub vertical faults and shear zones (Alavi, 1994). The ophiolitic belt of Naien-Baft Ocean was emplaced before the end of Cretaceous (Stöcklin, 1974; Stoneley, 1974, 1975) and is overlain unconformably by Paleocene–Eocene shelf sediments.

3.1.1. Naien ophiolite

The peridotites and serpentinites, with some lherzolites and pyroxenites, that comprise this ophiolite are presumed to have come from the mantle. The crustal plutonic and volcanic rocks include gabbros, diorites, granodiorites, diabase, basaltic andesites, andesites and more silicic rocks, such as tonalite, trondhjeimite and aplite.

Three $^{40}Ar/^{39}Ar$ ages 101.2 ± 0.9, 99.7 ± 0.9, 99 ± 1.2 Ma, for a hornblende gabbro, suggest an Upper Albian age for the generation of this ophiolite (Hassanipak and Ghazi, 2000).

The presence of compositionally diverse extrusive rocks (e.g. basaltic andesite and andesite) intercalated with a variety of Upper Cretaceous sedimentary rocks indicates that the Naien ophiolite has both island arc and intra-oceanic components (Hassanipak and Ghazi, 2000).

3.1.2. Shahr Babak ophiolite

The mantle rocks of this ophiolite include peridotites (lherzolite, harzburgite and dunites), serpentinites and websterite–pyroxenites. The crustal plutonic rocks consist of gabbro, diorite and plagiogranite. The volcanic sequences exhibit a wide range of composition from basaltic andesite to rhyodacites–rhyolites and trachy–andesites. Chemical data show clearly that the extrusive rocks were formed from two distinct magmatic sources (Ghazi and Hassanipak, 1999a): (1) basaltic andesites and rhyodacites were generated in an island arc environment; (2) trachyandesites were generated in an intra-plate environment. The presence of compositionally diverse extrusive rocks (basaltic andesite, andesite, rhyodacite, rhyolite and trachyandesite) tectonically intercalated with a variety of Triassic to Cretaceous sedimentary units indicates that the Shahr Babak ophiolite has both island arc and intra-oceanic components (Ghazi and Hassanipak, 1999a). This ophiolite was emplaced before the Paleocene (Desmon and Beccaluva, 1983).

3.1.3. Baft ophiolite

The mantle rocks of this ophiolite include serpentinitized peridotite with patches of chromite. The crustal plutonic rocks consist of gabbro and diorite while the volcanic rocks include pillow basalts (Alavi, 1994) of both mid-oceanic ridge and within-plate affinities (Arvin and Robinson, 1994). The Baft ophiolite also formed during the Late Cretaceous and was emplaced before the Paleocene (Lippard et al., 1986).

3.2. Neyriz-Kermanshah ophiolitic belts

Both exposures of this ophiolitic belt (at Neyriz and Kermanshah) are similar in composition and structural history to the ophiolitic complex in the Oman Mountain (Stöcklin, 1974). The emplacement of this ophiolite belt is considered to be the result of the Late Cretaceous closure of Neo-Tethys between Iran and Arabia (e.g. Stöcklin, 1974; Alavi, 1980, 1994; Berberian and King, 1981).

3.2.1. Neyriz ophiolite

The Neyriz Ophiolite Complex is tectonically juxtaposed beneath cataclastically deformed island arc volcanic and volcanoclastic rocks (Hassanabad unit, Babaie et al., 2000). The Hassanabad unit is tectonically intercalated with Cretaceous limestone. Geochemical analyses reveal a dominantly calc-alkaline island arc composition for the Hassanabad unit (Babaie et al., 2000). The Neyriz Ophiolite Complex includes peridotite, gabbro, and plagiogranite and mafic and silicic volcanic differentiates (including MORB).

On the basis of $^{40}Ar/^{39}Ar$ dating this ophiolite complex formed between 96–98 Ma (Haynes and Reynolds, 1980) and was emplaced at 89 Ma (Lanphere and Pamic, 1983).

The base of this complex includes the Pichakun series (Ricou, 1968) which, consists of Late Triassic to Middle Cretaceous sediments and represents the abyssal facies of Neo-Tethys. The ophiolite components were thrust onto the Pichakun series. The Neyriz Ophiolite Complex is overlain unconformably by anhydritic limestone of the Late Cretaceous Tarbur Formation (Ricou, 1974).

3.2.2. Kermanshah ophiolite

The Kermanshah ophiolite is highly dismembered. The igneous rocks of this complex consist of both mantle and crustal suites and include peridotites (dunite and harzburgite), cumulative gabbro and diorites, with a volcanic sequence that ranges in composition from sub-alkaline basalt, through alkaline basalt, to trachyte. The associated sedimentary rocks include a variety of Upper Triassic to Lower Cretaceous deep- and shallow-water sedimentary rocks.

Geochemical data clearly distinguish two distinct types of basalt (Ghazi and Hassanipak, 1999b): Sub-alkaline basalt that suggests an island arc affinity, and alkaline basalt suggestive of a typical oceanic island.

The Kermanshah ophiolites formed in both intra-plate oceanic islands and island arc environments. They were thrust onto the lower Triassic–Upper Cretaceous Bisoton seamount limestone (Berberian, 1995) during the Maastrichtian (Lippard et al., 1986). Paleocene volcanism and Eocene shallow-water limestone unconformably cover the Kermanshah ophiolite (Braud, 1987).

4. The Urumieh-Dokhtar Magmatic Assemblage (UDMA)

The UDMA forms a distinct linear intrusive–extrusive complex, which extends along the entire length of Zagros orogen, with a width of over 4 km (Alavi, 1994). The UDMA comprises various lithologic units including gabbros, diorites, granodiorites and granite bodies of different size. It also contains widely distributed basaltic lava flows, trachybasalts, ignimbrites and pyroclastic rocks, mostly tuffs and agglomerates (Alavi, 1994). Extrusive volcanism in the UDMA began in the Eocene and continued for the rest of that period, with a climax in Middle Eocene (Berberian and King, 1981). It is generally assumed that the UDMA was the magmatic arc overlying the slab of Neo-Tethyan oceanic lithosphere which was subducted beneath the Iranian plate (Berberian and Berberian, 1981; Alavi, 1980, 1994), but we prefer the model suggested by Davies and Blackenburg (1995).

One of the most important questions about the UDMA is: if it was a magmatic arc, why was it most active after the closure of the Neo-Tethys?

Referring to this question, Berberian and King (1981) wrote, “with the absorption of the down-going slab, the cause of this extensive post-suturing volcanic activity is not clear. Because of the wide-ranging composition of these volcanics, it is difficult to explain them simply as crustal melts due to rapid uplift and erosion, and it is necessary at least in part to invoke a lower crust or mantle source…”

They suggested an origin relating the UDMA to strike-slip faulting, while admitting that this scenario does not explain why the volume of UDMA diminished with time (Berberian and King, 1981).

5. Discussion

The evolutionary model presented in this section is based mostly on the data reviewed above. Rifting processes, leading to sea-floor spreading, are characterized by a sequence of events: a phase of extension involving simple shear that leads to asymmetric syn-rift volcanism (Stampfli et al., 1991, 2001).

The most important rifting phase in the Zagros Basin started apparently during Permian time. This phase was preceded by wide regional Pre-Permian erosion on both shoulders of the rift (SSZ and Arabian plate margin). This was followed by major asymmetric mafic (basalt, diabase and some intermediate) volcanic activity in the Late Permian along the SSZ. Permo–Carboniferous clastic accumulations infill topographic lows on the footwalls of half-graben along the Arabian margin before Permo–Triassic calcareous rocks on-lapped the entire Arabian margin. Neo-Tethys began opening between a lower plate in Arabia and the SSZ on the upper plate in Permian times (Figs. 3a and 4a). By Late Permian time, Neo-Tethyan simple shear rifting had affected the whole length of the present day Zagros orogen.

A second rifting phase started along the South SSZ during Triassic times (Fig. 3b). The Triassic Sikhoran ultramafic complex, the Upper Triassic tuff and andesitic and basaltic lava flow in the Abadeh area (Fig. 2), the basic and ultra-basic rocks to the west of Sirjan, and the Jurassic andesite-basaltic lavas and tuff, together with some silicic volcanism in the Sirjan, Hajiabad, Dehbid areas (Fig. 2), could all be considered as asymmetric magmatic activity along the South SSZ due to rifting of the Naien-Baft ocean from Triassic to Jurassic. Paleomagnetic data (Soffel and Forster, 1984) indicate that the central Iranian micro-continent rotated counter-clockwise during the Jurassic opening of the Naien-Baft Ocean (Sengör, 1990).

Late Jurassic–Early Cretaceous diabases, andesites and pyroxene andesites in the Dehsard area, Late Jurassic metamorphic rocks to the west of Sirjan, and low- to medium-pressure metamorphism accompanied by magmatic activity along the South SSZ, indicate that subduction of Neo-Tethys may have already commenced beneath the South SSZ by the Late Jurassic–Early Cretaceous (Sengör, 1990). Late Jurassic–Early Cretaceous granite in the Shirkuh area suggests subduction of oceanic lithosphere of the Naien-Baft Ocean beneath the Central Iranian Micro-continent (Sengör, 1990). A pronounced regional unconformity beneath the Cretaceous sequences (Stöcklin, 1968) indicates that Late Jurassic compressional movement was the most important deformational event in Central Iran. This movement led to the emergence and planation of many parts of central and northern Iran (Berberian and King, 1981). This erosion can be attributed to the commencement of the subduction of the floor of Naien-Baft Ocean.

Recent geochemical studies of the volcanic rocks of ophiolite complexes in the Zagros orogen (Ghazi and Hassanipak, 1999a,b; Hassanipak and Ghazi, 2000; Babaie et al., 2000) indicate that most (Naien, Shahr Babak, Neyriz, Kermanshah) were generated in an intra-oceanic island arc environment (supra-subduction ophiolite, Pearce et al., 1986). The development of this intra-oceanic island arc was complex. Data in hand (Miyashiro, 1973; Noiret et al., 1981; Lippard et al., 1986; Parlak and Delaloye, 1999; Bizimis et al., 2000; Al-Riyami et al., 2000) suggest that, during ocean–ocean subduction, an immature island arc developed before the ocean closure. Substantial slab collapse during a phase of intra-ocean subduction most likely led to large-scale extension of the overriding oceanic plate and the generation of supra-subduction ophiolites. Similar origins have been inferred for other ophiolitic complexes along the Alpine–Himalayan orogenic belt, such as Troodos in Cyprus (Miyashiro, 1973), Vourinos in Greece (Noiret et al., 1981), and Pindos and Orthis in Greece with Bulqiza in Albania (Bizimis et al., 2000), Bear Bassif in NW Syria (Al-Riyami et al., 2000), Mersin in the south of Turkey (Parlak and Delaloye, 1999) and Semail in Oman (Lippard et al., 1986).

Intra-oceanic island arcs in the Neo-Tethys and Naien-Baft oceans were obducted as ophiolites onto the north-eastern margin of the northern margin of Arabia and the South Sanandaj–Sirjan Zone in the Late Cretaceous, respectively. Subduction then continued beneath the Central Iranian Micro-continent and the western margin of the SSZ until the Central Iranian Micro-continent sutured with the South SSZ in the Paleocene and Iran was sutured to Arabia in the Early to Middle Eocene (Figs. 3 and 4).

The emplacement of ophiolitic complexes on the Arabian plate margin and northern edge of the South SSZ in the Late Cretaceous indicates island arc-continental suturing along these margins. Suturing in the Late Cretaceous created a narrow imbricate belt (the High Zagros) characterized by imbricated nappes folded and thrust over the full length of the Arabian plate margin (Figs. 3d and 4c). A long linear trough generated as a foreland basin in front of this belt and ophiolite–radiolarites provided the detritus supplying the Upper Maastrichtian–Paleocene Amiran flysch (Alavi, 1994; Hooper et al., 1994; Berberian and King, 1981).

Upper Cretaceous greenschist metamorphism and felsic granitoid plutons along the SSZ mark the continuation of subduction of Neo-Tethys along the western margin of the SSZ after the suturing of an intra-Neo-Tethys Oceanic island arc to Arabia (Figs. 3d and 4c). Pyroclastic and volcanoclastic rocks in the Nahavand and adjacent areas (Alavi, 1994) and Late Cretaceous volcanism along the Naien-Baft ophiolitic belt (Stöcklin, 1968) can be attributed

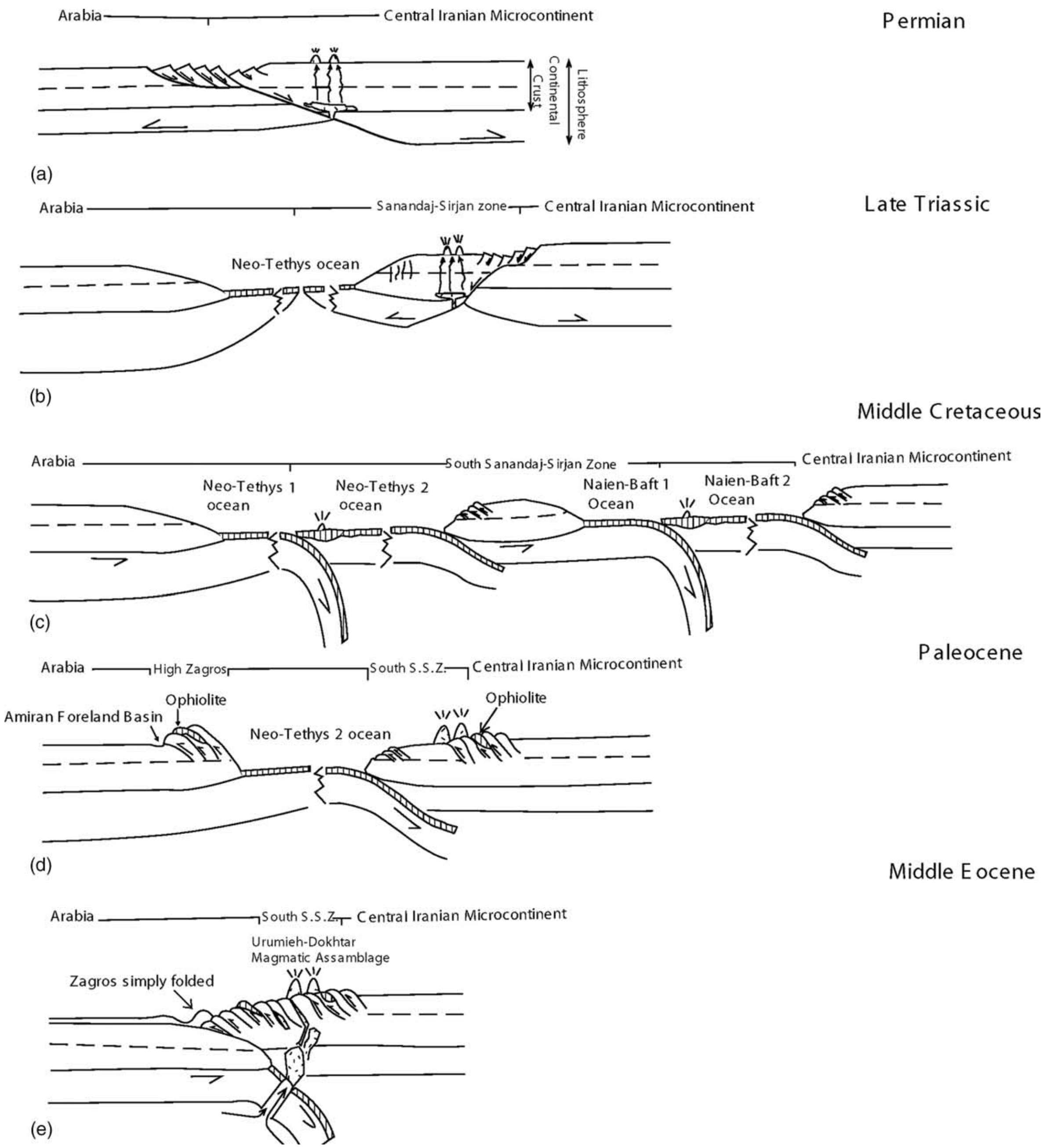

Fig. 3. Tectonic evolution of the South Sanandaj–Sirjan Zone (SSZ). (a) Permian rifting; (b) second rifting phase in Late Triassic; (c) the closure of the Neo-Tethys and Naien-Baft Oceans occurred at first as a collision with an oceanic island arc; (d) ophiolite emplacement along the SSZ and on the Central Iranian Microcontinent; (e) Middle Eocene slab break-off.

to a magmatic arc formed along the SSZ. Continuation of subduction beneath the SSZ in the Late Cretaceous caused eastward movement of the North-West Iranian Plate (NWIP), left lateral-reverse movements along the Alborz Mountains in the Late Cretaceous–Paleocene, and right lateral movement along the Darouneh Fault (Nabavi, 1976).

McCall (1997) and Sengör et al. (1993) proposed that the South SSZ continues eastward and is overlain by the ophiolite belt in the northern Makran. If this is correct, then the Band Ziarat ophiolite complex may be considered to be the remnant of the Naien-Baft Ocean. Isochron ages on hornblende gabbro from the Band Ziarat ophiolite complex range from 124 ± 4 to 146 ± 5 Ma and from 140 ± 7 to 160 ± 6 Ma (Hassanipak et al., 1996). These ages indicate that this ophiolite complex may have formed in the Early Cretaceous. However, there is paleontological evidence that the associated volcanics above the Band-Ziarat ophiolite complex extend up to Early Paleocene (Hassanipak et al., 1996). Strong folding, magmatism and uplift of the central Iranian micro-continent in the Late Maastrichtian–Paleocene and the fact that Paleocene–Eocene shallow-water sediments overlie the Naien-Baft ophiolitic belt above an

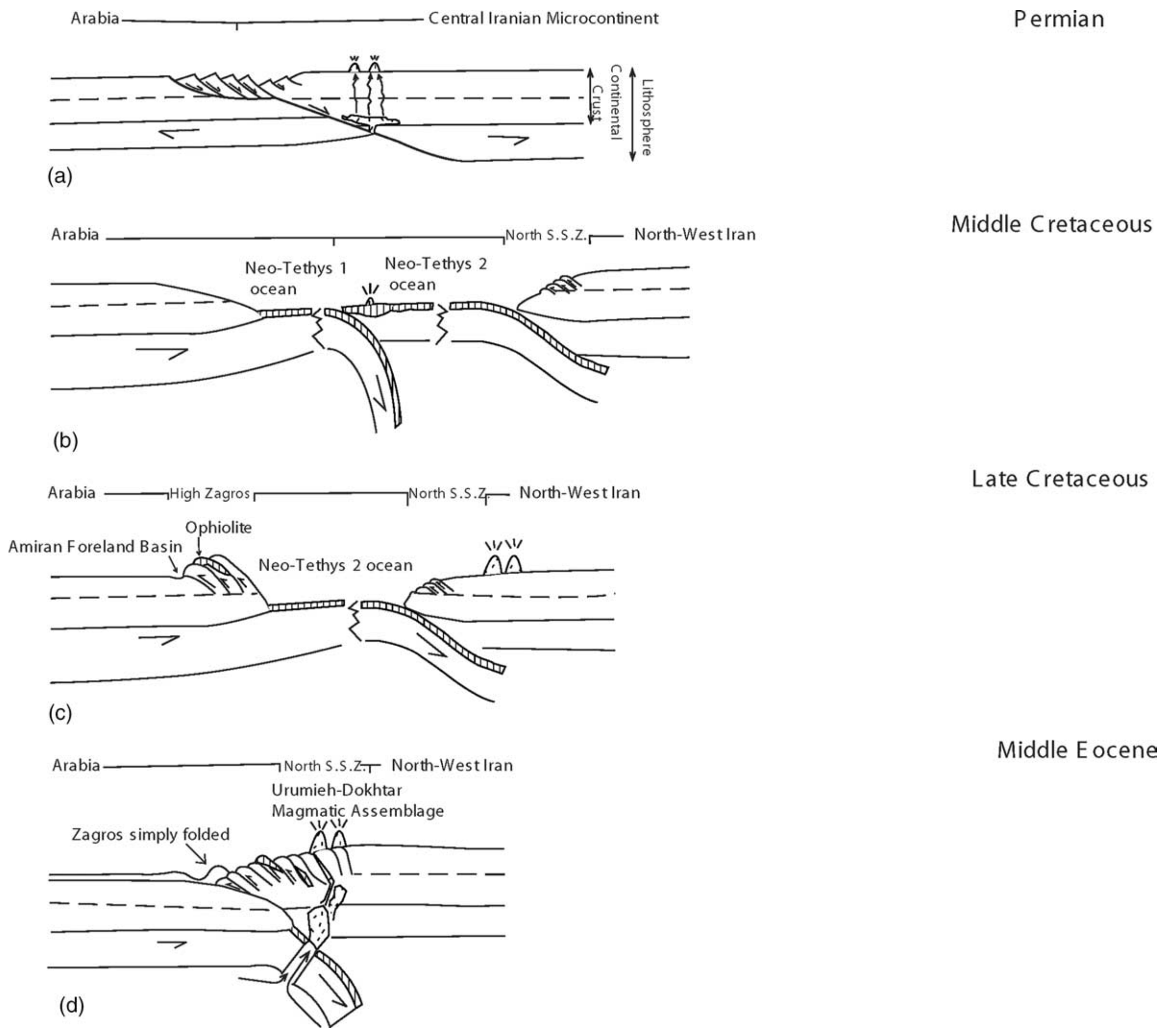

Fig. 4. Tectonic evolution of the North Sanandaj–Sirjan zone (NSSZ). (a) Permian rifting; (b) closure of the Neo-Tethys Ocean commencing with an oceanic island arc collision; (c) ophiolite emplacement along the NSSZ; Middle Eocene slab break-off.

angular unconformity, suggest that the Naien-Baft Ocean closed before the Paleogene. This closure which, continued to the south, may have reached the Band-Ziarat area in the Eocene.

The continuation of the Naien-Baft rift into the NWIP (east of the North SSZ) never developed into an ocean. Transtension in this area was not accompanied by any magmatic activity. Instead, several km of Upper Triassic-Upper Triassic–Upper Jurassic sandstones and shales accumulated along the northern part of the North SSZ (e.g. Amidi and Majidi, 1977; Mohajjel, 1992; Ghasemi et al., 2005). Stöcklin (1968) also emphasized strong subsidence along the region northeast of the Zagros during much of the Jurassic. These observations illustrate that the continuation of Naien-Baft Ocean along the northeastern margin of the North SSZ only rifted as a failed arm.

Undeformed Oligo-Miocene sediments (Lower Red and Qom formations) covered older rocks (along the North SSZ) above an unconformity with low relief. The absence of any later major deformational events indicates that Eocene was the age of final suturing between Iran and Arabia. The intrusion of large numbers of plutons along the North SSZ into Upper Cretaceous carbonate rocks and generation of the main syn-tectonic conglomerates along the SSZ in Eocene time (Alavi, 1994) confirms that the suturing occurred in the Early to Middle Eocene. Syn-tectonic conglomerates in Late Cretaceous–Paleocene, Eocene, Miocene, Pliocene and Pliocene-Quaternary in SSZ correlate well with the tectonic events that affected the SSZ. These are:

1. A Late Cretaceous increase in the rate of subduction of Neo-Tethys beneath the SSZ.
2. Early to Middle Eocene suturing between Iran and Arabia (along the Main Zagros Thrust zone).
3. Late Eocene extension along the site of the Red Sea (Hempton, 1987).
4. Late Oligocene–Miocene opening of the Red Sea (Izzeldin, 1987; Sultan et al., 1992).
5. The appearance of oceanic crust in the Red Sea since 10 Ma (Hempton, 1987).

During suturing between Arabia and Iran in the Early to Middle Eocene, the Amiran flysch was imbricated and carried piggyback into the developing fold and thrust belt in the High Zagros. The first stage of extension of the Red Sea in the Late Eocene coincided with horizontal shortening along the southern part of the High Zagros as deformation propagated southward into the Zagros fold-thrust belt (Hessami et al., 2001).

Detailed geological studies reveal the existence of a few suspect terrains in the Kermanshah ophiolite and the Sanandaj area. Oceanic island basalt, oceanic island arc volcanic rocks and the Bisoton seamount limestone in Kermanshah, together with the Barremian-Aptian sequences of thick shales in the Sanandaj area, can all be considered as suspect terrains carried to the trench during the subduction of Neo-Tethys. The erratic geological record along the SSZ can be attributed to the complexities of mosaic tectonics.

Post-suturing convergence between Arabia and Iran resulted in a right lateral-reverse displacement of about 100 km along the Zagros main recent faults (Bushara, 1995). The northward movement of Arabia closed the remnant basin of Neo-Tethys in the south of Turkey in Miocene time (Yilmaz et al., 1993).

After Arabia and Iran were sutured, large scale post-orogenic strike-slip faulting was accompanied by bimodal volcanism along the failed arm in the northern SSZ in the Middle Eocene. The widespread post-orogenic silicic and basic magmatic activity along the northern part of the UDMA and the Eocene–Oligocene plutons along SSZ can all be explained by slab breakoff process beneath the NWIP. Strike-slip movement along the linear depressions between the UDMA and the SSZ and the border between the SSZ and Central Iranian Micro-continent was suggested by Sengör (1990).

Because continental lithosphere is buoyant compared to the asthenosphere, suturing between Arabia and Iran was followed by the Arabian Plate indenting the Iranian Plate; this increased the thickness of the SSZ crust to about 55 km (Snyder and Barzangi, 1986). Following that, the slab of subducted Neo-Tethyan oceanic lithosphere detached from Arabia and sank (Bird, 1978) in the Middle Eocene. This rupture began in the North SSZ in the Middle Eocene (Fig. 4d) and opened southward like a zip-fastener. The asthenosphere welled upward into this intra-plate gap opened by slab breakoff behind the suture. The resulting thermal perturbation led to melting of the metasomatosed overriding mantle lithosphere, which complicates the geochemical characteristics of the UDMA. (Emami personal communication, 2003). Mantle melts intra-plated the overlying continental crust giving rise to granitic magmatism. Since the heat source would follow the track of the breakoff, we would expect the trace of the resulting magmatism to be nearly linear and parallel to the Zagros orogen (Davies and Blackenburg, 1995) (Figs. 3e and 4d). The cessation and replacement of cold oceanic lithosphere by hot asthenosphere also led to rapid uplift of the Zagros orogen and the exhumation of metamorphic rocks in the SSZ. The source of post-suturing magmatic activity in the Urumieh-Dokhtar Magmatic Assemblage, together with the associated intrusive activity and uplift of the SSZ, are therefore attributed to slab breakoff. This breakoff resulted in the peak of magmatic activity along the Urumieh-Dokhtar Magmatic Assemblage in the Middle Eocene.

6. Conclusions

1. Asymmetric magmatic activity along the SSZ in the Permian, and along the South SSZ in the Triassic, suggest that the opening of Neo-Tethys and Naien-Baft Oceans were controlled by simple shearing of half graben rifts.
2. Recent geochemical studies of the volcanic rocks indicate that the emplacement of ophiolitic rocks along the Arabian plate margin and South SSZ occurred as the result of continental–oceanic island arc suturing. Continent–continent suturing followed the emplacement of ophiolitic rocks.
3. The absence of continuing magmatic arc activity in time along SSZ and Central Iranian Micro-continent (the overriding continental plates) can be attributed to low angles of subduction during both stages of oceanic closure (island arc-continent, continent–continent suturing).
4. The presence of very thick Upper Triassic–Upper Jurassic sediments along the North SSZ can be considered as indicating a continuation of the Naien-Baft Ocean without the generation of any oceanic lithosphere.
5. The post suturing magmatic activity along SSZ and UDMA can be attributed to the slab break-off process.

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