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Geodynamic evolution of the Sanandaj-Sirjan Zone, Zagros Orogen, Iran

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Abstract: The Sanandaj-Sirjan Zone is a metamorphic–magmatic belt, associated with the Zagros Orogen and part of the Alpine-Himalayan orogenic system in Iran. Stratigraphic, metamorphic, magmatic, and tectonic evidence presented here indicates that the Sanandaj-Sirjan Zone, the Central Iranian Microcontinent, and the North West Iranian Plate were a part of the Arabian plate until the Late Permian, when they separated during the opening of the Neotethys. Later subduction of the Neotethys oceanic crust beneath the Sanandaj-Sirjan Zone resulted in the complete closure of the Paleotethys Ocean in the Early Upper Triassic. The following extensional regime (related to slab roll-back) caused separation of the Sanandaj-Sirjan block, Central Iran Microcontinent, and North West Iranian Plate during the Upper Triassic to Lower Jurassic. The separation of these continental blocks caused sedimentation differences during that time. The North Tabriz and Nain-Baft Faults are probably the boundary between the Sanandaj-Sirjan Zone and Central Iran. The basin between the Sanandaj-Sirjan Zone and the Central Iranian block (the Iranian Microcontinent and North West Iranian Plate) closed in the Late Cretaceous. After that, these terranes experienced similar geological evolution, especially from the Oligocene to the Miocene.

Key words: Sanandaj-Sirjan Zone, geodynamics, Iranian plate, Arabian plate, Neotethys

1. Introduction

The geology and especially the tectonic style of Iran are highly influenced by the history and evolution of the Tethyan oceans. The Iranian crust is divided into several geotectonic units, namely the Zagros, Makran, Sanandaj-Sirjan Zone, Urmia-Dokhtar Magmatic Assemblage (UDMA), Central Iran block, and Sistan Suture Zone (Figure 1). Each unit is characterized by a relatively unique record of stratigraphy, magmatic activities, metamorphism, orogenic events, tectonics, and overall geological style. The Zagros Orogen is part of the Alpine-Himalayan mountain chain. From the northeast to the southwest, the Zagros Orogen consists of four parallel tectonic zones: (i) the UDMA, (ii) the Sanandaj-Sirjan Zone, (iii) the Zagros Fold Thrust belt, and (iv) the Mesopotamian-Persian gulf foreland basin (Stöcklin, 1968; Berberian and King, 1981; Alavi, 1994; Mohajjel and Fergusson, 2000).

The metamorphic and igneous zone of the Zagros Orogen, the Sanandaj-Sirjan Zone, was named by Stöcklin (1968). The Sanandaj-Sirjan Zone extends ~1500 km from the northwest (Sanandaj) to southeast (Sirjan) with a width of 150–200 km, parallel to the Zagros Fold Thrust belt. Compared to the high Zagros Mountains, most of the Sanandaj-Sirjan Zone has a relatively low relief, typically no more than 1400 m. The Zagros Main Thrust bounds the southern margin of the Sanandaj-Sirjan Zone and separates it from Zagros. Central Iran is separated from the Sanandaj-Sirjan Zone by a belt of steep and straight faults including the Tabriz and Nain-Baft Faults (Şengör, 1979). Overall, the scarcity of Tertiary volcanic rocks, the high volumes of Mesozoic (and somewhat Tertiary) intrusions, the relatively high abundance of Paleozoic volcanic rocks (Silurian, Devonian, and Permian), and metamorphism due to Cimmerian movements are the main features of the Sanandaj-Sirjan Zone (e.g., Aghanabati, 2006; Ghasemi and Talbot, 2006). These characteristics indicate that the Sanandaj-Sirjan Zone cannot be assigned to any other geological and structural subdivision of Iran.

The geodynamic evolution of the Sanandaj-Sirjan Zone was controlled by the opening and subsequent closure of the Neotethys Ocean at the northeastern margin of Gondwana (Alavi, 1994). Two main opinions are postulated on whether the Sanandaj-Sirjan Zone was part of the Iranian or Arabian plate during the formation of the Neotethys:

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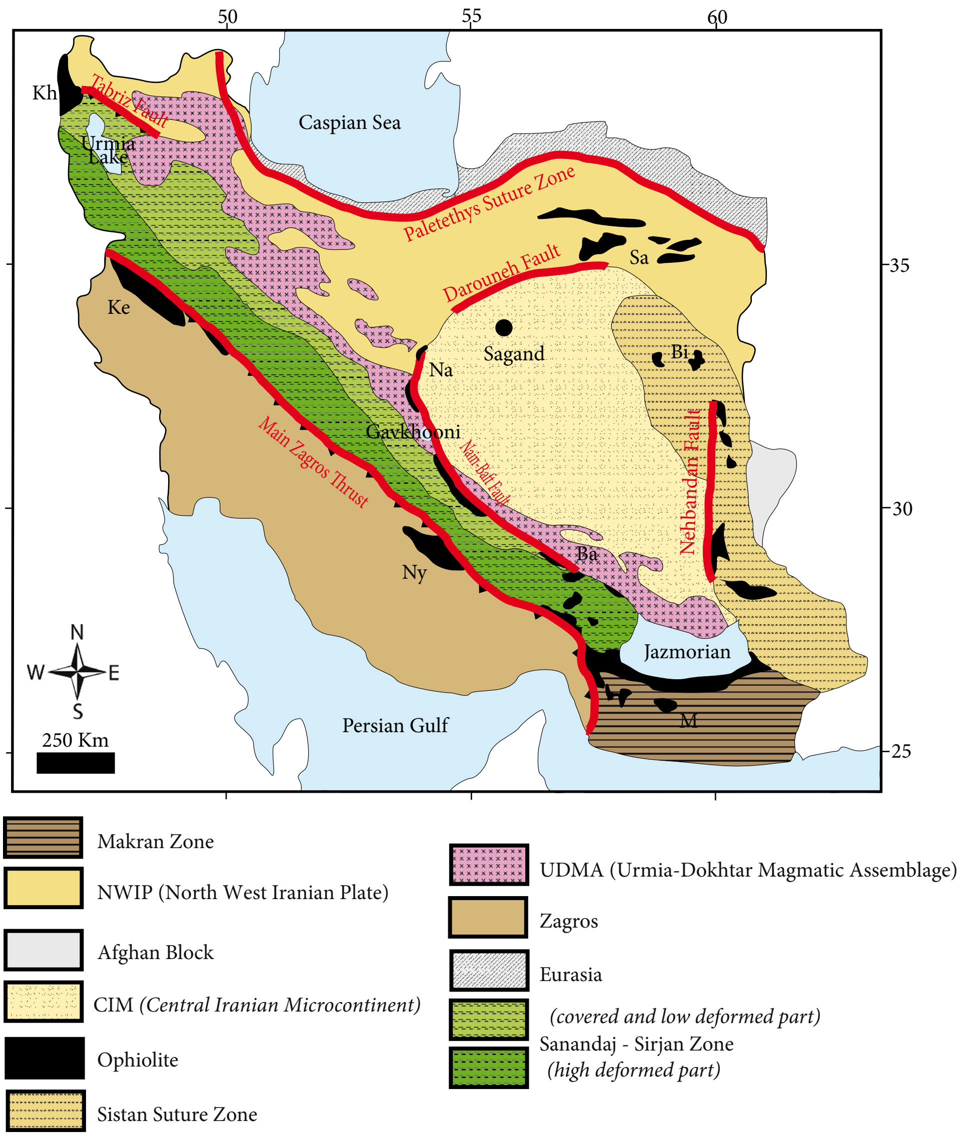

Figure 1. Main tectonic elements of Iran (modified after Stöcklin, 1968). Na: Nain, Ba: Baft, Kh: Khoy, Ny: Neyriz, Ke: Kermanshah, Sa: Sabzevar, M: Makran, and Bi: Birjand Ophiolites.

1) The Sanandaj-Sirjan Zone has been interpreted as an active continental margin of the Neotethys, separated from the passive Arabian continental margin by the Zagros suture (e.g., Dewey et al., 1973; Haynes and McQuillan, 1974; Berberian and King, 1981; Dercourt et al., 1986; Şengör, 1984). According to this model, the Neotethys opened and closed along the southwestern margin of the Sanandaj-Sirjan Zone, while the Paleotethys is placed to the north of the Sanandaj-Sirjan Zone. Based on similar sedimentary and tectonic history and common magmatic and metamorphic activities, the Sanandaj-Sirjan Zone is conventionally considered as a subzone of the Iranian plate. There are two interpretations regarding the position of the Paleo- and Neotethys:

i) The Sanandaj-Sirjan Zone was detached from Central Iran (Şengör, 1979, 1990; Stampfli and Borel, 2002) ever since they both separated from Gondwana in the Upper Permian.

ii) Ghasemi and Talbot (2006) suggested that the Central Iranian Microcontinent (CIM), the Sanandaj-Sirjan Zone, and the North West Iranian Plate (NWIP) formed one single block, the Iranian plate. The Sanandaj-Sirjan Zone was situated to the south of Central Iran and is considered as the active continental margin of the Iranian plate. The Paleotethys was located to the north of the NWIP, which itself borders the northern side of the CIM. These three blocks separated only after the Paleotethys closure during the Jurassic.

2) In this scheme, the Sanandaj-Sirjan represents the northeastern extension of the Arabian passive continental margin (Falcon, 1969; Haynes and McQuillan, 1974; Alavi, 1980, 1994) based on similar structural trends and deformation patterns in Zagros and the Sanandaj-Sirjan Zone. The Neotethys suture thus runs along the northeastern border of the Sanandaj-Sirjan Zone.

Obviously, the Sanandaj-Sirjan Zone is an important tectonic unit of Iran that remains poorly documented. However, it is crucial to understand this part of the Zagros belt, and especially to model the relationship between Central Iran and Arabia through Precambrian to Cenozoic times. Understanding its geological evolution could unravel the regional correlation to adjacent areas such as North West Iraq, South East Turkey, and the eastern continuation of the Alpine-Himalayan orogenic belt. We integrated existing data from sedimentary, igneous, and metamorphic rocks and structural features and characteristics of the related ophiolites in this paper to compare the various existing geodynamic models. We discuss the situation of the Paleo- and Neotethys with respect to the Sanandaj-Sirjan Zone and propose a regional scenario that may help understand this part of the Tethyan domain.

2. Geological setting

The Sanandaj-Sirjan Zone is a NW-SE trending belt of mainly metamorphic and igneous rocks, located at the northeastern extension of the Zagros Orogen (Figure 1). To the northeast, it is bordered by Central Iran and the UDMA, and to the southwest by the Zagros Fold Thrust belt (Alavi, 2004).

2.1. The Sanandaj-Sirjan Zone

The Sanandaj-Sirjan Zone consists mainly of Late Proterozoic–Mesozoic metamorphic rocks, such as metacarbonates, schists, gneisses, and amphibolites (Figure 2). They are overlain by Phanerozoic shallow-water sediments of a passive continental margin and intruded by large gabbroic to granitic Mesozoic plutons (e.g., Dilek et al., 2010).

Similar geological characteristics suggest a westward extension of the Sanandaj-Sirjan Zone into the Bitlis-Puturge Zone in Turkey (Dilek et al., 2010). Both these zones consist of Precambrian crystalline basement, Late Proterozoic–Mesozoic metacarbonates, schist, gneiss, and amphibolites that are intruded upon by deformed to undeformed granitoid plutons.

U-Pb dating of detrital zircons of Phanerozoic sedimentary rocks from several localities across Iran and the presence of inherited zircons in younger intrusions indicate that the bulk of the crystalline basement of Iran (both in Central Iran and the Sanandaj-Sirjan Zone) is Precambrian in age (Horton et al., 2008). However, the vast exposure of Paleozoic and Mesozoic metamorphic rocks makes this zone different from other Iranian geotectonic units.

Deformation recorded in the metamorphic rocks of the Sanandaj-Sirjan Zone and the I-type nature of plutons are related to the subduction of the southern Neotethys sea floor northeastwards beneath the continental blocks (Mohajjel, 1997).

2.2. Zagros

The Zagros Fold Thrust belt forms the less exposed external part of the orogen. This belt consists of folded and faulted mainly Paleozoic and Mesozoic successions of 4–7 km thick overlain by Cenozoic siliciclastic and carbonate rocks of 3–5 km thick, resting on highly metamorphosed Proterozoic Pan-African basement that was affected by Late Neoproterozoic–Cambrian Najd strike-slip faults (Alavi, 2004). The Zagros Mountains gradually rise northeastward from an unfolded shelf, extending through a fold belt into a thrust belt and imbricated zone (Berberian and King, 1981).

2.3. Central Iran

Central Iran is located between the convergent Arabian and Eurasian plates. Central Iran comprises two major crustal domains: the NWIP and the CIM. The NWIP comprises the region north of the Darouneh and Tabriz Faults. The CIM (Takin, 1972) comprises terrain limited by the Sistan, Nain-Baft, Makran, and Sabzevar Ophiolites (Şengör, 1990) and is affected by a complex system of active continental strike-slip faults causing an intensive N-S dextral shearing (Zanchi et al., 2009).

2.4. The Urmia-Dokhtar Magmatic Assemblage

The 150-km-wide UDMA is a distinctively linear and voluminous magmatic arc of the active Iranian margin in the Tertiary (Arvin et al., 2007; Omrani et al., 2008). It is composed of tholeiitic, calc-alkaline, adakitic, and K-rich alkaline intrusive and extrusive rocks with associated pyroclastic and volcanoclastic successions (Omrani et al., 2008). The UDMA comprises various plutonic lithologies including gabbros, diorites, granodiorites, and granite bodies of different sizes. 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 the Middle Eocene (Berberian and King, 1981). The youngest rocks are lava flows and pyroclastics related to Pliocene to Quaternary volcanic cones with adakitic composition (Omrani et al., 2008).

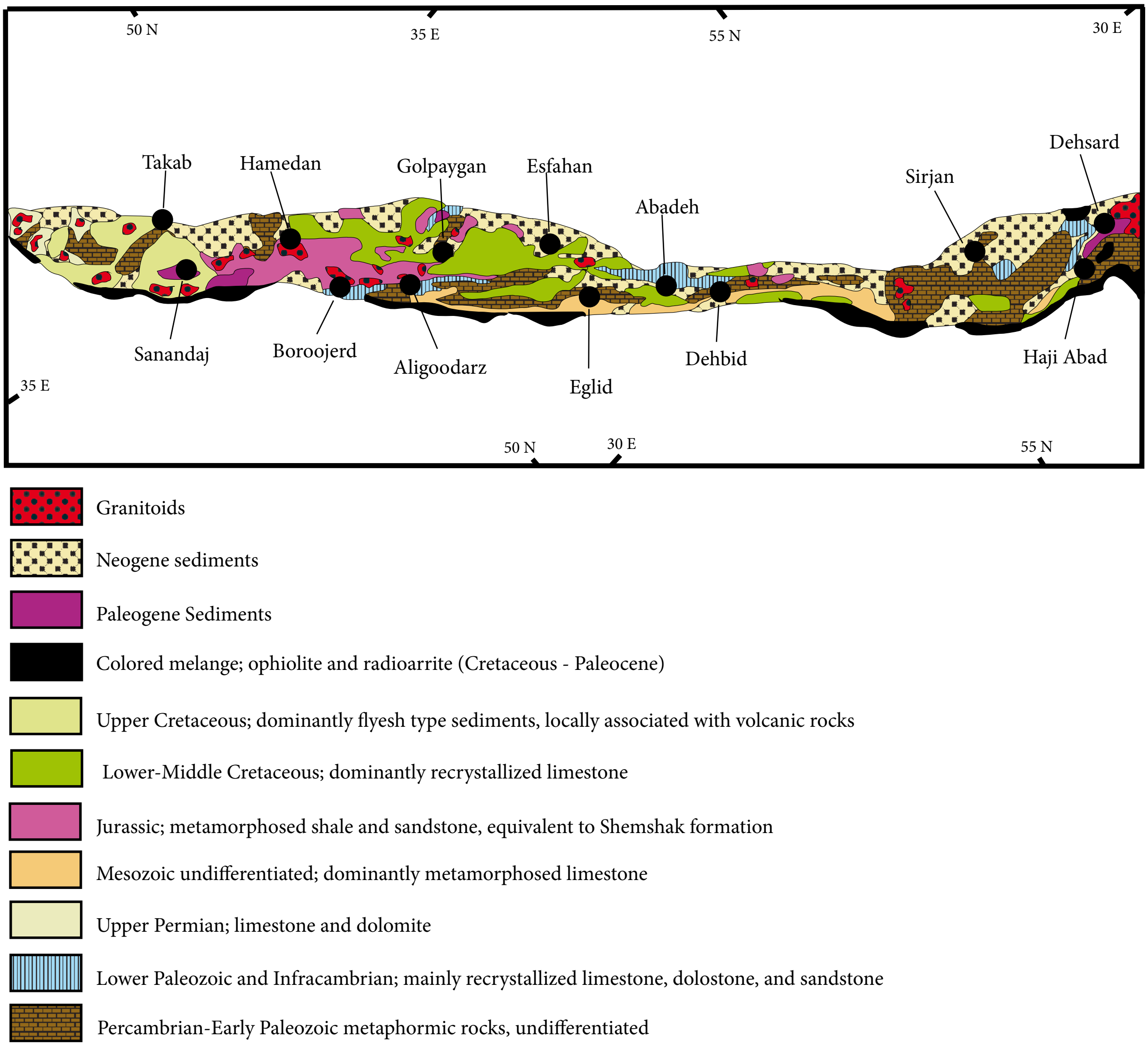

Figure 2. Geological map of the highly deformed part of the Sanandaj-Sirjan Zone (simplified after NIOC, 1975).

3. Stratigraphy records

3.1. The Sanandaj-Sirjan Zone

The oldest rocks of the Sanandaj-Sirjan Zone are amphibolites, gneisses, and amphibole schists with Precambrian protolith ages (Aghanabati, 2006; Nutman et al., 2014). The Golpaygan quadrangtle (Figure 3) is characterized by extensive outcrops of Precambrian metasandstones and various schists (Thiele et al., 1968). Along the northeastern border of the Sanandaj-Sirjan Zone, northeast of Eglid (Figure 3; Hushmandzadeh et al., 1978) and Golpaygan (Figure 3; Thiele et al., 1968), and in the Takab Region (Figure 3; Alavi-Naini et al., 1982), nonmetamorphosed Late Precambrian–Early Paleozoic sections of shallow marine coastal, deltaic, and fluvial and also carbonate facies rocks are exposed (Mohajjel, 1997). These successions are stratigraphically equivalent to the shallow marine sediments in Central Iran. A white quartzite layer often covers the Precambrian metamorphic rocks in the Sanandaj-Sirjan Zone (Aghanabati, 2006). The quartzite layer is comparable to the Cambrian Top Quartzite of Central Iran. The Ordovician-Carboniferous sediments are often missing in the Sanandaj-Sirjan Zone and most other parts of Iran, which is attributed to epeirogenic movements associated with the Caledonian and Hercynian orogenies in Europe and North West Africa (Stöcklin, 1968; Berberian and King, 1981; Aghanabati, 2006). However, in the southern part of the Sanandaj-Sirjan Zone occur sporadic assemblages of various types of Paleozoic rocks. Dolomitic marble, mica schist,

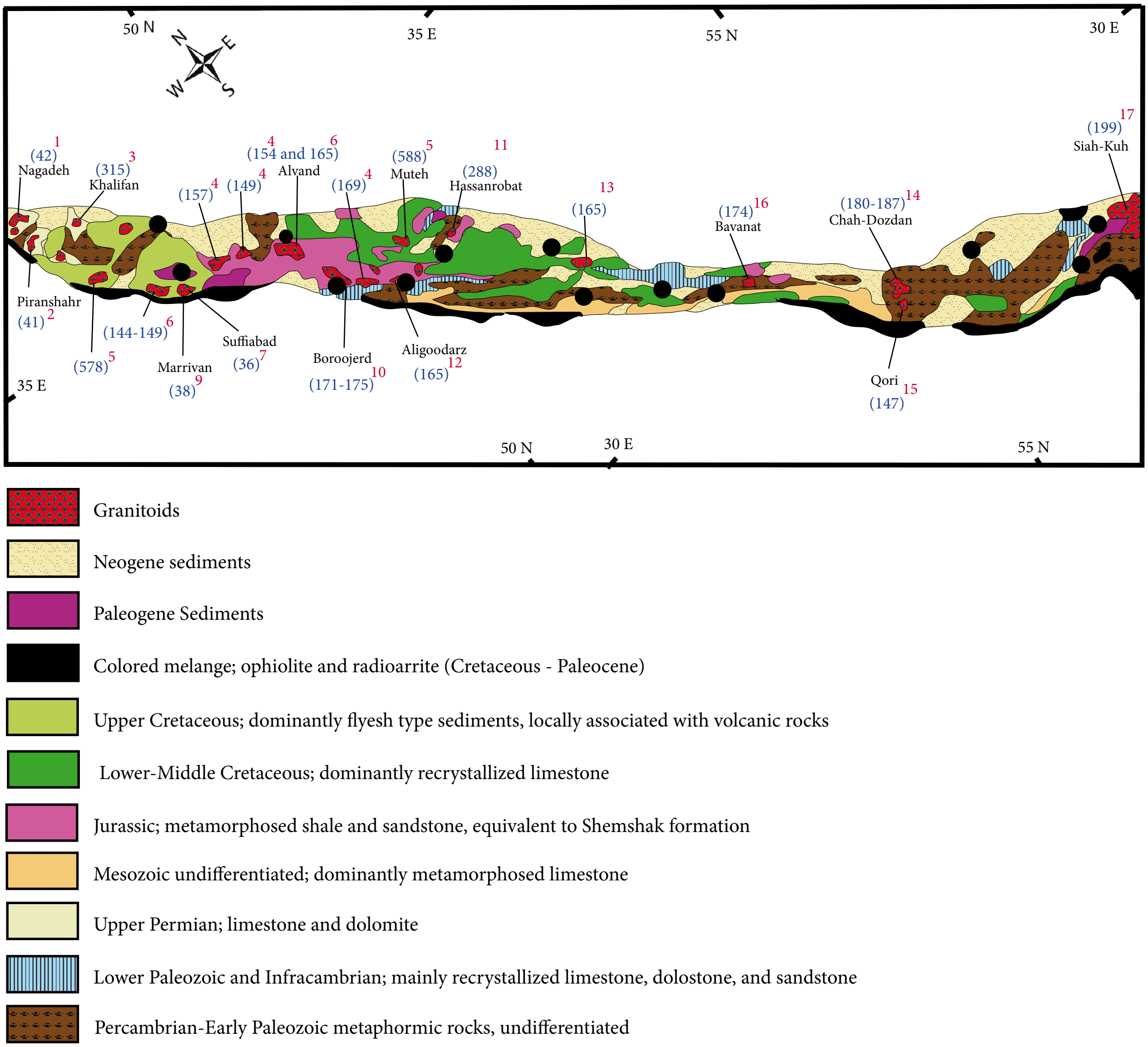

Figure 3. Locations, names, and ages of the granitoids in the Sanandaj-Sirjan Zone. Blue numbers are ages in Ma and red numbers are references (1: Mazhari et al., 2011; 2: Mazhari et al., 2009; 3: Bea et al., 2011; 4: Mahmoudi et al., 2011; 5: Hassanzadeh et al., 2008; 6: Azizi et al., 2011; 7: Azizi et al., 2011; 8: Shahbazi et al., 2010; 9: Sepahi et al., 2014; 10: Ahmadi Khalaji et al., 2007; 11: Alirezaei and Hassanzadeh, 2012; 12: Esna-Ashari et al., 2012; 13: Chiu et al., 2013; 14: Fazlnia et al., 2007; 15: Fazlnia et al., 2009; 16: Mousivand et al., 2012; 17: Arvin et al., 2007).

quartzite, and black slate constitute the Middle Cambrian to lower Silurian rocks (Aghanabati, 2006). Late Devonian units contain basaltic fragments with alkaline nature (Aghanabati, 2006).

The Late Carboniferous to lower Permian units consist of sandstone, shale, pillow lava, limestone, chert, submarine acidic rocks, and metamorphic rocks (Aghanabati, 2006). In some parts, Carboniferous detrital limestone, containing corals and gastropods, is interbedded with quartz sandstone (Alavi and Mahdavi, 1994).

Late Permian and Middle Triassic rocks are shelf limestone and dolomite in the Sanandaj-Sirjan Zone. The Sanandaj-Sirjan Zone had a platform condition during the Late Triassic to Lower Jurassic (Aghanabati, 2006). Then an active trough condition, occasionally accompanied by magmatism, dominated the area (Alavi and Mahdavi, 1994). This is evidenced by Mesozoic flysch and turbidite sediments in the Sanandaj-Sirjan Zone.

The Cretaceous rocks were deposited in continental, shallow marine, and locally marine environments

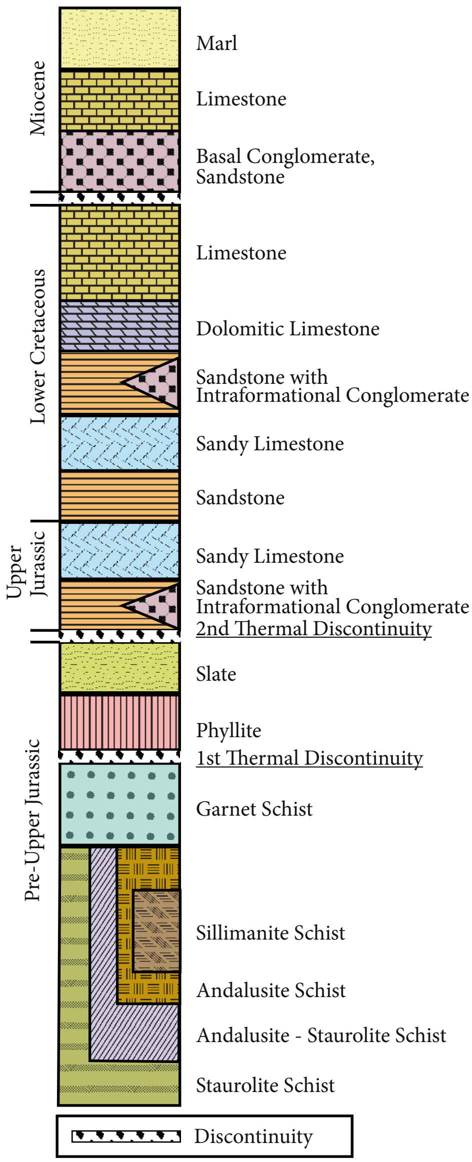

Figure 4. Stratigraphic column of Hamadan area (from Baharifar et al., 2004).

(Figure 4; Mohajjel, 1997). Apart from alluvium and colluvium, Cenozoic successions are largely absent from the complexly deformed subzone. These Cretaceous rocks are considered to have formed as part of a continuous sedimentary basin that developed throughout the southwestern border of the Sanandaj-Sirjan Zone and has been filled with Paleocene, Eocene, and young sediments (Mohajjel, 1997).

3.2. Zagros

The Precambrian basement of the Arabian plate is exposed in the west of the Arabian shield (Konert et al., 2001). In Zagros, Precambrian basement is found only as few granite, gabbro, basalt, amphibolite, and schist fragments brought to the surface by salt diapirs (e.g., Haynes and McQuillan, 1974; Taghipour et al., 2012). The Hormoz complex (salt, anhydrite, dolomite, shale, volcanic, and metamorphic blocks) was deposited in evaporitic basins during the Late Protozoic–Early Cambrian (Edgell, 1996). During the Early Paleozoic, shallow marine and fluvial sandstone, siltstone, and shale were deposited on the low-relief erosion surface formed either on the Precambrian basement or on the Hormuz basins (Lacombe et al., 2007). The large Silurian-Carboniferous sedimentary gap in Zagros is apparently the effect of epeirogenic movements, which led to a regional regression and general emerging of the region. The regional shallow marine transgression during the Permian caused the deposition of shallow subtidal facies on the Lower Permian basal costal clastics (Faraghan Formation), overlying the Ordovician and Silurian rocks (Berberian and King, 1981). In the Zagros basin, the deposition of marine sediments continued from the Permian to the Miocene (Sherkati and Letouzey, 2004). The Early Triassic period in Zagros was characterized by marine carbonate sedimentation, which had been persisting throughout the Permian (Koop and Stonely, 1982). The Middle-Late Triassic of Zagros was occupied by an evaporitic platform (Murris, 1980). During the Jurassic to Mid-Cretaceous times, sediments were deposited in a steadily subsiding basin (Berberian and King, 1981), in which subsidence was controlled by vertical movements and flexures along major basement faults. The Late Cretaceous to Miocene rocks represent deposits of the foreland basin prior to the Zagros Orogeny and subsequent incorporation into the colliding rock sequences. This sequence unconformably overlies Jurassic to Upper Cretaceous rocks (Vaziri-Moghaddam et al., 2010). The Miocene Zagros Orogeny controlled the sedimentary evolution of the Zagros basin. The Early to Middle Miocene formations were deposited in a subbasin in the southern part (Ahmadhadi et al., 2007). During Late Miocene and Pliocene times, regression of the sea and the creation of mountainous relief by folding and thrusting resulted in a continental environment (Bahroudi and Koyi, 2003; Sheikholeslami et al., 2008). Great quantities of clastic material and red beds were developed in adjacent synclines (Berberian and King, 1981). Finally, Pliocene–Pleistocene conglomerates unconformably overlie older formations (Berberian and King, 1981).

3.3. Central Iran

The Chapedony formation in the Sagand region (Figure 1) of Central Iran is predominantly composed of high-grade gneiss and associated migmatite, schist, amphibolite, marble, quartzite, and granite (Hushmandzadeh et al., 1978), and it is the oldest basement complex in Iran. The term “basement complex” is used here for the mostly metamorphic or igneous rocks (with the age ranging in most cases from 570 to 550 Ma; Nadimi, 2007) underlying the Pan-African unconformity. The “basement complex” is successively overlain by the Late Precambrian and Early Cambrian Kahar slates and Soltanieh dolomites, the Cambrian Zaigun shales and Lalun sandstones, and the Upper Cambrian–Lower Ordovician Mila limestones and dolomites (Thiele et al., 1968). Following the Late Precambrian, Pan-African orogeny, and basement consolidation, the Iranian Precambrian craton became a relatively stable continental platform with shelf deposits dominated by clastic sediments and a lack of major magmatism and deformation during most of the Paleozoic (e.g., Berberian and King, 1981; Aghanabati, 2006). The Middle Cambrian to Early Devonian shallow marine sediments consist of dolomite, limestone, shale, sandstone, and gypsum. Dolomite, limestone, and shale (with fragments of alkaline basalt) constitute the Late Devonian and Early Carboniferous deposits. In the Late Carboniferous, shallow marine and continental sediments were deposited in some parts of Central Iran. The Upper Carboniferous–Lower Permian transgression, documented from various localities in Iran, is represented by basal sandstone grading upward into a thick carbonate sequence (Aghanabati, 2006; Alavi-Naini, 2009). Late Permian sediments are shelf limestones and dolomites. The shallow marine to platform sediments were deposited during the Mesozoic to Paleogene. The Lower Mesozoic sediments contain coal-bearing shale and sandstone, which have been deposited in lagoons and environments near the shore line, but Upper Mesozoic (up to Late Cretaceous) sediments are composed of ammonite-bearing limestone and marl, ending with red clastic strata or evaporate deposits. A major regional stratigraphic gap and unconformity at the base of the Cenozoic is covered by Oligocene to Miocene limestone (Qom formation). Oligocene sediments in most parts of Iran have a shallow marine character, turning into marine facies in the Upper Oligocene through the Lower Miocene (Rahimzadeh, 1994).

In summary, the stratigraphic records indicate that the Iranian plate and Zagros have similar basements on one hand and that the Sanandaj-Sirjan and Central Iran show very similar stratigraphic units during the Paleozoic on the other hand. The Mesozoic flysch and turbidite sediments in the Sanandaj-Sirjan Zone suggest that this zone differs from the adjacent Zagros and Central Iran zones.

4. Metamorphism and deformation records

4.1. The Sanandaj-Sirjan Zone

Three main phases of deformation are recognized in the Sanandaj-Sirjan Zone (Mohajjel, 1997): 1) Late Jurassic-Early Cretaceous uplift, intense ductile deformation, and local amphibolite facies metamorphism; 2) Late Cretaceous–Paleocene regional deformation and associated greenschist facies metamorphism; and 3) Cenozoic regional thrusting and associated folding. These metamorphic and deformation phases are related to northeastward subduction of the southern Neotethys seafloor beneath the Sanandaj-Sirjan Zone (Berberian and King, 1981; Agard et al., 2006; Moritz et al., 2006; Oberhänsli et al., 2007; Dilek et al., 2010). The general structural fabric is defined by NW-trending and SW-overturned folds, SW-vergent thrust faults, and NW-trending reverse faults that collectively resulted in crustal thickening (Allen et al., 2004; Dilek et al., 2010; Mouthereau, 2011). This contractional feature was overprinted by regional-scale, right-lateral transpressional deformation indicated by pervasive subhorizontal stretching lineation and dextral shearing (Mohajjel and Fergusson, 2000).

The Sanandaj-Sirjan Zone is currently divided at the latitude of Golpaygan (Figure 2) into a northern and southern portion with different features (e.g., Eftekharnejad, 1981). The northern portion was affected by younger metamorphic events compared to the southern portion. The protoliths of the Mesozoic metamorphic rocks exposed in the Muteh area, NE of Golpaygan (Figure 2; the northern portion of the Sanandaj-Sirjan Zone), suggest that they represent a Paleozoic succession consistent in age and composition with the coeval units of Central Iran (Rachidnejad-Omran et al., 2002). In contrast, a metamorphic complex consisting of garnet–gneiss, amphibolite, and anatectic granites was identified in the southern part of the region by Ghasemi et al. (2002) that shows Late Carboniferous ‘Variscan’ Ar–Ar ages ranging from 330 to 300 Ma. A possible Late Paleozoic event followed by an Eo-Cimmerian deformation was reported by Şengör (1990) and Zanchi et al. (2009) in the Kor-e Sefid Mountains east of the Neyriz Ophiolites. Additionally, to the east of the Neyriz Ophiolites, metagabbro and anatectic granite were found in favor of the occurrence of a unique Eo-Cimmerian metamorphic event (Sheikholeslami et al., 2003). Both metamorphic events and young (Upper Cretaceous and Paleogene) batholiths are mostly accumulated in the northern portion of the Sanandaj-Sirjan zone (Figure 3).

The Hamedan area (Figure 2) is characterized by predominantly metamorphic rocks of sedimentary and magmatic origins (Berberian and Alavi-Tehrani, 1977; Sepahi, 1999) and the presence of the Alvand granitoid complex (Figure 3). A synthetic lithostratigraphic column (Figure 4) was established for the Hamedan area by Baharifar et al. (2004). The oldest units, pre-Upper Jurassic, are medium- and high-grade metamorphic rocks (garnet schist, staurolite schists, andalusite schist, and sillimanite schists) and low- to very low-grade metamorphic phyllites and slates, which contain *Arietites bisulcatus* (Stahl, 1911), *Posodina alpina* (Dehghan, 1947), and other ammonoids (Geological Survey of Iran, 1977) indicating a Jurassic age for the slates. These rocks are metamorphosed in amphibolite-greenschist facies during the late Jurassic–Early Cretaceous (Berberian and Alavi-Tehrani, 1977). Field observations have not revealed any structural discontinuities between the different pre-Upper Jurassic metamorphic units; nevertheless, the existence of two thermal discontinuities is indicated along the synthetic column (Baharifar et al., 2004; Figure 4). Very different ages were proposed for protoliths in the area. From the presence of paleontologically dated Jurassic sequences in the deformed rocks, it is concluded that a Mesozoic age, most probably Jurassic, for the protolith is the best choice (Baharifar et al., 2004). Both Jurassic and Cretaceous rocks were affected by tectonic phases similar in orientations and trends with a younger low-grade metamorphic phase that affected pre-Upper Jurassic metamorphic rocks (Baharifar et al., 2004). Additionally, the metamorphism extended from the slates to Cretaceous sediments, which show clear evidence of recrystallization due to metamorphism. As is shown in Figure 4, Cretaceous sedimentation stopped in the area by the end of Lower Cretaceous, probably due to deformation and metamorphism commencement at that time.

4.2. Zagros

Zagros is often cited as one of the regions in the world showing the best examples of large-scale detachment folds (e.g., Colman-Sadd, 1978). NW-SE trending folds and thrusts in the North West Zagros combine with right-lateral strike-slip faulting to produce the overall N-S convergence (Talebian and Jackson, 2002). The whole Zagros belt was folded and uplifted toward the end of Pliocene time (James and Wynd, 1965; Stöcklin, 1968). Continental collision of Arabia and the Sanandaj-Sirjan Zone (Iranian plate) probably began in the Oligocene at the northern promontory of the Arabian plate (Yilmaz, 1993) and in the Miocene to the southeast (Stoneley, 1981) to create the Bitlis-Zagros suture. Deformation in the central part of Zagros (Dezful Embayment) began or greatly accelerated in the Late Miocene–Early Pliocene (Sherkati et al., 2006). The structures are not similar in all parts of Zagros. For example, in the central part (Fars region), they are mainly E-W trending, whereas in the northern part they are NW-SE trending. The convergence is still active, in a roughly N-S direction at a rate of approximately 25–30 mm year^{-1} at the eastern edge of the Arabian plate (Sella et al., 2002; Vernant et al., 2004).

4.3. Central Iran

Central Iran in the Sagand area (Figure 1) shows structural vestiges of Precambrian deformational and the prevailing metamorphism, from low to high grade, during the pre-Pan-African Orogeny (Nadimi, 2007). Central Iran is an area of continuous continental deformation in response to the ongoing convergence between the Arabian and Eurasian plates. Central Iran was uplifted by NE-SW shortening during the Late Jurassic when many continental areas emerged from the sea (Stöcklin, 1968). During Maastrichtian–Paleocene time, Central Iran underwent strong folding, magmatism, and uplift (Ghasemi and Talbot, 2006). The rocks were eroded and covered by the Late Paleocene–Eocene sediments beneath a pronounced transgressive unconformity.

5. Magmatic records

Paleozoic igneous rocks occur as blocks in the sedimentary units of Central Iran and Sanandaj-Sirjan and are absent in Zagros. These rocks have a within-plate magmatism characteristic (Aghanabati, 2006) and more likely are related to the hot spots under this part of the crust. Late Jurassic–Early Cretaceous granite intrusions are documented in Central Iran (Şengör, 1990). Talbot and Ghasemi (2006) considered the Mesozoic plutons of Central Iran related to the subduction of the Nain-Baft oceanic crust beneath Central Iran. In the Cenozoic, magmatism of Central Iran occurred mainly in the Urmia-Dokhtar zone as a result of the Neotethys subduction. Overall, after the Precambrian, magmatism in Central Iran, the Sanandaj-Sirjan Zone, and Zagros was different in terms of intensity and the type of magmatism. Since the climax of magmatism in the Sanandaj-Sirjan zone was during the Mesozoic, these rocks are studied in more detail compared to other igneous rocks of this zone. In comparison, the studies on Mesozoic magmatism in Central Iran (there is no report on Mesozoic magmatism in Zagros) are scarce.

The Sanandaj-Sirjan Zone contains multiple plutonic assemblages (Figure 3), whose ages are poorly known. Although a few Paleozoic granitoids are reported, most have Mesozoic ages (Figure 3). The Mesozoic plutons are distributed in a narrow NW-SE trending band delineated by ophiolitic-mélange belts (Figure 3; Arvin et al., 2007). They have been interpreted as magmatic activity related to Neotethys subduction (Arvin et al., 2007). The southeastern plutons in the Sanandaj-Sirjan Zone have mainly Upper Triassic and Upper Jurassic to Lower Cretaceous ages, whereas the northwestern plutons show Upper Cretaceous ages (Arvin et al., 2007; Hajialioghli and Moazzen, 2012). During the Mesozoic, magmatic activity was episodic, probably due to changes in plate motions and the consumption rate of oceanic crust, with climaxed around the Middle Triassic, Late Jurassic, and Late Cretaceous (Berberian and Berberian, 1981; Sepahi et al., 2014).

5.1. Pre-Triassic magmatism

The Muteh, Khalifan, and Hasanrobat intrusions (Figure 3) in the Sanandaj-Sirjan Zone are pre-Triassic. The dominant leucogranite and granitic gneiss in the Muteh show zircon U-Pb ages of 578 ± 22 and 588 ± 23 Ma (Hassanzadeh et al., 2008; Alirezaei and Hassanzadeh, 2012). The Hasanrobat granite is metaluminous to slightly peraluminous and typical of ferroan (A-type) granites (Alirezaei and Hassanzadeh, 2012). Zircon grains separated from a representative granite sample yielded concordant U-Pb ages of 288.3 ± 3.6 Ma (Alirezaei and Hassanzadeh, 2012). Khalifan granitoid is a Carboniferous A-type peraluminous leucogranite (Bea et al., 2011).

5.2. Late Triassic and Jurassic magmatism

There were two types of magmatism: that forming mafic/ultramafic rocks and that forming granites. The Triassic/Jurassic Sikhoran mafic/ultramafic complex (Ghasemi et al., 2002; Ahmadipour et al., 2003), the Upper Triassic tuff, andesitic and basaltic lava flows in the Abadeh area (Figure 2), ultramafic and mafic rocks to the west of Sirjan, and silicic volcanism in the Sirjan, Hajiabad, and Dehbid areas (Figure 4; Berberian, 1977; Berberian and King, 1981) were considered as asymmetric magmatic activity along the south Sanandaj-Sirjan Zone related to the opening of a narrow transtensional Nain-Baft ocean from the Triassic to Jurassic in the active Iranian continent margin (Ghasemi and Talbot, 2006). The Siah-Kuh granitoid (Figure 3) has a Triassic (199 ± 30 Ma; Arvin et al., 2007) age. It is a metaluminous to slightly peraluminous I-type granite, with calc-alkaline characteristics typically found in a continental volcanic arc setting (Arvin et al., 2007). These observations support the interpretation that the Triassic plutonic rocks might form as a result of a steeply dipping Neotethys oceanic slab (Mariana-type) underneath southeastern Central Iran (e.g., Berberian and Berberian, 1981).

The leucogranitic (trondhjemitic) rocks in the Qori metamorphic complex (near Neyriz) (Figure 3), Alvand plutonic complex (Figure 3), Aligoodarz granitoid complex (Figure 3), and Sirjan andesite-basaltic lavas and tuffs are calc-alkaline and formed in a volcanic arc setting in the Jurassic (Ghasemi and Talbot, 2006; Rashid Moghadam and Esmaeli, 2007; Tahmasbi et al., 2008; Fazlnia et al., 2009; Shahbazi et al., 2010; Azizi et al., 2011, Esna-Ashari et al., 2012).

5.3. Late Cretaceous magmatism

Late Cretaceous I-type granitoids in the northern part of the Sanandaj-Sirjan Zone are subalkaline and show suprasubduction signatures (Athari et al., 2007; Ranin et al., 2010; Sepahi et al., 2010). A belt of black and green Cretaceous basalts to andesites occurs in the northern part of the Sanandaj-Sirjan Zone (Azizi and Jahangiri, 2008). The belt appears to be the northern extension of a subzone characterized by Cretaceous volcanic rocks and shallow marine sediments (Mohajjel et al., 2003). The volcanic rocks show calc-alkaline affinity, enrichment in LIL elements (Rb, Ba, Th, U, and Pb), and depletion in Nb and Ti, indicating a volcanic arc nature (Azizi and Jahangiri, 2008).

5.4. Cenozoic magmatism

The main Cenozoic rocks dated in the Sanandaj-Sirjan Zone are gabbroic (Leterrier, 1985; Mazhari et al., 2009) and granitic intrusions (Rachidnejad-Omran et al., 2002). The Eocene magmatic pulse was coeval with the magmatism in the UDMA (or the Central Iranian Volcanic Belt) to the northeast. It should be mentioned that there are some differences between these two. The magmatism is of plutonic nature in the Sanandaj-Sirjan Zone and Cenozoic plutons occur mainly at the northern part of the zone, whereas magmatism is mainly volcanic in the Urmia-Dokhtar Zone and plutonism occurs at the southern part of this zone.

In summary, the pre-Late Paleozoic magmatisms of the Sanandaj-Sirjan Zone, Central Iran, and Zagros are similar and show Gondwanan affinity. The Mesozoic plutons with Triassic to Upper Cretaceous (or Cenozoic) age are related to the subduction. The onset of subduction of the Neotethys oceanic crust beneath the Sanandaj-Sirjan Zone in the Triassic could account for the suprasubduction zone magmatism. Triassic plutonic rocks show tholeiitic or transitional nature and formed in a primitive island arc/continental margin volcanic arc setting, probably close to a trench zone (e.g., Arvin et al., 2007). This indicates that they probably belong to the early tholeiitic stage of arc development (Ringwood, 1974). As the convergence rate increased, the supply of arc-related magmas increased as larger amounts of slab-derived aqueous fluid were added to the mantle wedge. Partial melting of the metasomatized mantle led to calc-alkaline magmatism. Therefore, the Jurassic igneous rocks of the Sanandaj-Sirjan Zone are calc-alkaline and the younger rocks are changed to high-K calc-alkaline ones (e.g., Ahadnejad et al., 2013).

6. Ophiolites and tectonic records

The suture between the Sanandaj-Sirjan Zone and Zagros is marked by well-exposed Late Cretaceous Ophiolite associations: the southeastern Neyriz Ophiolite and the northwestern Kermanshah and Piranshahr Ophiolites (Figure 1). The Sanandaj-Sirjan Zone is bordered to the northwest by the Tabriz Fault and the Khoy Ophiolite and to the northeast by the Nain-Baft Fault and the Nain-Baft Ophiolitic belt (Figure 1).

6.1. Kermanshah Ophiolite

The Kermanshah Ophiolite includes isolated and dismembered fragments of mantle peridotites, gabbroic sequences, a complex dyke, and pillow basalts (e.g., Saccani et al., 2013). The associated sedimentary rocks include a variety of Upper Triassic to Lower Cretaceous deep marine sedimentary rocks (flysch to radiolarite). Geochemical data distinguish two basalt types (Ghazi and Hassanipak, 1999): subalkaline and alkaline basalt. Alkaline rocks mostly generated in the initial rifting stage in the Triassic, whereas calc-alkaline arc-type rocks formed in a Lower Late Cretaceous intraoceanic suprasubduction zone setting (Allahyari et al., 2010; Saccani et al., 2013). Some magmatic rocks of the ophiolite show oceanic back-arc basin setting characters (Allahyari et al., 2010).

The northwest of the Kermanshah Ophiolite was named the Piranshahr Ophiolite by Hajialioghli and Moazzen (2014). Mantle peridotites from this ophiolite indicate both mid-ocean ridge and suprasubduction components (Hajialioghli and Moazzen, 2014).

6.2. Neyriz Ophiolite

The Neyriz Ophiolite is one of several large allochthonous Tethyan Ophiolites exposed in the southwestern edge of the Sanandaj-Sirjan Zone, northeast of the Zagros Fold Thrust belt (Stöcklin, 1968; Stoneley, 1981). In some parts, the Neyriz Ophiolite is tectonically juxtaposed with cataclastically deformed island arc volcanic and volcanoclastic rocks, which are tectonically intercalated with Cretaceous limestone (Babaie et al., 2001). The Neyriz Ophiolite is unconformably overlain by Upper Cretaceous anhydritic limestone (Tarbur Formation; Ricou, 1971). Triassic mafic volcanic and siliciclastic-carbonate rocks, as well as a thick succession of probable deep marine Late Triassic to Jurassic age (Ricou, 1971) strata, are stratigraphic evidence for rifting (Berberian and King, 1981); neither of these units have been recognized in adjoining Central and North West Iran.

6.3. Nain-Baft Ophiolite

The northeastern contact between the Sanandaj-Sirjan Zone, NWIP, and CIM is difficult to establish because of widespread Tertiary and Quaternary cover. A series of depressions, including Urmia Lake, Gavkhuni, and Jazmorian depressions (Figure 1), separate the Sanandaj-Sirjan Zone from Central Iran (Aghanabati, 2006). However, faulted contacts between the Sanandaj-Sirjan Zone and Central Iranian blocks have been recognized in some areas, such as the strike-slip Nain-Baft Fault (Meyer et al., 2006). This fault is marked by the Nain-Baft Ophiolitic Belt, which includes mostly Late Cretaceous magmatic and metamorphic and rare Jurassic metamorphic rocks (Technoexport, 1984; Hassanipak and Ghazi, 2000). It is thought that the Nain-Baft basin formed during the uppermost Late Triassic, due to rifting at the active continental margin, almost between present-day Central Iran and the Sanandaj-Sirjan Zone (Mehdipour Ghazi et al., 2011, 2012). The presence of Late Triassic magmatic rocks with volcanic arc nature in the southern part of the Sanandaj-Sirjan Zone (such as the Siah-Kuh stock; Arvin et al., 2007) could be taken as proof for active Neo-Tethys subduction during rifting of the Nain-Baft basin. The continental back-arc basin existed between the Sanandaj-Sirjan Zone and Central Iran during the Jurassic and closed in the Late Cretaceous (Mehdipour Ghazi et al., 2012).

6.4. Khoy Ophiolite

The Khoy Ophiolite is divided into the eastern Late Triassic to Late Cretaceous metamorphosed part and the western unmetamorphosed Late Cretaceous part (Khalatbari Jafari et al., 2004). The Khoy Ophiolite is located at the continuation of the Tabriz fault, which separates the Sanandaj-Sirjan Zone from the NWIP (Figure 1; Azizi and Jahangiri, 2008; Moazzen et al., 2012).

Azizi and Jahangiri (2007) considered a basin (along the present-day Tabriz Fault), which separated the Sanandaj-Sirjan Zone from the NWIP, existing up to the Late Cretaceous-Paleocene when it closed. The Late Triassic protolith age of metamorphic rocks in the Khoy Ophiolite indicates that the basin opened in the Triassic, coinciding with the opening of the Nain-Baft basin, probably due to tensional condition after the closure of the Paleotethys (e.g., Khalatbari Jafari et al., 2004).

Eocene volcanic rocks with active continental margin geochemical characteristics at the northern side of the Tabriz Fault may have resulted from subduction of the oceanic crust of this basin under the north margin of the continental crust and closure of the basin in the Upper Cretaceous–Paleocene (Azizi and Jahangiri, 2007). This idea indicates that there were two subduction zones in North West Iran during the Cretaceous, one related to the subduction of the Neotethys lithosphere beneath the Sanandaj-Sirjan Zone to the south and the other related to the subduction of oceanic crust along the present-day Tabriz Fault beneath the NWIP. The Tabriz Fault is probably a continuation of the Nain-Baft Fault.

7. Discussion

Combining available stratigraphy, geochronology, and geochemical data, we present an evolution scenario for the Sanandaj-Sirjan Zone and adjacent domains (Figure 5).

The Paleozoic units of the Sanandaj-Sirjan Zone are similar to those of Central Iran with Devonian and Carboniferous volcanoclastic sandstones of within-plate nature pointing to a continental setting from the Silurian to Permian (e.g., Thiele et al., 1968; Wendt et al., 2005). There is a stratigraphic gap from the Ordovician to Permian in Zagros (Aghanabati, 2006), but paleomagnetic data indicate that the Sanandaj-Sirjan Zone remained part of the Arabian platform until the Early Mesozoic (Berberian and King, 1981). Therefore it may be concluded that the Sanandaj-Sirjan Zone had similar features to Zagros, at least in the Paleozoic.

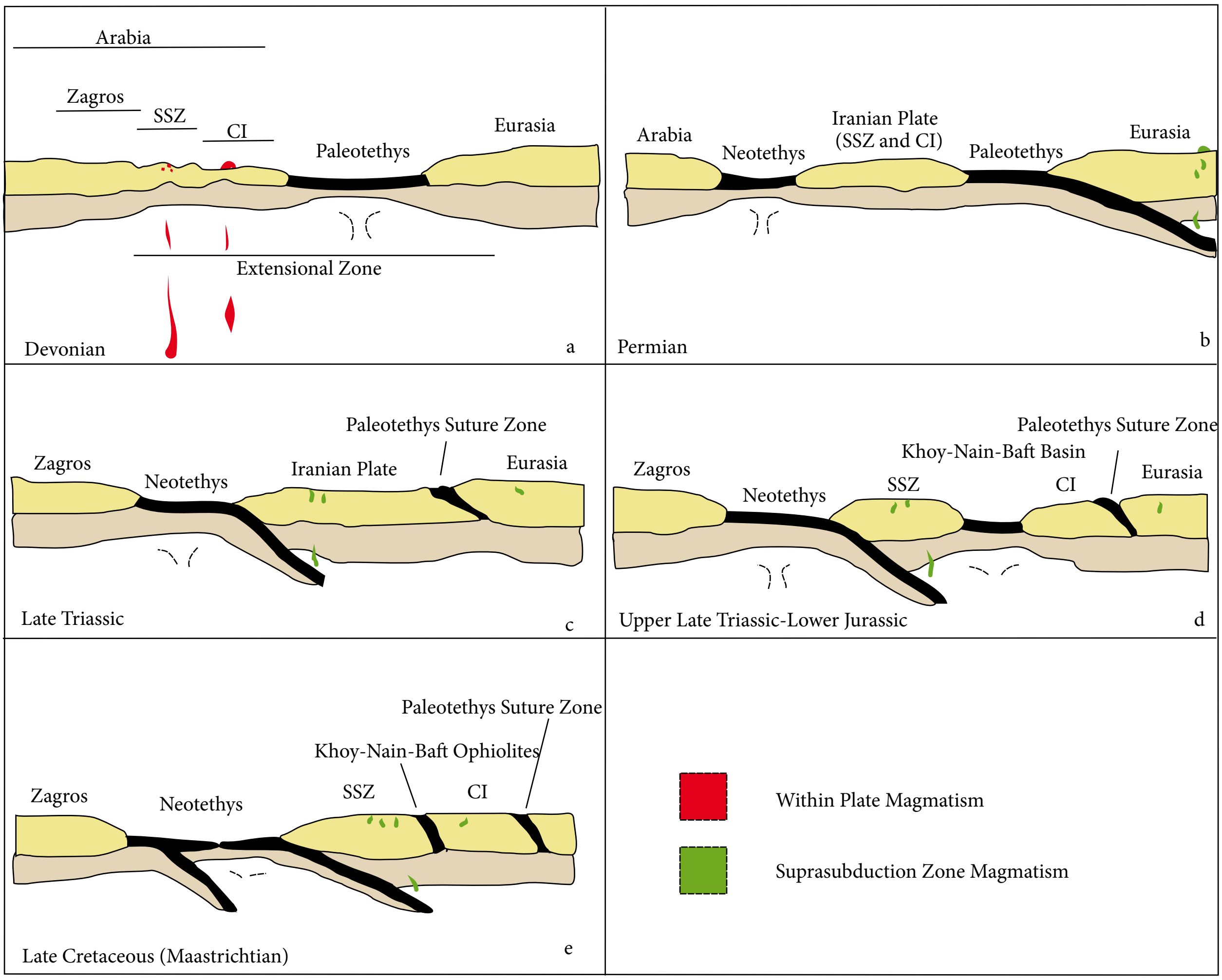

Figure 5. Simple geodynamic model for evolution of the Sanandaj-Sirjan Zone (SSZ: Sanandaj-Sirjan Zone, CI: Central Iran).

Several rock units with Permian age in the Sanandaj-Sirjan Zone could be related to the break-up of Gondwana and the opening of the Neotethys between the Sanandaj-Sirjan Zone and Zagros in the Permian (e.g., Alirezaei and Hassanzadeh, 2012).

The present-day Paleotethys Suture Zone (and conjugate territory) experienced a phase of broad and protracted extensional processes in the early to mid-Paleozoic, which ultimately led to the opening of the Paleotethys Ocean (Stampfli and Pillevuit, 1993). The northern margin of Gondwana (or southern margin of the Paleotethys) from then consisted of Central Iran, the Sanandaj-Sirjan Zone, and Zagros from north to the south (Figure 5a). Central Iran and the Sanandaj-Sirjan Zone were closer to the margin of Gondwana and the main extension axis of the Paleotethys as compared to Zagros. Alkaline igneous rocks of mid-Paleozoic age in several areas of the southern margin of the Paleotethys Suture Zone (Central Iran and the Sanandaj-Sirjan Zones) show that the extensional regime was probably affected in this part, due to extension, which caused the ascending of the asthenosphere as alkaline magmatism in these two zones (Hassanzadeh et al., 2008; Figure 5a). The extension also led to some thinning of the crust in the Central Iran and the Sanandaj-Sirjan Zones and created a shallow continental shelf basin during the Silurian to Carboniferous, while Zagros was located in the hanging wall (towards the continent) of this basin (mostly out of the basin), where an erosion condition was active similar to the Arabian plate.

The Paleotethys oceanic crust started to subduct beneath Eurasia in the Middle to Upper Paleozoic (Figure 5b; Stampfli and Pillevuit, 1993), so that the extensional regime in Central Iran and the Sanandaj-Sirjan Zone changed to compression and epeirogenic conditions gradually (mainly in the Carboniferous). Considering the climax of the opening and widening of the Paleotethys during the

Carboniferous, the adjacent areas experienced epeirogeny. Similar carbonate ramp deposit records dominate in all three domains during the Permian (Aghanabati, 2006), suggesting that these tectonostratigraphic units shared the same setting and were most likely connected.

The Iranian plate drifted from Arabia when the Neotethys Ocean opened in the Late Paleozoic or Early Triassic and collided with Eurasia (Ricou, 1994) by the end of the Late Triassic to complete the Paleotethys closure (Figure 5c; Davoudzadeh and Schmidt, 1984; Stampfli and Pillevuit, 1993; Stampfli and Borel, 2002). Simultaneously, platform conditions terminated in Zagros during the opening of the Neotethys Ocean (Berberian and King, 1981). Stratigraphic evidence for rifting in Zagros includes a succession of Triassic mafic volcanic and siliciclastic-carbonate rocks and a thick succession of deep marine sediments of Late Triassic to Jurassic age. Neither of these units is recognized in the Iranian plate (CIM, NWIP, and Sanandaj-Sirjan Zone; Berberian and King, 1981), indicating that it separated from Arabia (Zagros) in the Late Permian (Figure 5b).

A northeast-dipping subduction formed at the southwestern boundary of the Sanandaj-Sirjan Zone, which became an active continental margin of the Iranian plate in the Late Triassic (Figure 5c) and was continuing up to the Miocene (e.g., Arvin et al., 2007; Mehdipour Ghazi et al., 2012). Neotethys oceanic crust was consumed and associated with Late Triassic–Late Cretaceous plutonism (Berberian and King, 1981; Figures 5c–5e). The Neotethys subduction initiation caused a passive continental margin condition during the Late Triassic in Zagros (southern margin of Neotethys), whereas it caused the formation of a back-arc basin from Nain to Baft and along the Tabriz Fault during the Upper Late Triassic times (Figure 5d; Mehdipour Ghazi et al., 2012). During the Late Triassic to Late Cretaceous the Sanandaj-Sirjan Zone was an isolated block and limited by oceanic basins (Figure 5d). The closure of the Nain-Baft basin occurred at the Upper Cretaceous. There is no evidence so far to show that the basin closure was due to subduction of the oceanic crust beneath the CIM.

The closure of the Nain-Baft and Tabriz basins occurred in the Late Cretaceous and was probably initiated by almost simultaneous formation of the oceanic back-arc basin in the Neotethys (Figure 5e; Azizi and Moinevaziri, 2009; Allahyari et al., 2010; Mehdipour Ghazi et al., 2012; Hajialioghli and Moazzen, 2014). The closure of these basins (Nain, Baft, and Khoy basins) was associated with emplacement of the Nain-Baft ophiolites, the eastern part of Khoy Ophiolite along the Tabriz Fault, and the displacement of the active continental arc to the north where the UDMA formed (e.g., Omrani et al., 2008). The timing of Neotethys extension and location relative to the Sanandaj-Sirjan Zone is similar to Model 1 of the introduction section as proposed by Şengör (1990) and Stampfli and Borel (2002). However, the relation of the Neotethys to the Central Iran Block and timing of the segmentation of this block, as well as the geodynamic evolution, is somewhat different in our model. For example, Model 1 does not consider separation of the Sanandaj-Sirjan Zone from Central Iran in the Upper Triassic.

The major deformation events in the Sanandaj-Sirjan Zone are the result of collision with Zagros along the southwestern border after Neotethys closure, which is considered to have happened in the Miocene (e.g., Berberian et al., 1982; Mohajjel et al., 2003; Shahabpour, 2005; Azizi and Moinevaziri, 2009).

In summary, the Sanandaj-Sirjan Zone is a subblock of the Iranian plate and is partially limited on both sides by ophiolites. Compiling and comparing the stratigraphic, magmatic, and metamorphic records in the different subterrains of Iran in this paper supports a Gondwanan affinity for the Iranian plate and its separation from the Arabian plate in the Upper-Late Paleozoic. The Sanandaj-Sirjan Zone was an isolated block during the Jurassic and Cretaceous. Subblocks of the Iranian plate jointed each other in the Late Cretaceous and the Iranian plate jointed the Arabian plate in the Miocene. The evolution of the Sanandaj-Sirjan Zone through time (especially from the Mesozoic) is complex owing to the continuous change of the Neotethys subduction regime and differential aggregation of it with adjacent blocks. Since most of the rocks in the Sanandaj-Sirjan Zone are metamorphic, it is important to identify their protolith age in order to conclude the original stratigraphic relations. More studies on radiogenic age dating of the igneous rocks will help to put constraints on the geodynamic evolution of the Sanandaj-Sirjan Zone in the Tethys realm of the Middle East.

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