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Review article

Ophiolites of Iran: Keys to understanding the tectonic evolution of SW Asia: (I) Paleozoic ophiolites

Hadi Shafaii Moghadam [a,*], Robert J. Stern [b]

[a] School of Earth Sciences, Damghan University, Damghan, Iran
[b] Geosciences Dept., University of Texas at Dallas, Richardson, TX 75083-0688, USA

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ABSTRACT

Iran is a mosaic of Ediacaran–Cambrian (Cadomian; 520–600 Ma) blocks, stitched together by Paleozoic and Mesozoic ophiolites. In this paper we summarize the Paleozoic ophiolites of Iran for the international geoscientific audience including field, chemical and geochronological data from the literature and our own unpublished data. We focus on the five best known examples of Middle to Late Paleozoic ophiolites which are remnants of Paleotethys, aligned in two main zones in northern Iran: Aghdarband, Mashhad and Rasht in the north and Jandagh–Anarak and Takab ophiolites to the south. Paleozoic ophiolites were emplaced when N-directed subduction resulted in collision of Gondwana fragment "Cimmeria" with Eurasia in Permo-Triassic time. Paleozoic ophiolites show both SSZ- and MORB-type mineralogical and geochemical signatures, perhaps reflecting formation in a marginal basin. Paleozoic ophiolites of Iran suggest a progression from oceanic crust formation above a subduction zone in Devonian time to accretionary convergence in Permian time. The Iranian Paleozoic ophiolites along with those of the Caucausus and Turkey in the west and Afghanistan, Turkmenistan and Tibet to the east, define a series of diachronous subduction-related marginal basins active from at least Early Devonian to Late Permian time.
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* Corresponding author. Tel.: +98 9132762361; fax: +98 232 5235314.
E-mail address: hadishafaii@du.ac.ir (H. Shafaii Moghadam).

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1. Introduction

Ophiolites are relicts of oceanic lithosphere that delineate sutures between continental terranes. They are important, if controversial, markers of plate tectonic and oceanic magmatic events. Ophiolites are argued to form in a variety of plate tectonic settings including oceanic spreading centers, back arc basins, forearcs, as well as arc and other extensional magmatic settings including above mantle plumes (Kusky, 2004; Dilek et al., 2007; Santosh et al., 2009; Pearce and Robinson, 2010; Dilek and Furnes, 2011). However, supra-subduction zone (SSZ)-type ophiolites are more common globally as these are easily detached and obducted onto continents (Miyashiro, 1975; Pearce et al., 1984; Stern, 2004). The origin of SSZ-type ophiolites is increasingly ascribed to mantle upwelling associated with subduction initiation (Metcalf and Shervais, 2008; Whattam and Stern, 2011). According to their lithological units, geochemical signatures and tectonic setting, various types of ophiolites have been defined (Dilek and Furnes, 2011) including (1) continental passive margin-type, (2) mid-ocean ridge type (MORB-type of older classification), (3) plume-related type, (4) Supra-subduction zone-type (SSZ-type), (5) volcanic arc type and (6) accretionary prism-type. Each ophiolite in this classification has somewhat different lithological units and geochemical characteristics (for more information see Dilek and Furnes, 2011).

Regardless of controversy about tectonic environment of formation and emplacement, ophiolites approximate the former locations of ocean basins and convergent margins, and are key paleo-plate tectonic indicators. Understanding the age and nature of a region's ophiolites is thus essential for understanding how that region came to be. This is especially true for Iran, which has an unusual abundance of ophiolites. We focus here on Paleozoic ophiolites of Iran.

Paleozoic ophiolites interpreted as remnants of the Paleotethys ocean are preserved in southwestern Eurasia: in Iran, Turkey, Caucasus, Turkmenistan, Afghanistan as well as Tibet. The purpose of this contribution is to briefly summarize the Paleozoic ophiolites of Iran for the international geoscientific audience, to present their lithological, geochemical as well as geodynamic setting and their genetic link to Caucausus-Turkish ophiolites to the west and Turkmenistan–Afghanistan–Tibet ophiolites to the east and to use this information to understand the temporal and spatial evolution of the Paleotethys ocean. The many ophiolites of Iran have long been research foci; a "Google Scholar" search on "Iran ophiolites" in November 2013 revealed 5900 entries. Several studies over the past few decades impel an update to the review of Delaloye and Desmons (1980), which did not discuss Paleozoic ophiolites. Our overview of Paleozoic Iranian ophiolites will be followed by a review of the Mezosoic ophiolites of Iran. This is an ambitious undertaking because Iran is a large, rugged country covering 1,648,000 km^2. The field, petrologic, geochemical and geochronological data discussed in this contribution comes from the literature supplemented by our unpublished dataset.

2. Geologic background

Iran can be divided into 9 major tectonic zones (Fig. 1). Below we briefly discuss these tectonic zones, from N to S.

2.1. Southern Caspian Sea Basin

This has thick oceanic crust (e.g., Berberian, 1982; Mangino and Priestley, 1998) and is considered to be a Jurassic to Paleogene back-arc basin (Allen et al., 2004).

2.2. Kopet-Dagh zone in NE Iran

This zone is a part of the Turan block and is about 500 km long and 100 km wide in Iran. The Turan block is dominated by slightly folded sediments of Variscan (Late Paleozoic) age.

2.3. Alborz zone in NW Iran

This zone is a ~600 km long and ~100 km wide belt of Precambrian to Recent magmatic and sedimentary rocks. Paleomagnetic results indicate that this block separated from Gondwana during Ordovician–Silurian time as part of Cimmeria and collided with Eurasia in Permo-Triassic time (Wensink and Varekamp, 1980; Stampfli et al., 1991; Sengor et al., 1988).

2.4. The Central Iranian block

This block consists of three major tracts (from E to W): Lut, Tabas, and Yazd, separated by major faults (e.g., Alavi, 1991). These "Cadomian" blocks contain crust as old as Ediacaran–Cambrian (600–520 Ma; Jamshidi Badr et al., 2013; Azizi et al., 2011; Hassanzadeh et al., 2008; Shafaii Moghadam et al., 2013). These blocks drifted from Gondwana and accreted to Eurasia as the result of northward subduction and closure of Paleotethys in Permo-Triassic time (e.g., Sengor, 1987; Stampfli, 2000; Berberian and King, 1981).

2.5. Eastern Iranian suture zone

This zone is also called the Eastern Iranian Flysch Zone (Tirrul et al., 1983) and the Zabol-Baluch ophiolite mélange zone (Berberian and King, 1981). This defined the Cretaceous Sistan Ocean and lies between the Lut block in the west and the Afghan block in the east. Its tectonic evolution was dominated by the emplacement of the Cretaceous Birjand-Nehbandan-Tchehel-Kureh ophiolites followed by deposition of Upper Cretaceous–Paleocene flysch.

2.6. Urumieh-Dokhtar magmatic belt

This belt is a 50–80 km wide Andean-type arc formed by northeastward subduction of Neo-Tethys beneath Iran during Late Cretaceous and Cenozoic time (Berberian and Berberian, 1981;

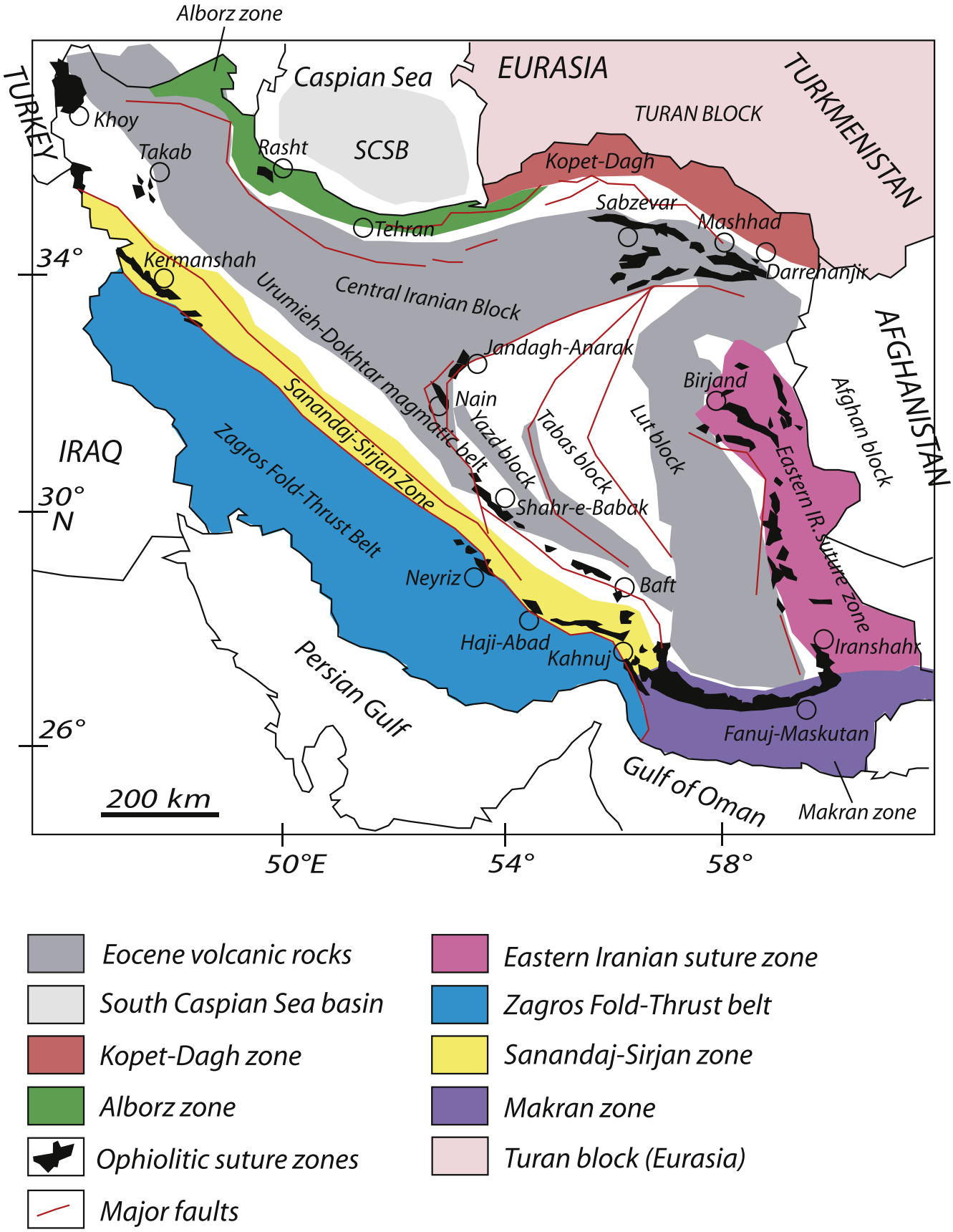

Fig. 1. Simplified geological map showing the nine main geologic provinces of Iran (see text for explanation). SCSB = South Caspian Sea Basin.

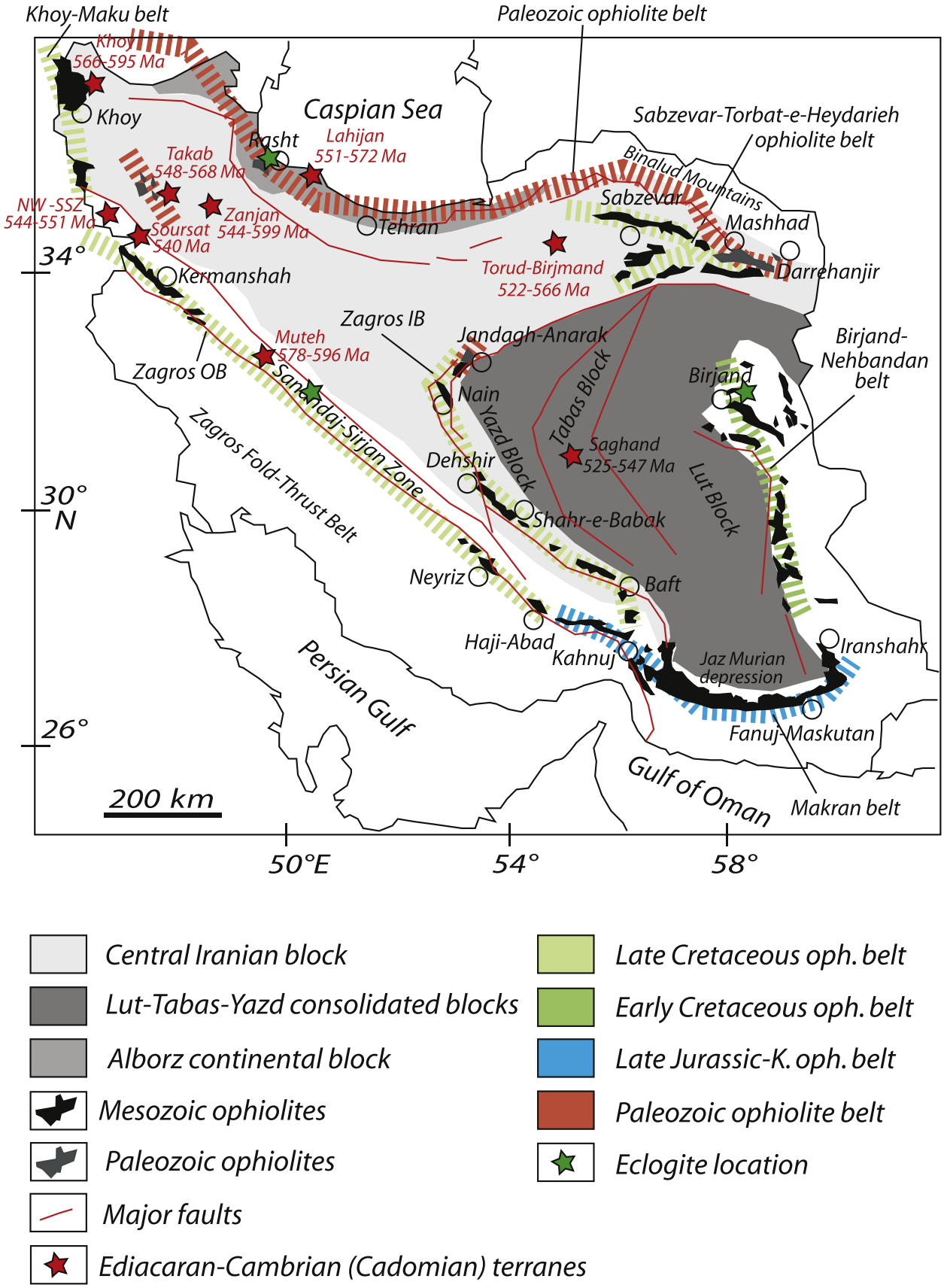

Fig. 2. Simplified geological map of Iran emphasizing the main ophiolitic belts (thick dashed lines) and places where Ediacaran–Cambrian (~600–520 Ma) radiometric ages are documented (stars). Numbers show U–Pb zircon ages (the age of Soursat is from Jamshidi Badr et al., 2013; Khoy age is from Azizi et al., 2011; Torud-Biarjmand from Shafaii Moghadam et al., 2013; other ages are from Hassanzadeh et al., 2008).

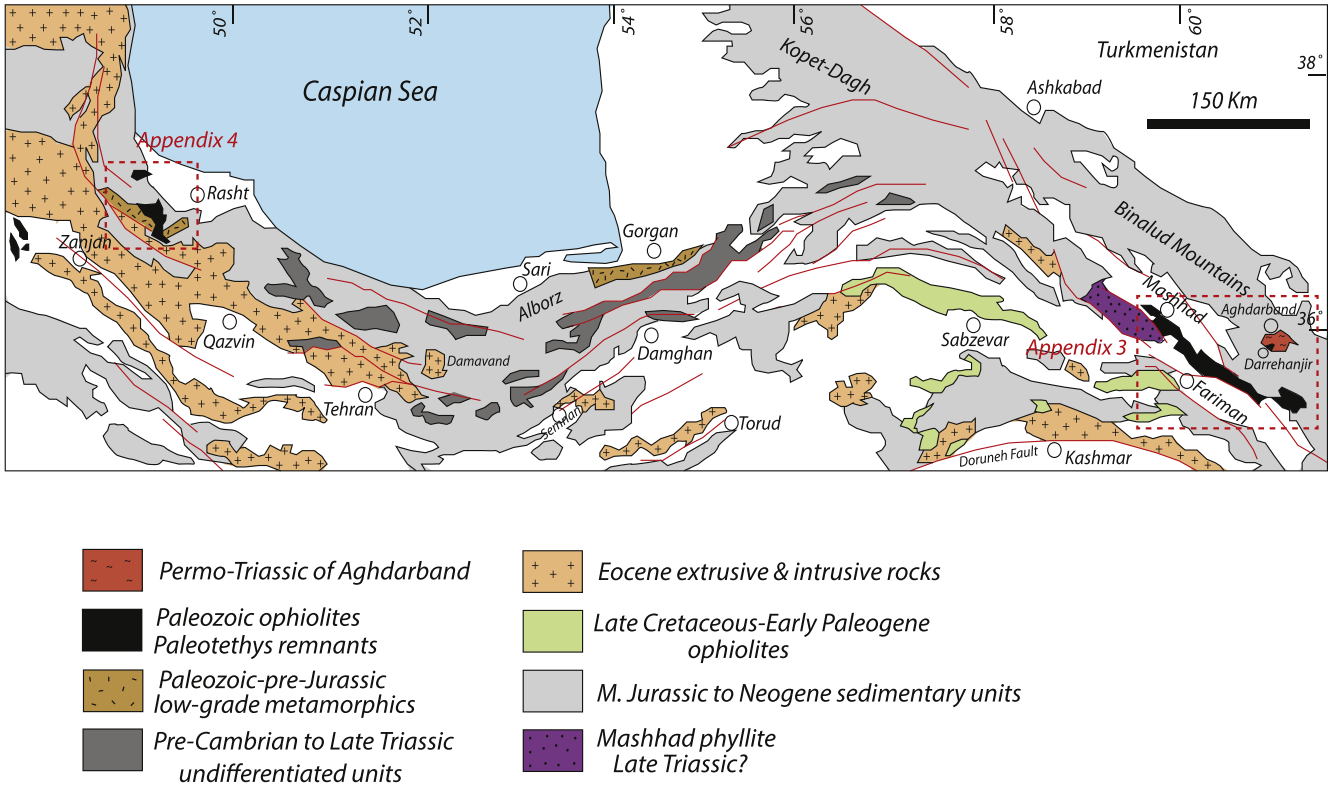

Fig. 3. Structural and geological map of northern Iran showing locations of Paleozoic ophiolites and associated units (modified after Zanchi et al., 2009).

Berberian and King, 1981; Berberian et al., 1982; Alavi, 1994; Shahabpour, 2007; Chiu et al., 2013). This magmatic assemblage includes a thick (~4 km) pile of early calc-alkaline and late shoshonitic as well as alkaline rocks (Alavi, 1996).

2.7. Zagros Fold-Thrust Belt (ZFTB)

The Zagros Fold-Thrust belt is an external (trenchward) deformed part of the Zagros Orogen (Alavi, 1980, 1991, 1994). ZFTB extends southeast for nearly 2000 km from southeastern Turkey through northern Syria and northeastern Iraq to western and southern Iran (Alavi, 1994). The ZFTB reflects the shortening and off-scraping of thick sediments from the northern Arabian platform, essentially behaving as the accretionary prism for the Late Cretaceous and younger Iranian convergent margin (Farhoudi and Karig, 1977).

2.8. Sanandaj–Sirjan Zone (SSNZ)

This zone is the metamorphic core of the Zagros orogen (Mohajjel et al., 2003) separating the inner and outer Zagros ophiolite belts. Several workers consider the SSNZ as the once-active margin of the Central Iranian block (e.g., Berberian and King, 1981; Sengor, 1990; Sheikholeslami et al., 2008; Fazlnia et al., 2009) reflecting northeastward subduction of Tethys during the Late Triassic-Early Jurassic (Berberian and King, 1981; Davoudzadeh and Schmidt, 1984) or Late Jurassic time (Mohajjel and Fergusson, 2000). Others suppose that the SSNZ is an accreted microcontinent that separated from Gondwanaland during the Early Jurassic (e.g., Golonka, 2004; Agard et al., 2005). SSNZ rocks span most of Phanerozoic time, including imbricated slices of marine and continental siliciclastic sediments metamorphosed under low- and medium-grade greenschist conditions (Alavi, 1994). There are some small outcrops of eclogite (with geochemical MORB affinities) near the Shahr-e-Kord, associated with amphibolites, gneissic rocks and schists. $^{40}Ar/^{39}Ar$ dating of phengites in the eclogite and paragneiss reveals a 184.3–172.5 Ma metamorphic age (Early Jurassic) (Davoudian et al., 2007). However U–Pb zircon protolith age of orthogneissic rocks give 568 ± 11 Ma (Cambrian-Ediacaran), with 900–800, ca. 2400, and ca. 3600 Ma inherited cores (Nutman et al., 2014).

2.9. Makran zone

This zone comprises Jurassic and Cretaceous ophiolitic units and younger flysch-type sediments, including Eocene to Miocene turbidites.

Ophiolites frame the Cadomian basement of Iran and separate this from surrounding tracts of continental crust (Fig. 2). Iranian ophiolites are younger than these continental fragments and can be divided into Paleozoic ophiolites (Paleotethys remnants) and Mesozoic ophiolites (Neotethys remnants) (Fig. 2). Paleozoic ophiolites are found in northern Iran, defining the boundaries between the Turan (Eurasia) block and Iranian Cimmeria (Central Iranian and Alborz blocks) where Paleotethys was consumed by subduction beneath southern Eurasia (Alavi, 1991). These comprise the Mashhad, Rasht, Anarak and Takab ophiolites (Fig. 2). Paleozoic ophiolites formed in Devonian to Permian time and define a suture that can be traced for >1000 km along northernmost Iran. Devonian-Permian ophiolites are rare worldwide, but are present in Japan (Yakuno), New Zealand (Dun Mountains), West USA (Canyon Mountains) and outside the Circum-Pacific belt (Dilek and Furnes, 2011; Erdenesaihan et al., 2013).

Although the global Paleozoic ophiolite record peaks in the Ordovician period (Abbate et al., 1985; Ishiwatari, 1994; Dilek and Furnes, 2011), Early Paleozoic ophiolites are unknown in Iran. Early Paleozoic ophiolites occur along the southwest margin of Eurasia and northern margin of the Tibetan Plateau (e.g., Sengor,

Table 1
Summary of Iranian Paleozoic ophiolite characteristics.

Ophiolite	Mantle lithology	Crustal lithology	U–Pb/Ar–Ar dating	Type of overlying sediments	Age of sediments	Lava geochemistry	Temporal changes of lavas	Cpx TiO_2 in lavas	Mafic/felsic lavas	Cr# spinel	Associated metamorphic rocks	Crustal sequence thickness	Ophiolite classification	Proposed tectonic setting	References
Aghdarband (Darrehanjir–Fariman) ophiolites ~5 × 2 km	Lherzolite, dunite, clinopyroxenite, wehrlite	Gabbro, diorite, plagiogranite, ultramafic–mafic pillowed to massive lavas, radiolarite, pelagic limestone	~383–380 Ma (U–Pb zircon)	Radiolarite and pelagic sediments, radiolarian shale, tuff, volcaniclastic sediments	Early to Late Permian	E-MORB-type, IAT/boninite and calc-alkaline	Devonian SSZ-type & Permian SSZ & MORB/OIB-type	0.5–1.4 in IAT & 1.4–3.3 in E-MORB-type lavas	Mafic lavas > felsic lavas	0.3–0.5	Schist, phyllite, marble, serpentinite, metabasalts	~400–500 m	SSZ to accretionary prism-type in Devonian–Carboniferous to volcanic arc-type in Permian	Intra-arc basin and/or nascent arc	This study, Shafaii Moghadam et al., submitted for publication, Zanchetta et al., 2013
Mashhad ophiolite ~150 × 4 km (not continuous)	Harzburgite, pyroxenite, wehrlite, gabbro–diorite	Pillow lava, massive ultramafic (komatiite) to mafic lava, pelagic sediments	288–282 Ma (Ar–Ar)	Radiolarite, pelagic limestone (marble now), pyroclastic rocks, turbidites	Early Permian	SSZ-type	–	0.3–0.5	No felsic lava	0.5–0.7 in komatiites	Schist, slate, marble, serpentinites, thermally metamorphosed sediments	>2000 m (arc-related sediments and lavas in a marginal basin)	Accretionary prism to volcanic arc-type	Marginal SSZ-related basin	This study, Alavi, 1991
Rasht ophiolite ~10 × 2 km (not continuous)	Serpentinites intermixed with metamorphic rocks	Flysch-type sediments (metamorphosed)	330–382 Ma (Ar–Ar, Rb–Sr)	–	–	SSZ-type (metamorphosed) metabasites and gabbros	–	–	No felsic lava	–	Slate, phyllite, gneiss, amphibolite, eclogite	–	SSZ-type and Accretionary prism-type	Marginal basin	Zanchetta et al., 2009; Omrani et al., 2013a
Jandagh–Anarak ophiolite ~100 × 80 km (not continuous)	Harzburgite–dunite, chromitite, gabbro, diabasic to felsic dikes	Various types of lavas, rhyolite, gabbro	262 Ma (U–Pb)	Pelagic limestones, radiolarite, turbidites	Late Devonian–Early Carboniferous	MORB, OIB, IAT, calc-alkaline, boninite	Simultaneous MORB and SSZ?	–	Mafic lavas > felsic lavas	0.4 & 0.6	Schist, phyllite, gneiss, blueschist	~2000 m	Very complex; early passive- to plume-type, then SSZ, volcanic arc tand accretionary-type	Mid-ocean ridge to late SSZ-related basin, back-arc basin	Bagheri and Stampfli, 2008; Buchs et al., 2013
Takab ophiolite	Harzburgitic–lherzolitic serpentinite, wehrlite	–	–	–	–	–	–	–	–	0.3–0.4	Pelitic schist, amphibolite, gneiss, granulite	–	–	–	Hajialioghli et al., 2007

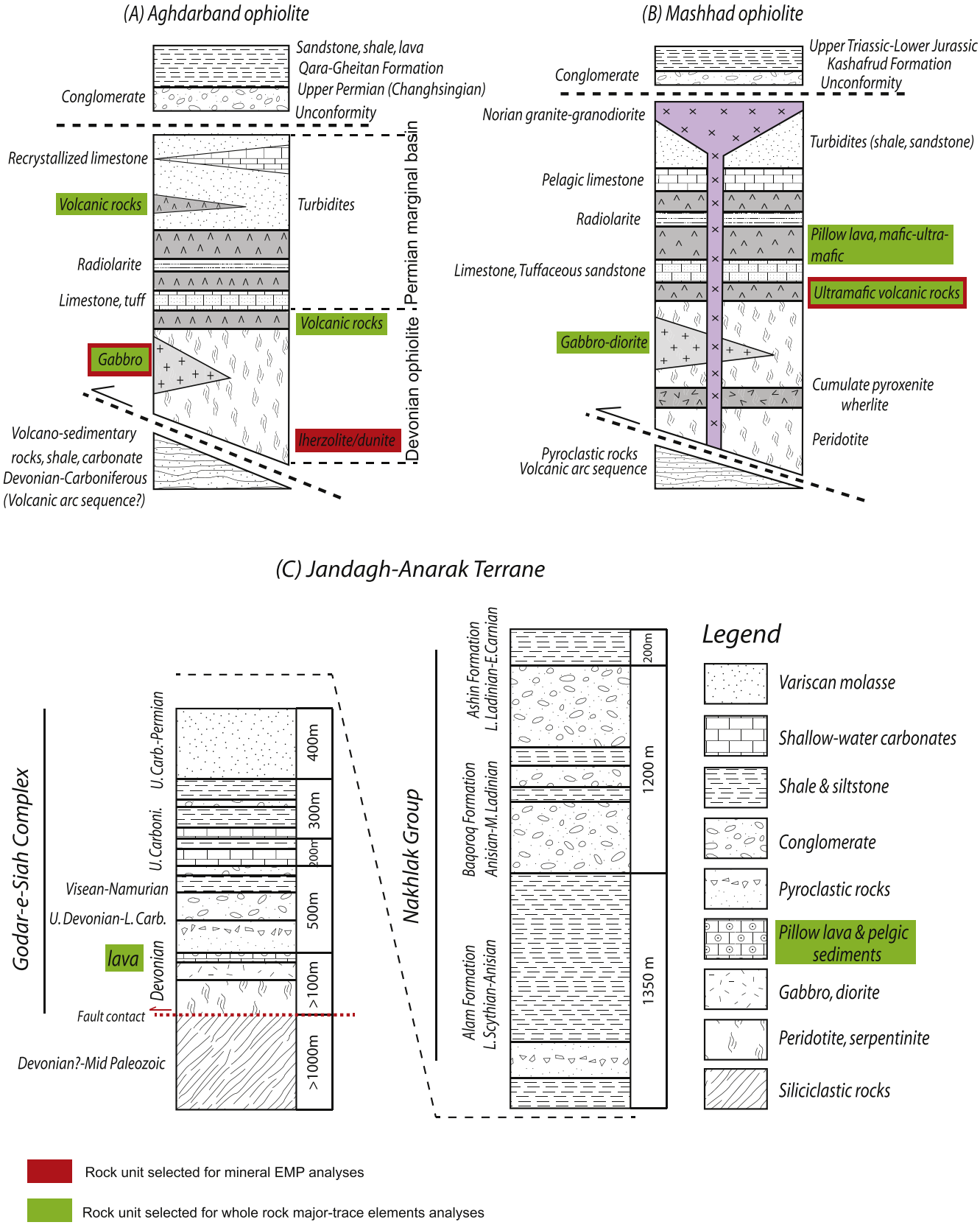

Fig. 4. Lithological columns showing pseudo-stratigraphic rock units of (A) Aghdarband, (B) Mashhad and (C) Jandagh–Anarak ophiolites (Jandagh–Anarak column is from Bagheri and Stampfli, 2008).

1990; Wang and Hao, 1994; Zhang et al., 2008). Early Paleozoic ophiolites in the Uralides and the Altaids in central Asia are remnants of the Pleionic Ocean, which evolved between the Baltica–Eastern Europe and Kazakhstan–Siberian continental masses (Dilek and Furnes, 2011; Windley et al., 2002; Xiao et al., 2004). These Early Paleozoic ophiolites are usually associated with

rifting, which occurred earlier than true seafloor spreading. Tectonic settings of these types of ophiolite are characterized by small ocean basins derived from the attenuation of continental crust along passive margins.

Ophiolites that are related to Paleotethys ocean opening (Early Paleozoic or Caledonian ophiolites) are absent in Iran as well as other parts of southwest Asia. This is probably related to the later opening of Paleotethys in Iran during Ordovician–Silurian time and hence ocean floor accretion in the Silurian–Devonian. Igneous rocks of Ediacaran–Cambrian (Cadomian) age in the Central Iranian Block record arc magmatism along the northern active margin of Gondwana and therefore document that Iran was a part of Gondwanaland at that time (Shafaii Moghadam et al., 2013).

We use the timescale of Walker and Geiissman (2009) to relate biostratigraphic ages to radiometric ages. More detailed geologic maps for Paleozoic ophiolites of Iran are found in Appendix 1.

3. Structural and petrological characteristics of Iranian Paleozoic ophiolites

The southwest margin of Eurasia preserves ophiolites that record evidence of closing two Paleozoic oceans: a Devonian–Carboniferous seaway in the Front Range of the Greater Caucasus and in the Sultan Uizdag of the Aral Sea region and a Permian seaway in north Turkey, Caucasus and north Iran (Sengor, 1990). Paleozoic ophiolites in Iran are distributed mostly in the north (Fig. 3), where northward subduction of Paleotethys and subsequent collision of the Iranian Cimmerian blocks with the Turan block occurred. The opening of Paleotethys may have reflected back-arc spreading related to the Gondwana-directed (southward) subduction of the Rheic Ocean. This ocean opened in Early Paleozoic time and closed during Triassic time, resulting in Eo-Cimmerian deformation in northern Iran, followed by Middle-Late Jurassic compression (Zanchi et al., 2009). Paleotethys opening is reflected in widely distributed Lower Ordovician alkali to tholeiitic continental flood basalts (Soltan-Meidan basalts), along with felsic to mafic plutons, dolomites, evaporites and terrigenous sediments in the Ordovician Ghelli formation (Ghaviden-Syooki et al., 2011). This was followed by rift shoulder uplift in Silurian time and then deposition of the Lower Devonian Padeha Formation in north Iran (Stampfli, 1978; Stampfli et al., 1991; Aharipour et al., 2010). Seafloor spreading took place in Late Silurian or Early Devonian time following thermal subsidence of the passive margin (Stampfli and Borel, 2002). Paleotethys opening is also recorded in the Early Carboniferous Misho Mafic complex of NW Iran (Saccani et al., 2013).

The trace of the Late Paleozoic to Triassic magmatic arc resulting from subduction of Paleotethys is represented by igneous and volcano-sedimentary rocks along the southern margins of both the Turan and Scythian Platforms (8300 km-long Silk Road Arc of Natal'in and Sengor, 2005) (Appendix 2). The arc system was built mostly on subduction–accretion materials (oceanic crust) of Middle to Late Paleozoic age. The Silk Road Arc stretches westward from the northern Pamir through the Paropamisus to the Aghdarband-Mashhad region in northern Iran, even to the Jandagh–Anarak ophiolites of central Iran (Sengor, 1984; Sengor and Natalin, 1996). The Silk Road Arc in the Turan sector died when Paleotethys closed and the Central Iranian Block (Cimmeria of Sengor, 1990) collided with Eurasia to form the Northern Iranian Paleozoic Suture. For example, in the Bukhara region of the Turan block,

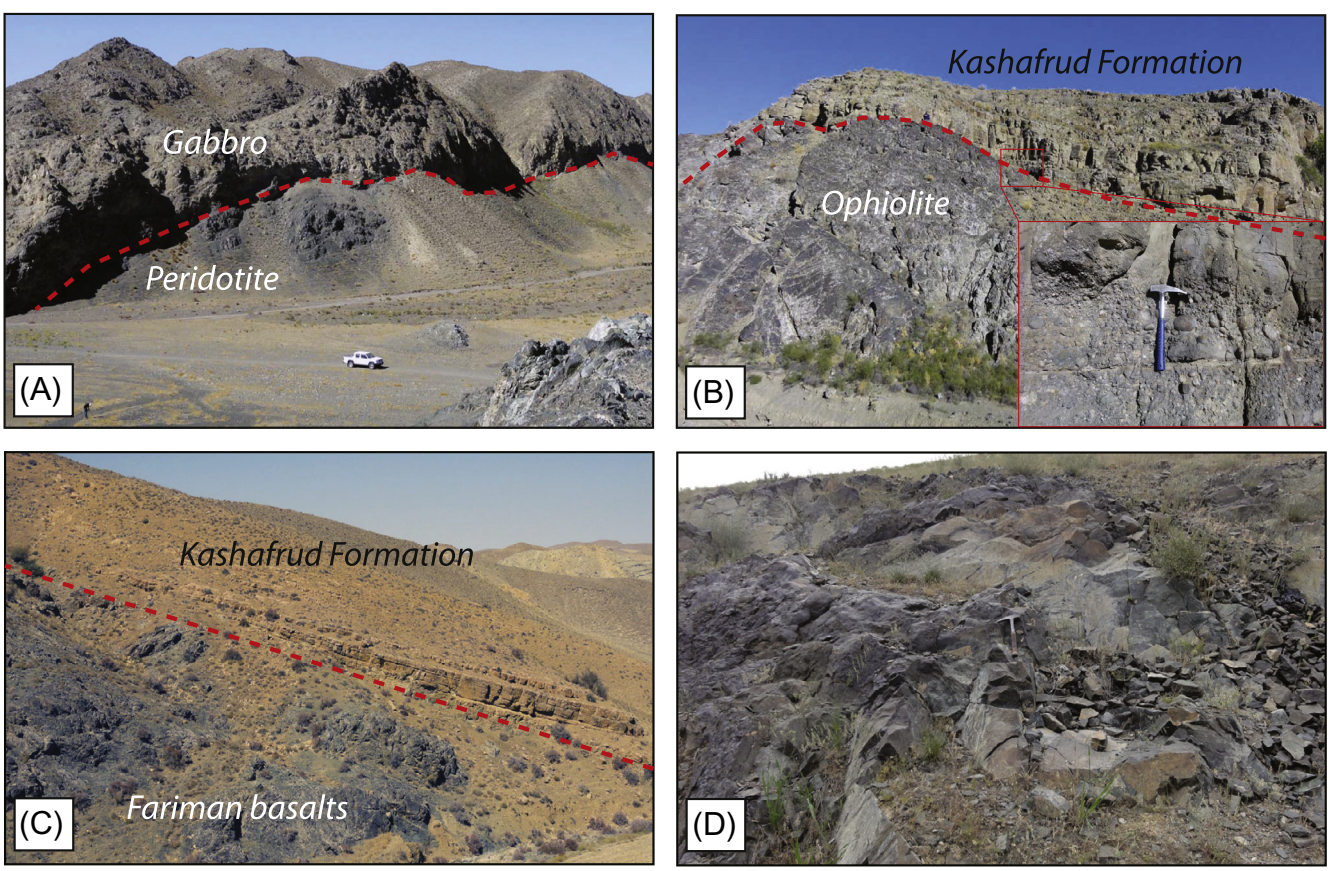

Fig. 5. Field photographs of Darrehanjir–Mashhad Paleozoic ophiolites. (A) Faulted contact between Darrehanjir ophiolite gabbro and underlying peridotite. (B) Sratigraphic contact between Kashafrud Formation with basal conglomerate (inset figure) and the Darrehanjir ophiolite. (C) Unconformity between Fariman basalts and Kashafrud Formation. (D) Outcrops of ultramafic rocks (wehrlites) in the Virani ophiolites.

Lower Paleozoic accretionary prism and magmatic arc rocks define the southern boundary of the Altay block (Burtaman et al., 1997). Magmatic arc rocks include 316–274 Ma granitic plutons (K–Ar ages on Gissar granites; Baymukhamedov, 1984) with overlying Upper Permian calc-alkaline andesites, dacites, and rhyolites (Afonichev and Vlasov, 1984). Permian rocks of the Tuarkyr complex (NW of Aghdarband) are represented by continental and shallow marine volcaniclastic rocks with interbedded pyroclastic deposits, interpreted to represent a continental magmatic arc (Garzanti and Gaetani, 2002). The trace of this arc may exist in the Fariman area of NE Iran (Zanchetta et al., 2013).

Below, we briefly describe five Late Paleozoic ophiolites associated with Paleotethys closure. These are aligned in two main zones in northern Iran; the first three (1) Aghdarband, (2): Mashad; and (3) Rasht in the north and the (4) Jandagh–Anarak and (5) Takab ophiolites to the south (Fig. 2). Information about lithological units of each ophiolite, their geochemical signatures and ages are summarized in Table 1. Paleozoic ophiolites are similar to accretionary-type ophiolites of Dilek and Furnes (2011), although plume related-type, SSZ-type and even volcanic arc-type signatures are also common (see next sections).

3.1. Aghdarband (Darrehanjir) ophiolite

The Aghdarband region is situated in the Kopet-Dagh zone, at the southern edge of the Hercynian Turan block (Fig. 3). Pre-ophiolitic rocks in this region include Upper Devonian–Carboniferous volcaniclastic sediments, shales and carbonates. This sequence may be basement beneath the Aghdarband basin and may reflect the growth of the Silk Road Arc along the southern Eurasian margin (Alavi et al., 1997).

There is a small outcrop (~5 × 2 km) of ophiolitic rocks NE of Mashhad city at Darrehanjir (Fig. 3), near Aghdarband village. The ophiolite consists of serpentinized peridotite (including lherzolites with dunite screens, impregnated via reaction with clinopyroxenitic/wehrlitic sills), gabbro (locally layered; Fig. 5A) and ultramafic (komatiite)-mafic volcanic rocks with intercalated carbonates, tuff, radiolarites and radiolarian shale near the base grading up into Permian turbidites and phyllitic shales with intercalated mafic rocks and recrystallized limestones (Fig. 4A). Microfauna in the upper carbonates are Early Permian (Asselian to Sakmarian–Kungurian). Upper Permian (possibly Changshingian) or younger Qara-Gheitan Formation (comprising red to green shale, sandstones, mafic lavas and tuffs) with basal conglomerates (including ophiolitic fragments) rests stratigraphically on the Darrehanjir ophiolite (Eftekharnezhad and Behroozi, 1991). In Darrehanjir village, ophiolitic rocks are overlain unconformably by Middle Jurassic shale, sandstone, and conglomerates with wood fossils of the Kashafrud Formation (Fig. 5B).

Ophiolitic rocks are also found W and SW of Darrehanjir, along the Fariman-Torbat-e-Jam Fault. The Fariman complex consists of two different tectonic units (Zanchetta et al., 2013): (1) a lower unit of mica schists, phyllites, metabasalts and marbles with serpentinites and (2) an upper unit including Permian carbonates with abundant basaltic lava flows interbedded with volcaniclastic sediments. Biostratigraphic data show a late Early or Middle Permian age for the sediments (Zanchetta et al., 2013).

Further south, both Darrehanjir and Fariman ophiolites are unconformably overlain by clastic sediments of the Middle Jurassic Kashafrud Formation (Fig. 5C). The Aghdarband complex (as well as Mashhad ophiolite) is lithologically similar to the Tuarkyr massif of the Turan block (NW of Aghdarband), although the former is older than the Tuarkyr Carboniferous massif. In this region there is an ophiolitic sliver including gabbro, pillow lava (OIB and IAT-types, Natal'in and Sengor, 2005; p. 184) and Middle Carboniferous chert, exposed with Permo-Triassic sedimentary rocks (Popkov, 1992; Sengor, 1995; Garzanti and Gaetani, 2002). Recent investigations of the Fariman–Darreanjir ophiolites led Zanchetta et al. (2013) to conclude that Fariman and Darrehanjir ophiolite volcano-sedimentary units were deposited during Permian time in a subsiding basin where siliciclastic turbidites shed from a magmatic arc and its basement were deposited, interfingered with carbonates and basaltic lava flows with calc-alkaline and transitional (alkaline) affinities. Thus the Fariman complex may reflect deposition in a marine basin near an active volcanic arc (Zanchetta et al., 2013). Zanchetta et al. (2013) interpret the Fariman–Darrehanjir ophiolites as remnants of a magmatic arc developed on the southern margin of Eurasia, above the north-dipping Paleotethys subduction zone.

3.2. Mashhad ophiolite

Remnants of Paleotethys oceanic sequences near Mashhad city (Fig. 3 and Appendix 3) include three distinct rock assemblages (Alavi, 1991; Ghazi et al., 2001): (1) ophiolite (Mashahd, Virani and Fariman-Torbat-e-Jam; Appendix 3), (2) deep sea turbidites and other metamorphosed sedimentary rocks; and (3) pyroclastic rocks. The ophiolite comprises mantle peridotite (harzburgite and cumulate pyroxenite), gabbro-diorite (locally layered), pillow lava and recrystallized pelagic limestone (now marble) and chert. Metachert interbedded with marble (pelagic limestone) are locally interlayered with basaltic and/or komatiitic lavas (Fig. 4B). Layered gabbro and sheeted dikes are missing (Alavi, 1991). The Virani ophiolite (Appendix 3) contains more basaltic lavas and komatiites (Fig. 5D), whereas the Mashhad ophiolite exposes more volcanic and sedimentary rocks. Farther southeast, in the Fariman-Torbat-e-Jam ophiolite, volcanic rocks and overlying sedimentary rocks become more abundant.

Majidi (1981) recognized 15 lava flows west of Mashhad, which change from ultramafic (komatiite) to tholeiitic basalt up-section over a stratigraphic interval of about 2000 m. Permian ultramafic pillow lavas are also found 80 km SE of Mashhad, underlain by hyaloclastic rocks and overlain by chert.

Mashhad ophiolites are overlain by metamorphosed sedimentary rocks consisting of slate, phyllite, schist, and marble with intercalated volcanic rocks (1–1.5 m. thick; Alavi, 1991). These are interpreted as deep-water flysch deposits, thought to have accumulated in a Permo-Triassic accretionary prism (Alavi, 1991; Ruttner, 1993). Pyroclastic rocks including lapilli tuffs and tuffs associated with lavas are present in the Mashad ophiolite and thicken toward the southeast (Torbat-e-Jam). Such pyroclastic and volcanic rocks reflect Silk Road Arc explosive volcanism (Alavi, 1991).

The afore-mentioned ophiolitic metasedimentary rocks are overlain unconformably by Middle Jurassic shale, sandstone, and conglomerate (Kashafrud Formation, Fig. 4B). The Kashafrud Formation seals the Paleotethys collision zone between Iran and Eurasia (Zanchi et al., 2009). Paleozoic Mashhad-Torbat-e-Jam ophiolites are also intruded by granitic–granodioritic plutons (Karimpour et al., 2010; Mirnejad et al., 2013) (Fig. 5D). These plutons have Late Triassic (Norian) ages (215 ± 4 and 217 ± 4 Ma; Karimpour et al., 2010 and 199.8 ± 3.7 and 217 ± 4 Ma; Mirnejad et al., 2013).

3.3. Rasht ophiolite

The Gasht and Shanderman complexes are minor isolated outcrops in the Talesh Mountains WSW of Rasht (Fig. 3). The Shanderman complex, described as a deformed association of slate, phyllite, gneiss and amphibolite with patches of serpentinized peridotite and eclogite (Omrani et al., 2013), was considered by Alavi (1991, 1996) and Sengor (1990) as equivalent to the Mashhad

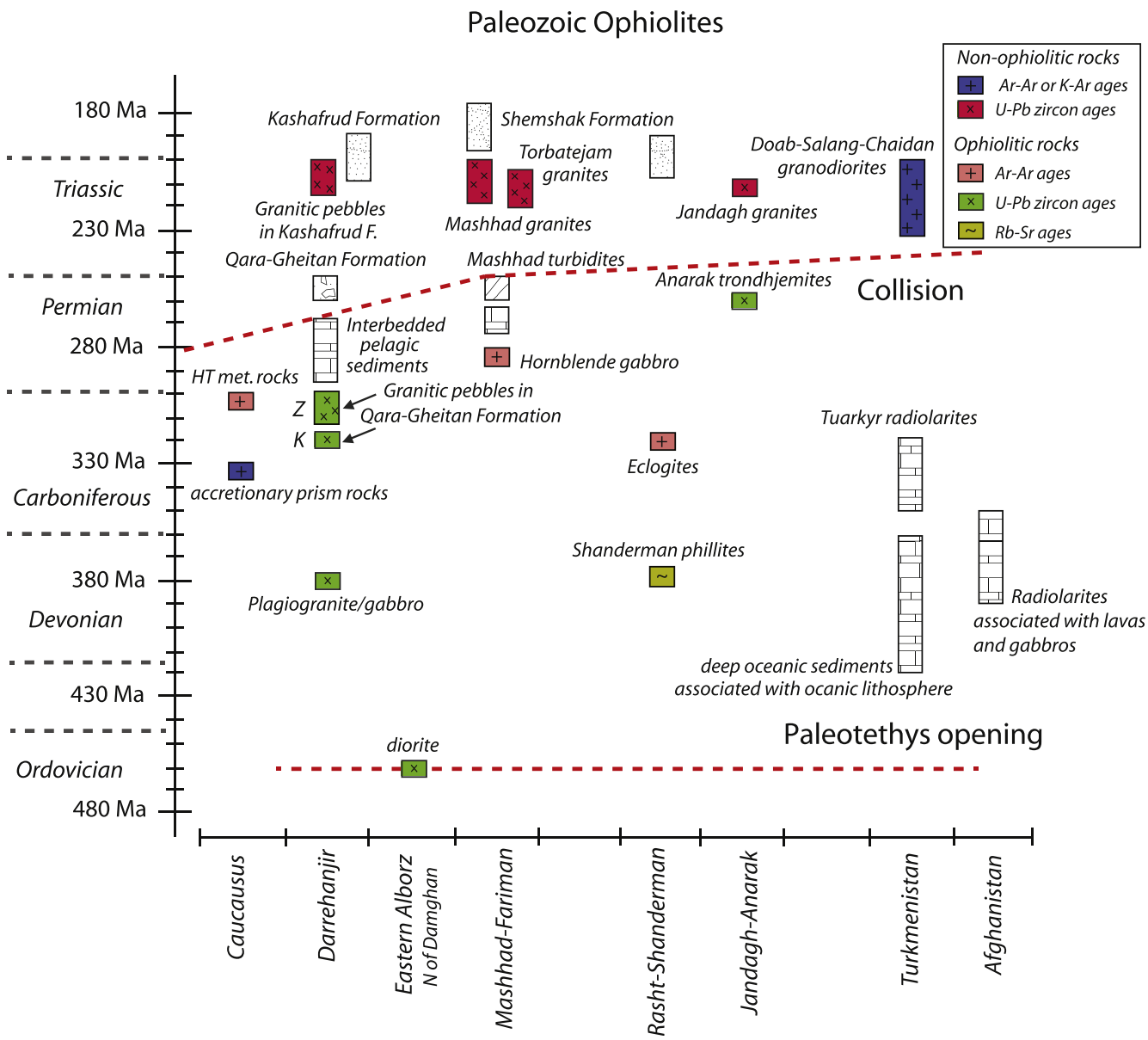

Fig. 6. Simplified chart showing the ages of magmatic and sedimentary sequences that constrain ages of Iranian Paleozoic ophiolites; greenish area inside dashed lines encompasses ophiolite ages. U–Pb dating of granitic pebble from Qara-Gheitan Formation (K) from Karimpour et al. (2011), Ar–Ar age data on the Mashhad ophiolites from Ghazi et al. (2001), U–Pb zircon ages on the Mashhad granites from Karimpour et al. (2010) and Mirnejad et al. (2013), Ar–Ar ages on the Rasht-Shanderman eclogites from Zanchetta et al. (2009), U–Pb zircon age data on the Anarak trondhjemites and Jandagh granites from Bagheri and Stampfli (2008), U–Pb zircon data on the Torbatejam granites, granitic pebble from Qara-Gheitan Formation (Z) and granitic pebbles from Kashafrud Formation from Zanchetta et al. (2013). Ar–Ar ages on the Caucausus accretionary prism and high-T metamorphic rocks a from Rolland et al. (2011); data on the Turkmenistan and Afghanistan pelagic sediments are from Garzanti and Gaetani (2002), Zakariadze et al. (2007), Treloar et al. (2009) and Boulin (1988) respectively.

ophiolite. The Gasht complex consists of two units with different metamorphic histories. The lower succession includes medium- to high-grade metapelite, amphibolite (considered as ophiolite equivalent) and gneiss (sillimanite-, kyanite, and staurolite-bearing), perhaps equivalent to deep-sea turbidites associated with the Mashhad ophiolite (Zanchetta et al., 2009; Zanchi et al., 2009). The upper unit includes slate, phyllite and quartzite.

The Shanderman complex is unconformably overlain by Jurassic Shemshak Formation (clastic sediments) (Appendix 4). Small bodies of metabasite and eclogite (mid-Carboniferous age) are common within the garnet–staurolite–kyanite schists (Omrani et al., 2013). Mafic intrusions and ultramafic cumulates (locally layered with rare felsic rocks) seem to intrude the eclogites, although the contacts are poorly exposed (Zanchetta et al., 2009). Peak metamorphic conditions of 600–700 °C and $P > 1.5$ GPa with retrograde metamorphism at lower amphibolite facies was inferred by Zanchetta et al. (2009). Metamorphism at 1.5–2.0 GPa and ~600 °C is proposed for Shanderman eclogites (Omrani et al., 2013). Zanchetta et al. (2009) concluded that the Shanderman complex does not mark the Paleotethys suture and instead represents an allocthonous nappe of Variscan continental crust, coming from the southern margin of the Transcaucasian region and stacked upon the northern margin of the Central Iranian block.

3.4. Jandagh–Anarak ophiolites

The Anarak, Jandagh and Posht-e-Badam metamorphic complexes occupy the NW part of the central Iranian block (on NW flank of the Yazd Block; Fig. 2) and belong to the Northern Iranian Paleotethys suture zone and related Variscan terranes of the Turan

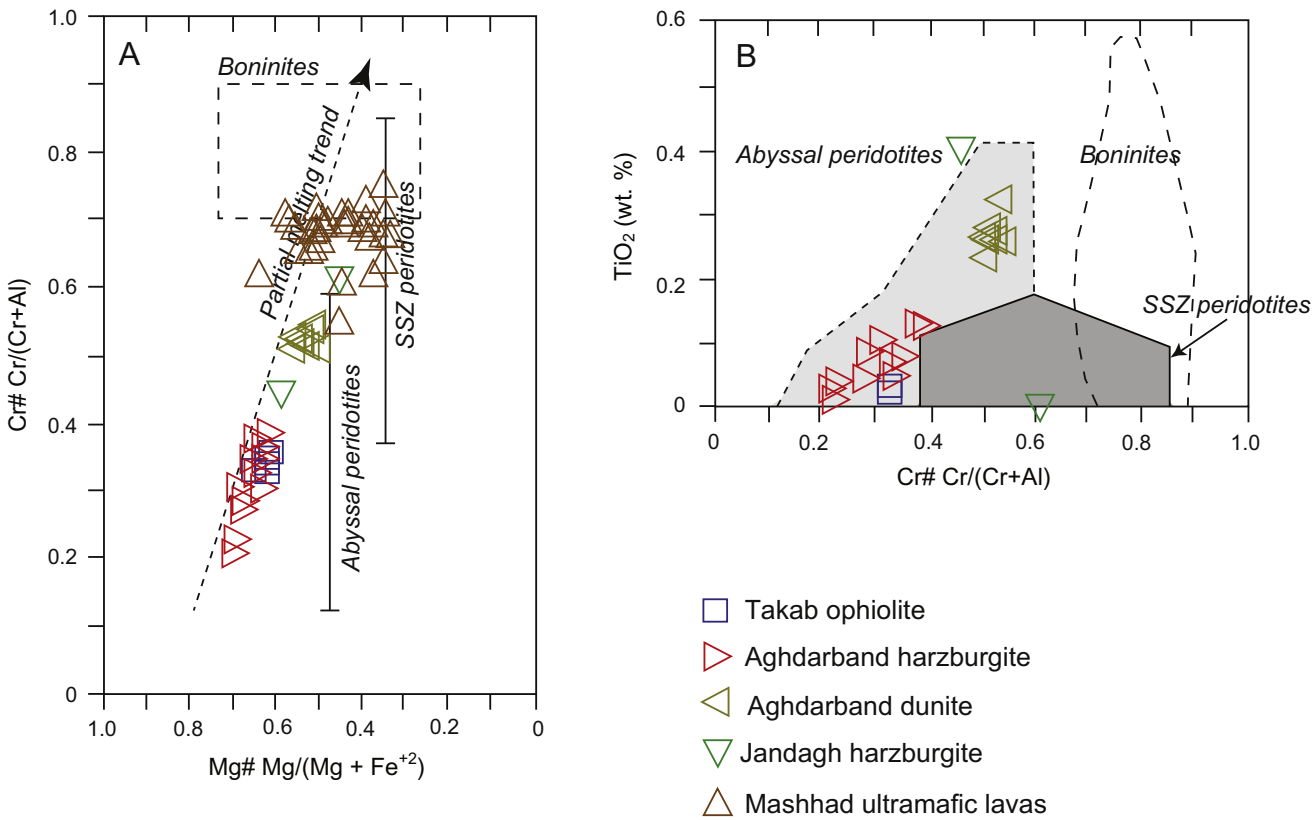

Fig. 7. Cr# vs. Mg# diagram displaying the composition of peridotite spinels. Data on the Jandagh peridotites from Torabi (2000); Takab peridotites from Hajialioghli et al. (2007), Mashhad lavas and Darrehanjir peridotites from Shafaii Moghadam et al. (unpublished data).

block (Fig. 2 and Appendix 3; Bagheri and Stampfli, 2008). This part of central Iran presents all the elements of an orogen such as dismembered ophiolites and deformed siliciclastic, calcareous and volcanic rocks (Bagheri and Stampfli, 2008). These complexes are thought to be related to the Triassic rocks of the Aghdarband region (e.g., Davoudzadeh and Schmidt, 1984) based on paleomagnetic evidence for 135° counter-clockwise rotation of the Lut block since Late Triassic time (Davoudzadeh et al., 1981; Soffel and Forster, 1984; Soffel et al., 1996), although this rotation is questioned by Zanchi et al. (2009). These workers argue that Anarak metamorphic rocks and associated ophiolites originated north of the Northern Iranian suture zone. The Jandagh–Anarak Paleozoic ophiolites are in fault contact with Late Cretaceous Nain-Ashin ophiolites.

The Jandagh–Anarak region was recently divided into five sub-terranes (Bagheri and Stampfli, 2008) (Appendix 5): (1) The Variscan accretionary complex is composed of two sub-units, the Jandagh high temperature metamorphic belt with the Arusan ophiolite subunit on its northern margin and the Morghab schist unit with the Palhavand gneiss subunit on its southern border. This accretionary complex is covered by two sedimentary groups: the Godar-e-Siah complex (Upper Devonian to Carboniferous volcano-sedimentary arc deposits, interpreted as a Eurasian Late Paleozoic convergent margin; see Fig. 4C) and the Triassic Nakhlak group (including Ashin and Alam Formation turbidites and Baqorouq Formation conglomerates); (2) Permian accretionary complex including the Anarak and Kabudan seamounts; (3) Doshakh accretionary wedge containing OIB-type basalts and gabbros, siliciclastic rocks and carbonates; (4) the Bayazeh flysch zone; and (5) the Early Cambrian (Cadomian) Airekan granitic complex.

The Morghab schists consist of low grade metamorphic rocks that include thick siliciclastic turbidites with minor carbonate, volcaniclastic, and basaltic layers. These are accompanied by dismembered ophiolitic rocks such as harzburgite and gabbro, along with a few diabasic and felsic dikes (Nakhlak-type ophiolite of Bagheri and Stampfli, 2008). Some of these igneous rocks show clear SSZ geochemical signatures, and some are boninite. The Arusan meta-ophiolite comprises peridotite, gabbro and basalt associated with pelagic limestone and chert. Because this ophiolitic unit is found behind (NW) the inferred Late Devonian–Carboniferous volcanic arc of the Godar-e-Siah group, it is regarded as a remnant of a younger back arc basin (see Appendix 4). Metagabbro and metabasalt of the Arusan ophiolite shows SSZ geochemical affinity (island-arc tholeiites with minor MORB). The Anarak ophiolite is composed of peridotite intruded by gabbroic–diabasic dikes. Pillow lavas (OIB-type) with overlying rhyolitic rocks are common in this ophiolite. Arc volcanic products of Paleotethys subduction are preserved in the Upper Devonian–Lower Carboniferous Godar-e-Siah unit, mainly including andesitic to dacitic pyroclastic rocks. Seven types of low grade to blueschist facies meta-igneous rocks of the Late Paleozoic to Late Triassic Anarak Metamorphic Complex (AMC) can be traced (Buchs et al., 2013). The origin of these rocks includes SSZ, MOR, oceanic intraplate and continental rift settings, suggesting a progression from rift to drift (Buchs et al., 2013). Buchs et al. (2013) give four reasons that the AMC should be interpreted as an ancient accretionary prism related to the subduction and closure of Paleotethys: (1) the presence of glaucophane schist; (2) the presence of SSZ igneous rocks intercalated with Carboniferous and Permo-Triassic metasediments; (3) trondhjemites (with SSZ signature) intruded into Permo-Triassic ultramafic rocks; and (4) voluminous sliliciclastic rocks associated with MORB-type oceanic crust.

3.5. Takab ophiolite

The Takab metamorphic complex in NW Iran (Fig. 2) is composed of granulite, amphibolite, calc-silicates, granitic gneiss and

pelitic schist (Saki, 2010; Appendix 6). In this region, metaperidotite (spinel harzburgite and dunite) and serpentinite occur as boudinaged interlayers and/or small bodies with calc-silicates, retrograded granulites and amphibolites (Hajialioghli et al., 2007). Unfortunately the region lacks detailed study and whether or not these peridotites are part of a dismembered ophiolite is not clear. Nevertheless, the presence of gneiss, metapelite and peridotites were interpreted as a proto-Tethyan remnant by Hajialioghli et al. (2007) and Saki (2010).

4. Age constraints of Iranian Paleozoic Ophiolites

In this section we summarize age information for Iranian Paleozoic ophiolites, using both biostratigraphic ages (based on microfossils) and radiometric ages (such as Ar–Ar and U–Pb ages).

U–Pb, Ar–Ar and biostartigraphic ages of Iran Paleozoic ophiolites and related rocks are summarized in Fig. 6. For comparison we also plotted the ages of Paleozoic ophiolites and related rocks from neigbouring regions including Turkey, Caucausus, Turkmenistan (Turan) and Aghanistan. The oldest age constraints for the Darrehanjir ophiolite are granitic pebbles in basal conglomerates of the Qara-Gheitan Formation (which unconformably cover the Darrehanjir ophiolite) with U–Pb zircon age of ca. 343 Ma (Carboniferous; Karimpour et al., 2011). U–Pb zircon ages obtained by Zanchetta et al. (2013) are somewhat younger, ca. 326–306 Ma. These ages indicate that the granitic clasts in the basal conglomerates of the Qara-Gheitan Formation come from Eurasian basement. Microfossils indicate Early Permian (Eftekharnezhad and Behroozi, 1991), Late Early Permian or Middle Permian ages (Zanchetta et al., 2013). However our new U–Pb zircon ages (Shafaii Moghadam et al., submitted for publication) indicate that the age of oceanic crust magmatism is ca. 380–383 Ma (Late Devonian, Frasnian). These are older than ages that previously thought to date Aghdarband ophiolite formation and support a Devonian age of oceanic crust formation as proposed by Stampfli and Borel (2002). $^{40}Ar/^{39}Ar$ dating of Mashhad ophiolite hornblende gabbros yielded ages of ca. 288–282 Ma (Ghazi et al., 2001) (Fig. 6), consistent with Early Permian ages for pelagic sediments interbedded with lavas (Kozur and Mostler, 1991). The new U–Pb zircon ages on the Aghdarband ophiolites (Shafaii Moghadam et al., submitted for publication) are ~100 Ma older than published Ar–Ar and biostratigraphy ages for gabbros and radiolarites intercalated with komatiitic and basaltic lavas from Mashhad and Fariman ophiolites.

Granitic–granodioritic intrusions into the Mashhad-Torbat-e-Jam ophiolites yield LA–ICP–MS U–Pb zircon ages of 215 ± 4 and 217 ± 4 Ma (Karimpour et al., 2010) and 199.8 ± 3.7 and 217 ± 4 Ma (Mirnejad et al., 2013). We take these Late Triassic ages to approximate when these plutons intruded the already-obducted ophiolites. This interpretation is supported by the fact that cobbles of these granites are found in the basal conglomerate of the Middle Jurassic Kashafrud Formation near Mashhad (Fig. 4B). These granitoids represent syn- or post-collisional magmatism, further indicating that Paleotethyan ophiolites were emplaced before Late Triassic time (Alavi, 1991). The presence of early S-type granites

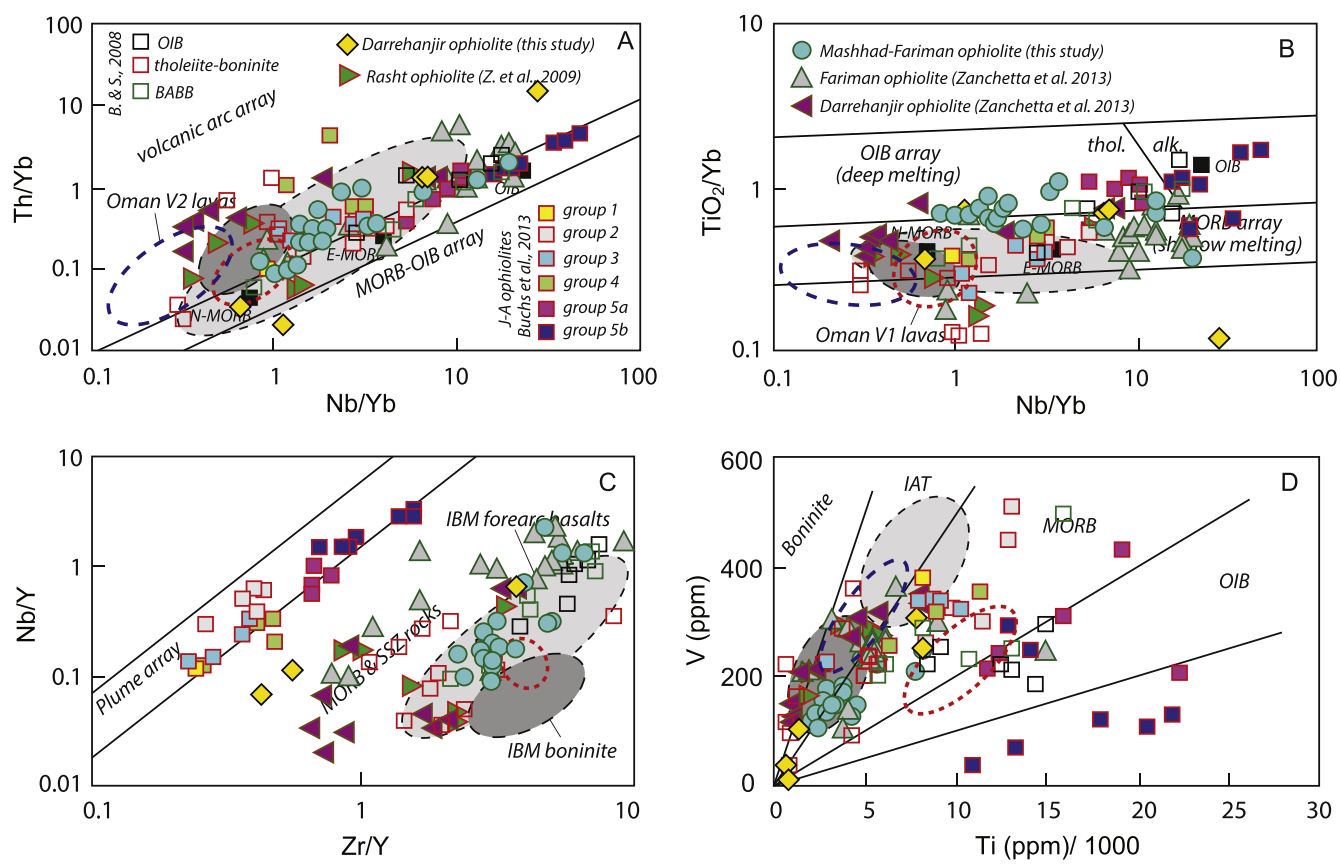

Fig. 8. Trace element compositional variations of Iran Paleozic ophiolitic magmatic rocks. (A) Th/Yb vs. Nb/Yb; (B) TiO_2/Yb vs. Nb/Yb; (C) Nb/Y vs. Zr/Y and (D) V vs. Ti diagrams. Th/Yb vs. Nb/Yb and TiO_2/Yb vs. Nb/Yb diagrams modified after Pearce (2008); Nb/Y vs. Zr/Y diagram from Fitton et al. (1997) and Ti vs. V diagram modified after Shervais (1982). Data on Oman ophiolites from Godard et al. (2003) and on Izu–Bonin–Mariana (IBM) forearc from Reagan et al. (2010). Data on the Jandagh–Anarak (J–A) ophiolites from Buchs et al. (2013); on Rasht ophiolites from Zanchetta et al. (2009) and on Darrehanjir–Mashhad ophiolites from Shafaii Moghadam et al. (unpublished data) and Zanchetta et al. (2013). For comparison we have also added data for OIB, BABB and tholeiitic–boninitic-type rocks from Bagheri and Stampfli (2008).

with metamorphic enclaves, geochemical signatures as well as Sr–Nd isotopes (Karimpour et al., 2010; Mirnejad et al., 2013; and our unpublished data) show that the Mashhad granitoids have post-collisional characteristics, produced from re-melting of continental crust. This constraint is somewhat different than that observed in the Aghdarband region, where ophiolite emplacement must be older than deposition of the post-Late Permian Qara-Gheitan Formation with basal conglomerates (including ophiolitic fragments), which rests unconformably on the ophiolites. Our results differ from the conclusion of Natal'in and Sengor (2005), that collision between Cimmeria and Eurasia took place at the end of Triassic time.

Rb–Sr dating of Shanderman phyllites gave Middle to Late Devonian ages of 382 ± 48 and 375 ± 12 Ma (Zanchetta et al., 2009). $^{40}Ar/^{39}Ar$ dating of white mica in Rasht eclogites indicates ca. 330 Ma (Middle Carboniferous; Zanchetta et al., 2009). This age clearly shows that high-pressure metamorphism and thus the Rasht-Shanderman ophiolite is older than 330 Ma, may be similar to 375–380 Ma Darrehanjir ages. Nakhlak ophiolites (within Jandagh–Anarak ophiolites) have peridotites, gabbros, felsic dikes and lavas with Devonian ages (Fig. 4; Bagheri and Stampfli, 2008), covered by Upper Devonian–Lower Carboniferous arc-related pelagic–terrigenous sediments. SSZ-type trondhjemite from the Anarak ophiolite yields a U–Pb zircon age of 262.3 ± 1 Ma (Late Permian, Bagheri and Stampfli, 2008), much younger than Rasht–Shanderman and Darrehanjir ophiolite ages. This shows that SSZ magmatim within the Jandagh–Anarak region began with Devonian SSZ-oceanic crust formation and evolved into active arc magmatism during Permian time. Jandagh ophiolitic metamorphic rocks are intruded by granitic to tonalitic plutons and dikes with U–Pb zircon age of 215 ± 15 Ma (Bagheri and Stampfli, 2008), similar to Mashahd and Torbat-e-Jam granites. Thus, age constraints for all Iranian Paleozoic ophiolites range from Devonian to Late Permian. These data clearly show that Paleotethys seafloor spreading lasted at least 120 Ma in the last half of Paleozoic time. Paleozoic ophiolites were emplaced, uplifted, and eroded before they were overlain unconformably by Middle Jurassic shale, sandstone, and conglomerate of the Kashafrud Formation, which seals the Paleotethys collision zone between Iran and Eurasia (Zanchi et al., 2009).

5. Compositional variations in Iranian Paleozoic ophiolites

In this section we summarize geochemical information for Iranian Paleozoic ophiolites. Data used in this section are mostly from the literature but a significant proportion is from our own unpublished data. The geochemical data we integrate in this section are whole rock trace element data and chemical composition of indicator minerals including Cr# (=100 atomic Cr/Cr + Al) spinel in peridotite. Appendix 7 presents data compilation for each Paleozoic ophiolite.

Darrehanjir lherzolites and dunites have low Cr# spinels resembling those from abyssal peridotites (Fig. 7). Mashhad Permian komatiites and high-Mg basalts have high Cr# spinels. The high Cr content of komatiite spinels indicates high melting degree of the source mantle.

Most of the Mashhad komatiites have clinopyroxene with relatively high TiO_2 contents (Table 1). Low Cr# (<40) and high Cr# (40 < Cr# < 60) spinels are common in the Takab and Jandagh

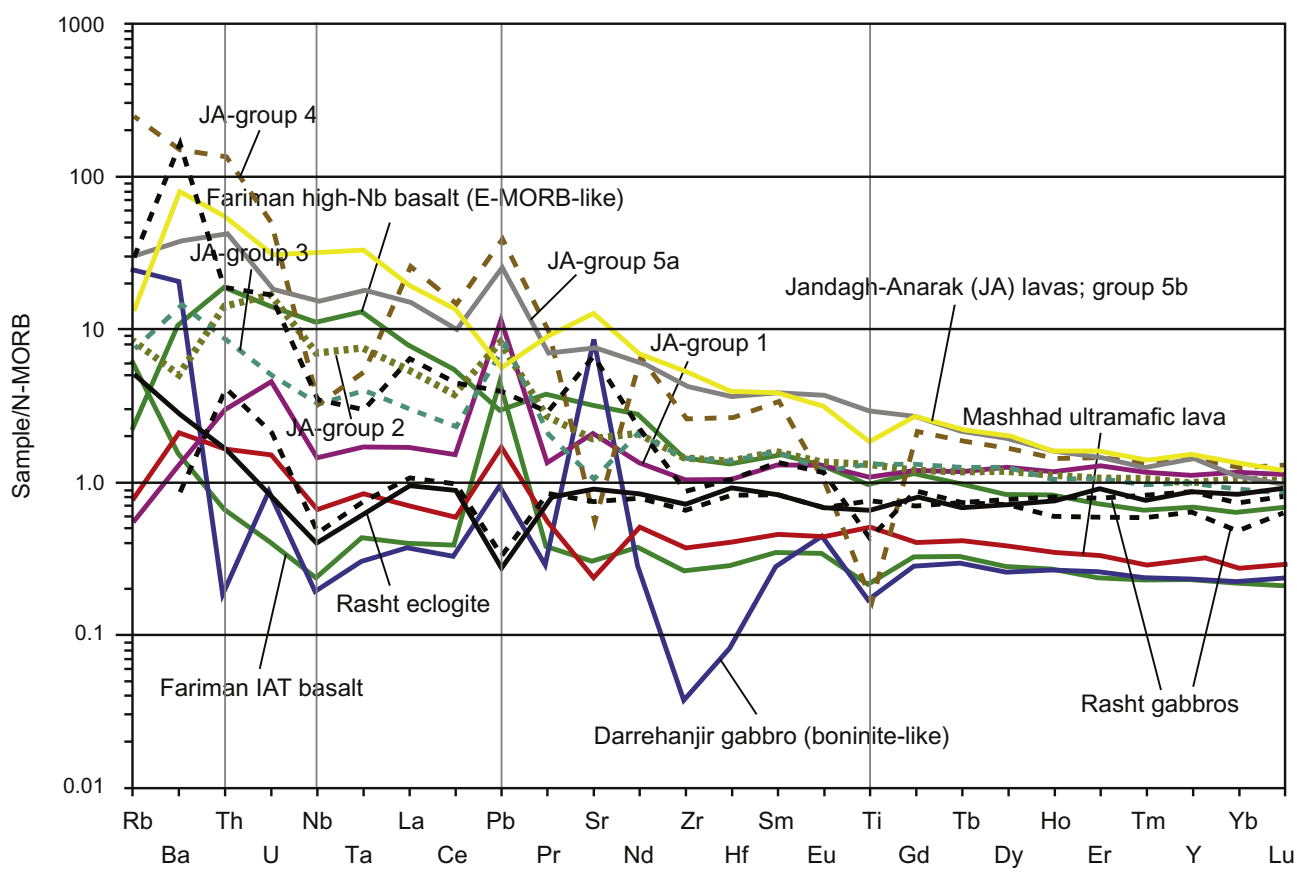

Fig. 9. N-MORB-normalized trace elements diagram for representative samples of the Paleozoic ophiolites. Data on the Jandagh–Anarak (J–A) ophiolites from Buchs et al. (2013); on Rasht ophiolites from Zanchetta et al. (2009) and on Darrehanjir–Mashhad ophiolites from Shafaii Moghadam et al. (unpublished data). N-MORB values are from Sun and McDonough (1989).

peridotites respectively (Fig. 7). Overall, these mineral indicators suggest a MORB- or BAB-like tectonic environment for forming these ophiolites.

Mashhad ophiolite lavas (of Permian age) are mostly high-Mg basalts to komatiites which show both E-MORB and arc-type signatures (Ghazi et al., 2001). In a V vs. Ti diagram the Mashhad lavas are MORB to IAT (Fig. 8), whereas their trace element patterns are consistent with formation in a SSZ setting (Fig. 9). Two distinct lava groups – both of Permian age – have been distinguished in the Fariman ophiolites (Zanchetta et al., 2013): (1) Transitional/alkaline lavas without Nb depletion, similar to within-plate basalts (OIB) with high Nb/Yb but low Ti/Yb (Fig. 8) and (2) high Mg-lavas with Nb depletion and higher Th/Yb ratio (Fig. 8). Our data show that high-Nb basalts from the Fariman ophiolite are similar to E-MORB and resemble Jandagh–Anarak group 5b lavas (Fig. 9). High Mg-lavas of Zanchetta et al. (2013) are similar to island-arc tholeiites/boninites (like Darrehanjir gabbros) with depletion in high field strength elements and enrichment in large ion lithophile elements (Fig. 9). Fariman Permian alkaline basalts may be derived from an OIB-type source whereas high-Mg basalts come from depleted mantle that was enriched in LILEs by subduction-related fluids (Zanchetta et al., 2013). Darrehanjir Devonian (U–Pb zircon ages, Shafaii Moghadam et al., submitted for publication) gabbros have calc-alkaline signatures (Zanchetta et al., 2013). Our unpublished data show that these gabbros are depleted in trace elements, with flat to spoon-shaped REE patterns with Nb–Ta depletion, resembling boninites (Fig. 9). Most gabbros have high Th/Yb and low Nb/Yb and Ti/Yb ratios (Fig. 8) resembling depleted arc tholeiites and boninites. However, late-stage dikes have calc-alkaline characteristics. A supra-subduction zone setting, characterized by arc splitting and basin opening related to upper plate extension, is thought to have been responsible for forming the Fariman and Darrehanjir ophiolites (Zanchetta et al., 2013). In this interpretation the Fariman and Darrehanjir ophiolites originated via spreading in an intra-arc or incipient back-arc basin along the active southern margin of the Turan domain (the same as Asiatic Hunic terrane in Fig. 9) (Zanchetta et al., 2013).

The Rasht eclogites (with basaltic protolith) and gabbros show Nb depletions similar to arc igneous rocks (Fig. 9; Zanchetta et al., 2009; Omrani et al., 2013). Geochemical data on the Jandag-Anarak ophiolites give equivocal results. Metagabbro and metabasalt of the Arusan ophiolite show SSZ geochemical affinity (Island-arc tholeiites with minor MORB; Buchs et al., 2013). Metabasites in the Anarak Metamorphic complex define six petrogenetic groups (Figs. 8 and 9; Buchs et al., 2013): (1) N-MORB like basalts showing a remnant of oceanic crust; (2) E-MORB like rocks, also formed in an oceanic setting; (3) BABB-like rocks with slightly enriched incompatible element patterns and variable Nb–Ta anomaliess. These rocks may reflect remnants of a back-arc basin. (4) Basalts with Nb–Ta depletion and Th enrichment suggesting a volcanic arc developed on a continental margin and/or on oceanic lithosphere. (5a) OIB-type basalts with positive Nb–Ta anomalies, considered as remnants of intraplate oceanic volcanism. (5b) OIB-like basalts formed at a Paleozoic rifted margin. Boninites were also reported from Jandagh–Anarak ophiolites by Bagheri and Stampfli (2008).

All these geochemical data show that the Paleozoic ophiolites have a composite geochemical signature from OIB-like to MORB- and SSZ-type characteristics. Chemostratigraphy of Paleozoic magmatic rocks is difficult to reconstruct but in the Jandagh–Anarak ophiolites it seems that SSZ-type magmatism followed MORB-like lavas. However, some of the igneous rocks from the Devonian–Carboniferous Nakhlak ophiolite show supra-subduction-related (SSZ) and sometimes boninitic geochemical signatures. Fariman ophiolite lavas with intercalated Permian radiolarites display both Nb-depleted and Nb-enriched signatures but Devonian ophiolitic plagiogranite and gabbro from the Darrehanjir region show SSZ-type characteristics. These data show that SSZ-type magmatism may have begun in Devonian time, approximately synchronous with MORB-type magmatism in other Paleozoic ophiolites.

6. Discussion

6.1. Comparison with other Paleozoic ophiolites in the Mediterranean-SW Asia region

Distinguishing Middle to Late Paleozoic ophiolite pulses is important for reconstructing the history of Paleotethys in SW Asia. The Paleotethys ophiolitic belt and the associated Silk Road Arc are aligned along the suture westwards from Tibet to Tadjikistan, Turkmenistan, Afghanistan, Iran and the Caucausus. The Paleotethys suture continues farther east and west but we do not discuss these extensions here. The Tibetan plateau preserves Paleotethys oceanic remnants and records amalgamation of Gondwana-derived fragments since the Paleozoic (e.g., Sengor and Natalin, 1996; Zhai et al., 2013; Zhu et al., 2011, 2013). The best-known ophiolites from the Tibetan plateau are those of Neotethys in the Yarlung Zangbo suture zone (e.g., Aitchison et al., 2000; Guilmette et al., 2009; Hebert et al., 2012) and Paleotethys ophiolites from the Jinsha, Changning–Menglian (e.g., Jian et al., 2008, 2009a,b) and Qilian–Qiling ophiolites (Zhang et al., 2008). Recent studies of eclogites with MORB protolith (Yang et al., 2009) and U–Pb dating of OIB-type gabbros (Dai et al., 2011) indicate that a Devonian to Carboniferous–Permian suture (North Gangdese suture zone; Yang et al., 2009) formed at the southern margin of the Lhasa block during Late Paleozoic time. In NE Tadjikistan, pillow lavas are intercalated with Famennian–Tournaisian (ca. 360 Ma) pelagic limestones and these igneous rocks are interpreted as back-arc basin oceanic crust (Jian et al., 2009b). The Turkman zone in Turkmenistan includes Lower Paleozoic to Upper Devonian pelagic sediments and ophiolites (Fig. 6; Boulin, 1980, 1988). NNW of the Aghdarband region, in the Kizilkaya and Tuar regions of Turkmenistan, there are outcrops of oceanic crust including 200 m thick cherty slates and 100 m thick pyroxenite, gabbro, diabasic rocks and pillow lavas intercalated with radiolarites for which a Middle Paleozoic age was infered (Mirsakhanov, 1989). The mafic rocks are low-TiO_2 basalts to basaltic andesites considered to have formed in a SSZ setting such as a back-arc basin (Garzanti and Gaetani, 2002). The slaty cherts contain Lower to Middle Carboniferous radiolaria (Garzanti and Gaetani, 2002).

The Paleozoic tectonic evolution of Afghanistan is very poorly understood, but Lower Paleozoic to Upper Devonian rock units include flysch-like sediments of Cambrian–Ordovician to Silurian age (Boulin, 1988) that may record Paleotethys opening. Devonian pelagic sediments associated with gabbros, serpentinites and volcanic rocks are common along the Herat-Akbaytal fault in NW Afghanistan (Boulin, 1988), perhaps indicating a Paleozoic suture. High pressure metamorphic rocks are associated with Devonian ophiolitic components in the western Hindu Kush (Boulin, 1972). Lower Carboniferous volcano-sedimentary rocks associated with calc-alkaline lavas and shallow marine, fossil-bearing limestones in the western Hindu Kush and Badakhshan regions of NE Afghanistan may reflect active continental margin magmatism (Boulin, 1988). However ophiolitic slices associated with calc-alkaline rocks of Early Carboniferous age are also present in northern Afghanistan. Early Triassic to Early Jurassic calc-alkaline granites and granodiorites from the western Hindu Kush-Badakhshan regions were dated ca. 200–234 Ma (K–Ar; Debon and Sonet, 1982). These granites were emplaced about the same time as Mashhad–Torbatjam granites in the Mashhad-Aghdarband

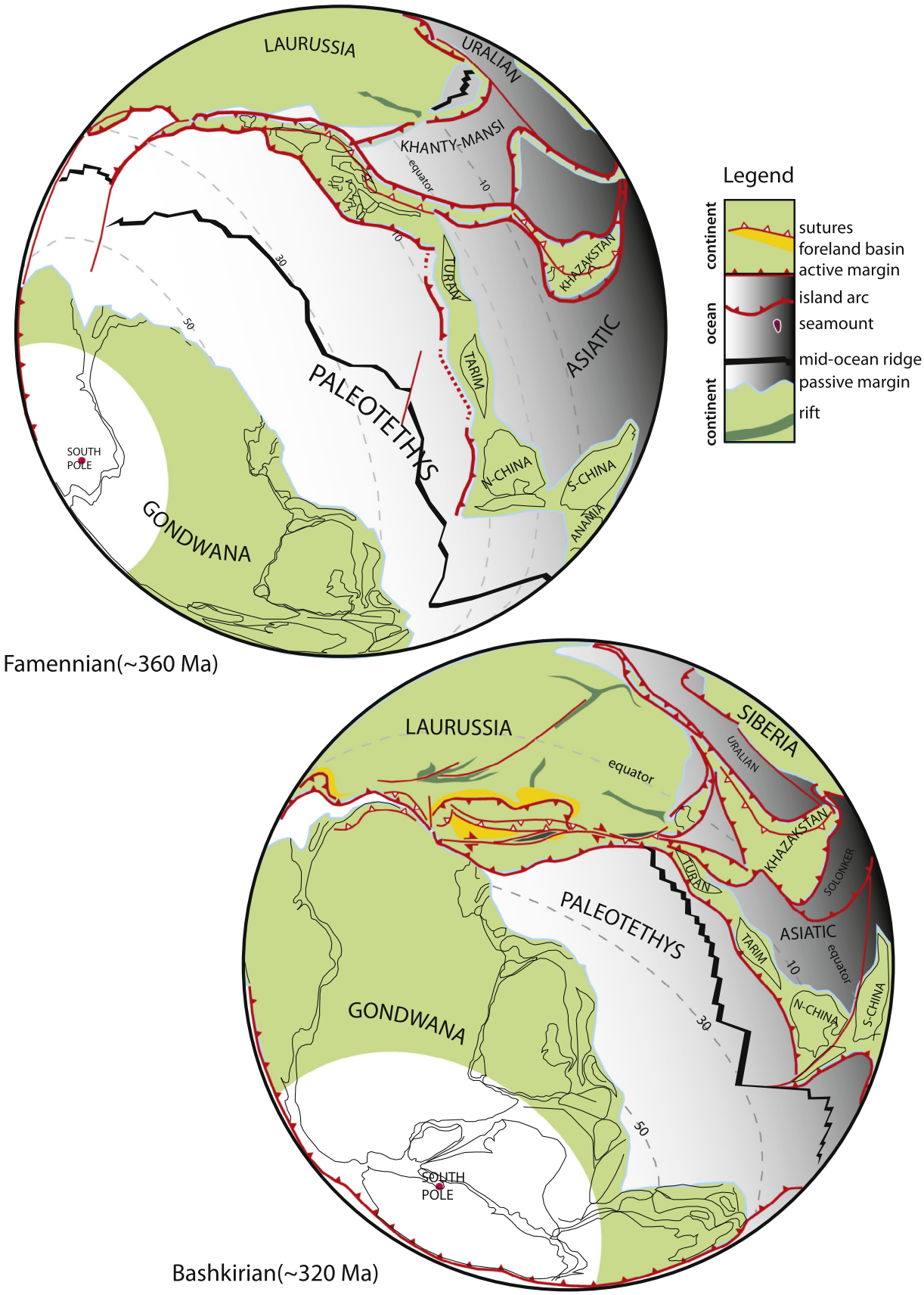

Fig. 10. Tethys reconstructions for the Late Devonian and middle Carboniferous (modified from Stampfli and Borel, 2002). Note that Paleotethys subduction initiated beneath the Turan block (Eurasia) before ca. 360 Ma.

ophiolites and Jandagh granites in the Jandagh–Anarak ophiolites (Fig. 6).

The Transcaucasian massif, situated between the Great Caucasus to the north and the Lesser Caucasus to the south (Zakariadze et al., 2007), contains traces of Early Paleozoic metamorphosed ophiolitic rocks including sheeted dikes and pillow lavas (Gamkrelidze et al., 1999; Rolland et al., 2011). A tectonic mélange zone north of the Sevan-Akera Suture includes

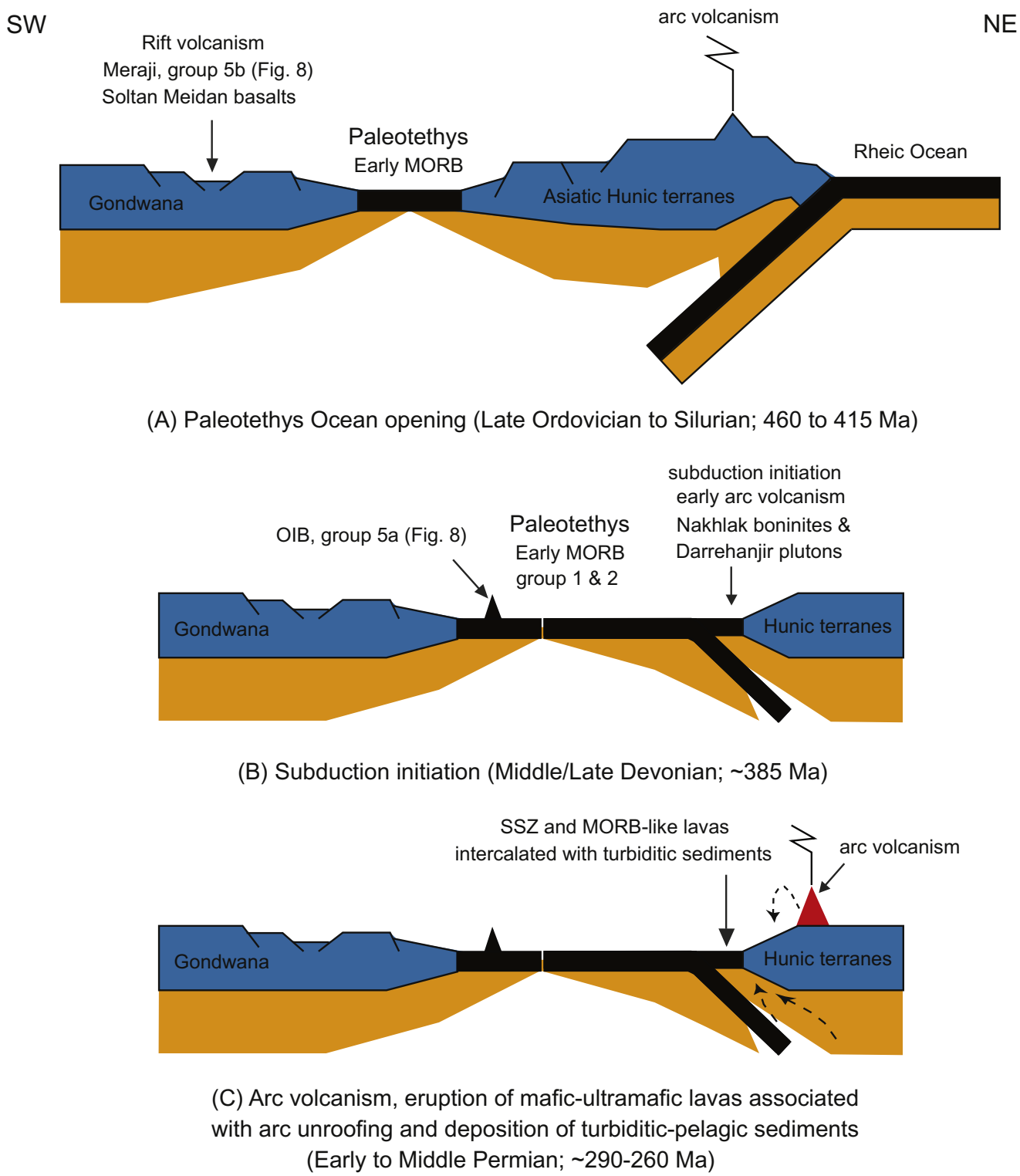

Fig. 11. Schematic model for the formation and evolution of Iran Paleozoic ophiolites with emphasis on the Jandagh–Anarak and Mashhad–Darrehanjir ophiolites (modofied after Buchs et al., 2013). (A) Continental rifting and opening of the Paleotethys Ocean in Late Ordovician to Silurian time associated with formation of OIB-type lavas from the Meraji area (Jandagh) and continental flood basalts from NE Iran (Soltan-Meidan basalts). (B) Subduction initiation in middle to late Devonian and formation of boninitic gabbros from the Nakhlak area. (C) Formation of intra-oceanic and continental margin arc volcanism and then arc unroofing in Carboniferous to Permian time with occurrence of arc-like and MORB-like lavas in Jandagh–Anarak and Fariman-Darrehanjir ophiolites.

allocthonous slices of Middle Paleozoic serpentinites, amphibolites, phyllites, granites and felsic volcanic rocks that display an early Variscan metamorphic overprint based on Ar–Ar dating (330–336 Ma; Zakariadze et al., 2007; Treloar et al., 2009). These rocks may reflect an accretionary prism developed along the Eurasian margin, with slices of oceanic lithosphere and continental arc-related volcano-sedimentary units.

Northward subduction of Paleotethys lithosphere beneath the southern margin of paleo-Asia started in Devonian time (Sengor and Natalin, 1996; Heubeck, 2001). Evidence of this subduction is revealed in igneous rocks of the Caucasus, western Turkey, Iran, western Hindu Kush, and northern Tibet (Sengor, 1990; Boulin, 1988; Sengor et al., 1988; Ruttner, 1984; Alavi et al., 1997). Late Carboniferous-Early Permian calc-alkaline intrusions and volcanism in the Mediterranean and Caucasus regions reflect the northward subduction of the Paleotethys beneath Eurasia (Stampfli and Borel, 2002; Rolland et al., 2011). High temperature-low pressure metamorphic rocks in southern Georgia yield Ar–Ar ages of 303 Ma (Carboniferous, Rolland et al., 2011), similar to Ar–Ar age of 330 Ma for high-pressure rocks of the Shanderman Complex in the Rasht ophiolite in northern Iran (Omrani et al., 2013; Zanchetta et al., 2009).

Collision between Gondwana-derived Cimmeria and paleo-Asia occurred in Permo-Triassic time. This terminated subduction beneath Eurasia. The collision may have begun in the west (Caucusus) in Permian time, becoming younger (Triassic) to the east (Fig. 6).

6.2. Petrological diversity of Iranian Paleozoic ophiolites

Global ophiolite pulses appear to be temporally and spatially linked to important magmatic and tectonic events (Dilek and Furnes, 2011). These global events and related mantle processes can control the development of different ophiolitic types in different tectonic environments (Dilek, 2003). Each ophiolite pulse seems to form different types of oceanic crust, for example Jurassic ophiolites in the Alps are mostly MOR-type (lherzolitic type of Nicolas, 1989 and Ishiwatari, 1985) or continental (passive) margin-type of Dilek and Furnes (2011), whereas the Cretaceous ophiolites in the eastern Mediterranean and SW Asia are mostly SSZ-type. The temporal and spatial distribution of different types of ophiolites is more useful for the Iranian Mesozoic than for Paleozoic ophiolites, which vary a lot. Most Iranian Paleozoic ophiolites display a complex history from continental break-up (continental-margin type ophiolites of Dilek and Furnes, 2011) to MOR-type, plume-type, SSZ-type and accretionary-type ophiolites. Each of these ophiolite types is recognized in different Iranian Paleozoic ophiolites with different geochemical signatures and geodynamic context. This indicates that Paleozoic ophiolites of Iran have complex and diachronous origins.

Paleotethys opening is reflected by Late Ordovician alkali to tholeiitic continental flood basalts (Soltan-Meidan basalts) and felsic to mafic plutons, and OIB-like basalts (plume-type ophiolite lavas of Dilek and Furnes, 2011) from Jandagh–Anarak ophiolites, which suggest formation at a Paleozoic rifted margin (Buchs et al., 2013). Evidence for rifted continental margin-type setting is absent elsewhere in Paleozoic Iranian ophiolites. MORB-type lavas are recorded in the Jandagh–Anarak as well as Mashhad-Aghdarband ophiolites. Darrehanjir peridotites with low Cr# spinels suggest low degree residues of partial melting and MORB-type mantle, similar to lherzolitic (L-type) type ophiolites of Nicolas (1989). This is true also for other Paleozoic ophiolites in Iran, similar to both H-type and L-type defined by Ishiwatari et al. (2003). Lherzolitic peridotites with low Cr# spinels and clinopyroxene-type cumulates in some Iranian Paleozoic ophiolites especially Takab and Aghdarband are similar to Yakuno-type ophiolites (Japan) of Ishiwatari (1985).

Most magmatic rocks from the Jandagh–Anarak, Rasht, Mashhad and Aghdarband ophiolites appear to be subduction-related (SSZ-type ophiolite of Dilek and Furnes, 2011). Although it seems that SSZ- and MORB-type magmatism are synchronous, OIB-like lavas erupted late in the life of this oceanic basin and may not be related to ophiolite formation (except groups 5a and 5b OIB-type lavas from Jandagh–Anarak ophiolites), but instead show arc magmatism along the active continental margin and/or accretionary prism at the foot of Eurasia after amalgamation of Devonian oceanic crust within the Permian accretionary prism Permian komatiites are special to the Mashhad and Fariman ophiolites; again probably indicating mantle unrest during Permian beneath Asia (Shafaii Moghadam et al., submitted for publication). The Permian was a time when repeated mantle plumes impacted Asia, beginning with Tarim (esp. 270–280 Ma; Zhang et al., 2010, 2011; Yu et al., 2011), followed by Emeishan (~260 Ma; He et al., 2007) and the ~250 Ma Siberian Traps (Reichow et al., 2009).

All Iranian Paleozoic ophiolites are associated with thick Middle to Upper Paleozoic volcanoclastic and turbiditic sediments intercalated with pelagic sediments, off-scraped oceanic crust and Silk Road Arc products (and even high pressure metamorphic rocks), suggesting a thick accretionary prism (accretionary-type ophiolite) during the last stages of basin evolution. However, large accretionary flysch wedges also grew during Early Mesozoic collision between Eurasia and Cimmeria.

6.3. Geodynamic evolution of Iranian Paleozoic ophiolites

The most prominent pulse of Iranian ophiolite formation during Early to Middle Paleozoic time coincided with episodes of rifting along the northern margin of Gondwana and the northward drift of these fragments. The Iranian geologic record suggests that Paleotethys started to open as early as Ordovician time (Stampfli, 1978; Stampfli et al., 1991) with subduction beginning by 380 Ma (Fig. 10). Subduction initiation may have been diachronous as Turkmenistan and Caucasus ophiolites represent Carboniferous SSZ-type oceanic crust. Zanchetta et al. (2013) concluded that volcano-sedimentary units of the Fariman and Mashhad ophiolites were deposited during Permian time in a subsiding basin. This included siliciclastic turbidites derived from the erosion of a magmatic arc and its basement, interfingered with Permian carbonates and basaltic lava flows with calc-alkaline and transitional (alkaline) affinities. In this view, the Permian Fariman–Mashhad ophiolites developed as remnants of a magmatic arc at the southern margin of Eurasia, above the north-dipping Paleotethys subduction zone, with Fariman and Mashhad ophiolites originating via spreading in an intra-arc or incipient back-arc basin along the southern margin of the Turan domain (Zanchetta et al., 2013), which was an active margin since at least Carboniferous time (Zanchetta et al., 2013). This scenario explains the Fariman–Mashhad ophiolite as a remnant of an accretionary prism. According to our scenario, the juxtaposition of peridotites with dunite screens and clinopyroxenitic dikes with mineralogy and geochemistry similar to those in abyssal peridotites and with Devonian (U–Pb zircon ages) gabbros and felsic rocks supports an interpretation of ophiolite formation above a Devonian subduction zone and then evolution into an accretionary prism in Permian time. The volcaniclastic sediments could have been fed from the Silk Road continental magmatic arc. In contrast to the conclusions of Zanchetta et al. (2013), our peridotite data as well as the composition of Devonian magmatic rocks do not support an intra-arc basin model. On the other hand, our unpublished U–Pb zircon data display a pulse of Devonian SSZ-type oceanic crust formation

(Fig. 10). However, $^{40}Ar/^{39}Ar$ dating of Mashhad ophiolite hornblende gabbros yielded ages of ca. 288–282 Ma (Ghazi et al., 2001), consistent with Early Permian ages for pelagic sediments interbedded with lavas (Kozur and Mostler, 1991). The new U–Pb zircon ages on the Aghdarband ophiolites (Shafaii Moghadam et al., submitted for publication) are ~100 Ma older than published Ar–Ar and biostratigraphy ages for gabbros and radiolarites intercalated with komatiitic and basaltic lavas from Mashhad and Fariman ophiolites. As suggested by Zanchetta et al. (2013), Permian oceanic crust could also represent an extensional/back arc basin, opened on the Asian margin due to extension accompanying subduction and roll-back of old Paleotethys seafloor. The occurrence of volcaniclastic (turbiditic) sediments with intercalated impure marbles and komatiites in Mashhad–Fariman ophiolites (sometimes with hypabyssal characteristics) could represent mantle plume activity within extensional basins over the Paleotethys subducted slab beneath Eurasia.

For palinspastic reconstruction of Iranian Paleozoic ophiolites (including Jandagh–Anarak and Darrehanjir–Mashhad) we follow the scenario proposed by Buchs et al. (2013) (Fig. 11). Metabasites in the Jandagh–Anarak ophiolites are related to different stages of ocean and arc development and can be classified into different groups: for example, group 5b represents OIB-like basalts formed during Ordovician rifting and formation of a continent to ocean transition. Groups 1 and 2 (N-MORB- and E-MORB-like basalts) may be related to spreading at a Late Ordovician–Silurian to Late Devonian mid-oceanic ridge. Intra-oceanic subduction initiation in Middle/Late Devonian time was accompanied by formation of both Nakhlak boninites (Figs. 10 and 11) and SSZ-type gabbros and plagiogranites in Darrehanjir ophiolite. Following Middle Paleozoic arc magmatism and Late Paleozoic back-arc extension, BABB-like (SSZ-type) volcanic rocks erupted (Fig. 11). SSZ-type trondhjemite from the Anarak ophiolite (associated with arc-like lavas) may reflect a plutonic phase of arc magmatism, developed on a continental margin and/or on oceanic lithosphere (Fig. 11). Late Triassic time witnessed Neotethyan propagation in the south and Paleotethys closure in the north (Fig. 11). Final collision between Cimmeria and Eurasia occurred in Triassic time and the Permo-Triassic orogen quickly collapsed to accumulate Kashafrud molasse.

7. Conclusions

We are at early stages of understanding the Paleozoic ophiolites of Iran and what they tell us about the evolution of the Paleotethys Ocean. Considering all data on these ophiolites as well as regional considerations lets us conclude that: (1) Iran Paleozoic ophiolites have a range of ages, from Devonian to Permian; (2) Iran Paleozoic ophiolites have SSZ-, MORB- and OIB-geochemical signatures and OIB-type magmatism is a later phase; (3) All Iran Paleozoic ophiolites are associated with thick accretionary prisms, including Carboniferous flysch, but mainly Permian turbidites, along with slices of oceanic lithosphere associated with rare high-P metamorphic rocks. (4) Nearly all Paleozoic ophiolites of Iran formed in backarc basins. (5) Nearly all Paleozoic ophiolites record oceanic closure in Permotriassic time with intrusion of Late Triassic calc-alkaline, collisional and/or post-collisional granitoids. (6) Jurassic molasse facies sediments sealed most of the Paleozoic ophiolites after closure of the oceanic basin.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2014.04.008.

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