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Foraminiferal-based paleobiogeographic reconstructions in the Carboniferous of Iran and its implications for the Neo-Tethys opening time: a synthesis

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| A B S T R A C T |

The biogeographic distribution of foraminifers and their belonging to either the southern or northern margins of the Paleo-Tethys are used here for paleogeographic reconstructions of Iran during the Carboniferous. Lower Carboniferous foraminiferal assemblages from northern and central Iran show a cosmopolitan character and affinities to both the southern and northern borders of the Paleo-Tethys. Hence, in the Early Carboniferous Iran occupied an intermediate southern latitude position, forming part of Gondwana. This conclusion is consistent with the Late Ordovician to Early Carboniferous drift history of Iran based on paleomagnetic data. In the Late Carboniferous, the foraminiferal affinities of northern and central Iran with the northern part of Paleo-Tethys suggest that Iran separated from Gondwana and moved northwards to a lower latitude. This separation is also evidenced by the Upper Carboniferous coal-bearing sandstones of the Sardar Formation and sandstones with high degree of chemical weathering, which would indicate warm and humid conditions. Considering the composition of foraminiferal fauna along with the evidence of magmatic activities in northwest Iran, it can be inferred that the commencement of the Neo-Tethys opening and continental break-up in Iran occurred sometime in the Late Carboniferous, which contradicts the previous claims that the separation of Iran from Gondwana occurred in Permian and/or Triassic times.

KEYWORDS | Iran. Mississippian. Pennsylvanian. Foraminifera. Paleogeography. Neo-Tethys Opening.

INTRODUCTION

Carboniferous deposits are sporadic and discontinuous in Iran except for Lower Carboniferous strata. The Alborz zone and central Iran have received most of the attention, being subject of stratigraphical and paleontological investigations (Bozorgnia, 1973; Vachard, 1996; Leven *et al.*, 2006; Leven and Gorgij, 2008; Falahatgar *et al.*, 2012, 2015; Zandkarimi *et al.*, 2014, 2017; Vachard and Arefifard, 2015). After the description of the Early Carboniferous Mobarak and Geirud formations by Assereto (1963, 1966), foraminiferal zonations were recognized in several stratigraphic sections of central and eastern Alborz Mountains (Bozorgnia, 1973; Lys *et al.*, 1978; Vachard,

1996; Ueno *et al.*, 1997; Brenckle *et al.*, 2009; Falahatgar *et al.*, 2012, 2015; Zandkarimi *et al.*, 2014, 2017). The Carboniferous deposits of central Iran have been studied in Tabas (Shotori, Shirgesht, and Ozbak-Kuh areas), Posht-e Badam and Yazd blocks and in the Shahreza area. Carboniferous foraminiferal associations of Central Iran have been reported from the Sardar Formation, at the North and South-East of the Tabas town, and from the Gachal Formation, Kalmard area, West of Tabas (Vachard, 1996; Leven *et al.*, 2006; Vachard and Arefifard, 2015). There are some other records of Carboniferous foraminifera in the Yazd Block (Leven *et al.*, 2006). In the Shahreza area only Upper Carboniferous foraminifers have been documented (Baghbani, 1993, Leven and Gorgij, 2008). In the Sabzevar

zone, poorly preserved upper Pennsylvanian foraminifers have been reported (Gorgij and Leven, 2013).

The paleogeographical position of Iran during the Carboniferous has been discussed by many authors (Meissami *et al.*, 1977; Sengör, 1990; Stampfli, 2000; Kalvoda, 2002; Torsvik and Cocks, 2004; Wendt *et al.*, 2005; Devuyst, 2006; Brenckle *et al.*, 2009; Muttoni *et al.*, 2009; Zandkarimi *et al.*, 2014, 2017; Vachard and Arefifard, 2015). In order to recognize the paleobiogeographic affinity of Iran during Carboniferous times, improved investigations of foraminiferal assemblages have been undertaken with the following results. In the Upper Paleozoic: i) foraminifers were widespread within tropical and subtropical paleolatitudinal belts (Boudagher-Fadel, 2008; Vachard *et al.*, 2010; Davydov, 2014); ii) they were very sensitive to water temperature, and their associations display different compositions in lower latitude tropical-subtropical belts versus intermediate and higher latitudes, *i.e.* temperate and boreal belts (Beavington-Penney and Racey, 2004; Murray, 2006; Davydov, 2013; Prothero, 2013); iii) foraminifers had a rapid evolution reaching a high taxonomic diversity and iv) they have adapted to abiotic factors such as the paleoenvironmental shift led by tectonics (Kalvoda, 2002). The data for this study comprise author's own published and unpublished data gathered during years of field work in different parts of Iran and data from literature. Attention is first focused on the distribution of Carboniferous foraminifers in Iran to analyse later their affinity to either warm-water paleoequatorial belts, temperate belts, or cold-water higher latitude belts. Furthermore, the time of the opening of Neo-Tethys in Iran is discussed based on the integration of paleontological data with published data on Carboniferous volcanism and tectonics (Saccani *et al.*, 2013; Tavakoli-Shirazi *et al.*, 2013; Dilek *et al.*, 2014; Moghadam *et al.*, 2014).

GEOLOGICAL SETTING

Iran is located in the center of the Alpine-Himalayan orogenic belt which starts in western Europe and passes through Turkey, Iran, Afghanistan into Tibet and probably Burma and Indonesia, where it links with the circum-Pacific orogenic belt (Stöcklin, 1974; Moores and Twiss, 1995; Prelevi *et al.*, 2013). Iran is divided into several tectonic units according to different stratigraphic, structural, magmatic and metamorphic features (Stöcklin, 1968; Stampfli, 1978; Berberian and King, 1981; Alavi, 1991; Golonka, 2002; Scotese, 2004; Torsvik and Cocks, 2004). For the structural divisions of Iran (Fig. 1), the tectonic maps by Alavi (1991) and Angiolini *et al.* (2007) are used herein.

PALEOBIOGEOGRAPHY

Foraminiferal realms during Late Paleozoic

Traditionally, three major paleobiogeographic realms have been distinguished for the Upper Paleozoic foraminifers: i) tropical/subtropical Paleo-Tethyan realm, represented by highly diversified foraminiferal faunas, ii) the North American realm and iii) the northern Boreal or Uralian-Franklian realm (Lipina, 1973; Reitlinger, 1975; Ross and Ross, 1985; Kalvoda, 2002). In addition, two transitional realms have been reported to the North and South of the Paleo-Tethyan realm (Rui *et al.*, 1991; Leven, 1993; Leven and Okay, 1996) that contain cold foraminiferal faunas which share common features. The southern transitional realm or peri-Gondwanan realm is reported from the Carboniferous to the mid Permian, latest Sakmarian and Artinskian up to the Guadalupian, (Leven, 1993; Kalvoda, 2002; Ueno, 2006; Davydov and Arefifard, 2007; Huang *et al.*, 2015; Ueno *et al.*, 2015). The northern transitional zone, known as the Arctic paleogeographic realm, subsisted from mid Pennsylvanian to early Sakmarian times. It included foraminifers with low diversity that developed from the northern Urals, in the East, to the Canadian Arctic and Alaska in the West (Rui *et al.*, 1991).

Carboniferous foraminiferal assemblages in Iran

Alborz zone

In the Alborz zone, Carboniferous deposits are widespread in the central and eastern parts and are better documented than in other areas of Iran. Foraminiferal faunas are mostly attributed to the Mississippian (Tournaisian-Serpukhovian), with rare early and mid-Pennsylvanian (Bashkirian-Moscovian) records in eastern Alborz (Fig. 2).

Lower Tournaisian foraminifers have been reported only from a few sections, where the Upper Devonian and Lower Carboniferous deposits show stratigraphic continuity (Bozorgnia, 1973). These faunas include species-poor assemblages of earlandiid and septabrunsiid species belonging to biozones MFZ1 to MFZ5 (Bozorgnia, 1973; Vachard, 1996; Ueno *et al.*, 1997; Brenckle *et al.*, 2009; Falahatgar *et al.*, 2015). There are conflicting ideas about the biogeographic affinity of these foraminifers. They have been both attributed to the southern Paleo-Tethyan domain (Meissami *et al.*, 1977; Vachard, 1980; Wendt *et al.*, 2005) and related to northern warm-water Paleo-Tethyan faunas (Kalvoda, 2002; Devuyst, 2006; Brenckle *et al.*, 2009). The lower Tournaisian foraminiferal biozone contains *Earlandia minor* (RAUSER CHERNOUSOVA, 1948) and *Septabrunsiina krainica* (LIPINA, 1948) along with *Archaeosphaera magna* SULEIMANOV, 1945, A.

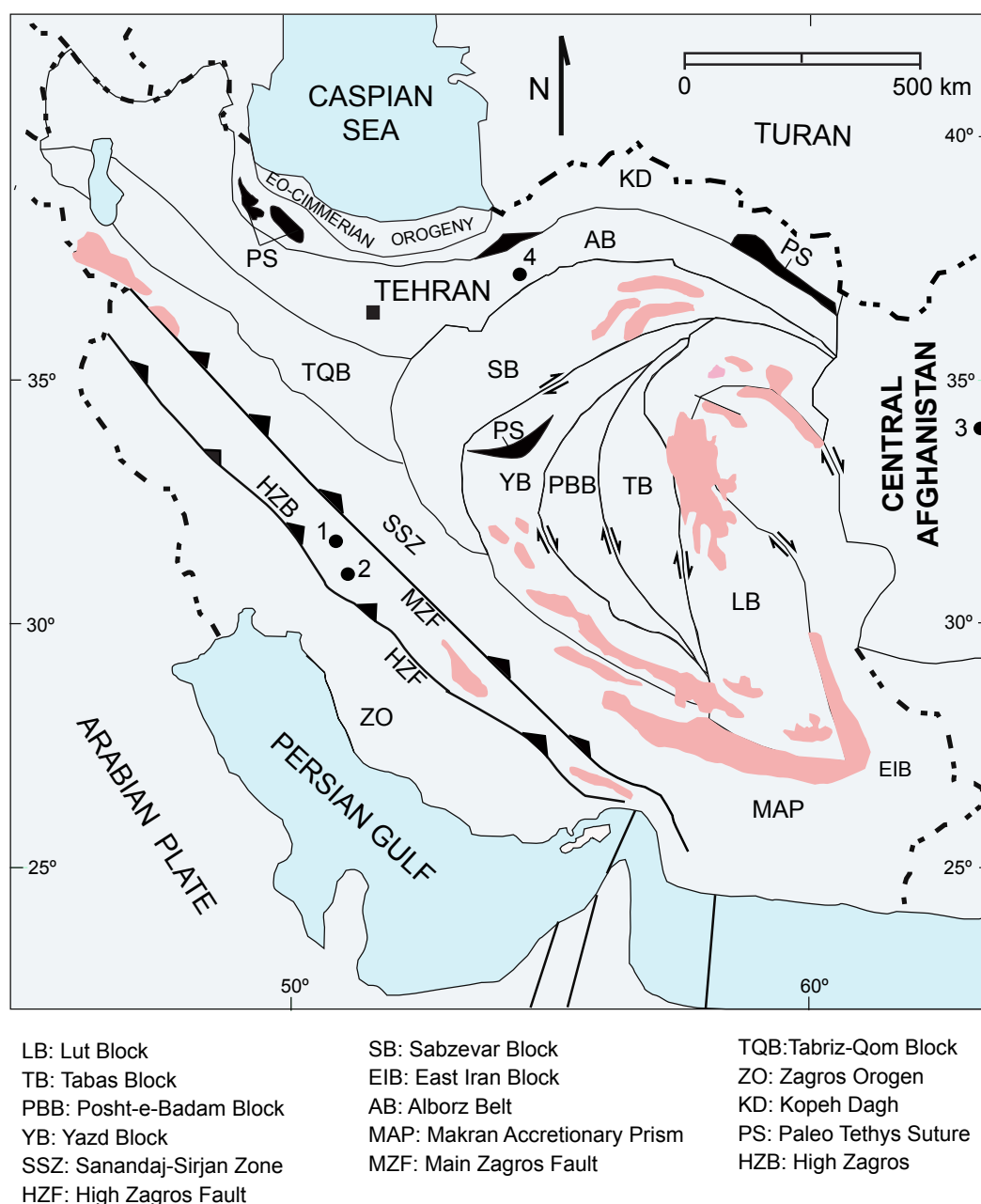


FIGURE 1. Generalized tectonic zonations of Iran (modified after Alavi, 1991; Angiolini *et al.*, 2007). Pink: Mesozoic ophiolites along Main Zagros Fault (MZF) and around central Iran. 1: Isfahan, 2: Shahreza, 3: Band-e Bayan, 4: Toyeh section.

minima SULEIMANOV, 1945, *Eotuberitina reitlingerae*, MIKLUKO-MAKLAY, 1958 and *Earlandia vulgaris* (RAUSER-CERNOUSSOVA and REITLINGER in RAUSER-CERNOUSSOVA and FURSENKO, 1937) (Bozorgnia, 1973).

A recent investigation on the Tournaisian in the Kahanag section, central Alborz, revealed that the biozones MFZ1 to MFZ5 do not contain rich species assemblages in this region (Falahatgar *et al.*, 2015). In Alborz, The upper Tournaisian foraminiferal assemblages are more diverse than the lower Tournaisian ones. The MFZ6 to MFZ8 biozones (upper

Tournaisian) include *Eotextularia diversa* (CHERNYSHEVA, 1948) (Bozorgnia, 1973) along with *Darjella monilis* MALAKHOVA, 1963 and *Eoforschia moelleri* (MALAKHOVA, 1953). Another upper Tournaisian foraminifer reported is *Eoparastaffellina rotunda* VDOVENKO, 1971 (Falahatgar *et al.*, 2015). The main representative species of the Tournaisian of western Europe, North America and the Russian Platform such as *Chernyshinella glomiformis* (LIPINA, 1948), *Chernyshinella multicamerata* (LIPINA, 1955), and *Brunsia* sp. MIKHAYLOV, 1935 (Kalvoda, 2002, 2003) are not found in this area. On the other hand,

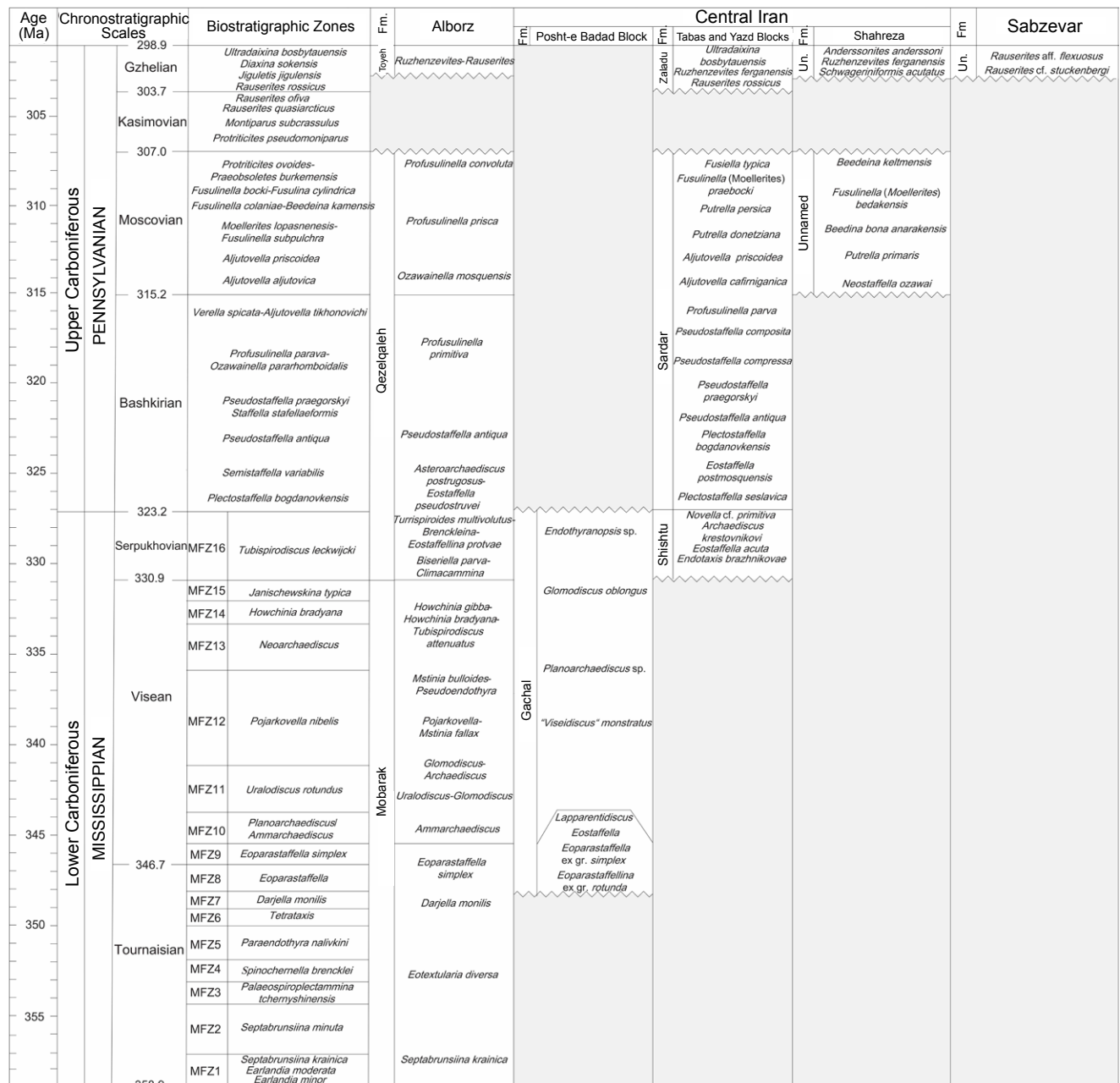


FIGURE 2. Correlation chart of the Carboniferous sections in Iran and their foraminiferal content. Alborz: Bozorgnia (1973); Lys *et al.* (1978); Vachard (1996); Gaetani *et al.* (2009); Zandkarimi *et al.* (2014, 2017); Falahatgar *et al.* (2015). Central Iran: (Tabas and Yazd blocks) Leven and Gorgij (2006a, b); Leven *et al.* (2011a, b); (Posht-e Badam Block) Vachard and Arefifard (2015). Shahreza: Leven and Gorgij (2008); Leven and Gorgij (2011c). Sabzevar: Gorgij and Leven (2013). Biostratigraphy adopted from Poty *et al.* (2006) and Davydov *et al.* (2014). Fm.: Formation, Un.: Unnamed.

the Alborz lower Tournaisian foraminifers have close similarity with their counterparts of South China, Turkey and Kazakhstan, which would indicate a peri-Gondwanan affinity (Arefifard, 1997; Falahatgar *et al.*, 2015).

Upper Tournaisian-upper Visean foraminiferal faunas have been reported in several studies (Bozorgnia, 1973; Vachard, 1996; Ueno *et al.*, 1997; Brenckle *et al.*, 2009; Zandkarimi *et al.*, 2014). Eight biozones were

recognized, that are correlated with the biozones MFZ8-MFZ14 of Poty *et al.* (2006), which include the following species: *Eoparastaffellina* ex gr. *rotunda* VDOVENKO, 1971-*'florigena'* DEVUYST, 2006-Lysella cf. *gadukensis* BOZORGNI, 1973; *Eoparastaffella simplex* VDOVENKO, 1971-Lapparentidiscus bakanensis VACHARD, 1980; Amarchaediscus CONIL and PIRLET, in PIRLET and CONIL, 1974; Uralodiscus MALAKHOVA, 1973-Glomodiscus MALAKHOVA, 1973; Glomodiscus MALAKHOVA,

1973-*Archaeodiscus* BRADY, 1873; *Pojarkovella* SIMONOVA and ZUB, 1975 emend. CÓZAR 2002 -*Mstinia fallax* (RAUSER- CHERNOUSOVA and REITLINGER in RAUSER-CHERNOUSOVA *et al.*, 1936); *Mstinia bulloides* (MIKHAILOV, 1939) emend. DAIN, 1953-*Pseudoendothyra* MIKHAYLOV, 1939 and *Howchinia gibba* (HOWCHIN, 1888)-*Howchinia bradyana* (HOWCHIN, 1888)-*Tubispirodiscus attenuatus* (MARFENKOVA, 1978) (Zandkarimi *et al.*, 2014). The foraminiferal assemblages from biozones MFZ8 to MFZ11 reported from the Mobarak Formation in the Valiabad section, have been suggested to have a peri-Gondwanan affinity, whereas those of MZF12 to MZF14 are similar to the assemblages from the northern margin of Paleo-Tethys (Zandkarimi *et al.*, 2014).

The Serpukhovian in central and eastern Alborz is represented by two foraminiferal biozones, *Asteroarchaediscus baschkiricus* (KRESTOVNIKOV and TEODOROVITCH, 1936)-*Globivalvulina* sp. SCHUBERT 1921 and *Eostaffella pseudostruvei* (RAUSER-CERNOUSOVA and BELJAEV in RAUSER-CHERNOUSOVA *et al.*, 1936) -*E. mirifica* BRAZHNKOVA in BRAZHNKOVA and ROSTOVTSOVA, 1967 (Bozorgnia, 1973; Vachard, 1996) which indicate North Paleo-Tethyan elements (Kalvoda, 2002). Recently, Zandkarimi *et al.* (2017) reported two Serpukhovian biozones in northern Iran, the lower Serpukhovian *Biseriella parva* CHERNYSHEVA, 1948-*Climacammina* BRADY, 1873, and the upper Serpukhovian *Turrispiroides multivolutus* (REITLINGER, 1949)-*Brenckleina* ZANINETTI and ALTINER, 1979-*Eostaffellina protvae* (RAUSER-CHERNOUSOVA, 1948). The Serpukhovian-Bashkirian in eastern Alborz comprises three foraminiferal biozones which are the *Asteroarchaediscus postrugosus* (REITLINGER, 1949)-*Eostaffella pseudostruvei* (RAUSER-CERNOUSOVA and BELJAEV, 1936), *Pseudostaffella antiqua* DUTKEVICH, 1934 and *Profusulinella primitiva* GROZDILOVA and LEBEDEV, 1954 (Lys *et al.*, 1978; Vachard, 1996). These biozones suggest southern Laurasian affinity (Kalvoda, 2002).

Gaetani *et al.* (2009) recognized the fusulinid species *Plectostaffella jakhensis* REITLINGER, 1971 indicative of early Bashkirian in the Dozdehband Formation in the Toyeh section from eastern Alborz. This fusulinid is also reported from Turkey, Russian Platform, Urals, Donets Basin and central Iran (Leven *et al.*, 2006).

Two Moscovian foraminiferal biozones were reported from eastern Alborz, the *Aljutovella tikhonovichi* RAUSER-CHERNOUSOVA in RAUSER-CHERNOUSOVA *et al.*, 1951 and *FUSULINELLA* ex gr. *bocki* MÖELLER, 1878 (Lys *et al.*, 1978; Vachard, 1996) indicative of the northern margin of Paleo-Tethys (Rui *et al.*, 1991, Kalvoda, 2002). Recently, Gaetani *et al.* (2009) reported fusulinids, e.g. *Ozawainella mosquensis* RAUSER-CHERNOUSOVA in

RAUSER-CHERNOUSOVA *et al.*, 1951, *Pseudostaffella* (P.) *paracompressa* SAFONOVA in RAUSER-CHERNOUSOVA *et al.*, 1951, *Taitzeoella* cf. *prolibrovichi* (RAUSER-CHERNOUSOVA, 1951), *Profusulinella prisca* (DEPRAT, 1912) and *P. convoluta* (LEE and CHEN in LEE *et al.*, 1930), from eastern Alborz and referred them to the early Moscovian. These fusulinid faunas are also found in Eurasia, North America, South China, and Turkey and have Paleo-Tethyan affinities (Zhang *et al.*, 2003; Groves *et al.*, 2007; Okuyucu, 2009; Kobayashi, 2011). There is no evidence of Kasimovian deposits in this area.

One fusulinid assemblage *Ruzhenzevites* DAVYDOV, 1986 -*Rauserites* ROSOVSKAYA, 1950, from the latest Ghzelian, has been reported in the Toyeh Formation (Gaetani *et al.*, 2009). The fusulinids of this age were widespread in the warm water Paleo-Tethyan realm from the Carnic Alps, in the West, to South China, in the East (Leven and Taheri, 2003; Leven *et al.*, 2006).

Central Iran

Carboniferous foraminiferal faunas of central Iran are reported and described from the Tabas, Posht-e Badam and Yazd blocks and from the Shareza area (Baghbani, 1993; Leven and Taheri, 2003; Leven *et al.*, 2006; Leven and Gorgij, 2006a, b; Leven and Gorgij, 2008; Leven and Gorgij, 2011a, b, c; Vachard and Arefifard, 2015) (Fig. 2).

Lower Carboniferous foraminiferal assemblages have been described from the Gachal Formation in the Posht-e Badam Block. The rich associations of the uppermost Tournaisian-lower Visean foraminiferal biozones contain *Eoparastaffellina* ex gr. *rotunda* VDOVENKO, 1971 (upper MFZ8), *Eoparastaffella* ex gr. *simplex* VDOVENKO, 1971 (lower MFZ8-9), and *Eostaffella* RAUSER-CHERNOUSOVA, 1948 along with *Lapparentidiscus* VACHARD, 1980 (upper MFZ9) (Vachard and Arefifard, 2015). They show a close resemblance with western Europe and southern Urals and have similarities with the coeval foraminiferal fauna from Alborz (Vachard and Arefifard, 2015).

The Visean-Serpukhovian foraminiferal fauna from the oolitic limestones at the topmost Gachal Formation, in the Padeh section, Posht-e Badam Block, have elements of northern Paleo-Tethyan affinity and contain “*Viseidiscus*” *monstratus* (GROZDILOVA and LEBEDEV, 1954), *Planoarchaediscus* sp. MIKLUKHO-MAKLAY in KIPARISOVA *et al.*, 1956, *Glomodiscus oblongus* (CONIL and LYS, 1964), *Earlandia* sp. PLUMMER, 1930, *Eogloboendothyra*? sp. VDOVENKO, 1972, *Pseudoplandoendothyra*? sp. BRAZHNKOVA and VDOVENKO in BRAZHNKOVA, 1982 and *Endothyranopsis* sp. CUMMINGS, 1955 (Leven and Gorgij, 2011a).

The foraminiferal fauna reported from the Zaladu section, Tabas Block, which is considered Serpukhovian in age, contains *Eostaffella acuta* GROZDILOVA and LEBEDEV, 1950, *Archaeodiscus krestovnikovi* RAUSER-CHERNOUSOVA, 1948, *A. aff. globosus* CONIL and LYS, 1964, *Biseriella minima* (REITLINGER, 1950), *Endotaxis brazhnikovae* BOGUSH and YUFEREV, 1966 and *Novella* cf. *primitiva* RAUSER-CHERNOUSOVA, 1951 (Leven *et al.*, 2006). It compares best with eastern European faunas (Rauser-Chernousova, 1948; Grozdilova and Lebedeva, 1950), Taurus faunas (Altiner and Özgül, 2001) and foraminifera from eastern Alborz (Lys *et al.*, 1978; Vachard, 1996).

Foraminiferal assemblages representative of the Bashkirian-Moscovian interval are reported both from the Zaladu section, in Tabas Block, and the Anarak section, in Yazd Block. These relatively abundant associations of Bashkirian foraminifers include *Plectostaffella seslavica* (Rumyantseva, 1970), *P. bogdanovkensis* REITLINGER, 1980, *Eostaffella postmosquensis* KIREEVA, 1951, *Semistaffella* sp. REITLINGER, 1971, *Pseudostaffella antiqua* DUTKEVICH, 1934, *P. praegorskyi* RAUSER-CHERNOUSOVA, 1938, *P. compressa* RAUSER-CHERNOUSOVA, 1938, *P. composita* GROZDILOVA and LEBEDEV, 1950, *P. paracompressa* SAFONOVA in RAUSER-CHERNOUSOVA *et al.*, 1951 and *Profusulinella parva* (Leven *et al.*, 2006).

A diversified association of Moscovian foraminifers in the Tabas and Yazd blocks contains *Aljutovella cafimiganica* BENSCH, 1969, *A. priscoidea* (RAUSER-CHERNOUSOVA, 1948), *Putrella* sp. RAUSER-CHERNOUSOVA in RAUSER-CHERNOUSOVA *et al.*, 1951, *P. donetziana* (LEE, 1936), *P. persica* LEVEN *et al.*, 2006, *Fusulinella* (*Moellerites*) *praebocki* RAUSER-CHERNOUSOVA in RAUSER-CHERNOUSOVA *et al.*, 1951 and *Fusiella typica* LEE and CHEN in LEE *et al.*, 1930 (Leven *et al.*, 2006; Leven and Gorgij, 2011b). The Bashkirian-Moscovian foraminiferal associations in the Tabas and Yazd blocks represent typical elements of the eastern European Platform (Leven *et al.*, 2006; Leven and Gorgij, 2011b).

There is no evidence of Kasimovian foraminiferal faunas in central Iran.

Baghbani (1993) reported on Moscovian foraminiferal associations from Tang-e Darchaleh section, near Shahreza town. They contain *Endothyra* spp. Phillips, 1846, *Pseudostaffella* sp. Thompson, 1942, *Ozawainella mosquensis* Rauser-Chernousova in Rauser-Chernousova *et al.*, 1951 and representatives of the Fusulininae subfamily. These foraminifers are assigned to the *Ozawainella mosquensis* Rauser-Chernousova in Rauser-Chernousova *et al.*, 1951 biozone with typical eastern European biogeographic affinities.

Moscovian fusulinids were also identified in the Asad-Abad section, NE of the Shahreza town and contain five typical assemblages of the northern Paleo-Tethyan domain (Middle Asia, Donbass, eastern European Platform), such as i) *Pseudostaffella gorskyi* (DUTKEVICH, 1934), *Neostaffella ozawai* (LEE and CHEN in LEE *et al.*, 1930), *Putrella* sp. RAUSER-CHERNOUSOVA in RAUSER-CHERNOUSOVA *et al.*, 1951 ii) *Neostaffella umbilicata* (PUTRJA and LEONTOVICH, 1948), *Putrella primaris* LEVEN, 2008 in LEVEN and GORGIJ, 2008 iii) *Beedeina* ex gr. *samarica* RAUSER-CHERNOUSOVA and BELYAEV in RAUSER-CHERNOUSOVA *et al.*, 1940, *B. bona anarakensis* LEVEN and DAVYDOV in LEVEN *et al.*, 2006, *Citronites* aff. *apokensis* (RAUSER-CHERNOUSOVA in RAUSER-CHERNOUSOVA *et al.*, 1951) iv) *Fusulinella* (*Moellerites*) *bedakensis* SOLOVIEVA, 1986, *F. (Fusulinella) pseudobocki* LEE and CHEN in LEE *et al.*, 1930, *F. (Fusulinella.) aff. fluxa* LEE and CHEN in LEE *et al.*, 1930, and v) *Beedeina keltmensis* (RAUSER-CHERNOUSOVA, 1953), *Kamaina* ex gr. *ozawai* (RAUSER-CHERNOUSOVA and BELJAEV in RAUSER-CHERNOUSOVA *et al.*, 1936) (Leven and Gorgij, 2008).

Data on the Gzhelian foraminiferal assemblages of central Iran were provided by Leven and Taheri (2003), Leven *et al.* (2006), Leven and Gorgij (2006a, b, 2011b). Their faunal lists contain mainly *Rauserites rossicus* (SCHELLWIEN, 1908), *Jigulites* cf. *formosus* ROSOVSKAYA, 1950, *Ruzhenzevites ferganensis* (DUTKEVICH, 1939), *Ultradaixina bosbytauensis* (BENSCH, 1962) (from Anarak section, Yazd Block), *Rauserites samaricus* (RAUSER-CHERNOUSOVA, 1949), *Rauserites elongatissimus* (ROSOVSKAYA, 1950) and *Ruzhenzevites ferganensis* (DUTKEVICH, 1939) (from Zaladu section, Tabas Block). These species were common along the northern margin of Paleo-Tethyan realm in Fergana (Bensch, 1972), Darvaz (Davydov, 1986), Carnic Alps (Forke, 1995, 2002, 2007), and Spain (Villa and Ueno, 2002). Typical northern peri-Tethyan elements have been reported from the Vazhnan Formation in the Asad-Abad section, North-East of the Shahreza town (Leven and Gorgij, 2011c). These faunas include *Schwageriniformis acutatus* LEVEN in LEVEN and GORGIJ, 2006a, *Ruzhenzevites ferganensis* (DUTKEVICH, 1939), *R. aff. curtus* LEVEN in LEVEN and TAHERI, 2003, *Rauserites baghbani* LEVEN and GORGIJ, 2011c, *R. karlensis* ROSOVSKAYA, 1950, *R. ishimbaji* ROSOVSKAYA, 1950, *Quasifusulina eleganta* SCHLYKOVA, 1948, *Anderssonites anderssoni* SCHELLWIEN, 1909 and *A. aff. zarjae* POTIEVSKAYA, 1964, *Schellwienia* ex gr. *stoecklini* LEVEN in LEVEN and GORGIJ, 2006b.

Sabzevar zone

In this zone there is no evidence of the Mississippian, only the upper part of the Pennsylvanian is represented (Fig. 2). Gorgij and Leven (2013) found poorly determined

fusulinid faunas, *Fusiella* (?) sp. LEE and CHEN in LEE *et al.*, 1930, *Schubertella* sp. STAFF and WEDEKIND, 1910, *Rauserites* cf. *stuckenbergi* RAUSER-CHERNOUSOVA, 1938, *R. ex gr. variabilis* ROSOVSKAYA, 1950, *R. aff. karlensis* ROSOVSKAYA, 1950, *R. aff. exilis* ROSOVSKAYA, 1950, *R. aff. flexuosus* ROSOVSKAYA, 1950, and *Rauserites?* sp. ROSOVSKAYA, 1950, which were referred to the Gzhelian and are probably of Russian Platform affinity.

DISCUSSION

The paleogeographic reconstruction of Iran for the Late Paleozoic has always been controversial. The absence of Variscan orogeny in Iran and the resemblance of most Paleozoic deposits to their coeval strata in the Arabian Plate led to the idea that Iran had a Gondwanan affinity during the Late Paleozoic. The Late Paleozoic was a period of major tectonic events. By the Early Permian, the supercontinent Pangea had coalesced, the Paleo-Tethys ocean was closed, and Cimmerian terranes including present-day Turkey, Iran, Afghanistan, South Pamir, Karakoram, Tibet, Qiantang, Burma, Thailand and Malaysia broke-off from the northern margin of Gondwana and drifted northward across the Paleo-Tethys as a result of the Neo-Tethys opening to collide finally with the Eurasian margin in the Late Triassic, giving rise to the Eo-Cimmerian Orogen (Sengör, 1984; Scotese and Langford, 1995; Besse *et al.*, 1998; Metcalfe, 1999; Angiolini *et al.*, 2003; Kent and Muttoni, 2003; Ruban *et al.*, 2007; Muttoni *et al.*, 2009; Berra and Angiolini, 2014).

The taxonomic composition of Carboniferous foraminifers in Iran has been studied since the 1960s by Iranian and European workers. But, there is no consensus on their paleobiogeography. The results of previous studies suggest that these foraminifera were related to either the southern margin of the Paleo-Tethys (Meissami *et al.*, 1977; Vachard, 1980, 1996; Stampfli, 2000; Torsvik and Cocks, 2004; Brenckle *et al.*, 2009; Zandkarimi *et al.*, 2014; Qiao *et al.*, 2016) or the northern margin (Kalvoda, 2002; Devuyst, 2006). According to the paleomagnetic data from the Alborz zone, Iran shows an Apparent Polar Wandering (APW), well-matched with that of West Gondwana (Besse *et al.*, 1998; Muttoni *et al.*, 2009). These data suggest a paleolatitude for Alborz of about 40–45° South in the Early Carboniferous. Considering these data, North Iran was positioned in the northern margin of Gondwana during this period (Angiolini *et al.*, 2007; Brenckle *et al.*, 2009; Bahrammanesh *et al.*, 2011; Falahatgar *et al.*, 2015; Qiao *et al.*, 2016).

Paleontological evidence stands in opposition to the presumed 40–45° South location of North Iran in the Early Carboniferous. The smaller foraminifers and

brachiopods reported from the Lower Carboniferous of Alborz are indicative of warm water (Brenckle *et al.*, 2009; Bahrammanesh *et al.*, 2011). Warm water faunas from Iran may be explained by a counterclockwise oceanic current that conducted equatorial warm Paleo-Tethyan waters to the peri-Gondwanan blocks, including Iran at the southern margin of the Paleo-Tethys (Kiessling *et al.*, 1999; Brenckle *et al.*, 2009; Bahrammanesh *et al.*, 2011). Additionally, during the Early Carboniferous there were no glacial events to hamper this warm surface current gyres and the dispersion of taxa from the tropics towards intermediate latitudes. Although the climate began to cool in the late Viséan because of the onset of the late Viséan glacial event (Melvin *et al.*, 2010), warm water and cosmopolitan faunas of this age in Alborz (Bozorgnia, 1973; Zandkarimi *et al.*, 2014) confirm the continuation of the warm surface-current gyres in the southern border of the Paleo-Tethys (Brenckle *et al.*, 2009).

Zandkarimi *et al.* (2014) and Falahatgar *et al.* (2015) speculated that Alborz was located in the southern margin of the Paleo-Tethys up to the early Viséan, based on the presence of foraminifers with typical elements of peri-Gondwanan affinity. They hypothesized that since the Paleo-Tethys was narrow in the early Viséan, the peri-Gondwanan terranes in the southern border of the Paleo-Tethys were easily connected with those of the northern margin. Moreover, these authors noted that the mid Viséan foraminiferal assemblages in Alborz were similar to those of the northern margin of Paleo-Tethys and concluded that Alborz rifted from the northern margin of Gondwana and migrated to the North in the early mid Viséan. They considered this as the first stage of the Cimmerian terranes assembly.

The upper Tournaisian-lower Viséan foraminifers of Posht-e Badam, central Iran, are similar to those of Alborz (Vachard and Arefifard, 2015). It has also been mentioned that the foraminiferal species identified in the Lower Carboniferous of the Posht-e Badam Block have common features with both the northern and southern margins of the Paleo-Tethys. Vachard and Arefifard (2015) suggested that since Alborz has been attributed to the peri-Gondwanan margin during the late Tournaisian-early Viséan by many authors, the Posht-e Badam Block was probably located in the southern margin of the Paleo-Tethys as well.

Bashkirian-Moscovian foraminiferal assemblages have been examined both in North and central Iran, but beyond these regions there are no reports in Iran, possibly due to the lack of deposition or erosion. In the Tang-e Darchaleh section, near the town of Shahreza, Moscovian foraminifers were reported and showed biogeographic affinity with the eastern European platform (Baghbani, 1993). The Bashkirian-Moscovian foraminiferal associations in

North and central Iran reveal great similarities. They also show strong relationship with coeval foraminifers from Turkey, central Asia, Donets, Russian Platform and the Urals located in the northern margin of the Paleo-Tethys during this period (Kalvoda, 2002; Leven *et al.*, 2006; Dzhenchuravea and Okuyucu, 2007).

Vachard (1980, 1996) compared the Carboniferous deposits in the Tabas region, Central Iran, with those of central Afghanistan, and the ones in Alborz strata with the Band-e Bayan sequences in northern Afghanistan. He concluded that there were no similarities between the Carboniferous basins in North and central Iran. Leven *et al.* (2006) objected to Vachard's correlations and suggested that there is no faunal evidence to support these comparisons. They argued that Bashkirian-Asselian foraminifers in Iran are not endemic and both central and North Iran belonged to the same basin in the Bashkirian-Moscovian time.

There is no evidence of Kasimovian foraminifers in Iran, may be as a result of a regional regression and subsequent subaerial erosion. The uppermost Gzhelian foraminiferal faunas in Alborz, central Iran and the Sabzevar zone contain typical elements of the northern margin of the Paleo-Tethys and have resemblance to those of the Carnic Alps, Donets Basin, Eastern European Platform, Darvaz and Fergana (Leven and Gorgij, 2006a,b; Gaetani *et al.*, 2009; Leven and Gorgij, 2011a,b,c; Gorgij and Leven, 2013).

Based on the available data on Lower Carboniferous foraminifera, it is plausible that Iran was located in the southern margin of the Paleo-Tethys and displayed a peri-Gondwanan faunal biogeographic affinity in the Early Carboniferous (Fig. 3). The presence of faunal elements of both northern and southern Paleo-Tethys supports this idea (Bagheri and Stampfli, 2008; Brenckle *et al.*, 2009; Bahramanesh *et al.*, 2011; Berra and Angiolini, 2014; Vachard and Arefifard, 2015). Furthermore, the concurrent occurrences of both faunas may be explained, either by the southerly circulation of the warm-water Paleo-Tethyan current along the northern margin of Gondwana (Brenckle *et al.*, 2009; Bahramanesh *et al.*, 2011) or by the narrowness of the Paleo-Tethys ocean allowing the connection of the peri-Gondwanan faunas with those of the southern margin of Laurasia (Zandkarimi *et al.*, 2014; Vachard and Arefifard, 2015; Falahatgar *et al.*, 2015). The paleogeographic position of Iran as part of Gondwana in the Early Carboniferous is also supported by the strong accordance of paleomagnetic poles of Iran and West Gondwana, during the Ordovician-Early Carboniferous (Muttoni *et al.*, 2009). In fact, based on paleomagnetic data, Iran has a similar drifting history as the Arabian Plate from Late Ordovician to Early Carboniferous (Muttoni

et al., 2009). The Ordovician-Carboniferous Gondwana apparent polar wander path shows that the Arabian Plate, as part of Africa, sustained an important plate motion, drifting from a high southern latitude in the Late Ordovician to a subequatorial latitude in the Early Devonian and then moved to intermediate southern latitudes in Late Devonian-Early Carboniferous times (McElhinny *et al.*, 2003).

The faunal assemblages of the Late Carboniferous in Iran are clearly different from those of the peri-Gondwanan realm. They differ both in taxonomic composition as in climatic affinity. The Bashkirian-Moscovian and upper Gzhelian fusulinids in Alborz, central Iran and the Sabzevar zone indicate warm water conditions and are typical of the northern margin of the Paleo-Tethys. This may be linked to the rifting of Iran from the northern margin of Gondwana in early Late Carboniferous and its migration northwards. The movement of Iran toward the North, to a low latitude position with a warm climate is suggested by the occurrence of the Upper Carboniferous coal-bearing sandstones of the Sardar Formation in central Iran (Stöcklin *et al.*, 1965). Coal is one of the most important paleoclimatic indicators of humid climate conditions. These sandstones are rich in quartz and poor in Al_2O_3 indicating humid to semi-humid climate. Moreover, the geochemical analyses of the Sardar Formation sandstones suggested a high degree of chemical weathering, indicative of warm and humid conditions during the deposition of these sandstones (Khanehbad *et al.*, 2012). Besides, the paleogeographic reconstruction of Iran based on paleomagnetic data suggests a 30°S position for Iran (Muttoni *et al.*, 2009). The whole dataset suggests a warm and humid climate during the Late Carboniferous in central Iran.

Neotethyan rifting started in Carboniferous times along the eastern Gondwana margin from India (Garzanti and Sciunnach, 1997) to Oman (Al-Belushi *et al.*, 1996). The continental breakup and the onset of the oceanic lithosphere formation followed from the Himalayas towards northern Oman in mid-Early Permian time (Garzanti, 1999; Angiolini *et al.*, 2003).

Indications of the early phases of the Neo-Tethys opening during the Carboniferous and rifting of the Cimmerian terranes from northern Gondwana are recorded in the Misho magmatic complex and Ghushchi complex in northwestern Iran (Saccani *et al.*, 2013; Dilek *et al.*, 2014; Moghadam *et al.*, 2014). Using SIMS U-Pb zircon ages, the Misho gabbros are dated at 356.7 ± 3.4 Ma and the gabbro-norites and granites of the Ghushchi complex yield an age of ~ 320 Ma. These igneous rocks may provide good evidence of the timing of the Neo-Tethys opening in Iran and cast doubts about the previous ideas of the rifting of Neo-Tethys in Iran in the Early Permian (Angiolini *et al.*, 2007; Gaetani *et al.*, 2009; Muttoni *et al.*, 2009).

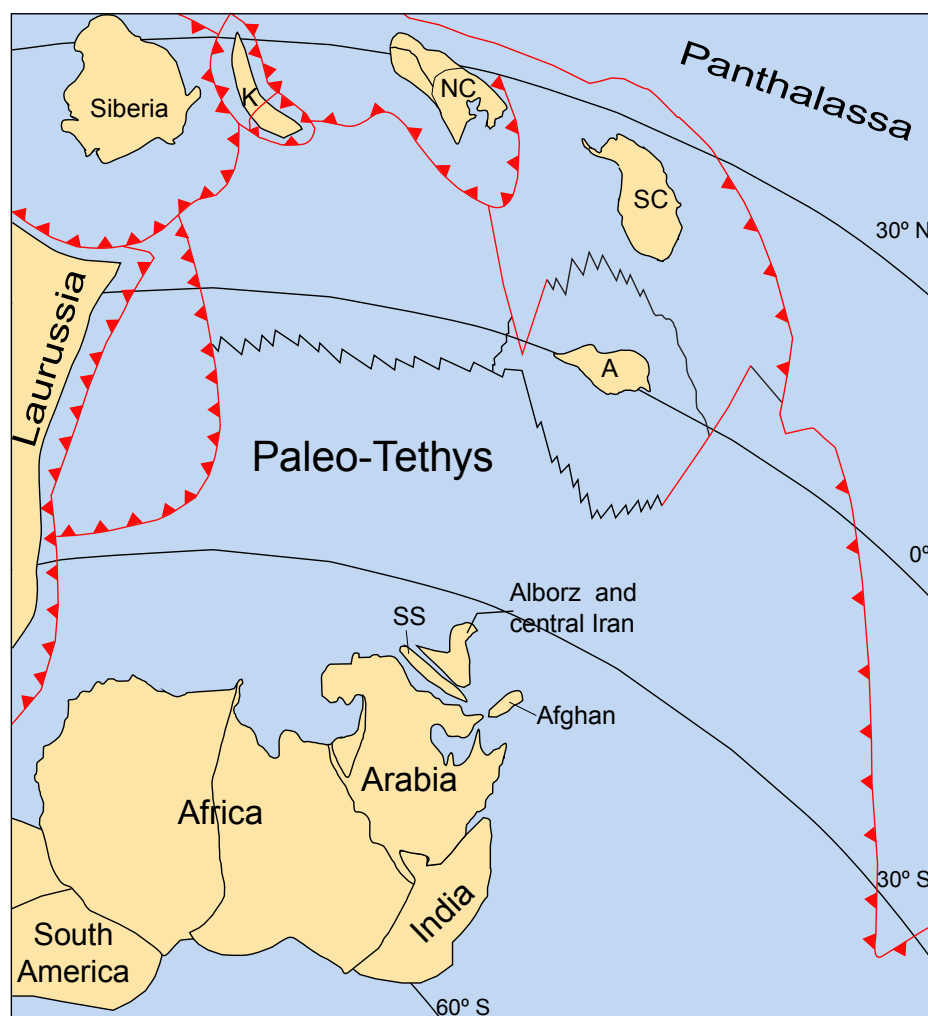


FIGURE 3. Early Carboniferous paleogeographic map simplified and modified from Domeier and Torsvik (2014) showing the location of Alborz and central Iran in the southern margin of the Paleotethys in the Early Carboniferous. A: Annamia, K: Kazakhstan, NC: North China, SC: South China, SS: Sanandaj-Sirjan.

Proofs about Carboniferous magmatic activities and extensional deformation, related to the Variscan orogeny are increasing in Iran. For instance, an angular unconformity below the Upper Carboniferous(?)–Lower Permian Faraghan Formation in the High Zagros Belt suggests a connection with the Variscan orogeny (Tavakoli-Shirazi *et al.*, 2013). However, the North to North-East trending faults and tilted blocks related to this Variscan unconformity show no signal of compressional deformation. The Ghushchi complex and Khalifan A-type granites in northwestern Iran are thought to be in conjunction with crustal movements in an extensional tectonic setting (Moghadam *et al.*, 2014). Zanchi *et al.* (2015), according to the radiometric ages of the trondhjemite dikes and stocks that intruded the accretionary wedge of the Anarak metamorphic complex in central Iran, it was proposed that the subduction of the Paleotethys happened during the Late Carboniferous. These

authors suggested that the Anarak metamorphic complex developed along the southern Eurasian margin and was part of an allochthonous crustal fragment belonging to the Variscan belt before the Cimmerian collision of Iran.

Therefore, the Neo-Tethys opening and rifting of Iran from the northern margin of Gondwana has probably occurred sometime between the latest Visean to early Late Carboniferous (Bashkirian) (Fig. 4). Evidence for this conclusion are: i) the northern Paleotethyan affinity of the foraminiferal associations in the late Visean-late Sepukhovichian in Alborz, ii) the unique similarity between the Bashkirian-Kasimovian and late Gzhelian fusulinid assemblages of Iran to the northern margin of the Paleotethys and iii) the Carboniferous magmatic activities in northwestern Iran and normal faulting and tilted blocks in the High Zagros Belt which, taken together, support extensional deformation related to the Variscan orogeny.

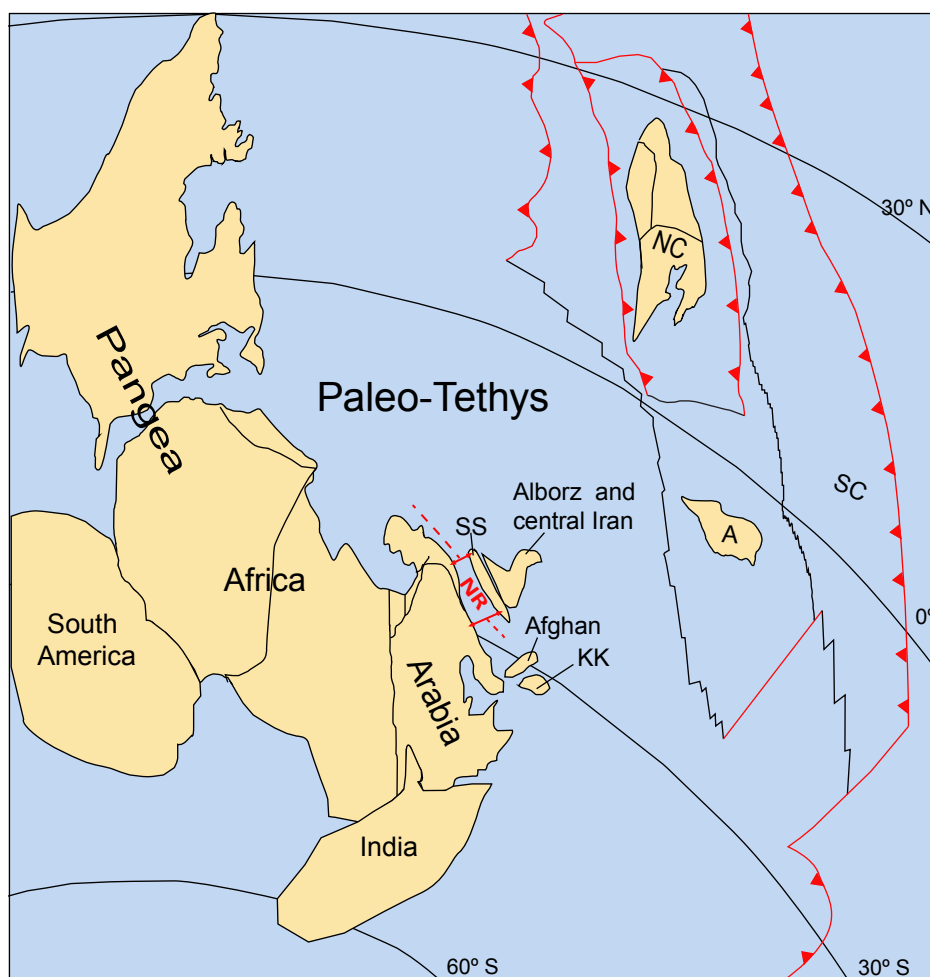


FIGURE 4. Late Carboniferous paleogeographic map simplified and modified from Domeier and Torsvik (2014) showing the rifting of Alborz and central Iran from the northern margin of the Gondwana in the Late Carboniferous. KK: Karakoram, NR: Neo-Tethys Ridge. For the other abbreviations see caption of Figure 3.

CONCLUSIONS

i) In the Early Carboniferous, foraminiferal associations in North and central Iran had a cosmopolitan character with elements from both the southern and northern margins of Paleo-Tethys. These faunal assemblages confirm the paleoposition of Iran in intermediate southern latitudes (ca. 30°S) and still forming part of Gondwana. This foraminiferal-based paleogeographic reconstruction of Iran is consistent with the results of paleomagnetic data by Muttoni *et al.* (2009).

ii) In the Late Carboniferous, data from both smaller foraminifer and fusulinid assemblages in North and central Iran reveal the similarity of these faunas with their northern Paleo-Tethys counterparts. This can be inferred as a sign of the commencement of the separation of Iran from the northern margin of Gondwana and its movement towards the North.

iii) The movement of Iran towards the North and its low latitude position in the Gzhelian also is inferred from the occurrences of the coal-bearing sandstones of the Upper Carboniferous Sardar Formation.

iv) The Neo-Tethys opening in Iran occurred during the Late Carboniferous, based on the foraminiferal associations and magmatic activities in North-West Iran. This conclusion contrast with previous ideas on the onset of Neo-Tethys opening between northern Gondwana and the Cimmerian terranes during the Permian/ and or Triassic.

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