Coeval calc-alkaline and alkaline Cadomian magmatism in the Bafq, central Iran: insights into their petrogenesis

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Abstract

The Chah-Gaz and Mishdovan areas in the Bafq magmatic complex, central Iran, contain thick series of terrigenous sediments (the Rizu-Dezu complex), and arc-related calc-alkaline and alkaline igneous rocks. Geochemical analyses of igneous rocks from both areas indicate two distinct rock clans: (1) high-K, calc-alkaline-shoshonitic rocks with strong depletions in Nb, P, and Ti, and (2) an alkaline quartz gabbro-diorite, with trace element patterns resembling oceanic island basalts (OIB). New geochronological data reveal that magmatic rocks of both clans crystallized almost simultaneously, with zircon U–Pb ages of 534 Ma and 537 Ma, respectively. The whole-rock Nd–Sr isotopic data (($^{87}Sr/^{86}Sr)_{(I)}$ = 0.7052 to 0.7064 and εNd(t) = +1.3 to +2.7) of alkaline quartz gabbro-diorite indicate an enriched OIB-like mantle source, while the high-K, calc-alkaline-shoshonitic rocks have εNd(t) = −5.5 to −7.6, clearly reflecting significant contributions from pre-existing Proterozoic basement. Apatite in both the Chah-Gaz and Mishdovan magmatic rocks is of magmatic origin, with light rare earth element (LREE) enrichment patterns. The low Sr/Y and Eu/Eu^* values in apatite demonstrate the non-adakitic character of the investigated rocks, while the moderately negative Eu anomaly and inverse correlation between δCe and δEu in the analyzed apatites may reflect reduced parental magmas. The geochemical and isotopic results presented here indicate that slab rollback and opening of an extensional basin could have initiated concurrent Cadomian arc-related calc-alkaline and rift-associated alkaline magmatism in the Chah-Gaz and Mishdovan areas.

Key words: Chah-Gaz and Mishdovan; Bafq province; Cadomian bimodal magmatism; Zircon U–Pb geochronology; extensional basin.

1. Introduction

The Alpine–Himalayan orogenic belt contains Peri-Gondwanan domains that formed by Ediacaran–Early Cambrian (Cadomian) arc-type magmatism at ~620 Ma to ~500 Ma. Several studies have proposed that Cadomian arc-type magmatic rocks formed due to Proto-Tethys Ocean subduction beneath the northern margin of Gondwana (Linnemann et al., 2008; Abbo et al., 2015; Moghadam et al., 2015; Moghadam et al., 2017a). These units are distributed in Iberia, through central and southeast Europe into the Middle East (e.g., Turkey and Iran; Ustaomer et al., 2009; Moghadam et al., 2015; Avigad et al., 2016) and pass into the Qingtang terrane of Tibet (Wang et al. 2016). Back-arc basin activity initiated in the Early

Paleozoic at ~560–530 Ma and was followed by coeval subduction-related and intraplate-type magmatism (Sanchez-Garcia et al., 2008; Linnemann et al., 2008; Abbo et al., 2015).

The geology of the Middle East contains an excellent record of Phanerozoic crustal growth processes, and consists of a complex mosaic of continental blocks that formed between Gondwana and Eurasia to the south and north, respectively (Ruban et al., 2007). These blocks share a common tectono-magmatic history, with several pulses of magmatism and both tectonic extension and shortening having occurred throughout the Phanerozoic (Linnemann et al., 2008; Linnemann et al., 2014; Topuz et al., 2013; Moghadam et al., 2015). These rocks and events are related to processes associated with opening of the Paleotethys and Neotethys oceans. Cadomian rocks in the Middle East region that preserve this arc/back-arc activity igneous association occur in the Tibetan Plateau, Iran, Turkey, and the Caucasus, and formed during Gondwana supercontinent amalgamation (Ruban et al., 2007). As such, this region is an ideal natural laboratory for investigating the ages and timescales, paleo-positions, and tectonic mechanisms that drive the formation and evolution of coeval subduction-related and intra-plate type magmatic rocks and related mineralization in a Phanerozoic supercontinent.

In Iran, the Cadomian crystalline crust is exposed in northwestern (Salmas, Khoy, Takab and Zanjan), northeastern (Taknar and Torud), central (Bafq and Golpayegan), south-eastern (Zarand), and southern (as exotic blocks within salt domes of south Zagros Fold-Thrust Belt) terranes (Moghadam et al., 2017) (Fig. 1).

The Cadomian crystalline crusts of Iran became separated from northern Gondwana during the Permian and collided with Eurasia during the Late Triassic (e.g., Moghadam et al., 2015). Thus, they preserve evidence of Gondwanan intra-continental magmatism, deformation, metamorphism, and sedimentation from at least the Late Neoproterozoic (Ediacaran) until the Permian (Moghadam et al., 2017; Honarmand et al., 2018). Nonetheless, magmatism along this Iranian crystalline crusts was diachronous, such that efforts to reconstruct its geological history in Iran have been complicated by Late Paleozoic rifting from Gondwana.

The Bafq province is located in the central parts the Kerman–Kashmar Tectonic Zone (Ramezani and Tucker, 2003), which is an arcuate and structurally complex fault-bounded belt in central Iran, stretching nearly 600 km in length. This tectonic zone exposes deeper sections of the central Iran basement, in which Late Neoproterozoic and Lower Paleozoic rocks are abundant. This zone is also associated with coeval calc-alkaline and alkaline Cadomian igneous host rocks, and iron oxide-apatite (IOA) mineralization with local REE enrichment, Fe–Mn exhalative deposits, and Zn–Pb–mineralized sedimentary sequences (e.g., Ramezani and Tucker, 2003). Some workers advocate continental rifting as the cause of high-tonnage IOA mineralization (e.g., Moore and Modaberi, 2003), whereas Ramezani and Tucker (2003) suggested that the evolution of the Bafq province was linked to arc magmatism alongside the margin of the Proto-Tethys Ocean. Previous studies have investigated these giant orebodies to elucidate their geological setting, geochemical evolution, and metallogenic features (Heidarian et al., 2016), but no study has focused on the alkaline suites of the region. In addition, apatite minerals in the host igneous rocks have been evaluated to investigate the genesis and mineralization potential of the Chah-Gaz and Mishdovan igneous host rocks in the north and central parts of Bafq province, respectively.

Here, we present new whole-rock geochemical and Sr–Nd isotope data, and zircon U–Pb ages for magmatic rocks from the Chah-Gaz and Mishdovan intrusions, and integrate them with published results from previous studies to explain the geodynamic framework in which these rocks formed. The main aims of this study are to determine the nature of the magma sources and elucidate the petrogenetic history of these magmatic intrusions, and develop a tectonomagmatic model for the origin and evolution of the Chah-Gaz and Mishdovan magmatic rocks. Moreover, the history of magmatic rocks in the area is investigated using apatite chemistry, thus demonstrating how this novel proxy can be applied to provide insight into the geological history of igneous intrusions worldwide.

2. Geological review

Cadomian magmatic rocks in Iran formed due to southward-dipping subduction of Proto-Tethys oceanic lithosphere beneath the Gondwanan continental margin (Moghadam et al., 2017), which formed widespread extensional basins within Iran. In these extensional basins, the Paleo-Tethys Ocean opened due to rifting and drifting away of fragments of Cadomia and Avalonia – together representing the Hun supercontinent from the northern margin of Gondwana during the Cambrian and Ordovician (Buchs et al., 2013).

Most such magmatic rocks in Iran have destructive plate margin characteristics and within-plate rocks are rare (Balaghi et al., 2014; Rossetti et al., 2015). The subduction-related magmas are thought to have generated by partial melting of Paleoproterozoic or Archean continental crust, or by mixing of melts derived from the sub-continental lithospheric mantle and pre-existing continental crust (Abbo et al., 2015; Moghadam et al., 2015, 2017a). Alkaline, felsic and mafic igneous rocks of Cadomian age with within plate-like geochemical characteristics occur in central Iran (Ramezani and Tucker, 2003), as well as in exotic blocks in salt domes from southern Iran (Asadi et al., 2020). These felsic magmatic rocks have different local names: in central Iran, these are termed the Zarigan-Narigan units and in northwestern Iran, they are known as the Qare-Dash rhyolites and in southern Iran, they are called the Hormoz rhyolites (Asadi et al., 2020). A range of tectonic settings have been invoked for generation of Cadomian within plate-like rocks, whereby Zarigan-Narigan alkaline magmatic rocks in central Iran, which show zircon U–Pb ages of 526 ± 3 Ma (Moghadam et al., 2015, 2017a), likely formed in supra-subduction zone arc systems, and

Hormoz rhyolites likely formed via submarine volcanism in an extensional back-arc setting (Faramarzi et al., 2015).

Central Iran is comprised of three main crustal blocks (the Yazd, Tabas and the Lut) that are divided by a series of regional-scale faults (e.g., Ramezani and Tucker, 2003). The Tabas and Yazd blocks are separated by the Kashmar-Kerman volcano-plutonic belt, which contains a variety of supra-crustal rocks (Fig. 1). Iron oxide mineralization is notably abundant in the Kashmar-Kerman volcano-plutonic belt, especially within the Bafq province (Jami et al., 2007), and different ore bodies are related in terms of ore type, paragenesis, and hydrothermal alteration. The Bafq province covers an area of 75 km × 30 km, and it is subdivided into three main magmatic complexes: northern (Chadormalu, Chah-Gaz, Se-Chahun), middle (Mishdovan), and southern (Esfordi and Choghart).

The oldest documented and isotopically dated rocks in the Bafq region of central Iran belong to the Tashk/Morad Formation. The depositional age of the formation is constrained between 627 Ma, the U–Pb age of the youngest concordant (detrital?) zircon found in a tuffaceous rock, and 533 Ma, which is the zircon age of the oldest known magmatic body (Ariz granodiorite) that intrudes into the formation. Accordingly, an overall Late Neoproterozoic to Early Cambrian age is assigned to the Tashk Formation. Considering its large thickness, at least a portion of the Formation was likely deposited during the latest Neoproterozoic. These units are overlain by the Boneh-Shurow and Chapedony Complexes (Haghipour and Pelissier, 1977).These complexes include gneiss, anatectic granite, migmatite and amphibolite, quartz-feldspathic gneiss, greenish-gray mica-schist, and dark-colored amphibolite, with subordinate dolomitic marble and mafic–intermediate magmatic intrusions. The granitic protolith(s) of the Boneh-Shurow gneiss crystallized at 544 ± 7 Ma (U–Pb zircon: Ramezani and Tuker, 2003) and are overlain by the Early Cambrian volcanosedimentary unit (VSU) of the Rizu and Dezu Formation (Ramezani and Tucker, 2003) (Fig. 1B).

The Early Cambrian VSU has been generally regarded as the Cadomian unit in the Bafq region (Haghipour and Pelissier, 1977), whereas its widespread equivalents throughout central Iran are referred to by the general term Rizu-Desu Series (see for example, Berberian and King, 1981). A U–Pb zircon age of 528.2 ± 0.8 Ma for the basal rhyodacite flow in the Douzakh-Darreh Mountain clearly indicates an Early Cambrian age for the VSU and its equivalents in central Iran. Lithologically similar basal flows have been reported from other successions of the Rizu-Desu Series (see for example, the Zebar-Kuh Range: Sahandi and others, 1984) and are likely to have a similar age.

It has been established that the last stages of the Neoproterozoic Pan-African orogeny in the Arabian Shield (approximately 686–517 Ma) was associated with emplacement of alkali-(A-type) granites and post-orogenic volcanic rocks of alkaline affinity (Brown and Jackson, 1979; Jackson and others, 1984). The Pan-African orogeny was in turn succeeded by a system of post-collisional, transcurrent faults and associated rift basins, known as the Najd system (Greenwood and others, 1976; Brown and Jackson, 1979; Jackson et al., 1984). Accordingly, the vast carbonate-evaporate deposits of the central Iran (Rizu-Desu Series), Persian Gulf and Zagros Mountains (Hormuz Formation), Oman (Ara Formation), Pakistan (Salt Range), and their correlative rocks are thought to have been deposited in the rift basins of the Najd system, with contemporaneous alkaline granites and volcanic rocks being interpreted as the products of post-orogenic, extensional magmatism (Berberian and King, 1981; Husseini, 1989).

The early Cambrian VSU (Rizu-Desu Series) of central Iran (Ramezani, 1997) is related to a major Late Precambrian rifting event (Greenwood et al., 1976; Brown and Jackson, 1979; Jackson et al,, 1984) and is characterized by carbonate, sandstone, shale, and volcanic rocks similar to the Najd system. It overlies sedimentary rocks of the Tashk Formation and is overlain by an Upper Cambrian intercalated sequence of upper amphibolite-facies mica-schists and marbles of the Sarkuh Complex (Hushmandzadeh, 1996). Hydrothermally altered Ediacaran to Lower Cambrian VSU are the major host rocks for regional IOA deposits and U–Th mineralization in the Kashmar–Kerman volcano-plutonic belt. The Chah-Gaz and Mishdovan magmatic rocks and the associated IOA mineralization in central Iran cover ~50 km^2, and most deposits are characterized by massive to variably brecciated IOA ores (Bonyadi et al., 2011).

Mineralization was either simultaneous with the Zarigan and Narigan granite(s) and the volcanic rocks of the early Cambrian VSU, or occurred shortly afterwards. Ramezani and Tucker (2003) reported ages of 528.2 ± 0.8 Ma and 527 ± 1 Ma for the Cambrian rhyodacite and dacite porphyry in the early Cambrian VSU, respectively, which are similar to the U–Th–Pb ages of 515 to 529 Ma determined from monazite preserved within apatite crystals in the Choghart ore deposit (Torab and Lehmann, 2007). The Zarigan granite has U–Pb ages between 529 ± 16 Ma and 525 ± 7 Ma (Ramezani and Tucker, 2003), similar to those for the rhyodacite and dacite porphyry of the early Cambrian VSU and related apatite-bearing ore bodies. Stosch et al. (2011) reported $^{206}Pb/^{238}U$ ages of 539 ± 6 Ma and 527 ± 8 Ma for apatite from the Lakkeh Siah, Esfordi, Mishdovan, and Zarigan bodies, whereas Bonyadi et al. (2011) report $^{206}Pb/^{238}U$ ages of 510 ± 8 Ma for apatite from the Se-Chahun magnetite-apatite orebody. The association of IOA deposits and apatite-rich rocks with the early Cambrian VSU suggest that the mineralization and Lower Cambrian magmatism were concurrent (Daliran, 2010).

3. Field observations and petrography

Ninety hand specimens were collected from the Chah-Gaz and Mishdovan regions (Fig. 2), representing the igneous host rocks.

3.1. The Chah-Gaz magmatic complex

The Chah-Gaz magmatic complex occupies an area of ~15 km^2, within the northern part of Bafq province, in the western parts Yazd block. It petrographically consists of rhyolite/rhyodacite, granite and alkaline quartz gabbro-diorite, which occur as elongated bodies bounded by NW–SE faults (Fig. 2B). The contact between granite and Cadomian deformed sediments is faulted in the Chah Gaz region (Figs. 2 and 3A).

The granite has a granular texture and contains euhedral to subhedral quartz (38–40 vol. %), K-feldspar (20–25 vol. %), plagioclase (30–35 vol. %), amphibole and biotite (3–8 vol. %). K-feldspar (0.5–2 mm) is subhedral to anhedral in shape, and often perthitic. Plagioclase (0.5–3 mm) is typically anhedral and occurs as interstitial grains between K-feldspar. It is often partially replaced by sericite via sericitization. Amphibole and biotite are occasionally replaced by secondary minerals, including chlorite and calcite (Fig. 3B). Accessory minerals include magnetite, ilmenite, zircon and apatite.

Dacite in the Chah-Gaz area shows a faulted contact with Cadomian deformed sediments and a normal contact with granitoid, and is overlain by Cambrian dolomite, limestone and shale (Fig. 3C). It contains resorbed quartz (~47 vol. %) (Fig. 3D), sanidine and plagioclase phenocrysts. The groundmass is microcrystalline to cryptocrystalline and consists of quartz and plagioclase–K-feldspar intergrowths. Accessory minerals include apatite, biotite and iron oxide, while common secondary minerals include calcite, sericite, titanite, hematite and chlorite. Plagioclase phenocrysts are altered to epidote and calcite, and K-feldspar is often altered to sericite.

Alkaline quartz gabbro-diorite/diorite bodies in the Chah-Gaz area have granular to porphyritic textures, are generally medium-grained (Fig. 3E), and contain plagioclase (60 vol.

%), brown amphibole (20–30 vol. %), clinopyroxene (5–10 vol. %) and quartz (5–8 vol. %) as the main primary constituents (Fig. 3F), although orthopyroxene and biotite occur in some samples. Opaque minerals and apatite are present as accessory minerals, whereas, epidote and chlorite are secondary minerals. Clinopyroxene is often altered to amphibole, and plagioclase is often altered to albite.

3.2. The Mishdovan magmatic complex

The Mishdovan magmatic complex has an exposed area of ~8 km^2 within the central part of the Bafq province. It is associated with sequences of Early Cambrian altered rhyolitic tuff, sandstone, dolomitic limestone and shale of the Rizu Formation and Cretaceous clastic rocks, marl and limestone. Magmatic rocks dominated by granodiorite, dacite, rhyodacite, rhyolite and basalt also occur in the region (Fig. 2). Granodiorites occur as hypersolvus porphyritic rocks and contain quartz (37–42 vol. %), plagioclase (37–48 vol. %), and K-feldspar (5–12 vol. %). Accessory minerals include apatite, titanite and iron oxide, and secondary minerals include calcite, sericite, hematite and chlorite. These intrusions contain interstitial grains, blebs and veinlets of hematite that may locally reach economic proportions.

Dacitic/rhyodacitic lavas in the Mishdovan area have aphyric to porphyritic textures. The rocks contain quartz (17–25 vol. %), sanidine (3–15 vol. %), and plagioclase (10–15 vol. %) phenocrysts in a microcrystalline to cryptocrystalline groundmass of quartz, with intergrowths of sodic plagioclase and K-feldspar. The main phenocryst mineral is quartz, which has resorbed textures. Plagioclase is commonly altered to epidote and calcite, and K-feldspars are altered to sericite. Apatite, biotite and iron oxides are accessory minerals, while calcite, sericite, titanite, and hematite are common secondary minerals. Tuffs mostly vary from lithic to crystal tuffs and are felsic to mafic in composition (Supplementary Table 2). Rhyolitic tuffs consist mainly of welded shards of feldspar and quartz. The crystal fragments in crystal tuffs include K-feldspar (~19–25 vol. %), quartz (61–64 vol. %) and plagioclase (<2 vol. %) in a cryptocrystalline-felsite groundmass. Coarse-grained quartz crystals show a resorbed texture. Plagioclase is commonly retrogressed to epidote and calcite and K-feldspar is partially replaced by sericite. Accessory minerals include apatite and iron oxide, and secondary minerals include calcite, sericite and chlorite.

4. Results

4.1 Geochronology

U–Pb ages were determined via LA-ICP-MS for zircon derived from a granite sample and a quartz gabbro-diorite sample from the Chah-Gaz region.

Quartz gabbro-diorite

Ten zircon grains from quartz gabbro-diorite Gb-Ch-2 were analyzed for U–Pb isotopes (Supplementary Table S1). Most grains are euhedral and have oscillatory zoning, and their U (132–754 ppm) and Th (77–680 ppm) contents produce Th/U ratios of 0.4–1.0, which are typical of magmatic zircon (Belousova et al., 2002). Zircon from Gb-Ch-2 produced a concordia age of 537.1 Ma (MSWD = 0.67) (Fig. 4A), which we interpret as the age of crystallization for the quartz gabbro-diorite.

Granite

Zircons from granite Gr-Ch-2 (Supplementary Table S1) have oscillatory zonation and subhedral to euhedral shapes. Their U (207–451 ppm) and Th (82–319 ppm) contents produce a Th/U ratio of 0.4–0.9, which lies within range of zircons from intermediate igneous rocks (Belousova et al., 2002). Fifteen spot analyses of various grains yielded a mean age of

534.1 ± 5.5 Ma (MSWD = 0.67) (Fig. 4B), which we interpret as the age of crystallization for the granite.

4.2 Major and trace element of magmatic rocks

Geochemical data obtained from igneous rocks from the Chah-Gaz and Mishdovan regions are presented in Supplementary Table S2, and the following section details the main results from the host rocks and the IOA mineralization in both areas.

Chah-Gaz magmatic complex

The Chah-Gaz Cadomian magmatic rocks can be divided into two groups based on their geochemistry: 1) alkaline quartz gabbro-diorite and 2) shoshonitic granite and dacite.

Group-1 alkaline quartz gabbro-diorite samples display a narrow range of SiO_2 (57.8–59.6 wt. %) and Al_2O_3 (13.8–14.2 wt. %). These rocks have low K_2O (0.96–1.2 wt. %) but high Na_2O (6.86–7.01 wt. %) contents, are thus enriched in alkali elements ($Na_2O + K_2O$ = 7.8–9.0 wt. %) and plot within the trachyandesite field on a TAS diagram (Fig. 5B; after Le Bas et al., 1986). The A/CNK ratios for alkaline quartz gabbro-diorite rocks are 1.15–1.30, implying a relatively peraluminous affinity (Fig. 5C). They are enriched in Na_2O, with $K_2O/Na_2O < 1$ and plot in the tholeiitic to somewhat calc-alkaline and within-plate fields in K_2O–silica and Y + Nb vs. Rb (Pearce et al., 1984) diagrams, respectively (Fig. 5D and E). Chondrite-normalized rare earth element (REE) patterns (Sun and McDonough, 1989) for quartz gabbro-diorite show that they are slightly enriched in LREEs relative to HREEs, with La_N/Yb_N ratio of 1.9–2.4, without Eu anomalies (Eu/Eu^* = 1.1–1.2) (Fig. 6A). The N-MORB-normalized trace element spider diagram of the quartz gabbro-diorite rocks (Fig. 6B) show relatively flat patterns of LREE to HREE and HFSE depletions.

Group-2 Chah-Gaz granitoids have similar SiO_2 (76.03–76.62 wt. %), MgO (~0.17 wt. %), Al_2O_3 (~10.9 wt. %) and K_2O (~7.1 wt. %), TiO_2 (~1.18 wt. %) and low Na_2O (~0.3 wt. %) contents. A group-2 Chah-Gaz dacite also shows a narrow range of SiO_2 (68.5–68.7 wt. %), Al_2O_3 (13.8–14.5 wt. %), and K_2O (5.9–6.8 wt. %) and has moderate TiO_2 (0.42–0.75 wt. %) and low Na_2O (0.3–1.7 wt. %).

The A/CNK ratio of granitoids is around 1.3 while those of dacites is around 1.8, signifying a metaluminous signature (Fig. 5C). Granite and dacite have high-K_2O contents (~5.9 to 7.1 wt. %) similar to shoshonitic rocks (Peccerillo and Taylor, 1975) (Fig. 5D) Due to their age, these samples may readily have been affected by secondary events, such as metasomatism that would alter their mobile element (e.g. K) contents. However, their low measured LOI contents (1.6–2.3 wt. %) (Supplementary Table S2) argue against secondary events having affected them, and thus are likely within-volcanic arc granites (Fig. 5E). Chondrite-normalized REE profiles of granite show relatively smooth patterns, with a La_N/Yb_N ratio of 1.14–1.17 and conspicuous negative Eu/Eu^* of 0.36 to 0.37, which resemble geochemical characteristics of continental arc magmas (Ducea et al., 2010) (Fig. 5C). By contrast, dacite is more enriched in LREEs relative to HREEs, has a La_N/Yb_N ratio of 9.9–10.2, and shows Eu/Eu^* anomalies of 0.46–0.70 (Fig. 6c).

On a N-MORB-normalized spider diagram, granite shows relatively smooth LREE to HREE trace element patterns with HFSE depletions and LILE enrichments, whereas, dacite show enriched LREE relative to HREE, plus significant HFSE depletions (Fig. 6D).

Mishdovan magmatic complex

The Mishdovan intrusive rocks are granodiorite, whereas lava and tuffaceous rocks have mafic to felsic compositions (Fig. 5B). Granodiorites have SiO_2 contents of 74.6–76.9 wt. %, MgO contents of 0.89–1.13 wt. % Al_2O_3 contents of 9.1–11.5 wt. %, and A/CNK ratios of 0.9

to 1.7, classifying them as metaluminous to peraluminous (Fig. 5C). The volcanic and tuffaceous rocks have variable SiO_2 (57.8–81.2 wt. %), MgO (0.23–4.25 wt. %), and Al_2O_3 (8.8–16.9 wt. %) contents, and have A/CNK ratios of 1.1–1.5, which are markedly peraluminous (Fig. 5C). The Mishdovan igneous rocks thus exhibit a wide variation in total alkali contents (4.9–7.3 wt. %), similar to tholeiitic to high-K calc-alkaline-shoshonites (Fig. 5D) that form at active continental margins (Fig. 5E).

The chondrite-normalized REE patterns of the Mishdovan rocks (Figs. 6E-F) reflect their high La_N/Yb_N ratios of 2.7–17.8, with strong negative Eu/Eu^* anomalies of 0.26–0.92. On a multi-element N-MORB-normalized diagram (Figs. 6E-F), most rocks exhibit enrichment in Rb, Th, U, K, Pb and depletion in Ti, Sr, P and Nb. These geochemical signatures, including depletions in Nb and Ti and enrichment in large-ion lithophile elements (LILEs) and high LREEs/HREE ratios, similar to the continental arc magmas (e.g., Ducea et al., 2010).

4.3 Whole-rock Sr–Nd isotopes

Six samples (two granites, two dacites, and two alkaline quartz gabbro-diorites) from the Chah-Gaz magmatic rocks were analysed for Sr and Nd isotopes (Supplementary Table S3), and their $^{87}Sr/^{86}Sr_{(i)}$ and $^{143}Nd/^{144}Nd_{(i)}$ ratios were calculated based on their zircon U–Pb ages of 534 Ma (granite) and 537 Ma (quartz gabbro-diorite). The $^{87}Rb/^{86}Sr$ ratios of Chah-Gaz calc-alkaline granitoid and dacitic rocks range from 0.54 to 0.63. They exhibit initial εNd(t) and $(^{87}Sr/^{86}Sr)_{(i)}$ values of −5.5 to −7.6 and 0.7168 to 0.7104, respectively, with depleted mantle model ages (T_{DM}) of ~1.6–1.8 Ga. The $(^{87}Sr/^{86}Sr)_{(i)}$ values for these silica-rich rocks are highly variable, although they have a restricted range of negative εNd(*t*) values.

The Chah-Gaz alkaline quartz gabbro-diorite has $^{87}Rb/^{86}Sr$ of 0.35 to 0.80. The quartz gabbro-diorite samples have positive initial εNd(t) and $(^{87}Sr/^{86}Sr)_{(i)}$ values of +1.3 to +2.7 and 0.7052 to 0.7064, respectively, with T_{DM} of ~0.7–1.1 Ga. Alkaline quartz gabbro-diorite from the Chah-Gaz complex has more juvenile (mantle-derived) isotopic compositions than the calc-alkaline dacite and granitoids (Fig. 7).

4.4 Apatite chemistry

Apatite grains from granitoid in the Chah-Gaz and Mishdovan deposits were analysed by EPMA and LA-ICP-MS (Supplementary Table S4). Apatite in the granitic rocks from Chah-Gaz contains <0.4 wt. % Na_2O, <0.30 wt. % SiO_2, 53.3–56.6 wt. % CaO and 40.3–43.0 wt. % P_2O_5. The apatite in the granitoid rocks is similar in composition, as shown in a binary $Na_2O + SiO_2 + Y_2O_3$ *vs.* $CaO + P_2O_5$ diagram (Fig. 8A). Apatite in the Mishdovan granitic rocks contains 0.04–0.42 wt. % Na_2O and <0.27 wt. % SiO_2, 53.5–55.3 wt. % CaO and 40.6–42.1 wt. % P_2O_5. Apatite in the Mishdovan granitic rock have similar Na_2O, SiO_2, and Y_2O_3 contents (Fig. 8A).

Apatite from Chah-Gaz and Mishdovan granitoids has an MnO content of 0.01–0.04 wt. %, which is lower than apatite from typical IOCG-type deposits, but similar to apatite in Kiruna-type systems (e.g., Frietsch and Perdahl, 1995; Williams, 2010). The Sr and Y values in these apatites plot in the granitoid and iron ore fields on a Sr–Y diagram (Fig. 8B). Apatite from the Chah Gaz granitoid rocks has ΣREE values of 3688–22,487 ppm. The Mishdovan granitic rock apatite is characterized by a more restricted range of ΣREE values (2190–6558 ppm). The La_N/Yb_N ratios in apatite from the Chah-Gaz and Mishdovan granitic rocks range between 7.7–5.9 and 10.9–56.1, respectively. The chondrite-normalized patterns of REE in Chah-Gaz and Mishdovan granitoid rock apatite have negative Eu anomalies, with Eu/Eu^* values of 0.17–0.68 (Fig. 9).

5. Discussion

Voluminous Cadomian igneous rocks were emplaced into the northern margin of Gondwana between ~620 Ma and ~500 Ma, and are now exposed as a 5000-km-long belt in eastern North America, Europe, Turkey, Iran and Tibet (Avigad et al., 2016; Wang et al., 2016). Alongside the tholeiitic to high-K calc-alkaline-shoshonitic magmatic rocks generated in these Cadomian arc settings, alkaline rocks also occur. In this discussion we consider four aspects of this Cadomian magmatism: (1) petrogenesis of magmatic rocks in the Chah-Gaz and Mishdovan complexes; (2) information deduced from apatite composition; (3) implications of these results for Cadomian magmatism; and (4) geodynamic implications for the formation of Chah-Gaz and Mishdovan igneous rocks

5.1. Petrogenesis of magmatic rocks in the Chah-Gaz and Mishdovan

Although the mafic and felsic magmatic rocks of Chah-Gaz formed at relatively similar times (537 to 534 Ma, respectively), they have different magmatic sources. The Chah-Gaz alkaline quartz gabbro-diorite rocks are enriched in LREEs, Rb, Ba, Th, and U, with or without depletions in Nb (Fig. 6A-B). These rocks have high Na_2O (6.86–7.01 wt. %) and FeO/MgO ratios (3.9–4.2), but low Al_2O_3 (13.8–14.2 wt. %), Cr (15–24 ppm), Co (30.1–41.0 ppm) and Ni (7.0–8.3 ppm) contents. Such geochemical signatures propose that these arc-related and intraplate magmas formed in subduction-related rift zones or continental back-arc settings (see Fig. 5E). In a Th/Yb *vs* Ta/Yb plot, the Chah-Gaz alkaline quartz gabbro-diorite shows geochemical features similar to E-MORB (Tindle and Pearce 1983). In a Nb/U *vs* Nb diagram, quartz gabbros-diorites show an affinity similar to MORB-OIB (Figures 10C-D). These rocks are characterized by positive bulk-rock εNd(t) (+1.3 to +2.7), which implies a juvenile mantle source. The primitive mantle-normalized profiles of quartz gabbros-diorite are comparable with those of both arc-related rocks and E-MORB-OIBs, with slight depletion in Nb and Ti. As an alternative, their enrichment in K, Rb, REEs, and depletion and enrichment in certain HFSEs, along with low Th/Yb (0.46–2.01) suggests an enriched mantle source similar to EM-I or EM-II; however, such enriched mantle sources can generate magmas with negative εNd(t) values (e.g., Zindler and Hart 1986). This was not the case for the Chah-Gaz quartz gabbro-diorites (εNd(t) of +1.3 to +2.7). Therefore, we suggest that the Bafq quartz gabbro-diorites are not associated with long-lived, enriched mantle sources (EM-I or EM-II), or did not have any involvement of crustal material.

On a Ce/Nb *vs*. Y/Nb diagram (Eby, 1992b), Chah-Gaz alkaline quartz gabbro-diorite units plot in the A2-type field (Fig. 10C), thus showing similarity to OIB rocks. These Chah-Gaz alkaline quartz gabbro-diorites have similar geochemistry to the Cadomian alkaline rocks of Saghand (central Iran), Sanandaj-Sirjan Zone, which occur as exotic blocks in Cadomian salt domes (south Iran) (Asasi et al., 2020) (Fig. 10C).

In contrast to these quartz gabbro-dioritic rocks, the Chah-Gaz granite and dacite along with Midhdovan igneous (intrusive and volcanic) rocks show strong arc-like geochemical signatures characterized by enrichment in LREEs and LILEs, and depletions in Nb, P, and Ti in chondrite- and N-MORB-normalized spider diagrams (Sun and McDonough, 1989). Felsic rocks also fall in the VAG and continental magmatic arc-related rocks in Rb *vs* Y+ Nb (Fig. 5E) and Th/Yb *vs* Ta/Yb (Fig. 10A) cross-plots, respectively. In a Nb/U *vs.* Nb plot, all felsic rocks plot as arc-related rocks (Fig. 10B). Volcanic rocks with high-K calc-alkaline/shoshonitic magma affinity, except for one tuff sample that has low K_2O + Na_2O, have similar trace element geochemical signatures (Fig. 10A-B) and Sr–Nd isotopes (Fig. 7). They are thus cogenetic and may possibly have generated from a similar source.

Arc-like, high-K, I-type felsic rocks igneous rocks from Chah-Gaz and Mishdovan are enriched in LREEs, Rb, Ba, Th, U, Pb, and K, and depleted in Nb and Ti, which are all geochemical features of active continental arc magmas (Pearce and Peate, 1995a; Baier et al., 2008). However, the Chah Gaz granites are less enriched in LREE (La_N/Yb_N = 1.14–1.17) and have relatively smoother LREE to HREE fractionation patterns than the dacite and Mishdovan granodiorite and volcanic rocks (La_N/Yb_N = 2.7–11.73). The flat MREE to HREE patterns for these rocks suggest that garnet was absent in their sources during partial melting (e.g., Palin et al., 2016).

High-K, I-type igneous rocks may be formed due to fractional crystallization (FC) of mantle-derived magmas (Grove et al., 2005), melting of hydrous mafic high-K magmatic rocks (*e.g.*, Sisson et al., 2005), and/or by mixing of mantle-derived components with crustal components (*e.g.*, Huang et al., 2013). The Chah-Gaz arc like felsic rocks show high SiO_2 contents (68.6–76.6 wt. %), low MgO (0.17–1.95 wt. %) and εNd of (−5.5 to −7.6), suggesting they did not formed from the mantle alone (Ridley, 1998). Moreover, the lower range of εNd isotopic composition with respect to older continental crust precludes a simple explanation of the Chah-Gaz magmas having formed by partial melting of lower continental crust (>0.710; Zhao and Zheng, 2009), but other mechanisms such as wall-rock assimilation can potentially explain the observed Nd isotope values. Therefore, the whole-rock geochemical and Nd isotopic compositions of the Chah-Gaz and Mishdovan arc like rocks indicate that mantle-derived magma and pre-existing crustal material were involved in their genesis.

The peraluminous compositions of these rocks supports a crustal component in their genesis, which was likely introduced via crustal melting and fractional crystallization (Rudnick 1992, 1995). Igneous rocks from Mishdovan have high Th (i.e. Th/Yb ratios of 2.23–9.02), confirming the importance of older continental crust during magma genesis and evolution. Moreover, their negative Eu anomaly requires that plagioclase fractionation occurred at low-pressure in a crustal magma chamber. It is commonly assumed that I-type granitic rocks may form from mixing of mantle-derived magmas with crustal melts and/or contamination of mantle melts with crustal components via assimilation-fractional crystallization (AFC) (e.g. Huang *et al*., 2013; Hernandez-Montenegro *et al*., 2021). The presence of Proterozoic xenocrystic zircons with ages of 1.7 Ga, the whole-rock Nd isotopic compositions of Chah-Gaz (−5.5 to −7.6) ranging between depleted mantle and lower crust indicate that both mantle-derived magma and pre-existing crustal material were involved in their genesis.

5.2. Metallogenic aspects of magmatic rocks as deduced from apatite chemistry

Compositional variation in apatite is primarily related to changes in the physical properties and chemistry of the melt or fluid from which it crystalized (e.g., Chen and Simonetti, 2014; Webster and Piccoli, 2015). Thus, the geochemistry of apatite in igneous rocks can reveal (1) the features of the magma source region, (2) the petrogenesis of its magmatic host rocks, and discriminate between (3) particular types of host rocks (carbonatites, lherzolites, and S- and I-type granites) (Sha and Chappell, 1999; Hsieh et al., 2008), and (4) styles of mineralization. Apatite in the granitoids of the Chah-Gaz and Mishdovan deposits occurs as euhedral phenocrysts, and defines magmatic trends on a SiO_2–MnO plot, suggesting that they have not experienced significant alteration following initial crystallization (Fig. 11A).

REE patterns for apatite from both Chah-Gaz and Mishdovan indicate moderately negative Eu anomalies, which shows that these granites formed under moderately reduced conditions (Figs. 9 and 11D). However, the magnitude of Eu/Eu^* also reflects the degree of plagioclase crystallisation, and thus a plot of δEu versus δCe can be used to explore the competing effects of variations in redox conditions and magma fractionation (Fig. 11D; Cao et al. 2012; Pan et al., 2016). The apatites from the Chah-Gaz and Mishdovan granitoids show a negative correlation between δCe and δEu values, suggesting that variations in these values are caused by changes in magma oxidation state. They have ranges in δEu and δCe values that are similar to those of moderately reduced granitoids, and so the felsic magmas of the Chah-Gaz and Mishdovan granites may have been produced under reduced conditions (Figs. 9 and 11D).

Apatite analyzed from granite in the Chah-Gaz and Mishdovan regions has relatively low Sr/Y (up to 0.4) and Eu/Eu^* (up to 0.4) values, similar to the non-adakitic character of the granites studied by Pan et al. (2016) (i.e. Sr/Y values up to 1 and Eu/Eu^* up to 0.4).

The Sr content and REE profiles, especially $(La/Sm)_N$ and $(La/Yb)_{N,}$ of apatite are sensitive to the degree of magma differentiation in granitic rocks (Pan et al., 2016) (Fig. 11B-C). Pan et al. (2016) showed that crystallisation of allanite from a melt can reduce the REE content in apatite; however, no allanite occurs in the studied samples. The observed decrease in REE ratios with Sr in apatite is thus thought to be a result of crystallization of other minerals, such as xenotime and monazite, which do occur in association with apatite (Heidarian et al., 2018; Bonyadi et al., 2011). Crystallization of xenotime and plagioclase, as mentioned previously, causes an increase in the La/Sm ratio and decrease in the Sr content in apatite. Figure 11B-C show there is no correlation between La/Sm ratio and Sr contents, suggesting that crystallization of monazite (causing LREE depletion) may better explain the decrease in REE contents, Sr, and La/Sm ratio in apatite.

Apatite chemistry during crystallization may also be influenced by apatite–melt partition coefficients (Cao et al., 2012). Experimentally constrained apatite–melt partition coefficients for MREEs are typically greater than those for LREE and HREE (Watson and Green, 1981; Fujimaki, 1986), resulting in lower values of $(La/Sm)_N$ in apatite compared to a silicate melt. Using such partition coefficients, our apatite samples show compatibility for Sr, La and Sm ($D > 1$; Supplementary Table S4), but incompatibility for the Sr/Y ratio ($D < 1$; Supplementary Table S4). Thus, the concentrations of trace elements in apatite from both the Chah-Gaz and Mishdovan granites reflect the magma composition and the apatite–melt partition coefficients. The concentrations of Sr and Y in apatite are used as tracers to define compositional fields for different lithologies. Measured Sr and Y values in apatite from host rock mostly plot in the mafic rocks, granitoids and iron ore fields (Fig. 8b).

5.3. Implications for the Cadomian magmatism

The oldest magmatic and metamorphic rocks in Iran are Cadomian granites and orthogneissic rocks (~500–600 Ma; Cadomian), which formed during Pan-African orogenic events that occurred along the northern margin of Gondwana (Moghadam et al., 2015, 2018, 2020; Rossetti et al., 2015; Hassanzadeh et al., 2008; Shakerardakani et al., 2015). These units occur in northwest (*ca.* 590–525 Ma; Honarmand et al., 2018), central (*ca.* 599–525 Ma; Ramezani and Tucker, 2003), and southeast Iran (*ca.* 547–535 Ma; Moghadam et al., 2017c). Neoproterozoic basement rocks are also pervasive in central Iran (Saghand) (Hassanzadeh et al., 2008; Moghadam et al., 2016a) (Fig. 2). The obtained ages of Chah-Gaz granite and alkaline quartz gabbro-diorite (534 and 537 Ma) are in agreement with previous ages of central of Iran (*ca.* 599–525 Ma; Ramezani and Tucker, 2003).

Most igneous rocks in Iran of Cadomian age are felsic in composition and occur as intrusive bodies and are geochemically categorised as volcanic arc granites (VAG) (Moghadam et al., 2017a; Ustaomer et al., 2009). Cadomian igneous rocks in northern Iran occur in Zanjan-Takab and Khoy-Salmas in the northwest and Taknar-Bardeskan in the northeast (Bagherzadeh et al., 2015; Moghadam et al., 2017c). The Zanjan-Takab and Khoy-Salmas Cadomian rocks are high-K, calc-alkaline granitoids, granitic to tonalitic gneisses, , migmatitic granulites, and rhyolites with zircon U–Pb ages of 620–500 Ma (Moghadam et al., 2017a, 2017c, 2019). The Cadomian rocks of northeast Iran comprise high-K, calc-alkaline granitoids, gabbro, diorite, rhyolite and tuff with zircon U–Pb ages of 556–530 Ma (Bagherzadeh et al., 2015; Moghadam et al., 2017c) (Fig. 12). Cadomian rocks in NW and NE Iran have highly variable εHf(t) and εNd(t) values of −7 to +8.5 and −4 to +8.4, respectively, suggesting petrogenesis involving older continental crust (Moghadam et al., 2017c and d; Nutman et al., 2014; Bagherzadeh et al., 2015). These bodies have model Hf ages of 1.1–2.3 Ga and ~2.5 Ga, respectively, and these pre-magmatic components are confirmed by Archean detrital zircons in Ediacaran to Middle Palaeozoic sedimentary rocks inherited from Gondwana or unexposed pre-Cadomian crust in Iran (Hajialioghli et al., 2007; Saki et al., 2011).

Coeval calc-alkaline and alkaline Cadomian rocks emplaced at ~547–538 Ma occur in central Iran (Ramezani and Tucker, 2003),the salt domes of southern Iran (Asadi et al., 2020), and southeast of Iran. Cadomian rocks from the southeast have widely variable εHf(t) and εNd(t) values, from −7 to +8.5 and −4 to +8.4 for high-K to shoshonitic rocks, respectively, and from +1.1 to +5.1 and +0.3 to +4.0 for alkaline rocks, respectively, indicating more pronounced mantle signatures in the alkaline Cadomian rocks. Alkaline intrusive exotic rocks from salt domes in southern Iran also have clear mantle signatures and positive initial εNd(t) values of +4.7 to +6.8 (Asadi et al., 2020), demonstrating their similarity with Cadomian alkaline rocks of southeast Iran.

The Chah-Gaz magmatic rocks include Cadomian high-K calc-alkaline-shoshonitic felsic and alkaline mafic rocks. Our results show that Chah-Gaz alkaline quartz gabbro-dioritic rocks have mantle-related signatures, with εNd(t) values of +1.3 to +2.7, in contrast to εNd(t) values of −7.6 to −5.5 for Cadomian high-K calc-alkaline rocks from the same region. These alkaline magmas were also generated with involvement of enriched mantle similar to Cadomian alkaline rock of southeast and south of Iran (Asadi et al., 2020).

The heterogeneity in whole-rock Nd isotopic compositions (Fig. 12D) of the Cadomian calc-alkaline rocks in the Chah-Gaz and Mishdovan along with other arc related Cadomian arc through Iran may indicate two discrete components involved in their genesis. Hybrid magmas were generated between ~572 Ma and 528 Ma (Asadi et al., 2020). The Cadomian alkaline rocks were originated from more enriched mantle with an OIB affinity at ~550 to 535 Ma (Fig. 12; e.g., Veiskarami et al., 2019).

Major and trace element data and isotope analyses of Cadomian igneous rocks reveal geochemical and isotopic across-arc trajectories from north Iran to south Iran. Felsic rocks predominate over mafic rocks in this succession (Fig. 13), despite our compilation suggesting that mafic and felsic rocks have similar abundances from north to south (Fig. 13A). Cadomian igneous rocks show similar K_2O contents from north to south Iran (Fig. 13B), although those in the north have more variable Ba/Th ratios than those in the south, which implies a greater contribution from subduction zone processes in the north (Fig. 13C). The Th/Yb ratio also varies, but generally increases toward the north, especially at 36° to 38° latitude (N–NW Iran) (Fig. 13D). This may indicate more sediment melt input, or a role for garnet peridotite in melt generation in the north. Crustal contamination is also supported by fluctuations in whole-rock Nd isotope values (Fig. 13E).

5.4. Geodynamic inferences and evolution of an extensional basin

Magmatic rocks from Chah-Gaz and Mishdovan are most geochemically (Figs. 5 and 10) and isotopically (Fig. 7) similar to units from other Cadomian exposures in Iran. However, there are differences in their inferred magmatic and depositional environments, relative to the likely trend and location of the main magmatic arc in the north. The dominance of plutonic rocks compared to volcanic rocks of calc-alkaline geochemistry in the Cadomian basement is associated with a main arc (magmatic front) to the north. This magmatic front contains minor sediments, most of which have transformed to greenschist and amphibolite metamorphic rocks, and which contain abundant 600–500 Ma detrital zircons (~70–90%) and minor (30–10%) Precambrian zircons (Balaghi et al., 2014).

At ca 560 Ma, a back-arc basin formed behind the Cadomian magmatic front, driven by crustal extension and thinning due to subduction of Proto-Tethyan oceanic lithosphere beneath northern Gondwana. This basin filled up with detrital sediments eroded from Cadomian arcs and by juvenile and reworked old components of both the Arabian plate and the African craton of Gondwana. However, alkaline magmatism related to rift basin formation in central/SE Iran seems to have waned earlier, at ~550 Ma, as suggested by obtained ages alkaline quartz gabbro-diorite (Chah-Gaz: 534 Ma; this study), Zarigan A-type granite (central Iran: 529 ± 16 Ma and 525 ± 7 Ma; Ramezani and Tucker, 2003) and E-MORB-OIB-like gabbros (south Iran: 539.0±1.8 Ma; Asadi et al., 2020).

The dominance of sequences of terrigenous sedimentary rocks interlayered with arc-related volcanic rocks, along with rifted basin OIB-like mafic/alkaline igneous rocks in the central (Rizu-Desu seris in the Chah-Gaz and Mishdovan; this study), southeast and south of Iran (Hormuz formation in the Chahbanu salt dome; Asadi et al., 2020), with relatively similar ages is associated with having a back-arc rifted basin located to the south. Geographically, AFC processes and subduction-related components were likely more important during Cadomian arc magmatism in the northern parts of Iran (Figs. 14 and 15), whereas more juvenile magmas became increasingly important in the Cadomian alkaline terrane to the central (Chah-Gaz; this study) and southern domains (Chahbanu salt dome; Asadi et al., 2020) (Figs. 14 and 15).

This evolution of the back-arc basin is emphasized by Cadomian bimodal OIB-like mafic/ alkaline rifted basin to arc-related igneous rocks in the Chah-Gaz region in central Iran, with relatively similar ages, but which formed from different sources. Such mafic alkaline rocks are also described in central and northeast Iran (Veiskarami et al., 2019). Further, Cadomian A2-type granites have been described from the Sanandaj-Sirjan Zone of Iran (Shabanian et al., 2018). Geochemical and isotopic evidence for a rifted basin origin for the alkaline rocks in Chah-Gaz (This study), Saghand (Ramezani and Tucker, 2003) and Hormuz series of Chahbanu salt dome (Asadi et al., 2020) (Fig. 12) is supported by a correlation between the occurrence of the alkaline group units and the thickness of coexisting sediments. Thick series of sedimentary rocks also occur interlayered with volcanic rocks and minor evaporites in the Rizu-Dezo Formations from Chah-Gaz and Mishdovan, similar to units found in the Hormoz series to the south. The mineralization of iron-salt deposits mainly in the Hormoz series (Atapour and Aftabi, 2017a; Atapour and Aftabi, 2017b) and Bafq IOA deposits (Stosch et al., 2011; Daliran et al., 2010) found mainly in Rizu-Desu series at about this time also indicate deposition in a rift basin.

The occurrence of calc-alkaline and subduction-related felsic rocks also indicates formation at a convergent plate margin. Here, both types of Cadomian igneous rocks have different geochemical (OIB and arc-related) and isotopic (Nd–Sr depleted and enriched) signatures, but formed coevally in the same back-arc environment (Fig. 14). Coexisting alkaline rocks indicate that this was a continent-surrounded rift basin associated with a continental arc, as documented elsewhere in the Paleogene arcs of Iran (Sepidbar et al., 2019). Such extensional rifts are often related to slab rollback, which can drive arc magmatic flare-ups and aid in the exhumation of subducted high-pressure rocks (Ducea et al., 2017). This process may also have facilitated extension, crustal thinning/rifting, and addition of juvenile crustal material in the region (Miskovic and Schaltegger, 2009), allowing decompression melting of the sub-continental lithospheric mantle (SCLM) or sub-arc mantle beneath an extensional basin. Importantly, moderate volumes of OIB-like melts can be produced by relatively small degrees of partial melting of enriched SCLM and/or plume-influenced sub-arc mantle (Fig. 14B). Such melts are more saturated and less isotopically evolved than melts formed at oceanic islands and/or above continental plumes. Further, mantle plumes also affect a significant area of the lithosphere, typically having a diameter of

~>300 km (Poore et al., 2011), which is much broader than Iran's Cadomian terranes. Thus, it is unlikely that mantle plume activity influenced formation of the Chah-Gaz alkaline units.

A key process required to generate Chah-Gaz OIB-like mafic rocks is incipient melting of the asthenospheric mantle. Impingement of asthenospheric mantle against an arc root may occur due to subduction or delamination of high-density cumulates, which generates mafic magmas with isotopic signatures matching other arcs (e.g., Paterson and Ducea, 2015). This model is plausible, given the occurrence of Cadomian ultramafic-mafic cumulates in northeast Iran (Moghadam et al., 2020). It has been suggested that in the central Iranian segment of the Gondwanan margin, extension was locally followed by Cadomian compression and formation of unconformities attributed to arc accretion and collision (Raumer et al., 2015).

Concentrations of Sr and Y in apatite can be used as tracers to define compositional fields for different lithologies. Measured Sr and Y values in apatite from granitoids mostly plot in the mafic rocks, granitoids and iron ore fields (Fig. 8b). In the Chah-Gaz, and Mishdovan granitoids and their orebodies, apatite ΣREE contents are highly variable. Heidarian et al. (2018) suggested that granitoids apatite types have higher ΣREE contents in CL bright spots; however, neither of these apatite groups resembles those documented in mantle-derived melts and carbonatite (Fig. 8b), which often have much higher Eu/Eu* ratios than the studied samples (Castor and Hedrick, 2006).

6. Conclusions

This study reveals that alkaline and high-K calc-alkaline-shoshonitic magmatic rocks in the Chah-Gaz region of Iran formed by subduction of the Proto-Tethyan lithosphere, driven by Late Neoproterozoic to Early Cambrian extension in a continental arc geodynamic setting. New U–Pb zircon ages for high-K calc-alkaline-shoshonitic rocks (534 Ma) and alkaline quartz gabbro-diorite (537 Ma) indicate coeval bimodal magmatism. In addition, trace element compositions and bulk-rock Nd isotopic data indicate that these rocks are SCLM-derived mafic magmas that have assimilated pre-existing Proterozoic crust.

Apatite from the Chah-Gaz and Mishdovan granitoids is enriched in LREE relative to HREE, and exhibits a moderately negative Eu anomaly. The inverse correlation between δCe and δEu in these apatites is a key feature of a reduced parental magma. The relatively low Sr/Y and Eu/Eu* values of these apatites indicates the non-adakitic character of the source melts.

The geochemical and isotopic characteristics of the studied rocks indicate that a back-arc basin formed behind the main Cadomian magmatic arc, which formed due to crustal thinning driven by subduction of Proto-Tethyan oceanic lithosphere beneath northern Gondwana. This back-arc basin was filled by detrital sediments eroded from Cadomian arcs.

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Figure caption

Figure 1. Geological map showing Cadomian basement rocks of Iran.

Figure 2. (A) Simplified geological map of the Bafq province from the Chah-Gaz in the north to the Mishdovan in the south Geological maps of the (B) Chah-Gaz and (C) Mishdovan areas.

Figure 3. (A) Intrusive contacts between granite and Cadomian deformed sediments; (B) granular texture of granite with euhedral to subhedral quartz, K-feldspar, plagioclase, amphibole and biotite; (C) Sharp contacts between felsic volcanic rocks with Cambrian dolomite, limestone and shale; (D) Resorbed quartz within the groundmass of quartz and plagioclase–K-feldspar intergrowths; (E) Medium-grained granular texture of quartz gabbro-dioritic rocks; (F) Plagioclase, brown amphibole, clinopyroxene and quartz as the main primary constituents of gabbro.

Figure 4. Concordia mean $^{206}Pb/^{238}U$ age plots for zircon from Cadomian calc-alkaline and alkaline Chah-Gaz magmatic rocks.

Figure 5. Geochemical data for and classifications of Chah-Gaz and Mishdovan igneous rocks. (A) Quartz–alkali feldspar–plagioclase (QAP) normative classification diagram and total alkali–silica diagram (Lebas et al., 1986); (B) ANK (molar $Al_2O_3/(Na_2O + K_2O)$) *vs* A/CNK (molar $Al_2O_3/(CaO + Na_2O + K_2O)$) diagram; (C) SiO_2 *vs* K_2O diagram (Peccerillo and Taylor, 1975) and (D) Rb *vs* Y + Nb diagrams (Pearce et al., 1984). Data for magmatic rocks are from Badr et al., 2013; Balaghi et al., 2014; Moghadam et al., 2015, 2016 2017a) and data for Cadomian exotic blocks within salt domes are from Asadi et al., (2020). Data for NE and Central Iran alkaline mafic rocks are from (Balaghi et al., 2010; Veiskarami et al., 2019). Data for Saghand rocks are from (Ramezani and Tucker, 2003).

Figure 6. Chondrite-normalized REE (left) and N-MORB-normalized trace element patterns (right) for Chah-Gaz and Mishdovan Cadomian magmatic rocks. Chondrite- and N-MORB normalized values are taken from (Sun and McDonough, 1989). Data from Chadormau come from Heidarian et al. (2018).

Figure 7. εNd *vs* $^{87}Sr/^{86}Sr$ diagram for the Chah-Gaz Cadomian magmatic rocks. Bulk-rock Nd and zircon isotope data for Cadomian magmatic rocks are from Sepidbar et al. (2020) and references therein.

Figure 8. (A) $SiO_2 + Na_2O + Y_2O_3$ versus $CaO + P_2O_5$; (B) Sr versus Y (C) and La_N /Yb_N plots of Chah-Gaz and Mishdovan apatite compositions. Note that most data plot in the granitoid and iron ore fields. The fields are from Belousova et al. (2002).

Figure 9. Chondrite-normalized REE patterns for the host apatites of the Chah-Gaz and Mihdovan bodies. Chondrite-normalized values are taken from (Sun and McDonough, 1989).

Figure 10. Tectonic discrimination diagrams for Chah-Gaz and Mishdovan Cadomian magmatic rocks. (A) Th/Yb *vs* Ta/Yb (Tindle and Pearce, 1983); (B) Nb/U vs Nb (Hofmann et al., 1986) and Ce/Nb *vs* Y/Nb diagrams (Eby, 1992b) for classification of alkaline quartz gabbro-diorite. Data for A-type granites are shown for comparison to show compositional similarities between OIB-like mafic rocks of Chah-Gaz and A-type granites. Data for Cadomian rocks in Iran are from (Moghadam et al., 2015, 2016, 217a, b, c, d, e; Asadi et al., 2020; Rossetti et al., 2014; Badr et al., 2013; Balaghi Einalou et al., 2014; Hassanzadeh et al., 2008).

Figure 11. Plot of (A) SiO_2 (wt. %) vs. MnO (wt. %); (B) Sr v. La_N/Sm_N; (C) Sr vs. La_N/Yb_N and (D) δEu vs. δCe for apatite hosted in Chah-Gaz and Mishdovan granite and ore (fields from Chen et al., 2017).

Figure 12. Plots of (A) $Na_2O + K_2O$, (B) Th/Ta, (C) Nb/Th and (D) isotopic (bulk-rock Nd) geochemistry of magmatism vs age for Cadomian magmatic rocks in Iran. The composition of active continental and within plate fields taken from (Schandl and Gorton, 2002); the field from Cadomian units comes from Moghadam et al. (2017).

Figure 13. Compiled data from North to south Cadomian regions of Iran to see across-arc geochemical variations. Whole rock major-trace elements and isotope data come from Sepidbar et al., 2020 and references therein) and (Moghadam et al., 2017).

Figure 14. Tectonic synthesis for Cadomian (600–500 Ma) rocks from Central Iran.