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Two-sided asymmetric subduction; implications for tectonomagmatic and metallogenic evolution of the Lut Block, eastern Iran

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Abstract

West directed subduction zones show common characteristics, such as low structural elevation, deep trench, steep slab and a conjugate back-arc basin that are opposite to those of the east directed subduction zones. The tectonomagmatic and metallogenic setting of the Lut Block is still a matter of debate and several hypotheses have been put forward. Despite some authors denying the influence of the operation of Benioff planes, the majority propose that it occurred beneath the Afghan Block, while others consider that oceanic lithosphere was dragged under the Lut Block. Cu-Au porphyry deposits seem to occur in an island arc geotectonic setting during the middle Eocene while Mo-bearing deposits are coincident with the crustal thickening during Oligocene. We introduce new trace element and isotope geochemical data for granitoids and structural evidences testifying the two-sided asymmetric subduction beneath both Afghan and Lut Blocks, with different rates of consumption of oceanic lithosphere.

Keywords *asymmetric subduction, tectono-magmatic, Lut Block, Afghan Block, isotope geochemical data.*

Introduction

The Lut Block has been considered one of the nine structural zones of Iran since the work of Stöcklin [1]. This block is bounded to the east by the Nehbandan and associated faults, to the north by the Doruneh and related faults (Sabzevar Zone), and to the west by the Nayband Fault (Fig. 1). The South Jazmourian fault, in the south of Sahand-Bazman magmatic arc, probably marks the southern limit of the block [2]. Some authors denied the influence of a subduction zone and attributed the mineralization in the Lut Block to an extensional geotectonic zone [3, 4, 5, and 6]. However, Saccani et al. [7] studied the ophiolitic complex of Eastern Iran, between the Lut and the Afghan continental blocks, and considered that the subduction of oceanic lithosphere played a major role and that it should have taken place beneath the Afghan Block. On the other hand, Eftekharnejad [8] proposed that magmatism in the northern Lut area resulted from subduction beneath the Lut Block. Additionally, Berberian [9] showed that igneous rocks of this block have calcalkaline signatures. The accretionary prism-forearc basin polarity, the structural vergence and younging of the accretionary prism to the southwest are consistent with a northeast-dipping subduction [10]. The purpose of these studies is to present major, trace element and Sr-Nd isotope geochemical data for many Cu-Au-Mo porphyry bearing granitoids (Fig. 1) and some structural evidences to make a discussion on the origin of magma and the tectonomagmatic evolution of the Eastern Iran zone. Recently, asymmetric subduction models have been discussed for situations similar to that of the Lut Block [11 and 12]. This type of hypothesis will be discussed in the present work, taking into account that subduction related magmatism occurs in both Lut and Afghan Blocks but also that the structural evidence alone would point to a single subduction under the Afghan Block.

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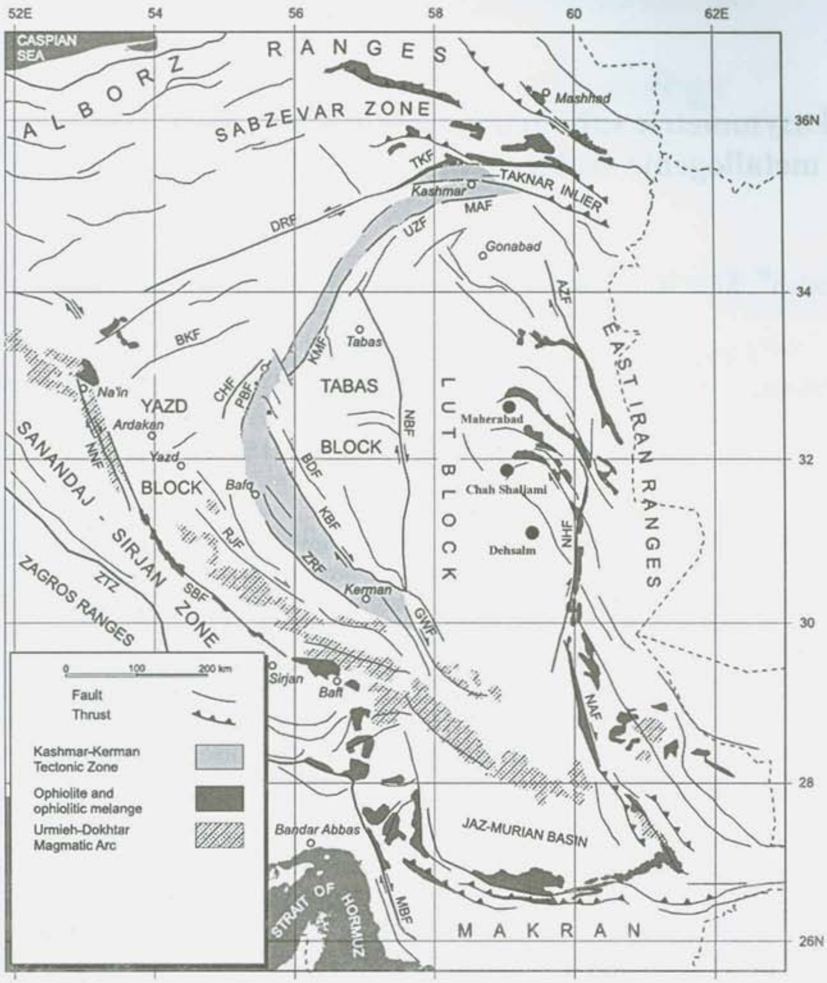

Fig. 1. The structural map of Central-East Iran and its constituent crustal blocks [13, 14, 15, 16 and 17]. AZF: Abiz Fault; BDF: Behabad Fault, BKF: Biabanak Fault, CHF: Chapedony Fault, DRF: Doruneh Fault, GWF: Gowk Fault, KBF: Kuhbanan Fault, KMF: Kalmard Fault, MAF: Mehdiabad Fault, MBF: Minab Fault, NAF: Nostratabad Fault, NHF: Nehbandan Fault, NNF: Na'in Fault, RJF: Rafsanjan Fault, SBF: Shahre-Babak Fault, TKF: Taknar Fault, UZF: Uzbak-Kuh Fault, ZRF: Zarand Fault, ZTZ: Zagros Thrust Zone.

Materials and methods

- 110 thin and 40 polished sections from various geolgical units of Dehsalm and Chah-Shaljami prepared for petrography and mineralography studies.
- 1091 soil, 187 rock and 41 mineralized samples from Dehsalm area analyzed for 45 elements at the AMDEL laboratory.
- 43 stream sediments, 7 heavy minerals, 26 mineralized samples from Chah-Shaljami area analyzed at the Exploitation Research Center of Iran, Karaj.
- 26 mineralized samples from Chah-Shaljami area analyzed for 28 elements at the ALS-Chemex laboratory.
- 25 samples of the intrusive rocks were analyzed for major elements by wavelength-dispersive X-ray fluorescence (XRF) spectrometry using fused discs and the Philips PW 1410 XRF spectrometer at the Ferdowsi University of Mashhad, Iran.
- 20 of these samples were analyzed for trace elements using ICP-MS, following a lithium metaborate/tetraborate fusion and nitric acid total

digestion, in the Acme Laboratories, Vancouver, Canada.

- Sr and Nd isotopic compositions were determined for 14 whole rocks and 4 mineral samples of plagioclase and biotite of the Dehsalm Chah-Shaljami granitoids at the Laboratório de Geologia Isotópica de Universidade de Aveiro, Portugal.
- 10 double polished samples are currently preparing for fluid inclusion studies at the Ferdowsi University of Mashhad, Iran.

Two-sided asymmetric subduction

Subduction zones can be analyzed in terms of a wide range of parameters, such as convergence rate, topographic and structural elevation of the related orogen, subsidence rate in the trench or fore deep, erosion rate, metamorphic evolution, magmatism, dip of the foreland monocline, depth and geometry of the decollement planes that generate the accretionary prism and the belt of the upper plate, the thickness and composition of the upper and lower plates, gravity, magnetic and heat flow anomalies, seismicity and slab dip. Therefore, there is a long list of parameters, which are relevant to the geometry and evolution of each particular subduction zone. Generally, the west directed subduction zones like Barbados, Apennines, Marianas and Tonga are characterized by low topography and low structural elevation, a deep trench or fore deep with high subsidence rates, generally a steep slab, an accretionary prism mostly composed by the shallow rocks of the lower plate and a conjugate back arc basin. In contrast, the east directed subduction zones (e.g., Andes) or north-east (Himalayas, Zagros) exhibit opposite signatures such as high structural and morphological elevation, generally no back arc basin, shallower trench or fore deep with lower subsidence rate, deeply rooted thrust planes affecting the whole crust and lithospheric mantle, ultra-high pressure rocks and wide outcrops of metamorphic rocks, and dominantly shallower dip of the slab. Such an asymmetry in the slab dip has been demonstrated in Fig. 2.

The W-directed subduction zones are generally faster because they have the subduction hinge generally moving away with respect to the upper plate, and converging relative to the lower plate faster than the upper plate. Therefore, these subduction zones should supply much larger volumes to mantle recycling than the opposite subduction zones (Fig. 3).

West-directed subduction should be hotter because it involves a thicker section of asthenosphere that is generally assumed >1300 °C. This can explain why it has lower P and S seismic velocity with respect to the E- or NNE directed subduction zones (Fig. 4).

Tatsumi and Eggins [22] have shown a correlation between convergence rate and volumes of magmatism along subduction zones. The larger volumes of subduction predicted along W-directed slabs should favour the formation of a greater amount of arc-related magma, and generation of large volumes of oceanic crust in the backarc setting for a number of reasons: 1) the larger subduction rate should generate also more abundant slab dehydration, lowering the melting temperature; 2) the thicker and hotter (asthenospheric) mantle wedge should have a thicker column of potential melting; 3) faster slab entering means also larger shear heating.

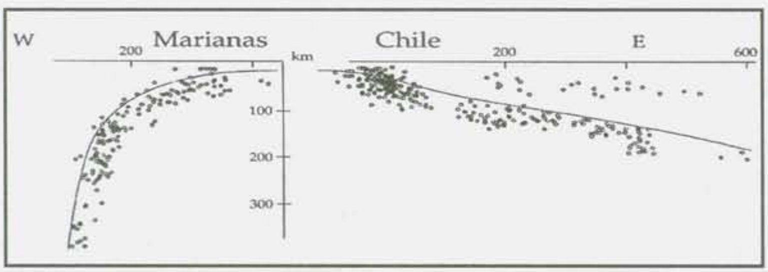

Fig. 2. Ipocenters of the Marianas and Chile subduction zones in the Pacific [18]

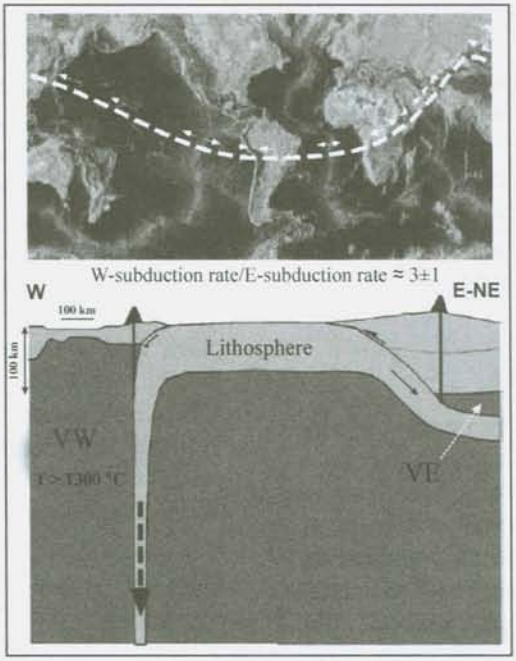

Fig. 3. The volumes recycled along W-directed subduction zones are about 2–3 times higher than along the opposite settings due to the aforementioned kinematic constraints. Moreover, the asthenospheric wedge above slabs is much thicker along W-directed subduction zones (VW) with respect to the E–NE directed subductions, if any (VE) modified after [19].

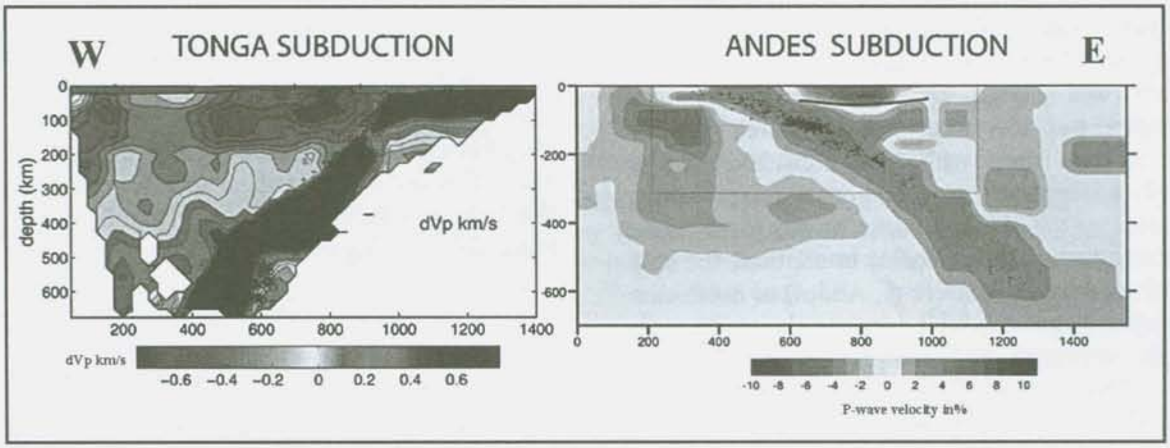

Fig. 4. Comparison between the Vp tomography of the Tonga and Andean subduction zones. Note the much slower velocities in the mantle wedge of the Tonga subduction [20] with respect to the opposite Andean setting [21].

Petrogenesis

Dehsalm and Chah Shaljami igneous rocks are classified as high-K calc-alkaline to shoshonite rocks on Peccerillo and Taylor (Fig. 5) [23]. Linear increase of K_2O content from high K calc-alkaline to shoshonitic series is related to the crystal fractionation as a result of crystallization of plagioclase, amphibole and pyroxene.

The magnesian numbers (#Mg= $100*MgO/[MgO+Fe_2O_3]$, molar) are moderately high, ranging from 41.5 up to 55.5 and 40.3 up to

60.9 respectively for Dehsalm and Chah-shaljami igneous rocks.

They are classified as volcanic arc granites on Pearce et al. (Fig. 6) [24]. Primitive mantle normalized trace element spider diagram [25] display strong enrichment in Large Ion Lithophile Elements (LILE) such as Rb, Sr, Ba, Zr and Cs; and depletion in some High Field Strength Elements (HFSE) e.g. Nb, P and Y (Fig. 7.a, b). The enrichment of the LILE and depletion of the HFSE and Heavy Rare Earth Elements (HREE) are the basic characteristics typical of the magmatism in a subduction belt [26] and calc-alkaline volcanic arcs. Their high Sr and low Nb, Ta and Ti contents are thought to be due to the absence of plagioclase and presence of Fe–Ti oxides in the residue [27].

All rocks show negative Nb anomalies as well as several other negative anomalies (P, Ta and Ti) that are also characteristic of subduction-related magmatism [28]. The negative peak of Nb is representative of arc zone and its depletion intensity might be related to the crustal effect [29]. The low Nb and Zr contents of the rocks argue more for a calc-alkaline affinity; and low contents of Y, Nb, Ta and Yb indicate volcanic arc granites. Furthermore, low molar ratios $Al_2O_3/Na_2O+K_2O+CaO < 1.1$ and low Rb/Sr ratios with the mean of 0.15 and 0.19 for Dehsalm and Chah-Shaljami intrusives indicate that these rocks are I-type granitoids.

Strontium/Y and La/Yb ratios of Dehsalm and Chah-Shaljami intrusives are 31.6-72.2, 21.5-33.5; 19.7-67 and 21.4-33.7, respectively covering geochemical characteristics of adakites and are evident on Sr/Y–Y and La/Yb–Yb discrimination diagrams [30 and 31].

In the Sr/Y–Y diagrams (Fig. 8a), many samples are located in both adakitic and normal arc volcanic rocks fields and many out of the both fields. Samples out of the both fields have Sr/Y content similar to that of adakites but Y slight enrichment by minor crustal contamination and/or crystal fractionation lead to such a position. Such samples show more adakitic affinities on La/Yb diagram (Fig. 8b).

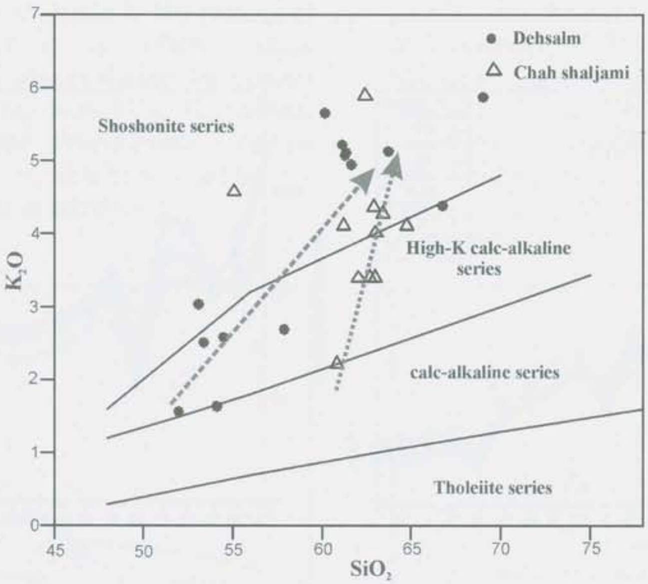

Fig 5. K_2O vs. SiO_2 plots for the different igneous suites in the Dehsalm and Chah-Shalghami. Peccerillo and Taylor [23].

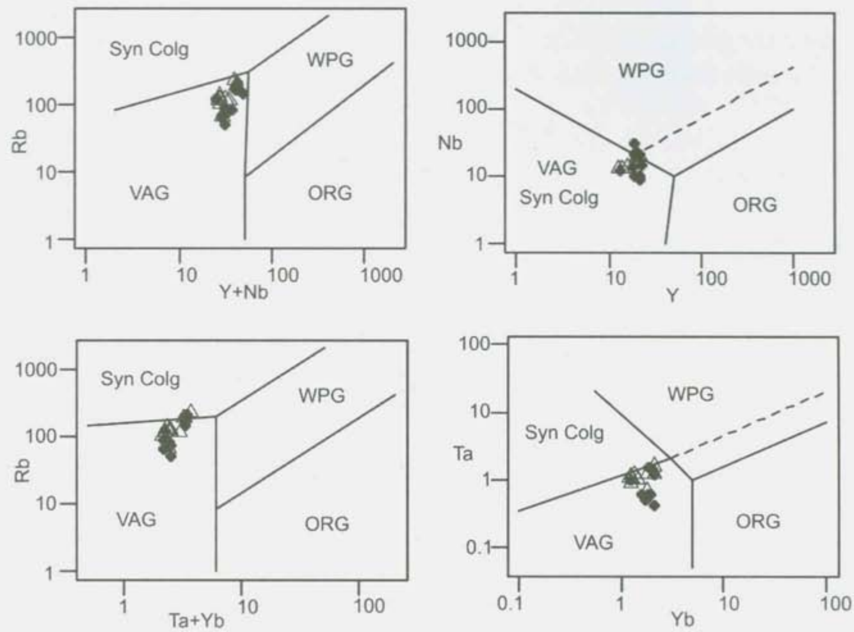

Fig. 6. Geotectonic diagrams of Pearce et al. [24]; for the different igneous suites of Dehsalm and Chah-Shaljami. The symbols like Fig. 5.

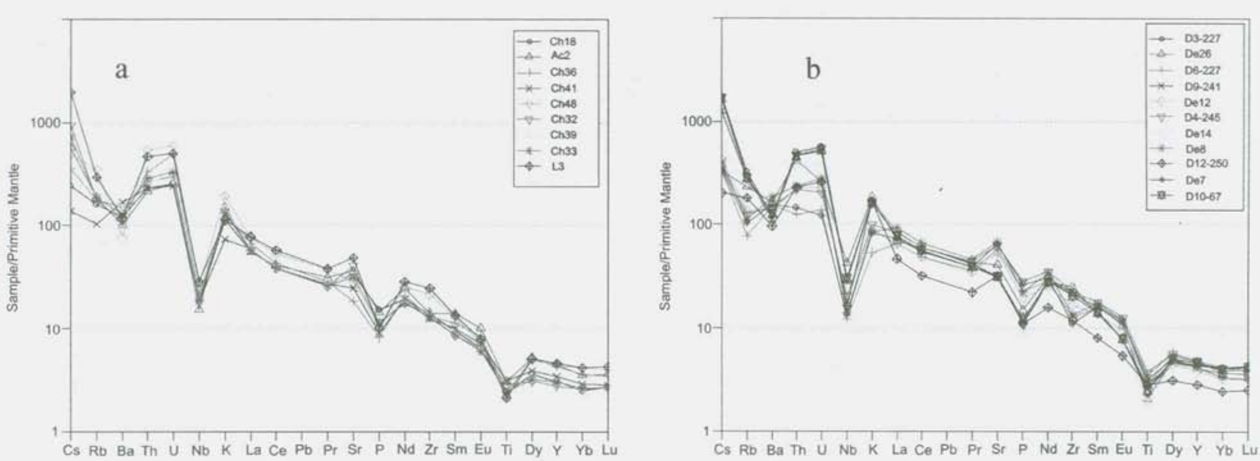

Fig. 7.a, b. Primitive mantle normalized trace element spider diagram [25] for the Chah-Shaljami and Dehsalm intrusives.

Origin of the adakitic magmas

The main geochemical features of Dehsalm and Chah-shaljami intrusives like high Sr/Y and La/Yb ratios, low abundance of HFSE and HREE are similar to adakites. These characteristics are satisfied by melting of garnet amphibolite or eclogite facies rocks, which may be found at the base of thickened (>40 km) continental crust or in eclogitized subducting oceanic crust. On the other hand, garnet is also a stable phase in subcontinental mantle lithosphere as well as asthenosphere [33]. In addition to slab melts, there are different origins such as assimilation-fractional crystallization (AFC) processes [34], melting of mantle peridotite under hydrous conditions [35], partial melting of thickened lower crust [36 and 37] or delaminated mafic lower crust [37, 38, 39 and 40] determined for adakitic compositional features. The low contents of Y and Yb and high ratios of Sr/Y and La/Yb can be attributed to the retention of Y and HREE in residual garnet, or fractionation of garnet and hornblende. High Sr content is attributed to absence of significant plagioclase fractionation. The low HREE content of adakites is classically interpreted as reflecting the presence of garnet and hornblende in the residue of partial melting of their source, whereas these minerals are not residual phases during the genesis of typical calc-alkaline magmas [41]. Hornblende and/or Fe–Ti oxides (rutile, ilmenite) are common residual minerals, thus, being able to account for Ti–Nb–Ta negative anomalies in adakites.

All measured isotopic ratios have been corrected for an age of 33 Ma based on the Rb-Sr mineral-whole rock internal isochron of samples CH33 and D3-227. The plot of the Dehsalm and Chah-Shaljami samples on the ϵNd_i-$(^{87}Sr/^{86}Sr)_i$ diagram (Fig. 9a, b) shows that their compositions do not fit into an origin of the parental magmas by melting of thick lower crust or Cenozoic subducted oceanic crust as proposed for typical adakites. In contrast, they have Sr and Nd isotope compositions very similar to those of normal island arc basalts, pointing to melting in a mantle wedge followed by magmatic differentiation.

Adakitic magmas, whether derived directly from partial melting of the subducted oceanic slab (MORB) or from lower crustal mafic rocks, usually show characteristics of low Mg#<40 and high Na_2O (>4.3 wt%) rather than high K_2O, regardless of melting degrees [42]. Moderately high Mg# of Chah-Shaljami intrusives from 40.3 up to 60.9 can also be attributed to the mantle derived melts.

If the source is inferred to have contained rutile residue, the adakitic rocks would be characterized by elavated super-chondritic Nb/Ta ratios (chondritic ratio: 19.9 ± 0.6) and Zr/Hf ratios (chondritic ratio: 34.3 ± 0.3) with strongly decreasing Nb and Ta concentrations [43]. The Dehsalm and Chah-Shaljami adakitic rocks are characterized by relatively lower Nb/Ta ratios and Zr/Hf ratios compared to chondrite. The low Nb/Ta ratios indicate the presence of a low-Mg amphibole in the restite, such that Nb is retained in the restite compared to Ta [44].

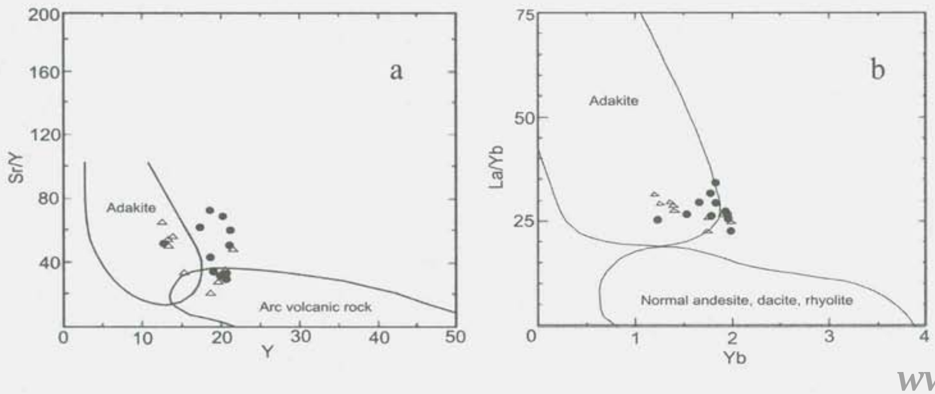

Fig 8. a,b: Y vs. Sr/Y and c, d: Yb vs. La/Yb diagram [32] used to differentiate adakitic magmas from typical calc-alkaline magmas for Chah-Shaljami intrusives. The symbols like Fig. 5.

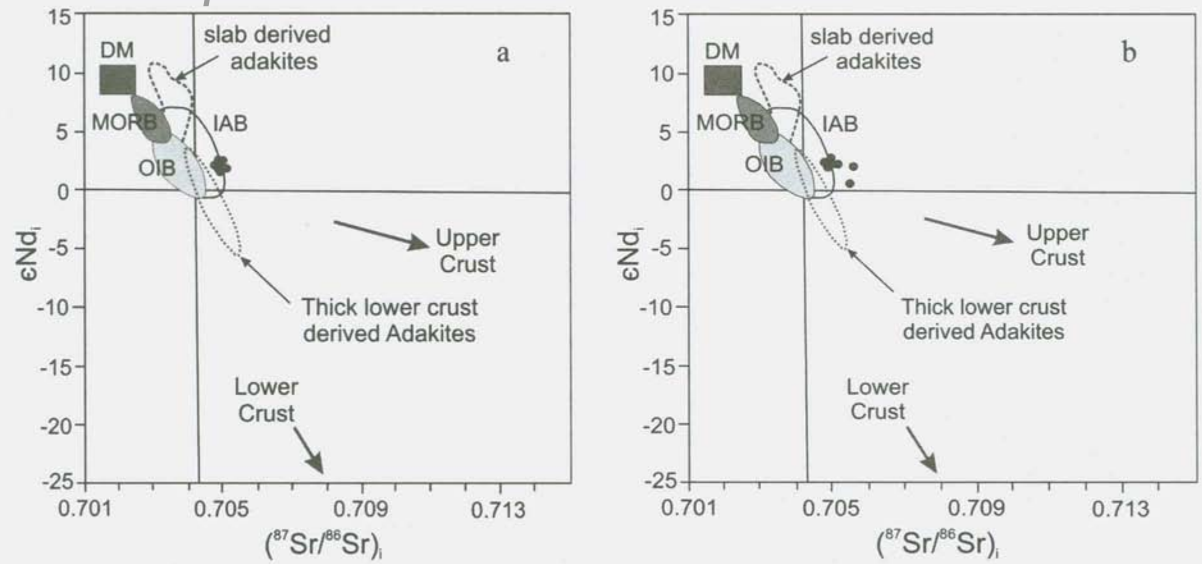

Fig. 9.a, b. ϵNd_i-$(^{87}Sr/^{86}Sr)_i$ diagram for the Dehsalm and Chah-Shaljami intrusive rocks, respectively.

These results also show that rutile-bearing eclogites cannot serve as the source as partial melting of such eclogites produces melts with high Nb/Ta ratios [44]. Depletion in HREE and low Nb/Ta ratios requires both garnet and low-Mg amphibole in the restite.

Ionov and Hofmann [45] have shown from mantle xenoliths that amphiboles can have high K and very low Rb concentration while coexisting phlogopite is rich in both K and Rb. Thus, selective melting of phlogopite would account for high Rb content and correlated high K/Rb as for the Dehsalm and Chah-Shaljami intrusives. Metasomatism of mantle peridotite by slab-melts produces orthopyroxene, clinopyroxene, garnet, phlogopite, and richterite or pargasite [46]. Therefore, we suggest a high K, low Mg amphibole, phlogopite and garnet as the major components in the restite to rationalize geochemistry of the Dehsalm and Chah-Shaljami intrusives.

Tectonomagmatic and metallogenic implications

In Iran, Adakitic magmatism for the first time was introduced for Kharvana porphyry stock (NW Iran) by Arjmandzadeh and Alirezaei [47] and has recently been introduced within the Lut Block with the shoshonitic affinities [12].

Aftabi et al. [48] believe that the potassic magmatism in Iran might be related to porphyry hydrothermal Cu-Mo-Au-Ag mineralization, which is a considerable exploration target in the area and merits further investigation. Various mineralizations like Cu-Mo-Au porphyry epithermal type deposits, Cu-Au-Ag IOCG type deposits, Cu and Au-Sb-Pb-Zn vein type deposits, Cu-Au massive sulfide type deposits, Sn-W-Au associated with reduced granitoids and Sn magmatic-skarn deposits formed during Jurassic to Tertiary magmatism phases in the Lut Block (Fig. 10). Sorkhkooh Cu-Mo and Gazu Cu porphyry type deposits are related to the subdution of oceanic lithosphere beneath the Lut Block [49]. Recent exploration and petrologic studies on the Lut Block volcanic-plutonic belt show capabilities and suitable targets for Cu-Au-Mo porphyry epithermal mineralization which are related to a subduction geotectonic setting [12 and 50].

While some authors deny the influence of the operation of Benioff planes [4, 5 and 6], most of the recent works consider that subduction of oceanic lithosphere had a major role in the tectonic evolution of this area. Until now, two types of geodynamic models considering subduction have been presented: some authors consider mostly structural evidences and propose that it occurred beneath the Afghan Block as shown in Fig. 11, [10, 51 and 7] whilst others consider the larger volumes of calc-alkaline magmatism and propose that oceanic lithosphere was dragged under the Lut Block (Fig. 12) [8, 9 and 49]. New trace element and isotope geochemical data, obtained for the Oligocene intrusives from Dehsalm and Chah-Shaljami areas, indicate that a subduction zone existed below the Lut Block [12]. On the other hand, structural evidence shows that subduction occurred beneath the Afghan Block. In order to explain the most important tectonomagmatic and metallogenic characteristics of the Lut Block, west-east directed subduction is discussed here.

As discussed above the E or NE directed slabs have slower sinking velocity than the opposite W-directed subduction zones (Fig. 3). West-verging subduction would be completely consumed before E or NE-verging subduction and consequently lead to the formation of structures that show evidences of one-sided subduction as reported between the Lut and Afghan Blocks (Fig. 13).

For example the accretionary prism-forearc basin polarity, the structural vergence and younging of the accretionary prism to the southwest are consistent with an NE dipping subduction beneath Afghan Block [10]. Therefore, structural evidences for E or NE-verging subduction does not preclude W-directed subduction under the Lut Block and a model with two-sided subduction has the advantage of also accounting for the very important Tertiary calc-alkaline magmatism and associated mineralization within this block. Camp and Griffis [52] reported the subduction of Sistan Ocean below the Afghan continental margin, as testified by the occurrence of both intrusive and extrusive Maastrichtian-Paleocene calc-alkaline rocks. The larger volumes of subduction predicted along W-directed slabs should favour the formation of greater amounts of arc-related magmas, as reported within the Lut Block, where voluminous Tertiary igneous rocks occur (Fig. 13). The ore-bearing intrusive rocks within the Maherabad Cu-Au porphyry deposit have been dated at 39 Ma (Middle Eocene) using zircon U-Pb and an island arc geotectonic setting proposed for the area [54]. The island arc geotectonic setting is coincident to the W-directed subduction (as shown in the Fig. 13) and the occurrence of Cu-Au mineralization during Eocene. According to Sengör and Natalin [55] the Ocean was closed in eastern Iran, between the Helmand and Lut plates in Oligocene–Middle Miocene. During this period, the crustal thickening occurred and a suitable geotectonic setting would result in the formation of Mo-bearing porphyry deposits as in cases of Oligocene Dehsalm and Chah-Shaljami deposits that have been dated at 33 Ma.

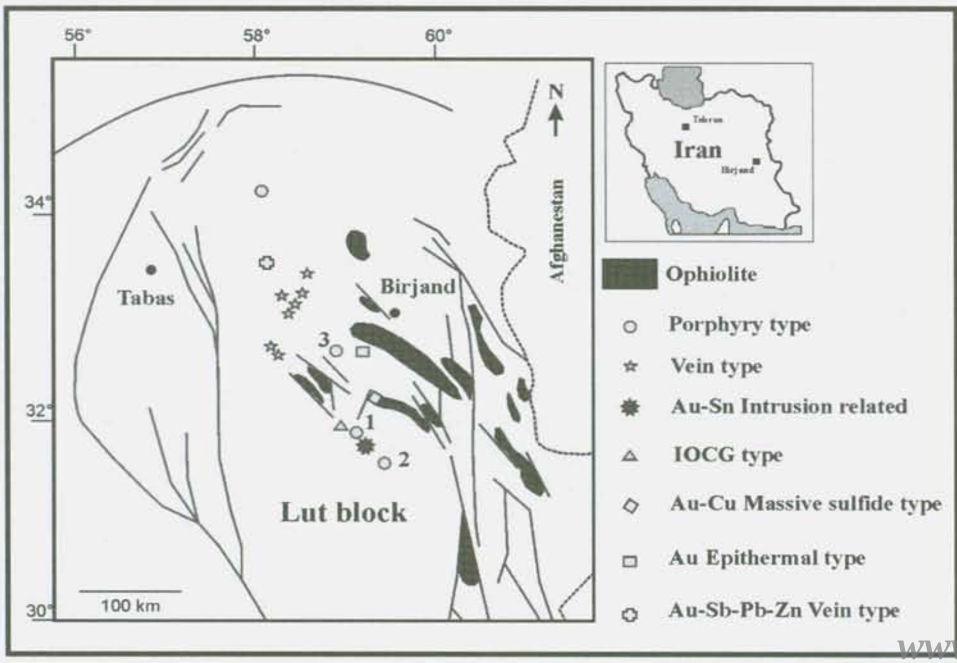

Fig. 10. Different types of mineralization occurrences within the Lut Block during Tertiary.

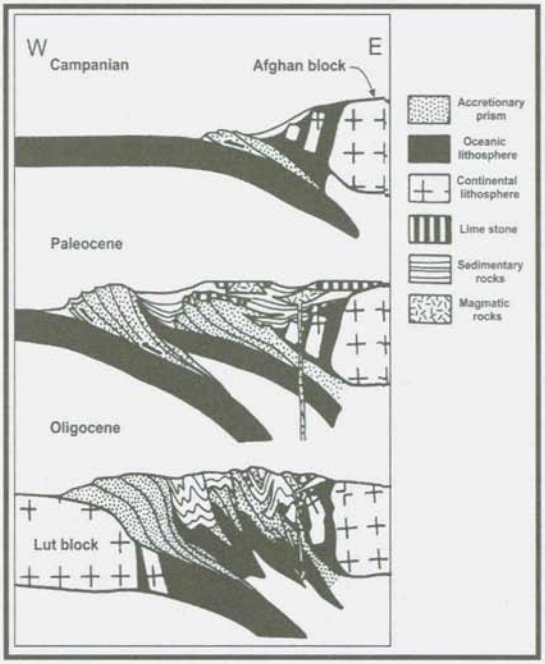

Fig. 11. Modified east verging subduction model of Eastern Iran [52, 10, 51, 53 and 7]. Such a geodynamic model cannot serve tectonomagmatic and metallogenic problems of the Eastern Iran.

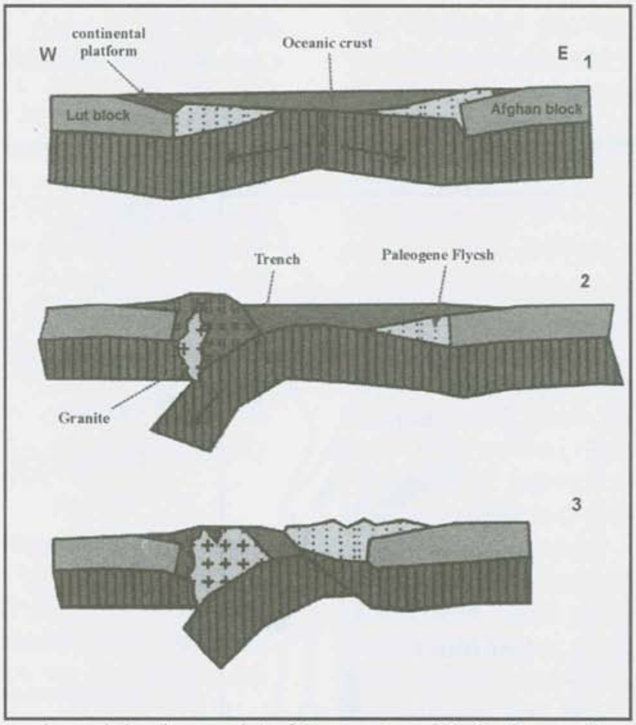

Fig. 12. Modified west verging subduction model of Eastern Iran [8]. Such a geodynamic model cannot serve tectonomagmatic and metallogenic problems of the Eastern Iran.

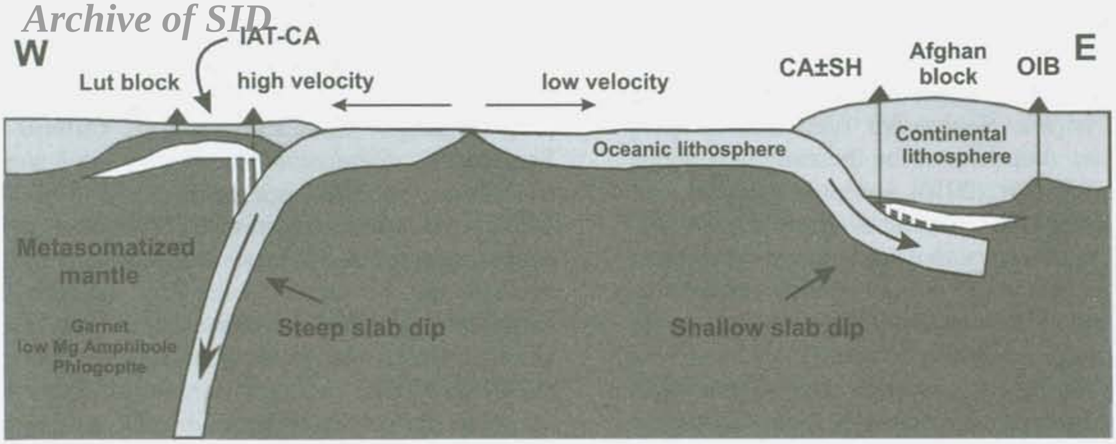

Fig. 13. Two-sided asymmetric subduction. This model is presented as a new hypothesis for the tectonomagmatic and metallogenic setting of the Lut Block. IAT: island-arc tholeiites; CA, SHO: calc-alkaline and shoshonitic series; OIB: basalts with ocean island or intraplate affinity.

Conclusions

Trace element features of Dehsalm and Chah-Shaljami granitoids show a typical magmatism related to a subduction zone, such as LILE-enrichment and marked Nb, Ta and Ti negative anomalies. The adakitic affinity of the Dehsalm and Chah-Shaljami rocks can be attributed to the presence of residual garnet and low-Mg amphibole in a mantle source. Isotope geochemistry and relatively high Mg# show that the parental magmas probably derived from partial melting of metasomatized peridotite in a supra-subduction mantle wedge. Copper-Au porphyry deposits seem to occur in an island arc geotectonic setting during Middle Eocene whilst Mo-bearing deposits are coincident with the crustal thickening during Oligocene. Such a geochemical data testify the West direction subduction beneath the Lut Block; along with the present structural evidences related to the east direction subduction beneath the Afghan Block we can consider a two-sided subduction. Two-sided asymmetric subduction is a new geodynamic model for this area, and it explains the tectonic, magmatic and metallogenic characteristics of the Lut Block.

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