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The behavior of rare-earth elements, zirconium and hafnium during magma evolution and their application in determining mineralized magmatic suites in subduction zones: Constraints from the Cenozoic belts of Iran

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ABSTRACT

Processes, such as partial melting, differentiation, assimilation, magma mixing, and liquid immiscibility, together with partition coefficients between minerals and melt, solubility, and redox conditions, are the controlling parameters for element distribution and enrichment processes. These factors can be evaluated through the geochemical variation of trace elements, such as Rare Earth Elements (REEs) and High Field Strength Elements (HFSEs), specifically Zirconium (Zr) and Hafnium (Hf), in magmatic rocks. For this purpose, two well-mineralized Cenozoic subduction-related magmatic belts in Iran—the Arasbaran and the Urumieh-Dokhtar—were evaluated. The results of this study showed that, in subduction zones, the increase in crust thickness with arc maturity caused low partial melting and more differentiation, which left behind magmas with low Zr, Hf and HREEs. These factors can be used to evaluate the degree of differentiation, degree of partial melting, and the correlation of different magma pulses, from initiation to the end of the subduction processes. Using Zr-Hf or Hf-(Zr/Hf) diagrams, we concluded that low Zr and Hf contents with low Zr/Hf ratios without a Europium (Eu) negative anomaly, and with high LREE/HREE ratios, indicated the more evolved and mineralized magmatic suites, which occurred particularly in the mature arcs.

1. Introduction

In subduction zones, magmatism may occur in several pulses over the course of several million years, during which only some magmas are fertile or mineralized. Processes from generating to the emplacement of magma, such as partial melting, differentiation, assimilation, magmas mixing, and liquid immiscibility, together with partition coefficients of elements between minerals and melt, solubility, and redox conditions of magma, are the primary controlling parameters for element distribution or enrichment (Vigneresse, 2004, 2007). Relative metal abundance in magmas and different types of intrusion-related deposits are functions of compositional evolution, fractionation, and oxidation states. For example, Cu-Au deposits are associated with oxidized, relatively unevolved magmas (Blevin, 2004). These factors are controlled by mineralogy and the depth of the magma source, geodynamic setting, and tectono-magmatic conditions. The radiometric age determination is the most common method for distinguishing different magmatic pulses. Using the relative concentrations and ratios of the element pairs LREE-HREE and Zr-Hf (Jochum et al., 1986), I studied their geochemical behavior during the subduction processes. The observed variations were attributed to these subduction processes and can be used as a tool to recognize the fertile suites for mineral exploration. In this paper, I used HFSE (occasionally Zr and Hf) and REE geochemical signatures from two magmatic belts, the Arasbaran area in northwestern Iran and the Urumieh-Dokhtar in central Iran, to assess the following: differences in HFSE and REE mobility during partial melting, mineral differentiation, the magma's evolution, and the determination of mineralized suites. Regional scale data in the Arasbaran belt and deposit scale data in the Urumieh-Dokhtar belt, including the Hararan area in the southern part of the belt, and Chah Goshar in the middle part of the belt, (Fig. 1) were also used to evaluate the used method.

2. Methodology

Sixty-one samples from sub-volcanic and intrusive rocks of the three study areas—the Arasbaran, Hararan, and Chah Goshar—were selected for bulk analysis, following a careful petrographic examination of >200 samples. Major elements were analyzed by X-ray fluorescence spectrometry (XRF), and trace elements were evaluated by inductively-coupled plasma mass spectrometry (ICP-MS). The Arasbaran samples were reviewed at Miami University's analytical laboratory, and the

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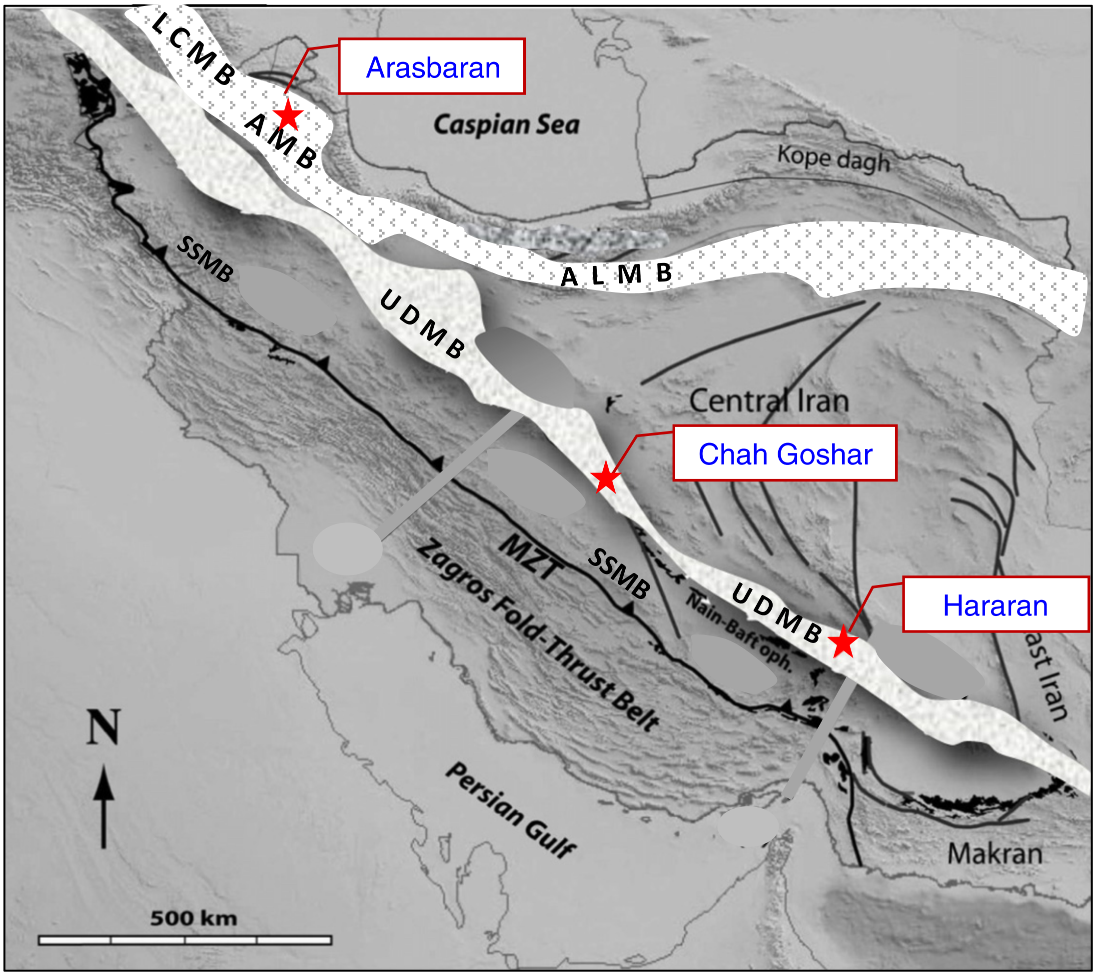

Fig. 1. Cenozoic magmatic belts in Iran. AMB: Arasbaran magmatic belt, LCMB: Lesser Caucasus magmatic belt, AlMB: Alborz magmatic belt, UDMB: Urumieh-Dokhtar magmatic belt, SSMB: Sanandaj-Sirjan magmatic belt, MZT: Main Zagros Trust. Note that the AMB, LCMB, and ALMB together make the northern magmatic belt of Iran versus the southern magmatic belt, which consists of the UDMB and the SSMB. Red stars indicate the study areas (modified from Omrani et al., 2008).

Hararan and Chah Goshar samples were investigated at ACME Analytical Laboratory of Canada. This paper focused on trace elements' geochemistry, so only some of the trace elements, such as Zr, Hf, Sr, Y, and REE are presented here (Tables 1 and 2). In addition, analytical data from other studies (Dilek et al., 2010; Karimzadeh, 2004; Khezerlu et al., 2008; Kheirkhah et al., 2009; Ahmadzadeh et al., 2010; Jamali, 2012) were used. Analytical data for the Chah Goshar and Hararan areas came from the National Iranian Copper Industry Company's (NICICO) internal report, which was prepared by Jamali and Baniadam (2012a), Jamali and Baniadam, 2012b).

3. Geological setting

The Meso-Cenozoic magmatic rocks of Iranian plateau is related to subduction of Neotethys oceanic crust beneath the Central Iran microcontinent. According to geographical distribution of ophiolite remnants, metamorphic rocks and arc-related magmatic rocks in Iranian plateau, two magmatic belts including Alborz-Azerbaijan, and Urumieh-Dokhtar distinguished (Jamali et al., 2012) (Fig. 1).

3.1. The Arasbaran magmatic belt (AMB)

The Arasbaran magmatic belt (AMB) in northwestern Iran constitutes the western part of the Alborz-Azerbaijan belt that continues northwestward to the Lesser Caucasus magmatic belt (LCMB) in the countries of Armenia and Azerbaijan and eastward to the Alborz magmatic belt (ALMB) in northern Iran (Fig. 1). Several Cu-Au-Mo porphyry deposits, including the Sungun, Haftcheshmeh, Masjeddaghi, Mivehrud, Sonajil, and Kighal, are coeval with the Upper Oligocene to Upper Miocene magmatic rocks in the AMB (Hassanpour, 2010; Jamali, 2012; Aghazadeh and Badrzadeh, 2015; Jamali and Mehrabi, 2015). The southernmost Lesser Caucasus belt consist of successive Eocene to Pliocene magmatic pulses and host two stages of porphyry Cu-Mo deposits. The Eocene magmatic events are coeval with the first stage of porphyry Cu-Mo formation at Agarak, Hanqasar, Aygedzor, and Dastakert. The Oligo-Miocene magmatic events coincide with the second porphyry Cu–Mo ore deposit stage, including the major Kadjaran deposit at 26–27 Ma (Moritz et al., 2015).

In the Lesser Caucasus belt, the subduction-related magmatism began in the Jurassic period and continued through the Quaternary period, although igneous events at Arasbaran are of the Upper Cretaceous to the Quaternary period in age. The Mesozoic and early Cenozoic eras' magmatic rocks within the AMB and the LCMB are directly related to subduction, while the Neogene magmatic rocks show characteristic signatures of post-collision environments (Moritz et al., 2011; Jamali, 2012; Jamali and Mehrabi, 2015; Moritz et al., 2015).

The Upper Cretaceous magmatic rocks consist of submarine volcanics of mafic to intermediate composition with a calc-alkaline to tholeiitic character of volcanic arc settings (Hassanpour, 2010; Moritz et al., 2015). These volcanic rocks are intercalated with Upper Cretaceous