Mineralogical and geochemical evolution of the Bidgol bauxite deposit, Zagros Mountain Belt, Iran: Implications for ore genesis, rare earth elements fractionation and parental affinity

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1. Introduction

Bauxite resources are economic concentrations of aluminum, formed from alteration and chemical weathering of
alumino-silicate-rich parent rocks. These residual deposits are generally developed under humid tropical to subtropical climate conditions with an average temperature higher than 22 °C and annual rainfall exceeding 1.2 m (Bárdossy and Aleva, 1990; Boni et al., 2013). The current classification of bauxite deposits divides them into three main genetic types, depending on the mineralogy, geochemistry, and host lithology: 1) Lateritic-type bauxites contain gibbsite as the main hydrated aluminium oxide, are generally residual deposits derived by in situ direct lateritization (autochthonous) of aluminosilicate rocks lying beneath the surface, and are the predominant global source of bauxite (about 88%) (Bárdossy, 1982; Bogatyrev et al., 2009; Ling et al., 2015); 2) Tikhvin-type bauxites are detrital and transported (allochthonous) deposits overlying the eroded surface of aluminosilicate rocks without any relationship with the original residual profile rocks; they are the erosional product of pre-existing lateritic bauxite deposits (Mameli et al., 2007; Abedini and Calagari, 2014; Zamanian et al., 2016); 3) Karst-type bauxites contain boehmite and/or diaspore as the main aluminum-rich minerals. These bauxites are formed on the more or less karstified and/or eroded surfaces of carbonate rocks (Bárdossy, 1982; Liu et al., 2012). Almost all circum-Mediterranean bauxites are related to subaerially exposed carbonates, and show local or regional unconformities (Boni et al., 2013). Based on the uplift rate, karst bauxites can be divided into four genetic subtypes: allochthonous, autochthonous, para-autochthonous and para-autochthonous (Combes, 1980; Combes et al., 1999). Previous studies indicate that karstification increases the economic importance of bauxite deposits in two principle ways: (i) as a secondary modifier of the primary carbonates that host bauxites, and (ii) as an agent for the generation of voids (e.g., cavities and solution collapse breccias) and basins (depressions, sinks) that become filled with bauxite materials (Laznicka, 2006; Zamanian et al., 2016). Generally, karstification of carbonate rocks by meteoric water is an important diagenetic process, which plays a significant role in bauxitisation. The formation of karstic bauxites involves four stages: weathering, transport/deposition, diagenesis, and supergene leaching. These ore deposits can be formed by three geological mechanisms: (i) bauxitisation (lateritization) of the aluminosilicate-rich materials accumulated/deposited on the limestone surface; (ii) chemical transport of Al in solution from the weathering crust; and (iii) mechanical exhumation of bauxite materials to the limestone surface (Ling et al., 2015).

Bauxites ores are generally enriched in many critical elements (e.g., REE, Ga, Ti, Nb, Cr, Sc, Zr), and as such, a great number of recent and less recent literatures has focused on the genetic mechanisms and processes that control their distribution within karst bauxite deposits (e.g., Mongelli, 1997; Mameli et al., 2007; Karadag et al., 2009; Liu et al., 2013; Boni et al., 2012, 2013; Gu et al., 2013; Yu et al., 2014; Peh and Kovačević Galović, 2014; Mongelli et al., 2014, 2016; Bucicione et al., 2016; Zamanian et al., 2016). Previous geochemical studies of the REE occurrences in the karstic bauxites suggested that there are four main occurrences; (1) REE replacing a similar ion in some minerals, such as aluminosilicate minerals (e.g. gibbsite, diaspor and boehmite), as diadochic replacement; (2) REE adsorbed on the surface of aluminosilicate and clay minerals; (3) authigeic REE minerals; and (4) detrital REE-bearing minerals (Bárdossy et al., 1976; Maksimovic and Pantó, 1996; Dai et al., 2003; Yang et al., 2004; Ye et al., 2007; Karadag et al., 2009; Wang et al., 2010; Zamanian et al., 2016). Besides, the study of the REE revealed that distributions of the light REEs (LREEs) and of the heavy REEs (HREEs) are controlled by the stability of the carrier complexes of REEs (e.g. REE–carbonate complexes) and the existence of REE-bearing mineral phases (Johannesson et al., 1995, 1996; Liu et al., 2013; Mongelli et al., 2014; Zamanian et al., 2016).

The conditions that promoted the formation of known bauxite deposits in Iran are associated with tectonic events occurring between the Permian and the Cretaceous. Accordingly, bauxite deposits in Iran can be divided spatially and temporally into five age groups (Fig. 1). These are: 1) Permian deposits in northwestern Iran and in some parts of the Central Plateau of Iran (CPI), 2) Permo-Triassic deposits in northwestern Iran, Alborz Mountain Chain (AMC), and in some parts of the CPI, 3) Triassic deposits in Central Plateau of Iran (CPI), 4) Triassic to Lower Jurassic deposits in the AMC and in some parts of the CPI, and 5) Cretaceous deposits in the Zagros Simply Folded Belt (ZSFB). Based on the world’s geographical distribution of bauxite deposits (Bárdossy, 1982), the most important known bauxite deposits in Iran belong to the Irano-Himalayan bauxite belt (Abedini and Calagari, 2014). They are similar to Mediterranean-type bauxites and formed in karst environments developing on exhumed carbonate platforms, where the formation of a karst network provided optimum drainage pattern and preserved the bauxite deposits from later surface erosion (Mongelli et al., 2014, and references therein). The most important bauxite deposits of Iran as well as other aluminum-rich deposits such as kaolinitic clays belong to Permian (47.61%) in northwestern Iran, AMC and in some parts of the CPI (Soheilí, 2004; Ghorbani, 2013). The contribution of other geological epochs is as follows: Triassic–Jurassic 21.8%, Permo–Triassic 19.04%, Triassic 9.52%, and Cretaceous 4.76% (Soheilí, 2004; Ghorbani, 2013). More than 190 bauxite deposits and occurrences (such as Sar-Faryab, Dehnow, Mombi and Mandan) have been recognized in the ZSFB by the Geological Survey of Iran (Zaravandi et al., 2008; Zamanian et al., 2016). These deposits were formed during a late Cretaceous hiatus (i.e. late Cenomanian to mid-Turonian) and their stratigraphic position is between the shallow-water, nerric carbonates of the Iram and Sarvak Formations (Zamanian et al., 2016).

The Bigidol bauxite deposit in southwest Iran, which is situated in the Koh-e-Hosseyn anticline, is one of the best known bauxite deposits in ZSFB. Several bauxite occurrences were recently explored in this area by the Geological Survey of Iran. Notwithstanding the works of Zaravandi et al. (2008, 2010, 2012), Ellahi et al. (2016) and Zamanian et al. (2016), who have studied and described the Sarfaryab, Hangam, Mandan, Dehnow and Mombi deposits (Table 1), there is no other published literature about the geological, mineralogical and geochemical characteristics of the bauxite deposits in the study area. These initial investigations provide a first insight into the mineralogy, geochemistry and conditions of karst-bauxite deposit formation in the ZSFB. However, the detailed ore-forming process, elemental behaviors during weathering, and the provenance material of the ZSFB bauxites have long been a matter of debate and remain ambiguous. In the present paper, besides of carrying out detailed petrographical and textural studies, we systematically utilized many different methods to reveal more details of the ore-forming process, identify the precursor rock(s), mass changes and determine the factors controlling the distribution and fractionation of REEs and selected trace elements throughout the Bigidol bauxitic horizons.

2. General geology

Three, distinctive, parallel structural zones with NW–SE trends are recognized in the Zagros orogenic–metamorphic province. These formed due to the collision of the Central Iranian microcontinent with the northeastern margin of the Arabian continental plate from Mesozoic to Miocene. They consist of (1) the Urumieh-Dokhtar Magmatic Arc (UDMA); (2) the Sanandaj-Sirjan metamorphic Zone (SSZ), and (3) the Zagros fold-thrust belt (ZFTB) (Alavi, 2004). The Zagros orogenic belt, as part of the extensive Alpine-Himalayan chain, is a major NW–SE trending tectonic zone that