Innovative applications of electric pulse disaggregation and hydro-separation techniques in the exploration of platinum group elements in the Zagros ophiolites

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Abstract

The Upper Cretaceous Zagros ophiolites of Iran host a significant number of chromitite deposits and occurrences. Platinum Group Element (PGE) anomalies have been previously reported; however, the available data on the PGE mineralization are scarce. Large chromitite pods and residual to cumulate dunitic lenses are restricted to the outer Zagros Neyriz and Haji–Abad ophiolites with a harzburgite-dominant mantle, because they have undergone a higher degree of partial melting than others with lherzolite-dominant mantle. Very little information is available concerning the distribution and mineralogy of PGE in the Zagros ophiolites. Novel mechanical separation techniques [Electric Pulse Disaggregation (EPD) and Hydro-Separation (HS)] therefore, should provide a more complete picture of PGE mineralogy in chromitites. In addition, in-situ investigations of polished sections provide more adequate information on the primary or secondary origin for Platinum Group Minerals (PGM), based on their textural position in the chromitites. Both methods are complementary and must be used jointly in order to precisely determine the distribution of PGM in Zagros chromitites. We propose accurate PGE mineralogical studies of Upper Cretaceous Zagros ophiolites by combining in-situ investigation in polished sections and mechanical separation (HS or EPD with HS).

Keywords: Zagros ophiolites, chromitite, platinum group elements, novel mechanical separation, in-situ investigation.

1. Introduction

Platinum Group Elements (PGEs) are considered strategic metals due to their increasing use in green technologies and the scarcity of their sources (South Africa and Russia supply 90% of Pt and 85% of Pd, respectively; Johnson Matthey, 2013). Stratiform chromitites in layered ultramafic–mafic complexes such as Bushveld Complex (South Africa), Great Dyke (Zimbabwe) and Stillwater Complex (USA) constitute economic reserves of PGEs (e.g., Naldrett and von Gruenewaldt, 1989). Ophiolitic chromitite is a major scavenger of PGEs although PGE contents in large chromite deposits are generally low (few hundreds of ppb; e.g., Economou-Eliopoulos, 1996). PGE enrichments of (a) all PGE, (b) Os, Ir and Ru only, and (c) Pt and/or Pd is a common feature of relatively disseminated chromite and/or small chromite occurrences, of both high-Cr and high-Al types in the uppermost parts of the mantle and/or in the lower crust sequences (Economou-Eliopoulos, 1996). Podiform chromitites occur in mantle sequences of a great number of ophiolites worldwide. Two main reasons make these peculiar rocks relevant from an economic point of view: 1) they represent the second most important natural source of chromium, and 2) they are a potential target for the recovery of PGEs. Podiform chromitites are commonly enriched in the most compatible PGE frequently referred to as IPGE (Iridium-subgroup of PGE: Os, Ir and Ru) with respect to the more incompatible ones, commonly referred to as PPGE (Platinum-subgroup of PGE: Rh, Pt and Pd; Barnes et al., 1985). During mantle melting, the Ir-subgroup of PGE tends to be concentrated in the early magmatic precipitates (i.e., chromian spinel), whereas the Pt-subgroup tends to be retained in the residual melt (Barnes et al., 1985; Matveev and Ballhaus, 2002; Ballhaus et al., 2006; Finnigan et al. 2008). Ir-subgroup of PGE is concentrated by Platinum Group Minerals (PGM), which are found either as discrete inclusions in chromite or more rarely in the silicate matrix interstitial to chromite. Their mineralogical appearance, as sulfides or as alloys, is mainly controlled by the degree of partial melting, temperature and sulfur fugacity (Tredoux et al., 1995; Brenan and Andrews, 2001). Thus, chromite chemistry, geochemistry and mineralogy of PGE as well as silicate and base metal mineral inclusions can provide important information on the formation of ophiolitic chromitites. According to González-Jiménez et al. (2013), formation of PGEs has been attributed to new several mechanisms: (a) assimilation of pre-existing PGMs from the host rock which suggest that PGM may have been scavenged from wall-rock peridotite during migration of the parental melts of the chromitite and incorporated as a solid or a solid/melt mush into the parental melts of chromitites; (b) mantle veining that suggest PGM may have precipitated from metasomatic fluid/melts that infiltrated and veined existing chromitites; and (c) subsolidus recrystallisation that involves partial or complete destruction of PGMs, and their recrystallisation, during polyphase metamorphism or recycling of the chromitites in the deeper mantle.

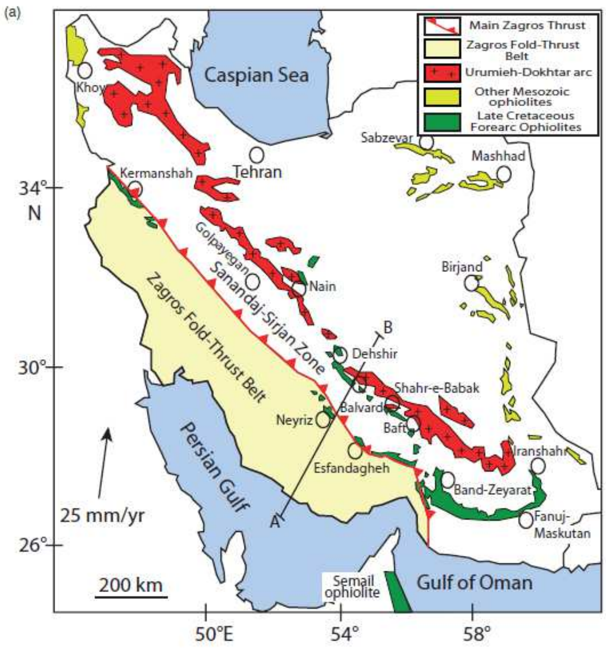
Study of these features/origins was obtained by in-situ analysis of PGEs in chromite and analysis of Os isotopes by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) in individual Os-rich PGM. During the last few years, novel separation techniques [Hydro-Separation (HS) and Electric Pulse Disaggregation (EPD)] have been able to recover numerous tiny PGMs as concentrate from low-PGE samples and thereby provide a more complete picture of PGM mineralogy in chromitites (González-Jiménez et al., 2009). Both in-situ and concentrate methods are complementary and must be used together in order to have a precise look on distribution of PGM in ophiolitic chromitites, the origin of the PGMs and finally, to understand the history of chromitites in the upper mantle. The main aim of this paper is to introduce these novel techniques and investigate the use of the two methods, in-situ and concentrate, in exploration of PGE mineralization in chromitites of the Upper Cretaceous Zagros ophiolites.

2. Geology of Zagros ophiolites

Iranian ophiolites (Fig. 1) belong to the Tethyan ophiolite belt of the Middle East. They have been divided into four groups (Takin, 1972; McCall, 1997), namely, (i) ophiolites of northern Iran, considered as remnants of the Paleo-Tethys Ocean (e.g., Ruttner, 1993); (ii) ophiolites of the Zagros Suture Zone, including those of Neyriz and Kermanshah (Lanphere and Pamić, 1983); (iii) ophiolites of the Makran region, located south of the Sanandaj-Sirjan Zone, including non-fragmented complexes such as Sorkhband and Rudan (e.g., McCall, 1997); and (iv) ophiolites enclosed as tectonic blocks in the Late Cretaceous coloured mélange along the main boundaries of the Central Iranian Micro-continental (CIM) (=Lut) block. The Zagros ophiolites have been divided into two ophiolitic belts which are separated by the Sanandaj–Sirjan metamorphic terrane (Shafaii Moghadam and Stern, 2011): (A) The Outer Zagros Belt includes three main ophiolites with NW-SE trending, Neyriz, Kermanshah and Haji–Abad which are separated by the Main Zagros Thrust (MZT) from the Zagros Fold-Thrust Belt (ZFTB); (B) The Inner Zagros Belt lies along the southwest margin of the Central Iranian block, comprising sporadic massifs from NW to SE, the Nain, Dehshir, Shahr-e-Babak, and Balvard–Baft ophiolites. Mantle sequences of both ophiolitic belts include depleted harzburgites with diabasic–gabbroic dikes; melt impregnations, chromite pods, ultramafic cumulate sills, pegmatite gabbroic pockets/sills and isotropic gabbro lenses (Shafaii Moghadam and Stern, 2011). Crustal sequences of these ophiolites include rare gabbros, sheeted dyke complexes, pillowed lavas and felsic rocks. These ophiolites are overlain by Upper Cretaceous pelagic limestone (Shafaii Moghadam and Stern, 2011).

Ophiolites in southern and southeastern Iran including Neyriz ophiolite, Esfandagheh-Sikhuran complexes in the Esfandagheh district, and the Faryab complex (ranging from 100 to >5000 ppb, with median values around 200 ppb PGEs in all complexes; Jannessary et al., 2012) are examples of Iranian ophiolites with PGE anomalies. Most of Iranian ophiolites host a great number of chromitite deposits. However, few of these deposits have been investigated for their PGE contents and mineralogy in the literature (Page et al., 1979; Moore and Rajabzadeh, 1993; Rajabzadeh, 1998; Alinia and Facherabadi, 2005; Azimzadeh et al., 2011; Jannessary et al., 2012; Rajabzadeh and Moosavinasab, 2012). In general, chromitite as a scavenger of the PGEs is generally absent in ophiolites that are characterized by a lherzolite-dominant mantle section, whereas it is present in ophiolites with a harzburgite-dominant mantle because these ophiolites have undergone a lower degree of partial melting than harzburgite-dominant ones. Although the Zagros ophiolites have remarkable chromitite occurrences, large chromite pods and residual to cumulate dunitic lenses are restricted to the outer Zagros Neyriz and Haji–Abad ophiolites (Shafaii Moghadam and Stern, 2011) because they have undergone a high degree of partial melting than others with lherzolite-dominant mantle.

The knowledge on the distribution of PGE and PGM in these ophiolites and the PGE potential of chromitites is limited. However, some of chromitite occurrences of these ophiolites have been investigated by in-situ examination of polished thin sections by a number of researchers (Moore and Rajabzadeh, 1993; Rajabzadeh, 1998; Alinia and Facherabadi, 2005; Jannessary et al., 2012).



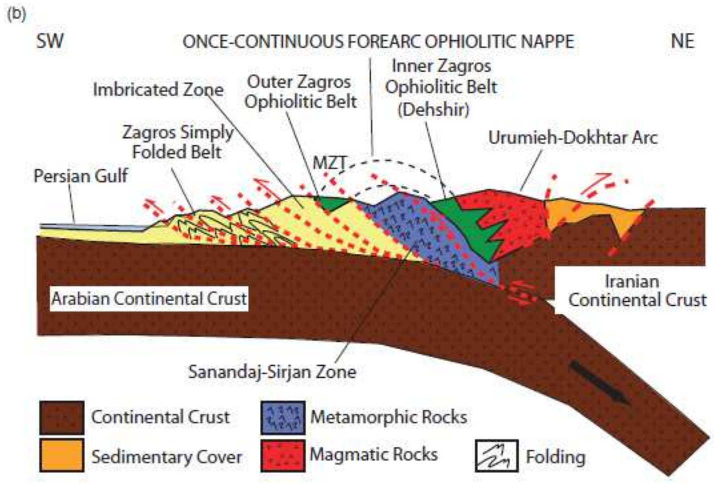


Fig. 1. (a) Map showing distribution of Iranian ophiolites and location of Urumieh–Dokhtar magmatic arc (Eocene–Quaternary), Zagros Fold–Thrust Belt (ZFTB) and Main Zagros Thrust (MZT). (b) Schematic cross-section showing the relationships between Outer and Inner Zagros Ophiolitic Belts, Zagros Thrust-Fold Belt, Sanandaj-Sirjan Zone, and Urumieh-Dokhtar Magmatic Arc (Shafaii Moghadam and Stern, 2011).

3. Methods

3.1. *Electric-Pulse Disaggregation (EPD)*

This mineral separation technique has been used extensively instead of normal mechanical crushing. EPD liberates mineral grains from associated rock without regard to its lithology or grain-size distribution by the rending effect of an explosion, which is produced by applying an electric current from a high-voltage power source (greater than 100 kV) on a sample in a water bath. Disintegration occurs preferentially along grain boundaries as zones of weakness. As a result, this technique quickly releases individual, undamaged mineral grains in their natural size distributions and in their original shape. For example, Scanning Electron Microscope (SEM) images are shown from crystals and grains of Pt-Fe alloys from EPD product of disseminated chromite ores in dunites of Nizhniy Tagil platiniferous massif in the Central Ural (Fig. 2) (Rudashevsky and Yefimov; http://www.cnt-mc.com), and EPD product by hydro-separation (HS) from one sample of Driekop Pipe (Bushveld Complex, South Africa) (Fig. 3) (Oberthür et al., 2008).

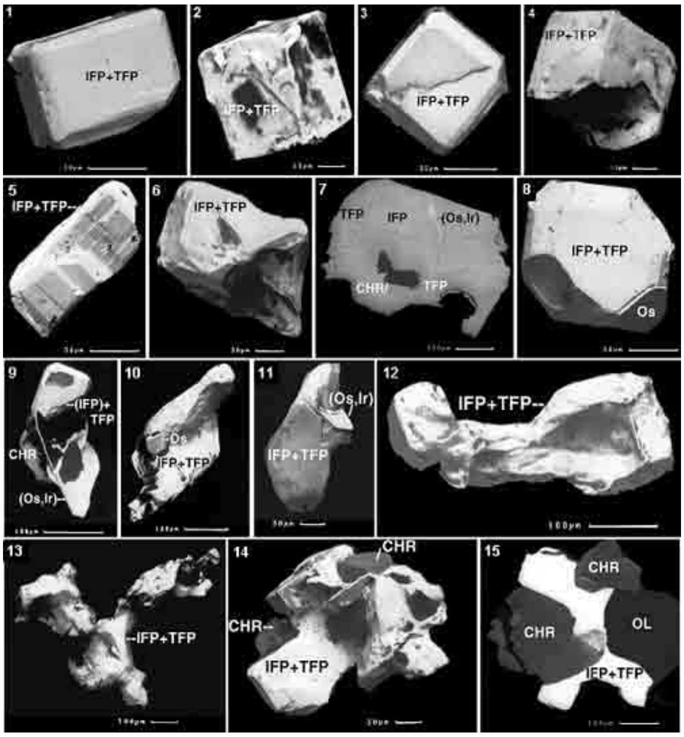


Fig. 2. SEM images from crystals and grains of Pt-Fe alloys from EP-product of disseminated chromite ores in dunites of Nizhniy Tagil massif (IFP: isoferroplatinum, TFP: tetraferroplatinum; Os, (Os,Ir) - Os-Ir alloys, CHR: chromite, OL: olivine; by Rudashevsky and Yefimov; www.cnt-mc.com).

3.2. *Hydro-Separation (HS)*

Hydro-separators are used to process solid water-insoluble powdered samples that ideally should have densities between 3 and 20 g/cm^3 and grain sizes of less than 0.3 mm, including industrial flotation size fractions (-45 µm) and finally produce representative “heavy-mineral concentrates” of particles that follow Stokes’ law when settling in a carefully controlled upward pulsating water stream. Hydro-separation works using a water flow regulator which modulates the water flow in a Glass Separation Tube (GST). The hydro-separation process moves the light fraction upwards in the GST with water, eventually collecting in a beaker under the GST. The heavy mineral concentrate collects inside the GST at its base. Different sizes of GST are used for separation, depending on the grain size and the required productivity of processing/amount of the loaded sample. More technical descriptions of the EPD and HS apparatus can be found at www.cnt-mc.com.

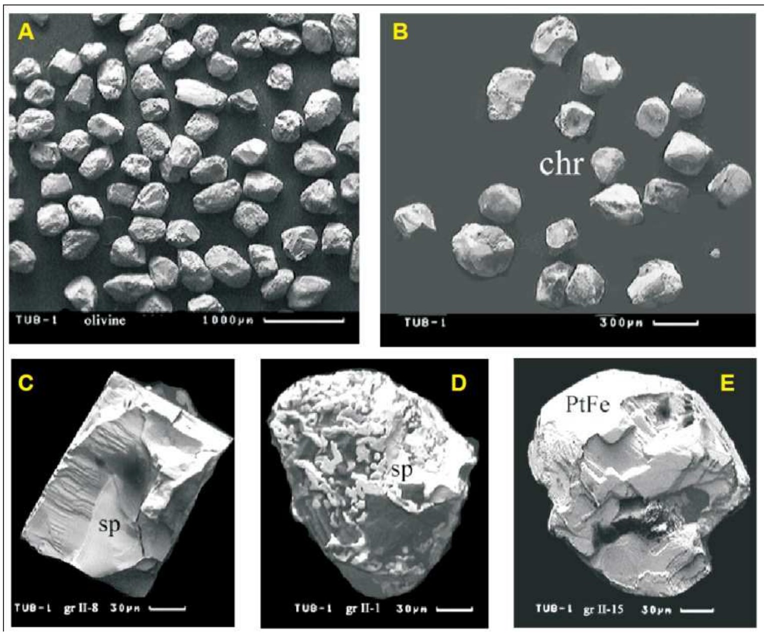


Fig. 3. SEM images of olivine, chromite and PGM extracted from the EPD product by HS from one sample of Driekop Pipe (Bushveld Complex, South Africa), (A) Olivine crystals. (B) Chromite crystals. (C) and (D) Sperrylite (Oberthür et al., 2008).

4. Conclusions

Iran hosts a significant number of ophiolite complexes. Chromite chemistry, geochemistry and accurate mineralogy of PGE as well as silicate and base metal mineral inclusions can provide important information on the formation of Iranian ophiolitic chromitites. Novel mechanical separation techniques (HS and EPD) can provide a more complete overall picture of the PGM mineralogy in chromitites. Supported by in-situ investigations of polished sections, more adequate information on the primary or secondary origin of PGM can be obtained based on their textural position in the chromitites. Both in-situ and concentrate methods are complementary; and when used in conjunction, will provide a precise picture on the distribution of PGMs in the Zagros chromitites.

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