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Platinum-group elements distribution and spinel composition in podiform chromitites and associated rocks from the upper mantle section of the Neoproterozoic Bou Azzer ophiolite, Anti-Atlas, Morocco

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ABSTRACT

The distribution of platinum-group elements (PGEs), together with spinel composition, of podiform chromitites and serpentinized peridotites were examined to elucidate the nature of the upper mantle of the Neoproterozoic Bou Azzer ophiolite, Anti-Atlas, Morocco. The mantle section is dominated by harzburgite with less abundant dunite. Chromitite pods are also found as small lenses not exceeding a few meters in size. Almost all primary silicates have been altered, and chromian spinel is the only primary mineral that survived alteration. Chromian spinel of chromitites is less affected by hydrothermal alteration than that of mantle peridotites. All chromitite samples of the Bou Azzer ophiolite display a steep negative slope of PGE spidergrams, being enriched in Os, Ir and Ru, and extremely depleted in Pt and Pd. Harzburgites and dunites usually have intermediate to low PGE contents showing more or less unfractionated PGE patterns with conspicuous positive anomalies of Ru and Rh. Two types of magnetite veins in serpentinized peridotite, type I (fibrous) and type II (octahedral), have relatively low PGE contents, displaying a generally positive slope from Os to Pd in the former type, and positive slope from Os to Rh then negative from Rh to Pd in the latter type. These magnetite patterns demonstrate their early and late hydrothermal origin, respectively. Chromian spinel composition of chromitites, dunites and harzburgites reflects their highly depleted nature with little variations; the Cr# is, on average, 0.71, 0.68 and 0.71, respectively. The TiO_2 content is extremely low in chromian spinels, <0.10, of all rock types. The strong PGE fractionation of podiform chromitites and the high-Cr, low-Ti character of spinel of all rock types imply that the chromitites of the Bou Azzer ophiolite were formed either from a high-degree partial melting of primitive mantle, or from melting of already depleted mantle peridotites. This kind of melting is most easily accomplished in the supra-subduction zone environment, indicating a genetic link with supra-subduction zone magma, such as high-Mg andesite or arc tholeiite. This is a general feature in the Neoproterozoic upper mantle.

1. Introduction

It is now widely accepted that ophiolite represents fragments of oceanic lithosphere. Due to the limitations of the study of in situ oceanic lithosphere, ophiolite studies can be of great help to characterize sub-oceanic deep-seated magmatic processes. Formation of podiform chromitite is one of the important mantle processes that gives constraints on the physico-chemical conditions and evolution of mantle lithosphere (e.g. Lago et al., 1982; Leblanc and Ceuleneer, 1992). Chromian spinel, both in chromitites and/or in peridotites, occasionally survives alteration and can be used as a reliable petrogenetic indicator to determine the primary mantle lithology even in highly serpentinized ultramafic rocks (e.g. Liipo et al., 1995; Ahmed et al., 2005a). Platinum-group elements (PGEs), on the other hand, are a potential geochemical monitor of the deep-seated processes taking place in the mantle (e.g. Naldrett, 1981; Garuti et al., 1997). The distribution of PGE in chromitites and associated ultramafic rocks gives constraints on the petrological nature and evolution of the mantle source from which they were derived. Three different processes are responsible for the distribution and fractionation of noble metals in ophiolitic rocks: partial melting, magmatic fractionation and hydrothermal alteration (e.g. Leblanc, 1991). The first two seem to be the most effective ones, whereas the last has only a minor effect on the

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remobilization and redistribution of Au and to a lesser extent Pt and Pd. Very little information is available concerning the distribution and mineralogy of PGE in the Bou Azzer Neoproterozoic ophiolite in general, especially in its upper mantle rocks (Fischer et al., 1988; Leblanc and Fischer, 1990; Ikenne et al., 2005; Ahmed et al., 2005b). The general conclusion of earlier studies (Fischer et al., 1988; Leblanc and Fischer, 1990; Ikenne et al., 2005) is that the Bou Azzer chromitites and associated serpentinites show PGE patterns typical of mantle rocks, but without any discussion about the petrogenetic significance of PGE distribution. In this study new data about the concentration and distribution of PGE, Au and some base metals, Cu and Ni, as well as additional petrological data on chromian spinel, in podiform chromitites and associated rocks from the Bou Azzer ophiolite are presented to try to elucidate the nature of the Neoproterozoic lithospheric mantle during formation of podiform chromitite. The hydrothermal redistribution of PGE and Au in chromitites and associated rocks of Bou Azzer ophiolite is also discussed.

2. Geological setting and sample locations

The Pan-African Anti-Atlas belt of Morocco is located at the northern edge of the Eburnian Western African craton; it is separated from the High-Atlas Mountains to the north by the South Atlas fault (e.g. Gasquet et al., 2005). Precambrian basement of the Anti-Atlas belt comprises several units of Paleoproterozoic to Late Proterozoic age. The Bou Azzer, along with several other Precambrian inliers (e.g. Ifni, Kerdous, Akka, Igherm, Sirwa, Zenaga, Saghro and Ougnat), is distributed along two major fault zones: South Atlas Fault, and Central Anti-Atlas Fault (e.g. Gasquet et al., 2005, and references therein). The Bou Azzer inlier (Fig. 1A) is of particular importance to the understanding of Pan-African events, because it is considered as a relict of a Neoproterozoic suture zone (Leblanc, 1976, 1981; Leblanc and Billaud, 1982; Bodinier et al., 1984; Saquaque et al., 1989; Hefferan et al., 2000; Gasquet et al., 2005; D'Lemos et al., 2006), marking the boundary between the Paleoproterozoic Eburnean basement and Neoproterozoic accreted arcs to the north. The Bou Azzer district, like the other parts of the Anti-Atlas Mountains, is composed of two major tectonic provinces: (I) Paleoproterozoic basement rocks (Eburnean), mainly gneisses, amphibolites and schists (Fig. 1A) of the West African Craton to the southwest; and (II) Neoproterozoic Pan-African crystalline basement to the northeast (e.g. Saquaque et al., 1989; Thomas et al., 2000; Ennih and Liégeois, 2001; Gasquet et al., 2005). The latter can be subdivided into two major tectonic units: a lower unit and an upper unit of a volcano-sedimentary series. The lower unit exhibits a mafic-ultramafic ophiolitic sequence of about 5 km thickness that is best exposed in the Ait Ahmane Wadi and comprises the following rock units (Fig. 1B): upper mantle serpentinized peridotite, mafic-ultramafic cumulates (locally layered gabbro), dyke swarms, submarine basaltic to intermediate pillow lavas (spilites and keratophyres), and a volcano-sedimentary sequence (Leblanc, 1976; Bodinier et al., 1984; Thomas et al., 2000). Quartz dioritic bodies of 650–640 Ma (Inglis et al., 2005), believed to have been emplaced syn-tectonically during the main period of the Pan-African orogenesis (Saquaque, 1991), intruded within many units of the central and northern parts of the Bou Azzer inlier. Large Co–Ni arsenide ores are occasionally found at the contact between serpentinite and quartz diorite intrusions (e.g. Leblanc and Billaud, 1982). These ophiolitic rocks are unconformably overlain by (Fig. 1A): (a) a volcano-sedimentary series, (b) a weakly metamorphosed molassic sedimentary succession (Tiddeline Formation), (c) a thick succession of sub-horizontal ignimbrites and conglomerates (Ouarzazate Formation) and (d) a thick shallow marine carbonate sequence of late Proterozoic to early Cambrian age (Adoudounian Formation) (Gasquet et al., 2005; D'Lemos et al., 2006, and references therein).

Serpentinized harzburgite and dunite are the dominant rock units in the Bou Azzer ophiolite, forming about 40% of the total complex (Bodinier et al., 1984). Less altered wehrlite of maximum 50 m thickness shows intrusive contacts with the overlying ophiolitic gabbros. Several small-scale chromitite pods, at most a few meters thick, are seen in the serpentinized peridotite at Wadi Ait Ahmane (Fig. 1B). The largest chromitite pod, a few tens of meters long and about 1.5 m thick, is located at Inguejem along Wadi Ait Ahmane (Fig. 1B). Several magnetite veins are present in the sheared serpentinized peridotite at Gebel Oumarou and may be subdivided into two types according to the magnetite habits, either fibrous (type I) or massive octahedral (type II) (Gahlan et al., 2006).

3. Petrographical features

3.1. Harzburgites and dunites

Due to severe serpentinization, almost all primary silicate minerals in harzburgites and dunites have been altered to secondary ones represented mainly by serpentines, talc, carbonate and chlorite (e.g. Ahmed et al., 2005a). Serpentinized dunites are found either as large masses or as thin sheaths, a few tens of centimeters thick, enveloping the chromitite lenses. Dunite commonly shows a mesh texture of chrysotile–lizardite serpentine after olivine (Fig. 2A). Compared to harzburgites, chromian spinel in dunites is both more abundant and larger, with euhedral to subhedral shapes (Fig. 2B). Ferritchromite, the alteration product of chromian spinel, is usually developed as relatively thick rims and along cracks. Chlorite appears at the expense of the spinel component, rimming relict chromian spinel grains (Fig. 2B). Spinel microscopic zonation is defined by an increase in reflectivity from unaltered core to ferritchromite or magnetite rim. Despite the intense alteration of harzburgite it is easy to recognize its primary lithology from the orthopyroxene pseudomorphs (Ahmed et al., 2001, 2005a). Less than 10% modal amount of orthopyroxene pseudomorphs is estimated in the serpentinized harzburgite of the Bou Azzer upper mantle. Chromian spinel in harzburgites is much smaller in size, irregular in shape and less abundant than in dunites (Fig. 2C). Carbonate-rich veins associated with free silica as perfect prismatic quartz grains are common in some places in the serpentinized harzburgites (Fig. 2D). In such places, chromian spinel commonly shows pseudomorphic alteration to a characteristic mineral called stichtite, a Cr-bearing magnesian hydroxycarbonate. In hand specimen, the stichtite of the Bou Azzer ophiolite occurs as purple rounded to irregular aggregates of several millimeters in the serpentinized peridotite. It is occasionally found replacing the alteration rims of the chromian spinel. The mineral first attracted our attention due to its optical properties and low analytical totals for conventional microprobe analysis of spinel and associated minerals. The weight percent total of this mineral is far less than 100 wt%, occasionally around 65 wt%, which was ascribed to the possible presence of some light elements not detected by conventional electron microprobe analysis. Its chemical analysis demonstrates the exclusive presence of MgO and Cr_2O_3 as major constituents with considerable amounts of FeO and CaO. The mineral was later interpreted as stichtite. Stichtite, with similar properties, has been described from several localities worldwide, associated with serpentinized peridotites (e.g. Hall, 1922; Read and Dixon, 1933; Mondal and Baidya, 1996; Ashwal and Cairncross, 1997; Barnes, 2000). A detailed description of the Bou Azzer stichtite is beyond the scope of this paper.