INTRODUCTION

Cr-spinel as a geochemical indicator

Cr-spinel [(Mg, Fe^{2+})(Cr, Al, $Fe^{3+})_2O_4$] is a common mineral in ultramafic-mafic rock sequences of various origin. Usually, it occurs as an accessory mineral together with olivine and pyroxene as the rock-forming minerals. Magmatic processes can cause accumulation of significant volumes of Cr-spinel to form nearly monomineralic rocks of economic value – chromitite. Chromitites are found as stratiform layers in the great mafic-ultramafic complexes such as Bushveld (South Africa) and Stillwater (United States), or form pods discordant with the main structures or, less commonly, concordant layers within ultramafic rocks as part of ophiolitic complexes (e.g. Oman ophiolite, New Caledonia ophiolites). In ophiolitic sequences, accessory Cr-spinel occurs in all varieties of the ultramafic rocks and lower crustal gabbros, whereas chromitite pods and layers are found mainly close to the Moho zone, within the upper part of the residual mantle zone (mantle tectonites) and the lower crustal zone (ultramafic cumulates), respectively (zones of the ophiolitic sequence according to Coleman 1977).

In such settings, Cr-spinel displays a large range of chemical composition, reflecting a primary, magmatic origin. The primary composition is extensively used as an petrogenetic and geotectonic indicator (Irvine 1965, Dick and Bullen 1984, Arai 1992b, Roberts and Neary 1993, Kamenetsky et al. 2001, Barnes and Roeder 2001, Arai et al. 2011). For example, the Al_2O_3 content of Cr-spinel is a useful guide to the degree of partial melting of parental mantle peridotites, whereas the Mg/(Mg+Fe^{2+}) ratio (*mg#*) measures the degree of the fractional crystallization and the rate of cooling. The TiO_2 content and the Fe^{2+}/Fe^{3+} ratio can be used to discriminate between magma types, tectonic affinities and mantle sources. The trivalent cation ratios together with the TiO_2 content help to determine tectonic setting of formation of plutonic rocks.

Since Lago et al. (1982) many researchers have agreed that Cr-spinel accumulation to form chromitite bodies takes place within open conduits in the upper mantle. The tectonic setting and the detailed mechanism of precipitation of massive Cr-spinel bodies, however, still remain subjects of debate. Most researchers favor an island-arc or back-arc setting for their formation (e.g. Roberts 1988, 1992, Arai and Yurimoto 1995, Robinson et al. 1998, González-Jiménez et al. 2011), whereas some propose also a mid-ocean ridge setting (Nicolas 1989, Nicolas and Al Azri 1991, Arai and Matsukage 1998, Uysal et al. 2009). It is, however, widely accepted that Cr-spinel concentration takes place due to complex magmatic processes depending on the degree of partial melting, melt and wall rock composition, mixing/mingling of melts migrating through the mantle, exsolution of a fluid phase from a water-rich melt and the oxygen fugacity and P-T conditions (e.g. Lago et al. 1982, Leblanc 1987, Leblanc and Nicolas 1992, Arai and Yurimoto 1994, Arai 1997a, Ballhaus 1998, Matveev and Ballhaus 2002, González-Jiménez et al. 2011).

Cr-spinels are refractory and resistant to alteration processes over a wide range of conditions (Evans and Frost 1975) so can be used as reliable petrogenetic indicators even in highly serpentinized ultramafic rocks. However, they must be interpreted carefully because magmatic Cr-spinels may reequilibrate with the surrounding silicates during cooling (Talkington et al. 1984) and they undergo alteration during serpentinization and later metamorphism (Kimball 1990, Burkhard 1993, Suita and Strieder 1996, Barnes 2000, Mellini et al. 2005, Merlini et al. 2009). In chromitites, reequilibration plays a minor role because silicates as accessory constituents can not significantly influence the Cr-spinel composition. Metamorphism, however, can result in modification of Cr-spinel composition. These processes result in the formation of the spinel alteration rims which surround relic Cr-spinel cores. As a result, only the chemical composition of the core can be used in petrogenetic reconstructions. The study of the chemical composition and mineral inclusions of the alteration rims in Cr-spinel is a clue to understanding the metamorphic processes that affected the host rocks (e.g. Evans and Frost 1975, Suita and Strieder 1996). During the alteration, Cr-spinel changes its composition mainly through Al_2O_3 and MgO depletion and Cr_2O_3, Fe_2O_3 and FeO enrichment. In the first stage a so-called "ferrichromite" rim (Spangenberg 1943) is formed that is accompanied by alteration of olivine to serpentine and finally to chlorite transformation of the matrix silicates (Mellini et al. 2005, Merlini et al. 2009). Frequent Cr-magnetite outer rims are the final phase of alteration, usually formed by serpentinization. Change in minor constituents as Ni, Zn, Mn, V and Ti is also indicative for alteration processes (Barnes 2000). Chromitite is the best rock type to unravel the alteration features of Cr-spinel because of its simple primary chemical composition compared to other igneous rocks where unaltered Cr-spinel may show originally variable intra-grain zonation (for example in basalts).

The Sudetes and the Central Sudetic ophiolite

The Sudetes form the NE part of the Bohemian Massif (Fig. 1 – inset), bounded by two major NW-SE trending fault systems: the Elbe fault zone (in the south-west) and the Odra fault zone (in the north-east), that cut the Variscan Saxothuringian zone parallel to the East European Craton (Kryza and Pin 2010). The area is divided into two different morphological parts by the Sudetic marginal fault: the Sudetic block (the south-west mountainous part), where crystalline rocks are usually exposed, and the Fore-Sudetic block (the north-east, a mainly unexposed plain), mostly covered by Cenozoic sedimentary rocks (Żelaźniewicz and Aleksandrowski 2008). The Sudetes and the Fore-Sudetic block consists of various geological units that form a complex structural mosaic (Cymerman et al. 1997, Kryza et al. 2004). They comprise fragments of Cadomian crustal blocks, metamorphosed Palaeozoic sedimentary rocks, metaingenous complexes and Variscan granitoid intrusions that are covered by post-Variscan sedimentary successions (non-continuously from the Lower Carboniferous to the Cenozoic). Due to significant differences in geological setting and tectonic evolution, the Sudetes can be divided into three main units: the West, the Central and East Sudetes (Mazur et al. 2006). The Central Sudetes that are the aim of this study comprise the gneissic Góry Sowie massif together with the Central Sudetic ophiolite ultramafic-mafic rocks (Fig. 1), the Kłodzko and the Orlica-Śnieżnik metamorphic massifs, the Niemcza and Skrzynka shear zones, the Nové and Staré Město metamorphic belts, the Kamieniec Ząbkowicki metamorphic belt and the Niedźwiedź amphibolite massif covered by partly eroded Palaeozoic sedimentary rocks.

Kryza et al (2004), Mazur et al. (2006), Kądziałko-Hofmokl et al. (2006), Kryza and Pin (2010) and many others have proposed several models for the geological evolution

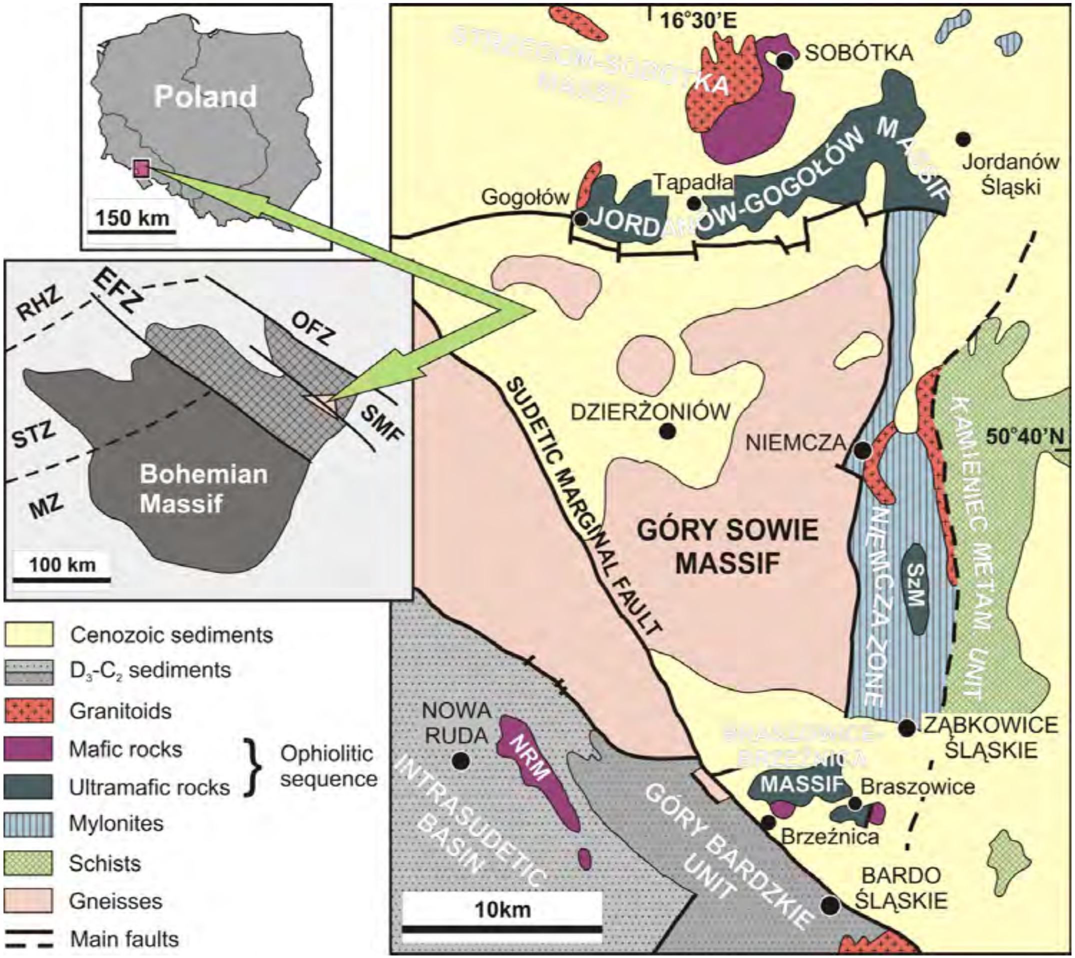

Fig. 1. Simplified geological map of the Góry Sowie massif and the Central Sudetic ophiolite (modified after Delura 2000 and Kądziałko-Hofmokl et al. 2006) showing location of the study area (green arrows) in Poland and in the Bohemian Massif. Abbreviations are: NRM – the Nowa Ruda gabbroic massif, SzM – the Szklary serpentinite massif; inset: EFZ – Elbe fault zone, MZ – Moldanubian zone, OFZ – Odra fault zone, RHZ – Rhenoherzynian zone, SMF – Sudetic marginal fault, STZ – Saxothuryngian zone.

of the Central Sudetes provided by structural, stratigraphic, geochemical and petrological studies. An important role in these models has been played ultramafic-mafic complexes, especially those interpreted as fragments of ophiolite complexes (Majerowicz 1979). The best known ultramafic-mafic sequences of this type are located along all borders of the gneissic Góry Sowie massif, SW Poland (Fig. 1 – main picture). This massif is interpreted as a marginal part of the Bohemian Massif (Moldanubian zone) incorporated into the Saxothuringian zone during Devonian subduction-collision (Franke and Żelaźniewicz 2000) or, according to Aleksandrowski and Mazur (2002), as one of a series of terranes that were accreted during the Devonian and formed the Sudetic fragment of the Variscan belt. The ultramafic-mafic assemblages that surround the Góry Sowie massif comprises four massifs of various size and geological setting which are located mainly in the Fore-Sudetic block. They are: the large Ślęża massif (with an ultramafic unit known as the Jordanów-Gogołów massif) in the north, and three smaller ones – the Szklary massif in the east, the Braszowice-Brzeźnica massif in the south and the Nowa Ruda massif in the south-west. Together they are known as the Central Sudetic ophiolite (e.g. Majerowicz 1979, Pin et al. 1988, Narębski 1992, Majerowicz and Pin 1994, Dubińska and Gunia 1997, Kryza and Abdel Wahed 2000, Mierzejewski 2000, Floyd et al. 2002, Dubińska et al. 2004). According to Mazur et al. (2006) this ophiolitic suite was formed during Late Devonian as a result of collision of the Góry Sowie – Kłodzko terrane and the Śnieżnik terrane, followed by thrusting of the latter together with fragments of oceanic structure.

Although the Central Sudetic ophiolite is described as one of the best preserved ophiolitic suites in the Variscan Belt (Majerowicz 1981), its rock sequences are not complete and seem to be dismembered (in terms of the pseudostratigraphic sequence, cf. Coleman 1977). It is thought to consist of blocks of various petrological characteristics (e.g. Gunia 1989, Majerowicz 1994, Dubińska and Gunia 1997, Kryza et al. 2010) that have been set together as a nappe pile during Variscan collision and ophiolite obduction. The mechanism of obduction, however, still remains uncertain. One of the questions is the geotectonic position of rocks that have been obducted as the Central Sudetic ophiolite. From the geochemical characteristics of the ultramafic-mafic ophiolite rocks, most researchers assert that they were predominantly formed in a mid-ocean ridge (MOR) environment (compiled by Kryza et al. 2010); however, some may display a supra-subduction zone (SSZ) signature (Dubińska 1997). The geochemical and petrological studies of chromitites can help to answer this question and clearly support one of these environments. The best preserved upper mantle unit of the ophiolitic suite (mantle tectonites) that hosts chromitites, being the aim of this study, are represented by the serpentinized ultramafic rocks of the Jordanów-Gogołów and Braszowice-Brzeźnica massifs.

This paper presents for the first time the petrological and chemical features of high-Al chromitites associated with serpentinized ultramafic rocks of mantle origin in the Jordanów-Gogołów and the Braszowice-Brzeźnica massifs, the Sudetes. It also shows the effects of serpentinization and later metamorphism on the composition of Cr-spinel and associated silicate minerals. The achieved data will be used in order to discuss the primary petrological characteristics and geotectonic environment of the chromitite formation as well as to describe later alteration processes that affected both studied chromitite occurrences.