

melting points, they are chemically inert to a wide variety of elements and compounds at elevated temperatures and thus resist corrosion; and, finally, they display the excellent catalytic properties to which I have already referred. These unique properties consequently determine their principal commercial applications which will be reviewed fully later in this study. The successful commercial substitution of the metals of the platinum group by cheaper metals is exceedingly rare, and I shall also examine this aspect later. However, one metal within the platinum group may readily be replaced by another, particularly when they are alloyed, where one metal in the group may enhance certain chemical or physical properties of the others.

1.4. Scope and Standards of this Review

A truly tremendous amount of highly sophisticated research has been undertaken concerning all aspects of the platinum-group metals. These laudable scientific enquiries have generated an inordinate volume of literature, such as is seldom surpassed in any of the sciences. Particularly prominent is the large number of geologically orientated contributions dealing with the mineralogy and ore deposits of the platinum-group elements. These offer their readers highly skilled interpretations, and wonderfully ingenious scientific models of magma addition and mixing, as well as many other artful thermodynamic or geochemical explanations concerning the very complex processes that govern the concentration of the platinum-group elements in nature.

The scientific sophistication of the literature is impressive. However, I conceived the need for a down-to-earth review of the platinum-group metals that would prove useful to a very much wider variety of readers who are intimately involved in their everyday mining, refining, producing, trading, and industrial utilization. In my view, such a nuts-and-bolts review is long overdue, since so many publications cover only single aspects of the topic. I hope to fill a very obvious gap, but readers should not expect any blue-sky thinking — I shall be concerned with thicknesses, grades, tonnages, beneficiation and refining, production and demand, and the like. I trust that my readers will enjoy this rather more mundane look at the practical side of the platinum-metals industry, particularly in a world where drastic political changes are currently manifest.

This review is based on a comprehensive literature search concerning all aspects of the platinum-group metals.

The compilation was not without a multitude of both lesser and greater problems. Foremost among the major problems lay in evaluating the platinum-metals industry, and attempting to breach the impenetrable shroud of secrecy that pervades virtually all of the component aspects. This is particularly true of the producers. The major South African producers are so obsessed with confidentiality that virtually all aspects of option holdings, reserves, grades, and mine production are veiled in absolute secrecy. Unfortunately, I shall be compelled,

where pertinent, to refer to this aspect throughout the review, in order to sift the limited factual information from educated guesswork, or even plain speculation. It is noteworthy that, after the discovery of platinum in South Africa, there was open disclosure of all prospecting results. These have been an invaluable source of data. However, when the industry was consolidated, the major players immediately imposed a very strict policy of company confidentiality on all grade, resource, and production information. This was supposedly to protect their monopolies, or to withhold vital information on their activities and results from potential competitors. Moreover, producers like Russia have never disclosed any information on their platinum-metals resources or production. This attitude has, of late, even spread to the USA and Canada, which traditionally disseminated all mineral-related information freely. This secretive attitude now pervades the whole platinum-metal industry. In particular, competing companies strictly conceal their vital data.

Another source of confusion revolves around nomenclature. It is extremely confusing to find that the term 'platinum' is commonly used without qualification to refer to the metal as such, or to the platinum-group metals. For the sake of brevity, the acronym PGM was introduced, but this has also resulted in complications. Although the majority of users use this term to indicate the platinum-group metals, the mineralogists and metallurgists, bent on the efficient extraction of the metals, for which a knowledge of their mineralogy is a vital factor, used the acronym to describe the highly complex platinum-group minerals. To overcome this problem, it has become the vogue for most geological and related scientists to use the acronym PGE for platinum-group elements in the place of the ambiguous PGM. This review will use the term PGE when referring to ore deposits and reserves, but will use PGM for the platinum-group metals for the rest of the review. Since the platinum-group minerals, as a very specialized subject, have been adequately catered for in the literature particularly by Cabri and his co-workers, PGM will not be used to refer to the platinum-group minerals in this review.

1.5. Units

The SI system of units (*Système International d'Unités*) is used throughout this review. Although the metric system is used almost universally today, it remains one of the peculiarities of the PGM industry that imperial units, and specifically troy ounces, are still in common use. Many buyers on world markets and end-users and manufacturers in the USA and the UK still persist in using the imperial unit, and many producers have also not bothered to change. Important amounts of the PGM are therefore given in troy ounces as well as in metric units, but this is the only imperial unit that is used. The term 'ton' (abbreviation t) refers to the metric ton of 1000 kg. The comma (,) is used as the decimal indicator between digits.

Appendix I explains the SI system of units in greater detail.

Chapter 2

SOURCES AND RESOURCES

GLOBAL deposits containing the PGE are invariably related to, or contained within, either differentially stratified and layered or massive mafic to basaltic magmatic complexes that have intruded stable cratonic or continental rocks at various periods in geological time. They may also occur as primary hydrothermal-magmatic deposits associated with major continental rifting. The historically oldest exploited deposits, which are currently of lesser global importance, are the placer gravels in which the PGE have undergone secondary concentration by rivers draining mountainous areas in which weathered ultramafic to mafic rocks of various ages occur. This process has taken place throughout geological time.

Apart from the placers, PGE deposits are always associated with nickel-copper sulphides in magmatic rocks. Naldrett (1980, 1989) has classified these deposits into two main categories: the PGE-dominated deposits and the Ni-Cu dominated deposits.

The economics of mining and extraction of deposits in the first category depend directly on the current market prices of the individual PGE. The economics of deposits of the second group are determined by the ruling markets and prices for the base metals (nickel and copper), the PGE being by-product of the Ni-Cu exploitation process.

The PGE-dominated deposits include the Merensky-type deposits, which include the Merensky Reef itself, the UG2 chromitite and the Platreef deposits, the deposits of the Great Dyke of Zimbabwe, the Stillwater deposit of the USA, and the Lac des Isles deposit of Canada. The Ni-Cu dominated deposits include the Sudbury deposit of Canada, the ores related to continental rifting — such as those in the Noril'sk-Talnakh area of Russia, the Finnish deposits, the Jinchuan deposits of northwest China, the Duluth complex of the USA, and the numerous deposits related to komatites of the ancient greenstone belts.

2.1. The Republic of South Africa

The Bushveld Complex is the largest and most important repository of the PGE in the world. It contains (Odendaal, 1992) at least 85 per cent of the world's PGE reserves, and is responsible for some 49 per cent of its supply. The magmatic event that gave rise to the Complex commenced with the extrusion of large volumes of basaltic (Dullstroom) and felsic (Rooiberg) magma at the close of the Transvaal sedimentation. This sedimentary pile was then intruded by a 2 km thickness of pre-Bushveld sills, followed closely at 2095 My by the main mafic sequence, and ultimately by the intrusion of the various Bushveld granites. The mafic magma spread upward and laterally along shallow-angled

fractures (Sharpe and Snyman, 1980), giving rise to seven shallow, overlapping cone-like intrusions, the feeders of which are marked by major gravity anomalies. These cones were eventually enlarged, with the addition of more magma, to produce the three main magma lobes, or compartments, in the western, eastern, and Potgietersrus sectors of the Bushveld Complex. The rock sequences in these separate intrusions are broadly similar, particularly in the middle (upper critical and lower main zone) portions, although detailed work has also highlighted many differences. This illustrates that fractional crystallization of a basaltic magma, will under similar conditions, yield successions of layered rocks. This concept holds for all the major layered intrusions of the world.

Apart from the minor satellite bodies (in Botswana and at Nietverdiend in the western Transvaal), the main Complex has an elliptical form (Vermaak, 1976b), measuring 370 km in an east-west direction and 365 km in a NW-SE direction (Figure 2.1). It covers an area of some 60 000 km², large tracts of which are covered by younger geological formations. The thickness of the mafic rocks varies between 7 and 9 km. The two main bracket-like western and eastern lobes (Figures 2.2 and 2.3) are here termed the 'main' Bushveld Complex, as distinct from the north-trending Potgietersrus lobe, which has been treated as a separate entity.

The stratigraphy of the Bushveld Complex (Figure 2.4) resembles that of most major layered intrusions. The lower part contains dark-coloured and dense ultramafic rocks, and the upper part, light-coloured gabbro-noritic rocks. The contact zone of the Complex with the Transvaal sediments consists of chilled rocks of varying composition, depending on the part of the Complex in contact with the sedimentary floor or wall. The lower zone, 1700 m in thickness, consists mostly of cyclical ultramafic units (harzburgites, bronzites, feldspathic bronzitites, and minor norites. These make up roughly 18.5 per cent of the Complex. They are followed by the important critical zone, which contains all the mineralized layers of interest. It consists of cyclic units of chromitites and bronzites at the base, followed by repetitive cycles of chromitites, orthopyroxenites, norites, and anorthosites from the base upwards.

The critical zone is 1400 m thick and makes up about 15 per cent of the Complex. It is remarkable for the enormous lateral extent and persistence of the its mineralized and non-mineralized layers, which measure tens — if not hundreds — of kilometres, seemingly with little variation. The main zone consists of 3900 m of norites, gabbro-norites, gabbros, and anorthosites, comprising 42.4 per cent of the Complex. The upper zone which consists of 2200 m of magnetite layers,