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MINERAL DEPOSIT MODELS: NICKEL SULFIDE DEPOSITS OF THE KAMBALDA TYPE[1]

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ABSTRACT

Mineral deposit models provide a framework for research in economic geology as well as a basis for mineral exploration and resource assessment. Three kinds of models are recognized: descriptive, genetic and process. Although well-documented descriptive models are of the most direct use to the exploration geologist, it is very difficult to develop a sound descriptive model in the absence of a good genetic model. Similarly, the formulation of genetic models relies upon an understanding of the physics and chemistry of ore-forming processes. The development of mineral deposit models is therefore an iterative process. Kambalda-type nickel sulfide deposits provide a useful illustration of the relationship among the three kinds of deposit models. Models of the process of magmatic segregation suggest that the sulfide ores formed by batch segregation and that the magma was sulfide-saturated during fractional crystallization that produced the differentiation of the komatiite sequence overlying the ores. This implies that assimilation of crustal sulfur, which makes up a significant proportion of the sulfur in the ore, occurred at depth rather than by thermal erosion of footwall rocks as the komatiite lavas flowed across the seafloor. This suggests, in turn, that the occurrence of sulfidic sediments at the top of the footwall succession is not an essential element of the descriptive model. The concentration of platinum-group elements in spinifex-textured rocks at Kambalda implies lower partition coefficients and higher silicate liquid : sulfide liquid ratios than generally believed.

Keywords: mineral deposits, models, Kambalda-type nickel sulfide deposits, platinum-group elements, partition coefficients.

SOMMAIRE

Les modèles visant à expliquer l'origine des gîtes minéraux favorisent un bon encadrement des activités de recherche en géologie économique, et offrent aussi une base pour l'exploration minérale et l'évaluation des ressources. Trois sortes de modèles sont impliqués: descriptif, génétique, et orienté aux processus. Quoique ce sont les modèles descriptifs bien étayés qui ont l'utilité la plus immédiate pour le géologue impliqué dans un programme d'exploration, il est très difficile de développer un modèle descriptif correct sans modèle génétique. De même, la formulation d'un modèle génétique repose sur les connaissances de la physique et la chimie des processus de formation du minerai. Le développement d'un modèle pour expliquer une catégorie de gîtes minéraux résulte donc d'itérations. Les gîtes de sulfures de nickel du type Kambalda illustrent bien la relation parmi les trois sortes de modèles. Les modèles du processus de ségrégation magmatique font penser que le minerai a été formé par ségrégation lors d'une seule étape et que le magma était saturé par rapport aux sulfures lors de sa cristallisation fractionnée, qui rend compte de la différenciation de la séquence komatiitique au dessus des niveaux minéralisés. L'assimilation du soufre d'origine crustale, fraction importante du soufre du minerai, a eu lieu à une profondeur non spécifiée plutôt que par érosion thermique des roches encaissantes au cours de l'épanchement des laves komatiitiques sur les fonds océaniques. Ceci suppose donc que la présence de sédiments sulfurés dans la partie supérieure de la séquence de roches sous-jacentes n'est pas un élément essentiel du modèle descriptif. La concentration des éléments du groupe du platine dans les roches à spinifex à Kambalda impliquent des coefficients de partage plus faibles et des rapports de liquide silicaté à liquide sulfuré plus élevés que ceux qui sont couramment acceptés.

(Traduit par la Rédaction)

Mots-clés: gîtes minéraux, modèles, gisements de sulfures de nickel de type Kambalda, éléments du groupe du platine, coefficients de partage.

INTRODUCTION

Mineral deposit models are a major preoccupation of economic geologists, whether they work in industry, academia or government surveys. Mineral exploration and resource assessment are usually based on the combination of regional geological knowledge with one or more deposit models. The formulation of deposit models is an important objective of numerous research projects. Indeed, it is difficult to find a paper in the contemporary literature on economic geology that does not use the term "model".

The geological surveys of both Canada and the United States have produced compendia of mineral deposit models (Eckstrand 1984, Cox & Singer 1986). However, given the currency of deposit models, it is curious that more effort has not been devoted to the definition of different kinds of models and to an understanding of the model-building process. Terms such as conceptual, genetic, process, descrip-

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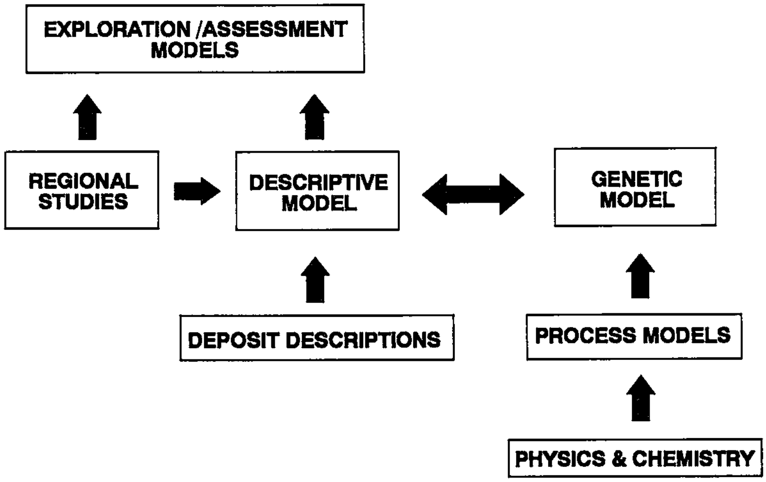

FIG. 1. The relationships among descriptive, genetic and process models.

tive, empirical, grade-tonnage, and probability of occurrence are in common use to denote different kinds of models, but there is not yet a single, universally accepted terminology. For the present purposes, I will define three types of mineral deposit models: descriptive, genetic and process. My terminology is similar to that of Cox & Singer (1986) and Barton (1986), except that I regard the "grade-tonnage model" as an integral part of the descriptive model.

Descriptive models derive from the documentation of the geological, geochemical and geophysical features of individual mineral deposits. A model may be based on a single deposit, but more typically comprises the essential common attributes of a group of related deposits. Genetic models describe the origin of a deposit or deposit type and represent the combination of a descriptive model with one or more process models. Process models simulate physical and chemical ore-forming processes, and are generic inasmuch as they may apply to a variety of deposit types. Conversely, a single genetic model will normally incorporate a number of different processes (Barton 1986). The industry geologist engaged in mineral exploration and the government geologist carrying out a mineral-resource assessment combine descriptive deposit models with an understanding of the regional geological framework to develop exploration or resource-potential models. These relationships are illustrated in Figure 1.

I believe that of the various kinds of mineral deposit models, well-documented descriptive models are of the most direct use in mineral exploration or resource assessment. However, it is very difficult to develop a sound descriptive model in the absence of a good genetic model. It is only by understanding the origin of a deposit type that we can identify its truly critical attributes. Descriptive data, whether qualitative or quantitative, are often collected within the framework of a genetic model or "working hypothesis". However, the model must not be allowed to blind the scientist to other possibilities. Data are all too often collected to prove rather than truly test a favored hypothesis.

In this paper, I will attempt to illustrate the linkages among these various types of model by reference to an important class of deposits that have been one of my particular research interests: nickel sulfide deposits of the Kambalda type.

DESCRIPTIVE MODEL

Kambalda-type nickel sulfide deposits occur in sequences of extrusive komatiites in Archean greenstone terranes in Australia, Canada and Zimbabwe. I believe that the first deposit of this type to be mined was the Alexo near Timmins, Ontario; however, the most important production has come from numerous deposits at Kambalda in Western Australia.

An excellent description of the Kambalda deposits has been published by Gresham & Loftus-Hills (1981). Figure 2 is a cross- section of the Lunnon Shoot deposit, which was the first to be discovered and to go into production at Kambalda. This diagram is from the classic paper by Ross & Hopkins (1975), who recognized that the ultramafic sequence was a succession of ultramafic lavas and that the "ore shoots" appear to be localized in footwall depressions. They suggested that these depressions are bounded by faults that were active when the ore was emplaced. The sulfide deposits are typically small but of relatively high grade, and tend to occur in clusters. For example, reserves and past produc-

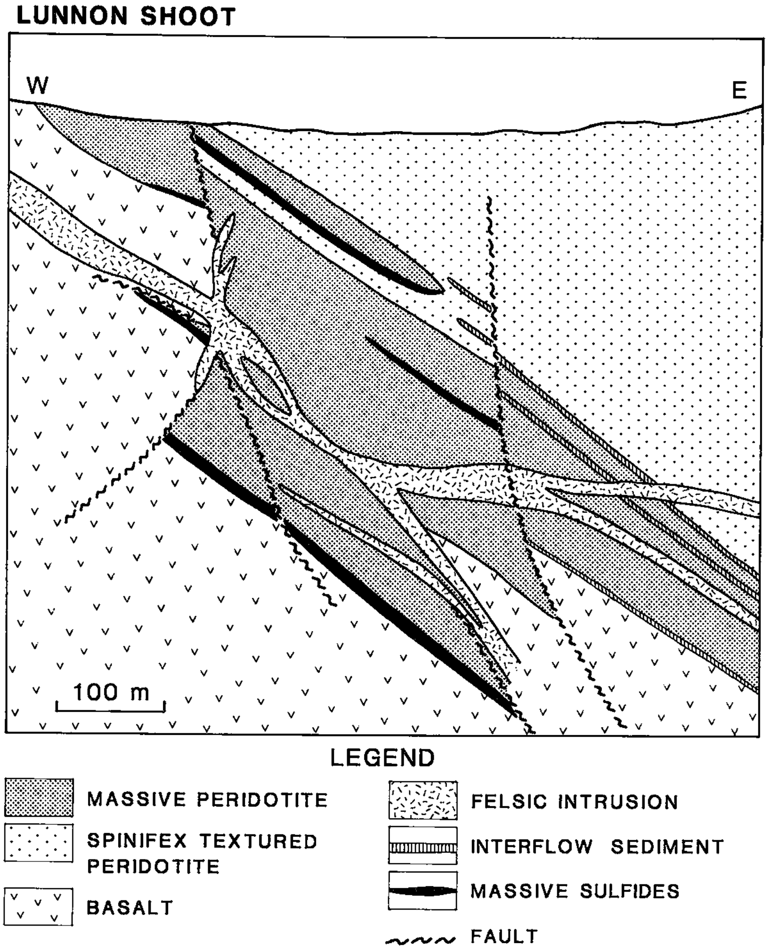

FIG. 2. Geological cross-section of the Lunnon Shoot deposit, Kambalda (after Ross & Hopkins 1975).

tion for 18 deposits at Kambalda amounted to 34 million tonnes grading 3.2% Ni (Gresham & Loftus-Hills 1981).

Some essential features of a descriptive model for Kambalda-type deposits are depicted in Figure 3. The nickel sulfide deposits occur in the lower parts of komatiitic lava sequences. The bulk of the ore is at the base of the lowermost flow-unit, directly in contact with footwall rocks, but some massive sulfides do occur at the base of overlying flows. The ore-bearing flow units toward the base of succession are distinctly thicker and more magnesium-rich than those higher up. Individual komatiite flows in the lower part may exceed 100 m in thickness in the ore environment, and are typically 15 to 20 m thick remote from ore. In contrast, flows from 1 to 10 m thick characterize the upper part of the sequence.

Two elements of the descriptive model have loomed large in the formulation of genetic models. These are the localization of ore in footwall troughs or embayments and the occurrence of sulfide-rich interflow sediments at the ore horizon but outside the immediate environment of the ore. The major footwall troughs are from 1000 m to more than 2300 m in length and generally 150 to 250 m in width (Gresham & Loftus-Hills 1981). They have been variously interpreted as primary topographic irregularities (Lesher *et al.* 1984), depressions bounded by faults that were active during volcanism (Ross & Hopkins 1975), thermal erosion channels (Huppert *et al.* 1984), or artifacts of deformation (Cowden 1988).

GENETIC MODELS

Deposits of the Kambalda type have been

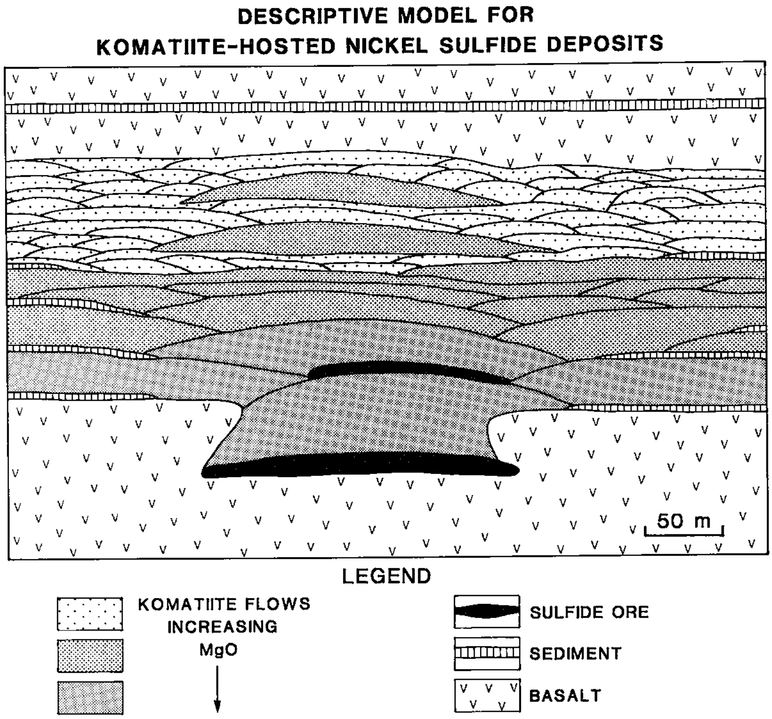

FIG. 3. Elements of the descriptive model for Kambalda-type deposits (after Lesher *et al.* 1981).

attributed to a variety of origins, including metasomatic replacement and volcanic exhalation; however, it has now been established beyond reasonable doubt that they formed by processes of magmatic segregation. Figure 4 illustrates the various stages in the generation and evolution of magmatic sulfide deposits and their parent magmas. The parental komatiite magmas are known to have been derived by partial melting of peridotite at depths of 200 kilometers or more in the mantle. These magmas eventually found their way to the surface and were extruded as lavas on the seafloor. What happened in between is less clear, but the fact that the komatiite sequences are differentiated, with the most primitive lavas at the base, suggests that the magmas underwent fractional crystallization during their ascent.

The existence of magmatic sulfide deposits requires that at least four events happened. Sulfur was incorporated in the magma, the magma became saturated in sulfide and liquation occurred, the immiscible sulfide phase segregated and, finally, the sulfides accumulated and were emplaced. It is the precise location and timing of these four processes that are critical to our understanding of the ore deposits.

According to early models, sulfur was incorporated in the zone of partial melting in the mantle. Naldrett (1973) postulated that sulfide would be molten in the uppermost part of the mantle and that the source region of komatiites could become enriched by downward percolation. He suggested that liquation may have occurred in the zone of melting or during magmatic ascent, the molten sulfides being carried upward as finely dispersed droplets. Segregation of sulfides and accumulation in the footwall embayments could have occurred by a rifling process during lateral flow (Naldrett & Campbell 1982).

Other authors have argued that the contrasting viscosities and densities of sulfide and silicate melts would have led to effective segregation during vertical or horizontal flow. Indeed, in one of the first models to explain the emplacement of the melts, Ross & Hopkins (1975) suggested that sulfide and silicate magmas became segregated during vertical flow such that the sulfide was emplaced before the silicate.

One of the most important realizations over the past decade is that the ores contain a significant proportion of crustal sulfur, which means that incorporation of sulfur occurred after the magma had ascended into the crust. Perhaps the best evidence for this is the selenium/sulfur ratio of the ores, which is very different from the mantle value but similar to the value in sedimentary sulfides (Green & Naldrett 1981, Eckstrand & Hulbert 1987).

The quantitative thermal and flow models of Huppert *et al.* (1984) indicate that komatiites are characterized by regimes of turbulent flow and are capable of melting footwall rocks. This led them to suggest that the footwall embayments, which contain the ore, were formed by thermal erosion. They suggested, furthermore, that sulfur was incorporated following eruption of the magma by assimilation of sulfidic sediments as the lava flowed across the seafloor. This is not merely of academic interest; if the proposal is correct, it means that the presence of sediments at or near the top of the footwall succession is a prerequisite of ore formation which, in turn, has important implications for any exploration model.

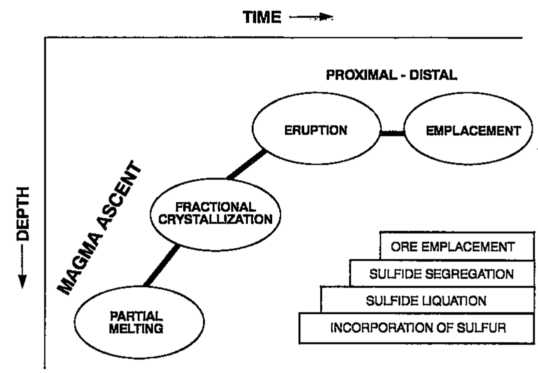

FIG. 4. A framework for the development of genetic models for magmatic sulfide deposits. The timing and location of the four processes listed in the lower right are critical to an understanding of ore genesis.

PROCESS MODELS

A number of quantitative process-models have been applied to the genesis of Kambalda-type deposits. For example, Usselman *et al.* (1979) used thermal calculations to quantify the "billiard ball model" of Naldrett (1973) to account for the disposition of massive, net-textured and disseminated sulfides. Reference was made above to Huppert *et al.* (1984), who modeled the emplacement and cooling of komatiite flows. I would like to examine two models of the process of magmatic segregation and see how these constrain the descriptive and genetic models. These are the fractional segregation model (Duke & Naldrett 1978) and the batch segregation model (Campbell & Naldrett 1979).

Fractional segregation

A significant aspect of the descriptive model is the presence of a differentiated succession of komatiites, with the most primitive lavas at the base and an upward decrease in magnesium content of the spinifex-textured rocks. This differentiation is best explained by the fractional crystallization of olivine from the parental magma in a magma chamber at depth. If the magma is saturated with sulfide, however, crystallization of olivine will cause the liquation of sulfide. Segregation and accumulation of the olivine and sulfide on the floor of the magma chamber preclude further equilibration with the main body of magma. Alternatively, finely dispersed sulfide droplets may be carried to the earth's surface, where they may accumulate by, for example, a rifling process.

Duke & Naldrett (1978) and Duke (1979) quantitatively modeled the fractional segregation process in order to predict whether there are compositional differences between the differentiation products of sulfide-undersaturated magmas and sulfide-saturated (and potentially ore-bearing) sequences. Their model showed that fractional segregation of sulfide would deplete the magma in chalcophile elements by an amount proportional to the solubility of sulfide. The concentrations of Ni and MgO in model komatiite liquid undergoing fractional segregation are illustrated in Figure 5.

This model was tested by Lesher *et al.* (1981), who showed that spinifex-textured peridotites from the entire Kambalda succession are indeed depleted in nickel. Although the data are scattered, they are consistent with the differentiation of a parental magma initially containing 32% MgO by fractional segregation of olivine and sulfide in a average ratio of 200 to 1.

The numerical model of Duke & Naldrett (1978) also allows calculation of the compositions of fractionally segregated sulfide (Fig. 6). The average composition of the Kambalda millhead, recalculated to 100% sulfide, plots reasonably close to the cumulative sulfide for an olivine:sulfide ratio of 200. Therefore, one might propose that the ores at Kambalda represent sulfides accumulated during differentiation of the silicate liquid from 32 to 20% MgO. However, although such a model would be consistent with the observed compositions of both silicate and sulfide compositions, it would be difficult to reconcile with the occurrence of the orebodies at the base of the ultramafic sequence in association with the most magnesian komatiites. If the ores had formed by the accumulation of fractionally segregated sulfides, they should occur at the top of the ultramafic pile, in association with less magnesian flows.

Batch segregation

This process is conceptually very simple: the sulfide liquates and segregates in a single stage, thereby

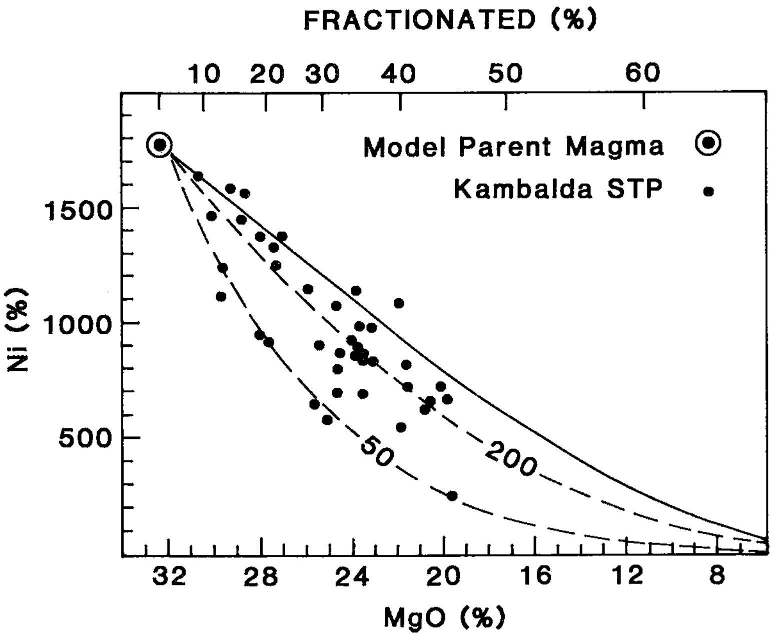

FIG. 5. The concentration of Ni and MgO in komatiitic liquid undergoing fractional crystallization of olivine under sulfide-undersaturated (solid line) and sulfide-saturated conditions (dashed lines; numbers give olivine:sulfide ratio). The compositions of spinifex-textured peridotites from Kambalda (Lesher *et al.* 1981) are consistent with fractional segregation of olivine and sulfide in a 200:1 ratio.

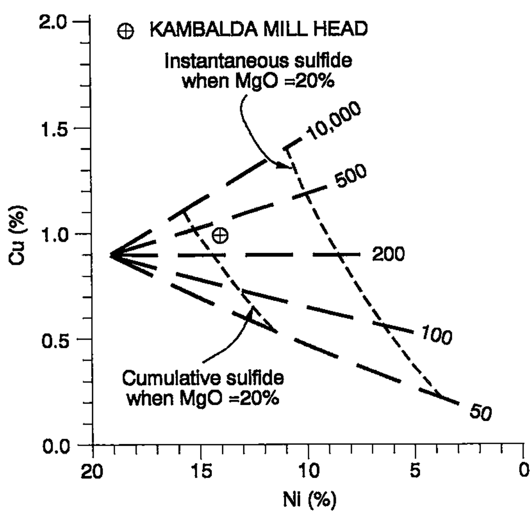

FIG. 6. The concentrations of Ni and Cu in fractionally segregating sulfides. The dashed lines give the compositional trends for a range of olivine:sulfide ratios. The dotted lines indicate the compositions of the sulfide segregating when the silicate liquid contains 20% MgO (instantaneous) as well as the average composition of all the sulfide that has segregated up to that point (cumulative).

equilibrating with the entire body of magma. Intuitively, this model is more consistent with the observed field relationships of the Kambalda-type deposits.

The batch segregation process was quantitatively modeled by Campbell & Naldrett (1979). A key parameter in the calculation is the so-called "*R* factor", the mass ratio of silicate liquid to sulfide liquid. The parental liquids for the lower, ore-bearing member of the Kambalda succession are inferred to have contained from 28 to 32% MgO (Lesher & Groves 1984), and the variation of Ni and Cu concentrations in sulfides equilibrating with this range of liquids is shown as a function of *R* in Figure 7.

It is difficult if not impossible to calculate the *R* factor that prevailed in a natural system with any degree of certainty. Naldrett *et al.* (1979) suggested that the compositions of Kambalda sulfides indicate an *R* factor of 2500. More recently, the low concentration of platinum-group elements (*PGE*) in the ores has been used to argue that the *R* factor was as low as about 500 (Naldrett 1981) or even 300 (Campbell & Barnes 1984).

An alternative estimate of the *R* factor that prevailed at Kambalda can be made on the basis of the observed proportions of the ores and their host rocks. Suppose that the ultramafic succession

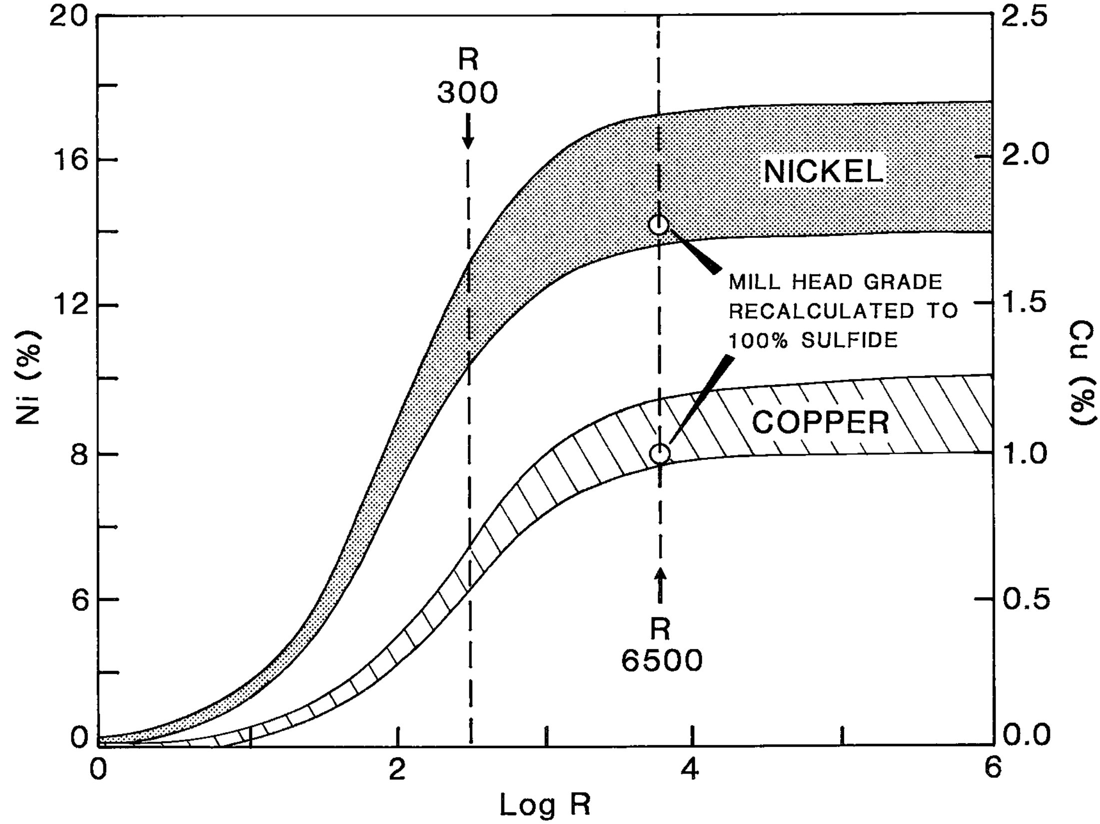

FIG. 7. Concentrations of Ni and Cu in sulfides resulting from batch equilibration with komatiite liquids containing from 28% to 32% MgO as a function of R, the mass ratio of silicate to sulfide. The concentrations in the Kambalda millhead, recalculated to 100% sulfide (Ross & Keays 1979) are plotted for R = 6500, the value inferred in this paper.

represents the volume of silicate liquid derived by the differentiation of a parental komatiitic magma in a crustal chamber. The average thickness of the sequence is 500 m (Gresham & Loftus-Hills 1981). The observed range of chill spinifex compositions, 32 to 20% MgO, implies that derivative silicate liquids accounted for 53% of the initial mass of magma (Duke & Naldrett 1978). Therefore, the observed ultramafic rocks equate to a 943-m-thick body of parent magma. The average thickness of the orebodies, expressed as massive sulfide equivalent, is about 1 m, and Lesher *et al.* (1981) have estimated that about 10% of the footwall surface at Kambalda is mineralized. After correcting for the different specific gravities of molten silicate and sulfide, the resultant R factor is about 6500.

The Ni and Cu concentrations in the average Kambalda millhead composition falls within the range of model compositions for R factors of about 1000 or greater (Fig. 7). Therefore, batch segregation would appear to be a viable ore-forming process at Kambalda. However, this process does not account for the depletion of chalcophile elements observed in the compositions of spinifex-textured peridotites in the overlying ultramafic succession, which indicates protracted fractional segregation of olivine and sulfide.

IMPLICATIONS FOR GENETIC AND DESCRIPTIVE MODELS

These process models impose the following constraints on the genetic model for Kambalda-type deposits:

(1) The sulfide ores probably formed by a batch segregation process. This was followed by fractional segregation of sulfide during subsequent magmatic differentiation, as indicated by the Ni depletion in the ultramafic sequence overlying the ore.

(2) Although much of the differentiation within individual komatiite flows probably occurred *in situ* (Lesher *et al.* 1984), the overall upward decrease in Mg content of the succession most likely reflects fractional crystallization of olivine at depth.

(3) These considerations suggest that the magma

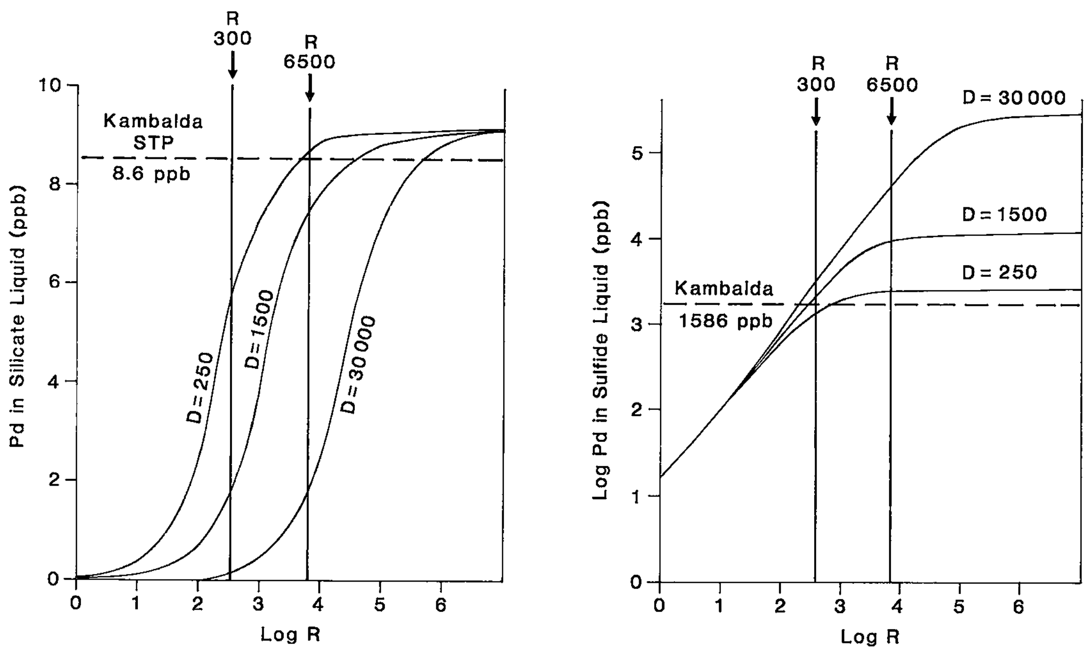

FIG. 8. Concentration of Pd in silicate and sulfide liquids resulting from batch equilibration as a function of *R* and plotted for partition coefficients of 250, 1500 and 30,000. The concentration of Pd in the Kambalda millhead (recalculated to 100% sulfide) and in spinifex-textured peridotite are from Ross & Keays (1979) and Keays (1982), respectively.

incorporated sulfur prior to fractional crystallization and therefore prior to eruption.

(4) Although sulfur-to-selenium ratios are consistent with the derivation of sulfur from sulfidic sediments, assimilation must have occurred in a crustal magma chamber rather than by thermal erosion of sediments as the komatiite lavas flowed across the seafloor.

The process models have two important implications for descriptive and exploration models:

(1) If, as seems likely, assimilation of sulfur occurred at depth, prior to fractional crystallization, the presence of sulfidic sediments at the top of the footwall succession is not a prerequisite for ore.

(2) Even though fractional segregation does not appear to have given rise to the sulfides that constitute the massive orebodies, its occurrence subsequent to ore accumulation bestowed a distinctive geochemical signature upon the overlying ultramafic rocks of the ore-bearing sequence. This signature is present in rocks several hundred meters stratigraphically removed from the orebodies, and may be useful in identifying successions of mineralized komatiite (Duke & Naldrett 1978, Naldrett *et al.* 1984).

THE PGE PROBLEM

The concentrations of *PGE* in the ores and the associated succession of komatiites are not entirely consistent with these conclusions, given our current understanding of the partitioning behavior of these elements. The problem is illustrated in Figure 8, where the concentration of Pd resulting from the batch equilibration of molten silicate and sulfide is plotted as a function of *R*. There is no reliable experimental determination of the value of the partition coefficients for the *PGE*, and estimates range over three orders of magnitude. Note that the partition coefficient *D* is given by the ratio of the concentrations of an element in two phases in equilibrium. In the present context, *D* is the ratio of the concentration of Pd in molten sulfide to concentration of Pd in silicate liquid. Naldrett *et al.* (1979) proposed that the *D* for Pd is 1500, but subsequent investigators have proposed values on the order of 10^4 to 10^5 (*e.g.*, Campbell & Barnes 1984). Similarly, there are insufficient data on the concentrations of *PGE* in komatiites, particularly those spinifex-textured rocks that represent parent liquids, to make an accurate estimate of the Pd concentration in the Kambalda parent magma. In the event, I have used 9.2 ppb, the average of 42 spinifex-textured peridotites reported by Keays (1982).

As noted above, many investigators believe that the very high inferred partition-coefficients for the *PGE* and the relatively low concentrations of *PGE* in the Kambalda ores require that the sulfides equilibrated with a relatively small proportion of silicate liquid. However, although batch equilibration with an R factor of 300 and a D of 30,000 yields a reasonable match for the concentration of *PGE* in the sulfide, the silicate liquids would be almost completely stripped of their *PGE* (*i.e.,* 0.1 ppb Pd). In fact, the spinifex-textured rocks at Kambalda do not appear to be strongly depleted in the *PGE*. For example, 10 samples from thin, overlying komatiite flows range from 4 to 14 ppb Pd and average 8.9 ppb (Keays 1982). In order for the model to achieve a match of both sulfide and silicate compositions, a combination of a higher R factor and a lower partition coefficient is required. Using the R factor of 6500 calculated above, a reasonable match is obtained with a partition coefficent of 250 for Pd, the same as that used for Cu.

The resolution of the *PGE* problem will require a much better understanding of the partitioning behavior of these elements in silicate–sulfide systems, as well as more precise documentation of their concentrations in komatiites. In the meantime, we cannot have complete confidence in the genetic model.

Conclusion

In this paper, I have attempted to demonstrate the interrelationships among different kinds of mineral deposit models. My premise has been that whereas descriptive models are of the most direct use in mineral exploration or resource assessment activities, it is difficult to construct a sound descriptive model in the absence of a good genetic model. Genetic models, in turn, are based on an array of geological process-models that may be either qualitative or quantitative. Our ability to quantitatively model ore-forming processes is still in the formative stages. Too often it is possible to model only one or two of the processes that may have contributed to the formation of a mineral deposit. Ultimately, a much better genetic understanding will be achieved when it is possible to quantitatively and simultaneously model all relevant processes.

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