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THE RELATIVE ROLES OF MAGMATIC SEGREGATION, VOLCANIC EXHALATION AND REGIONAL METAMORPHISM IN THE GENERATION OF VOLCANIC-ASSOCIATED NICKEL ORES OF WESTERN AUSTRALIA

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ABSTRACT

Archean nickel deposits of Western Australia are related to highly magnesian, phenocryst-rich ultramafic flows (or subvolcanic sills or both) of komatiitic affinity within sequences of komatiitic and tholeiitic volcanic rocks and volcanogenic metasedimentary units. Despite an amphibolite-facies metamorphic imprint, many primary features can be determined. Lack of wall-rock alteration beneath most basal massive ores, and comparative geochemistry of massive ores and along-strike volcanic-exhalative sulfidic metasediments, indicate that most ores did *not* form by exhalative processes. Ore association with the ultramafic units, consistent Ni/Cu ratio, abundant platinum-group elements (PGE), relatively low Pd/Ir ratios and contained ferrochromites indicate initial crystallization of sulfides and spinels from immiscible oxy-sulfide liquids. The sulfur contents of mineralized and unmineralized ultramafic units, and $\delta^{34}S$, S/Se and mean Ni/Fe ratio of ores, are equally consistent with two magmatic models: (1) contamination of ultrabasic lavas by Fe-sulfide-rich metasediments; (2) eruption of phenocryst-rich melt carrying sulfide droplets derived from a pre-existing reservoir of sulfide liquid. Model (2) is favored by lack of evidence for contamination, combined with observed undepleted Ni and PGE contents of mineralized ultramafic units and igneous olivines. The proposed model for massive sulfide production postulates both gravity separation and differential flow between silicate liquid, olivine-rich mush and sulfide liquid during eruption of a single flow. In some environments metamorphic upgrading of more disseminated sulfides offers an alternate mechanism of formation for sulfide-rich matrix ore as well as massive ore; metamorphic modification and remobilization of ores are common features.

SOMMAIRE

Les gisements nickelifères archéens de l'Australie occidentale sont associés à des coulées (ou des filons-couches) ultramafiques komatiitiques, très magnésiens et riches en phénocristaux, dans des séquences de laves tholéitiques et komatiitiques et de roches métasédimentaires volcanogéniques. Sous l'oblitération d'un métamorphisme à facies amphibolite, plusieurs caractères primaires restent visibles. L'absence d'altération des roches encaissantes en-dessous du minerai massif, et la géochimie comparée de ce minerai et de métasédiments sulfurés latéraux provenant d'émanations volcaniques, montrent que ces émanations ne sont pas, en général, à l'origine de la minéralisation. L'association du minerai aux unités ultramafiques, des rapports Ni/Cu convenables, l'abondance des éléments du groupe du platine, de faibles rapports Pd/Ir et la présence de ferrochromites, tout indique que la cristallisation initiale s'est produite à partir de liquides immiscibles à oxy-sulfures. La teneur en soufre des unités ultramafiques minéralisées et stériles, ainsi que $\delta^{34}S$, S/Se et Ni/Fe moyen du minerai, sont compatibles avec deux modèles magmatiques: (1) contamination de laves ultrabasiques par des sédiments riches en sulfures de fer; (2) éruption de roches en fusion riches en phénocristaux, chargées de gouttelettes de sulfures provenant d'un réservoir préexistant de liquide sulfuré. Le deuxième modèle est préférable, vu l'insuffisance d'indices de contamination et la préservation des teneurs originelles, en nickel et en métaux du groupe du platine, des unités ultramafiques minéralisées et des olivines ignées. Le modèle proposé postule à la fois un triage par gravité et un écoulement différentiel (entre liquide silicaté, bouillie d'olivine et liquide sulfuré) pendant l'éruption d'une seule coulée. Dans certaines conditions de milieu, l'enrichissement de sulfures du type disséminé, à la suite du métamorphisme, expliquerait aussi bien l'origine du minerai, tant interstitiel que massif; la modification par métamorphisme et la remobilisation du minerai par métamorphisme sont phénomènes courants.

(Traduit par la Rédaction)

INTRODUCTION

Following discovery of Kambalda there was rapid realization that it represented a new type

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of Ni–Cu deposit, and subsequent exploration in Western Australia led to discovery of several similar ores (*e.g.*, Windarra, South Windarra, Scotia, Nepean, Mt. Edwards, Spargoville, Redross and Wannaway). Equivalent deposits occur in Canada (*e.g.*, Naldrett 1973, Green 1978) and some Rhodesian ores (*e.g.*, Trojan, Perseverance, Shangani) show similarities (*e.g.*, Viljoen *et al.* 1976, Anderson *et al.*, in press) although the deposits are generally poorly documented.

The term volcanic-associated Fe–Ni–Cu sulfide deposit (Groves & Hudson, in prep.) defines ores associated with komatiitic ultramafic flows (or shallow sills, or both) within sequences of komatiitic and associated tholeiitic volcanic and volcanogenic metasedimentary rocks. They are equivalent to volcanic-type ores of Barrett *et al.* (1977) and to class 1-(ii) lenses of Naldrett (1973).

The objectives of this paper are to summarize the important characteristics of the volcanic-associated ores of Western Australia, to critically review the various genetic models erected to explain them, and to highlight any outstanding problems.

MAJOR FEATURES OF VOLCANIC-ASSOCIATED DEPOSITS

The regional setting of volcanic-associated nickel deposits in Western Australia is described by Barrett *et al.* (1977, Fig. 1). The deposits are typically located in amphibolite-facies environments (Barrett *et al.* 1977, Table 1) around the periphery of granite-cored domes. Most deposits occur in mid- to high-amphibolite-facies metamorphic environments of high strain, although the Kambalda deposits occur in a lowermost-amphibolite-facies and low-strain environment. The orebodies typically exhibit elongation subparallel to the dominant regional fold or extensional axes (*e.g.*, Windarra, South Windarra, Kambalda, Scotia), or are controlled by prominent shear zones (*e.g.*, Redross). Most structures and all textures of the ores are metamorphic, with many ores having tectonite fabrics (*e.g.*, Barrett *et al.* 1977, Ostwald & Lusk 1978).

Although there is a strong tectonic and metamorphic imprint, it is possible to understand the mineralization environment by selectively studying areas of relatively low strain (*e.g.*, Ewers & Hudson 1972, Ross & Hopkins 1975) or com-

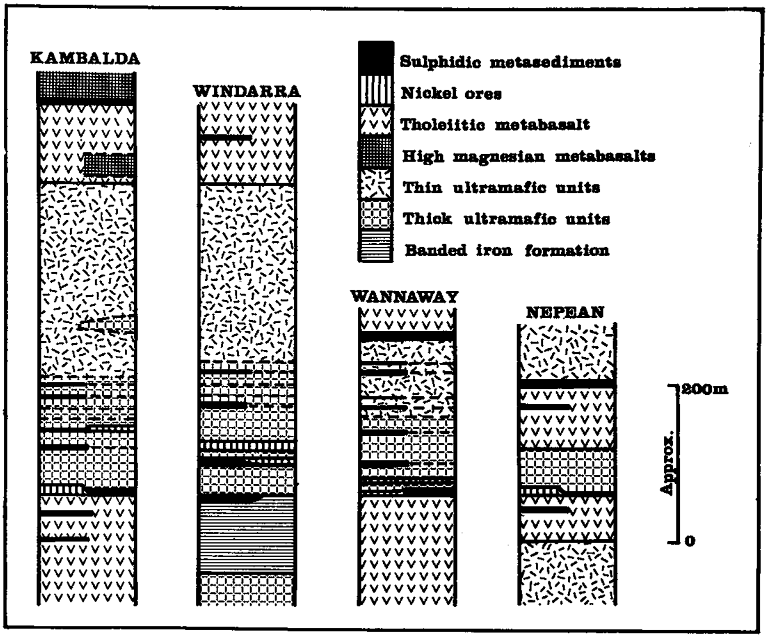

FIG. 1. Schematic stratigraphic sections showing distribution of nickel ores and sulfide-rich metasediments at Kambalda, Nepean, Wannaway and Windarra. Thickness of sulfidic metasedimentary units is exaggerated and is shown as a function of lateral persistence. The distinction between dominantly thin ultramafic flows and dominantly thick flows is arbitrarily taken as *ca.* 10 m. Dashed lines represent flow boundaries.

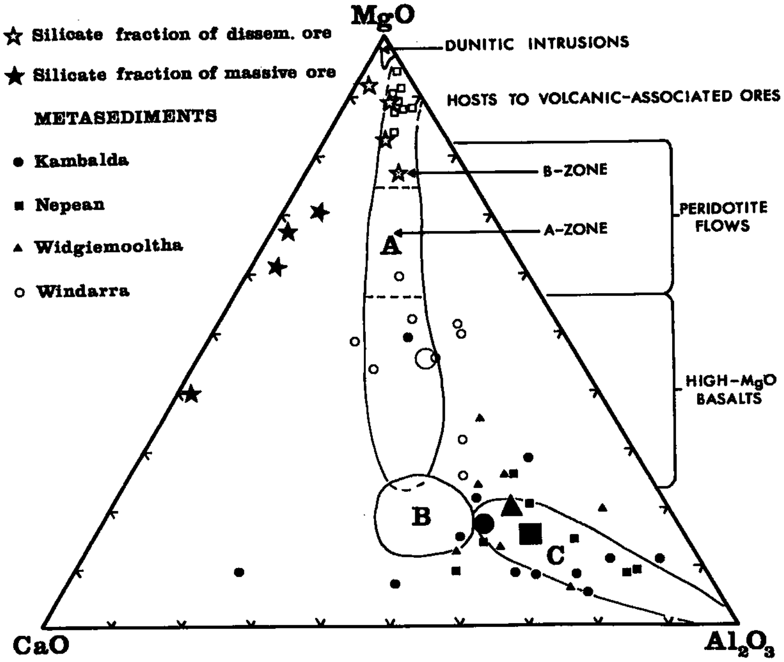

FIG. 2. CaO–MgO–Al_2O_3 plot of analytical data for mineralized ultramafic rocks, silicate fraction of ores and sulfidic metasediments. Large symbols for metasediments are arithmetic mean compositions. Data for silicate fraction of ores are taken from Ross & Hopkins (1975, Table 6) and from Table 2. Data for Kambalda metasediments contributed by O.A. Bavinton of Western Mining Corporation. Marked fields are as follows: A. field of komatiites, overlapping with B at low MgO end (*e.g.*, Nesbitt & Sun 1976); B. field of tholeiitic metabasalts (*e.g.*, Hallberg 1972); C. field of Archean calc-alkaline rocks from Western Australia (*e.g.*, Hallberg *et al.* 1976).

bining metamorphic and structural studies with mineralogical and geochemical studies of the ore environment (*e.g.*, Barrett *et al.* 1976), or both. Generalized stratigraphic sections of the better documented examples (Fig. 1) show the relationship of the ore to the enclosing rocks.

The sulfide ores are at or towards the base of peridotitic komatiite lenses, up to *ca.* 150 m but generally 30 to 50 m thick, that are most probably the basal portions of ultramafic lava flows; although an origin as subvolcanic sills cannot be completely negated, the units are discussed as flows in the following discussion. These may now be talc–carbonate rocks (*e.g.*, Windarra, Redross, Kambalda), serpentinites (Kambalda, Wannaway, Scotia) or partly serpentinized forsterite–talc rocks (Nepean). They are typically overlain by progressively thinner and less magnesian peridotitic and pyroxenitic komatiite flow units (*cf.*, Barnes *et al.* 1974). The host peridotites are more magnesian (Fig. 2) and have lower CaO, Al_2O_3 and TiO_2 contents than the cumulate zones of most, if not all, the overlying ultramafic flows. Calculation of mean compositions of the mineralized units, combined with various constraints on the possible composition of a silicate liquid fraction (Table 1) suggest that they contained a high percentage of intratelluric phenocrysts at time of emplacement.

The mineralized ultramafic sequence is normally underlain by tholeiitic metabasalts, but at Windarra the footwall unit is an unmineralized ultramafic body overlying a thick banded iron-formation (Fig. 1). The ultramafic sequence is overlain by komatiitic or tholeiitic metabasalts (or both). Discontinuous sulfidic metasedimentary rocks occupy interflow positions throughout the volcanic pile but are commonly best developed in the lower part of the ultramafic flow sequence (*e.g.*, Kambalda: Fig. 1), where they may be along strike from ore.

The ores, consisting largely of pyrrhotite, pentlandite, chalcopyrite, pyrite and spinel, vary

TABLE 1. MEAN COMPOSITIONS FROM GEOCHEMICAL PROFILES AND CALCULATED INTRATELLURIC PHENOCRYST CONTENT OF SOME ULTRAMAFIC HOSTS TO VOLCANIC-ASSOCIATED NICKEL ORES, WESTERN AUSTRALIA

Locality	Mean MgO Content	Percent Olivine Phenocrysts* 23% MgO	28% MgO	32% MgO	Source for Calculation
Nepean	*ca.* 36%	45	35	15	Barrett *et al.* (1976)
Lunnon Shoot	*ca.* 38%	50	40	25	Ross & Hopkins (1975)
Windarra	*ca.* 39.5%	60	50	35	(UWA-unpublished data)
Wannaway	*ca.* 40.0%	60	50	35	McQueen (1979)
* All calculations made assuming $Fo_{92.5}$ as olivine composition.					
Juan Main	*ca.* 40.7%		56+		Marston & Kay (in prep.)
+ Using a liquid composition of 26.2% MgO (Juan Main quench) and Fo_{94}.					

Phenocryst contents are calculated for various estimates of silicate liquid composition: 23% MgO from Ross & Keays (1979), 28% MgO from Usselman *et al.* (1979), the most likely estimate of mean composition from possible quench zones of mineralized ultramafic rocks, and 33% MgO, the most magnesian liquid yet recorded (*e.g.*, Green *et al.* 1975), approximating the model composition of Duke & Naldrett (1978).

from massive through matrix to disseminated types. Where all varieties occur, massive ores normally underlie matrix ores and both are overlain by disseminated sulfides (*e.g.*, Ewers & Hudson 1972, Ross & Hopkins 1975), but there is considerable variation in individual ore sections. In some deposits, matrix to disseminated ores are dominant and massive sulfides are rare (*e.g.*, Nepean, Windarra, South Windarra, Wannaway), whereas in others breccia ores are important (*e.g.*, Redross). Although orebodies are normally confined to the basal ultramafic unit and immediately underlying footwall, mineable ores also occur at the base of overlying ultramafic units (*e.g.*, hanging-wall ores at Kambalda). As there is no detailed information available on hanging-wall ores and as initial indications suggest some differences between these and basal ores, only the genesis of the basal ores ("contact ores") is considered below.

SUMMARY OF GENETIC MODELS

Although most authors favor genetic models involving magmatic segregation of oxy-sulfide liquids, there are a number of alternatives. Proposed models, commonly for *specific* deposits, are outlined below.

A. Ores formed as lateral equivalents of sulfidic metasedimentary rocks.

1. Volcanic exhalative or volcanogenic model (Lusk 1976).
2. Nickel enrichment of sulfidic metasedimentary rocks (Seccombe *et al.* 1977).

B. Ores formed from magmatic immiscible sulfide liquid.

1. Separation of magmatic sulfide liquid by flow and *in situ* settling (e.g., Ewers & Hudson 1972, Hudson 1972, 1973; Naldrett 1973).
2. Early separation and eruption of magmatic sulfide liquid (Ross & Hopkins 1975).
3. Sulfur derived by assimilation of associated sulfidic metasedimentary units (*e.g.*, Green 1978, Groves *et al.* 1978).

C. Ores formed by sulfurization processes (*e.g.*, Naldrett 1966, Prider 1970).

D. Ores formed by metamorphic modification of preexisting, less-concentrated sulfides formed at the magmatic stage (*e.g.*, Barrett *et al.* 1977, Binns *et al.* 1977).

PRIMARY ORIGIN OF SULFIDES

Introduction

Although all volcanic-associated deposits have undergone metamorphic modification, their strata-bound nature combined with their consistent geological associations and setting represent strong arguments for the existence of premetamorphic syngenetic sulfides. The following discussion represents an assessment of the relative roles of synvolcanic intramagmatic processes (models B1, 2, 3 above) and volcanic-exhalative processes (model A1) in their generation. Models A2 and C are also briefly reviewed. The similarity of most deposits within the volcanic-associated group suggests that they have a common origin. In the following discussion evidence for their genesis is contributed from a number of individual deposits, but important differences as well as similarities are noted.

Authors favoring a magmatic model invoke the generation and separation of an immiscible oxy-sulfide liquid from an ultramafic crystal mush comprising mainly olivine crystals, magnesian silicate liquid and rare chromite. Detailed models are given by Ewers & Hudson (1972), Naldrett (1973), Ross & Hopkins (1975) and Usselman *et al.* (1979), but in this section only proof for existence of a separate oxy-sulfide liquid is considered.

Although alternative volcanic-exhalative models have been previously considered, only Lusk (1976) has formally presented a genetic model. He envisages the formation of the Ni deposits in a similar manner to the volcanogenic Cu–Zn deposits of the Abitibi belt (*cf.*, Sangster & Scott 1976) with sulfidic metasedimentary material representing distal equivalents of massive nickel sulfides. Matrix and disseminated ores are considered by Lusk to result from melting of volcanogenic sulfides as high-temperature ultramafic lavas are extruded over them.

Sulfidic metasedimentary rocks and their relationship to nickel ores

Many features of the ores, such as the occurrence of mineral layering, pyrite and millerite, used by Lusk (1976) to negate the magmatic model, are largely due to metamorphism (Groves *et al.* 1976). However the volcanic-exhalative model has some appeal because it potentially explains the puzzling spatial relationships between massive ores and metasedimentary rocks, *e.g.*, the lack of such rocks in some ore zones and probable thinning beneath others (*e.g.*, Hudson 1972, Ross & Hopkins 1975, Barrett *et al.* 1977). Clearly the nature of metasedimentary rocks and their relationship to massive ore require definition to assess the volcanic-exhalative model. O.A. Bavinton (pers. comm. 1978) suggests that the sulfidic metasedimentary rocks at Kambalda postdate the basal ultramafic unit and its underlying sulfide ore, thus negating a genetic link in this case. Elsewhere, however, relationships suggest that the metasedimentary rocks predate or were approximately contemporaneous with ore (*e.g.*, Windarra).

The composition of metasedimentary rocks is highly variable (Table 2, Fig. 2), apparently owing to variable proportions of tuffaceous detritus, exhalative components and carbonaceous material (Groves *et al.* 1978). With the exception of Windarra, the tuffaceous material does not normally have a significant ultramafic component (Fig. 2), and available analyses of those metasedimentary units within predominantly metabasaltic sequences (*e.g.*, Nepean data), at the base of the ultramafic sequence (most Kambalda data) and from within the ultramafic sequence (most Widgiemooltha data), although

TABLE 2. MEAN AND STANDARD DEVIATION FOR COMPOSITION OF SULFIDE-RICH METASEDIMENTARY ROCKS IN VOLCANIC-ASSOCIATED ORE ENVIRONMENTS COMPARED TO COMPOSITION OF SILICATE FRACTION OF ORE, WANNAWAY, RECALCULATED VOLATILE-FREE

	KAMBALDA		NEPEAN		WIDGIEMOOLTHA		WINDARRA		ORE-WANNAWAY			
%	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	W10C-12	W10C-14	W10C-16	A
SiO_2	52.95	8.77	48.01	3.36	51.02	7.74	52.00	10.05	35.49	39.00	44.08	45.7
TiO_2	0.45	0.10	0.46	0.07	0.38	0.11	0.48	0.20	0.07	0.13	0.19	0.21
Al_2O_3	11.35	2.50	11.65	2.14	11.44	2.31	8.95	2.93	1.79	2.16	3.88	3.1
Fe_2O_3									10.65	4.02	1.91	
FeO	12.45	5.61	18.95	5.84	13.23	7.11	12.08	6.12	5.92	5.36	9.57	8.8
MnO	0.17	0.33	0.10	0.05	0.06	0.03	0.19	0.06	0.39	0.42	0.12	0.13
MgO	3.55	4.23	2.93	2.07	3.94	2.08	12.64	5.35	27.87	35.92	36.07	40.0
CaO	5.79	4.36	4.05	2.70	4.37	1.70	6.05	2.26	16.48	12.12	3.77	1.5
Na_2O	3.01	2.32	1.99	0.58	3.87	2.11	2.72	2.27	0.04	0.02	0.12	0.05
K_2O	1.50	1.15	1.50	1.10	0.66	0.63	1.82	1.89	0.04	0.05	0.04	0.08
P_2O_5	0.11	0.03	0.06	0.01	0.06	0.02	0.08	0.10	0.04	0.02	0.01	0.02
C	0.24	0.33	2.43	2.60	4.82	3.47	0.0	0.0				
S	4.3	2.18	8.56	2.60	4.97	3.65	2.56	2.86				
ppm												
Ni	632	1200	1021	1460	863	1310	1270	1001				
Co	66	24	153	72	103	44	152	20				
Cu	433	297	860	469	483	289	449	710				
Zn	991	618	3680	3083	2773	2525	140	52				
Cr	246	371	220	105	274	214	1340	1473	7800	4960	1500	3670
No. of specimens	12		7		7		9		1	1	1	58

W10C-12 and W10C-14; massive ores : W10C-16; disseminated ore.

A; mean composition of 58 ultramafic hosts to volcanic-associated ores recalculated volatile-free from Binns *et al.* (1977).

Kambalda analyses from O.A. Bavinton, Western Mining Corporation.

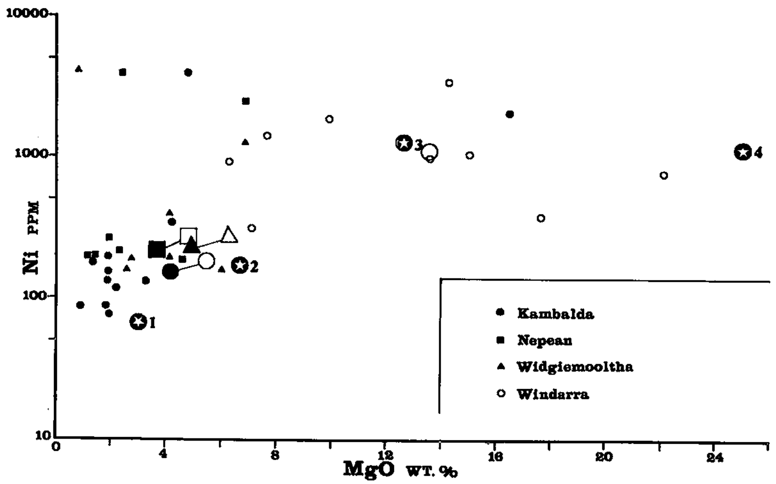

FIG. 3. Plot of Ni *vs.* MgO for sulfidic metasediments from volcanic-associated ore environments. Mean compositions of Archean rocks are shown for comparison as circled stars: 1. Mean meta-andesite Marda area (Hallberg *et al.* 1976). 2. Mean of 123 metabasalts from Norseman area (Hallberg 1972). 3. Mean of 4 high MgO–high Mg metabasalts from Mt White–Lawlers area (Nesbitt & Sun 1976). 4. Mean composition of ultramafic komatiite flow, Mt Clifford (Barnes *et al.* 1974). Two mean compositions are shown for Kambalda, Nepean and Widgiemooltha area: solid symbols represent uncorrected means and open symbols represent means corrected for FeO in sulfide and reduced to 51% SiO_2.

highly variable, are not distinguishable (Table 2). These factors suggest that the metasedimentary rock may not be genetically associated with any specific lava series. The unit at the base of the ultramafic sequence, however, is more likely to be associated with waning basaltic volcanism than to ultrabasic volcanism (Groves *et al.* 1978). An association of very Ni-rich (Ni/Cu = 10–15) exhalative ores with basaltic volcanism seems unlikely, particularly where there are no ultramafic footwall rocks as potential sources for leaching of Ni by hydrothermal solutions. Significantly, Ni contents of the metasedimentary rocks generally are below 200 ppm, and when compared to MgO content (Fig. 3), consistent with Ni concentrations in basaltic detritus. It is not clear whether anomalously high Ni contents in metasedimentary units (Fig. 3) do represent hydrothermal concentrations or subsequent metamorphic interaction between metasedimentary and ultramafic rocks or remobilized nickel ores or both (Groves *et al.* 1978), but at least some metasedimentary rocks sampled adjacent to ore have high Ni contents (Univ. W. Aust., unpubl. analyses).

A plot of metasedimentary rock compositions in terms of Cu–Ni–Zn for Kambalda, Nepean and Widgiemooltha samples (Fig. 4) demonstrates their marked contrast with the volcanic-associated ores: most metasedimentary rocks are markedly enriched in Zn or Cu (or both) relative to Ni compared to ores. Precious metals show extreme contrast both in concentration and relative proportions (Bavington & Keays 1978), with Kambalda metasedimentary rocks having low PGE (platinum-group element) contents and relatively high Pd/Ir (arithmetic mean Pd = 9.8 ppb, Ir = 0.28 ppb, Pd/Ir = 35) and a weak correlation between PGE and Ni when compared to Kambalda ores (arithmetic mean Pd = 360 ppb, Ir = 60 ppb, Pd/Ir = 6.0) and much stronger PGE–Ni correlations (Keays & Davison 1976). Au/(Pd+Ir) ratios for Kambalda metasedimentary rocks of 14.5 contrast with ratios of 0.26 for Kambalda ores. The strong enrichment of Au and Pd relative to Ir is consistent with a hydrothermal origin for the metasedimentary sulfides (*e.g.*, McCallum *et al.* 1976, Bavinton & Keays 1978), whereas the relatively high total Pd+Ir and lower Pd/Ir ratios of the ores are indicative of a more direct magmatic origin.

Data on the silicate phase of massive ores are limited, but geochemical analyses from Lunnon Shoot, Kambalda (Ross & Hopkins 1975) and from Wannaway indicate that it is

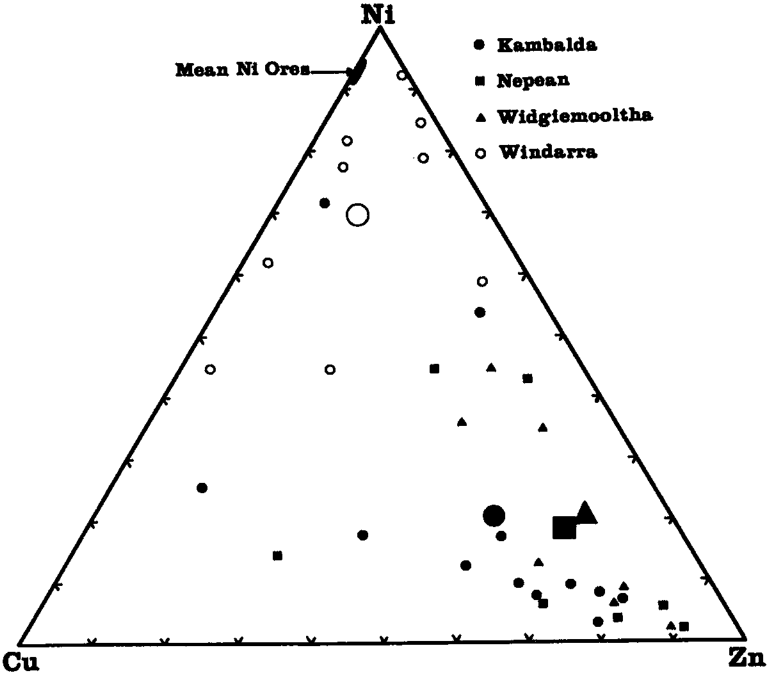

FIG. 4. Plot of composition of metasediments in terms of Cu–Ni–Zn. Arithmetic means are shown in large symbols. The compositional field of volcanic-associated nickel ores is shown for comparison.

also markedly different from the non-sulfide portion of the metasedimentary rocks (Table 2, Fig. 2).

The above data could conceivably be interpreted in terms of proximal to distal zonation similar to that observed in volcanogenic Cu–Zn–Pb deposits (*cf.*, Fryer & Hutchinson 1976); available solubility data (*e.g.*, Barnes 1975) are broadly consistent with such zonation. However, the lack of observable transitions between massive ore and metasediment and the geochemical data taken *in toto*, in particular the lack of significant overlapping compositions for nickel ores and metasediments from most localities, when combined with indications that the metasedimentary units along strike from ore are not specific to the Ni-rich ultramafic environment, all argue strongly for a separate origin for the volcanic-associated ores and most sulfidic metasediments.

Supporting data for preexisting magmatic sulfides

Factors that add support to the prior existence of oxy-sulfide liquids at the magmatic stage and argue against a volcanic–exhalative origin (Groves *et al.* 1976) are briefly reviewed below.

There is no definitive evidence of widespread wall-rock alteration in the volcanic-associated ore environments, such as exists beneath volcanogenic Cu–Zn deposits (*e.g.*, Sangster & Scott 1976), although alteration, including discordant sulfides, does occur beneath some ore shoots at Kambalda. Some retrogressive metamorphism may appear similar to wall-rock alteration, but it is confined to the highest grade metamorphic environments (*e.g.*, Barrett *et al.* 1976).

Volcanic-associated deposits show a virtually exclusive association with highly magnesian ultramafic hosts (Fig. 2) even though sulfidic metasedimentary rocks occur elsewhere in the ultramafic pile (Fig. 1). The geochemical similarity of massive and matrix ores in some deposits (*e.g.*, Lunnon Shoot: Ewers & Hudson 1972, Barrett *et al.* 1977) would not be expected if the former had evolved by hydrothermal fluids but would be expected if both ore types had at some stage equilibrated with ultrabasic liquids.

The volcanic-associated deposits have very consistent mean Ni/Cu ratios of 10–15 (Cu/Cu + Ni $\leq$ 0.1), consistent with a fundamental control of composition by partitioning between immiscible sulfide liquids and peridotitic magmas (*e.g.*, Rajamani & Naldrett 1978) but at variance with the wide range of Cu/Zn ratios shown by volcanogenic ores. The high precious-metal tenor of the deposits (approximately equivalent to Sudbury ores), their relatively low Pd/Ir ratios and the good correlation between Ni and PGE (Keays & Davison 1976) are all consistent with a magmatic origin as discussed above.

The ores commonly contain distinctive ferrochromites (Groves *et al.* 1977), similar to those in sulfides from unmetamorphosed gabbros (Czamanske *et al.* 1976); their composition is consistent with crystallization from an oxy-sulfide liquid (Ewers *et al.* 1976). Such spinels are absent from sulfidic metasedimentary rocks.

The available evidence is clearly in favor of the existence of sulfides at the magmatic stage and against volcanic-exhalative processes as a *general* mechanism for nickel-ore formation. Much of the above data, particularly the geochemical dissimilarities between sulfides and silicates of massive ore and sulfidic metasedimentary rocks, argues against nickel uptake in metasediments (Model A 2) as a general genetic model. Before leaving this question, however, a possible exception to these generalizations is briefly examined.

Possible volcanic-exhalative or metamorphic ores

At Windarra, breccia ore is developed at the contract between footwall sulfidic metasedimentary rocks and ultramafic units; in some cases an ultramafic unit containing disseminated nickel ore occurs above a basal barren zone relatively depleted in Ni. Sulfides occur as a matrix to fragments of metasediments and metasomatic reaction-zone lithologies in the breccia ore that grades laterally and vertically into layered Ni-rich metasedimentary units. The breccia ores are the most Fe-rich of all mined ores (Fig. 5) and their sulfide geochemistry is intermediate between the sulfidic metasedimentary rocks and normal volcanic-associated deposits (Seccombe *et al.* 1977). This, combined with the spatial overlap of disseminated ores and breccia ores led Seccombe *et al.* to suggest that the breccia ores formed by predeformation Ni enrichment of metasedimentary rocks by metamorphic diffusion of Ni from adjacent ultramafic rocks. The geochemical data are also consistent with a syngenetic volcanic–exhalative

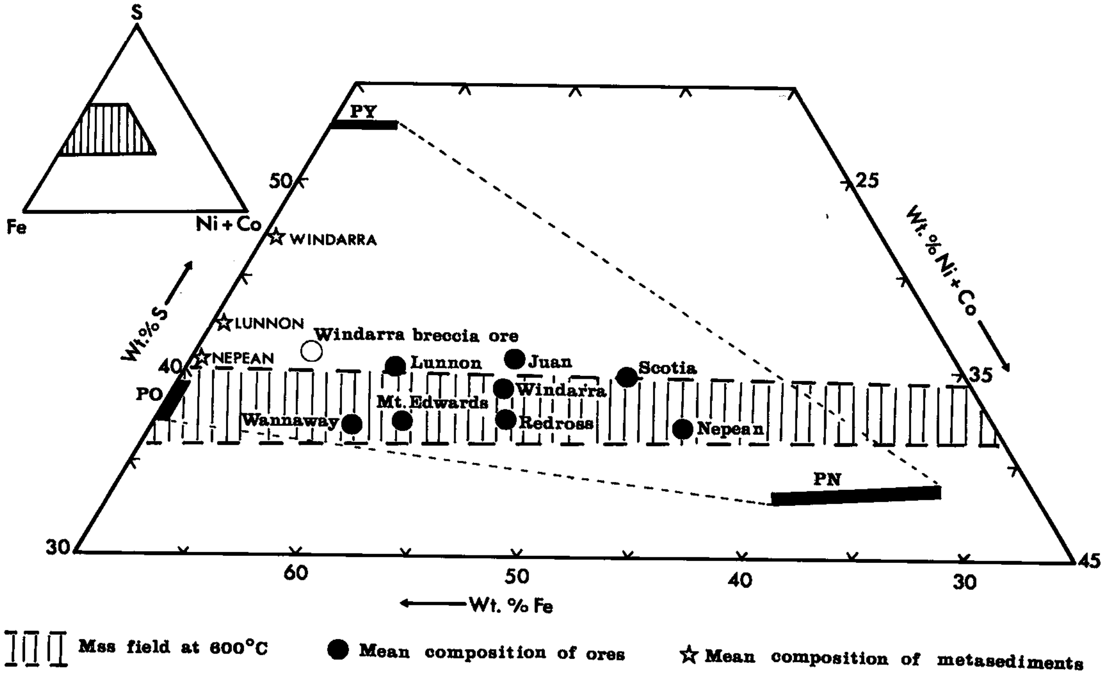

FIG. 5. Fe–Co+Ni–S plot of mean compositions of volcanic-associated nickel ores compared to mean compositions of sulfidic metasediments and Windarra breccia ore. The Wannaway mean includes Fe-rich contact vein samples as well as main ores.

origin. It is significant in terms of the latter possibility that the Windarra metasedimentary rocks are much more magnesian and Ni- and Cr-rich than most other sulfidic metasedimentary rocks (Table 2): magnesian and Ni- and Cr-rich metasedimentary rocks do occur in other sequences but they are not dominant. There is thus a stronger probability that the Windarra metasedimentary units are genetically related to the enclosing ultramafic flows, so that the occurrence of volcanic–exhalative nickel deposits is more probable here than in other environments. Other possible volcanic-exhalative deposits include Windarra F Shoot (R. J. Marston, pers. comm. 1978) and Sherlock Bay (*e.g.*, Miller & Smith 1975) but neither is associated with *basal* ultramafic units.

Constraints on Magmatic Models

The data discussed above indicate that the majority of volcanic-associated deposits consist of sulfides that initially formed from oxy-sulfide liquids at the magmatic stage. The following discussion is concerned with the source of sulfur for these liquids, their separation from initially S-saturated or undersaturated extruded magmas, and the generation of the present ore configuration.

Source of sulfur

Most authors formulating a model of Type B1, 2 envisage eruption of ultrabasic magma carrying immiscible sulfide droplets of sufficient size to rapidly settle to form basal sulfide ores. The most comprehensive of these models is presented by Naldrett (1973) and Naldrett & Cabri (1976). They suggest that the magma source was a sulfur-enriched part of the mantle at approximately 200 km depth resulting from melting of sulfides and their downward percolation below 100 km depth. However, Arndt (1977) has shown that even with less than 20% partial melting of the mantle, solids and liquids will separate; the high sulfur contents of Archean basaltic and other volcanic rocks (*e.g.*, Naldrett *et al.* 1978) suggest that significant sulfur was removed from the mantle in these separated melts. If sulfides did sink to depths equivalent to komatiite derivation and become incorporated into ultrabasic magmas, they would then have to be kept in suspension in the silicate liquid during very rapid ascent to the surface as the high density of the sulfides (*ca.* 4.0 g. cm^{-3}) combined with the low viscosity of most ultrabasic magmas would provide ideal conditions for separation of the sulfide liquid.

If komatiitic magmas did originate in mantle diapirs, it seems likely that any sulfide liquid present would tend to concentrate at the base of the diapir and normally remain there. If this is the case, then most extruded komatiites should be sulfur-undersaturated. Only those tapping the basal sulfide-liquid reservoir would be expected to be sulfur-saturated. Although reliable data on original sulfur contents of Archean ultramafic rocks are rare owing to possible remobilization of sulfur during subsequent alteration, the data of Cameron *et al.* (1971) indicate that most ultramafic rocks, even those from mineralized areas, have sulfur contents far below 0.3 to 0.4% S, the saturation levels suggested by Shima & Naldrett (1975). Preliminary data from Western Australia (Fig. 6), indicate that ultramafic flows with a wide range of mineralogy from varied metamorphic environments, even those overlying mineralized units, generally have low to very low sulfur contents. On the basis of limited data, it seems that for most deposits only the upper portions of mineralized units have sulfur contents equivalent to saturation levels; Wannaway is a probable exception (McQueen 1979).

Isotopic data for Archean sulfides in ultramafic and metasedimentary rocks from Western

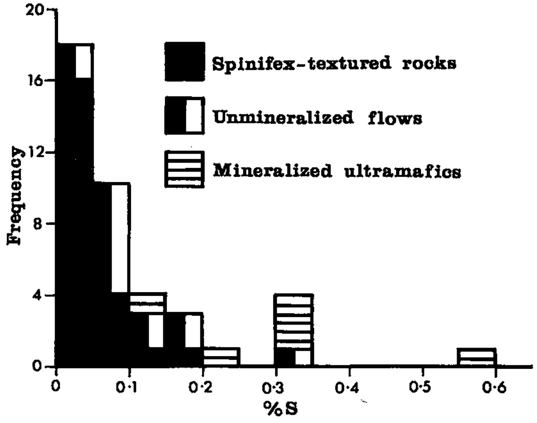

FIG. 6. Histogram showing S contents of Archean ultramafic rocks from Western Australia. Spinifex-textured rocks are taken from unmineralized environments ranging from middle greenschist to upper amphibolite facies and include serpentinites, talc–carbonate rocks and relict-olivine rocks. Unmineralized flows overlie mineralized units at Kambalda and Wannaway: Kambalda flows contain relict olivine. Samples from mineralized flows are from the upper portion of the Wannaway unit. Analyses using Leco furnace by R.F. Lee.

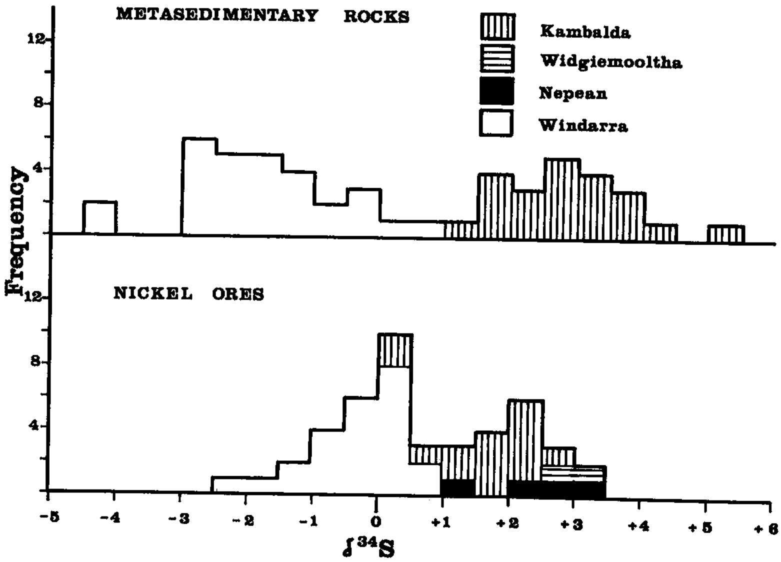

FIG. 7. Histogram of $\delta^{34}S$ values of metasedimentary rocks compared to nickel ores from the same environments. Data derived from Donnelly *et al.* (1978) and Seccombe *et al.* (1977). Data for individual minerals are not shown as there is no systematic difference between coexisting sulfides.

Australia (*e.g.*, Donnelly *et al.* 1978, Seccombe *et al.* 1977) indicate that sulfur is exclusively of magmatic origin and that there was limited fractionation in the sedimentary environment (*e.g.*, Lambert *et al.* 1979). Therefore, marked variation in $\delta^{34}S$ is not expected between sulfides from situations where sulfur was derived directly from the mantle and those where it was derived by crustal contamination. However, there are some data from Windarra and Kambalda to suggest the likelihood of contamination.

For Kambalda deposits, $\delta^{34}S$ and S/Se have typical magmatic values with a restricted and indistinguishable range for both nickel ores and metasedimentary rocks (Figs. 7, 8). In contrast, Windarra metasedimentary rocks typically have slightly negative $\delta^{34}S$ values and a wide range of S/Se ratios (Figs. 7, 8). These latter data are consistent with minor oxidation of magmatic H_2S (Rye & Ohmoto 1974, Yamamoto 1976) either in ascending fluids or more likely in the sedimentary environment which includes oxide-facies banded iron formation lower in the sequence (Fig. 1). The nickel ores (excluding breccia ores) have a similar, although slightly more restricted, distribution of $\delta^{34}S$ values and S/Se compared to the metasedimentary rocks (Figs. 7, 8). The negative $\delta^{34}S$ values and wide range of S/Se are difficult to reconcile with thorough equilibration between oxy-sulfide liquid and ultrabasic magma as its inception, and the preservation of delicate isotopic layering in metamorphosed stratiform ores (*e.g.*, Campbell *et al.* 1978), argue against complete metamorphic equilibration between metasedimentary rocks and disseminated nickel ore, particularly as the two are separated, in places, by relatively barren ultramafic rock. The most likely explanation is that the Windarra ultramafic body was contaminated at some stage with sulfur from a crustal source. The similarity of $\delta^{34}S$ and S/Se of nickel ores and metasedimentary rocks at Kambalda is consistent with such a model, but it is not definitive as both metasedimentary sulfides and nickel ores could have formed independently from completely unoxidized magmatic sulfur.

At Wannaway, disseminated sulfides with anomalously high S/Se ratios together with high-Zn ultramafic rocks occur immediately above a disrupted basal sulfide layer that has geochemical characteristics intermediate between metasedimentary rocks and normal volcanic-associated deposits. This may represent a case of *in situ* arrested assimilation, although alternative mechanisms involving deformation of preexisting volcanic-exhalative sulfides or metamorphically enriched sediments (*cf.*, Windarra breccia ore) are equally probable.

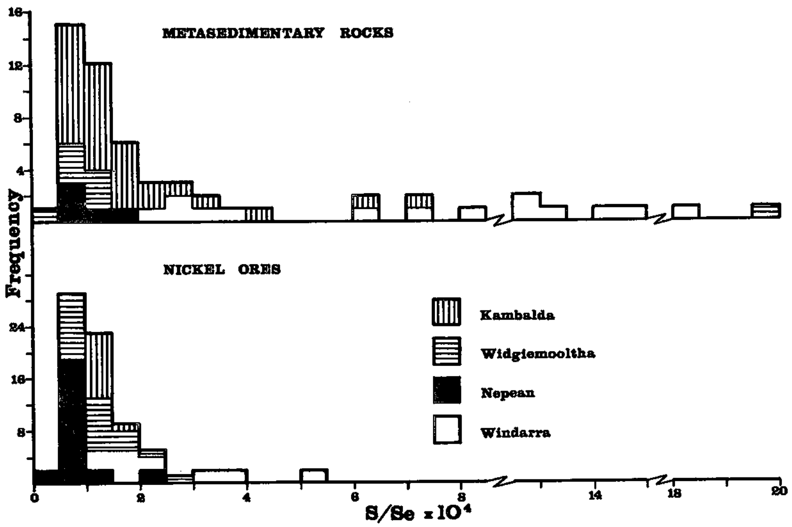

FIG. 8. Histogram of S/Se ratios of metasediments compared to S/Se of nickel ores from the same environments. Analysts: S.S. Michael and K.G. McQueen.

Timing of sulfide separation

The timing of separation of immiscible oxy-sulfide droplets represents an important constraint on genetic models; it also indirectly constrains sulfur sources. Data relating to this problem include Ni/Fe ratios of ores, Ni (and PGE) concentrations in mineralized ultramafic units and Ni contents of sparse relict olivine grains within the cumulate sections of these units.

The highly variable *mean* Ni/Fe ratios of various ores (Fig. 5), derived by averaging analyses of individual ore samples, are an important feature of the deposits. Although (1) there may be considerable redistribution of Fe and Ni on a local scale during metamorphism (*e.g.*, Barrett *et al.* 1976) and (2) there is a sampling problem due to the coarsely layered nature of some ore, the variation in ratios determined by this means is supported by careful sampling of bulk ore (Ross & Keays 1979).

Rajamani & Naldrett (1978) showed that there is a regular partitioning of Fe and Ni between sulfide liquids and silicate liquids, so that approximately equivalent volumes of sulfide liquid derived from silicate liquids of similar composition should have a restricted and predictable range of Ni/Fe ratios. Although in most cases the composition of the silicate-liquid portion of the magmas at the time of eruption cannot be precisely determined owing to poorly defined quench zones and rarely preserved igneous olivines, the restricted range of calculated mean compositions of the magmas (Table 1) argues for a limited range in composition. Further, theoretical modeling of the composition of sulfide liquids produced by early separation (necessary if magmatic matrix and/or massive sulfides are to form) from highly magnesian, S-saturated liquids suggests Ni/Fe ratios that are approximately a factor of two greater than those of Lunnon massive and matrix ore (Duke & Naldrett 1978). Modeling of expected sulfide compositions by applying the Duke & Naldrett partition coefficients to probable quench compositions and relict olivines (*e.g.*, Wannaway) from several deposits indicates that predicted Ni/Fe ratios of sulfides are normally greater than observed ratios.

These low mean Ni/Fe ratios may be partly attributed to metamorphic modification. For example, comparison of disseminated ores from peridotites showing variable serpentinization at Wannaway indicates that considerable Fe has been added to the sulfides during serpentinization. Low ratios in massive ore are even more difficult to explain unless these formed by subsequent upgrading of Fe-enriched disseminated sulfides. However, in both cases the Ni/Fe ratios are too low, even allowing for metamorphic modification, for the sulfides to have exsolved *in situ* from the very magnesian host ultrabasic flow.

One alternative explanation is that previously segregated oxy-sulfide droplets were brought up with the ultrabasic magma (*cf.*, Ewers & Hudson 1972, Naldrett 1973). Variation in the timing of eruption relative to fractional crystallization of silicate magmas and extent of sulfide-liquid separation in a magma reservoir could explain the variable Ni/Fe ratios (*cf.*, Duke & Naldrett 1978). Another alternative is that the erupted ultrabasic magma assimilated Fe-rich metasedimentary sulfides and diffusion of Ni and Cu within the magma was not sufficiently rapid to establish equilibrium sulfide-melt compositions in terms of Ni/Fe and Cu/Fe prior to gravity separation; see Barrett *et al.* (1977) for further discussion.

There are severe problems with extraction of metals from an olivine-rich mush, as solid-state diffusion rates are very slow (*e.g.*, Clark & Long 1971). This could be overcome if the mush remelted because of depression of the olivine solidus by incorporation of alkalis, FeS and H_2O from assimilated sedimentary material. Data on the FeS–FeO–Fe_2O_3–SiO_2 system (MacLean 1969) indicate that though significant, the fluxing effect of FeS on iron silicate liquids is too small; however, data show that addition of K_2O (Seifert & Schreyer 1968) and Na_2O (W. Schreyer, pers. comm. 1978) at concentration levels equivalent to those in the metasedimentary rocks significantly lowers the liquidus temperatures of very magnesian liquids.

Discrimination between models can potentially be made by considering Ni contents of ultramafic rocks and relict igneous olivine overlying the ore zone. The composition of these cumulate zones is generally 0.25 ± 0.05% Ni (*e.g.*, Nepean: Barrett *et al.* 1976, Lunnon Shoot: Ross & Hopkins 1975, Wannaway: McQueen 1979, Windarra: Univ. W. Aust., unpubl. data), *i.e.*, a normal undepleted value for relevant MgO contents when compared to other komatiites (*e.g.*, Bickle *et al.* 1977) and to overlying unmineralized units. These Ni concentrations support the previously cited evidence against *in situ* separation of sulfide droplets from initially S-undersaturated magmas, as Ni concentrations in both residual silicate liquid and derived olivine would decrease rapidly if sulfide liquid were extracted in this way (Duke & Naldrett 1978). The similarity of Pd and Ir concentrations in mineralized and unmineralized peridotitic komatiites (Ross & Keays 1979) supports this conclusion.

These data also argue against *in situ* contamination as a major process in the generation of most ores, as scavenging of Ni (and PGE) from the silicate liquid and possibly redissolved olivines would also be expected to lower concentrations of these elements in the residual magma. In view of the indirect evidence for contamination, the model involving assimilation does warrant further consideration, particularly as it appears to be a relatively common phenomenon in mafic–ultramafic rocks with associated Ni mineralization (*e.g.*, Haapala 1969, Papunen 1971, Kovalenker *et al.* 1975, Mainwaring & Naldrett 1977). The behavior of elements during assimilation of more felsic rocks by ultrabasic melts, in particular whether they would be incorporated into the melt, lost to a fluid phase (*e.g.*, alkalis) or form immiscible silicate liquids (*e.g.*, Cawthorn & McCarthy 1977), combined with a precise understanding of the three-dimensional shape and total volume of the mineralized ultramafic units (required if mass-balance calculations are to be undertaken to check the feasibility of derivation of ore elements from the ultrabasic magmas) are clearly required before contamination models can be completely negated. However, at this stage the evidence favors eruption of ultrabasic magma carrying sulfide droplets that formed from, and equilibrated with, a larger volume of magma than that represented by the enclosing flow unit. The $\delta^{34}S$ and S/Se data suggest that the sulfide liquid could have evolved in a magma chamber contaminated by crustally derived sulfur. The phenocryst-rich magmas would have been more viscous than less magnesian magmas, thus potentially accounting for their ability to bring sulfide droplets from depth to the surface. The eruption of phenocryst-rich magmas derived from depths of *ca.* 200 km (*cf.*, Naldrett 1973) is unexpected as superheating would be likely during ascent. Separation of both sulfide liquid and formation of the phenocryst-rich ultrabasic magma thus probably occurred at an intermediate stage in a rising diapir.

Segregation models to explain present ore sections

Having established the likelihood of eruption of ultrabasic magma carrying sulfide droplets, the segregation processes during eruption warrant discussion: constraints imposed if *in situ* contamination *had* contributed to ore formation are considered. Major discussion of segregation models centres around the generation of massive ore.

There has been considerable discussion in the literature of a single-stage settling model, the "billiard-ball" model of Naldrett (1973), to explain the present ore configuration. This involves formation of a basal pool of oxysulfide liquid (massive ore) that is partly displaced upward by the weight of overlying olivines to replace less dense interstitial silicate (matrix ore); the basal pool is overlain by small sulfide liquid droplets trapped between crystallized olivines (disseminated ore).

Objections presented by Barrett *et al.* (1977) to such a model are listed below:

(1) At Lunnon Shoot, the most persistent ferrochromite layer occurs at the base of matrix ore (Ross & Hopkins 1975, Groves *et al.* 1977). Consideration of densities and experimental results (Ewers *et al.* 1976) indicates that such chromites would have settled to the base of any sulfide pool beneath matrix-sulfide liquid.

(2) Calculations of vertical distribution of the components of an ultrabasic crystal mush according to Archimedes' principle indicate that all the oxy-sulfide liquid at Lunnon Shoot would be displaced by olivine at the magmatic stage. Flattening of matrix ore during deformation is a possibility, but a decrease in thickness to *ca.* 0.1 original thickness would be required to affect the above conclusion. Lowering the solidus temperature of the host ultrabasic rock by contamination with alkali-rich sediments would narrow the temperature gap between crystallization of silicate and sulfide liquids and could allow sulfides to solidify before complete crystallization of the silicates.

(3) The volume of matrix sulfides at Kambalda and Nepean (50 to 65 vol. %: Ewers & Hudson 1972, Barrett *et al.* 1976) is too great to have been interstitial to close-packed, discrete olivine grains at the magmatic stage (*cf.*, Visscher & Bolsterli 1972).

(4) The massive ore contains discontinuous ferrochromite layers at *both* its basal and upper surfaces and also contains disseminated ferrochromite and silicates throughout. As indicated by Goryainov & Sukhov (1976), the marked density contrasts between components should lead to magmatic zonation with an upper silicate-rich layer, an intervening sulfide-rich layer and a basal chromite-rich layer.

Usselman *et al.* (1979) present a more sophisticated treatment of the "billiard-ball" model taking into account the cooling history of the sulfide-rich flow; they demonstrate that preservation of basal sulfide liquid, and hence resultant massive ore, is possible in a *ca.* 60 m thick flow if the phenocryst content is below *ca.* 10%. Our calculations (Table 1) suggest that this percentage is exceeded even assuming a silicate liquid with maximum MgO content, and therefore argue against this as a general model for massive ore formation. However, Usselman *et al.* (1979) do point out that chains of olivines may settle rather than discrete grains, allowing interstitial space equivalent to the observed volume of matrix sulfides, thus providing a possible explanation for objection (3).

Ross & Hopkins (1975) envisage the massive and matrix ore as representing separate lava flows that preceded the basal ultramafic unit. This model overcomes objections (1) to (3) above, but itself generates the problem of spatial overlap of the massive, matrix and disseminated ores from separate sources. Although the ores are currently situated in footwall "troughs", it is difficult in the examples studied to establish the relative importance of primary and structural control on ore localization (*e.g.*, Barrett *et al.* 1977). The model does not completely overcome objection (4), although more rapid cooling of the sulfide magma would be expected if it were a separate flow. The model is incompatible with *in situ* contamination as it relies on preeruption segregation of oxy-sulfide liquid.

A third, and more likely, explanation for the formation of massive sulfides by magmatic processes is a modification of the Ross & Hopkins (1965) model and involves gravity separation of olivine phenocrysts and sulfide liquid *during* eruption, with differential flow between silicate liquid, olivine-rich magma (*cf.*, Lajoie & Gélinas 1978), and sulfide liquid due to density and viscosity contrast: this model is also preferred by Marston & Kay (in prep.). The lower-viscosity basal sulfide liquid could have become separated and slightly preceded the olivine mush, becoming more rapidly cooled in sea water so that displacement upward into overlying olivine was not possible: this potentially overcomes objection (1) to the "billiard-ball" model and warrants theoretical modeling. If concentration did occur in sea-floor depressions, it is possible that preferential olivine accumulation also occurred in these depressions, so that present geochemical profiles indicate higher intratelluric phenocryst contents than existed initially. However, objections to the "billiard-ball" model are still valid because the phenocryst contents of the vertical column above the sulfide liquid would remain as calculated in Table 1.

METAMORPHIC MODIFICATION

Barrett *et al.* (1977) have reviewed the effects of amphibolite-facies metamorphism on Western Australian volcanic-associated ores. Common effects include the formation of metamorphic layering, fabrics and textures in massive ores and localized remobilization of Cu (± Fe) relative to Ni, sulfur diffusion and formation of breccia ores during repeated remobilization of massive sulfides. However, the major question from a genetic viewpoint is whether preexisting ores were simply modified and remobilized during metamorphism or whether preexisting, more disseminated magmatic sulfides were significantly upgraded during metamorphism. The available evidence is briefly reviewed below.

Around broad subhorizontal and subvertical flexures in some underground exposures at Nepean, normal matrix ore gives way to disseminated sulfides in thick metasomatic reaction zones with discontinuous lenses of massive sulfides in the adjacent footwall or hanging wall. These spatial relationships suggest that massive ores formed as a result of remobilization and upgrading of original matrix ore that moved off the basal contact during premetamorphic shearing (Barrett *et al.* 1976). The formation of massive ore from matrix ore is even more clearly shown in hanging-wall ore, developed at the *upper* contact of the mineralized ultramafic unit, where all gradations between the two ore types are represented on a mesoscopic and microscopic scale. Massive ore has also formed in rare environments of high chemical potential gradients such as thin slivers of matrix ore faulted into the footwall amphibolites (Barrett *et al.* 1976). In a number of cases (*e.g.*, Redross, Juan Main, Kambalda), massive ore is overlain and underlain by, or contains blocks of, disseminated ore with no matrix ore developed (Barrett *et al.* 1977, Marston & Kay, in prep.) attesting to at least considerable relative movement if not upgrading of sulfides.

The precise mechanism of upgrading is not clearly defined due to lack of relevant experimentation. In high-metamorphic-grade areas such as Nepean, dehydration reactions in the silicate fraction can increase the relative sulfide volume of disseminated sulfides (Barrett *et al.* 1976) but cannot upgrade matrix ore to massive ore, and is not applicable to lower-grade environments where deformational or diffusional processes (or both) are more likely responsible.

Barrett *et al.* (1977) suggest that the anomalously high volume percentage of sulfides in matrix ore results from metamorphic upgrading, thus removing objection (3) to magmatic segregation models discussed above: this interpretation represents an alternative to that of Usselman *et al.* (1979). The question of whether all massive ores, including those from lower-strain environments such as Kambalda, could form by metamorphic upgrading is still open. The major problem in resolving this question is that once massive ores formed they moved independently of more disseminated ore during subsequent deformation, thus destroying much of the evidence for their mode of formation. Factors that remain in favor of a metamorphic origin include the distribution of silicates and chromites (point 4 above) and the anomalous nature of the silicate fraction of Lunnon Shoot ores when compared to the composition of the adjacent ultramafic unit and the silicate fraction of more disseminated ore (Table 2, Fig. 2). These features may also represent a metamorphic imprint on magmatic ore; for example, the massive ore gangue may represent metamorphosed and deformed quartz-carbonate veins formed in contraction joints in cooling sulfide liquid.

RELATIVE ROLES OF MAGMATISM, VOLCANIC EXHALATION AND METAMORPHISM: CONCLUSIONS

The lack of wall-rock alteration and the geochemical contrast with sulfidic metasedimentary units that are proposed lateral equivalents argue against a volcanic-exhalative origin for most basal volcanic-associated ores. Breccia ores at Windarra and restricted massive ores at Wannaway represent possible exceptions. The association of mineralization with specific, highly magnesian ultramafic rocks when combined with geochemical and mineralogical data from the ores, particularly the consistent Ni/Cu ratio, high total PGE, relatively low Pd/Ir ratios and contained ferrochromites, all argue for initial crystallization of sulfides and spinels from immiscible oxy-sulfide liquids.

Development of an unequivocal model for formation of basal volcanic-associated ores is impeded by lack of definitive evidence for sulfur source, timing of oxy-sulfide liquid separation, precise behavior of sulfide-rich magmas during eruption and importance of metamorphism in upgrading of original magmatic sulfide concentrations. Sulfur contents of mineralized *versus* unmineralized peridotitic komatiite units, variable Ni/Fe ratios and undepleted Ni (and PGE) contents of mineralized units and sparse relict olivines all argue against *in situ* formation of immiscible oxy-sulfide droplets from an originally S-undersaturated flow. These data seem consistent with eruption of an ultrabasic magma carrying oxy-sulfide droplets derived from a source region in which variable volumes of such liquids formed in equilibrium with a larger volume of silicate liquid than that represented by the enclosing flow. The high viscosity of the sulfide-rich magmas, controlled by high phenocryst content relative to other peridotitic komatiites, is also consistent with their ability to maintain significant concentrations of sulfide droplets during ascent.

Sulfur isotope and S/Se data suggest the possibility of derivation of at least some sulfur from a crustal source, but lack of direct evidence of contamination (*e.g.*, presence of graphite, high SiO_2, alkalis, Zn, *etc.*) combined with available data on Ni concentrations in mineralized ultramafic units and olivines argue against *in situ* contamination: preeruption contamination seems more likely. However, further consideration of a surface-assimilation model, including mass-balance calculations for ore elements, the behavior of contaminated ultrabasic melts and the relative ages of metasedimentary rocks and ores, is required before it can be negated as a viable model.

Segregation models for oxy-sulfide liquids in ultrabasic flows are also problematical. Initial, or induced, high intratelluric olivine phenocryst concentrations argue against simple gravity separation of sulfide liquids at the present site of ore concentration (the "billiard-ball" model), unless assimilation led to reduced liquidus temperatures for the ultrabasic melt; the spatial overlap of ore types argues against completely separate multiple sulfide-rich flows producing the basal ore sequence. A dynamic model involving gravity settling and flow separation of olivine phenocrysts and sulfide liquid during eruption of a single sulfide-rich flow best explains the formation of massive and matrix ores in terms of magmatic processes: objection (4) above potentially remains a residual problem for all magmatic processes; it must at least represent a metamorphic imprint.

Metamorphism has been an important process in modifying previous sulfide accumulations. The strong metamorphic and deformational imprint on the ores is a major factor hampering more precise definition of magmatic processes. Metamorphic upgrading of sulfides can be established locally in a number of ore environments, and overcomes several of the objections to alternative magmatic models of massive ore formation, but unequivocal evidence for the generation of *all* massive ores by this process is lacking. Once formed, the massive ores have such low strength that they are mobilized relative to other ore and rock types, thus obscuring evidence of formational mechanism.

It must be concluded that there are as yet insufficient constraints to unequivocally support one particular model involving formation and separation of oxy-sulfide liquids for generation of volcanic-associated ores to the exclusion of all others. The possibility that more than one mechanism may be involved has previously been discussed for Windarra breccia ores and some Wannaway massive ores. With these cautions in mind, we prefer a hypothesis involving eruption of a high-viscosity, phenocryst-rich ultrabasic magma carrying oxy-sulfide droplets derived from a sulfide liquid reservoir formed from a large volume of possibly contaminated ultrabasic melt. A dynamic model of separation of sulfide liquid during eruption is preferred to explain the generation of matrix sulfides and probably some massive sulfides. These magmatic concentrations were subsequently modified and upgraded, with formation of further massive ores, and structurally controlled during amphibolite-facies metamorphism. This hypothesis and the alternate contamination hypothesis require further testing by both experimental and field studies.

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REFERENCES

ANDERSON, I.G., VARNDELL, B.J. & WESTNER, G.J. (1979): Some geological aspects of the Perseverance nickel deposit, Rhodesia. *In* Metallogenesis '76 (M.J. Viljoen, ed.). *Geol. Soc. S. Afr. Trans.* (in press).

ARNDT, N.T. (1977): Ultrabasic magmas and high-degree melting of the mantle. *Contr. Mineral. Petrology* **64**, 205-221.

BARNES, H.L. (1975): Zoning of ore deposits: types and causes. *Roy. Soc. Edin. Trans.* **69**, 295-311.

BARNES, R.G., LEWIS, J.D. & GEE, R.D. (1974): Archaean ultramafic lavas from Mount Clifford. *W. Aust. Geol. Surv. Ann. Rep.* **1973**, 59-70.

BARNES, H.L. (1975): Zoning of ore deposits: types MARSTON, R.J. & MCQUEEN, K.G. (1977): Structural history and metamorphic modification of Archean volcanic-type nickel deposits, Yilgarn Block, Western Australia. *Econ. Geol.* **72**, 1195-1223.

———, GROVES, D.I. & BINNS, R.A. (1976): Importance of metamorphic processes at the Nepean nickel deposit, Western Australia. *Inst. Mining Met. Trans.* **85**, B252-B273.

BAVINTON, O.A. & KEAYS, R.R. (1978): Precious metal values from interflow sedimentary rocks from the komatiite sequence at Kambalda, Western Australia. *Geochim. Cosmochim. Acta* **42**, 1151-1163.

BICKLE, M.J., FORD, C.E. & NISBET, E.G. (1977): The petrogenesis of peridotitic komatiites: evidence from high-pressure melting experiments. *Earth Planet. Sci. Lett.* **37**, 97-106.

BINNS, R.A., GROVES, D.I. & GUNTHORPE, R.J. (1977): Nickel sulphides in Archaean ultramafic rocks of Western Australia. *In* Correlation of the Precambrian (A.V. Sidorenko, ed.), Nauka, Moscow.

CAMERON, E.M., SIDDELY, G. & DURHAM, C.G. (1971): Distribution of ore elements in rocks for evaluating ore potential: nickel, copper, cobalt and sulfur in ultramafic rocks of the Canadian Shield. *In* Geochemical Exploration, Proceedings of the 3rd International Geochemical Exploration Symposium 1970 (R.W. Boyle, ed.), *Can. Inst. Mining Met., Spec. Vol.* **2**, 298-313.

CAMPBELL, F.A., ETHIER, V.G., KROUSE, H.R. & BOTH, R.A. (1978): Isotopic composition of sulfur in the Sullivan orebody, British Columbia. *Econ. Geol.* **73**, 246-268.

CAWTHORN, R.G. & MCCARTHY, T.S. (1977): Partitioning of nickel between immiscible picritic liquids. *Earth Planet. Sci. Lett.* **37**, 339-346.

CLARK, A.M. & LONG, J.V.P. (1971): The anisotropic diffusion of nickel in olivine. *In* Diffusion Processes (J.N. Sherwood, ed.), Proc. Thomas Graham Mem. Symp., Gordon and Breach, London.

CZAMANSKE, G.K., HIMMELBERG, G.R. & GOFF, F.E. (1976): Zoned Cr, Fe-spinel from the La Perouse layered gabbro, Fairweather Range, Alaska. *Earth Planet. Sci. Lett.* **33**, 111-118.

DONNELLY, T.H., LAMBERT, I.B., OEHLER, D.Z., HALLBERG, J.A., HUDSON, D.R., SMITH, J.W., BAVINTON, O.A. & GOLDING, L.Y. (1978): A reconnaissance study of stable isotope ratios in Archaean rocks from the Yilgarn Block, Western Australia. *J. Geol. Soc. Aust.* **24**, 409-420.

DUKE, M.J. & NALDRETT, A.J. (1978): A numerical model of the fractionation of olivine and molten sulfide from komatiite magma. *Earth Planet. Sci. Lett.* **39**, 255-266.

EWERS, W.E., GRAHAM, J., HUDSON, D.R. & ROLLS, J.M. (1976): Crystallization of chromite from nickel–iron sulfide melts. *Contr. Mineral. Petrology* **54**, 61-64.

——— & HUDSON, D.R. (1972): An interpretive study of a nickel–iron sulfide ore intersection, Lunnon Shoot, Kambalda, Western Australia. *Econ. Geol.* **67**, 1075-1092.

FRYER, B.J. & HUTCHINSON, R.W. (1976): Generation of metal deposits on the sea floor. *Can. J. Earth Sci.* **13**, 126-135.

GORYAINOV, I.N. & SUKHOV, L.G. (1976): Phase state of material that formed copper–nickel sulfide shoots. *Dokl. Acad. Sci. USSR, Earth. Sci. Sect.* **221**, 173-176.

GREEN, A.H. (1978): Evaluation of Fe–Ni sulphide ores associated with Archean ultramafic komatiites, Langmuir Township, Ontario. *Econ. Geol.* **73**, 310-311 (Abstr.).

GREEN, D.H., NICHOLLS, I.A., VILJOEN, M. & VILJOEN, R. (1975): Experimental demonstration of the existence of peridotitic liquids in earliest Archean magmatism. *Geol.* **3**, 11-14.

GROVES, D.I., BARRETT, F.M., BINNS, R.A., MARSTON, R.J. & MCQUEEN, K.G. (1976): A possible volcanic-exhalative origin for lenticular nickel sulfide deposits of volcanic association with special reference to those in Western Australia: discussion. *Can. J. Earth Sci.* **13**, 1646-1650.

———, ———, ——— & MCQUEEN, K.G. (1977): Spinel phases associated with metamorphosed volcanic-type iron-nickel sulfide ores from Western Australia. *Econ. Geol.* **72**, 1224-1244.

———, ——— & MCQUEEN, K.G. (1978): Geochemistry and origin of cherty metasediments within ultramafic flow sequences and their relationship to nickel mineralization. *In* Archaean Cherty Metasediments: Their Sedimentology, Micropalaeontology, Biogeochemistry and Significance to Mineralization (J.E. Glover & D.I. Groves, eds.), *Geol. Dep. & Ext. Serv., Univ. W. Aust.* **2**, 57-69.

——— & HUDSON, D.R. (1979): The nature and origin of Archean stratabound volcanic-associated Ni–Fe–Cu sulfide deposits. *In* Handbook of Stratabound and Stratiform Ore Deposits (K.H. Wolf, ed.). Elsevier, Amsterdam.

HAAPALA, P.S. (1969): Fennoscandian nickel deposits. *In* Magmatic Ore Deposits (H.D.B. Wilson, ed.), *Econ. Geol. Mon.* **4**, 262-275.

HALLBERG, J.A. (1972): Geochemistry of Archaean volcanic belts in the Eastern Goldfields region of Western Australia. *J. Petrology* **13**, 46-56.

———, JOHNSTONE, C. & BYE, S.M. (1976): The Archaean Marda igneous complex, Western Australia. *Precambrian Res.* **3**, 111-136.

Hudson, D.R. (1972): Evaluation of genetic models for Australian sulphide nickel deposits. *Proc. Newcastle Conf., Austral. Inst. Mining Met.* 59-72.

——— (1973): Genesis of Archaean ultramafic-associated nickel–iron sulphides at Nepean, Western Australia. *Proc. W. Aust. Conf., Austral. Inst. Mining Met.*, 99-109.

Keays, R.R. & Davison, R.M. (1976): Palladium, iridium, and gold in ores and host rocks of nickel sulfide deposits in Western Australia. *Econ. Geol.* **71**, 1214-1228.

Kolvalenker, V.A., Gladyshev, G.D. & Nosik, L.P. (1975): Isotopic composition of sulfide sulfur from deposits of Talnakh ore node in relation to their selenium content. *Int. Geol. Rev.* **17**, 725-733.

Lajoie, J. & Gélinas, L. (1978): Emplacement of Archean peridotitic komatiites in LaMotte Township, Québec. *Can. J. Earth Sci.* **15**, 672-677.

Lambert, I.B., Donnelly, T.H., Dunlop, J.S.W. & Groves, D.I. (1979): Stable isotope studies of early Archean sulphate deposits of probable evaporitic and volcanogenic origins. Nature **276**, 808-811.

Lusk, J. (1976): A possible volcanic-exhalative origin for lenticular nickel sulfide deposits of volcanic association, with special reference to those in Western Australia. *Can. J. Earth Sci.* **13**, 451-458.

MacLean, W.H. (1969): Liquidus phase relations in the FeS–FeO–Fe_3O_4–SiO_2 system and their application in geology. *Econ. Geol.* **64**, 865-884.

Mainwaring, P.R. & Naldrett, A.J. (1977): Country-rock assimilation and the genesis of Cu–Ni sulfides in the Water Hen intrusion, Duluth complex, Minnesota. *Econ. Geol.* **72**, 1269-1284.

McCallum, M.E., Loucks, R.R., Carlson, R.R., Cooley, E.F. & Doerge, T.A. (1976): Platinum metals associated with hydrothermal copper ores of the New Rambler mine, Medicine Bow Mountains, Wyoming. *Econ. Geol.* **71**, 1429-1450.

McQueen, K.G. (1979): *Metamorphism and Deformation of Volcanic-Associated Nickel Deposits around the Widgiemooltha Dome, Western Australia.* Ph.D. thesis, Univ. Western Australia, Nedlands.

Miller, L.J. & Smith, M.E. (1975): Sherlock Bay nickel–copper. *In* Economic Geology of Australia and Papua–New Guinea. I. Metals (C.L. Knight, ed.). *Austral. Inst. Mining Met. Mon.* **5**, 168-174.

Naldrett, A.J. (1966): The role of sulphurization in the genesis of iron–nickel sulphide deposits of the Porcupine district, Ontario. *Can. Inst. Mining Met. Trans.* **69**, 147-155.

——— (1973): Nickel sulfide deposits – their classification and genesis, with special emphasis on deposits of volcanic association. *Can. Inst. Mining Met. Trans.* **76**, 183-201.

——— & Cabri, L.J. (1976): Ultramafic and related mafic rocks: their classification and genesis with special reference to the concentration of nickel sulfides and platinum-group elements. *Econ. Geol.* **71**, 1131-1158.

———, Goodwin, A.M., Fisher, T.L. & Ridler, R.H. (1978): The sulfur content of Archean volcanic rocks and a comparison with ocean floor basalts. *Can. J. Earth Sci.* **15**, 715-728.

Nesbitt, R.W. & Sun, Shen-Su (1976): Geochemistry of Archaean spinifex-textured peridotites and magnesian and low-magnesian tholeiites. *Earth Planet. Sci. Lett.* **31**, 433-453.

Ostwald, J. & Lusk, J. (1978): Sulfide fabrics in some nickel sulfide ores from Kambalda, Western Australia. *Can. J. Earth Sci.* **15**, 501-515.

Papunen, H. (1971): Sulfide mineralogy of the Kotalahti and Hitura nickel–copper ores, Finland. *Ann. Acad. Sci. Fenn.* **A109**, 1-74.

Prider, R.T. (1970): Nickel in Western Australia. *Nature* **226**, 691-693.

Rajamani, V. & Naldrett, A.J. (1978): Partitioning of Fe, Co, Ni, and Cu between sulfide liquid and basaltic melts and the composition of Ni–Cu sulfide deposits. *Econ. Geol.* **73**, 82-93.

Ross, J.R. & Hopkins, G.M.F. (1975): Kambalda nickel sulphide deposits. *In* Economic Geology of Australia and Papua–New Guinea. I. Metals (C.L. Knight, ed.), *Austral. Inst. Mining Met. Mon.* **5**, 100-121.

——— & Keays, R.R. (1979): Precious metals in volcanic-type nickel sulfide deposits in Western Australia. I. Relationship with the composition of the ores and their host rocks. *Can. Mineral.* **17**, 417-435.

Rye, R.O. & Ohmoto, H. (1974): Sulfur and carbon isotopes and ore genesis: a review. *Econ. Geol.* **69**, 826-842.

Sangster, D.F. & Scott, S.D. (1976): Precambrian, strata-bound, massive Cu–Zn–Pb sulfide ores of North America. *In* Handbook of Strata-bound and Stratiform Ore Deposits. II. Regional Studies and Specific Deposits. **6**, Cu, Zn, Pd, and Ag Deposits. (K.H. Wolf, ed.), Elsevier, Amsterdam.

Seccombe, P.K., Groves, D.I., Binns, R.A. & Smith, J. (1977): A sulfur isotope study to test a genetic model for Fe–Ni sulfide mineralization at Mt. Windarra, Western Australia. *In* Stable Isotope Developments in the Earth Sciences (B. W. Robinson, ed.). *N.Z. Dep. Sci. Ind. Res. Bull.* **220**, 187-202.

Seifert, F. & Schreyer, W. (1968): Die Möglichkeit der Entstehung ultrabasischer Magmen bei Gegenwart geringer Alkalimengen. *Geol. Rundsch.* **57**, 349-362.

Shima, H. & Naldrett, A.J. (1975): Solubility of sulfur in an ultramafic melt and the relevance of the system Fe–S–O. *Econ. Geol.* **70**, 960-967.

USSELMAN, T.M., HODGE, D.S., NALDRETT, A.J. & CAMPBELL, I.H. (1979): Physical contstraints on the localization of nickel sulfide ore in ultramafic lavas. *Can. Mineral.* **17**, 361-372.

VILJOEN, M.J., BERNASCONI, A., VAN COLLER, N., KINLOCH, E. & VILJOEN, R.P. (1976): The geology of the Shangani nickel deposit, Rhodesia. *Econ. Geol.* **71**, 76-95.

VISSCHER, W.M. & BOLSTERLI, M. (1972): Random packing of equal and unequal spheres in two and three dimensions. *Nature* **239**, 504-507.

YAMAMOTO, M. (1976): Relationship between Se/S and sulfur isotope ratios of hydrothermal sulfide minerals. *Mineral. Deposita* **11**, 197-209.

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