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DISTRIBUTION OF COPPER AND GOLD IN OPHIOLITES FROM NEW CALEDONIA

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ABSTRACT

In noncumulate ultramafic rocks of the New Caledonian ophiolites, Cu and Au decrease with the increasing residual character of the rocks. Such a distribution suggests that both elements are enriched in the melt relative to the residue. In cumulate and basaltic rocks, the behavior of these elements differ. Cu is strongly enriched in basaltic flows and doleritic dykes, whereas early cumulates (dunites and pyroxenites) and dykes have high Au contents. Chromites from refractory ultramafic rocks are significantly lower in Au than those from layered intrusions such as Bushveld.

Keywords: gold, copper, ophiolite, chromite, New Caledonia.

SOMMAIRE

Dans les roches ultramafiques d'origine noncumulatives des ophiolites de la Nouvelle-Calédonie, les teneurs en cuivre et or diminuent lorsqu'augmente le caractère résiduel des roches. Cette diminution pourrait indiquer un enrichissement des deux métaux dans le bain fondu plutôt que dans le résidu. Dans les cumulats et les basaltes, Cu et Au se comportent différemment: le cuivre est fortement concentré dans les coulées de basalte et les dykes de dolérite, tandis que, dans les premiers cumulats (dunites, pyroxénites) et dykes associés, c'est l'or qui se concentre. La chromite est sensiblement plus pauvre en Au dans les roches ultramafiques réfractaires que dans les complexes stratiformes du type Bushveld.

(Traduit par la Rédaction)

Mots-clés: or, cuivre, ophiolite, chromite, Nouvelle-Calédonie.

INTRODUCTION

Gold and copper are two geochemically similar elements of economic importance found in many mineral deposits associated with ancient oceanic rocks (*e.g.*, Mitchell & Bell 1973, Fryer & Hutchinson 1976, Ferrario & Caruti 1979, Papino 1979, Tischler 1979). However, there is only a limited amount of information on the behavior of these elements during the evolution of the ancient oceanic lithosphere. The purpose of this paper is to present some data on the distribution of Au and Cu and, for purposes of comparison, also of Cr, Ni, Co, V and Ti in ophiolitic sequences from the Pacific island of New Caledonia.

GEOLOGICAL AND PETROLOGICAL NOTES

Mesozoic ophiolites of New Caledonia (Brothers & Blake 1973, Guillon 1975, Rodgers 1976, Prinzhofer *et al.* 1980) represent a slab of oceanic lithosphere obducted during the Eocene (Paris *et al.* 1979) onto an island underlain in part by continental rocks. The ophiolitic complex, which extended over an area of about 8000 km^2, was dismembered by erosion into several isolated massifs. The largest, the Massif du Sud, covers the southern third of the island (Fig. 1). The ophiolitic massifs have a thickness of 2–4 km and are composed mainly of ultramafic rocks. Cumulates and basaltic lavas were found only in the Massif du Sud, where they locally overlie ultramafic rocks. One of several sections where basaltic flows and cumulates are well exposed occurs at Montagne des Sources (Fig. 1). The ultramafic rocks of the New Caledonian ophiolites were intruded by dykes, mostly of basaltic composition, that are considered to be feeders for the overlying cumulates and basaltic lavas. From bottom to top, the ultramafic sequence consists mainly of plagioclase and spinel lherzolite, harzburgite and dunite. At the base of the massifs, peridotites are strongly sheared and mylonitized.

Podiform chromite deposits are abundant in the ultramafic rocks of the New Caledonian ophiolites. They occur in two structurally different positions. One type of deposit includes numerous small chromite pods and is located in the ultramafic rocks close to the contact with the cumulates (Cassard *et al.* 1981). The

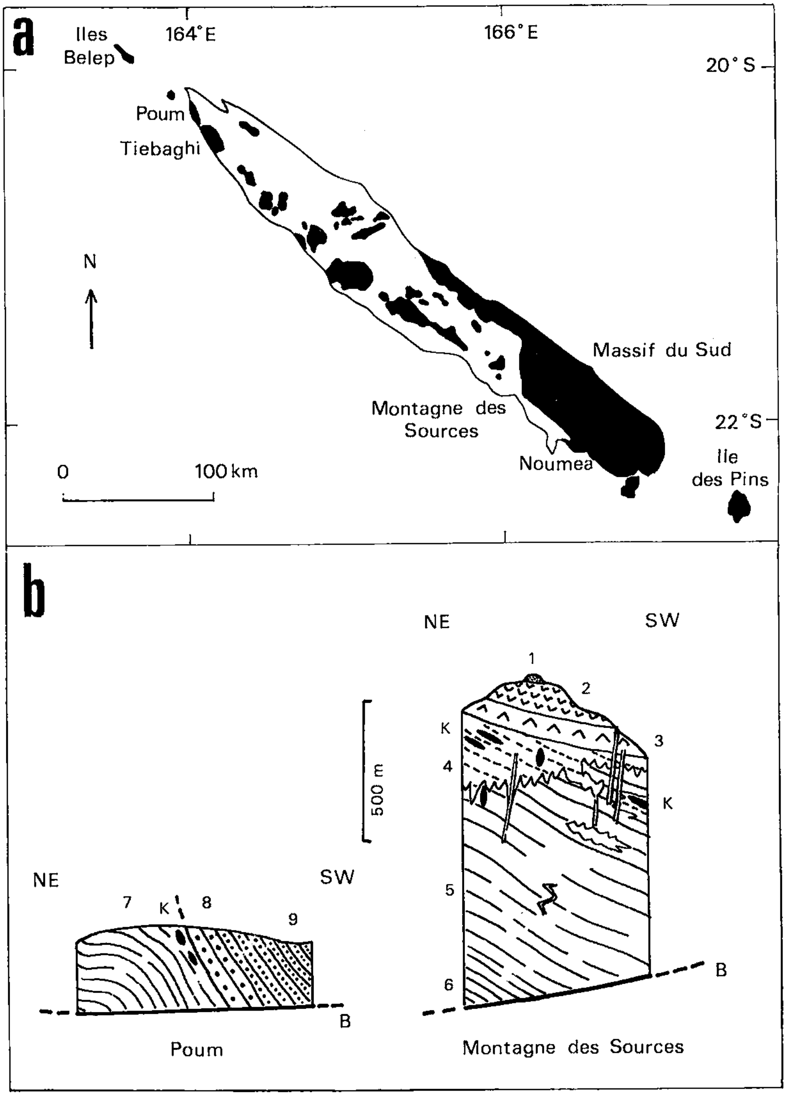

FIG. 1. a. Generalized geological map of New Caledonia. Dark areas indicate the occurrence of ophiolites. b. Schematic sections of ophiolitic sheet. Poum section is the lowest part of the sheet whereas the section of Montagne-des-Sources is the uppermost part. 1 dolerite, 2 layered gabbro, 3 ultramafic cumulate, 4 foliated residual dunite with chromite pods (K) cross-cut by basic dykes, 5, 6 harzburgite with Al increasing towards the bottom, 7 Al-rich harzburgite, 8 spinel lherzolite, 9 plagioclase lherzolite, B basal thrust-contact.

TABLE 1. COMPOSITION OF MINERAL PHASES FROM THE ULTRAMAFIC ROCKS

	Olivine (% Fo)	Orthopyroxene (% En)	Clinopyroxene	Spinel
Spinel lherzolite	91-92	91-92	Wo47 En48 Fs5	$(Al_{11.30}\ Cr_{4.53}\ Fe_{0.30})\ (Mg_{5.46}\ Fe_{2.51})$ to $(Al_{7.69}\ Cr_{7.80}\ Fe_{0.47})\ (Mg_{5.17}\ Fe_{2.78})$
Plagioclase lherzolite	90-91	87-89	Wo45 En50 Fs5	$(Al_{12.53}\ Cr_{3.08}\ Fe_{0.39})\ (Mg_{6.23}\ Fe_{1.77})$ to $(Al_{6.70}\ Cr_{8.28}\ Fe_{1.03})\ (Mg_{4.52}\ Fe_{3.48})$
Harzburgite	91-93	92-93		$(Al_{9.01}\ Cr_{6.69}\ Fe_{0.30})\ (Mg_{4.73}\ Fe_{3.27})$ to $(Al_{4.65}\ Cr_{11.27}\ Fe_{0.08})\ (Mg_{4.72}\ Fe_{3.28})$
Dunite	92-96			$(Al_{4.93}\ Cr_{10.80}\ Fe_{0.28})\ (Mg_{4.86}\ Fe_{3.14})$ to $(Al_{2.50}\ Cr_{13.34}\ Fe_{0.16})\ (Mg_{5.23}\ Fe_{2.77})$

other type, which is situated at the lherzolite–harzburgite boundary, includes the economically important deposit at Tiebaghi (Moutte 1979).

A brief summary of the mineral chemistry of the ultramafic rocks from New Caledonian ophiolites is given in Table 1 (Leblanc *et al.* 1980). The composition of the spinel ranges from chrome spinel to Al-rich chromite. Plagioclase occasionally occurs in association with spinel in lherzolites. The Mg contents of olivine and orthopyroxene and the concentrations of Cr in spinel increase from lherzolite through harzburgite to dunite. These changes are accompanied by variations in the chemical compositions of the whole rocks, involving a decrease in Al and Ti and an increase in Cr, Ni, Co and the $Mg/(Mg + Fe_{total})$ ratio passing from lherzolite to dunite. This change in the New Caledonian ophiolitic ultramafic suite from plagioclase lherzolite and spinel lherzolite to dunite has been attributed to partial melting (Leblanc *et al.* 1980); the increasingly residual character of the sequence in the direction of dunite is thus due to the removal of a progressively larger amount of melt from the primary lherzolite. The plagioclase lherzolites were probably not affected to any significant degree by the partial melting, since their chemical compositions are rather similar to the pyrolite of Green & Ringwood (1963).

The New Caledonian ophiolites also include subordinate amounts of cumulates, lavas and dykes. Cumulates, with grain sizes ranging from 1 to 5 mm, consist of pyroxenes, plagioclase (labradorite–bytownite) and olivine (Fo_{87-89}). The proportions of all three minerals, particularly olivine, are highly variable. Although olivine is chiefly present in subordinate amounts (<5%), locally it constitutes the bulk of the rocks (dunites). According to modal composition, cumulates include wehrlites, orthopyroxenites and gabbros. These rocks have typical cumulate textures and chemical compositions similar to those of oceanic cumulates (*e.g.*, Hodges & Papike 1976). They have high $Mg/(Mg + Fe^{2+})$ ratios (> 0.70 for $Fe^{2+}/Fe^{3+} = 0.15$) and high contents of Cr and Ni (in some samples > 1000 ppm), and are strongly depleted in lithophile elements.

Basaltic lavas are olivine-normative tholeiites that closely resemble recent ocean-floor basalts. They show tholeiitic trends of fractionation such as a negative correlation of Ti and V with Mg/Fe ratio. Basalts are distinctly depleted in incompatible elements and have a flat *REE* pattern with a slight depletion of light *REE* (Dupuy *et al.* 1981). The lavas are considered to be derived from noncumulate ultramafic rocks (Leblanc *et al.* 1980). Doleritic dykes consist predominantly of plagioclase (labradorite) and clinopyroxene, which is commonly replaced by poikilitic hornblende. Olivine is absent or occurs in very small amounts (1–2%).

Most dykes are olivine-normative tholeiites similar to associated lavas. However, they show a diversity of composition that may reflect the

TABLE 2. AVERAGE ABUNDANCES OF Cu, Au, Ni, Cr, Co, V AND Ti IN THE ROCKS FROM THE NEW CALEDONIAN OPHIOLITES

		Cu (ppm)			Au (ppm)			Ni (ppm)			Cr (ppm)			Co (ppm)			V (ppm)			TiO_2(%)		
		n	$\bar{X}$	s	n	$\bar{X}$	s	n	$\bar{X}$	s	n	$\bar{X}$	s	n	$\bar{X}$	s	n	$\bar{X}$	s	n	$\bar{X}$	s
Non-cumulate ultramafic rocks	Plag. lherzolite	1	50		1	10		1	1775		1	2660		1	85		1	98		1	0.10	
	Spinel lherzolite	6	15	6	3	11	7	4	2206	160	4	2633	154	4	108	1	1	59		1	0.02	
	Harzburgite	22	9	5	4	5	4	21	2374	497	21	2781	630	21	107	6	21	37	20	21	0.01	
	Dunite	14	7	3	3	1	0.9	12	2734	560	12	3512	2103	12	117	9	10	36	16	10	0.01	
Cumulates and basic rocks	Dunite	6	7	2	3	4	3	5	1702	200	5	3866	1882	5	126	15	5	38	10	5	0.01	
	Wherlite	7	10	3	3	1		7	1944	360	7	7943	1240	7	108	12	9	57	17	9	0.018	0.004
	Orthopyroxenite	3	7	4	1	10		3	1052	674	3	5050	534	3	73	15	4	106	83	4	0.047	0.025
	Cumulate gabbro	11	14	12	4	1	1	6	227	108	6	1294	984	6	33	6	12	123	38	12	0.053	0.022
	Dolerite dike	10	74	32	5	3	2	7	405	84	10	1148	203	7	50	5	9	243	51	9	0.43	0.24
	Basalt flow	7	101	96	3	1	0.9	7	185	70	7	397	242	7	43	3	7	234	13	7	0.89	0.18

n = number of samples; $\bar{X}$ = averages; s = standard deviation
Replicate determinations (6 analyses) of standard rocks are as follows: Cu: W-1 = 115 (4) ppm, BCR-1 = 19 (1), AGV-1 = 60 (2), PCC-1 = 10 (1); Cr: W-1 = 121 (3), BCR-1 = 17 (3), AGV-1 = 12 (1), UBN = 2375 (152); Co: W-1 = 46 (1), BCR-1 = 39 (1), AGV-1 = 16 (1), UBN = 103 (5); Ni: W-1 = 77 (2), BCR-1 = 15 (1), AGV-1 = 20 (2), UBN = 1935 (30); V:W-1 = 244 (7), BCR-1 = 400 (9), AGV-1 = 123 (5), PCC-1 = 27 (4); values in parenthese are 1 standard deviation.

complexity of their origin. In fact, Dupuy *et al.* (1981) have shown that although the mafic ophiolites (cumulates, dykes and lavas) are closely associated in space and time, simple processes of crystal fractionation (involving differentiation of a parental magma or variable degrees of partial melting of a single upper-mantle source) cannot explain the relationship among the various rock types. The authors suggested that the variations in chemical compositions of the mafic ophiolites can be accounted for by dynamic partial melting.

TABLE 3. ABUNDANCES OF Au IN CHROMITES

Location	Host Rock	n	Range of Au (ppb)
New Caledonia	Lherzolite	4	15 - 1
	Harzburgite	3	3 - 1
	Dunite	2	1
Bushveld	Cumulate	2	180 - 40

n = number of samples

ANALYTICAL NOTES

Cu, Cr, Co, Ni and V were determined by atomic absorption. The precision and accuracy of the method can be judged from the replicate analyses of the USGS standard rocks (Table 2). The samples were analyzed for gold by X-ray Assay Laboratories, Toronto, using neutron activation. The technique involves preconcentration by fire-assay followed by irradiation. Included in the analyzed suite were three aliquots of a single sample, which yielded a reproducibility of about 35%. Ti was determined colorimetrically. The mineral separates were approximately 95% pure. With the exception of a few peridotites, all analyzed rocks are relatively fresh.

RESULTS AND DISCUSSION

Eightly-seven ophiolite samples were analyzed for Cu, and thirty rocks for Au. The average abundances of Cu and Au in the individual rock types are given in Table 2, where they are compared with those of Ni, Cr, Co, V and TiO_2. Several samples have concentrations of Au below the detection limit (about 1 ppb). Thus, to calculate the average Au contents for the rock units, we arbitrarily took abundances of Au in these samples as 0.5 ppb. In addition. Au was determined in eleven chromites (Table 3).

The analyzed ophiolitic rocks have been subdivided into two groups: the first comprises noncumulate rocks probably representing residual material after upper mantle anatexis (Leblanc *et al.* 1980); the second group includes cumulates and basaltic rocks from lavas and dykes (Table 2).

Noncumulate ultramafic rocks

Among the analyzed ultramafic rocks, plagioclase lherzolite has the highest Cu content (Table 2). Its concentration is similar to an estimate by Wedepohl (1974) for the upper mantle (47 ppm). The other ultramafic rocks have significantly lower abundances of Cu, comparable with those from the Mid-Indian Ocean ridge (Engel & Fisher 1969) or with peridotites from Alpine intrusions (Fisher *et al.*

1969). On average, the Cu abundances decrease from plagioclase lherzolite to dunite, suggesting that during the partial melting of peridotite this element preferentially concentrates in the melt relative to the refractory residue. The variations of Cu do not correlate with the abundances of other transition elements.

As in many other ultramafic rocks (Borisenko *et al.* 1972, Li & Kornev 1972, Sighinolfi & Gorgoni 1977), the Au content of noncumulate peridotites from New Caledonia is highly variable. From the limited number of samples analyzed, it appears that, on average, lherzolites have the highest Au contents whereas dunites have the lowest concentrations. The Au abundances in lherzolites and harzburgites are comparable to those reported by Anoshin & Yemelyanov (1970) and Crocket & Teruta (1977) from ocean-floor ultramafic rocks. On the other hand, dunites are significantly lower in Au than the ocean-floor rocks or even the average of Crocket (1974) for ultramafic rocks in general (~ 4 ppb). Similar low concentrations of Au in ultramafic rocks, however, have been reported from Alpine peridotites by Crocket & Chyi (1972), Sighinolfi & Gorgoni (1977) and Ukhanov & Pchelintseva (1972). Assuming that noncumulate ultramafic rocks were mainly affected by variable degrees of anatexis, the gradual depletion of Au from lherzolites through harzburgites to dunites suggests that during melting, this element was preferentially enriched in the liquid. Although few of the peridotites show variable degrees of serpentinization, there is no systematic correlation between Au content and the degree of alteration.

In ultramafic rocks, Cr, Ni and, to some degree Co, increase with increasing Mg/(Mg + Fe) ratios, from lherzolites through harzburgites to dunites. This variation partly reflects a gradual increase of modal proportions of chromite and olivine towards dunites. However, the lower abundances of Ni in cumulate dunites, compared with equivalent noncumulate rocks, are not only related to the modal contents of olivine but probably also reflect the different origins of these rocks.

Mafic rocks and cumulates

Cumulate dunites, pyroxenites and wehrlites have very low Cu contents (Table 2), similar to those of most noncumulate ultramafic rocks. Cumulate gabbros are higher in Cu, but these contents are still low compared with basaltic rocks from dykes and lavas. On average, dolerites and basalts have abundances of Cu typical of tholeiitic basalts (Engel *et al.* 1965, Bougault & Hekinian 1974, Clarke 1970, Gunn 1971).

The increase of Cu from dunites to basalts is accompanied by variations of Ti and V. Such variations may be due to their low bulk partition-coefficients (< 1). In detail, however, the variations of Cu in these rocks seem to be more complex. Figure 2 shows that the content of Cu, particularly in dolerites and basalts, is highly variable and that the ophiolites can be subdivided into two groups. The first group, with higher Cu concentrations, consists of dolerites and basalts, whereas the second group includes cumulate dunites, orthopyroxenites, wehrlites and gabbros. Figure 2 also suggest that, unlike other transition elements (Ni, Co, V, Ti), there is no obvious correlation between Cu and the Mg/(Mg + Fe^{2+}) ratio. Such a distribution of Cu in the ophiolites, which is also observed in most magmatic rocks (Andriambololona & Dupuy 1978), cannot readily be explained by a process of fractional crystallization. It is possible, however, that the behavior of Cu in many igneous suites was affected by the presence of sulfur. The geochemical relationship between Cu and S has been well documented (Almukhamedov *et al.* 1975, MacLean & Shimazaki 1976, Moore & Calk 1971, Andriambololona & Dupuy 1978); Naldrett (1973) has suggested that in magmatic processes the geochemistry of Cu is related to the behavior of S in silicate liquids.

Although generally low, gold abundances are highly variable in cumulates, and it is difficult to evaluate the average abundances in the individual rock types. However, there are some systematic variations of Au among these rocks. Orthopyroxenites and dunites have the highest Au contents. High Au concentrations in pyroxenites have also been reported by Borisenko *et al.* (1972) and Sighinolfi & Gorgoni (1977). The cumulate dunites are higher in Au than noncumulate dunites. The Au abundances in other cumulates and basaltic lavas are very low, in fact, lower than in the dykes. The Au contents in gabbro are similar to the ocean-floor gabbros of Anoshin & Yemelyanov (1970) but are significantly lower than the Au content of one sample of oceanic olivine gabbro given by Crocket & Teruta (1977).

Chromites from several small pods of the ophiolites have also been analyzed for Au. The abundances in chrome spinels are similar, overall, to those of chromites from peridotites of the Mount Albert complex (Crocket & Chyi

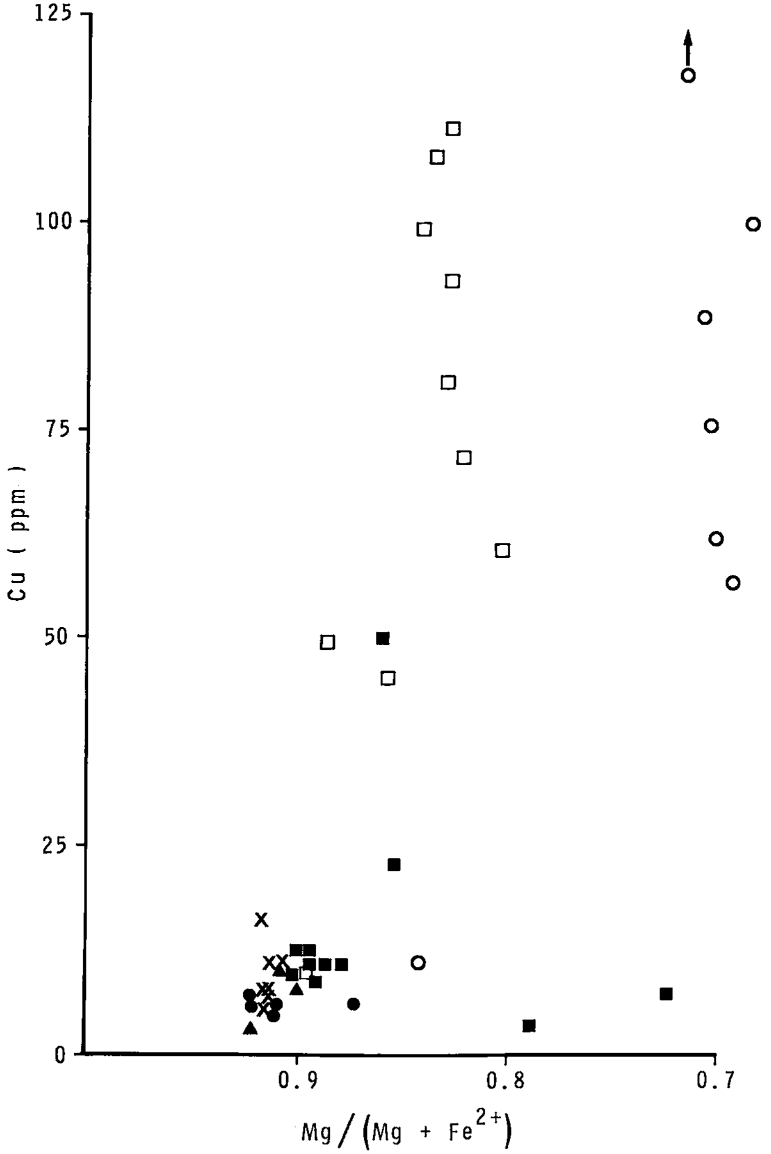

FIG. 2. Variations of Cu *versus* Mg/(Mg + Fe^{2+}) atomic ratio (for $Fe^{3+}/Fe^{2+} = 0.15$) in cumulate and mafic rocks of New Caledonian ophiolites. Basalt with arrow has 309 ppm Cu. Dunite (●), wehrlite (×), orthopyroxenite (▲), cumulate gabbro (■), doleritic dyke (□) and basaltic flow (○).

1972) but are significantly lower than chromites from the Bushveld complex (Table 3). Chromites from lherzolites have higher contents of Au than those from harzburgites and dunites.

The abundances of Cr, Ni, Co, V and Ti in basic rocks and cumulates are comparable with those of equivalent recent ocean-floor rocks (Bougault & Hekinian 1974, Bougault 1980) and rocks from other ophiolitic complexes (Montigny *et al.* 1973). Ni and Co, which show a strong positive correlation with each other, decrease from dunites through other cumulates and dykes to lavas. With the exception of high Cr abundances in orthopyroxenites, chromium displays a variation trend similar to that of Ni and Co. Unlike Cu and Au, the concentrations of Ni, Cr and Co increase with increasing Mg/(Mg + Fe) ratios, suggesting that they occur in major rock-forming minerals (pyroxenes, olivine, spinel).

CONCLUSION

In noncumulate ultramafic rocks, Cu decreases from lherzolites to dunites, suggesting that during upper mantle anatexis this element preferentially enters the melts. The Cu variations in these rocks do not show any correlation with other transition elements. On the contrary, in basalts, dolerites and cumulates, Cu has an overall positive correlation with Ti and V. Basalts and doleritic dykes have the highest Cu abundances among the analyzed rocks, whereas the cumulates are rather low in Cu. The behavior of Cu in ophiolites is probably related to S.

In noncumulate ultramafic rocks, Au seems to decrease with the increasing residual character of the rocks. Such a distribution of Au supports the suggestion of Sighinolfi & Gorgoni (1977) that Au, like Cu, is enriched in the melt relative to the residue. On the other hand, in mafic and cumulate rocks, Au has the highest contents in early cumulates and dykes, and it does not show affinities with Cu.

Although an association of noble metals with Cr–spinel in mafic and ultramafic rocks is well documented (*e.g.*, Keays & Scott 1976), it seems that the Au contents of chromite are influenced by its origin. The available data suggest that Cr–spinels crystallized from basaltic liquids (*e.g.*, in the Bushveld complex) are enriched in Au, whereas those from refractory ultramafic rocks are depleted in gold.

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